Challenges Facing Irrigation and Drainage in the New Millennium

Volume I, Technical Sessions

Meeting Human and Environmental Needs through Sustainability, Rehabilitation and Modernization

Proceedings of the
2000 USCID International Conference

Fort Collins, Colorado
June 20-24, 2000

Sponsored by

U.S. Committee on Irrigation and Drainage

Edited by

Wayne O. Deason
Bureau of Reclamation
Timothy K. Gates
Colorado State University
Darell D. Zimbelman
Northern Colorado Water Conservancy District
Susan S. Anderson
U.S. Committee on Irrigation and Drainage

Published by

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

USCID

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

USCID published the *USCID Newsletter*, proceedings of USCID meetings, and special reports; organizes and sponsors periodic technical meetings and conferences; and distributes publications of the International Commission on Irrigation and Drainage. ICID publications include the *ICID Journal*, *Irrigation and Drainage in the World*, and the *Multilingual Technical Dictionary on Irrigation and Drainage.*

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

U.S. Committee on Irrigation and Drainage
1616 Seventeenth Street, Suite 483
Denver, CO 80202

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

Printed in the United States of America
Library of Congress Number 00-103608
ISBN 1-887903-09-7 (two-volume set)
ISBN 1-887903-10-0 (Volume I)

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.

Wayne O. Deason
Conference Co-Chairman
Denver, Colorado

Timothy K. Gates
Conference Co-Chairman
Fort Collins, Colorado

Darell D. Zimbelman
Conference Vice Chairman
Loveland, Colorado

Contents — Volume I

Technical Session 5 — Water Management

MULTICRITERIA STRATEGIC PLANNING FOR REHABILITATION OF THE WIND RIVER IRRIGATION PROJECT, WYOMING

Gerald A. Gibbens[1] Timothy K. Gates[2]

ABSTRACT

This study uses multicriteria decision analysis to plan system-wide rehabilitation of the Wind River Irrigation Project in central Wyoming. The developed computerized decision support system analyzes the effects of alternative improvement strategies on various project goals. Potential improvements to the system include rehabilitation and replacement of existing facilities, reconfiguration of the system with gravity-delivery pipelines, increased water storage, on-farm improvements, managerial improvements and various combinations of each of these singular alternatives. Project goals include technical measures of increased adequacy, efficiency, dependability and equity of water delivery, as well as non-technical measures such as relative cost, social acceptability, institutional acceptability and environmental impact. The technical measures of system performance are analyzed using the MODSIM river basin network flow model and fuzzy membership functions. The non-technical measures of system performance are analyzed using either ordinal scales or ratio scales that are developed interactively with the project decision makers. Each performance measure is weighted to allow more importance to be placed on certain performance measures over others. A multicriteria decision analysis is then used to develop an aggregate ranking of each alternative based on the system performance ratio/scale and weighting. The final product gives decision makers a ranking of alternatives which can be used to identify desirable projects for future study.

INTRODUCTION

During the late part of the 19th century and early part of the 20th century, significant work was completed on irrigation systems throughout the western United States to promote settlement of the arid West. Since that time, a significant portion of these irrigation systems have fallen into various states of disrepair and are in need of significant rehabilitation and modernization if irrigation is to continue. In addition, due to the controversial nature of water development projects in the United States and throughout the world, attention is turning more

[1] Project Engineer, Montgomery Watson, 1401 Seventeenth Street, Suite 600, Denver CO 80202
[2] Associate Prof., Civil Engineering Dept., Colorado State University, Fort Collins, CO 80523

and more towards repair and rehabilitation of existing irrigation systems rather than the construction of new systems. The controversial nature of water development also affects rehabilitation of existing systems. Opinions and requirements of entities other than end-user irrigators can have significant impacts on the course of action taken. Therefore, multicriteria planning analysis is an integral part of selecting feasible rehabilitation alternatives.

The purpose of this study is to employ multicriteria decision-making techniques to evaluate and rank various rehabilitation alternatives on the Wind River Irrigation Project in Wyoming. Previous studies have developed potential system rehabilitation alternatives, such as physical system improvements, on-farm improvements, management improvements and increased storage, and provided general estimates of their affects on water supply, as well as a general cost estimate (Roncalio 1982, SCS 1993a, NRCE 1994a, NRCE 1994b, NRCE 1995). However, ranking of the alternatives has not been performed. This analysis will utilize a system simulation model to evaluate the technical performance of each of the alternatives for a given set of objectives. In addition, surveys of decision makers will be used to develop the effects of each alternative on subjective criteria. Fuzzy set theory and multicriteria decision analysis techniques will be used to rank each of the alternatives given the preference criteria and weightings for each criterion.

The technical basis for the work performed in this study is work conducted by Gates, et al. (1991) and Heyder, et al. (1991) in the San Luis Valley of Colorado. The study presents a methodology and application of multicriterion strategic planning for irrigation system improvement considering multiple planning criteria. Several alternatives for irrigation system rehabilitation are evaluated in terms of several criteria used to rank the alternatives. Whereas traditional water resources planning problems have utilized constrained single-objective problems using traditional optimization techniques, this analysis utilizes multicriteria decision- making (MCDM) to assess rehabilitation strategies.

SITE DESCRIPTION

The Wind River Irrigation Project (WRIP) is located on the Wind River Indian Reservation in Central Wyoming. The Project is currently owned and operated by the Bureau of Indian Affairs of the United States Department of the Interior, although the Shoshone and Northern Arapaho Tribes are assuming increasing levels of responsibility for operations and maintenance. The Project has a gross acreage of approximately 40,000 acres, and can be divided into two hydraulically separate units. The Little Wind Unit diverts water from the Little Wind River. The Upper Wind Unit, Johnstown Unit and Lefthand Unit all divert water out of the Wind River. Only the Little Wind Unit will be analyzed in this study. The

Little Wind Unit is the largest of the units with approximately 25,000 potentially irrigable acres. A general map of the unit is shown in Fig. 1.

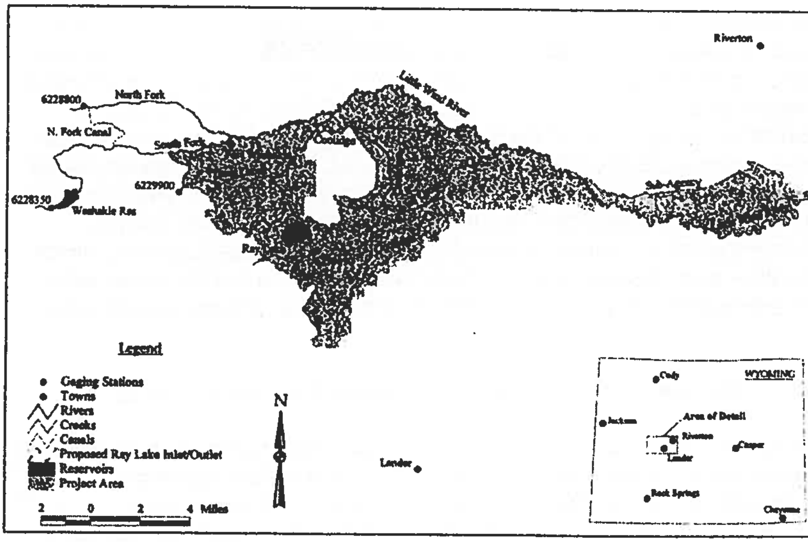


Fig. 1. Little Wind Unit, Wind River Irrigation Project

The Little Wind Unit contains two main sources of water supply: the North Fork of the Little Wind River, which has a mean annual discharge of 103,151 acre-feet; and the South Fork of the Little Wind River, which has a mean annual discharge of 93,728 acre-feet. Trout Creek and Mill Creek, which have a combined mean annual discharge of 11,031 acre-feet, are also available for diversion. All of the sources are fed primarily by mountain snowmelt and exhibit short, high duration peak flow events in late May to early June lasting only a few weeks. No groundwater is currently used as irrigation supply on the Project.

The Little Wind Unit consists of Ray, Coolidge and Sub-Agency main canals, as well as the North Fork diversion canal, which diverts water from the North Fork to the South Fork upstream of the Ray Canal headworks. Several non-project ditches, or private ditches, also divert off of the North Fork, South Fork, mainstem of the Little Wind River and Trout Creek. The Project diversion works, canal structures and canal channels are generally in poor condition. Two reservoirs serve the Little Wind Unit. Washakie Reservoir is an on-stream facility with a capacity of 7,440 acre-feet. Ray Lake is an off-stream facility with a capacity of 6,980 acre-feet. Water is primarily stored at the beginning of the irrigation season for use in the dryer months at the end of the irrigation season with little or no carryover storage. While Washakie Reservoir can serve the entire

Little Wind unit, Ray Lake currently only serves the lower portions of Coolidge Canal and Sub-Agency Canal.

The existing cropping pattern consists of 8.9 percent alfalfa, 30.3 percent grass hay, 25.6 percent pastures, 2.7 percent grains such as barley, and 3.0 percent row crops such as corn and sugar beets (NRCE 1994b). The remaining 29.4 percent of assessed lands are idle, resulting in 17,600 irrigated acres. Current irrigation methods primarily consist of flood and contour irrigation. The use of gated pipe has increased in recent years due to introduction of a cost-share program between the Tribes and individual irrigators. The use of sprinkler systems is very limited, with a few side-roll sprinklers used to irrigate alfalfa fields. Formal project drainage systems are primarily limited to earthen ditches ranging from five to ten feet below grade designed to move shallow return flows out of the ground water and back into the irrigation system. Few formal on-farm drainage systems exist.

IRRIGATION SYSTEM IMPROVEMENT ALTERNATIVES

Several structural and non-structural system improvement alternatives have been proposed for the Wind River Irrigation Project. Many of these improvements are not mutually exclusive. Therefore, combinations of the alternatives are considered in the analysis. A listing of the alternatives and their combinations are shown in Table 1. The effects of the system management improvements, on-farm improvements, rehabilitation and reconfiguration will be simulated in the model through increased efficiencies. The increase in storage will be simulated through changes in the model reservoir capacities.

Table 1. Irrigation System Improvement Alternatives

Alternative No.	Alternative Description
Singular Strategies	
1	Existing System
2	System Management Improvements
3	Rehabilitation of Existing System
4	Reconfiguration of Existing System
5	On-farm Improvements
6	Increased Storage
Combined Strategies	
7	Rehabilitation and On-farm Improvements
8	Reconfiguration and On-farm Improvements
9	Rehabilitation and Increased Storage
10	Reconfiguration and Increased Storage
11	Rehabilitation, On-farm Improvements and Increased Storage
12	Reconfiguration, On-farm Improvements and Increased Storage

Non-Structural Alternatives

The current irrigation project is primarily managed without many of the technologically advanced tools available to irrigation project managers today. The Project does not have a system simulation model, rule curves for reservoir operations or models which can predict system inflows based on available snowpack and precipitation. In addition, fee assessment collection and routine maintenance suffer due to understaffing. The improved management alternative has been included in the analysis to improve these tasks within the irrigation office, some of which are already underway in the irrigation office. In addition, all of the improvement alternatives considered in the analysis assume that some form of improved system management will occur along with the alternative.

Although current methods of irrigation can be effective, other irrigation alternatives exist which could more efficiently apply water to the crops and result in less diversion requirements for the system. The systems include the increased use of gated pipe, side-roll sprinklers and center-pivot sprinklers, as well as the training and increased management of irrigators. The Natural Resources Conservation Service (NRCS, formerly SCS) has provided several alternatives for increased on-farm efficiencies, ranging from simply increasing gated pipe use by 24 percent, to complete conversion of all farms to sprinkler irrigation (SCS 1993a). The most likely improvement scenario, as indicated by previous studies, was chosen. This scenario includes ten percent gated pipe, 44 percent gated pipe with surge, two percent concrete-lined ditches, two percent sprinkler, 30 percent contour flood and 12 percent uncontrolled flood (SCS 1993a).

Delivery System Alternatives

The rehabilitation alternative considers a general "as-is" replacement of the existing structures and repair to the channels. No significant realignment or re-engineering of the project would take place as part of the work, although structures that are obviously deficient in design or canals that can easily be realigned to take advantage of certain physical features could occur. In many cases, the technology currently available in terms of structural engineering and construction techniques could result in a system that would provide a longer life than the existing structures. Although the rehabilitated system would not offer significant changes or improvements other than increased efficiencies, the irrigators and operators are familiar with the existing system and a rehabilitated system would offer proven long term reliability in water deliveries.

The reconfiguration alternative is a replacement of nearly all laterals and sub-laterals with low-pressure reinforced concrete pipe (RCP) and polyvinyl chloride (PVC) pipe distribution systems. This system could take advantage of pressure head in closed conduits to traverse uphill gradients in the alignments. For this reason, following the existing lateral alignments would not necessarily be required, hence the project would be reconfigured. The advantages of reconfiguration include improved project viability, a decrease in operations and maintenance costs, increased system reliability, use of gravity pressure for sprinklers, reduced environmental impacts, and conserved water (NRCE 1994b).

Storage Alternatives

Due to topographical, hydrologic, geotechnical and environmental constraints, the enlargement of Ray Lake was considered as the only feasible storage enlargement alternative available for the Little Wind Unit (NRCE 1995). Studies have shown that there exists potential to enlarge Ray Lake to beyond 50,000 acre-feet (WWC 1995). The Ray Lake System Analysis report (NRCE 1995) indicates that an active pool volume of 26,000 acre-feet would provide full demand satisfaction for the 80 percent exceedence year (or that 20 percent of the years would experience some type of shortage). This 26,000 acre-foot alternative is used in the simulation model as the proposed Ray Lake enlargement capacity. In addition to reservoir enlargement, enlargement of the inlet canals would be required to adequately fill the reservoir and two additional outlet canals would be required to distribute storage to a larger portion of the irrigation system, including the upper portion of Coolidge Canal and the lower portion of Ray Canal.

Combinations of Alternatives

Many of the alternatives can be combined to offer more benefits to the project than the singular alternatives alone. Each of the system repair alternatives was considered in combination with on-farm improvements alone and the increased storage alternative alone. In addition, a combination of the system improvements, on-farm management and increased storage also were considered. Although the reconfiguration and rehabilitation alternatives considered in this analysis are mutually exclusive, further scenarios could be considered that involve partial rehabilitation and partial reconfiguration. This type of scenario has not been considered in this analysis, but it is anticipated that under the rehabilitation alternative, some reconfiguration of the project could occur, especially for laterals that contain numerous drop structures or larger laterals that run along major roadways and pose hazards to motorists.

SYSTEM SIMULATION METHODOLOGY

The Little Wind River basin was modeled to determine the criterion function values of the technical criteria. The simulation model considered major system inflows, WRIP diversions from the River and its tributaries, and major private ditch diversions from the river and its tributaries. Inflows to the system were based on USGS gaged flows that are generally located upstream of all diversions.

Irrigation system diversions were based on calculated crop water requirements, effective rainfall and irrigation system efficiencies.

The system simulation has been performed on a weekly time basis, with a study period from water year 1977 to 1997. Daily historical streamflow data were available from several stations throughout the Little Wind River Basin for various periods of record. The North Fork of the Little Wind, South Fork of the Little Wind, Trout Creek and Mill Creek gaging stations represent "natural" flows, as no accretions or diversions take place from the river upstream of the gaging station. Climatic data were available from Lander, Riverton and Fort Washakie. Missing data, primarily precipitation data, were filled in using regression techniques. In addition, North Fork, Trout Creek and Mill Creek data were correlated to the South Fork data using regression analysis techniques.

Irrigation Water Requirements

The main demands within the Little Wind River basin are irrigation water requirements. Because of the arid climate of the area, a significant portion of the crop gross water requirement comes from irrigation water. Evapotranspiration calculations were performed for each weather station (Lander, Fort Washakie and Riverton), and then prorated at each service area based on the proximity and relative similarity in climate to the base stations. The FAO-24 Radiation method developed by Doorenboos and Pruitt (1977) was selected for this analysis. This method allows computation of evapotranspiration on a weekly basis and generally predicts evapotranspiration in arid climates at or slightly above measured lysimeter evapotranspiration (Jensen 1990). Evapotranspiration calculations were calibrated at each weather station with the Penman-Monteith method calculated at the Lander station. Crop coefficients were derived from University of Wyoming Cooperative Extension data (Pochop et al. 1992) and SCS data (SCS 1993b).

Irrigation Efficiencies: Efficiencies were divided into two categories. Conveyance efficiencies were defined as the efficiency which accounts for losses between the time the water is diverted out of the river to the time the water reaches the farm turnout structure. On-farm efficiencies account for water losses that occur at the farm level, from the time the water is delivered to the farm to the time water is taken up by crops. Overall efficiency is the product of the conveyance efficiency and the on-farm efficiency.

Several studies have been conducted on the potential for increased efficiencies. Roncalio (1982) suggested that on a system-wide basis with redistribution of return flows the existing overall efficiency would be approximately 35 percent with potential for improvement to 40 percent by utilizing improved management practices. NRCE (1994a) found through water balances and basin-wide modeling that existing on-farm efficiencies are approximately 47 percent, and when factored with an 85 percent distribution efficiency, result in an overall efficiency of 40 percent. In addition, NRCE (1994a) estimated that conveyance efficiencies would increase by five percent due to rehabilitation and ten percent due to reconfiguration. Based on these analyses, Table 2 shows the efficiencies used for evaluation of alternatives in this study.

Table 2. Efficiencies Used in this Analysis

Scenario	Conveyance Efficiency	On-farm Efficiency	Overall Efficiency
Existing System	85.0%	41.2%	35.0%
Existing with mngt. improvements	85.0%	47.0%	40.0%
Rehab. with no on-farm improvements	90.0%	47.0%	42.3%
Rehab. with on-farm improvements	90.0%	50.2%	45.2%
Recon. with no on-farm improvements	95.0%	47.0%	44.7%
Recon. with on-farm improvements	95.0%	50.2%	47.7%

Notes:
(1) All improvement alternatives assume management improvements

<u>Leaching Requirements:</u> The overall salinity levels in the irrigation water supply at the Ray and Coolidge Canal diversions are within the range of no restrictions as identified by the NRCS (Grasso 1995, Daddow 1996). The Sub-Agency Canal diversions are within the range of slight restrictions. Basin inflows above Washakie Reservoir are within the low hazard class identified by the USGS. In addition, it is clear that existing irrigation water application is flushing a significant amount of salts from the soils and into return flow drains due to the increase in salinity from the upper portions of the basin to the lower portions of the basin. Because of the high soil salinity rating for over 50 percent of the arable soils within the unit, any improvements in on-farm efficiencies must take into account leaching requirements of the soils. However, estimations of leaching requirements using the standard NRCS approach indicated that return flows for all alternatives are greater than the maximum leaching requirements calculated. Therefore, it has been assumed in this study that all leaching requirements are satisfied on a system-wide basis through deep percolation, which is accounted for in on-farm efficiencies.

<u>System Simulation Model</u>

The system simulation model has been constructed using the MODSIM River Basin Network Flow Model. MODSIM is a generalized network flow model that uses an optimization algorithm to simulate water allocation in river basins according to physical, hydrological and institutional parameters and constraints (Labadie 1995). The network is represented by a collection of links and nodes that contain physical information regarding the network. Systems inflow, reservoir and demand points are represented by nodes. Canals, rivers and other conveyance mechanisms are represented by links. The model allows input of basic data requirements, as well as more complex network operating parameters such as water rights (including storage rights accounting), exchanges, instream flow requirements, augmentation plans, and rule curves, all of which can vary with each time period. Microsoft Excel has been used as the data preprocessor and postprocessor.

MULTICRITERIA DECISION ANALYSIS METHODOLOGY

Multicriteria decision analysis provides a systematic framework for evaluating and ranking alternative strategies based on several decision criteria. Criteria can range from technical water supply and distribution goals to subjective and non-commensurable goals such as social acceptability, cost and environmental goals. For this analysis, both technical and subjective decision criteria, or goals, were assigned commensurable values using fuzzy sets and ordinal scales as determined from interviews with decision makers. Each alternative could then be ranked based on their scores for each of the decision criteria. Two ranking methods were used in this study: the weighted average method and the PROMETHEE II method.

Criterion Functions

In conjunction with recommendations made by the Wind River Water Resources Control Board (Water Board), eight decision criteria were selected for the analysis, and are shown in Table 3. Four of these decision criteria are technical criteria that can be measured given the results of the system simulation model. The other four criteria are non-technical criteria that were evaluated using ratio scales based on interviews with decision makers. Each criterion was assigned a function for alternative ranking. Criterion functions for technical criteria were based on the system simulation model and fuzzy membership functions. Criterion functions for non-technical criteria derived from surveys of decision makers.

Table 3. Decision criteria

No.	Technical Criteria	No.	Non-technical Criteria
1	Adequacy	5	Capital Costs
2	Dependability	6	Operation and Maintenance (O&M) Costs
3	Equity	7	Long-term Viability
4	In-stream flows	8	Social/Tribal Acceptability

Each of the technical criteria are a measure of the ability of the irrigation system to serve demands, and have been defined in previous reports (Gates et al. 1991). The following equations present the definition of each of the measures as they relate to specific irrigation system variables:

Adequacy: $$P_A = \left(\frac{1}{T}\right)\sum_T\left[\frac{1}{\Re}\sum_{\Re}(p_A)\right] \quad (1)$$

Dependability: $$P_D = \left(\frac{1}{\Re}\right)\sum_{\Re} CV_T(p_A) \quad (2)$$

Equity: $$P_E = \left(\frac{1}{T}\right)\sum_T CV_{\Re}(p_A) \quad (3)$$

Where:

p_A $= Q_D/Q_R$ for $Q_D \leq Q_R$
$= 1$, otherwise
(Note: in this analysis, Q_D was always less than or equal to Q_R);

Q_R $= Q_R(x_i, t_i)$ = the amount of water required at diversion points x_i during time period t_j ($j = 1, N$);

Q_D $= Q_D(x_i, t_i)$ = the amount of water delivered to diversion points x_i during time period t_j ($j = 1, N$);

CV_T = temporal coefficient of variation over the time period T;

$CV_{\Re}$ = spatial coefficient of variation over the region $\Re$.

The Project is currently not operated to maintain instream flows. Also, reserved water rights are not permitted to be used for maintenance of instream flows. However, the Tribes have realized the importance of instream flows to maintain a biological equilibrium in the river ecosystem. Therefore, instream flows have been included in this analysis as a technical criterion. The following equation represents the instream flow performance measure, P_{IF}:

Instream Flows: $$P_{IF} = \left(\frac{1}{T}\right)\sum_T\left[\frac{1}{R}\sum_R(p_{IF})\right] \quad (4)$$

Where:

p_{IF} $= Q_A/Q_{RR}$ for $Q_A \leq Q_{RR}$
$= 1$, otherwise;

Q_{RR} $= Q_{RR}(r_i, t_i)$ = the amount of water required within reach r_i during time period t_j ($j = 1, N$);

Q_A $= Q_A(r_i, t_i)$ = the actual amount of water flowing within reach r_i during time period t_j ($j = 1, N$);

N_r = total number of reaches.

A Monte Carlo analysis was used to obtain the expected value, $E_\omega(P_i)$ of each performance measure over a number of possible realizations, ω. Each realization represented an irrigation season in this study. Therefore, the total number of time periods T was equal to the number of realizations, ω, and the expected values for each measure was the average over the total number of realizations. The number of realizations in this analysis is limited to the study period, or 21 years.

Because of the subjective qualifications, decision makers often do not perceive a linear correspondence between values of the performance measures and the degree of satisfaction of the respective criteria. Therefore, fuzzy sets are used to transform the expected values of each performance measure into membership functions for use in the multicriteria decision analysis. Fuzzy sets allow a degree of uncertainty and preference to be used in the assessment and ranking of alternative strategies. Data for the membership functions were obtained through interviews with the decision makers. Curves were then fitted through the data points to estimate the membership function, μ, for each of the performance measures. These curves are shown in Fig. 2.

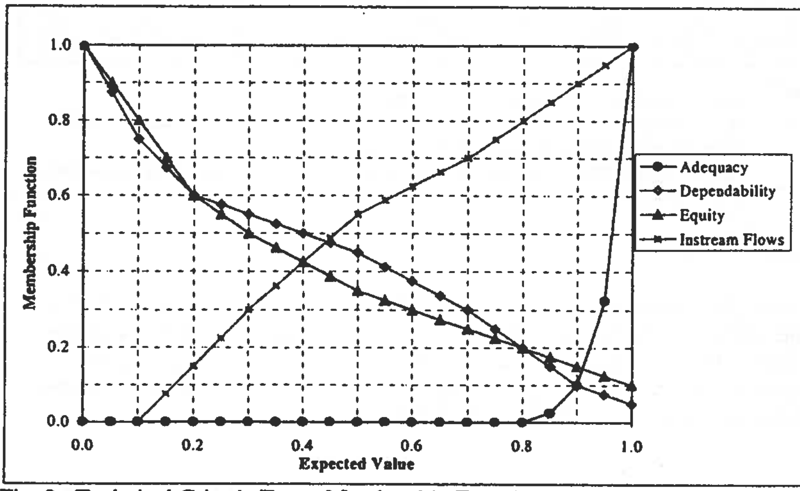


Fig. 2. Technical Criteria Fuzzy Membership Functions

Non-Technical Criteria: Non-technical criteria include capital engineering and construction costs, operations and maintenance costs, fulfillment of long-term project viability and social/Tribal acceptance. Unlike the technical criteria, the evaluation of these criteria cannot be obtained through simulation model results. Instead, the criteria are assigned values based on an ratio or ordinal scale. Ratio scales involve a ranking of values based on relative preference, such as an assignment of values between zero and ten for each alternative. Ordinal scales simply rank the alternatives in order of preference, with no gage for preference as related to each other. In this analysis, ratio scales have been used to assign values for all alternatives. To develop commensurable values for the weighted average method, a linear normalization of the scores for each alternative, i, was performed to develop criterion function values C_i, as shown in Table 4. For each criterion function value, 1.0 indicates the most preferred alternative.

Table 4. Non-technical Criterion Function Values

Alt. No.	Capital Costs [1]		O&M Costs [2]		Long-term Viability [3]		Social/Tribal Acceptability [4]	
	$ x 10^6	C_C	Rating	C_{OM}	Rating	C_V	Rating	C_A
1	$0	1.00	0	0.00	0	0.00	0.0	0.00
2	$0.15	1.00	4	0.40	5	0.50	10.0	1.00
3	$19.2	0.57	5	0.50	10	1.00	8.0	0.80
4	$14.0	0.69	10	1.00	10	1.00	10.0	1.00
5	$8.0	0.82	3	0.30	5	0.50	10.0	1.00
6	$12.5	0.72	8	0.80	5	0.50	10.0	1.00
7	$29.9	0.33	4	0.40	10	1.00	10.0	1.00
8	$24.7	0.45	6	0.60	10	1.00	7.0	0.70
9	$34.2	0.24	5	0.50	10	1.00	10.0	1.00
10	$29.0	0.35	10	1.00	10	1.00	8.0	0.80
11	$44.9	0.00	5	0.50	10	1.00	10.0	1.00
12	$39.7	0.12	8	0.80	10	1.00	7.5	0.75

Notes:

(1) Costs from (NRCE 1994b) indexed to 2000.

(2) Based on interviews with Water Board. Values indicate expected O&M costs, with highest rated alternatives requiring the least O&M costs.

(3) Ability of alternative to provide facilities necessary for long-term project operations.

(4) Based on interviews with Water Board.

Ranking Methods

The weighted average method is a more traditional method of ranking which ranks alternatives based upon the worth of the alternative, or the average of the weighted sum of its criterion function values. The alternative which has the greatest worth receives the highest ranking. The worth of the alternative can be defined as (Gates et al. 1991; Labadie 1999):

$$MC_j = \sum_i^K w_i C_{ij} \qquad (5)$$

where: MC_j = worth for alternative j

w_j = weighting factor for criterion i, where $\Sigma w_j = 1$.

C_{ij} = criterion function value for criterion i and alternative j

K = total number of criteria

Weights for each of the criteria also were included in the surveys of the Water Board. The Water Board was asked to weight each of the alternatives based on their importance in decision making. A ratio scale of zero to ten was used for the weights, with ten indicating the most important criterion. The advantage of the weighted average method is its simplicity and its traditional use as a ranking method. Its disadvantage is the requirement that quantitative scales, such as ratio scales, must be used to define the criterion function values.

The PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation) II is an outranking method where the multicriteria are replaced by a single criterion that establishes a complete dominance relation between alternatives. Comparisons between alternatives are evaluated to measure a dominance relationship between the pair. Preference relations, $P(a,b)$, measure the intensity of the preference of given alternative a to a given alternative b. General preference relations include no preference, weak preference, strong preference and strict preference (Labadie 1999). Preference function values, $H(d)$, can be used to numerically describe the preference relation $P(a,b)$. Values of the preference function vary from zero for those alternatives which are indifferent to one for those alternatives in which one alternative is strictly preferred over the other alternative.

The PROMETHEE II method provides a complete preorder of alternatives. This is accomplished using a net outranking flow:

$$\phi(a) = \phi^+(a) - \phi^-(a) \tag{6}$$

where: $\phi(a)$ = net outranking flow;
$\phi^+(a)$ = the amount by which alternative a outranks all other alternatives;
$\phi^-(a)$ = the amount by which alternative a is outranked by all other alternatives.

Outranking flows are calculated from preference function values for each pairwise comparison of alternatives. Ranking of the alternatives is then made with the alternative containing the most positive net outranking flow being the highest ranked alternative. Preference function structures are chosen based on the type of data and the general relative strength and structure of the dominance relation between alternatives. Criteria in which there is a high degree of uncertainty in the preference function values would have structures with some degree of indifference threshold, while those with strict preference may have a structure with no indifference zone. Criteria in which the preference is related to the magnitude of difference between the preference function values may use a function structure which allows this variable nature.

RESULTS

Average annual diversion requirements ranged from 108,092 acre-feet for alternative 1 (existing system) to 79,373 acre-feet for alternative 12, with average annual deliveries ranging from 92,215 to 78,159 acre-feet, respectively. The number of years with full demands met ranged from five percent for the existing system to 81 percent for alternative 12.

Criterion function values for the four technical criteria were determined from the performance indicators based upon the simulation results. Table 5 presents a summary of the performance indicators and criterion function values for each of the technical criteria. The alternatives which include increased storage (alternatives 6 and 9-12) all had adequacy measures which met or exceeded the maximum values for those alternatives that do not include increased system storage. This shows the importance of increased storage for improved system adequacy. Dependability, equity and instream flows generally improved with increasing project efficiencies.

Table 5. Performance Indicators and Criterion Function Value Results

Alt.	Adequacy		Dependability		Equity		Instream Flows	
No.	$E_d(P_A)$	μ_A	$E_d(P_D)$	μ_D	$E_d(P_E)$	μ_E	$E_d(P_{IF})$	μ_{IF}
1	0.85	0.03	0.17	0.65	0.08	0.84	0.40	0.43
2	0.89	0.08	0.15	0.68	0.06	0.87	0.41	0.44
3	0.90	0.10	0.14	0.69	0.06	0.88	0.41	0.44
4	0.91	0.15	0.13	0.71	0.05	0.90	0.42	0.44
5	0.90	0.11	0.14	0.70	0.06	0.89	0.41	0.44
6	0.97	0.58	0.07	0.82	0.02	0.97	0.43	0.46
7	0.92	0.17	0.12	0.72	0.05	0.90	0.41	0.44
8	0.93	0.21	0.12	0.72	0.05	0.91	0.42	0.45
9	0.98	0.66	0.06	0.84	0.02	0.97	0.42	0.46
10	0.98	0.73	0.06	0.86	0.01	0.97	0.42	0.45
11	0.98	0.74	0.06	0.86	0.01	0.97	0.42	0.45
12	0.99	0.81	0.05	0.88	0.01	0.98	0.42	0.45

<u>Ranking</u>

The results of both the weighted average and PROMETHEE II multicriteria decision analysis schemes are shown Table 6. Alternative 10, reconfiguration and increased storage, was the highest ranking alternative in both methodologies. In general, the highest ranked alternatives included increased storage and/or reconfiguration. The highest ranking rehabilitation alternative was alternative 9 in the weighted average method and alternative 11 in the PROMETHEE II method. Both of these alternatives incorporate increased storage with rehabilitation, and alternative 11 includes on-farm improvements.

CONCLUSION

The results clearly show the advantages of using a multicriteria decision analysis for investigation of irrigation system rehabilitation alternatives. Previous techniques primarily have considered only technical goals. But, for the Wind River Irrigation Project, as well as many other projects, non-technical goals can have equal or more importance than technical goals. In addition, multicriteria analysis allows a systematic procedure for ranking based on sometimes conflicting goals, such as increased irrigation adequacy, long-term project viability, capital costs and Tribal/social acceptability. This same benefit also allows a sensitivity analysis of alternative scoring schemes (fuzzy sets and ratio scales) and alternative weighting schemes to determine the overall affect of individual goals on the project. In this analysis, it was found that those alternatives which ranked highest in technical criteria also ranked high in the multicriteria analysis. However, the alternative with the highest technical ranking did not rank first in the multicriteria analysis.

Table 6. MCDA function values and rankings

Alt. No.	Alternative Description	Weighted Average		PROMETHEE II	
		MC_i	Rank	$\phi(a)$	Rank
1	Existing System	0.370	12	-8.01	12
2	System Management Improvements	0.592	9	-3.78	11
3	Rehabilitation of Existing System	0.611	8	-2.75	10
4	Reconfiguration of Existing System	0.727	2	1.60	6
5	On-farm Improvements	0.558	11	-2.72	9
6	Increased Storage	0.714	4	3.14	3
7	Rehab. and On-farm Improvements	0.588	10	-0.70	8
8	Recon. and On-farm Improvements	0.620	7	0.05	7
9	Rehabilitation and Increased Storage	0.689	5	2.57	5
10	Reconfiguration and Increased Storage	0.777	1	4.01	1
11	Rehab., On-farm Impr. and Inc. Storage	0.665	6	2.94	4
12	Recon., On-farm Impr. and Inc. Storage	0.721	3	3.65	2

The purpose of this analysis was to present the Water Board with a tool for making rational decisions regarding future irrigation system improvements within the Wind River Irrigation Project. The analysis is not intended to provide a firm answer to the question of which improvements should be selected. However, the results show that increased storage is the single most effective means to increase system adequacy, and is in the top-ranking alternatives in both analysis methodologies. However, increased storage alone does not address long-term viability of the project. Either rehabilitation or reconfiguration will be required if the project is to survive for the long term; the existing system will continue to degrade until many of the channels and structures can no longer deliver irrigation water and/or catastrophic failures occur. The results of the analysis could also be used to stage improvements. Since all high-ranking alternatives include increased storage, Ray Lake could be expanded first. Then, the chosen delivery system improvement, either reconfiguration or rehabilitation, could be implemented, followed by on-farm improvements.

REFERENCES

Daddow, R.L. (1996). "Water Resources of the Wind river Indian Reservation, Wyoming." U.S. Geological Survey, Water-Resources Investigations Report 95-4223. Cheyenne, Wyoming.

Doorenbos, J., and Pruitt, W. O. (1977). "Guidelines for Predicting Crop Water Requirements." *FAO Irrig. and Drainage. Paper No. 24*, 2nd ed., FAO, Rome, Italy.

Gates, T.K., Heyder, W.E., Fontane, D.G., Salas, J.D. (1991). "Multicriterion Strategic Planning for Improved Irrigation Delivery. I: Approach." *Journal of Irrigation and Drainage Engineering*. ASCE, 117(6), 897-913.

Grasso, D.N., Jennings, M.E. and Sadler, J.S. (1995). "Field Screening of Water Quality, Bottom Sediment, and Biota Associated with Irrigation Drainage, Wind River Indian Reservation, Wyoming, 1992-93." U.S. Geological Survey, Open-File Report 95-121. Cheyenne, Wyoming.

Heyder, W.E., Gates, T.K., Fontane, D.G., Salas, J.D. (1991). "Multicriterion Strategic Planning for Improved Irrigation Delivery. II: Application." *Journal of Irrigation and Drainage Engineering*. ASCE, 117(6), 914-934.

Jensen, M.E., Burman, R.D. and Allen, R.G., eds. (1990). Evapotranspiration and Irrigation Water Requirements. Irrigation and Drainage Division, ASCE, Manuals and Reports on Engineering Practice No. 70. New York.

Labadie, J.W. (1995). "MODSIM: River Basin Network Flow Model For Conjunctive Stream-Aquifer Management Program User Manual and Documentation." Colorado State University, Fort Collins, Colorado. September.

Labadie, J.W. (1999). "Engineering Decision Support and Expert Systems." Class Notes, EG610, Colorado State University, spring 1999 semester.

Pochop, Larry, Travis Teegarden, Greg Kerr, Ronald Delaney and Victor Hasfurther. (1992). "Consumptive Use and Consumptive Irrigation Requirements in Wyoming." University of Wyoming Coorperative Extension Service and Wyoming Water Research Center, M87. October.

Natural Resources Consulting Engineers (NRCE). (1994a). "Draft Summary of the Wind River Basin Water Management Studies." Fort Collins, Colorado.

Natural Resources Consulting Engineers (NRCE). (1994b). "Wind River Irrigation Project Assessment and Plan." Fort Collins, Colorado. June.

Natural Resources Consulting Engineers (NRCE). (1995). "Ray Lake System Analysis." Fort Collins, Colorado. July 26.

Roncalio, Teno. (1982). "Report Concerning Reserved Water Rights Claims By and On Behalf of The Tribes of the Wind River Indian Reservation, Wyoming." District Court of the Fifth Judicial District, State of Wyoming, Civil No. 4993. December 15.

Soil Conservation Service (SCS). (1993a). "Irrigation on-farm report for Wind River Basin Water Supply Study." United States Department of Agriculture. February. [Note: Only the

Interim report, May 1992, was available for review in its full text. Materials extracted from the Interim report were verified with other sources referencing the Final report.]

Soil Conservation Service (SCS). (1993b). National Engineering Handbook (NEH, Part 623, Chapter 2 - Irrigation Water Requirements. United States Department of Agriculture. September.

Western Water Consultants (WWC). (1995). "Ray Lake Dam Rehabilitation and Enlargement Final Conceptual Design of Enlargement Report." Laramie, Wyoming. January.

ENVIRONMENTAL MANAGEMENT PLAN FOR THE IRRIGATION IMPROVEMENT PROJECT (IIP) - TAJAN SUBPROJECT

Ramiz Namvargolian[1] G. Ayaz[2]
Adel Bichara[3] Andrew Bond[4]

ABSTRACT

The Irrigation Improvement Project (IIP) is funded jointly by the Government of Iran and the World Bank. The project with an estimated cost of US$ 312 million started in 1994 and is expected to be completed by end of 2001.

The project implements irrigation improvement measures in about 107,000 hectares in four subproject areas located in northern and southern Iran. Existing irrigation and associated agricultural practices are having environmental impacts on natural and important man made ecosystems both within and downstream of each of the subprojects areas particularly on local and migratory wildlife. A major part of IIP is an Environmental Management Plan (EMP) which includes in part a) strengthening the institutions and training the personnel responsible for addressing long-term environmental issues related to irrigated agriculture, b) establishing agricultural chemicals management program and surface water and groundwater quality monitoring programs, and c) preparing special studies and mitigation plans to address long-term environmental management issues related to the development of irrigated agriculture.

Good progress has been made with respect to the civil engineering works associated with the project, but a number of issues have delayed environmental mitigation activities associated with the project.

[1] Senior Groundwater Engineer, TechLink Environmental Inc., Fort Collins, CO 80526; rnamvar@TechLink.com

[2] Environmental Specialist, Khazar-Ab Consulting Engineers, Pasdaran Blvd, Sari, Iran.

[3] Senior Irrigation Engineer, Middle East and North Africa Region, The World Bank, 1818 H Street, N.W., Washington, DC 20433. Abichara@worldbank.org

[4] Environmental Specialist, The World Bank, 1818 H Street, N.W., Washington, DC 20433. Abond@worldbank.org

Special environmental issues of IIP, particularly those associated with the Tajan Subproject and related mitigation actions are presented in this paper. The traditional irrigation in the Tajan subproject area on the Caspian coast of Iran has resulted in the creation of large irrigation water storage ponds locally known as "ab-bandan". Ab-bandans have evolved into complex man-made and man-maintained ecosystems which are highly valuable to local residents and to local and migratory wildlife. A plan of management for the complex ecosystems of Ab-bandans is being developed.

IRRIGATION IMPROVEMENT PROJECT DESCRIPTION

Irrigation receives the largest amount of public agricultural investment in the developing countries. From 1950 through 1993, seven percent of World Bank lending (US$ 31 billion) has been devoted to irrigation projects (Jones, 1995). About 69 percent of Bank lending has gone to Asia, while the other 31 percent has been split between Africa, the Americas, and Europe. According to Jones (1995),

> "In the 1950s the Bank approved, on average, one irrigation project a year; in the 1960s, four per year; in the 1970s and in the 1980s, 26; and so far in the 1990s, 15. Average irrigation lending per year was $37 million in the 1950s, $343 million in the 1960s, $1,120 million in the 1970s, $1,273 million in the 1980s, and $1,032 million so far in the 1990s."

More than half of the World Bank's recent lending for irrigation projects has been for extensions, rehabilitations, and upgrades of existing systems.

The Irrigation Improvement Project (IIP) with an estimated cost of US$ 312 million is funded jointly by The World Bank and The Government of Iran (GOI). IIP includes four subprojects and preparation of all subprojects is well advanced and investments will complete and improve existing schemes thus allowing relatively quick returns in comparison with other potential subsectoral investments in irrigation. GOI is promoting a strategy of full cost recovery for operation and maintenance costs and recovery of 40 percent of on-farm development costs. The project serves as a vehicle for a dialogue on technical issues and on areas where the Bank's experience such as prevention of environmental degradation will be used to enhance the governments longer term irrigation improvement and development objectives.

The overall objectives of the project (The World Bank, 1993) are to: (a) enhance water resources management through the rehabilitation and improvement of irrigation and drainage systems in four subprojects; (b) upgrade agricultural research and extension in the four subprojects in order to raise crop output, farm incomes and foreign exchange savings through increased agricultural production; and (c) improve the planning and implementation capacity of sector institutions, including the Ministries of Agriculture, Energy, and the Department of Environment.

Location, Climate and Soils

The project with a total area of 107,000 ha and is composed of four subproject areas (Figure 1): Behbahan (11,500 ha), Moghan (35,600 ha), Zarrineh Roud (36,000 ha), and Tajan (23,900 ha). Climatic conditions in the subproject areas vary from semi-arid in the first three subprojects with average annual rainfalls of about 300 mm to sub-humid in Tajan with an average annual rainfall of 650 mm. Soils in the four areas are of alluvial origin and are deep with textures varying from silty loams to clay loams. Moderate to insignificant slopes in each of the subproject areas has led to poor drainage, and improved water management, drainage and land leveling activities are supported by the project..

Land and Farming

Before the project, 77 percent of the project area was irrigated, 16 percent was rainfed and the remaining 7 percent was marginal land used for grazing or left uncultivated, mainly due to salinity and drought problems. In general, land in the subproject areas is privately owned and farmed. Plots are small and land fragmentation is a problem in some areas. Farmers generally cooperate in traditional groups which are valuable asset to the project. Agricultural research and extension centers are present at each of the subprojects and Tajan also benefits from an additional research center dedicated to research on rice. Levels of mechanization differ in each subproject and depends largely on farm size. Farm operations are almost totally mechanized at Moghan subproject. In the other subprojects, land preparation is generally by tractor or on the small farms by power tiller. The most common fertilizer in the project area is urea followed by diammonium phosphate. Potassium sulphate and triple super phosphate are used in smaller quantities. Pesticide use is widespread with extension services providing training in pesticide use and safety.

The agricultural research stations and service centers are being strengthened through the upgrading of existing staff and through the construction of facilities and the provision of additional staff, vehicles and specialized equipment. Specialized farm machinery would be made available. Strengthening the operation and maintenance of all facilities starting from the main to the tertiary system, developing farmer participation through users groups, and addressing critical environmental issues are being emphasized. The project has provided various training and education programs.

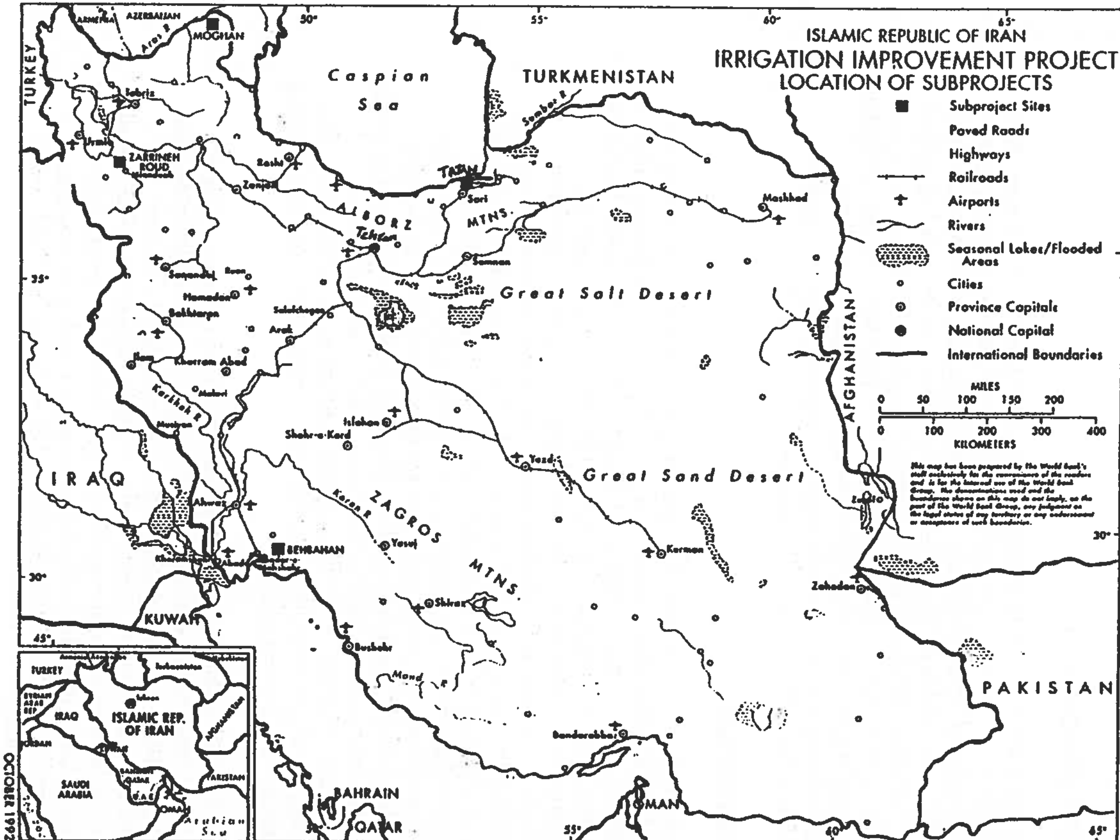


Figure 1 – Irrigation Improvement Project – Location of Subprojects.

Irrigation and Drainage Systems

The existing traditional irrigation systems or partially completed modern ones are highly inefficient in using the scarce water resources. Maintenance of irrigation and drainage networks needs major improvement. Inadequate water conveyance and inefficient on-farm water use have reduced the overall irrigation efficiency to 20 to 30 percent. As a result, there is not enough water to extend the presently irrigated area or to increase yields in the existing areas. Additionally, water logging problems in the low lands reduce crop yields and keep significant areas permanently or intermittently uncultivated. All four subproject areas receive their primary supply from existing or future water management infrastructure and based on available river flows it is expected that irrigation requirements be met at all times of the year. A planned overall irrigation efficiency of 50 percent is anticipated under the project.

The irrigation and drainage improvement section of the project includes the construction or lining of main, secondary, and tertiary canals and drains. The details of irrigation and drainage works are presented in Table 1. The project consists of the improvement and upgrading of four existing irrigation and drainage systems, serving a total of net irrigable area of about 90,600 ha and the intensification of agricultural services on these 90,600 ha and on an additional 16,400 ha in Tajan subproject area. Existing main and secondary canals are provided with concrete lining and in some areas new canals are being added. Main and secondary drains are being improved and expanded to cover all the subproject areas. The tertiary systems are being developed selectively using canalletes, concrete lined or unlined laterals, and open drains. Selective land leveling and subsurface drainage with the emphasis on water management at the tertiary and farm levels are included in the on farm development section of the project.

Environment

The environment component of IIP consists of: (i) the strengthening of the environmental management capacity of Ministries of Agriculture and Energy and Department of Environment and their provincial offices through specialized training programs and the provision of equipment; (ii) the development of agricultural chemical management programs (including integrated pest management) and model surface and groundwater monitoring programs for each subproject; (iii) erosion control programs for canal banks in Moghan and river channels in Tajan, (iv) an archaeological site survey in Behbahan; (v) special environmental management studies of the Shadegan Marshes Protected Area in Behbahan subproject area, Lake Orumiyeh National Park in Zarrineh Roud subproject area, "ab-bandan" man-made ecosystems in the Tajan subproject area; and (vi) fishery resources of Behbahan and Tajan subprojects.

Table 1 - Irrigation and Drainage Works and On-Farm Development by Subproject (World Bank, 1993).

Behbahan	Subsurface drainage on 3,300 ha; land leveling on 8,000 ha; and soil amendment on 1,700 ha.
Moghan	Concrete lining (17.5 km) and slope stabilization (60 km) on the main canal; concrete lining on secondary canals (21,000 ha); the construction of tertiary canals and drains (27,400 ha); a pumping station for the reuse of drainage return flows; subsurface drainage (11,000 ha); and land leveling (4,500 ha).
Zarrineh Roud	Concrete lining of the main canals (97 km); the extension and lining of the left main canal (17 km); construction of the lined secondary canals and surface drains (24,800 ha); a tertiary irrigation and drainage system (36,000 ha); subsurface drainage (7,500 ha); land leveling (4,500 ha); and two irrigation lift stations and one drainage pumping station.
Tajan	The construction of the lined main canal (35 km), the main drain (22 km), and secondary and tertiary canals and drains (7,500 ha).

TAJAN SUBPROJECT

Water Resources Development

The Irrigation Improvement Project is part of several large water resources development projects in Iran. In the Tajan subproject area the water resources project, extending from the Caspian Sea in the north to the Alborz Mountains in the south, includes watershed management, a storage dam, a diversion dam, irrigation development, urban and industrial water supply, electricity generation. The upper reaches of the Tajan is regulated by the storage dam and a watershed management plan for the area above the storage dam is under development. The construction of the reservoir dam has been completed recently. It is a 133 m high double curved concrete dam built on Tajan River about 40 km south of city of Sari (Figure 2). Its reservoir can hold up to 192 million cubic meters and can cause a regulated flow of 316 million cubic meters in the Tajan River. The diversion dam was built in 1995 for regulating Tajan River flow to the Tajan plain farm lands. It is located in Sari and has a length of 264 m and 18 outlet gates (Figure 2). The irrigation network consists of two main canals that extend to left and right sides of the Tajan River. Several subsidiary canals branch off these two main canals and extend to the farm lands.

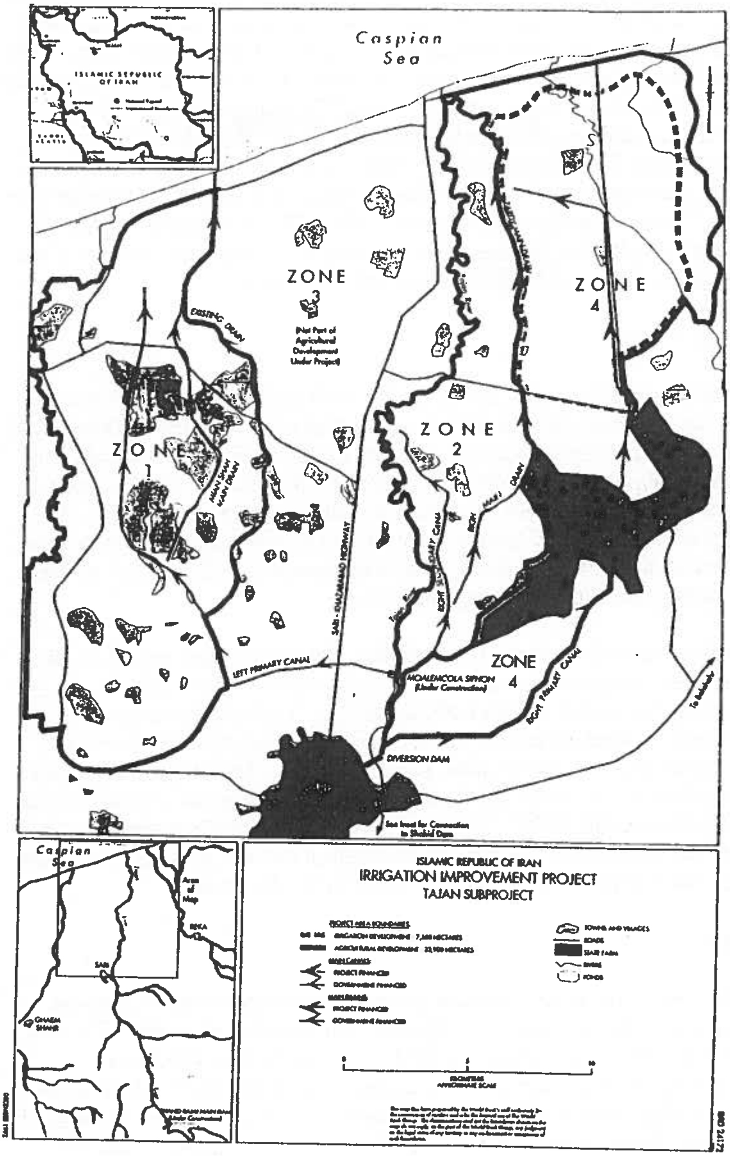


Figure 2 – Tajan Subproject.

The water resources project of Tajan is located in the eastern and western banks of Tajan River in an area of about 3500 square km in two upper and lower sections. The upper section, south of the provincial railway, is part of the Tajan basin on the northern slopes of the Alborz Mountains and extends from the reservoir dam to the city of Sari. This section with an area of about 2750 square km is the middle Tajan River basin and encompasses the eastern and western banks of the Tajan River. The middle Tajan River basin includes vast irrigated farming, main part of dry farming, major river sand and gravel exploitation, and pulp and paper and dairy industries. The lower section with an area of about 700 square km extends from the City of Sari to the Caspian Sea. The Ab-bandan ecosystems are located in the lower section on the left and right banks of the Tajan River.

Ab-bandans

Most of the irrigated farm lands are on the left bank and the rainfed lands are mostly on the right bank of Tajan River. Accordingly, the left bank of Tajan River with an area of about 40,000 hectares contains 78 Ab-bandans, and the right bank with an area of about 30,000 hectares contains 31 Ab-bandans. The Ab-bandans in the left and right banks cover about 3515 and 800 hectares, respectively. Ab-bandans have been developed mostly on lands with no direct water rights to Tajan River. More than 340,000 migratory birds come annually to Ab-bandans of Tajan plain for feeding, breeding, wintering, and nesting.

There are 649 pieces of developed Ab-bandans, with a total pond area of about 15,000 hectares, in the western and central regions of the province of Mazandaran, in the southern shores of Caspian Sea. Tajan plain contains 109 pieces of these Ab-bandans and they cover an area of about 4,300 hectares and annually reserve about 65 million cubic meters of water. Ab-bandans vary in size, with the smallest and largest in Tajan area having surface areas of 1 ha and 382 ha, respectively (Khazar-Ab, 1997). While Tajan River provides the largest quantity of water to the Ab-bandans, rainfall, irrigation return flows or drainage water, and two nearby rivers contribute to the water stored in the Ab-bandans.

Tajan River

In addition to being the most important source of agricultural water of the area, the Tajan River is the best habitat of migratory fish including sturgeons. The river originates in the Alborz mountains and after a flowing through 170 km of mountainous and flat areas terminates in Caspian Sea. Tajan River with an annual flow of 527 million cubic meter and water quality class of C2S1 is one of the most important habitats of various endemic and migratory fish among more than 90 rivers of Mazandaran province in southeastern coast of Caspian Sea.

The city of Sari, which does not have a municipal wastewater collection and treatment system, is immediately upstream of the diversion dam. Additionally, more than 20 nearby villages discharge their untreated wastewater to the Tajan River. Wastewater from a thermal mechanical paper plant and a milk plant is discharged up gradient from the diversion dam. Water quality of the Tajan River is also affected by cultivation to the edge of the river and sand and gravel extraction operations.

Impacts of the Irrigation Improvement Project - Tajan Subproject

The implementation of the Irrigation Improvement Project in Tajan region was expected to have the following positive impacts:

(i) improved management of irrigated agriculture in a region with extensive irrigated agriculture,
(ii) improved water use efficiency, and
(iii) improved drainage with a reduction in water logging and salinization risk in an extensive portion of the subproject area.

It was anticipated that the project may increase the potential for some negative impacts if mitigation measures were not included as integral project activities. Converting 7,500 hectares of rainfed agricultural land to an irrigated agricultural system without improvement in the existing management of agricultural chemicals would result in adverse environmental impacts. The project accomplishment may be influenced by the adverse impacts resulting from the periodic contamination of the irrigation water supply by the upstream discharge of wastewater and excessive sedimentation behind the diversion dam and in the canal system by sediment generated in the mid-Tajan River Basin which are beyond the scope of the project. Risk of prevention of passage of migratory fish through the diversion dam and its fish ladder and outlet gates; and entrance of migratory fish into the irrigation canal system constitute another possible adverse impact. Also the invaluable Ab-bandans may be developed into farmlands or their surface area may be decreased subsequent to the installation of the irrigation system.

Several mitigation actions are undertaken to reduce the adverse impacts of the project and the risks that may negatively influence the project achievements. The mitigation actions include: (i) an Agricultural Chemical Management Program, (ii) a Water Quality Monitoring Program with emphasis on the monitoring of upstream wastewater discharges and discharges from the drains to marine environment, and (iii) a management program for the Middle Tajan River Basin to establish a river zoning system to support land use decisions, development of a riverside "set-back" system to reduce bank erosion, pilot riverside afforestation program, and an evaluation of actions which can be taken to reduce excessive sediment generation and stream bank damage from the extensive sand and gravel excavation and washing operations.

ENVIRONMENTAL MANAGEMENT PLAN ACTIVITIES IN TAJAN

The Environmental Management Plan in Tajan includes implementation of (i) surface and groundwater quality monitoring, (ii) strengthening of institutional and personnel capacities for addressing environmental issues of the project, and (iii) development of an agricultural chemicals management program.

The project supports many institutional and personnel strengthening activities concerned with environmental management issues at the national and subproject levels. Training of personnel was to be conducted through international training, in-country training, and "train the trainer" programs. The project has provision for training for personnel from the Department of Environment at subproject level in environmental management, preparation of environmental assessment, environmental monitoring and in the development of work plans. The project also provides office equipment, computers, reference materials, vehicles, and support for the construction of field facilities

In Tajan two special studies are focused on addressing long-term environmental management issues related to the development of irrigated agriculture. These studies include:

(a) Management Plan for the man-made "Ab-Bandan" Ecosystems, and
(b) Tajan River Migratory Fish Management Plan.

Surface Water and Groundwater Quality Monitoring Programs

Improved water quality and quantity management is being implemented to improve the present water use which has an efficiency of 30% and results in wastage of water, water logging and salinization. The water management issues are addressed through increased user fees for water to promote conservation and efficient use, rehabilitation of irrigation and drainage systems to provide water in a timely manner and reduce seepage from canals, improving the capacity of farmers for efficient water management through on-farm programs. A surface and groundwater monitoring program has been developed for collection, analysis and interpretation of data to support the operation of the irrigation system, protection of domestic water supplies, and the conservation of natural habitats, fish and wildlife populations. The development of monitoring program is being coordinated with on-going water quality data collection programs.

Local authorities routinely monitor surface and groundwater quality by collecting information on parameters related to water quality requirements for irrigated agriculture (cations and anions) and bacteriological and chemical aspects of water quality related to the safety of drinking water supplies. Prior to the project, however, there was no program for collection, analysis, and use of water quality monitoring data for the management of this irrigation project. Water quality in Tajan area is variable with better quality obtained during irrigation season and lower quality occurring following the irrigation period. The quality of surface water is effected by fertilizers which along with low flows and inadequate channel maintenance practices results in growth of algae and reeds in the systems. Transport of fertilizers and pesticides into the local aquifer, drainage from farm lands, and seepage in the canals greatly influence groundwater quality. Monitoring of several significant parameters at representative locations such as key points within irrigation and drainage network, major domestic water supply intakes, and municipal and industrial wastewater discharge points has been included in the surface/groundwater monitoring programs.

Agricultural Chemicals Management Programs

Agricultural chemicals, including fertilizers and pesticides, due to their subsidized low price are not utilized appropriately. Private farmers and state farms may use up to twice the recommended amounts of pesticides and fertilizers. The extent of negative impact of these practices on surface water, groundwater, soil quality, human health, and wildlife is not known. An agricultural chemical management program has been developed for improved management and reduced use of chemicals. The program is supporting application of alternative means of crop fertilization and crop protection including integrated pest management.

Migratory Fish Management Plan for Tajan River

A management plan has been prepared and will be implemented to revitalize the fishery resources of the Tajan River following completion of the diversion dam which includes a fish ladder and the establishment of a backwater pond of a sufficient depth to allow migratory fish to go upstream of the diversion dam. This management plan includes the development of information concerning anadromous and catadromous fishes traditionally found in the river including caviar sturgeon and trout; an ecological analysis of the Tajan River and monitoring of the fish ladder particularly during periods of low flow and migration. Support is being provided for strengthening the monitoring program of the Fisheries Research Center of the province through staff training, consultancy support, and procurement of specialized equipment.

Development of Management Plan for the Man-Made Ab-bandans Ecosystems

As a result of the traditional spate irrigation practices in the irrigated areas of the Caspian coast of Iran and in particular in the Tajan subproject many large irrigation water storage ponds have been constructed. These storage ponds are locally known as "Ab-bandan" or water holders. Over the years, Ab-bandans have evolved into complex man-made and man-maintained ecosystems with a high economic value to local residents and as a habitat for local and migratory wildlife, specially waterfowl. Ab-bandans are important for irrigation water control, production of fish, hunting of birds, rental to the local Department of Environment for bird protection, harvesting of reeds, and recreational use. These ecosystems are collectively owned and managed by groups of families, with sometimes over 250 families involved. It is a complex task to manage the dynamic and important ecosystems of Ab-bandans.

A special study is supported by the IIP project to develop practical approach for the management of the Ab-bandans by their collective owners with the support of the local Department of Environment. The Ab-bandan management plan includes: an inventory of the ab-bandans with information on their size, physical status, irrigated command areas and ownership; a detailed inventory of the birds wintering on the Ab-bandans; development of topology and mapping of Ab-bandans in regard to their ecological roles and conditions, type of bird feeding grounds, and socioeconomic uses by farmers; and evaluation of costs of different management options. In coordination with local government offices, the Department of Environment will implement the management plan by reaching agreements with the owners of Ab-bandans for their rental and monitoring their use by birds and their modifications as part of their management.

PROGRESS TO DATE - TAJAN ENVIRONMENTAL MANAGEMENT

The project due for completion by the end of 2001 was initially beset by a number of delays which have affected nearly all aspects of the project. With respect to the projects civil works, in the main these have recovered and are now proceeding well although attention to the on-going needs for operation and maintenance of the works, critical for the longevity of the project objectives, is only beginning to be the focus of project management.

The reasons for these initial delays are complex. World Bank operations in Iran have been limited and experience in the implementation of complex projects in a partnership with the Bank and GOI was not well established at the outset of the project. This was evidenced for example by delays in basic procurement procedures including the provision of necessary budget resources in a timely manner consistent with the project schedule, delays in consultant selection and tendering and to some extent were all result of differing requirements of the Bank and the GOI. These issues took time to resolve. The project management designed for the project, involving the establishment of two Liaison Offices for the two sectoral Ministries (Agriculture and Energy) has ultimately been successful but in the light of project experience should be reexamined for future activities.

With respect to the environmental activities a complex set of factors has emerged. Technical issues within the Iranian institutional context took time to resolve. These included acceptance of Terms of Reference for the relevant studies and dealing with a limited private environmental consulting sector in Iran. The sectoral Ministries, more accustomed to the delivery of high quality mainstream engineering and agricultural development activities, took time to absorb the project objectives with respect to relatively innovative environmental management practice.

Albeit late in the project, most environmental aspects with respect to Tajan are producing or are likely to produce impacts on the ground and a legacy for the future. To date it is premature to attempt to quantify these impacts, but a number of outcomes can be indicated at this stage. These include:

(a) institutionalisation of surface and ground water and agriculture chemical monitoring programs with the possible establishment of an inter-ministerial committee on residues, norms and monitoring

(b) at least in the pilot areas, increased environmental awareness, health and safety issues pertinent to agrochemical usage enforced by clear demonstrations of increased yields while decreasing chemical usage with biological control

(c) completion of the Tajan Ab-bandan and Middle River Basin studies which will likely result in considerable implementation activities in the next 18 months. As such a number of ab-bandans will be afforded management with a primary focus for conservation alone, while others will maximize opportunities for sustainable use with the benefits directly flowing to the traditional owners. The Middle River Basin studies, in terms of implementation, are more complex. Priority programs such as afforestation and development set backs will only be initiated in the remaining project period.

REFERENCES

1. Khazar-Ab Consulting Engineers, 1997. Natural aquatic ecosystems of Tajan. Project Report, Khazar-Ab Consulting Engineers. Sari, Iran.

2. Jones, William, J. 1995. The World Bank and Irrigation - A World Bank Operations Evaluation Study. The World Bank, Washington DC, USA.

3. The World Bank, 1993. Irrigation Improvement Project - Staff Appraisal Report. The World Bank, Washington DC.

ORGANIZATIONAL REQUISITES OF SUCCESSFUL IRRIGATION SYSTEM REHABILITATION: CASES FROM NEPAL

David M. Freeman[1]

ABSTRACT

This paper describes two irrigation systems in Nepal that have undergone rehabilitation – Sirsia-Dudhaura and Bangeri. The experience of farmer-irrigators and their interaction with authorities of the Department of Irrigation is compared and analyzed according to criteria drawn from the literature of common property resource and collective goods theory. The analysis specifies organizational attributes hypothesized to make for successful and sustainable irrigation system rehabilitation, compares the two cases with regard to them, and notes implications. Bangeri is found to have much greater success with its rehabilitation than Sursia-Dudhaura, and the Bangeri irrigation community also possesses the organizational attributes advanced as important to effective local organization whereas Sursia-Dudhaura does not. The operation of local organizations are a most critical part of any canal rehabilitation.

INTRODUCTION

What kind of local organizations effectively mobilize local people--their knowledge, material resources, and loyalty--and empower them to sponsor and sustain rehabilitated irrigation works as partners with central state irrigation bureaucracies? What kind of organizations provide vehicles for meaningful participation in irrigation development, and also constitute viable links between central government ministries and local social-ecological niches in the countryside? What attributes do effective local irrigation organizations have that distinguish them from organizations which can be expected to fail in these respects?

It is the purpose of this paper to address these questions employing lessons learned from the study of local irrigation organizations (Freeman, 1989); most specifically, the ideas will be illustrated by materials drawn from a comparison of

---

[1]Professor, Department of Sociology, Colorado State University, Fort Collins, CO 80523

two irrigation systems in Nepal[2].

THEORY

Importance of Local Organization

A tradition of inquiry has emerged (Bromley, 1992; Cernea, 1985; Freeman, 1989; Korten and Alfonso, 1983; Lam, 1998; Montgomery, 1974; Ostrom, 1990; Ostrom, Gardener, and Walker, 1994; and Tang, 1992), representatives of which have contended that local quasi-public non-governmental organizations are essential to any vision of productive, equitable, socially and ecologically sustainable democratic development. This is so because properly-designed and managed local organizations:

1. Are uniquely able to administer centrally supplied resources (e.g., money, canal water, etc.) to specific needs in particular socio-ecological niches.

2. Unite the general knowledge of central tendencies across large administrative units, commanded by occupants of central ministries, with the local knowledge of site-specific particulars that associates with local citizens.

3. Provide a form of social organization that insures that, in some "fair share" way, all prospective beneficiaries contribute to provide the collective good or common property resource, that each contribution be matched by a "fair share" contribution from each other member, and that, in return, members in good standing receive a "fair share" portion of the benefit stream(s). Attributes of public goods and common property resources have been discussed in a well developed literature (Olson, 1965; Mueller, 1979; Frohock, 1989; Ostrom, 1990: 29-55)[3]. Social organizations defeat "free riding" and make possible the provision

---

[2]This paper draws heavily for its case material from my report to His Majesties' Government of Nepal (Freeman, 1992).

[3]The terms, "collective good" and "common property resource" represent closely related, but distinguishable, concepts. Whereas a private good produces benefits which can be captured by the investor-owner, a public or collective good is one which an investor cannot capture any greater share of the benefit than can a non-investor (non-excludability), and consumption of some portion of the benefit does not reduce the portion available for another party (non-rivalness of consumption). Examples would include street-lighting, flood control projects, national defense, smoke abatement in an airshed. A common property resource is taken to be one in which the criterion of excludability is fulfilled for some easily

and operation of a canal network.

4. Provide viable arenas for meaningful citizen democratic participation. Citizens practice democracy as members, leaders, and employees of appropriately designed local organizations, implementing public and quasi-public organizational business in ways responsive to agendas of state ministries and local citizen-members.

To examine the argument more closely, the discussion now turns to the world of irrigated agriculture.

Organizing For Water Control

Irrigation water, to be productive, must be controlled. It must arrive at the crop root-zone in the proper amount and at the required time to fulfill crop consumptive needs and soil leaching requirements. Water coming too soon, too late, too much, or too little relative to crop and soil requirements is of low, or even negative, value. Irrigation water control, in turn, is dependent upon the quality of irrigation organization (Freeman, 1989). If water gets to the plant root zone at the proper time, and in the proper amount, it is because people have organized collectively to perform tasks beyond the capacity of individuals, and beyond the scope of private consumer markets. Individuals can enter marketplaces to buy private goods such as seeds, fertilizers, and farm implements, but no farmer anywhere in the world can order up a quantity of water control in the local shop, place it in a cart, and take it back to the farm. Water control is provided only by effective farmer organization linked to upstream central supply bureaucracies and downstream member irrigators who represent water demand.

Characteristics of Effective Local Water Organizations

What are the characteristics which define effective local water user organizations (WUO's) which make it possible for citizen-members to democratically and equitably provide water control for agricultural productivity? Researchers have been investigating the question of what constitutes WUO effectiveness in many cultures for years, and debates about issues continue (cf. Maass and Anderson, 1986; Freeman, 1989; Lam, 1998; Ostrom, 1990; Ostrom, Schroeder, and Wynne, 1993, Tang, 1992). On the basis of literature review and empirical field research

---

defined "outsiders" but is not fulfilled for "insiders" in a resource consuming community. Furthermore, there is considerable rivalness of consumption--i.e., water applied to the field of farmer X, is not available to farmer Y. Yet, in common property resources there must be joint action to provide, and divide, the resource if the resource stream is to be sustained (See Ostrom, 1990: 30-33).

(Freeman, 1989: 24-59), I assert that a few variables are strategic--i.e., small changes in them may have large consequences in effectiveness of local organization. The strategic variables and their relationships are depicted in Figure 1 and are synthesized as follows:

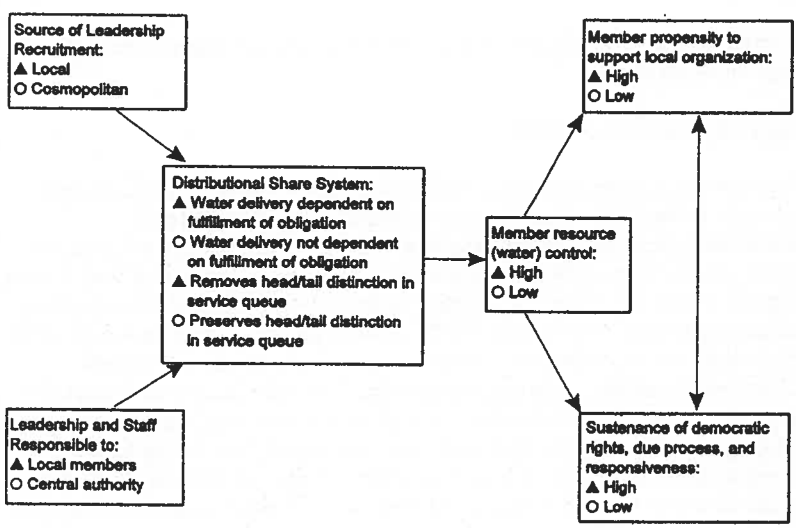


Figure 1. Strategic Variables in Organizational Analysis

1. What kind of people will lead the local WUO by virtue of their election/appointment to membership on the governing board, council, or irrigation committee, and what kind of people must be hired by that representative body of the irrigators to do the daily staff work of the organization? The answer is clear and has two aspects:

a. It is important (Freeman, 1989:26-27) that members of the local organizational board be local citizen-irrigators who are elected in democratic ways representing various reaches of the local canal system. The rejected option is to fill leadership and staff positions with "cosmopolitans" who are employed on national or regional labor markets far exceeding the scope of the local community, placed on the payrolls of central ministries, and who are appointed by higher authority to the local organization for specified periods of time--usually in two or four year rotations.

b. Leaders and staff must be fully accountable to the local organization member-irrigators as distinguished from looking upward to the central bureaucracy for definitions of success and failure. This is so because central bureaucracy staff, however well trained in various disciplines relevant to irrigation and however well intentioned, will virtually never develop: 1) the required site-specific local knowledge to operate the share system effectively; 2) the local social capital necessary to deal with the innumerable local conflicts and problems that must be dealt with by irrigators who spend their lifetime in the local community. The educated cosmopolitan outsider who serves in district, provincial, or national offices has an important role to play, but that role is not on the irrigation committee or staff of the local WUO. WUO's must provide a protected social space where farmers in possession of detailed local knowledge can administer their water share distributional systems, knowing they will bear the consequences of their decisions in terms of both cost and benefit.

2. At the very heart of any effective WA is a functioning water share distribution system (Freeman, 1989:27-33) (See Figures 1 and 2). For farmers in successful water cultures around the world, the idea of a water share organizational agreement is two sided: a share confers upon each member of the irrigation community a legitimate access to water within the arranged rules and tools; and it confers an obligation to contribute an agreed upon "fair share" of the costs of managing water in the system. The concept of a water share distribution system unites two essential aspects of organizational operations - resource

---

I. Distributional Shares Involve:
   A. A right to a proportion of benefit — e.g. water
   B. An assessment obligation to pay costs of organizational provision of the benefit.

II.

Share/Benefit	Share/Cost
1/100	1/100
1/300	1/300
1/1000	1/1000
1/10,000	1/10,000

III. Members vote their shares in conduct of organizational business.
   A. Member X – owns 9 shares out of 100; votes 9 shares.
   B. Member Y – owns 7 shares out of 100; votes 7 shares.

Figure 2. Concept of Distributional Share

acquisition for operations and maintenance and water allocation along the canals; and delivery of a stream of organizational benefits such as water under control. The specifics of water share arrangements may vary considerably from locale to locale (Freeman, 1989: 27-28), but three considerations are always important in successful WUO's:

a. Does getting the water service to the field depend directly upon the irrigator paying his/her share of the local system management cost, or is water delivery divorced from fulfillment of the irrigator's cost obligations? Where payment and dividend are tightly connected, it is possible for farmers to successfully organize. Where payment and delivery of the benefit are divorced, farmers will not pay, local resources will not be mobilized, management will suffer, and water control will be diminished to unacceptable levels for many organizational members.

b. Are water volumes received roughly proportionate to shares of system costs paid? This is essential to equity. Farmers will not be willing to give loyalty to systems, and be supportive of democratic procedures, where at least rough equity is not served--i.e. where members receive benefit streams disproportionate to their investment in the organization.

c. Does the quality and quantity of organizational service depend on position in the membership queue? As irrigation water flows from head to tail positions, irrigators farther downstream are more vulnerable to water losses due to leaks, seepage, evaporation, non-routine breakdowns, and the self interested manipulations of upstream irrigators. Head-tail issues become divisive if the share system allows inequitable advantage for head irrigators, since head irrigators are uninterested in investing their resources on behalf of those less well located. However, it is possible to organize the head-tail distinction out of the irrigation community by creating an interest common to all users. This can be achieved by measuring water volume delivered to the field gate. If water is distributed by volume, "head" farmers will feel the pinch of poorly performing canals (which take longer to deliver to the tails) because heads cannot obtain their next delivery until tails are served. Thus all farmers become interested in reducing the loss or "shrink" of poorly performing canals. By organizing the flow of benefits and losses so that all members, regardless of position in the dividend queue, will share equally in the system, an organizational life of much higher quality is achieved that provides a basis for general membership loyalty and active democratic participation.

3. What do irrigators do when they organize? They collectively organize a board or council which employs staff to operate and maintain the water share distribution system. Operation and management means exactly this. If members do not have a workable share system, they may constitute a pressure group to

obtain funds from a higher agency but they cannot be an irrigation organization because they then have no appropriate rules and tools for controlling and dividing water. What does the irrigation board or council discuss? It discusses the share system and how to keep it implemented in day-to-day operations. What is maintenance all about? It is about how to do what must be done to keep the share system operative. Maintenance activity, divorced from a viable share system, has no justification. Maintenance of facilities is hard work, costs money, and is of no intrinsic interest to citizen-farmers unless a viable share system assures a payoff--in this case, water under acceptable control. How about conflict resolution and management? Conflicts emerge out of problems with the share system and are resolved by getting the share system to work on behalf of the farmers. Conflicts among irrigators can only be resolved in terms of rewarding those who support the share system, punishing those who violate it (by local leadership/membership denying the offender her-his share of the benefit stream), or possibly reforming share system defects so that it no longer generates grievances.

In summary, heart of a water users' organization is its share distribution system, and all important organizational activities center upon it. Small changes in the water share distributional system have big consequences for irrigation water control, productivity, and equity, and willingness to democratically participate. When water is effectively controlled through a viable share system, it makes for effective organizations which earn the support of members, and in turn makes possible participation in a civic democratic community.

Viewed in this light, one now sees how effective WUO's become the centerpiece of disciplined and productive farmer participation, democratization, accountability, productivity, and social equity.

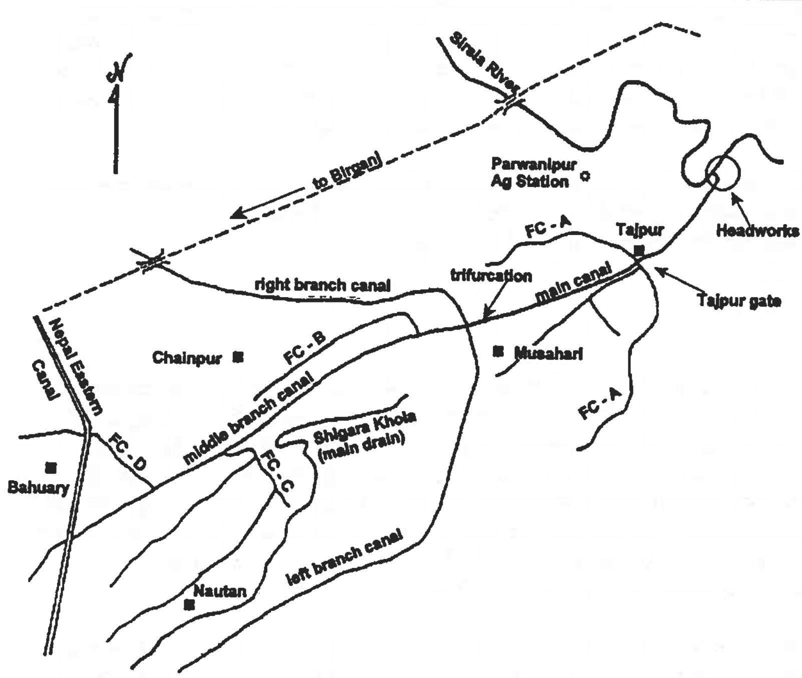
CASES

The discussion now turns to specific cases of local water user organizations (WUO's) observed in Nepal. The purpose is to take the abstract concepts discussed above to the world of Nepali irrigation. One system – the Sirsia-Dudhaura – has good potential but does not have the organizational attributes necessary to make it an effective vehicle for democratic social development. The second system – the Bangeri – has been successfully functioning nearby for three generations. Observation reveals that the Bangeri has the attributes of a successful organization as outlined above.

Total irrigated area in Nepal is estimated to amount to about 1,000,000 hectares. This represents about 38% of the cultivated area of the nation (Rana, 1989: 6). The Government of Nepal Department of Irrigation (DOI) accepts responsibility for administering roughly 300,000 hectares of irrigated land in Nepal, of which about 260,000 hectares are in agency assisted joint-managed systems such as Sirsia-Dudhaura. Farmer managed systems such as Bangeri amount to about 700,000 ha.

<u>Sirsia-Dudhaura — Failure in Organizational Design</u>

This irrigation system has been the subject of much investigation, policy discussion, and USAID/ DOI investment. No attempt will be made here to give a full physical, agronomic, or organizational description of the system; that has been done by others (Laitos, *et. al*, 1985). Suffice to say that Sirsia-Dudhaura is one of the older government managed systems in Nepal as DOI constructed the original headworks, one main and five branch canals with USAID assistance between 1953 and 1957. A high quality government-installed pucca headgate diverts water from the Sirsia River to the main canal, then the flow is to two channels at Tajpur, and on to three branch canals at a trifurcation structure (See map, Figure 3). The Sirsia portion of the system was originally designed to command 1,400 ha. (Laitos, et al., 1985:11) and it came to incorporate an already existing



Source: Laitos, et al., p. 3

Figure 3. The Sirsia Irrigation System

Dudhaura system irrigating about 650 ha. fed by flows from the Dudhaura River. The water allocation system is to rotate water from head to tail of the main canal and five secondary channels. In the Sirsia portion of the system, groundwater use was reported to be insignificant.

After initial construction, the system rapidly deteriorated and remained in an advanced state of deterioration for years. In 1984, an interdisciplinary team funded by USAID, working with the DOI and farmers, conducted a diagnostic analysis (Laitos, et al., 1985). A subsequent rehabilitation effort during 1986-88 improved the physical works and organized farmers at three levels: a) sub-block units (4-5 ha.); b) block units (20-50 ha.); and c) at the system level. Farmer informants expressed satisfaction that the Irrigation Management Project got them involved; they reported that farmer involvement in this work was highly valued by many farmers.

During kharif (summer), crops center on early and late varieties of rice. During rabi (winter) season, farmers focus on wheat, potatoes, maize, mustard, and oilseeds. Sugarcane grows over the course of both kharif and rabi seasons; given the lack of water, larger farmers are reported to plant sugarcane as insurance against drought during rabi given that even 10-20% of potential yield promises sufficient cash to be worth the investment. Informants reported that so many farmers have gone to sugarcane as drought insurance, that local sugarcane mills in the area were operating well over 8 months per year even though they were designed to operate only about 3 months per year. In an especially good year, a farmer can grow early rice, late rice, and rabi wheat. Cropping intensities are generally high (reportedly about 250%) but much land is planted in lower value drought resistant crops during rabi due to the generally insufficient water supply. Farmers and other informants reported that yields diminish as one moves from the head to the tails of the system. All of these factors suggest that water control is seriously problematic in this irrigation system.

Administratively, Sirsia-Dudhaura is under the jurisdiction of the DOI. The District Officer is charged to render technical assistance to privately managed systems in the district, to conduct programs of "river training" (erosion and flood control), to manage district tube-wells, and to manage irrigation water flows in the main and secondary canals of the Sirsia-Dudhaura system. He is assisted by two engineers, one of whom is given responsibility for Sirsia-Dudhaura, one Overseer, a number of Dhalpas (gatekeepers), and a Chowkidar (headgate watchman), all hired by DOI, and paid out of the District Office budget.

How does the system work? Toli (Block) Committees, supposedly working collaboratively with the DOI Engineer, Overseer, and Gatekeepers, decide upon a rotation system to allocate water among the five secondary canals that will serve crop needs in the system. During kharif, if the rains are good and continuous, there is relatively little stress on the allocation system. However, when monsoon rains are sparse and crop consumptive demand great, much demand for water comes on the system and there is no other allocation method than just to run water in each secondary canal for 4-5 days at a time, then rotate to the next canal or two for a similar period. How many secondary canals can be on at once depends on the river flow at the headgate. Most often the 4-5 day flow period in secondary canals is not sufficient to satisfy demand in either kharif or rabi. Most often it is not. Demand from lower distributaries necessitates a cut-off of water leaving middle and tail farmers without water. Later, on the next general rotation, block committees will try to start the flow of water to the tertiary canals at the point where it had to be stopped many days earlier on the prior rotation. What if head farmers jump in and take water before it gets to those downstream? It happens. Toli committees try to put social pressure on those who abuse up-stream positions to extend their turns, but there is no effective share distribution system to insure equity. Some farmers, in middle and tail locations who are politically weak, have not had water for many seasons and are struggling to improve this situation. Technically, farmers are charged for water without regard for volume received or the timing of the delivery. In fact, virtually no farmer has paid the irrigation fee for at least 5-6 years preceding this author's visit.

There are many water measurement structures situated at appropriate places in the canal network. But there is no clear share system to guide their use; virtually nobody takes the trouble to make measurements. After all, why should they? Without a sense that a given specific quantity, or proportion, of water flow must be delivered to any given point in the canal network, there is little reason to go about the business of measurement. Within the memory of the informants neither farmer nor official has made an attempt to compute river flow at the headgate staff gauge.

What about farmer relationships with DOI? Farmer informants agreed that the most important problem is lack of communication and coordination between farmer leaders at the system level and DOI personnel. Farmers spoke frankly, clearly, and with good will, but they clearly indicated dissatisfaction with DOI management on several counts.

The agency, in the view of most farmers, grossly mismanages resources. It spends far too much money on cars, fuel, badly designed and constructed equipment, and "experts" like me. DOI pays Rs 1,050/month to the headgate watchman and built him a quality pucca house at the headgate site. Yet, he is never around. Even if he stayed on the site, it is not clear that he could do anything really worth doing. It is a small thing to complain about given all the bigger waste, but it irritates farmers when they see this kind of fund mismanagement.

DOI provides nothing of value on a day-to-day Operation and Management

(O&M) basis. Anything worth doing is done by the farmers themselves. The DOI engineer assigned responsibility for Sirsia-Dudhaura is housed at the Rice Research Institute near the headworks, but he does nothing. What can he do? It is unclear what his job description is or should be.

DOI is guilty of lack of "transparency." The government agents expect the farmers to keep their records and activities open for review, but they do not let farmers review government records and operations. Farmers are insulted by this. Control over funds is a source of conflict. There was much that the farmers wished to communicate to me about this but I failed to grasp all of the aspects of this problem. Much was lost in the translation. Farmers made it clear that they think they should have full control of any funds due to them.

The agency, farmer-informants unanimously reported, has no real respect for farmers or farmer leaders. In the informants' view, DOI wants "dummy" leaders who will be quiet, compliant, and continue the pretense that things are going along in an acceptable fashion. Real leaders speaking honestly about problems are not welcome and their election to positions of WA authority are resisted by the DOI. Farmers and their leaders are angered by this. One said: "The agency comes into our territory and does things to us without our permission. They are like a hunter who expects the animal to assist the hunter by helping to steady the gun which is pointed at the hunted."

Sirsia-Dudhaura — An Analysis

The Sirsia-Dudhaura system exhibits problems that are found in many irrigation systems in other countries. It was designed to be constructed, but was not designed to be operated and maintained. Water and money can flow through the system if available from sources above the headworks, but it is not a system which can do proper irrigation--i.e., it cannot control water to serve consumptive need of crops in a way which serves productivity, social equity, or democracy.

The problem is not deficiency of the individual farmers or DOI personnel. They are people of competence and good will who are trying to deal with difficult circumstances as best they can. Problems are:

1. There is no viable water share distributional system worked out which can reconcile supply at the headgate with crop demand. Also a viable share system will specify the details of operations and maintenance which must be accomplished. If it can be agreed that a given fraction of available flows at the headgate must be distributed to particular points then operations and maintenance begins to take on real meaning. Specifically:

   a. There is no compelling connection between payment of water management charges and delivery of water at the farm gate.

b. There is no effective way of making payment contributions proportional to water payouts.

c. The head-tail distinction is re-enforced, not removed.

2. Without organization of viable rules and tools for operating and maintaining functioning water share system, it is impossible to define meaningful organizational job roles either for farmer leaders or DOI people.

3. Expecting cosmopolitan District DOI staff who rotate in and out of the irrigation area every few years and who are paid by, and responsible to, authorities above them for definitions of good and bad work, who are therefore not fundamentally accountable to farmers, all compounds the difficulty caused by the lack of an effective water share distribution system.

a. What exactly should district staff do? Nobody knows because there is only a badly broken share system being implemented and that is being done as best farmers can. There are no real daily O&M jobs that district staff can do.

b. Given the above it is not surprising that there is no real communication or coordination between DOI staff and farmers.

4. It is, therefore, not surprising that:

a. Many farmers in the middle and tail reaches are farming in virtually dryland conditions and are thereby forgoing increased production of higher yielding and more valuable crops. Production, welfare, social equity, and the practice of democracy are being unnecessarily sacrificed on this system.

b. Lack of effective daily O&M means frequent calls for non-routine and expensive rehabilitation to be funded by the central treasury.

c. Farmers are effectively organized to demand expensive and scarce capital resources to substitute for their own funds and potentially abundant labor--farmer resources which will not be delivered by the inadequate organization now in place. Farmer labor and capital will be forthcoming when improved organizational arrangements provide assurance that they will result in a real payoff meaningful to them--improved water supply and control.

d. Farmers are not effectively organized to irrigate. Individually they are competent and hardworking but collectively are constrained by the lack of properly organized joint agreements about rules and tools constituting an effective water share distribution system, recruitment of leaders and staff, and unworkable lines of authority.

In sum, the Sirsia-Dudhaura irrigation organization reflects a configuration of variables and relationships that are unsupportive of effectiveness and democracy in the provision of local public goods and/or common property resources. In short, it does not work.

The Bangeri System — An Organizational Success

This community of irrigators has been functioning for three generations and their records established that there are approximately 300 irrigation households which work a total of 400 ha., 300 ha. of which are irrigated (See Figure 4).

Water of the Bangeri river is captured by an earthen barrage about 100 meters

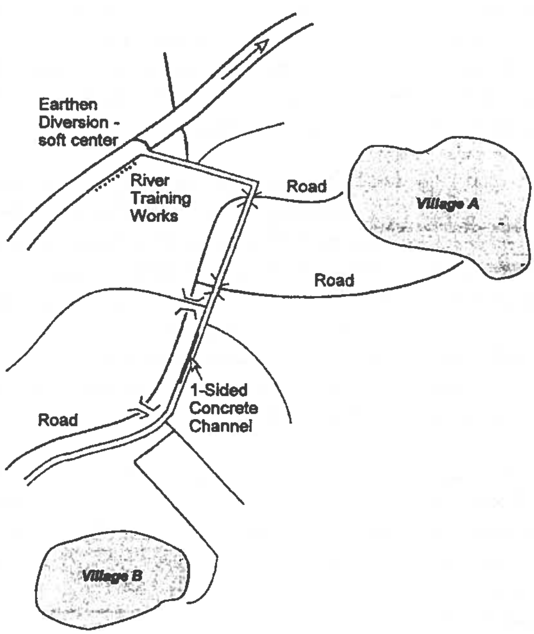


Figure 4. The Bangeri Irrigation System

long and constructed by farmers to create a head of water at the inlet of the main canal 1 meter deep. The technology employed in this barrage is virtually identical to others in this region of Nepal--large stones provide a hard core for the ends of the weir while a softer earthen center section will give away to high river flows. This saves the side sections and leaves a hard bund fragment which continues diverting water into the canal during periods of high water. Farmers reported that they may have to re-build this barrage as many as 7 times a year. The Deputy Chairman reported that farmers were quite capable of mobilizing as much as 900,000 Rupees (Rs) worth of labor in a 30 day period. Unfortunately, these farmers have the lowest intake on the river due to a combination of low river flows during rabi (winter) season and high demand for water by the four farmer managed systems above them. This means that the Bangeri main canal generally fails to capture a full one meter head of water at the barrage.

The main canal is 2 km. long; total length with secondary canals (See Figure 4) is 6 km. The command area is divided into 9 zones within each irrigators select a leader who represents them on the system Irrigation Committee. The largest farm on the system is 10 ha.; the smallest is 0.1 ha. with an average farm size of 1.0 ha.

The Irrigation Committee (i.e., Board of Directors), composed of the 9 zone representatives, elects a Chairman, Deputy Chairman, a Secretary for record keeping, and a Treasurer for fund management and accountability. The Bangeri Irrigation Committee operates and maintains a clearly defined and viable water share distribution system. This is how it works:

1. Prior to the beginning of rabi irrigating season each year, the Irrigation Committee estimates the total funds required to control water in the system for the next year--rabi and kharif. They must fund a variety of items such as barrage work, hire a landless laborer for a chowkidar (Rs 700/mo. plus 300 kilos of rice/yr for night work, plus Rs 30/month for flashlight and batteries), brick, mortar, and bank loan payments. Like such systems in many countries, no money is appropriated for Irrigation Committee Members who serve voluntarily at no cash cost to the system. This year (1992) the Irrigation Committee estimated a total need of Rs 28,000 for water management.

2. The total annual cost includes a loan payment to the Agricultural Development Bank in the amount of Rs 20,000. The loan was taken out several years ago to finance improvement of a leaky main canal (See Figure 4) by putting in a one-sided concrete bank. Also the loan funded purchase of better gates to the secondary canals, and 13 culverts where roads crossed canals. The Farmers secured technical assistance and support for the loan approval from the District Office; although the District Officer had final approval authority, the improvements were designed according to farmer wishes and they are satisfied with what was done. Given that they were going to be responsible for paying

back the cost of improvements, farmers wanted to make each Rupee go as far as possible--hence the single sided concrete portion of the main canal as an alternative of a two-sided concrete ditch.

3. The costs of securing water control are then assigned to water shares; which are determined by amount of land to be irrigated, independent of what crop is grown. Farmers allocate costs to units called bighas. Since that is a complicated computation, I will employ hectares. The farmers agreed that, given 300 irrigated hectares in the system, and given a total appropriation of Rs 28,000, each irrigated hectare would be assessed Rs 93.33. Of this, Rs 30 was payable in labor equivalent.

4. Assessments, due each January, are reviewed and adopted by the Irrigation Committee members and then by the general assembly of irrigators. If not paid by March, a 5% surcharge is levied to the assessment. All funds are deposited in the organization's bank account in a nearby town. There is total "transparency" among the farmer members.

5. Since part of the assessment is contributed labor for maintenance, irrigators are called out by the Irrigation Committee when needed. If a farmer does not wish to work on the job to be done, he or she contributes Rs 30/day to the Irrigation Committee which employs a laborer plus a tip of Rs 2/day for breakfast.

6. Costs paid are tightly connected to the delivery of water, and just like a bank savings account--no deposit, no withdrawal. When asked if there are delinquent farmers who wish to get water without paying, the answer was that there are always a few. "They come crying, 'my crops are dying, give me water.' We give it to them, but they pay." Sometimes in a really serious case, all of the farmers are called together in a general assembly of irrigators to put pressure on the delinquent--when the social pressure gets intense, the laggard pays the amount owed.

a. Before the first seasonal irrigation, the Irrigation Committee inspects the whole command area and make a preliminary assessment of water consumptive needs.

b. The Committee decides priorities of fields and farmers according to crop--top priority is given to vegetables, then wheat, oilseeds, maize, etc. Sugarcane was one of the lowest priority crops, and viewed as a hedge against drought.

c. Depending on the quantity of river flow, 2-5 secondary canals can be served with a sufficient head of water. Water is rotated not simply head to tail, but modified by: 1) crop consumptive needs; and 2) the Irrigation Committee's best judgement as to how to keep from losing water unnecessarily in wetting dry ditch bottoms.

There is much fine toothed local knowledge that goes into these calculations which escaped discussion and my notes. Farmers were agreed that their number one problem is lack of sufficient water at the headgate. If they had a better water supply in rabi they would shift from sugarcane, mustard, and lentils to higher value vegetable crops.

Bangeri — An Analysis

There are problems in the Bangeri system-- the most notable is insufficient water supply, but farmers could also use improved water measurement and control structures to help administer their share system. However, these farmers are organized to control water in a way that serves productivity within their constraints, maintains a rough but effective distributional equity, and embodies authentic democratic political control in the community of irrigators. Nobody pays for water that is not delivered; nobody takes water without contributing an approximate "fair share" to the cost of managing it. The share system succeeds in uniting cost and benefit, but it struggles with the head-tail problems which, while not eliminated, are kept within acceptable bounds. No matter where the irrigator is positioned in the queue, s/he can be confident that by fulfilling their organizational obligation, by paying their share assessment, they will receive an acceptable water delivery dividend.

The management authority administering the water share distributional system is composed of local people having detailed local knowledge who are accountable to the irrigation community. DOI personnel make no pretense of involving themselves in the daily operation and maintenance of the share system. They are kept in their proper place--providers of technical assistance in the design of improvements and in obtaining outside financial help.

Bangeri represents an effective and democratically responsive irrigation organization, rather than being more fitted for lobbying the central bureaucracy for resources than for the work of irrigation and agricultural production as is the case in Sursia-Dudhaura. The farmers at Bangeri are empowered to control water. Their organization provides them with a vehicle for productivity, equity, and the daily practice of local democracy.

CONCLUSION

Why do some local organizations earn the support and loyalty of their memberships, successfully empower people within democratic frameworks to provide themselves with essentials of local infrastructure, and provide crucial linkages between central government bureaucracies and local people? Why do others fail in these tasks?

In sum, the argument here has contended that the difference lies in the configuration of a few strategic variables. Small changes make for large differences in organizational outcomes. The critical variables have to do with recruitment of leaders and staff (local/cosmopolitan), configuration of responsibility (are citizen-leaders accountable to the agendas of authorities above or to irrigators below?), and the design of the resource share distribution system in a way which unites delivery of the organizational benefit stream to member fulfillment of obligation and delivery quality service without respect to position in the service queue.

Likewise, irrigation system rehabilitation is not simply a technical matter of interest to those who design and construct physical works; it is most importantly a process which must address those social organizational considerations that all too often account for degradation of the physical works in the first instance.

Acknowledgment

I wish to express my appreciation for the able graphical and editorial assistance of Ms. Annie Epperson.

REFERENCES

Bromley, Daniel W., *et al.* 1992. *Making the Commons Work: Theory, Practice, and Policy.* San Francisco: Institute for Contemporary Studies Press.

Freeman, David M. 1989. *Local Organizations for Social Development: Concepts and Cases of Irrigation Organization.* Boulder, Co: Westview Press.

Freeman, David M. 1992. "Creating a Supportive Policy Environment for Irrigation System Turnover and Joint Management." Report submitted to His Majesty's Government, Ministry of Water Resources, Department of Irrigation, Irrigation Management and Water Utilization Division. Government of Nepal. January.

His Majesty's Government. 1991. National Planning Commission. *Approach To The Eighth Plan, 1992-97.* Kathmandu: HMF/N: Department of Printing and Publications, November.

Korten, David C. 1990. *Getting to the Twenty First Century: Voluntary Action and the Global Agenda.* Westport, CT: Kumarian Press.

Korten, David C. And Felipe B. Alfonso (eds.) 1983. *Bureaucracy and the Poor: Closing the Gap.* West Hartford, CT: Kumarian Press.

Laitos, W.R., *et al.*, 1985. *Diagnostic Analysis of the Sirsia Irrigation System, Nepal.* Colorado State University: Water Management Synthesis Report 38. Ft. Collins, Co.: Water Management Synthesis Project Publication.

Lam, Wai Fung. 1998. *Governing Irrigation systems in Nepal: Institutions, Infrastructure, and Collective Action.* Oakland, California: Institute for Contemporary Studies Press.

Maass, Arthur, and Raymond Anderson. 1978. *...and the Desert Shall Rejoice: Conflict, Growth, and Justice in Arid Environments.* Cambridge, Mass.: MIT Press.

Montgomery, John D. 1974. *Technology and Civic Life: Making and Implementing Development Decisions.* Cambridge: MIT Press.

Olson, Mancur. 1965. *The Logic of Collective Action.* New York: Schocken Books.

Ostrom, Elinor. 1990. *Governing the Commons: The Evolution of Institutions for Collective Action.* New York: Cambridge University Press.

Ostrom, Elinor. 1993. *Institutional Incentives and Sustainable Development: Infrastructure Policies in Perspective.* Boulder, Colorado: Westview Press.

Ostrom, Elinor, Roy Gardner, and James Walker. 1994. *Rules, Games, and Common-Pool Resources.* Ann Arbor: University of Michigan Press.

Rana, Jitendra. 1989. "Improving O&M of Agency Managed Irrigation Systems: Issues and Options," Discussion Paper. Irrigation Management Project, Systems Management Division.

Tang, Shui Yan. 1992. *Institutions and Collective Action: Self-Governance in Irrigation.* San Francisco, California: Institute for Contemporary Studies Press.

VERIFICATION-BASED PLANNING FOR MODERNIZING IRRIGATION SYSTEMS

Joseph I. Burns[1] Grant G. Davids[2] Arnold K. Dimmitt[3] Jack Keller[4]

ABSTRACT

Verification-based planning is a tool to improve the irrigation system modernization planning process and to effectively monitor the post-project effects on system performance. Modernization of irrigation systems results in water *flow path changes* within the system. The planning process for modernization of an irrigation system requires careful documentation and analysis of the pre-project *(without-project)* condition and *quantified prediction* of the effects of the planned improvement *(with-project)*. Procedures and strategies for predicting, monitoring and quantifying *Targeted Flow Path Changes* caused by an irrigation system modernization project for both *without- and with-project* conditions are presented.

INTRODUCTION

Background

Rehabilitation of irrigation systems is done to bring the systems back to their initial performance capabilities. Rehabilitation may be necessary because of poor maintenance and is undertaken to take care of a backlog of deferred maintenance. On the other hand, modernization implies upgrading a system to improve its performance beyond its original potential. The purpose of this paper is to present concepts for using verification-based planning in the modernization planning process and for post-project monitoring of its effects on irrigation system performance.

Verification-based planning involves additional time and expense compared to traditional planning, due to the additional effort and data needed to achieve an in-depth understanding of the irrigation system. However, verification improves the likelihood that modernization program objectives will actually be accomplished. This is critical where public money is being spent and is of special importance for programs where the rights or interests of other water users may be compromised.

---

[1] Consulting Civil Engineer, 1730 Cathay Way, Sacramento, CA 95864
[2] Principal Engineer, Davids Engineering, Inc., 1772 Picasso Avenue, Suite A, Davis, CA 95616
[3] Principal Engineer, Metropolitan Water District of Southern California, 107 South 5th Street, Suite 200, El Centro, CA 92243
[4] Chief Executive Officer, Keller-Bliesner Engineering, 78 East Center Street, Logan, UT 84321

The same methods that are presented herein for verification-based planning can also be used to verify the conservation savings that result from project implementation. Additionally, verification-based planning provides the necessary details, coupled with project cost estimates, to permit a close economic evaluation of each component of a modernization program. This provides managers and other decision makers with the information needed to evaluate alternatives for each program component before deciding whether to proceed with its implementation. Thus verification provides the quality control that assures planning objectives will be met in a cost-effective manner.

Objectives of Modernization & Flow Path Changes

Typical *local (or internal)* objectives for irrigation system modernization programs include combinations of the following:

- reduced delivery and on-farm system operational losses
- reduced operation and maintenance costs
- improved reliability in the delivery of water to farmers
- increased flexibility to provide farmers more control over their water supply
- decreased water usage per unit of land area
- increased crop production.

Typical *regional (or external)* objectives for publicly supported modernization programs are to:

- conserve water so it can be utilized for other uses and by other users
- facilitate adoption of new, desirable on-farm irrigation technologies and practices that increase water use efficiency both physically and economically
- re-manage irrigation flows to mitigate environmental, water quality and water supply conflicts

Most of the local objectives and all of the publicly supported ones involve *flow path changes* of one sort or another that are often broadly referred to as conservation practices. Reduced canal seepage and evaporation losses, and reduced delivery system operational spillage are examples of these. The focus of this paper is the use of verification-based planning for modernizing projects. This involves the implementation of new practices or measures that result in changes in one or more of the three general flow path categories. These are: *evaporative depletion flow paths*, such as evaporation from free water surfaces and evapotranspiration by crops or phreatophytes; *surface flow paths*, such as canal operational spillage and farm runoff/tailwater; and *subsurface flow paths*, such as canal seepage and deep percolation.

Conceptual Overview

Verification is commonly thought of as an assessment conducted *after* improvements are made to see how well modernization objectives were met. However, when included in the planning process, verification involves careful analysis of the pre-project conditions and *quantified predictions* of the effects of the planned improvements. Thus the anticipated effects can be estimated with reasonable certainty in advance of project implementation. Typically, initial predictions are made with available data and may be improved through collection of additional data, which is needed to validate assumptions and improve understanding of the irrigation system. The goal is to increase confidence in the quantification of the predictions. The desired level of confidence depends on the risks posed by uncertainty and who is taking those risks.

Once modernization objectives that involve re-managing flows are clearly identified, it is necessary to identify the flow paths into, within and leaving the system that must be changed and the degree of change necessary to achieve the desired outcomes. We call these the *Targeted Flow Path Changes*. Then it is necessary to identify the specific system characteristics that must be manipulated to achieve the *Targeted Flow Path Changes* for each of the projects that make up the modernization program. Here it is necessary to take a mechanistic view of the system, recognizing that both physical and behavioral mechanisms may need attention.

A verification-based planning strategy is a combination of an approach and a procedure for carrying out the approach for each *Targeted Flow Path Change*. There are several basic strategies for estimating the *Targeted Flow Path Changes* associated with the various components or projects of a modernization program. Selecting the most appropriate strategy for any given component or project can be a tedious and time consuming exercise. This is because each strategy has its drawbacks and each component and verification strategy combination has specific data and quality requirements.

In the text that follows we will use the word "verification" to imply both quantifying and monitoring *Targeted Flow Path Changes*.

PREDICTING AND MONITORING TARGETED FLOW PATH CHANGES

Water Balances and Flow Paths

The use of water balances and their associated flow paths are essential for the verification-based planning process. Figure 1 is a schematic of a comprehensive water balance that was developed for the Mid-Pacific Region of the US Bureau of Reclamation. It shows both the internal and external flow paths for a typical

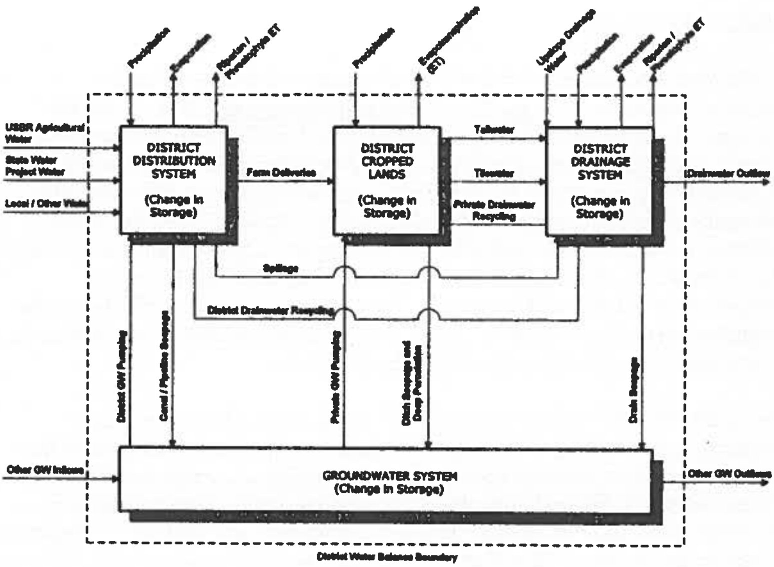


Fig.1. Global Water Balance with External Inflow and Outflow Paths and Internal Sub-system Water Balances with the Related Internal Flow Paths for a Typical Irrigation District

irrigation district. The sum of all the external flows into and out of the district (the flow paths that cross the dotted line surrounding the internal water balances) plus the change in the amount of water stored within the district's boundary must be in balance. The same holds true for the four sub-water balances depicted within the district.

Over yearly time periods there is usually little change in storage in the district distribution system, cropped lands and drainage system, but there is often a considerable change in storage within the groundwater system. However, over short time periods the change in storage in all of the subsystems may be considerable and must be taken into consideration in the verification analysis.

Verification requires estimating, measuring, and/or synthesizing volumes of flow related to the various flow paths that the modernization program's individual projects are designed to target. As will be discussed later, the first step is to identify and quantify the *Targeted Flow Path Changes* that are required to meet the desired outcomes. This requires a combination of measured or estimated flow volumes that represent post-project conditions.

General Verification Perspective

Irrigation water use, and thus the quantity of water associated with the various flow paths, is affected by modernization measures and many additional factors such as cropping patterns, weather conditions and water management practices. In most cases, it is not appropriate to base the quantification of modernization effects on a direct comparison between pre- and post-project water use measurements because the additional (or non-modernization) factors will vary with time. Instead, the measurements need to be normalized to account for changes in non-modernization factors that have taken place between the pre- and post-project periods.

The general verification perspective involves a comparison between the *with- and without-project* depictions in which all non-project conditions are identical so that differences between the two represent the effects of the project. This is different than a comparison between *pre- and post-project* scenarios, which involves a span of time and thus requires making adjustments to account for any changes that are not related to the modernization project. For example, consider a tailwater recovery system installed on a 160-acre field where before the system was installed, the field discharged 80 acre-feet of tailwater per year and afterward it discharged only 20 acre-feet per year. Without consideration of changes in other factors, it would appear that the addition of the system has resulted in 60 acre-feet of conservation. However, further investigation reveals that the crop was changed between the *pre- and post-project* period from a crop for which there is little tailwater (for example, wheat) to one for which, without the system, there would be much more tailwater (for example, sugar beets). In this case, the simple pre- and post-project comparison would result in an under-estimation of conservation savings, unless the pre-project record of tailwater is adjusted to account for the crop change.

Verification-based planning requires estimating the anticipated *Targeted Flow Path Changes* and then monitoring them to provide insight and guidance as a modernization program progresses. For each flow path that will be affected (typically a delivery, spillage, return flow, or storage flow path), it is necessary to first estimate a *without-project* volume and subtract the appropriate estimated *with-project* volume from it, such that:

$$VC = V_{without} - V_{with} = VN - V \qquad \text{(Equation 1)}$$

in which,

- VC is the estimated *Targeted Flow Path Change*, acre-feet;
- $V_{without}$ or VN is an estimate of the flow path's volume of water *without the project*, acre-feet; and

- V_{with} or V is an estimate of the volume of water that would follow the flow path *with the project* in place, acre-feet.

It is not possible to measure both the *with- and without-project* conditions at the same point in time. Consequently one of the data sets must be synthesized. Figure 2 shows the typical phases that occur chronologically along the Project Timeline (from Project Conceptualization & Planning to Full Utilization) and the *with- and without-project* data sets relative to these phases. Data Sets 1 and 4 are representative of conditions prior to the implementation of each of the projects that make up a modernization program. Data Sets 1E and 1M represent estimated and measured *without-project* data. Data Sets 4E and 4S represent estimated and synthesized *with-project* data.

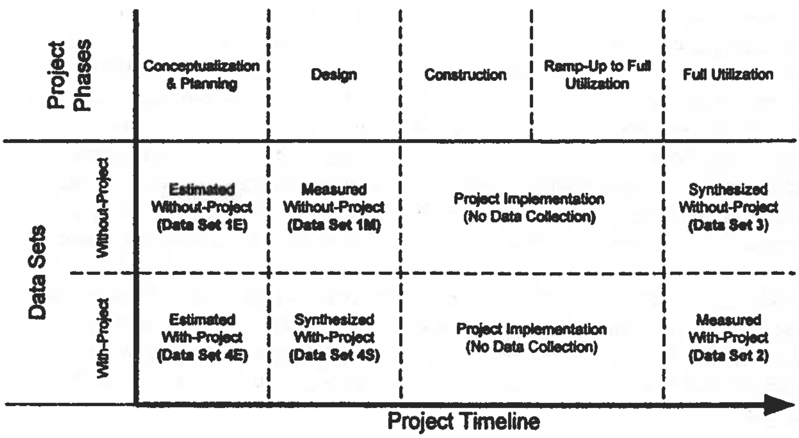


Fig.2. Modernization Program Phases and Related *With- and Without-Project* Data Sets

<u>Predicting Targeted Flow Path Changes</u>

During the Project Conceptualization & Planning Phase there are often no or only crude flow path measurements available and it is necessary to base both the *with- and without-project data* sets (Data Sets 1E and 4E, respectively) on estimated values (see Figure 2). Projects that appear feasible based on these estimated values are normally carried forward to the Design Phase; and for verification planning purposes, field measurements should be made of actual *without-project* system performance to develop Data Set 1M. Data Set 4S representing *with-project* conditions must be *synthesized* for design purposes by employing the information gathered in generating Data Set 1M, along with necessary assumptions, operations studies, simulations and other techniques that are commonly used during the design process. This can be a major challenge, especially for new types of projects designed to target losses requiring flow path changes that have not been addressed in the same manner before, such as lateral interceptor systems and automation of conveyance and distribution system operations.

To quantify the estimated *Targeted Flow Path Change* during the Design Phase, Equation 1 is changed to indicate the data sets (see Figure 2) needed to estimate the anticipated *without- and with-project* conditions:

$$VC = VN_{f(Set\ 1M)} - V_{f(Set\ 4S)} \qquad \text{(Equation 2)}$$

in which:

- $VN_{f(Set\ 1M)}$ and $V_{f(Set\ 4S)}$ are measurements of *without-* and estimates of *with-project* delivery or spill volumes respectively for the pre-project time period and associated environmental conditions, acre-feet.

The practical level of rigor to apply when collecting design data and developing Data Sets 1M and 4S depends on several factors, including the cost of the project, the factors involved in predicting *with-project* conditions (projects involving operator and grower behavior are much harder to predict than those that do not depend on behavior), the risk posed by inaccurate predictions, and who is assuming the risk.

It is important to carefully plan the design data collection processes so there is a high level of confidence in Data Sets 1M and 4S, especially when dealing with projects for which the *without-project* conditions can never be replicated once project construction begins. For example, consider a main canal regulating reservoir that is being designed to eliminate a main canal spillage flow path at a particular site. If the *without-project* spillage is not adequately measured prior to constructing the reservoir, it may never be possible to completely restore the *without-project* conditions. When measuring temporally variable flow paths such as spillage, it is important to assure that diurnal, weekly and seasonal patterns are adequately characterized. As a minimum, such flow paths should be measured for at least one complete season and measurements spanning several seasons are preferable.

Monitoring Targeted Flow Path Changes

The need and approach for post-project monitoring of modernization projects depends on: a) the sensitivity of the *Targeted Flow Path Change* to environmental changes that occur over time; and b) how well the relationship between the actions or measures employed and the *Targeted Flow Path Change* is understood. For measures whose effects are well understood and are not sensitive to environmental changes, such as canal lining, monitoring is not necessary and the pre-project predictions developed using Equation 2 hold for the post-project period.

However, where the above two criteria do not hold, Data Set 3 is needed to verify that the estimated *Targeted Flow Path Changes* have in fact occurred (see Figure 2). This is typically the case for actions or measures targeted at flow paths that are sensitive to environmental change or are affected by human behavior, such as reducing or capturing spillage. To quantify the estimated *Targeted Flow Path Change* during the Full Utilization Phase, Equation 1 is changed to indicate the data sets (see Figure 2) needed to estimate the anticipated *without-* and *with-project* conditions:

$$VC = VN_{f(set\ 3)} - V_{f(Set\ 2)} \qquad \text{(Equation 3)}$$

in which:

- $VN_{f(Set\ 3)}$ and $V_{f(Set\ 2)}$ are estimates of *without-* and measured *with-project* delivery or loss volumes respectively for the post-project time period and associated environmental conditions, acre-feet.

Data Set 3 can be developed by normalizing Data Set 1M or by synthesizing it from Data Set 2. In either case, this can be a major challenge. The normalizing process involves either: a) adjusting the estimated *VN* values based on pre-project Data Set 1M to simulate post-project time and environmental conditions, but without the project; or b) adjusting Data Set 1M to simulate Data Set 3 and then computing *VN*. However, sometimes it is possible to synthesize values for $VN_{f(set\ 3)}$ from a mixture of pre- and post-project Data Sets 1M and 2.

When collecting post-project Data Set 2 it is important to note that for projects affecting the system's behavioral characteristics there may be a period following project construction when the project is "ramping up" to Full Utilization. In such cases, for example, a lateral interceptor project, data collected during the start-up phase may not be representative of the project's long term potential. This is not a concern for projects that only involve physical characteristics such as canal lining.

<u>Verification Feedback to Modernization Programs</u>

Importantly, the predicted *Targeted Flow Path Changes* need to be accurately quantified during the Design Phase of a modernization project. However, these predictions depend on assumptions that involve speculation, especially for new and innovative projects that depend on behavioral responses by operators and irrigators. However, where a modernization program involves implementing several similar projects, the opportunity may exist to validate and refine design assumptions based on the early operating results from the first project or projects. This is illustrated in Figure 3, where operating knowledge gained through *with-project* monitoring is fed into the Design Phase of subsequent similar projects.

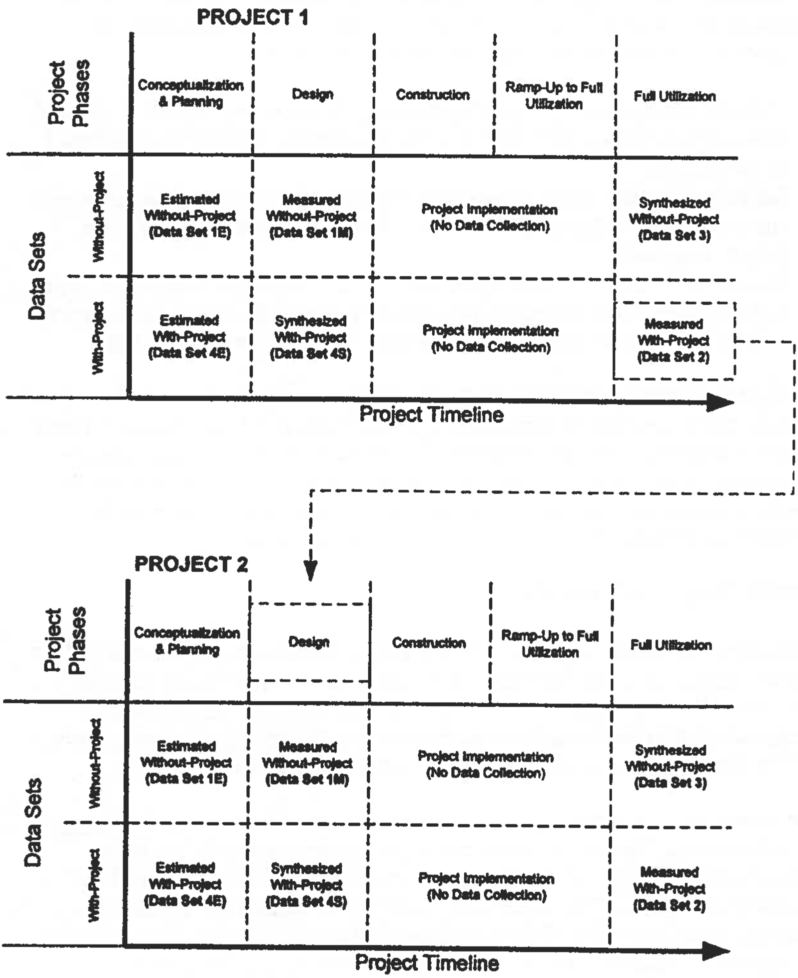


Fig. 3. Verification Feedback Into Design of Subsequent Modernization Projects

STRATEGIES FOR QUANTIFYING FLOW PATH CHANGES

Verification Approaches

As mentioned earlier each verification strategy is made up of an approach and a procedure for carrying it out. The three basic approaches for estimating the *Targeted Flow Path Change* associated with a project are:

- Delivery differential, which is the difference between representative pre- and post-project volumes of irrigation water delivered to the entire area affected by the project;
- Spill/seepage differential, which is the difference between representative pre- and post-project volumes of irrigation water that spills or seeps from the project area; and
- Return-flow fraction, which is the estimated portion of the return-flow water that results from the project and is effectively reused to reduce the amount of irrigation water required, thus representing "real" conservation savings.

Estimating the appropriate *with- and without-project* volumes to use in Equation 1 is necessary to quantify the *Targeted Flow Path Change* when using the delivery or spill/seepage differential approaches. The total return-flow volume sets the upper limit on the *Targeted Flow Path Change*. Return-flow volumes must be used in conjunction with delivery or spill differentials estimates in order to calculate the fraction of the volume that is effectively used.

Procedures for Quantifying Flow Path Changes

There are several basic procedures for estimating the necessary *with- and without-project* volumes required for each of the approaches for quantifying *Targeted Flow Path Changes*. They are differentiated by considering combinations of where and what volume estimates are needed, and the when (or time-step) to be used in converting flow rate data into the volumetric estimates.

One way to begin selecting a procedure is to first select an approach and where the subsystem or "free-body" is that encompasses the *Targeted Flow Path Changes*. (For example see the subsystem water balances in Figure 1 and the associated flow paths.) Then select the places on (or within) the free-body boundary where estimates of flow volumes are needed and when measurements are required to address the targeted changes. Following is a listing of the possibilities within these where, what, and when categories.

1) Where measurements will be made refers to both the increment of land or portion of the system that comprises the "free-body" under study and the places on (or within) its boundary where measurements are required. The

basic choices for increments of land are: a furrow, a set, a field, a farm, a lateral service area, a drainage lateral service area, the area served by multiple laterals, the area served from a main canal operating reach, or the system wide service area. The basic choices for portions of the system are: farm ditch, tailwater pond, farm drain, drainage lateral, lateral, lateral check-pond, interceptor lateral, interceptor reservoir, main drain, main canal reach, main canal check-pool, and main reservoir. The basic choices of the places on (or within) the boundary of the free-bodies where estimates of flow volumes may be required are: at farm turnouts, along farm ditches, at tailwater ponds, along field drains, along drainage laterals, at lateral headings, along laterals, at lateral check-gates, at lateral spill points, along interceptor laterals, at interceptor reservoirs; at main canal headings, along main canals, at main canal control- and check-structures, at main canal spill points, and at main reservoirs.

2) What will be measured is in effect established by the verification approach selected. It refers to the paths or components of flow that are expected to change because of the project. The basic choices are: the inflow or delivery; the outflows, which are ordered deliveries to downstream uses, spill, seepage, and evaporation; return flow; and storage changes (see Figure 1).

3) When refers to the time-step that will be used to estimate the volumes and associated differential volumes from the flow rates being measured or estimated. The basic choices are a crop season cycle, and single or multiple farm delivery cycles, 24-hour or week-long system operating cycles, and calendar cycles (such as a week or a month). A single farm delivery cycle is a multiple of 12-hour or 24-hour deliveries, and a crop season cycle is made up of the number of farm delivery cycles required for the particular crop season.

The procedures for carrying out the basic verification approaches are differentiated by the where/what volume estimates employed and the associated time-steps used. They are further differentiated by the process used in determining accumulated volume of savings. The following terms are used to differentiate between these differences:

- *Individual-event* is used when individual volume differential estimates are made for single point where/what flow rate values and single cycle time-steps (i.e., single events in both space and time) and then added to obtain the accumulated volume of savings;
- *Sequential-event* is used when individual volume differential estimates are made for single point where/what flow rate values and multiple-cycle time-steps (i.e., single events in space and multiple events in time) and then added to obtain the accumulated volume of savings; or

- *Multi-event* is used when the differential volume estimates are based on accumulated where/what values or multiple cycle time-steps (i.e., multiple events in either time or space or both).

SUMMARY

Objectives of irrigation system modernization are varied and generally involve making changes to flow paths in one or more of three general categories - *evaporative depletion flow paths, surface flow paths* and *subsurface flow paths*. Verification-based planning involves careful analysis of the pre-project *(without-project)* conditions and *quantified predictions* of the effects of the planned improvement *(with-project)*. Care must be exercised that any changes not related to the modernization project are removed or excluded from the *without- and with-project* analysis. It is not appropriate to make a direct comparison between pre- and post-project water use without normalizing conditions to account for changes in non-modernization factors.

Targeted Flow Path Changes resulting from the modernization project must be identified and quantified. During the Design Phase of the project, *without-project* flow path measurements can be made. It is necessary to synthesize the *with-project* flow path quantities for the related flow path changes. The data collection process must be carefully planned to ensure that there is confidence in both data sets and that the *with-project* data set when collected can demonstrate that the *Targeted Flow Path Changes* have in fact occurred.

Three basic verification approaches for estimating volumes of irrigation water in *Targeted Flow Path Changes* associated with a project are delivery differential, spill/seepage differential and return-flow fraction. The procedures for estimating *without- and with-project* volumes required for these approaches must consider where measurements will be made, what will be measured and the time-step as to when measurements will be made.

Verification-based planning, while requiring additional time and expense to conduct more detailed predictive analysis of conditions and to gather data, will more accurately predict water conservation results of the completed modernization project. This also provides more accurate feedback to validate and refine design assumptions for other similar projects. Coupled with cost estimates, verification details permit more accurate economic evaluation of a modernization project. This is important, even critical, for managers and other decision makers in evaluating alternatives for a program and its individual components prior to committing to proceeding with implementation. It provides a quality control component that can assure planning objectives are attained in a cost effective manner.

An actual application of verification-based planning, conducted during the implementation of the 1988 IID/MWD Water Conservation Program, titled *Lateral Canal Lining Project Case Study* is presented in the conference poster session. This case study illustrates how, through the application of verification-based planning, more accurate estimates permitted the selection and implementation of more cost-effective canals to be lined. This resulted in reducing initial concrete lining projects exceeding $250 per acre-foot to a final project cost of $131 per acre-foot.

POLICY REFORMS FOR SUSTAINABLE IRRIGATION MANAGEMENT A CASE STUDY OF INDONESIA

Ramchand Oad[1]

ABSTRACT

This paper is based on the results of a one-year study and analysis of irrigated agriculture in Indonesia (1997-98). The research was funded by the Asian Development Bank, and implemented with cooperation of the National Development Planning Board (BAPPENAS) and the Directorate General of Water Resources (DGWRD, Ministry of Public Works) in Indonesia. The overall purpose of the study was to review past policy approaches to irrigation development and management, evaluate their effectiveness, and recommend options for future.[2]

MACROECONOMIC CONTEXT

Until mid-1997, the Government of Indonesia had made impressive progress in a number of social areas including poverty alleviation, employment generation and ensuring adequate access to food for the poor. Since the financial crisis in 1997-98, these trends are in reverse. One of the severest droughts in this century associated with El Nino and the unprecedented financial crisis dealt a severe blow to Indonesia's food security. Food and Agriculture Organization (FAO/WFP) Mission (1998) estimated that the country would need to import a record 4 million tons of rice for the 1998/99 marketing year. In addition to rice, Indonesia is importing other major food crops including maize and soybeans.

The events of 1997 and 1998 have changed the setting of agriculture and rural Indonesia in some fundamental ways. Decelerating economic activity, higher

---

[1] Professor, Colorado State University, Fort Collins, Colorado. The author was team leader of a nine-member interdisciplinary team that conducted the study in Indonesia.

[2] Detailed information is available in the study team report: Consortium of International Development (1998). Assessment of Options for Sustainable Irrigation Development in Indonesia (ADB TA 2679-INO). Final report submitted to the Asian Development Bank and the Government of Indonesia.

prices and surging urban unemployment have propelled large numbers of households into impoverishment. Once again, the rural areas are characterized by mass poverty. Fortunately, the currency devaluation and tight liquidity in the financial markets should raise the relative returns to land and labor intensive activity, providing a sharp boost to economic incentives in rural agricultural sector.

The immediate priority is to cushion the fall in incomes and employment with a combination of food relief, job creation and the provision of essential foods at affordable prices. In the long run, to alleviate the crisis, policy makers must restore high-quality rural growth by promoting sustainable uses of land and water. Indonesia must return to a "back to basics" policy in which the agricultural sector is the main engine of growth. A resource-based recovery provides the best opportunity to stimulate a sustainable growth that addresses food security, poverty, and income distribution concerns. Historically, agriculture has driven rural economic growth. Irrigation, as a subsector of agriculture, plays a strategic role in improving national food security, especially for rice, by helping farmers increase food production and generate income.

Rice Production and Consumption Trends

The growth rate of Indonesian rice production has declined since early 1990s, especially in Java. Paddy production in Java grew from 26.3 million tons in 1990 to 27.4 million tons in 1996, an average annual growth rate of 0.74 %. Off-Java, the growth rate for the same six-year period was 3.32 %. For all Indonesia, it was 1.76 % compared to 3-6% for the 1970s and early 1980s (Table 1). FAO (1998) report confirms these findings, "...in the 1990s, production has fallen behind demand, with rice imports amounting to 1.8 and 3.0 million tons in 1994/95 and 1995/96 marketing years.... With the productivity gains leveling off in the early 1990s Indonesia's rice deficit showed a rising trend with the peak reached in 1995....".

Table 1. Growth Rates of Rice Harvested Area, Production and Yields

	Rice Harvested Area			Rice Production			Rice Yields		
Years	Java	Off-Java	Indonesia	Java	Off-Java	Indonesia	Java	Off-Java	Indonesia
	%			%			%		
1967-76	1.42	2.7	1.92	7.2	5.8	6.59	6.97	3.0	4.56
1977-86	1.8	2.6	2.14	3.13	3.0	3.1	0.41	0.52	1.1
1982-96	0.54	2.7	1.53	2.17	4.25	2.97	1.66	1.5	1.4
1987-96	0.31	2.8	1.45	1.53	3.82	2.43	1.22	1.1	0.96
1990-96	0.14	2.58	1.29	0.74	3.32	1.77	0.61	0.73	0.47

Source: Consortium for International Development, 1998. Assessment of Options for Sustainable Irrigation Development in Indonesia. Final Report presented to the Asian Development Bank and the Government of Indonesia. Vol. 1 of 3, p.3.

According to the FAO (1998) report, the fundamental reason for low growth rates is the leveling-off of productivity factors, i.e., cropping intensity and yields. Analysis additionally reveals that not only are cropping intensity and yields low, but they have been stagnant for a decade. Data presented in Fig. 1 confirm that average national paddy yields have remained at a level of 4.5 tons/ha since 1990. For other important food crops, such as maize, yields have been stagnant at 2.2 tons/ha since 1989 and soybeans averaged 1.2 tons/ha. Information on cropping intensity indicates similar trends -- currently low and low for the last 10 years, 1.5 level for Java and 0.9- 1.0 for off-Java. Nationwide it is about 1.18.

On the consumption side, it is estimated that the total population will expand from 198 million in 1996 to 262 million in 2020. Per capita rice consumption will expand from 151.6 kg/capita/year to a peak of 154 kg/capita/year around 2006 and then decline to 147 kg/capita/year as income increases and further urbanization takes effect. That is, total rice consumption will increase from 30.068 million tons in 1996 to 38.65 million tons in 2020. At a conversion rate for paddy to rice of 65%, this increase will require 46.26 million tons of paddy in 1996; advancing to 59.463 million tons of paddy in 2020.

During the next five-year period, the rice consumption is estimated to increase at a rate of 1.45% per year -- but over the next 25-year period, the overall increase will average slightly less than 1.0% per year. Both of these rates are less than the expected population growth rate and therefore seem reasonable compared to other regional rice consuming countries.

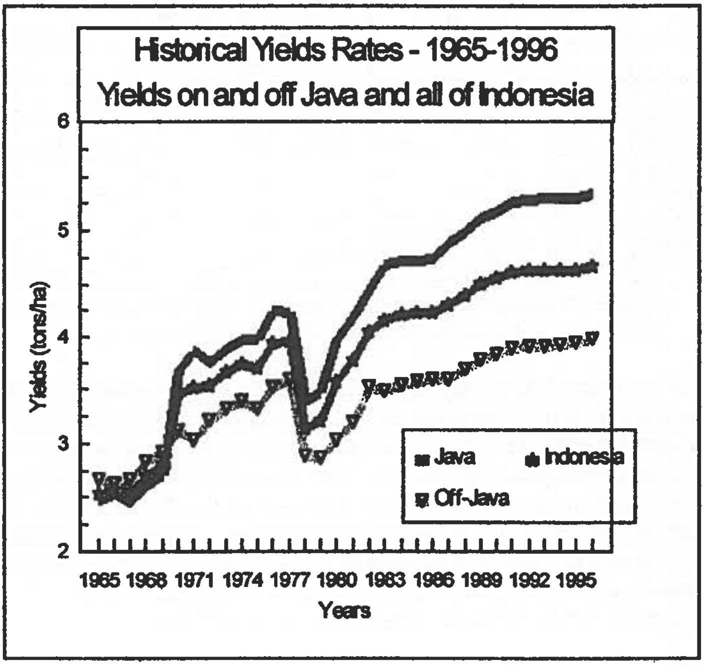


Figure 1. Historical Rice Yields, On-and Off-Java and All Indonesia

Implications for Future Irrigation Development

The study modeled several future development and management scenarios that can be employed by the government to balance expected consumption of rice and paddy production. The fundamental concern is to know whether rice self-sufficiency can be maintained through better management of existing irrigation resources, or there will be need to develop new irrigated lands. Following background information was used in the simulation exercises.

- In the base model, annual rice yield growth rates are assumed to be 0.36% on-Java and 0.96% off-Java;
- In the base model, annual rice cropping intensity growth rates are assumed to be 0.76% on-Java and 0.68% off-Java; and
- To assess agricultural land loss to urban and industrial use in Java, the model assumes three rates of land conversion. The first rate of -0.57% (about 20,000 ha/year) is an estimate of land conversion over the past two years. The second rate of -0.35% (around 12,500 ha/year) assumes a slowing of land conversion on Java. This slowing might result from financial crisis impacts and strengthened enforcement of the existing laws. The final rate of zero ha/year in land conversion is unrealistic but it dramatically illustrates the importance of protecting the good agricultural land on Java.

The results of the simulation exercise are presented in Table 2, and show the effect of increased yield and cropping intensity growth rates and additions and subtractions of land area on the future rice balance.

Option 1. Increasing Production with Constant Cropping Intensity and Yields
The first development option assumes the cropping intensity and yield growth rates to be the same as the last few years (Base option in Table 1). The results indicate if the land area conversion on Java continues and there is no new land development off-Java over the next 25 years, the average rice shortfall will be 2.6 million tons/year. That is, with no improvement in crop yield and/or cropping intensity growth rate, it will be necessary to develop new land outside Java– about 60,000 ha/year from 1999 until 2020.

Since the implementation of Irrigation Operation and Maintenance Policy (IOMP) in 1987, Indonesia developed around 30,000 ha/year of new irrigated land. In contrast, the study suggests that the country will need to develop about 60,000 ha/year, at least up to 2010. This is only possible if much of the "new" development can actually be land completion in existing irrigation systems, where much of the infrastructure such as diversion weirs and main canals are already in place. The strategy of land consolidation has a good potential for increasing production, in a cost-effective way, and is discussed in detail in policy reform formulation section.

If the crop yields cannot be improved and the new lands cannot be developed, the remaining solution is to decrease the agricultural land loss in Java (scenarios 1-1 and 1-2). Even then, rice production will be less than estimated consumption both over the 5-year and 25-year period.

Option 2. Increasing Production with Increased Yield and Cropping Intensity
Another option for increasing production is to improve growth rates of crop yields and cropping intensity. If the country can obtain modest yield increases, say 0.24% per year (that is, improved growth rate of 0.6% for Java and 1.2% off-Java), the amount of new land they need to bring in production is about 25,000 ha/year, which is feasible. The yield increases can result from introduction of new agricultural technology, better extension and irrigation management. The increase does not sound significant, but will increase yields in 2020 to 6.38 tons/ha on-Java compared to the base rate of 5.84 tons/ha and 4.95 tons/ha off-Java compared to the base rate of 4.8 tons/ha.

Even with faster yield increases, continued land conversion on Java will result in rice imports during the next five years. If the government slows land conversion to 12,500 ha per year along with an annual increase of 50,000 ha per year of irrigated land, this scenario could result in an average rice surplus of over 2.1 million tons/year throughout the 25-year period.

Table 2. Required Irrigation Expansion under Different Development Scenarios

Options & Scenarios	Annual Land Additions & Subtractions (ha)		Annual Rice Balance for 5 and 25 Year Period (000 tons)					
			Constant yield and CI growth rates[1]		Increased yield and constant CI growth rates[2]		Stagnant yield and constant CI growth rates[3]	
	Java	Off-Java	5 Yr.	25 Yr.	5 Yr.	25 Yr.	5 Yr.	25Yr.
Option 1 Base	-20,000	0	-1143	-2603				
Scen. 1.1	-12,500	0	-949	-1842				
Scen. 1.2	0	0	-522	-549				
Option 2 Scen. 2.1	-20,000	50,000	-772	-351	-581	1300	-680	-3045
Scen. 2.2	-12,500	50,000	-531	410	-343	2111	-445	-2317
Scen. 2.3	0	50,000	-158	1673	39	3458	-68	-1107
Scen. 2.4	-20,000	60,000	-698	100	-506	1757	-605	-2645
Scen. 2.5	-12,500	60,000	-289	861	-268	2568	-370	-1916
Scen. 2.6	0	60,000	-94	2124	113	3915	7	-707

[1]Constant yield growth rates (Java 0.36% & Off-Java 0.96%); constant CI growth rates (Java 0.76% & Off-Java 0.68%).

[2]Increased yield growth rates (Java 0.6% & Off-Java 1.2%); constant CI growth rates (Java 0.76% & Off-Java 0.68%).

[3]Stagnant yield growth rates (Java 0.0% & Off-Java 0.0%); constant CI growth rates (Java 0.76% & Off-Java 0.68%).

IRRIGATION POLICY AND PERFORMANCE

The food balance modeling exercise illustrates that while Indonesia will have to increase rice production to satisfy demand in the next 25 years, the country has a variety of viable options to meet the need. All scenarios require developing a limited amount of new land. However, if the country can slow agricultural land loss on Java and improve yield growth rates, a modest investment will be sufficient to fully utilize resources in schemes where irrigation facilities are already provided. All these findings imply a policy approach that focuses on better management of existing irrigation resources, rather than developing new resources. This realization is not new; in fact, it was the basis for the current IOMP policy formulated in 1987. Indonesia, with assistance from donor agencies, has made serious efforts to introduce more sustainable and efficient ways of managing irrigation systems. The facts as previously presented, however, indicate that:

- In spite of the large public expenditures in irrigation system development, production growth rate of all major food crops including rice has declined, and

- The irrigation sector faces increasingly difficult challenges arising from the current financial crisis. It must restore momentum of food production, its security and self-sufficiency. And, it must do so with much reduced monetary resources.

Important questions are raised as these facts are considered: What fundamental reasons would explain this rather low performance of irrigated agriculture? What lessons can be learned from past experiences? And, what approaches in the future would improve system performance?

Current Policy

When Indonesia achieved rice self-sufficiency in 1984, the government had responsibility for managing 2.3 million ha of technical irrigation systems, and another 900,000 ha of semi-technical irrigation[3]. After this achievement there was a realization that to maintain and/or increase rice production, the government would have to shift to a policy of properly operating and maintaining existing irrigation systems. The Irrigation Operation and Maintenance Policy (IOMP) was

---

[3] "Technical" irrigation systems are usually constructed by government agencies and have the potential of better water control in the sense that they are provided with flow regulation, measurement and other control structures. However, with better management, semi-technical and village irrigation systems may provide equally good or even better service to the farmers.

introduced in 1987, and since then the Indonesian government and several major foreign donors have invested large resources to support its implementation[4]. The policy initiatives include following programs:

- Establishment and development of water users' associations (WUA),
- Irrigation system turnover,
- Irrigation service fees,
- Efficient operations and maintenance and needs based budgets, and
- System rehabilitation or special maintenance.

IOMP attempted to shift government irrigation roles from a construction to one of improved O&M, cost recovery, and WUA involvement. The policy hoped to create new institutional roles and responsibilities for government personnel, and an expanded decision-making role for water users. However, IOMP has not lived up to expectations and its overall results with respect to ISF, institutional strengthening of WUAs and improved maintenance have been less than planned. Fundamentally, IOMP failed to establish a system of institutional incentives that favor efficient management over system extension, and proper maintenance over periodic rehabilitation. It did not establish the critical link between the consumers and the providers of irrigation service. Instead of empowering farmers, the original and innovative concepts of System Turnover to WUAs and ISF were used to justify more and more public funding for construction and system rehabilitation projects. Consequently, while government funding for system O&M has continuously increased since 1987, there has been no corresponding improvement in the quality of irrigation service provided to the farmers.

Reasons for Low Performance

To suggest future policy reforms, it is necessary first to understand why IOMP fell short of fulfilling expectations. Following major reasons were identified:[5]

---

[4] The study estimated that IOMP has been supported by projects valued at U.S $2.12 billion, of which $1.4 billion were provided by ADB and the World Bank.

[5] A parallel ADB study of agriculture sector supports the finding that the combination of low irrigation system performance and poor agricultural support services have caused crop yields and intensities to stagnant (Ministry of Agriculture, 1998). Over the last eight years new technologies, especially high-yielding rice varieties, have not been introduced. Input costs are high compared to the prices that farmers receive for their produce, all of which are frequently controlled by government monopolies. Credit facilities and marketing of agricultural produce remain major concerns for farmers.

- The institutional setting and approach have not been supportive or appropriate.
- Implementation of the policy and strategy has not been done properly.
- Allocation of resources supporting IOMP has not been supportive.
- The policy has often been implemented incorrectly.
- The IOMP reforms have been too modest.

Inappropriate Institutional Setting and Approach. The mandate and responsibility for IOMP's implementation were never clearly defined, and there never has been an institutional "home" for IOMP in the Ministry of Public Works (DGWRD). Responsibility for each program is scattered among multiple central government agencies, and no one government agency has overall responsibility and authority for IOMP's successful implementation.

IOMP's planning and decision-makings have primarily been hierarchical and generally top-down. Local government officials and farmers are often unclear about their roles and responsibilities in the Turnover and ISF programs. For WUA establishment, for example, Ministry of Public Works, DGWRD offices (*BinLak/PTGA* and *PPSDA*) are responsible for planning, while the Ministry of Home Affairs (*BANGDA*) develops regulations for WUAs. Likewise, in the Turnover program, *BinLak* office in DGWRD is in charge of planning and decision-making for construction, but *PPSDA* (also in DGWRD) is responsible for the institutional aspects.

Misunderstanding of the Policy Content. There has been a general misunderstanding of IOMP's content. Though IOMP stressed mechanisms for increased funding for O&M, the ultimate objective of the policy was improved O&M performance and service. In the past 12 years, the funding focus took precedence over the performance focus, perhaps because of the incorrect perception that the increased funding will result in improved performance.

A good example of this misunderstanding of policy content is the ISF program. Originally planned to emphasize cost recovery from beneficiaries and improved service, the program has changed into a pure ISF collection exercise. The lack of improved service has caused farmers to withdraw from the program. It was envisaged that by year 1996, ISF program would provide major share for O&M funds which would increase to 100% by year 2000 (Fig. 2). Data in Fig. 3 clearly shows that what has actually happened in O&M funding is exactly opposite to IOMP expectations. It is still the central government, which finances irrigation system O&M.

Fig.2. Projected Funding Sources for O&M

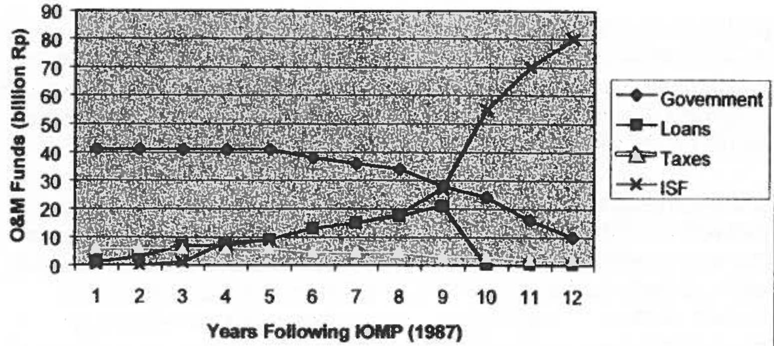
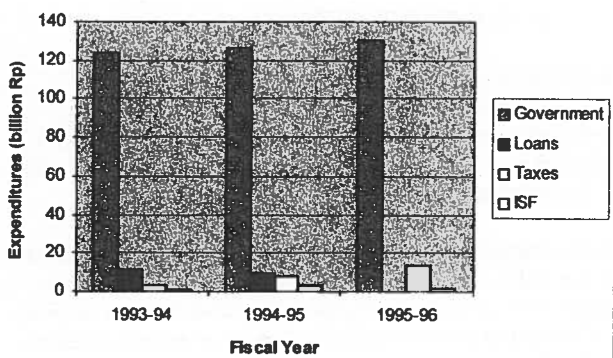


Fig.3. Actual O&M Funding Sources



Inappropriate Allocation of Resources. In Indonesian government, budgets define programs. Budgets for IOMP institutional development activities (for example, farmer training) are extremely limited. WUA training budgets are less than 1% of construction budgets, and only 2% of system rehabilitation budgets in the World

Bank's JIWMP Project. Even in JIWMP's Turnover program, where WUA sustainability is absolutely crucial, WUA formation budgets are only 6-7% of the construction budgets (The World Bank, 1997).

Target-Driven Programs. IOMP institutional programs are often too target-driven, and tend to neglect the policy's real objective - sustainable O&M. IOMP performance monitoring has focused on items such as area coverage (ha), revenues (ISF collections), numbers of WUAs established, but has neglected to emphasize and monitor sustainability and better O&M performance.

Too Modest Reforms. Despite the seemingly significant innovations introduced into Indonesia by IOMP (e.g. turnover of irrigation systems), in reality, the actual reforms are comparatively modest. In the ISF program, ISF collections become a part of the district's local revenue (*PAD*), to be allocated and disbursed by the government. In the Turnover program, the government still maintains a large degree of control over irrigation functions, and the program began by emphasizing turnover of small 150 ha schemes.[6] WUAs have been given the opportunity to attain legal status, but few of the WUAs know what to do with that status and still rely on the government for direction.

FUTURE POLICY REFORMS

The fundamental issue for future policy reform is that even after massive investments in irrigation infrastructure and agriculture support programs, the growth rate of crop yield and cropping intensity have remained low for all major food crops. However, while past performance has been rather disappointing, study findings indicate valid opportunities for increasing food production.

There is a good potential for improving rice yields and cropping intensity, both in- and off-Java. Average rice yields of 4.0 tons/ha off-Java and 5.5 tons/ ha in Java are low for lowland paddy, 78% of which is irrigated. Yet, in some areas of Java and Bali rice yields of 8 tons/ha have been reported. Current cropping intensities of 1.7 for Java and 1.3 for the outer islands also are low. Cropping intensities of 2.5 in irrigated lowlands of Java-Bali and 2.0 in irrigated lands outside Java are possible.

[6] This might be compared to Nepal's Irrigation Management Transfer Program, where irrigation systems of 10,000 ha size have been turned over to farmers.

Strategy and Programs

Large extension of irrigation system will not be a feasible strategy for increasing crop production, at least the next five or more years. The government simply will not have the funds to develop new irrigation schemes. A primary option for the irrigation sector, therefore, is to increase food production through better management of its existing resources; that is, improve crop yields and cropping intensity. This is an appropriate strategy since major problems with crop production seem to be due to inadequate management of irrigation resources and inadequate agricultural support services.

The emphasis on system management has been advocated before. Indeed, it was the primary motive behind the 1987 introduction of IOMP. So, what current actions will help ensure improved management and not merely justify more construction?

Evidence indicates that public management of the irrigation subsector has been less than effective. The future policy must try the other available option -- namely, empower WUAs with responsibility for O&M of their irrigation schemes. The current policy fails to recognize the central role of farmers in irrigation development and management. IOMP needs to be reformed in order to promote the centrality of farmers within irrigation management. Briefly stated, the fundamental strategy of the Reformed IOMP would be to:

- Empower WUAs for better O&M in order to increase productivity of irrigated agriculture, and
- In the context of better management, consolidate existing irrigation resources for optimum use of available land and water resources.

Fundamental policy approach would be to develop incentive systems that empower WUAs to routinely maintain irrigation schemes and provide reliable water supplies to the members. Also, WUAs and federations of WUAs need to be involved in the provision of quality agriculture support services so that the users have access to better seeds and other inputs, at reasonable prices. In the long run, federated associations can use their economies of scale to help their members to establish market opportunities for non-rice crops. To support implementation of this policy, the study recommended five programs.

- Empower and strengthen WUAs
  - Institute a system of water rights that formally recognizes the rights of WUAs to manage public waters,
  - Expand the rights of WUAs to institute proper O&M programs, and
  - Involve WUAs in requesting and supporting system rehabilitation.
- Expand and accelerate Irrigation Turnover program,
- Accelerate Irrigation Service Fee program with WUAs collecting and managing the funds,
- Promote capacity-building programs to strengthen WUAs, and
- Complete land and water resources in existing irrigation systems.

Development of Sustainable WUAs/WUA Federations

One clear finding from the study team's field investigation was that a strong WUA is an excellent indicator and predictor for improved O&M performance. The overall goals of a WUA development program would be: (1) improved, sustainable O&M performance, and (2) increased farmers' income. The team recommended following strategies for WUA development.

Empower Farmers and WUAs. Government regulations should empower WUAs legally and economically. WUAs should be authorized to collect necessary management fees from their members and use it for proper system O&M. Helmi (1997) has suggested a three-stage process to encourage WUAs seeking increased income. First, WUAs should become proficient in routine O&M activities. Second, the WUAs need to request Government assistance in income producing activities directly related to water, for example small water storage reservoirs that can also function as fish ponds. The final stage would be to facilitate WUAs and Federated WUAs involvement in larger agricultural activities such as accessing inputs and marketing produce.

Direct WUA Assistance Programs..The establishment and development of WUAs should not promote a dependency on the government. Rather, government assistance programs to WUAs should be in response to requests from the WUAs and focus on activities that the WUAs can and should perform on their own -- for example, irrigation functions, bookkeeping for income generation activities, and the legalization process.

WUA Federations. As WUAs take on added responsibility and authority in the Reformed IOMP, it is likely that WUA federations will play a larger role. With the current size of WUAs at only 50-150 ha, the organizations are too small to have a significant impact and to be able to recruit professional staff. WUA development efforts, therefore, should include specific programs to establish and develop larger WUA federations that can hire professional management staff while the members ensure the system is governed properly.

Region-Specific Initiatives. WUAs or traditional farmer irrigation groups behave in unique ways in different parts of Indonesia. The WUAs should be village based and incorporate and integrate local traditions into their development programs. It is critical that all WUA and WUA federation development programs and activities address the needs of the users and the villages, not the needs of the government.

Accelerated Turnover Program

Despite real problems in its implementation, much of the basic philosophy of turnover program remains sound. The program's goals and objectives are clearly in line with the Reformed IOMP's overall principles of farmer-based development and self-reliance. The accelerated turnover program would be based on the following strategies and reforms.

Turnover First, then Physical Improvements. The key to developing a more sustainable turnover program was adequately described by farmers: first develop a strong WUA, and then let the farmers request assistance from government for physical improvements. The current procedure of rehabilitating a system first before turning it over sends wrong signals to farmers and government staff.

Turnover of larger irrigation systems. There should not be any limitations on the sizes of irrigation systems turned over. The current approach of focusing on schemes 150 ha to 300 ha should be replaced with an incentive structure where district-level irrigation offices are rewarded for turning over larger schemes, even over 5,000 ha. In very large systems such as Jatilahur it is possible to have a two phase transfer program with WUAs taking responsibility for the secondary canals first, and a federated WUA eventually taking responsibility for the primary canals.

Farmers' Contributions in Physical Improvements. WUAs need to be involved in physical improvements, including formalized cost-sharing arrangement. Farmers requesting improvements will be expected to make an equity contribution, either in cash, labor, and/or materials. In the second Irrigation Sub-Sector Project (ISSP-II) project, the World Bank estimated that the level of farmer equity contribution was about 9% of the construction cost. The contribution was mainly land and labor.

Role of the Government. Government irrigation officials would take on new roles as advisors, trainers, and supporters of the newly turned over WUA-managed schemes. The government would maintain control of the headworks and weirs since river flows and downstream users would be affected. Presently, after rehabilitation and turnover, the government budgets for a turned-over irrigation scheme are reduced to zero. In their new role of water resource managers, local or semi-private agencies will be provided a public budget as needed to manage the water resource system.

Irrigation Service Fee (ISF)

The Government has already issued instructions to expand and accelerate the present ISF program. These instructions are in line with the proposed Reformed IOMP program and its increased emphasis on management of irrigation systems. The overall goals of the expanded ISF program would be to:

- Improve irrigation service, management, and performance,
- Assist with O&M funding, and
- Develop the philosophy among farmers that irrigation management is not free.

The principles and strategies that will guide the implementation of the ISF program would be as follows.

Simplify Institutions and Procedures. The ISF program should empower local institutions, including WUAs and WUA federations: this is its primary purpose. Government will assist, monitor, train, and provide guidance, but the true "executing agency" will be the WUAs themselves. The key decision-making body in ISF would be composed of representatives from the WUA or WUA federation with advice from local government officials (*Camat, Kepala Desa*), and local irrigation officials (*Pengamat*). This would be at the sub-district level; there is no need for a large, central bureaucracy with numerous forms, rules, and procedures. WUAs will collect and manage ISF.

Establish a Clear Link between the Providers and Consumers of Service. ISF should concentrate on genuine O&M tasks and improved service and management, not on new construction. The fees collected from a scheme must all be used for improving irrigation service in that scheme.

Improved System O&M

Key elements of an improved O&M program would be as follows.

Institutional Incentives. Irrigation O&M is not exclusively a funding problem. If proper maintenance is not done, it is often because the current system of institutional motivation makes it a low priority item. The fundamental solution would be to reform the system of institutional incentives whereby routine maintenance becomes as attractive as construction projects. The first step would be to ensure that WUAs view themselves as the decision-makers. In the government, the functions of system development and management should be assigned to one local institution so that an evaluation of tradeoffs is optimally made.

Institutional Accountability. There is fundamentally no accountability from the suppliers of maintenance services to the users. IOMP tried to provide a direct link between the supplier and consumer of irrigation service by introducing ISF. Irrigation service fee is the correct way of introducing the link, but its management by government agencies has resulted in failure. In the Reformed IOMP, the process will be reversed with WUAs responsible for collecting and managing ISF funds.

Adequacy and Use of O&M Funds. It is correct that the government funds are not sufficient for proper O&M, but more funds would not necessarily result in better performance and service. Institutional motivations are simply against routine maintenance, and that needs to be changed first. A related problem with main system O&M is not only the lack of funds but also the way in which existing funds are used. Data indicate that well over 60% of the O&M funds are used for operational purposes (salaries and office supplies, etc.), and the rest for construction related activities.

At present, there are central block grants (*INPRES*) available to district-level offices. Few if any, of these *INPRES* block grants are used for irrigation O&M. It may be necessary to make specific *INPRES* grants for irrigation O&M, ensuring that the funds are transferred directly to the district level offices and/or WUAs.

Monitoring and Evaluation of O&M Performance. There are a variety of ways to measure O&M performance, but finding simple and practical methods to use for the diverse conditions of Indonesia has proved difficult. Further, it is important that data are regularly analyzed and used to improve irrigation system performance. This can be a very simple recording of basic information such as:

- Adequacy and reliability of water supply
- Cropping intensity
- Yields and farm incomes
- Functioning of WUAs including ISF collections
- Planned maintenance vs completed maintenance, and
- Conflict resolution.

Resource Consolidation

Optimum use of existing irrigation facilities is in tune with the Government's tight monetary conditions. There are several irrigation schemes where the actual irrigated area is reduced by incomplete canal systems, incomplete land development, and water shortage. Completing the necessary infrastructure and land development optimizes the use of land and water resources as well as takes advantage of the sunken investment. Where water shortage is a constraint, in many cases, providing small storage reservoirs can relieve it.

Table 3 summarizes reasons why the lands are not optimally used based on information from field visits. As expected, the reasons vary widely, but the common themes are as follows.

- Shortage of water is one major reason why some service areas are not irrigated. Most schemes are run-of-the-river systems and the abundant water supplies during the rainy season are not stored. Small off-stream storage reservoirs can be very effective in alleviating this constraint (Achmad Fagi, 1994).

- Tertiary channels and control structures are not provided, and the lands are not yet developed to paddy fields. Most often, however, some of these lands may be used for plantation crops such as coconut and coffee since rice is not as profitable.

- Incomplete main system including the absence of main water delivery canal and related control facilities. Many irrigation systems are developed on a modular or "piecemeal" basis so that, in the first phase, only a weir and a limited length of main canal are built. The system is then enlarged in successive years, depending on the availability of project funds.

Table 3. Reasons for Incomplete Use of Irrigation Resources -- Examples from Field

Province/ Scheme	Design Area (ha)	Actual Irrg. Area (ha)	Improvement Potential (ha)	Reasons
<u>West Java</u>				
Padawaras	6,000	80	2,500	Land and tertiary systems not developed. Some area under tree crops.
<u>Central Java</u>				
Dumpil	11,300	2,000	9,300	Insufficient water supplies.
Lanang	1,817	0	1,817	Main supply system from reservoir/ weir not completed.
<u>West Sumatra</u>				
Lolo Tuhur	658	213	None	445 ha already converted to coffee.
Galo Gadang	1,111	758	353	Insufficient water, need small village reservoirs to store water.
Lubuk Buaya	1,568	300	1,268	Main system including weir needs repairs.
Batang Surantih	1,864	968	896	Need rehabilitation of main system.

Source: Information from W.Java, C.Java and W.Sumatra Provincial Water Resources Services, 1998.

CONCLUSIONS

Indonesian stakeholders must broadly rethink agricultural and rural development strategies. A resource-based recovery provides the best approach to stimulate economic growth and address food security, poverty, and income distribution concerns. Controlled prices and subsidies have confused the market and reduced farmers' economic incentives. Food security will not be achieved until the farmers know that they can make a reasonable profit. Policies to ensure fair prices must be implemented as a foundation for sustainable irrigated agriculture.

The challenge to irrigated agriculture in Indonesia is to sustain food security while expanding into more flexible, diversified cropping. Improving cropping intensity and yields, rather than developing new irrigated lands can efficiently increase Indonesian food production. Comparatively low cropping intensity and yields clearly imply a lack of good management of land, water, and production inputs. A fundamental emphasis on proper management of irrigated agriculture is required.

Public management of the irrigation subsector has been less than effective. Future irrigation policy should try the other option: enable the farmer communities to accept responsibility for their irrigation systems. The current IOMP policy needs to be reformed to promote the centrality of farmers and WUAs in irrigation system management.

Sustainable irrigation requires a system of institutional incentives that establishes accountability in the relationship between the providers and users of irrigation service, and inspires them to properly operate and maintain irrigation facilities. Reformed IOMP would encourage following programs.

- Reinforce the commitment to the Irrigation Service Fee (ISF) program. This means a simplified program that ensures funds raised are used in the irrigation system where they were collected, with the users having a final say over how the funds are expended.

- Expand the successful Irrigation Turnover program to eventually include all public irrigation systems. The size of the schemes need not be a limiting factor. The program also needs redesigning so that no rehabilitation is done until after transfer, when WUAs can make inputs on the nature of improvements.

- Recognize the central role of farmers and their WUAs. WUAs should be in charge of their irrigation systems, with a federation of WUAs responsible for planning water allocation and main canal maintenance in larger schemes.

REFERENCES

Achmad Fagi, 1994. *Embung* (Small Water Reservoirs). Ministry of Agriculture Center for Research and Development of Food Crops, Bogor, Indonesia.

FAO/WFP, 1998. FAO/WFP Crop and Food Supply Assessment in Indonesia. FAO, Rome April 17,1998.

Ford Foundation, 1998. Participatory Strategies for Irrigation in Indonesia. P.T. Artama-LP3ES, Jakarta, Indonesia.

Helmi, 1997. Developing Sustainable Farmers Organizations for Irrigation Management: an Assessment of Indonesian Experience. National Seminar on Development and Management of Water Resources, sponsored by DGWRD, Ministry of Public Works, Jakarta.

JICA (Japan International Cooperation Agency), 1993. The Study for Formulation of Irrigation Development Program in Indonesia. Ministry of Public Works/ BAPPENAS, Government of Indonesia, Jakarta.

Ministry of Agriculture, 1998. Agriculture Sector Strategy Review, Ministry of Agriculture, Republic of Indonesia: Constraints and opportunities for further growth in agriculture, Study A-2. ADB TA 2660-INO. Hunting Technical Services, Ltd, Jakarta.

-----------. 1998. Agriculture Sector Strategy Review, ADB TA 2660-INO: Decentralization of agricultural support services. Hunting Technical Services, Ltd. Jakarta.

Tabor, Steven, 1998. Back to Business: Revitalizing Rural Development in Indonesia. Bulog, the National Food Logistics Agency, Jakarta.

Asian Development Bank, 1993. Project Completion Report of the Second Irrigation Package Project in Indonesia, June 1993. Loan No. 627-INO, PCR:INO 16003.

The World Bank, Agriculture Operations Division. 1997. A Review of Public Agricultural Expenditures in Indonesia. World Bank, Washington, D.C.

The World Bank, 1997. Java Irrigation and Water Resources Management Project (JIWMP) Mid-Term Review (MTR)- Mission Objectives, Office Memorandum, 26 May 1997.

Acknowledgements

The author is greatly thankful to his team members for their able assistance and hard work in Indonesia. The financial support of the Asian Development Bank and the institutional support of Colorado State University and Consortium for International Development are greatly appreciated. In Indonesia, Ministry of Public Works provided work place for the study team and BAPPENAS provided the overall supervision. Several government officials and farmers in North and West Sumatra, Lombok, and Java provinces provided invaluable assistance in collecting field information. Last but not least, the patience and support of his family is highly appreciated.

Acronyms

ADB	Asian Development Bank
BANGDA	Directorate for Regional Development, Ministry of Home Affairs
BAPPENAS	National Development Planning Board
BINLAK	Regional Directorates of DGWRD (western, central and eastern regions)
BULOG	National Logistics Agency
DGWRD	Directorate General Water Resources Development, Ministry of Public Works
EOM	Efficient Operations and Maintenance
FAO	Food and Agriculture Organization
INPRES	Presidential Instruction
IOMP	Irrigation operation and maintenance policy, 1987
ISF	Irrigation Service Fee
ISSPI-I & II	Irrigation Sub-Sector Project I & II
JICA	Japan International Cooperation Agency
JIWMP	Java Irrigation Water Management Project
MOA	Ministry of Agriculture
O&M	Operations and Maintenance
PPSDA	Subdirectorate of Institutions in the Dir. of Utilization and Preservation,
PTGA	*Proyek Tata Guna Air* (Water Users Training Program)
WUA	Water Users Association

BENCH TERRACING
A COST EFFECTIVE ALTERNATIVE TO TRADITIONAL IRRIGATION IN THE PHILIPPINES

John E. Priest[1]

ABSTRACT

The case study presented in this paper, a pilot program for the construction of permanent bench terraces throughout the Philippine islands, was designed to increase grains production at costs that would be competitive internationally. Additionally, the terraces would alleviate the severe problem of hillside erosion that currently is silting rivers, reservoirs and canals. Compacted dikes would form terraces for capturing all depths of rainfall, in-place, for crop production. With the generally predictable rainfall regimes particular to each island of the Republic, one to three high yielding crops could be produced annually without the construction of flood-vulnerable diversion works, reservoirs, and long canals.

A Pilot Project was designed to achieve construction of some 1400 separate terraces averaging 50 hectares each, in several areas of the three regions of the country -- Luzon, Visayas, and Mindanao. For execution of the project, the central government could decide to purchase equipment and employ personnel to complete construction. Alternatively, the central government could elect to contract construction and engage local government to provide legal, social, and administrative support. The landowners, in this case, likely would enter into a tripartite contract with a bank and a developer, not with the government.

For either scenario, the objective of the pilot program would be to demonstrate to landowners, nationwide, that they could come together and transform now largely unproductive hillsides into land that could produce high yielding crops of maize, sorghum, millet and grain amaranth. Besides encouraging private investment on a broad scale, it was anticipated that through the pilot program, local government would gain expertise and resources. Local government and landowner cooperation would be of critical importance because then on-going reforms had subdivided land to an extent that would require a range of legal and social actions to re-aggregate small holdings into viable project blocks.

Development costs would approximate US $800 per acre ($2000 per hectare), 1997/98 prices, whether carried out totally as a private development or as a government program.

---

[1] Consultant and Executive Vice President, RDT International, 2442 West Dry Creek Court, Littleton CO 80120

OBJECTIVE

The objective of the combined policy proposals of this author was to realize the mobilization of private resources for expansion of corn producing lands and the focus of available public resources for the expansion of rice producing areas of the Republic of the Philippines.

INTRODUCTION

During the decade of the 1990s agricultural trade worldwide was liberalized. Rules changes for agriculture within the framework of the World Trade Organization (WTO) and the then evolving preferential trade rules among the ASEAN countries required that fundamental modifications be made to the policy foundation and the structure and operations of the grains sector in the Philippines. Consideration of policy options required that a thorough review be made of the conditions that prevailed with the infrastructure of the Nation and how the key organizations were constituted, operated and financed.

The Grains Project

To address the considerable anti-competitive, inefficient distortions that had arisen in the agricultural sector, the Department of Agriculture (DA) of the Philippines secured funding from the Asian Development Bank. The financing was used to develop a set of policy initiatives. The policy initiatives addressed institutional capacities, issues and constraints that restrict efficient production of grains, and modifications to infrastructure required to release constraints and to increase cost-competitive agriculture.

Development Alternatives Inc. (DAI) of Bethesda, Maryland was awarded a contract to assist the DA with the development of a set of policies and companion programs that crosscut all sectors and institutions that affected grain production. The policies and programs analyzed and proposed varied from those for research and marketing to the construction of works. It was as a member of the DAI team that this author carried out a broad study of how to rehabilitate and expand deteriorated irrigation systems largely dedicated to rice production.

As well, water law and legislation was studied and policies were drawn to guide reorganization of the administration and use of water. Formulated was an organizational framework of governments and water user organizations to undertake sustainable operation, maintenance, and rehabilitation of existing irrigation systems with minimal input of financial resources by the Federal government.

The bench-terrace case study was formulated in recognition of the impossibly large financial commitments required to rehabilitate and to expand the irrigation systems of the country. Of equal importance was the need to introduce a program that would facilitate and hasten the on-going devolvement of many technical, administrative, and coordination functions away from the central government to provincial and local units of government (LGUs).

It was assumed that following implementation of the proposed Pilot Project, and if there would be continuing allocation of adequate financial resources, LGUs would have considerably enhanced capacities to directly support cultivators. Such support would be expected to emerge as traditional extension services to irrigation farmers and as the support necessary for the conduct of a program of bench terracing which would be financed and carried out by private interests, ie entrepreneurs.

Threat of Erosion

The Congress of the Republic and the World Bank both had identified erosion of the volcanic hillsides as the defining threat to the environment. Hillside erosion had filled river channels such that even small frequent floods overtopped levees and damaged hydraulic structures. Topsoil on hillsides is naturally shallow. Thus any erosion results in diminished capacity for supporting desirable vegetation, cultivated or natural.

Simplicity and Economy of Bench Terraces

Bench terraces effectively are lineal reservoirs with the entire terrace constituting the catchment area and the soil profile affording storage. Effectively the water supply is derived through subirrigation. The dike heights were designed to retain the precipitation of a typhoon.

Designs and costs were developed at the reconnaissance level for the formulation of policies to be adopted by the government of the Philippines and for use in securing international financing for the bench terracing and companion programs. It was estimated that bench terraces could be constructed for approximately US $800 per acre ($2000 per hectare). By contrast, construction of irrigation works, with storage and hydraulic capacity adequate to assure a low risk of crop failure would require an initial investment in excess of US $4000 per acre ($10,000 per hectare). In fact, costs for large-scale reservoir storage, major conveyance, diversion works, and the on-farm development of the land, a drainage system, and minor canals could cost as much as US $7500 per acre ($30,000 per hectare).

Farmers would be capable of maintaining and repairing dikes and drainage works of a terraced area under most circumstances. It was anticipated that the farmers would be part of a cooperative through which they would be able to pool resources and secure the support of provincial and local governments.

Grain Production

Rice is irrigated whereas corn largely is produced from rainfall. Rice and corn are the two basic grains for human consumption and for animal feed. When corn is in short supply, rice is used as animal feed. Changes to the trade agreements occurred even as the demand for grain was increasing some three-percent per year and supply was declining. It was during the first half of the decade of the 1990s that the area of corn harvested decreased 4.9 percent while the availability of rice decreased precipitously during 1995 due to a combination of circumstances.

Condition of Infrastructure

Major irrigation projects, with a few exceptions, are serviced by low gated structures that lie across river channels. Often the channel has filled with sediment upstream from the structures, and levees have been built to prevent water from flowing overbank. These structures and levees sustain severe damage or destruction when a typhoon centers or passes over their drainage basin. It was due to the occurrence of several severe typhoons, earthquakes, and the volcanic eruption of Mt. Pinatubo that several sizeable blocks of agricultural lands were lost to production during the 1990s.

In-place programs for operation and maintenance (O&M) and for rehabilitation of typhoon damage were reviewed by the author and were identified as totally inadequate. Their shortfalls occurred due to under-funding of the responsible agencies and the inability of farmers to retain their water taxes and dues for direct use for O&M. The resulting severe lack of O&M and rehabilitation money was a major determinant of the level of grain production realized during the 1990s.

On-going Legislative and Administrative Programs

In the context of legislative and planning programs, far-reaching efforts were in progress to catalyze grains production to higher, more economic levels. These programs dealt with project planning and legislation regarding decentralization/devolution of federal functions to the provinces and LGUs and with the strengthening of cooperatives in conjunction with the program of land distribution. The demand for a limited supply of land had resulted in the breakup of large holdings into non-economic units with many small holders of limited financial capacity. To counter the economic effects the government was promoting the reorganization of cooperatives to bring together the many new small-landowners.

The second program related to the devolution of governmental functions from the Federal level to the local level. The program of devolution had yet to be funded and supported for startup. It was the anticipated increase of local capacity, however, that was the basis for the training component of the proposed Pilot Project and the incorporation of the principle of extension support by LGUs of future landowners and entrepreneurial activities.

Agrarian Reform: The Department of Agrarian Reform and the Department of Environment and Natural Resources had distributed 9.25 million acres (3.7 million hectares) of land to small farmers and workers, including 0.5 million share tenants, through the Comprehensive Agrarian Reform Program, implemented in 1987. During the period from 1987 to 1996, three associated activities with importance for the future potential increases of grain production were undertaken and required funding. The activities were: 1) agrarian reform communities which would serve as the focal point of reform activities and interaction between government and beneficiaries, 2) the expediting of land titling through a memorandum of agreement between the Department of Agricultural Reform and the Land Registration Authority, and 3) coordination with the Land Bank of the Philippines to simplify the process of land valuation.

Effects of Devolution: Devolution had the potential to place decision making closer to recipients and, thus, to be more responsive and efficient than programs operated from a central bureaucracy. Devolved agricultural extension staff were experiencing considerable difficulties, however, in securing administrative and financial support. Even though agriculture provides some 43 percent of employment, the need for training, budget and infrastructure were not commonly recognized.

It was observed that devolution temporarily had slowed or stopped programs that formerly were run by a centralized bureaucracy. It was for this reason that both the proposed hillside agriculture program and the in-place irrigation systems were viewed as important to the securing of resources for equipping and training local administrative and technical staff.

Conditions for Re-aggregation of Small Holdings

The program for the breakup of large land holdings and the distribution of these lands in small parcels to the landless has created technical, legal, and social challenges for the implementation of a successful national program of terracing,

Only if the new small holders would join a viable, active cooperative that could secure the advantages of strength in numbers, would there exist the conditions required for government or an entrepreneur to negotiate agreements for the financing and physical development of large tracts of land.

Problems could occur, for example, because dikes and drainage ways would occupy some 20 to 25 percent of terraced areas. Consequently the cultivable terraced land would have to be proportionally distributed or the produce would have to be marketed proportionally.

Similarly the soundest opportunity for recovery of investment costs would occur with the execution of firm agreements drawn before the start of construction. If legal, technical and financial staff of LGUs would be properly funded and trained during the execution of the Pilot Project, they should be able to support and even spearhead the drawing of pre-construction agreements subsequent to the execution of the Pilot Program. Thus, it was assumed that staff of local governments would facilitate the preparation of triangular agreement among landowners, banks, and entrepreneurs.

Widespread bench terracing could be an important catalyst for the successful devolution of responsibilities from the central government to LGUs.

Environment

Climate and weather were recognized as both an asset and an impediment to the production of grains. Intense rainfall was eroding the topsoil from hillsides and was clogging the rivers and canals. Yet rainfall originates from four great global systems to the benefit of rainfed agriculture either year round, as in northern Mindanao, or seasonally as on the northern end of Luzon. Understanding of the climate of the archipelago is essential to a full understanding of the potential for hillside agriculture.

Conclusion Regarding the Future of the Irrigation Program

The author realized early that no matter how artfully revenues would be collected and disbursed by the government, they would be inadequate. Revenues were required to support a sizeable national bureaucracy for operation, maintenance, and rehabilitation of typhoon-ravaged existing irrigation systems, even as efforts were underway to free up monies for construction of new or expanded areas for irrigation. Construction of large new irrigation systems would require substantial inputs of front-end capital, perhaps US $2500 to $7500 per acre ($10,000 to $30,000 per hectare). Also lands still to be developed would be those that would be technically difficult to service and would require high unit cost investments to develop low risk agriculture.

As shown below, extensive land areas could be developed on hillsides to produce one to three high yielding crops of corn per year based on a system of terraces to retain all rainfall, even that of typhoons. Costs would average some US $800 per acre ($2,000/ ha.) depending on the cost of diesel fuel and the necessary profit to motivate the mobilization of substantial private resources.

It was this recognition, coupled with a study of legislation before the National Congress, which led the author to focus on the potential for rapid, extensive expansion of the area dedicated to the cultivation of corn.

THE HILLSIDE PROGRAM

A hillside agriculture program would represent the best means to set the farmer of the Philippines on the road to prosperity and international competitiveness. The objective was to greatly expand acreage dedicated to grains and to reduce hillside erosion and consequent sedimentation. This would be accomplished with a program of bench terracing modified to create permanent dikes.

A bench terrace, as designed for the Pilot Project, would be effectively a total self-contained water supply system within the confines of an agricultural field. Similar to an irrigation system, the dike impounds rainfall on-site, the water is throughput to storage in the soil profile through infiltration, and it is returned to the crop through a form of sub-irrigation.

It would be important that the government would implement a Pilot Project to demonstrate to farmers, entrepreneurs, and local governments that much would be gained by a nationwide program of bench terracing. A program for the development of, say, 140 125-acre (50-hectare) parcels would provide for the training of equipment operators across all three island-groups, Mindanao, Visayas and Luzon. Farmers would immediately realize the great benefits, local governments could learn their roles, and entrepreneurs could be introduced to a potentially profitable undertaking that would continue for 20 years or more. The stock of land with slopes between 5 percent and 20 percent is extensive across all the islands.

Bench Terraces

Bench terracing, as defined for purposes of this analysis, would be a series of land terraces each of which would lie along a topographic contour on a hillside. Such terraces could readily be formed on hillsides with slopes of 5 to 20 percent and where the total soils mantle would be adequately deep. The steepness of the land slope and the depth of soil would determine the width of terraces. It was noted that, for legal reasons, terracing likely would be limited to lands with slopes not in excess of 18 degrees (20 percent). It would be lands with slopes below 18 degrees that could be "alienated" and "disposed" to private ownership for agricultural uses.

For example, as is shown on Fig. 1, lands with 10 percent of natural slope and topsoil with a depth of approximately one-half meter could be benched with terraces 10 meters wide without exposing the subsoil on the uphill side of the bench. Should the depth of the topsoil be less than 0.5 meters, the bench would best be formed with a lesser width. Or, topsoil could be stockpiled or moved into areas of shallow soil depth.

Water Balance on the Terrace

As may be seen on Fig. 1, dikes would be constructed about one meter high on their uphill side. When the leveling would be completed, there would be about 40 to 60 centimeters of dike freeboard. This freeboard, along with infiltration during a storm, should be sufficient to contain all but the most extreme rainfalls. Pipes would be installed near the tops of dikes to permit controlled downhill flow of any rainwater that otherwise could overtop the dikes.

There are four climatic patterns that influence rainfall across the Philippines, Fig. 2. Air streams that enter the Philippines from differing directions determine these four zones. The air streams are the Northeast Monsoon, the North Pacific Trades, the Southwest Monsoon, and the South Pacific Trades. Generally it is only the Northeast Monsoon that brings rains during the November to March period. Thus, with the exception of Mindanao, it is not coincidental that the western sides of mountains receive little or no rainfall from November to April. It may be that rainfall occurs throughout the year in Mindanao because the island is affected by the instability of the Intertropical Convergence Zone most of the year as it is near the equator.

Fig. 3 presents a prefeasibility level risk analysis that would need to be made in more detail for each area prior to development.

Cropping

The level shelf would retain a water supply adequate for dry-season cultivation of high yielding grains such as, maize, amaranth, sorghum or millet as well as providing the opportunity for cultivating high value vegetable and tree crops. The terraces would be designed to widths that would permit mechanized cultivation.

Crop selection and planting dates should be made on the basis of average and/or some dry year rainfall basis. If it is common, as in western Luzon, that an area would experience an abrupt secession of rainfall during the month of November, and knowing the probability that there would be little or no rainfall for five months, then farmers should be advised to plant drought tolerant crops. In other

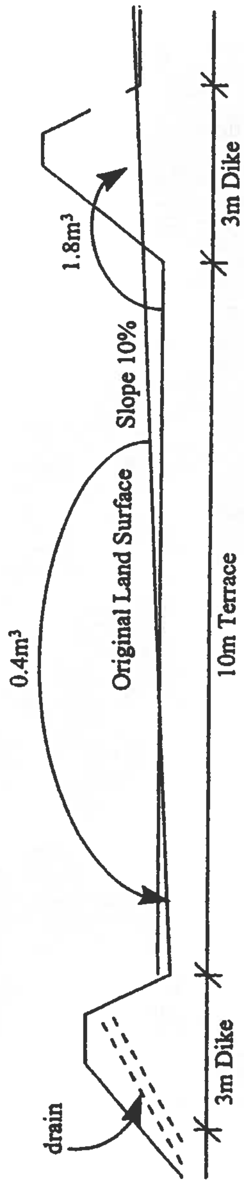
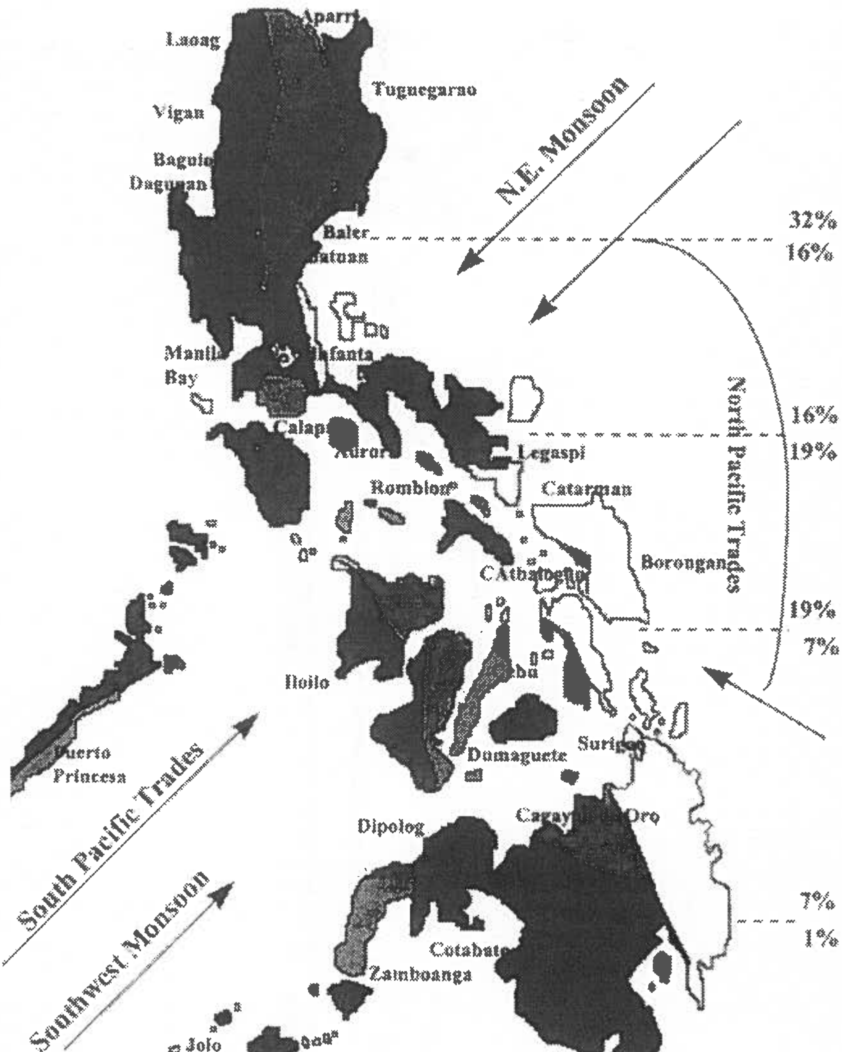


Fig. 1. Bench Terrace, 10 Percent Land Slope



1 Two seasons; dry November to April, wet rest of the year.

2 No dry season, high rainfall November to January.

3 Seasons not very pronounced, relatively dry from November to April and wetter during the rest of the year.

4 Rainfall more or less evenly distributed throughout the year.

(7%/1%) Frequency of Tropical Cyclanes by zone

Fig. 2. Seasons of Rainfall

Data Used   Rainfall record for Camp Phillips, Bukidnon, 1962 to 1989

Assumption

+Gram crops are to be planted in September or October and May or June.
+Consumptive use for corn is 400 mm over a period of 3.5 months, is 300 mm for grain sorghum or grain amaranth, and 200 mm for millet.
+If October is the month for planting and the soil moisture reservoir is nearly fall at the end of the rainy season, then rainfall of 300mm during the November, December, January period will be sufficient to water a corn crop, with only 200mm being required for grain amaranth or sorghum, and 100 mm to mature a millet crop.

Risk Test

+Inspection of the rainfall record shows that total rainfall during the May to August period is more than adequate for maturing a crop of corn during every year of the 28-year record.
+ Aggregate rainfall is shown for the October through January period, in the table below to test the viability of cropping corn into the early calendar year dry season.

ANALYSIS OF RAINFALL ADEQUACY
FOR OCTOBER THROUGH JANUARY GROWING SEASON
CampPhillips, Bukidnon

Year	October	Nov/Dec/Jan	Year	October	Nov/Dec/Jan
1962/1963		400+	1976/1977		400+
64	208	230	78		339
1964/1965		400+	79		380
66	201	224	1979/1980		400+
67		400+	81		400+
68		328	82		400+
69	166	267	83	162,	195
1969/1970		321	84		335
71		400+	1984/1985		400+
72		381	86		400+
73		400+	87		332
74		400+	88		400+
1974/1975		400+	1988/1989		400+
76		400+			

It is noted that during only one season in 28 years (1962to 1989) was rainfall marginal for a corn Crop planted in October and matured during the November through January period.
Inspection of the full monthly record also indicated that water supply would be more than adequate every year for a crop planted in May or June and matured by August or September.
Further, should farmers of Bukidnon wish to plant a grain crop during the January through April Period rainfall would be marginal I in 4 years except for millet crops.

Fig. 3. Critical Rainfall Period for Hillside Grain Production, Northern Mindanao

areas of the country, such as in Mindanao, pests permitting, two high yielding crops could be planted and there could even be scope for cultivating a third short season vegetable or fodder crop.

Implementation

Proposed was a Pilot Project with the objective of promoting a nation-wide program of treating hillside tracts ranging in area from only a few hectares to those that cover entire slopes comprised of hundreds of hectares. The four-year pilot program would realize the construction of bench terraces in some 140 areas. Areas would average 125 acres (50 hectares) each. Approximately 17,500 acres (7000 hectares) of land would be treated. The primary objective of the program would be the establishment of trained cadres of technicians at the provincial and local levels along with the mobilization of private resources. Private resources for the Pilot Project largely would be in the form of labor, whereas if entrepreneurs would be attracted to extend the program to other areas the financing should be essentially all private.

It was expected that landowners, farmers, and their cooperatives would recognize the major levels of crop output that could be obtained with modest investment required per hectare and with very modest requirements for maintenance by each cultivator. It, also, was expected that entrepreneurs would recognize the possibilities for organizing their own machinery pools and providing the mechanized service for bench terracing to farmers for a fee. Thus, a second component of private funding would be mobilized and would contribute to acceleration of bench terracing at a rate greatly in excess of that achieved by the pilot program, some 17,500 acres (7,000 hectares) over a four-year period.

It would be essential that entrepreneurs and bankers be included at one or more stages of the training and implementation cycles of the Pilot Project. It then should be relatively simple to foster triangular organizations of farmer, banker, and entrepreneur. Contracts would be drawn and would specify that the bank would reimburse the entrepreneur directly for his terracing operations upon receiving a signed certificate from the landowner. The landowner would then pay the bank at the end of each cropping season until the debt would be retired. It should be possible for the farmer to retire the full debt and interest in just a few seasons where two high-yielding crops could be cultivated.

Particularly essential to sustainability of the program at a technical assistance level and at the extension level for high crop productivity would be continuing funding and administrative support to local governments. Local government would in turn provide technical and equipment support to farmers both during construction and following, during cultivation.

Contractual Considerations

Contracts would be drawn between landowners/cooperatives and government for the Pilot Project. Thereafter contracts would be drawn among landowners/cooperatives, entrepreneurs and banks. Of prime importance to the launching of the Pilot Project would be how to create a sustainable program that eventually would realize the recovery of tens of thousands of hectares nationwide. Among considerations could be the establishment of a short grace period before farmers and cooperatives undertake amortization of the physical works. This would permit DA or LGU extension staff and the farmer to assess the productive capacity of the soils of the terraces, adjust crops and inputs, and give farmers a chance to progress from subsistence level operations to a production level that would sustain the farm family even as it would undertake repayment.

TERRACE CONSTRUCTION, PILOT PROGRAM

Approach

It was proposed that six teams with tracked vehicles would be formed to accomplish construction of terraces on about 150 hectares of hillside lands per month. Each team would be equipped with the equivalent of a Caterpillar Challenger for rapid clearance of land. Tracked D-4 and D-6 bulldozers would be used to strip and stockpile or reposition topsoil. The dozers then would work with tracked frontend loaders to cut terraces and push the soil into dikes.

Laborers equipped with portable power equipment would shape and compact the dikes to their final grade level and shape. Laborers would position drainpipes to the specified locations and elevations.

Following dike construction small tractors and the Challengers, if still at the site, would assist farmers with preparation of the benched lands for the planting of a first crop. Initially the benches may not be perfectly level, but early cultivation could be oriented to promote final leveling through erosion of unexcavated soils from the high side of a terrace

The equipment teams would be supported and supplied by a fleet of 4-wheel drive pickup trucks, passenger vans, lowboy tractor-trailers, fuel tankers, and maintenance vehicles.

Professionals and technicians would lay out the plans, prepare area maps, survey soils, and stake the sites. The plans would detail each operation in terms of the sequential use of the different machines and specify for each operator the intended paths of earth movement whether it would be uphill, downhill, or along the contour. The objective would be to minimize the reworking of the same material several times. Stockpiling of topsoil also could be minimized, for example, by directly depositing soil stripped from a new part of a bench onto a part of the bench that already would have been diked.

Areas would be selected and dikes would be designed and sited to minimize the need to rework and improve existing drainage ways.

Implementation

At least six months would be required for training and mobilization prior to the start of programmed construction. Required would be the indoctrination of federal, provincial, and local government decision makers and the assembly of equipment for the start of training of a cadre of operators. Program planning and indoctrination and training functions likely would be carried out by a consultant organization. Staff of the consultant would include experts in bench terracing and personnel experienced with the conduct of training and coordinating with staff of local government.

Specifically, the design and execution of the four-year Pilot Project should:

1. Detail the program.
2. Mobilize the necessary equipment, training resources, and personnel.
3. Conduct a training program at the national level for professional and technical staff of the extension arm of the DA, the Bureau of Soil and Water Management (BSWM) of the DA, and the National Irrigation administration (NIA). Training of extension workers and engineers at provincial and local government levels would follow the national program. Possibly bankers and entrepreneurs would be invited as observers at this stage of preparations.
4. Select pilot areas in the several provinces, sign contracts with beneficiaries, farmers and/or cooperatives, then carry out the detailed topographic and soil surveys for specific areas. It was suggested that it would be most efficient to collect data in a form that would permit preparation of a grid layout of topographic and soils information.
5. Assist owners of land tracts, large and small, to form cooperatives for each target area. The cooperative would be dedicated to the purchase of necessary inputs and marketing. Again it could be timely to involve bankers and entrepreneurs.
6. Design the earthmoving operations to the detail of: a) the precise equipment passes that would be made, and b) the sequence of hand operations to compact and dress dikes and possibly to re-distribute topsoil that may have been stockpiled. Consider whether the area has trees (coconut or other) to be preserved. In this case there would be an

opportunity for intercropping. Entrepreneurs should be invited to the site for observing operations that they may be able to provide in the future for areas outside those of the pilot program.

7. Provide on-site extension services to farmers, guiding them through the cultivation practices that should be followed while the terraces would be brought under cultivation. Extension workers would help farmers select which of the grains would be best for growing on their soils, assess what dependable soil moisture conditions would be with a particular rainfall conservation regime, and identify marketing prospects for the produce.

Costs

Purchase of equipment, costs for four years of operations and the funding of project design and a training program would total nearly $15 million for a pilot program to develop 17,500 acres (7000 hectares). Some 20 percent of the total would be for diesel fuel and lubricants at a cost of US $0.65/liter. Also, from the perspective of economics, after four years the machines would have a salvage value of $3.5 million. Gross costs of purchases and operations would be approximately as follows in 1997/98 US dollars:

Consulting Contract and Training Components	$2,000,000
Equipment Procurement - Challenger Tractors, Bulldozers	$2,060,000
Vehicles, Tractors, Trailers, Pickups, Vans and Tools	$1,720,000
Operation Costs *	$7,660,000
Site and Office Support Personnel	$ 1,210,000
Sum	$14,650,000

* Computed in the format of the Caterpillar Performance Handbook

CONCLUSION

The draft of House Bill No. 9820 of 1997 recognized that there were vast areas of sloping land being used by hillside farmers who were existing at or below subsistence level. The bill proposed Sloping Agricultural Land Technology (SALT) be implemented nationwide over a period of three years to promote comprehensive rural development. The bench terrace program proposed herein would provide a highly specific technological component to address the concerns that motivated the original legislative proposal. The bench terrace program likely would continue for 20 to 30 years and result in the terracing of perhaps 1,250,000 acres (500,000 hectares) before it would begin to decrease in intensity.

The following is largely a qualitative evaluation of the bench terrace technology and the proposed modality for accomplishing a pilot program. The technology should spread throughout the provinces if there were to be a vigorous extension campaign. The campaign could be conducted by the DA through the BSWM at the national level and at the farm level through the staffs of local governments.

Cost Evaluation -- The cost of a full-scale program should approximate US $800 per acre ($2,000/ha). This general level of cost should hold true for the Pilot Project of the government as well as with private entrepreneurs running the entire operation with some level of support from the Local Units of Government.

Financial Evaluation -- The most important financial effect would be the potential for involvement of landowners and entrepreneurs and the consequent mobilization of private resources.

Environmental Evaluation -- The primary environmental benefits of bench terraces would be two-fold: reduction of hillside erosion and the reduction of flooding through water conservation. As well there would be a major increase in the stock of productive lands of the Nation.

Social Evaluation -- The building of close working relationships between extension staffs of the provinces and "dry land farmers", coupled with the assumption of the need for conservation by landowners, should be the most enduring aspect of the program. Further the restoration of hillside lands to high productivity should partially arrest the migration of farm workers to urban areas.

Local Government-Landowner Partnership -- Participation of administrative, legal and agricultural extension staff of the LGUs in the pilot program would do much to facilitate devolution. And, should the MDF program for funding of provincial and local governments be successfully implemented, the LGUs should have the capacity and vitality to support and sustain an aggressive program of hillside agricultural development.

GIS-BASED MANAGEMENT SYSTEM FOR IRRIGATION DISTRICTS

Guy Fipps[1] Eric Leigh[2]

ABSTRACT

In 1998, eight irrigation districts in the Lower Rio Grande Valley of Texas initiated efforts to develop GIS-based District Management Systems (DMS). This paper provides a description of GIS (geographical information system) as applied to irrigation districts, its potential for improving the day-to-day management of districts, and the progress and difficulties encountered by the 8 districts in GIS mapping and implementation. Examples of how districts are using GIS are given, along with the value and use of the DMS in a regional water planning project.

INTRODUCTION

The Lower Rio Grande Valley (Valley) is located at the Southeast tip of Texas and contains 28 irrigation districts (Fig. 1). The Region has approximately 740,000 irrigated acres and uses 1 to 1.4 million ac-ft of water a year to grow a wide range of fruit, vegetable and field crops. Just across the border in Mexico is a similar irrigated region containing about 1 million ac. All the water used in the region comes from the Rio Grande River which is divided between Texas and Mexico as stipulated by international treaty.

The region is also one of the fastest growing areas in Texas, and the water demand of municipalities and industries is also rapidly increasing. Water to meet the increasing demand must come from agriculture which holds 90% of all the water rights in the basin. A state-mandated regional water resources planning effort is currently underway which includes a detailed analysis of the current conveyance efficiencies of the districts. Planners are attempting to determine how much water could be freed up for other users through improvements in the districts and with on-farm irrigation.

The region is also entering it's 5th straight year of reduced water supply due, in part, to a drought in the Lower Rio Grande Watershed of West Texas and

---

[1]Professor and Extension Agricultural Engineer, Department of Agricultural Engineering, Texas A&M University, College Station, TX 77843-2117

[2]Assistant Research Scientist, Texas A&M Research and Extension Center, 2415 E. Hwy 83, Weslaco, TX 78596.

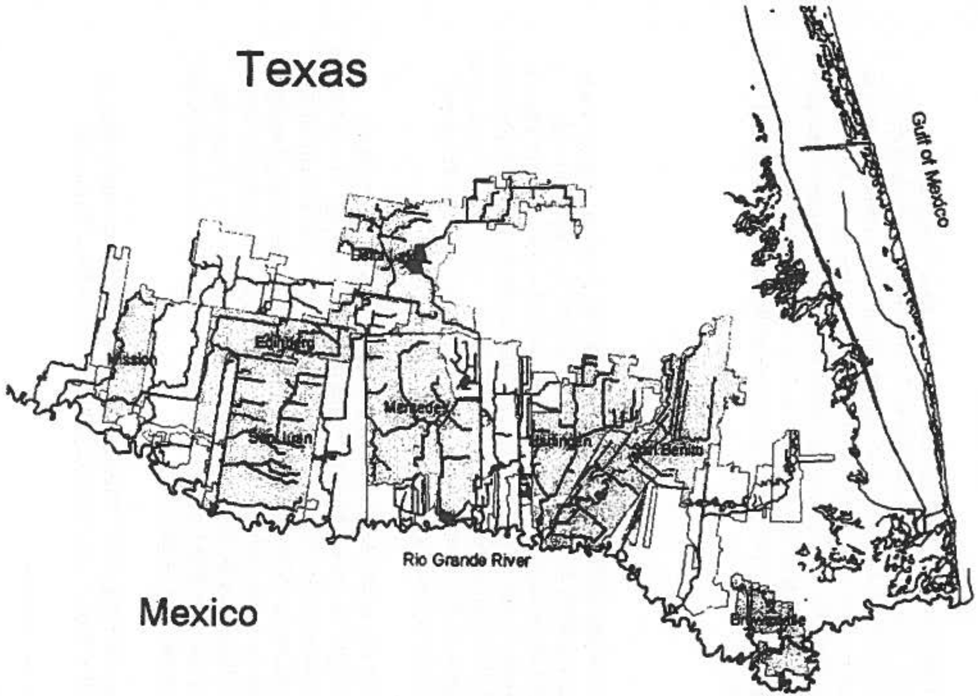


Figure 1: The main distribution canals of the 28 irrigation districts in the Lower Rio Grand Valley of Texas, and the 8 districts implementing GIS-based district management systems.

Northwest Mexico and severe regional droughts in 1996 and 1998. Irrigation districts are beginning to recognize the need to restructure their distribution systems, management decisions, and operating methods in order to improve efficiency.

In 1996, Harlingen Irrigation District and the Texas Agricultural Extension Service (TAEX) began an effort to develop visual system using GIS (geographical information system) that would allow the district to visually display and analyze all data used in daily district management. After evaluating several GIS options, *ArcView* was chosen as the GIS-tool for this effort. In 1998, Harlingen and 7 other irrigation districts began GIS implementation with technical support provided by TAEX and the DMS (District Management System)Team in the Agricultural Engineering Department of Texas A&M University. A description of this program is provided by Fipps and Pope (1998). This paper reviews the progress of GIS development and implementation since 1998.

GIS IMPLEMENTATION IN DISTRICTS

We have developed a program that encourages GIS development and implementation in districts through a step-by-step process. Keys to our success have been focusing the following:

- demonstrating ways in which GIS management systems can be a benefit and an important asset to the district,
- teaching the practical applications of *ArcView* and making suggestions as to what steps should be taken in what order to build GIS-based maps and databases, and
- providing continuous support in the process at each level, from the initial introduction to the software, to the confident use of ArcView as a daily management tool.

Common Uses For GIS in Districts

To encourage continuing progress in GIS development by districts, we focus on aspects that are the most beneficial based on their current stage of GIS development. These include the following.

Map Making: Accurate and up to date maps are vital for daily operations. GIS allows districts to quickly produce new maps as changes occur. Maintenance crews and canal riders can obtain maps of specific areas or segments which are tailored to them and contain only the information needed This map making ability is not only useful for district personnel, but helps districts, municipalities, growers, and utility companies to share and understand information and ideas.

Boundary Disputes: After years of farming, urban development, and canal replacement, district right-of-ways and property boundaries often are not clear when compared to out-of-date maps. In some situations, irrigation districts need to reclaim encroached upon areas and settle property disputes. GIS maps coupled with recent aerial photographs (Fig. 2) are uniquely suited to such tasks.

Determining Net Acreage: Irrigation districts, insurance companies, and others may assess fees based on the water account acreage or the amount of land actually in production. In any given year, the difference between total acreage and net acreage under production may be significant. Extracting net acreage can be easily and accurately determined from the GIS maps and databases

Projecting Water Usage Patterns: Irrigation districts can use GIS to visually represent the distribution of water use in any or all fields over the past week, month, year, or period of record. This process can be taken a step further by overlaying two or more consecutive years to find patterns in water usage. Differences in water use may directly or indirectly occur due to crop rotation, weather, irrigation methods, tillage practices, etc.

Analyzing Other Types of District Information: Proper maintenance and planning for rehabilitation of distribution networks is greatly enhanced by having immediate access to such information as trends in urban development, past and current canal use, changing cropping patterns, and the conditions and dimensions of the canal segments under review.

For example, we developed a canal condition rating system (Table 1) to help identify segments needing increased maintenance or rehabilitation. Figures 3 - 5 show the condition rating system as applied to the Edinburgh Irrigation District. Figure 3 shows the main distribution network consisting of canals and pipelines. In Fig. 4, canals are highlighted by their condition ratings. High rating numbers indicate serious problems. However, the current extent of urbanized land and expected growth patterns (Fig. 5) also impact rehabilitation decisions.

Encountered Obstacles

Problems that have been encountered in GIS implementation include lack of data, existing AutoCAD maps and databases, lack of standardization of terms, improperly registered aerial photographs, and lack of manpower devoted to the task.

Lack of Data: Districts generally have limited updated data readily available on the exact physical dimensions and conditions of their entire distribution networks.

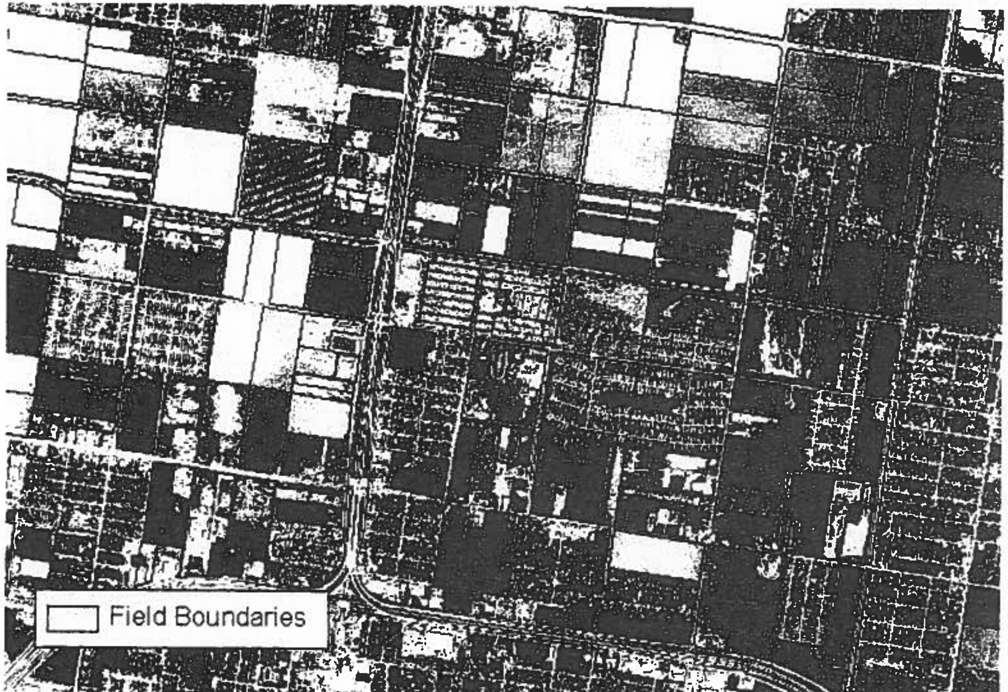


Figure 2. Water account boundaries created in GIS using an aerial photograph as a guide. This photograph is from a USGS DOQQ (digital ortho quarter quad), a high resolution photograph that has been registered.

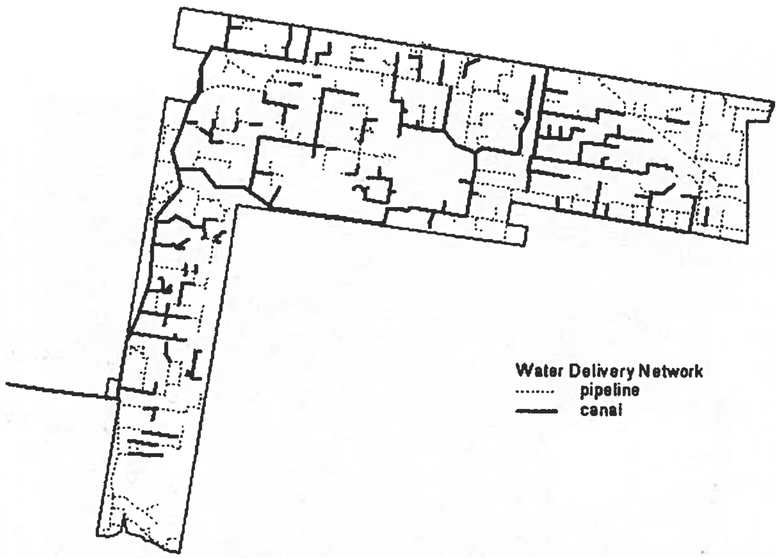


Figure 3. The main distribution network of the Edinburg Irrigation District consisting of canals and pipelines.

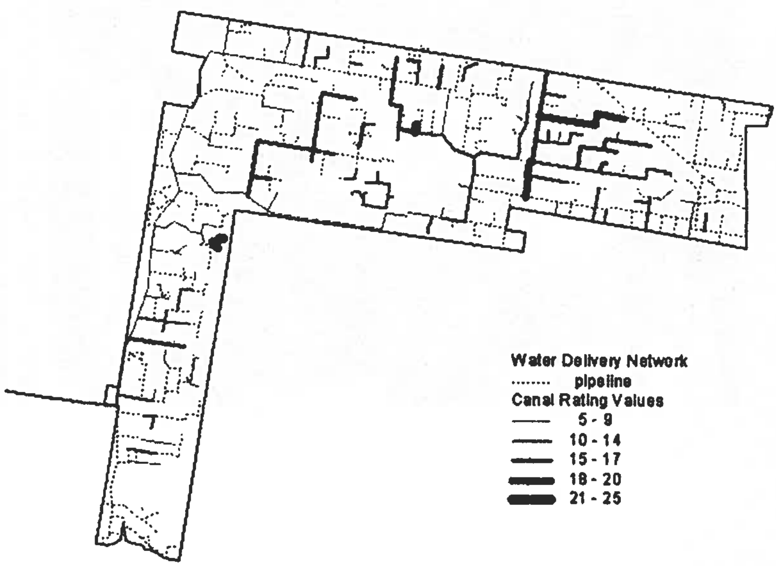


Figure 4. Edinburg canals highlighted based on their condition rating.

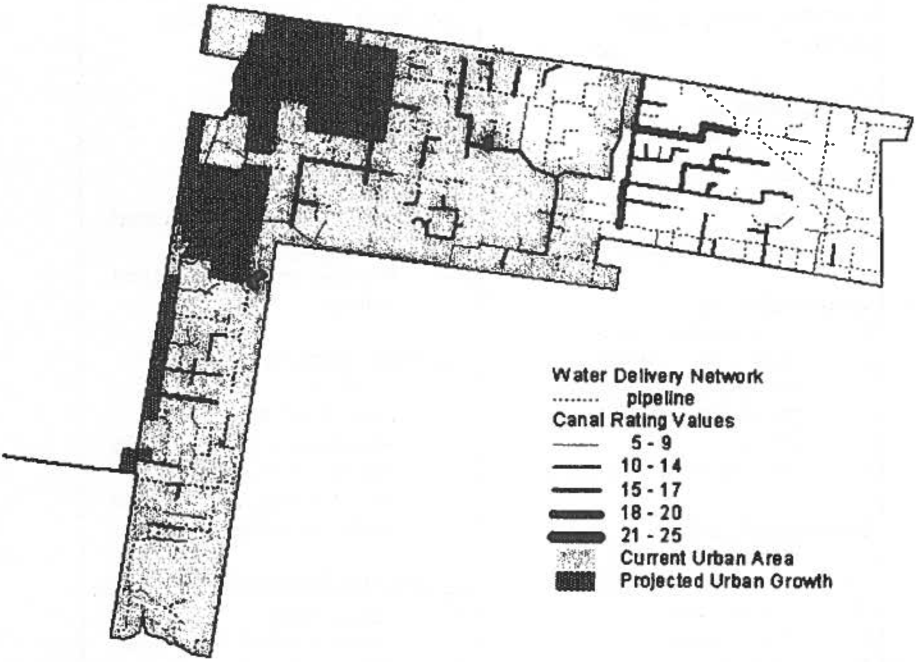


Figure 5. Distribution network, canal condition ratings, and present and projected urban growth of the Edinburg Irrigation District.

Table 1. Rating System for lined and unlined canals. Canal use frequency rating can be combined with the condition rating to help prioritize segments.

LINED CANAL RATING SYSTEM	UNLINED CANAL RATING SYSTEM
<u>Lining Condition</u> 1 - excellent 2 - good 3 - fair 4 - poor 5 - serious problems	<u>Interior condition of canal</u> 1 - excellent 2 - good 3 - fair 4 - poor, some holes and/or cracks and leakage 5 - seriously eroded and obvious leakage
<u>Cracks/holes - size</u> 1 - a few hairline cracks 2 - hairline to pencil size 3 - predominately pencil size 4 - pencil size and a few large cracks 5 - predominately large cracks	<u>Condition of embankment</u> 1 - excellent 2 - some minor erosion 3 - moderate amounts of erosion 4 - high levels of erosion 5 - severe erosion, levee/canal in danger of failing
<u>Frequency of cracks</u> 1 - sparse 2 - greater than 10' apart 3 - 5' to 10' apart 4 - 3' to 5 ' apart 5 - less than 3' apart	<u>Vegetation in Drainage Ditch or along base of embankment</u> 1 - normal; rain-fed weeds only 2 - above average 3 - moderate 4 - dense 5 - dense and lush
<u>Vegetation in Drainage Ditch or along base of embankment</u> 1 - normal; rain-fed weeds only 2 - above average 3 - moderate 4 - dense 5 - dense and lush	

CANAL USE FREQUENCY	
1 -	never
2 -	rarely
3 -	seasonal
4 -	regular
5 -	constant

Such information is beneficial when considering reconstruction projects, calculating future demands on particular segments, and evaluating the cost efficiency of rehabilitation options. Assembling this data takes considerable time and may require weeks of field work or reviewing numerous rehabilitation reports going back decades.

Existing *AutoCAD* Maps: Some districts have investigated the incorporation of existing AutoCAD maps with GIS. After much trail and error, we have found that the process is difficult and time consuming. Due to differences in mapping techniques, warping and overlaying, the resulting GIS maps are often inaccurate and still require modifications, including redrawing of the canals, pipelines and account boundaries in *ArcView*.

Database Design and Connectivity: Effectively structuring and linking data are difficult and critical tasks. *ArcView* allows users to connect themes to data sources external to the software. For example, in the GIS, the water account boundaries are mapped and linked to the existing accounting database. The link typically is through the account number or property identification number which is included in the *ArcView* attribute table. This provides the ability to view all available data directly on the GIS map, such as property owner, water use history, and cropping patterns.

In the Lower Rio Grande Valley, several types of commercial and custom accounting databases software packages are used by districts. Some databases are not structured for accounting at the field level, but for accounting based on owner or water ticket holder. Often growers irrigate several fields which are under the same account number. In such situation, displaying specific field information requires modification of the existing database.

Consolidation of GIS Maps at a Regional Level: Figure 1 shows a portion of the data that is included our *Regional GIS of the Valley*. This GIS contains locations of district boundaries, cities, water ways, the extent of the main distribution networks, etc. The DMS team is attempting to incorporate the more detailed information being assembled by each district into this regional GIS. We have promoted standard attribute names and formats (number, string, decimal places, etc.) among the districts to help streamline the process. Merging of data sources to combine a single, comprehensive map requires a working knowledge of how the software performs this task. Failure to understand the process has resulted in data being overwritten, duplicated, and even removed altogether. However, each crisis has resulted in a better understanding of how the system functions.

PRESENT STATUS OF DISTRICTS' GIS

Large differences exist between the districts in the Lower Rio Grande Valley, including size of the district, revenue, personnel, management, distribution networks, crop types, and degree of urbanization. All of these factors have effected the progress of each district in GIS implementation as discussed below.

Brownsville Irrigation District

Use of aerial photographs as a guide for mapping Brownsville Irrigation District (BID) is limited since the water delivery network is 90% under ground pipeline. Canals are easily distinguished on aerial photographs, while pipelines are not visible except for the stand pipes, if they still exist. The district originally explored the idea of importing their *AutoCAD* engineering maps into *ArcView*, but decided that it would be easier to redraw the district from scratch.

GIS development in the BID was delayed due to lack of personnel for the effort. Initially, a secretary was trained and did GIS mapping as time would allow, but a full-time effort is required in the initial GIS mapping and database linking. In September 1999, BID hired a part-time student intern who has since mapped all of their water account boundaries, resacas, canals, pipelines, and re-lift pumps. BID also acquired a large format plotter and now produces useful maps for maintenance crew and canal riders.

Harlingen Irrigation District

The Harlingen Irrigation District (HID) initially reassigned a canal rider to serve as their GIS technician on a part-time basis. Mapping of the distribution network was completed by the DMS team as part of the Phase II project (see Fipps and Pope, 1998). In 1999, HID hired a summer intern who was able to map 60% of the water accounts and link them to the district's accounting database.

The district uses the GIS regularly to settle land disputes and other spatially related issues. HID is currently evaluating the use of a Global Positioning System (GPS) to map exact easement boundaries and locations of other facilities for incorporation into the GIS.

San Benito Irrigation District

The San Benito Irrigation District (SBID) also reassigned a current employee as a part-time GIS technician. The district had almost no attribute data on their water distribution system. All 8 canal riders were instructed to collect basic information on canal width, depth, lining material, and segment length. It took 6 weeks of full-time work to collect this information. Their water delivery system, consisting of 90% canals, was mapped by the DMS team during the Phase II Project. The district has now entered all attribute data and mapped 80% of their water account boundaries.

The first efforts to link water account boundaries with the water account database were not successful. The district's accounting system is based on an account number, not a field or location number. When querying an account number, multiple locations appear for the same account. Thus, records for a specific field cannot be separated. SBID has now added a personal identification number associated with each field location.

Delta Lake Irrigation District

Delta Lake Irrigation District began collecting attribute data upon GIS implementation in 1998. Their water delivery system was also mapped by the DMS team during the Phase II Project. During the second half of 1999, Delta Lake hired two part-time GIS technicians to map account boundaries and re-lift pump locations, and to improve and update the work done during the Phase II Project. They mapped 90% of the water account boundaries, complete with account numbers and field identification numbers.

The next step for Delta Lake is to link their accounting database system to the GIS. However, the district has a customized database running on an old mainframe computer. Linking the GIS to this database requires a special connector and customized programing which has not yet been completed.

Edinburg Irrigation District

Edinburg Irrigation District (EID) realized an urgent need for developing maps and databases when the district's senior canal rider, also known as the districts "walking database," announced his upcoming retirement. EID began an intensive mapping effort, compiling and entering as much attribute data on the distribution network as possible.

The mapping completed to date includes 100% of the account boundaries and 80% of the delivery network. Currently, EID is concentrating on mapping excluded areas due to the upcoming board elections. Excluded areas are land that have gone out of irrigation usually due to urbanization. These areas are excluded from the district, and landowners in these areas are not allowed to vote.

San Juan Irrigation District

San Juan Irrigation District (SJID) reassigned a canal rider as their full-time GIS technician. He has made rapid progress in mapping the entire district, including the distribution network, water account boundaries, gates, pumps, turn-out valves, pipeline shutoff valves, and district right of ways. SJID has successfully linked the GIS and water account databases which are automatically updated whenever changes occur. The district uses the GIS on a daily basis for quickly retrieving information on water accounts, as well as pipelines and canals, including construction material and sizes of specific segments.

The district has also begun using the GIS to help with decisions in canal replacement. The GIS is used to determine total net irrigated acres and cropping patterns serviced by a specific canal network by accessing the water account records. With this information, the district then calculates the size of the replacement pipeline needed to deliver this water volume. A consulting firm, on the other hand, had oversized a pipeline since their calculations were based on the total or gross acres in the area. Thus, SJID saved a considerable amount of money with the reduced pipeline size.

Mission Irrigation District

Mission Irrigation District initially hired a full-time technician for a 3-month period in 1998. The technician began by drawing water account boundaries. Over 90% of the district's water account boundaries were mapped, and this theme was successfully linked to their water account database. With assistance from the DMS Team, all main canals were mapped by the end of Summer '98. However, the district has little attribute data describing the delivery network.

Due to changes in management in 1998, GIS development came to a halt. However, the secretaries routinely use the GIS to verify account information and location when farmers come in to purchase water tickets. Farmers have expressed appreciation about the GIS capabilities to visually show their property and all account information. As a result, the district has been able to update and make numerous corrections in their records.

Mercedes Irrigation District

Mercedes Irrigation District reassigned a secretary to be their full-time GIS technician. Mapping completed including the entire water distribution network, all water account boundaries, and canal rider service areas.

During district elections in 1999, the directors requested maps of all excluded areas and subdivisions to help determine voter eligibility. The GIS maps and database had to be modified for legal descriptions of properties in terms of metes and bounds. Mercedes hired a second part-time GIS technician to help with the work load and purchased a large format plotter. Other endeavors have included coordinating efforts with the U.S. Border Patrol in mapping check points and surveillance areas along the Rio Grande River (the southern border of this district lies on the Rio Grande) and working with land realtors to provide property lines and maps.

REGIONAL GIS USES AND ACTIVITIES

Water Saving Strategies

Currently, we are participating in a Regional Water Planning Project to identify the amount of water that could potentially be freed up from improvements in distribution networks and on-farm irrigation for transfer to other users. This is a major expansion of the efforts conducted in the Phase II Project (see Fipps and Pope, 1998). An intense effort is underway to assemble detailed information on operational methods and physical features of the districts' distribution systems. Canal rider surveys were conducted in all or parts of 6 districts to identify:

- the condition of canal segments (Table 1), including physical dimensions and lining materials
- on-farm irrigation methods and technologies in use on a field by field basis,
- water supply or loss problems identified by canal segment and individual fields, and
- locations of turnout valves, check gates, pipeline control valves, and operational spill drains

In addition, the DMS team is conducting seepage loss tests across the Valley on variety of canals segments, monitoring operational spill sites and recovery projects, and documenting water savings from metering programs. After these surveys and studies are complete, the results will be entered into the appropriate GIS databases for analysis.

GIS Support

As part of the cooperative arrangement with the 8 districts shown in Fig 1., we are offering continuing support on GIS implementation. In 1999, the DMS Team conducted two, 1-day GIS workshops for irrigation districts. A complete set of instructional materials were developed for the workshops and can be found on the District Management System Program Web Site (http://dms.tamu.edu).

Monthly support sessions are held with the GIS technicians to foster collaboration on new uses and problems, and to teach advance techniques. Attendance at the workshops and monthly meetings are not limited to district personnel, but includes tax appraisal districts, the US Border Patrol and others implementing GIS. Support is also available by phone and through the internet.

GPS Evaluation

We are investigating the use of GPS receivers for more precise mapping and quick updating of existing maps. GPS receivers determine a location on the Earth surface from satellites. This information can be exported to the *Pathfinder* software and then converted directly to an *ArcView* theme. The DMS team has used GPS receivers to locate sites, map areas and rectify discrepancies in GIS maps.

District Management System Development

We are currently conducting research to extend GIS applications and create a total District Management System (DMS). This involves three major efforts:

- continued collaboration with districts on developing and implementing GIS,
- development and incorporation of a distribution network accounting and routing simulation model; and
- incorporation of an crop water use and irrigation scheduling simulation model.

A GIS interface for the irrigation district simulation model IRDDESS (see Fipps and Pope, 1998) has been completed and is currently being tested.

REFERENCE

Irrigation District Management System Program Web Site, http//dms.tamu.edu.

Fipps, G. and C.N. Pope. 1999. Implementation of a District Management System in the Lower Rio Grande Valley of Texas. Proceedings of the 14th Technical Conference - 1998. US Committee on Irrigation and Drainage, Denver.

ACKNOWLEDGMENTS

Contributors to this paper also include Kenneth Carpenter, Stuart Beall, Craig Pope, Bryan Treese, and Rahul Verma.

CAPACITY BUILDING FOR THE PRACTICE OF IRRIGATED AGRICULTURE

Anisa Joy Divine, Ph.D.[1]

ABSTRACT

Irrigated agriculture is sustainable when irrigation experts join with other community members to develop and apply sound principles and practices in the common interest. Necessary and sufficient principles and practices are presented as an action map consisting of two parts: 1) nine essential processes - ecological, administrative, accounting, educational, integrative, scientific, marketing, entrepreneurial, and service processes; and 2) a development spiral that, when institutionalized, matures into an achievement cycle. When these tools are applied according to a proven protocol, significant and sustainable success has been achieved. The action map and protocol are described in this paper.

The map is based experiences in sustained agricultural and industrial development over the last 150 years in Denmark, the USA, Greece, Guatemala, and elsewhere. The map and protocol allow the user to integrate the principles and practices into a blueprint that provides a framework for the diagnostic analysis and program design needed to develop successful, sustainable irrigated agricultural systems.

INTRODUCTION

By applying insights and labor to irrigation and drainage activities, human beings manage the output of their ecological system to sustain and improve human life. Principles and practices used by individuals, singly or in community, to create successful, sustainable agricultural and industrial systems have been distilled into in a map-for-action (Argyris, 1985) that consists of a nine essential processes, a development spiral and an achievement cycle. Irrigation community members can use this map as a diagnostic or design tool. Either use will enhance their capacity to produce, sustain and enjoy wealth from irrigated agriculture.

Each development path follows a necessary pattern and yet, like each snowflake, is unique. Thus, irrigation community members will want to use the map to chart their path with creativity and an entrepreneurial spirit. Users will be reassured to know that the action map, when applied using a particular protocol, has proven to be both necessary and sufficient for developing and sustaining a desired output.

---

[1] Water Resources Planner, Imperial Irrigation District, 333 E. Barioni Blvd., Imperial, CA 92251

The action map itself rests on three abstractions: 1) the nine essential processes 2) a development spiral, and 3) an achievement cycle. In addition, a protocol is provided for effectively using the map. Seven steps are presented that community members can use to design an action map to initiate, achieve, and sustain the results they desire from their irrigation activity.

By employing these tools, individuals, singly or in community, can engage their capacity to conceive, manifest, and enjoy ever-increasing levels of well being to achieve a sustainable irrigated agriculture.

THE ACTION MAP

The action map is based on performance requirements formulated from research into successful human endeavor agricultural development over the past 150 years. Four programs in particular are the folk high schools in Denmark, from1844 (Manniche, 1939); the agricultural demonstration method in the USA, from 1886 (Martin, 1941); the American Farm School in Greece, from 1904 (Lansdale, 1986); and the small farm self-help irrigation projects in Guatemala, from 1977 (Embry and Adams, 1983).

These projects were selected because each resulted in: 1) the transformation of a community, 2) an enterprise that was profitably sustained to the present time, and 3) insights that have been extended to and adopted successfully by other communities. From them, the nine essential processes were distilled.

The Nine Essential Processes

A concise statement of the nine essential processes is presented (Table 1). History indicates that the nine processes incorporate the necessary and sufficient elements for achieving success in any enterprise. As such, it can be used as a blueprint for creating action maps for any type of project.

In practice, the nine processes work as a synergistic system, with the result limited by the least strong or viable of its elements. Furthermore, individuals can use the nine essential processes both as a diagnostic tool to determine what needs changing and as a design tool for making improvements.

An Analogy: To get a feel for the nine essential processes, consider how a transportation system works. A vehicle must be designed to meet mechanical, thermodynamic, and ergonomic requirements. At the same time, effectively operating a vehicle requires specific individual behaviors that include knowing and skillfully meeting the physical requirements such as fluids in the appropriate tanks, using the correct key, air in the tires, steering correctly, and so on.

Table 1. The Nine Essential Processes

1 **The ecological process** of interacting with the physical and biological environment so as to live and be at ease within it, thereby producing sustainable wealth.

2 **The administrative process** of organizing, energizing and monitoring the operations of individuals and institutions that impinge on community members and their environment, thereby managing wealth.

3 **The accounting process** of recording, analyzing, verifying and reporting transactions among community members and their institutions, thereby counting wealth.

4 **The educational process** of instructing and coaching community members in the skillful use of proven knowledge, information and practices, thereby sustaining wealth.

5 **The integrative process** of structuring, maintaining and evolving institutions that blend the diverse beliefs, behaviors and traditions of community members, thereby harmonizing wealth.

6 **The scientific process** of hypothesizing, testing, verifying and reporting the laws of nature, both ecological and behavioral, thereby perceiving wealth.

7 **The marketing process** of storing, valuing and exchanging goods, information and services of a desired quantity, type and quality, thereby extending wealth.

8 **The entrepreneurial process** of innovating, taking risks and changing the ways in which community members think, act, work and live, thereby creating wealth.

9 **The service process** of respecting, loving and caring for oneself and for that in which one participates; that is, noticing what is needed and wanted and doing it whether it is one's job or not; thereby appreciating wealth.

Additionally, the community must establish a physical support system of roads, mechanics, spare parts and fuel stations. Behavioral requirements promote safety and community well being. Common requirements include proven ability to operate the vehicle safely and knowledge of the socially accepted rules of operation, symbolized by a driver's license. Liability insurance as well as safety and environmental features may also be required.

Finally, trust and faith are needed. Drivers trust that fuel, parts, roads and all other requirements will be available. Drivers also have faith that the vehicle will work as expected and that each driver will obey socially agreed-upon operating rules.

New or prospective drivers need instruction to operate a vehicle. In addition, if the driver comes from a society where driving is uncommon or has had an unpleasant experience, specific education as well as personal choice may be needed simply to determine whether or not one wants to drive at all.

Similarly, irrigated agriculture imposes specific requirements. Some are purely physical, some biological, some ecological and some behavioral, while others are socially prescribed. All such requirements must be both known and satisfied to secure a sustainable irrigated agriculture.

The Development Spiral

Sustainable project development can be described as a spiral that is the basis of humanity's ever-increasing wealth (Schumpeter, 1989). The spirals consist of four elements: context, action, and results - enlightened by insight. These may be conceived, as follows:

Context: a way of being by which **community members synthesize** the content of their environment, including their knowledge, attitudes, capabilities, skills, and resources; from which emerges an opportunity to increase wealth.

Action: a way of doing through which **community members express** their knowledge, attitudes, capabilities, skills and resources to create wealth: to organize matter, energy or thought in a way more pleasing or beneficial to someone.

Results: a way of having through which **community members celebrate** their achievement and synthesize it into a new context.

Enlightenment: a way of experiencing through which **community members integrate** previously unknown or disassociated ideas to realize principles that form the basis for new wealth.

The development spiral is characterized by knowledge, volition, and action that are enlightened by insight and vision to attain a newly perceived, desired result. Such spirals are generated by the more creative, innovative, and risk-taking members of a community.

As these insights are integrated into the everyday fabric of individual and community life, the spiral gives rise to an achievement cycle. Thus, practical, productive individuals - without whom the innovator's insight would never be incorporated into community life - dedicate their lives to the achievement cycle, Elements of the development spiral, along with relevant issues for consideration and action needed to achieve and sustain new levels of wealth are cited in Table 2. Most often overlooked are the context for development and the need to include enlightenment and choice for all participants. The importance of each aspect of the spiral becomes apparent when considering how to apply the protocol.

THE PROTOCOL

Irrigation professionals can identify performance requirements needed to ensure success by determining how the elements of each essential process relate to the project at hand. The mechanism by which success is secured in human terms is described in the protocol, which follows.

Whereas the action map provides a blueprint for design and diagnostic analysis of sustainable irrigated agriculture, the protocol describes the practical steps for its successful use in the community. The protocol has a sense of familiarity: All have followed its steps whenever success, no matter how small or large, was achieved. Its seven steps are described below.

Step 1. What to think about. Identify concretely the requirements for and the value of each of the nine essential processes. This activity enables irrigation professionals to approach the task with certainty, knowing they can clearly communicate the opportunities and requirements to others.

Step 2. Whose thoughts to change. Network with people who have the power and authority to work for sustainability. Irrigation professionals must know who has power at each decision point. Whoever these people are, their appropriate and willing participation is essential

Step 3. Establish relationship. Involve mutually concerned individuals and organization representatives.

Step 4. Determine value and requirements. Consult on the value and requirements of the new behavior so they can contribute and make an enlightened choice of whether to positively support and sustain the proposed activity.

Step 5. Choice. Choice is a central activity. It is to be made freely and after consideration of the value and requirements of a project. Choice occurs when persons undertake a course of action, because they see the value of the project and are willing to accept the requirements.

Table 2. The Development Spiral

Context: Ever-changing perceptions, knowledge, attitudes, habits and resources; informing the approach to opportunities by community members	
Existing elements	**Relevant issues**
Neutral knowledge and boundary conditions	Traditional and current knowledge and constraints
Neutral state-of-the-art	Traditional and current known possibilities
Neutral awareness and beliefs	Traditional and current values, expectations and beliefs
Neutral action	Traditional and current activities
Neutral results	Traditional and current achievements
Action: Ever-changing activities by community members	
Necessary steps	**Relevant issues and actions**
Become enlightened	Expand consciousness, perceive opportunity, have insight, note more pleasing alternative
Apply volition	Choose to pursue insight and act, or not
Appreciate existing context	Act to know and appreciate existing context
Investigate development context	Act to know and appreciate alternative, potentially more pleasing context
Apply volition	Compare existing and development contexts, consider benefits and requirements, then choose
Create action plan	If choosing to act on potential, create action priorities using action map and protocol
Implement action plan	Enroll specific individuals to act; allocate resources; establish accountability, timelines
Foster feedback and refinement	Monitor actions and results; measure physical and behavioral inputs and output
Celebrate	Notice and enjoy increased well-being
Results: Ever-changing experience of well being by community members	
New elements	**Relevant issues**
The next context and venture	Intended or other result is integrated, contextual issues shift

Choice is an activity based on human freedom and dignity. Choice is the basis of human empowerment that comes only from personal experiences of one's own strength and integrity. If the choice is to participate, proceed to Step 6. Otherwise, return to Step 4 and interact with the interested community member(s) again or go to Step 2 and identify new individuals or groups. If necessary, go to Step 1 and identify another arena of action.

Step 6. Close. The irrigation professional must ensure that enrollees can produce, access, or procure the support and requirements needed to carry out the activity as agreed upon. Often, closure simply reiterates known facts; however, new facts or areas of uncertainty may emerge. A major function of closure is to provide an opportunity for such unknowns to surface, to be communicated and resolved before final commitment to action is made.

Step 7. Re-close. Re-closing provides the opportunity to make sure the enrollees have, or can get, the support of those people whose acceptance of the newly chosen activity is necessary. Such people include family and community members, supervisors, co-workers, government and religious leaders. If support from such individuals is needed, but not forthcoming, irrigation professionals must assist the individuals to discover how it can be obtained and support the individual in obtaining it. If so requested or deemed advisable, the irrigation professional may need to return to Step 2 and go through the enrollment protocol with these people. If a major obstacle arises, returning to Step 1 may be appropriate.

By including deliberate thinking, consulting, and enabling purposeful choice about the performance requirements, the protocol plants the seed from which project success can grow. When this happens, everyone involved knows what has been agreed upon, what their individual role is, what community expectations are, and that the choice has been made freely and willingly. Further, by offering numerous opportunities for feedback and revision of plans, carefully conducted enrollment gives community members a sense of enterprise ownership, resulting in interest and pride in the quality of the outcome.

When the commitment to participate is made, freely and after full consideration, the plan can be implemented, the participants supported to keep their agreements, and the achieved results celebrated.

<u>Implementing the Protocol</u>

R. Buckminster Fuller stated, "... All the individuals of humanity are looking for the answer to what the little individual can do that can't be done by great nations and great enterprises. The things to do are: the things that need doing: that you see need to be done, and that no one else seems to see need to be done" (Fuller, 1981). The application of the protocol is an individual proposition. However, once grasped, instances of the protocol's use are found to be widespread. For one, consider the following:

From Guatemala: In 1976, an extraordinarily successful, USAID-assisted, small farm, self-help irrigation program was started in Guatemala. The Guatemalan Agricultural Development Bank made loans to organizations of farmers for the purchase of materials to build small, gravity pressure sprinkler irrigation systems. Project beneficiaries furnished all labor. Engineering design, construction, supervision and instruction use was furnished by the Guatemalan government.

By 1981, 40 irrigation projects serving 2000 farmers had been completed. Of these 40 irrigation systems, 17 also provide potable water for the water users. The projects were constructed at a cost of $600 to $800 per hectare. The cost included materials for the main line and all on-farm irrigation equipment. The projects promoted crop diversification, with fruits and vegetables frequently replacing production of traditional corn and beans. Farm productivity increased from two to five times and more (Embry and Adams, 1983).

An engineer, Dr. Bert Embry was working in Guatemala on another project at the time the idea of a small-farm irrigation project was brought to his attention by Carl Koone, the USAID Rural Development Officer for Guatemala. Dr. Embry determined to act on this insight. To this end, he and other American and Guatemalan engineers conducted survey trips to various parts of Guatemala and developed hypothetical projects for sites they visited. Ultimately, Dr. Embry was able to bring together the elements needed for the work – the idea, a team with experience to design the scheme, a group of farmers who wanted the project, and financial and other resources to do the job (Divine, 1988).

> Dr. Embry reported: "A group in Santa Rita ... first heard of us in one of the traveling school sessions. They had been working on their own to get an irrigation project, but could not find financial or technical help. This was an ideal location for the original project. It could be a gravity-operated sprinkler system with no pumping costs. (Many Guatemalans insist that you cannot have an irrigation system without a pump and tank). And, the main highway between Quezaltenango and San Marcos runs through the project, so everyone could see the sprinklers operating on both sides of the road.
>
> "[Construction of] the first project was supervised by the advisors. Field foremen, who were Santa Rita farmers, supervised subsequent projects. These foremen lived in the community where the project was being built,

and the local farmers supplied their food and a place to sleep. The engineers visited the projects under construction as often as necessary (at least weekly) to check on details and see that the work was being done according to the plan. Several farmers on each project were required to learn how to install the equipment, so they could make repairs or extensions in the future without needing outside help" (Embry and Adams, 1983).

To implement the action plans, Dr Embry organized irrigation teams to work with the farmers. He intended the teams to be cohesive, and he defined everyone hired - engineers, draftsmen, agronomists, secretaries, and chauffeurs - as a team member. Their activities were based on job descriptions, and they were hired and assigned on the basis of their ability to do the job.

Professional project staff worked with the funding agency, so loan money would be available and loan guidelines established. Technical personnel helped farmers estimate the loan repayment period, but the final decision about financing was left up to the farmers. Because of the Embry team's service achievements, local farmers gained significant rewards:

- Farmers own the system and are responsible for operating and maintaining it;
- Farmers maintain the system they learned to fix during and after construction - thus, farmers know the system is dependable and their risk is low;
- Farmers produce and market fruits and vegetables which have higher value;
- Farmer groups manage their own system, so they cooperate to provide maximum benefit for all families involved; and
- Farmers experience pride of ownership and confidence that they can do something for themselves, their families, and for the future of the nation.
- Meanwhile, effectively used resources represent a lasting benefit to the nation
- Human nutrition improves as fruits and vegetables become available in the villages and cities at prices people can afford;
- Increased farm production for local use and for export contributes to the overall food supply and to the economic and social well-being of the nation;
- Eroded areas become productive, new lands are brought under cultivation, and supplemental irrigation makes agriculture less dependent on natural rainfall;
- Land and water resources are used more efficiently, so the present value is increased; while, future generations can expect to inherit the resources in improved condition for their own use and the country's lasting benefit.

In this case, as in others, success began with appreciation of the context associated with the nine essential processes: hilly land, with running springs; a market for fruits and vegetables, a method for training, a willingness to take the risk, etc. This appreciation, followed by action that duplicated the protocol steps, produced outstanding results - sustainable irrigated agricultural systems that produce healthy levels of well being and prosperity for the community and beyond.

CONCLUSION

By developing a sound action map and agreeing to use it in the common interest, irrigation and other interested community members embark on the adventure of fostering sustainable irrigated agriculture. As they become adept at using their insights and growing body of knowledge about how the nine processes relate to their endeavor, they will use the map and protocol to achieve increasing levels of success and satisfaction.

REFERENCES

Argyris, Chris. 1985. Making knowledge more relevant to practice: maps for action. In Edward E. Lawler, III, and Associates. 1985. Doing Research that is Useful for Theory and Practice. Jossey-Bass Publishers. San Francisco, Washington, London.

Divine, Anisa Joy. 1988. A Performance Map for Human and Irrigation Development. Dissertation submitted in partial fulfillment of requirements for degree of Doctor of Philosophy in Agricultural and Irrigation Engineering. Utah State University. Logan, Utah.

Embry, Bertis L, and Adams, Nancy L. 1983. Small Farm Self-Help Irrigation Projects. Planning Guide 5. Water Management Synthesis Project. Utah State University. Logan, Utah.

Fuller, R Buckminster. 1981. Critical Path. St Martin's Press. New York.

Lansdale, Bruce. 1986. Master Farmer: Teaching Small Farmers Management. Westview Press. Boulder, London.

Manniche, Peter. 1939. Denmark, A Social Laboratory. Oxford University Press. Humphrey Milford.

Martin, Oscar B. 1941. The Demonstration Work: Dr. Seaman A. Knapp's Contribution to Civilization. The Stratford Co., Publishers. Boston.

Schumpeter, Joseph A. 1989. The Theory of Economic Development. Transaction Publishers. New Brunswick (USA) and London (UK)

PLANNING OF MODERN IRRIGATION SYSTEMS INTEGRATED WITH HUMAN SETTLEMENT FOR ENHANCED REUSE OF WATER

Eng. Dharmasiri de Alwis[1]

ABSTRACT

There are five independent development areas situated in the dry zone of Sri Lanka each consisting of irrigation systems which are similar in principle, but substantially different as far as the design concept and the operations are concerned. These systems are to receive surface water in the corresponding basins plus diverted waters of the largest river in Sri Lanka, for socio-economic development.

The five systems presently in operation following settlement of farmer-families and non-farmer families, are H, C, B, G, and L. The irrigation and drainage network in each system demonstrates a planning concept, which is a combination of minor reservoirs, irrigation canals and drainages, towards optimization of irrigation system efficiency. The principle incorporated into the planning concept is therefore the "Cascade of minor reservoirs" constructed across the secondary and tertiary drainages to command the farm area below. This concept which was adopted several centuries ago, is still in existence in the dry zone.

In some of the major integrated rural development projects, the minor reservoirs have been incorporated into the irrigation and drainage system to provide a number of purposes, benefiting the human settlements and their environments. Another beneficial function of these reservoirs, when combined with the canals and drainages is its versatility in fitting into the irrigation and drainage network at any location.

The quality of irrigation water has still not been a serious problem in any of the areas described above. However, it has been recognized that there should be field research into the quality of water, from the planning stage to operation & maintenance.

The social benefits, both direct and indirect, are concerned collection and distribution of return flows, by means of Canal-Reservoir integration have produced a successful concept, in integrated rural development based on human settlement and irrigated agriculture.

---

[1]Managing Director/Team Leader, River Basin Management Secretariat, Mahaweli Authority of Sri Lanka, No. 11, Jawatte Road, Colombo 05, Sri Lanka

INTRODUCTION

The exercise of water resource development planning is a highly complex task. A new approach needs to be adopted in the initial planning, which ensures environmental aspects are integrated with social and economic considerations. The extension of irrigation and settlement systems can be justified in many areas, from the point of view of economic necessity and social betterment. The principal issues, upon which attention should be focussed on irrigation and human settlement in the tropics are, (a) Efficiency of water-use including conveyance from the source to farms (b) Socio-economic impacts, and (c) Integration of human settlement with the natural resources in the basin.

The ecological consequences of irrigation are part of a complex of practices, comprising management of available water resources, controlled distribution of water over cultivable land, and withdrawal of excessive water through drainage. These implications include the following changes:

(a) Creation of new ecological systems related to water bodies such as reservoirs, irrigation canals and drainages.

(b) Radical modification of ecological systems of the terrestrial habitat due to ploughing, cropping and addition of agro-chemicals.

(c) Modification of downstream flow regime within the river basin.

Irrigation is a significant change to the ecology of an area which creates new productive systems and land such as crop fields, forest areas, pasture and homegardens, and in water it produces fisheries and aquaculture. These changes in the physical and biological environment lead to radical changes in the ecology. In this transformation, human ecology occupies a significant place in the irrigation based settlement project.

GENERAL DESCRIPTION ABOUT SRI LANKA

Sri Lanka is an island lying off the southern tip of India. It is centrally located in the Indian Ocean with a land area of 65,000 Sq.km. Throughout its 2500 year history, kings of ancient Sri Lanka built large reservoirs and trunk canals to carry water for irrigation and agricultural systems to produce food to sustain the civilization. The early civilization centered around these reservoirs which were built to store rain water for agriculture. It was in the dry zone of Sri Lanka that the early settlements based on irrigated agriculture began. To cultivate a single annual crop of rice, the early people depended on the NE monsoon which brings in rain from October to February.

There are 103 river basins in the country. They flow radially from the highlands in the central part to the sea (Fig. 1).

Hydrology

The climate is controlled by its location within the tropics and the presence of Central Mountain mass within the country. Mean monthly temperatures in the lowlands, Range between 26^0 C and 29^0 C with little seasonal variations. In the central highlands, however the mean monthly temperature varies between 10^0 C to 21^0 C.

The island can be divided into the distinct wet and intermediate zones. The combined wet and intermediate zone covers about 30% of the land area. Annual mean rainfall in the wet and intermediate agro-climatic zones ranges from about 2200 mm to 3900 mm and is fairly distributed throughout the year (Fig. 2). Paddy and other food crops can be grown in these zones under rainfed conditions.

The annual rainfall in the dry zone, with average annual rainfall bellow 1800mm, is concentrated in the "Maha" season (September to March) and displays considerable year-to-year variability. Therefore irrigation is essential for cultivation in the "Yala" season (April to August) with some supplemental irrigation often necessary during the "Maha" season.

HYDRAULIC CIVILIZATION AND TRADITIONAL CULTURE

The traditional culture of Sri Lankans is agrarian and the most significant feature of the culture centres around the conservation and distribution of water. Since early times the people and their rulers began to store water and developed the distribution of the resource for agriculture and other purposes. This hydraulic civilization had its origins in the dry zone until about the end of the twelfth country. The dry zone receives water only during the North-East monsoons and the need for storing this water to be used during the long dry season that followed became the major concern of the people, whose responsibilities was to ensure availability of water for bountiful crops.

The traditional irrigation schemes are dependent on storage reservoirs designed to provide supplemental irrigation to the "Maha" crop, with any residual water used for limited dry season cropping. There are a total of about 180 such major irrigation schemes sustaining nearly 200,000 Ha. under agriculture, along with a vast number of minor irrigation schemes.

All these irrigation schemes in the dry zone, irrespective of the size, are supported by reservoirs, which have been formed by the construction of earthen bunds across ephemeral streams. A high utilization of the scarce water resource has been achieved by providing a number of storage reservoirs across the streams in cascade formation.

Systems of Irrigation

According to historians, two different systems of irrigation in the dry zone were built many centuries ago. Some function today for the same purposes, as they did many centuries ago. Those that have been damaged by time are of such quality that they can be repaired and made operational today.

One system was that water was impounded in reservoirs which gradually passed either directly onto the fields, or by man-made canals, which conveyed water to the fields.

With the other system, part of the water flowing down the rivers, was diverted along man-made canals, which diverted water into distant lands and reservoirs. Some of these diversions are transbasin diversions to bring water supplies from nearby basins with richer water resources.

Reservoirs (Tanks) in the Dry Zone

Literally, hundreds of small and large reservoirs occupy the vast expanse of dry scrub jungle, making it the "Kingdom of Reservoirs" (Tanks). The credit for building the reservoirs and canals that link them should go to the kings or rulers, who inspired the people to install such multipurpose facilities. (Fig. 3).

The earliest reservoirs were simple, consisting of an earthen dam across a small river. These village reservoirs served the needs of only a village or two. But with the discovery of the "valve-pit" (structural arrangement in the sluice), larger reservoirs were built.

Reservoir (Tank) and Village

The reservoir (Tank), even today, is the pivot on which life in the dry zone revolves. The villages that depend entirely on reservoirs for their economic sustenance are called Tank Villages. The structure of the Tank Village and its functioning illustrates not only the economical use of land and water but also the political and social mechanisms.

There have been four types of agricultural settlements in the country:

(a) Reservoir (Tank) villages
(b) Mountain villages of the central hills
(c) Rain-dependant villages in the East
(d) Chena villages

In the Reservoir villages, the amount of water supplied for irrigation can be controlled by sluices and spills. These villages consist of four main components:

(a) the reservoir or the Tank
(b) the paddy field under irrigation
(c) the jungle
(d) the cluster of houses

The reservoir, which is normally situated on a higher elevation, provides water for agricultural and domestic needs. It also provides fresh water fish and water plants for domestic consumption. The jungle provides the village with firewood, timber, meat and honey. The cattle are grazed and allowed to rest in the jungle.

AVAILABLE WATER RESOURCES

The hydrographic pattern is a function of the topography and in Sri Lanka with its central hilly area, a radial pattern of the rivers is clearly revealed. The rivers flowing to the West, South, and East are shorter that those flowing to the North.

There are 103 basins, draining areas varying from 10 sq. km to the maximum of 10500 sq. km. The largest and the longest river is the Mahaweli Ganga, which is 325 km. in length from source to outlet.

The average annual rainfall over the whole island is approximately 13.2 Million Ha.m. The average annual run-off into the sea from all rivers and streams has been estimated at 4.3 Million Ha.m, or approximately 30% of the precipitation. This volume of run-off is equivalent to an average depth of 660 mm over the total area of the Island.

The monsoonal rains are dependent upon the prevailing winds during both the south-west and north-east monsoon seasons, and the annual average rainfall varies from below 1000mm. on the north-western and south-eastern fringes of the Island to over 5000mm. at certain places on the south-western windward hill slopes. One of the most significant features of the climatological characteristics of Sri Lanka, caused primarily by the orographic effect of the central mountains on the two monsoons, is that the Island can be divided into two distinct parts, The "wet zone" and the "dry zone"(Fig. 4). The wet zone, receives the major portion of its annual rainfall during the south-west monsoon.

However, it is more rational to define the dry zone as an area where the average annual rainfall is less than the average annual potential evapotranspiration. This implies that there can be little or no run-off if the rainfall is evenly distributed throughout the year. Since the potential evapotranspiration ranges from 1400 mm.

to 2000 mm per year in the low altitude areas of the Island, It is greater than the 1000 mm of rainfall.

The rivers flowing through the wet zone are perennial and their mean annual yield is about 65% of the yield of all the rivers.

The dry zone, which covers about 75% of the Island, exhibits wide variations in average annual precipitation and run-off and their spatial distribution merits discussion in greater detail. The available land resources suitable for agriculture are located in the dry zone, but shortages of water resources hamper their development.

About 750 mm. to 1900 mm. of rain falls on the dry zone in an average year, mostly during the short NE monsoon. During the rest of the year, there is practically no rainfall, so that productive plant growing is only possible with irrigation supported by regulation of the variable stream flows with storage reservoirs.

PLANNING OF IRRIGATION SYSTEMS

Sri Lanka has been somewhat fortunate that the combined effects of the mountain barrier and the monsoons have ensured ample quantities of water for all purposes including the irrigation of all available arable land in the country. Even though significant storage and regulation have been provided in the dry zone, the long-term mean water resources for irrigation have not been great enough to ensure a reasonable degree of success under individual projects. The implementation of the Mahaweli Ganga Development Scheme (MGDS) has further improved the existing conditions in most of the dry zone. It has provided an increase to the ground water resources.

Efficiency in irrigation requires that water be conveyed to the system and distributed with minimum losses in such a way as to secure maximum efficiency of water use as determined by the ratio of the amount of water used by plants to the amount of water withdrawn from the system.

Irrigation efficiency is also significantly affected by other factors such as the level of training of users, quality of management, type of flow being operated, method of water distribution and the size of the irrigation area. Therefore in designing an irrigation canal system, it is vital to strive for a distribution network, which is simple in function and requires a minimum of management.

Planing for multipurpose utilization of the water resources commenced about 50 years ago. The emphasis at that time was on basin-wide development and several promising rivers were taken up for detailed studies. The main purposes of multipurpose development have been irrigation, hydro-power generation and settlement of farmers and non-farming families.

In the case of paddy farms, cultivation has been traditionally using excessive irrigation water. With projects implemented several years ago, there has been a need for economical use of water, partly due to well-drained soils in the command area and partly due to unauthorized expansion of irrigable land area.

Planning irrigation systems is based on the findings of soil classification surveys. Greater control is being exercised over conveyance and distribution losses. Damage to crops due to water deficits are considerably reduced, while substantial increase in productivity are realized.

LEGISLATION

The most important legislative enactment governing the utilization and development of the water resources has been the Irrigation Ordinance of 1946 amended in 1968. This is an Ordinance to amend and consolidate the laws relating to water rates, irrigation districts, agriculture committees, construction, maintenance and protection of irrigation infrastructure and the conservation of water.

Another legislative enactment is the Paddy Lands Act of 1958, which has the objective to ensure the proper utilization and maximum productivity of all available land resources for the cultivation of paddy.

IRRIGATION SYSTEM INTEGRATED WITH MINOR RESERVOIRS

Reservoirs are important in the lives of settler-farmers and other resident in a development area, as water bodies mean more than water and the various sciences of water.

A reservoir cannot be separated from its drainage area. Its bund is designed using 50-year flood return intervals. The spillways adopted for these reservoirs were broad crested weirs. An earth or concrete spillway constructed in natural ground should convey the flood discharge over the spillway, to fall into the stream at a point downstream of the structure and the bund. Special consideration must be given to the design, if failure of any structural element could cause danger to life or serious property damage.

The capacity of the reservoir must be such that when used in combination with the other components of the irrigation system, it will provide the needed volumes of water at an adequate variable flow rate and in a timely manner.

Since the volume of water lost is dependent upon the surface area, evaporation losses should be minimized. Seepage losses are much more difficult to estimate to precision, based on the permeability of the foundation materials. Local experience with existing reservoirs built in similar soils in the area are the best guide for sealing the embankment. Seepage losses can seldom be completely eliminated.

USE OF MINOR RESERVOIRS

Under many circumstances, minor reservoirs are essential components in a complete irrigation system. Reservoirs are management facilities whereby a variable or steady flow can be regulated into a different variable steady flow that is more convenient or efficient in terms of water, labour, energy and crop production.

The most common uses of minor reservoirs in which the irrigation system is the key component, is to provide a number of functions as listed below.

(a) Storage of run-off from rainfall for irrigation during dry periods.

(b) Long term or temporary storage of water that may be available from surface or subsurface sources. 'Overnight' storage of the flow from a system delivering for use during the day. Re-regulating capacity needed to adjust flows of an undesirable size or to match the flow requirement of other elements of the irrigation system.

(c) Control needed to maintain a desired surface or sub-surface water elevation in an adjacent area.

(d) Flood mitigation.

(e) Domestic needs of settlers. Water needs for wild animals and domestic animals such as buffaloes.

(f) An aquatic environment for several water plants. Habitat for inland fish.

(g) High water table in the highlands and forest lands.

(h) Flexibility in the irrigation system. Re-use of drainage water.

RE-USE ASPECT IN DIFFERENT IRRIGATION SYSTEMS

The integrated development areas considered in the study are fully in operation except System-L of the Mahaweli Ganga Development Scheme (MGDS). To illustrate the principle of re-use of return flows in the MGDS, there are thirteen such Systems identified for development. They are scattered in the dry zone of Sri Lanka. System-H, System-C, System-B and System-G are the other independent development areas under evaluation. In each development area of the MGDS, there are three components, which form the integrated concept. They are given below.

- Terrestrial environment
- Aquatic environment
- Human environment

The five Systems of MGDS under consideration have been developed with the provision of irrigation and social infrastructure and settlement of both farmer and non-farmer families, in the last three decades. Of these areas being examined, analysed and compared, the concepts of planning in respect of irrigation, landuse and human settlement are similar in System-H, System-C and System-B (Fig. 5).

System-H of MGDS

The irrigable extent of System-H is about 30,000 Ha. The physical components of it shown in (Fig. 6) are listed below.

(a) Approximate boundaries of command area

(b) Large and medium size reservoirs incorporated into the irrigation system

(c) Main canals, Branch canals, Minor reservoirs, Distributory canals, Primary and Secondary drainages

(d) Town centres and Urban Centres

A salient feature in System-H is that the Large and Medium size reservoirs are in cascade, providing storage and regulation. All reservoirs receive drainage water in addition to augmentation by irrigation canals (Fig. 7).

However, the availability of reservoirs in close proximity to the settlement areas or villages is considered inadequate, as there are over 30,000 settler families resident in the highlands. The size of a village varies from 100 to 150 families or homesteads. Return flows are necessary to augment these minor reservoirs to cater to the needs of the settlers.

System-G of MGDS

The development area lies below an ancient trunk canal, which conveys water from the river Amban Ganga to a large reservoir. The trunk canal runs along a contour. Therefore all canals commanding the project area cut the ground contours laterally dropping towards the main drainage (river) with a substantial gradient. The irrigable area in System-G is about 5500 Ha. This system has been in operation for over four decades.

The command area, its boundaries, and the irrigation and drainage system are shown in (Fig. 8), a physical component that is not seen in System-G in reservoirs of any size. The irrigable area is therefore commanded by a system of canals only. Even the villages which are located in the areas above the canal are not facilitated with small reservoirs, thus compelling the settlers to depend on the canal or the ground well for their domestic needs.

In contrast to the irrigation system in System-H, the distribution canals in system-G have been constructed along the contours with single banking, so that seepage and surface runoff could be collected. Some field canals also have been constructed to accomplish the concept of water reuse (Fig. 9).

Another significant feature in the design of the irrigation system is that small anicut structures are constructed across some secondary and tertiary drainages.

System-C of MGDS

The irrigable extent in System-C, which is shown in (Fig. 10), is about 3000 Ha. There are nearly 31000 settler families engaged in agriculture and services. The size of a village varies from 200 to 300 homesteads. The command area lies between Mahaweli river and a series of large and medium-size reservoirs which are storage facilities on the main canal. These reservoirs receive surface run-off from their own catchments, in addition to augmentation. Therefore, these reservoirs perform dual functions in receiving return flows and enhancing the flexibility of the canals with storage (Fig. 11).

System-B of MGDS

The irrigable lands in System-B are mostly of well-drained soils. The underlying layer below the top soil is nearly impervious. The irrigable area on the left bank of the main drainage, across the command reservoir, is about 30,000 Ha. The specification extent on the right bank is about 14000 Ha which has yet to be developed for agriculture and settlement of farmers. (Fig. 12) depicts the developed area of the basin below " Maduru Oya Reservoir", with a large number of minor reservoirs, which are settled. One important feature in the canal-reservoir irrigation system is that there are no reservoirs in cascade. The minor reservoirs are either fed by the canals or located to receive return flows (Fig. 13).

Pimburettewa is the only medium size reservoir constructed across a secondary drainage. All minor reservoirs are stipulated across the tertiary drainages. Of the six development areas which are subjected to evaluation, system-B is the only project having concrete lined Main and Branch canals.

Similar to System-C, the size of each village in System-B is in the range 200-300, and is in close proximity to a reservoir or two. The storage capacity of the entire developed area is concerned with the total volume of water available for agriculture.

Walawe Basin (Right Bank of Walawe River)

The project area or the study area (Fig. 14) lies in the dry zone of the southern part of Sri Lanka. The irrigable extent is about 12500 Ha. commanded by two large reservoirs. Udawalawe is the main reservoir situated across the river, while the Chandrikawewa reservoir is built across the main tributary, to receive water from the main reservoir via the main canal, which transverses along a contour.

The entire farm extent is irrigated by the canal network, which does not have a single minor reservoir within the command area. The only way return flows are collected is by Distributory canals and Field canals where they are in single banking.

On lands with well-drained soils, water has to be saved by growing subsidiary crops such as banana and vegetables.

System-L of MGDS

This is an area situated in the heart of the dry zone. Ma-Oya is the river basin, that is being provided with irrigation and physical infra-structure under the integrated development planning concept. The right bank of Ma-Oya had been provided with an irrigation system about 50 years ago, with the restoration of an ancient reservoir across a tributary of Ma-Oya. The boundaries of System-L, Padaviya reservoir, Ma-Oya and the minor reservoirs in operation on the left bank of Ma-Oya are shown in (Fig. 15). However, to date only about 2000 settler-families have been established on the left bank. The command area on the right bank is in operation independently and managed by the Department of Irrigation.

Although, System-L is among the thirteen development areas identified under the MGDS, this basin is yet to receive diverted waters of the Mahaweli River. At present the left bank is being developed under as integrated plan, with the construction or restoration of minor reservoirs. Villages are being established around the reservoirs. Each village consists of homesteads or farmer-families in the range 100-200 people.

The water use efficiently needs to be very high due to scarcity of water and limited storage capacity, therefore a cascade of irrigation system is to be established, wherever possible (Fig. 16). Thus, the return flows should be arrested, and stored or diverted by means of pick-up anicuts which then provides water supplies for both agriculture and settler needs.

CONCLUSION

Irrigation is a long established agricultural practice that enabled civilization to establish permanent settlements in the dry zone of Sri Lanka. The basic concept on which these hydraulic societies existed was their dependence on water reservoirs built across ephemeral streams to collect surface and ground water run-off during each year. The water reservoirs are multipurpose to accommodate the community living around it. This idea has been incorporated into the irrigation and settlement planning of the integrated rural development projects during the second half of this century.

Water reservoirs help to maintain the balance between surface run-off and water demand. Water is one of the basic elements of the environment and reservoirs have a fundamental impact, which cannot be overlooked when planning, designing and operating a reservoir system.

The minor reservoir concept can be described as the integration of the water reservoir system with the other important sub-systems to yield several beneficial results, which finally lead to community development.

Water is necessary for all forms of life. However, fresh water is a finite and vulnerable resource, which is essential to sustain life, development and the environment. It is therefore appropriate, in the light of the analysis and evaluation of this study, to reproduce below, a cardinal principle adopted by one of the greatest kings of Sri Lanka. "Not a single drop of water received from rain should be allowed to escape into sea without being utilized for human benefit"
(KING PARAKRAMABAHU THE GREAT, 1153-86 AD)

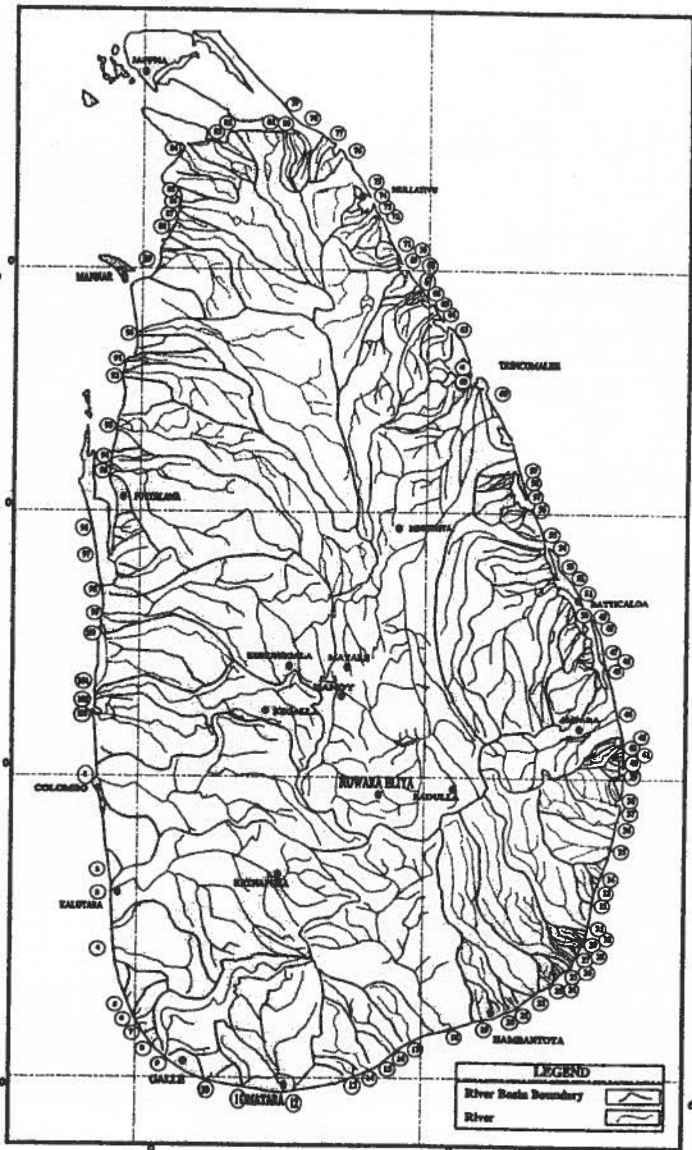


Fig. 1. River Basins of Sri Lanka

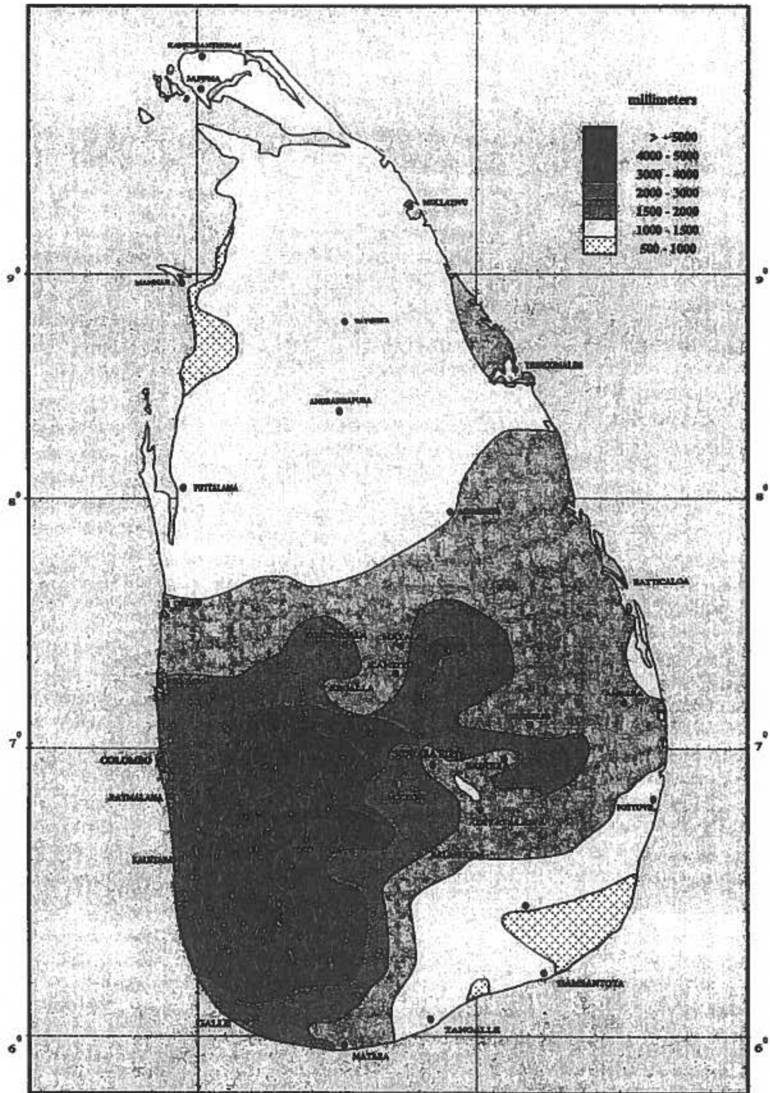


Fig. 2. Average Annual Rainfall (1961-1990)

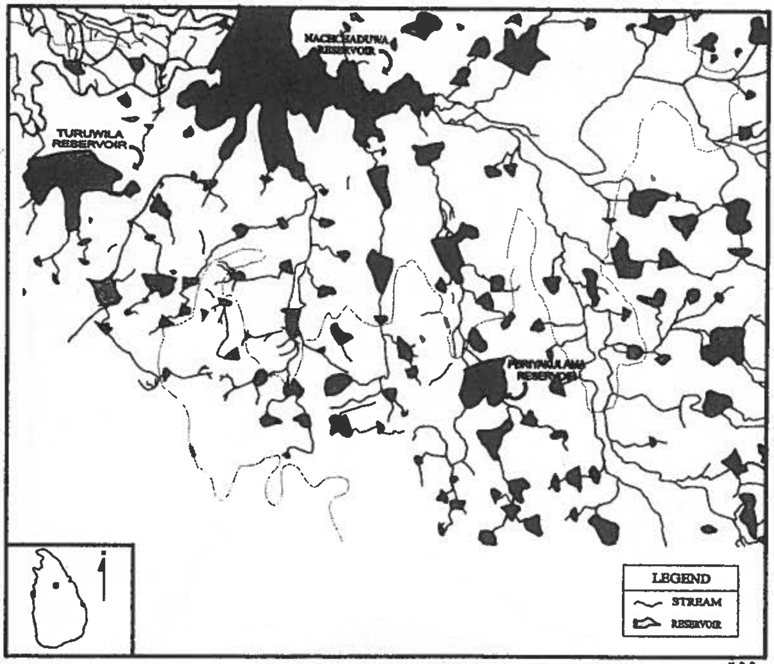


Fig. 3. Topographic Map Showing Minor Reservoirs In Cascade

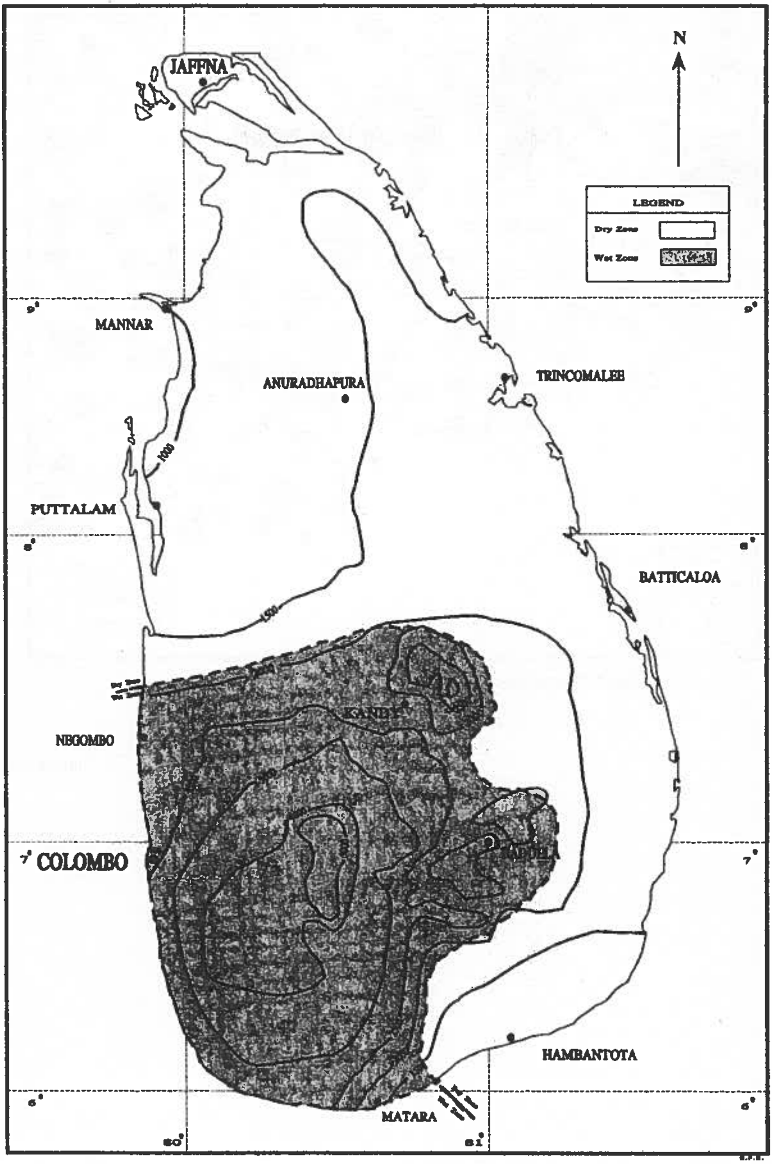


Fig. 4. Isohyets, Dry Zone and Wet Zone

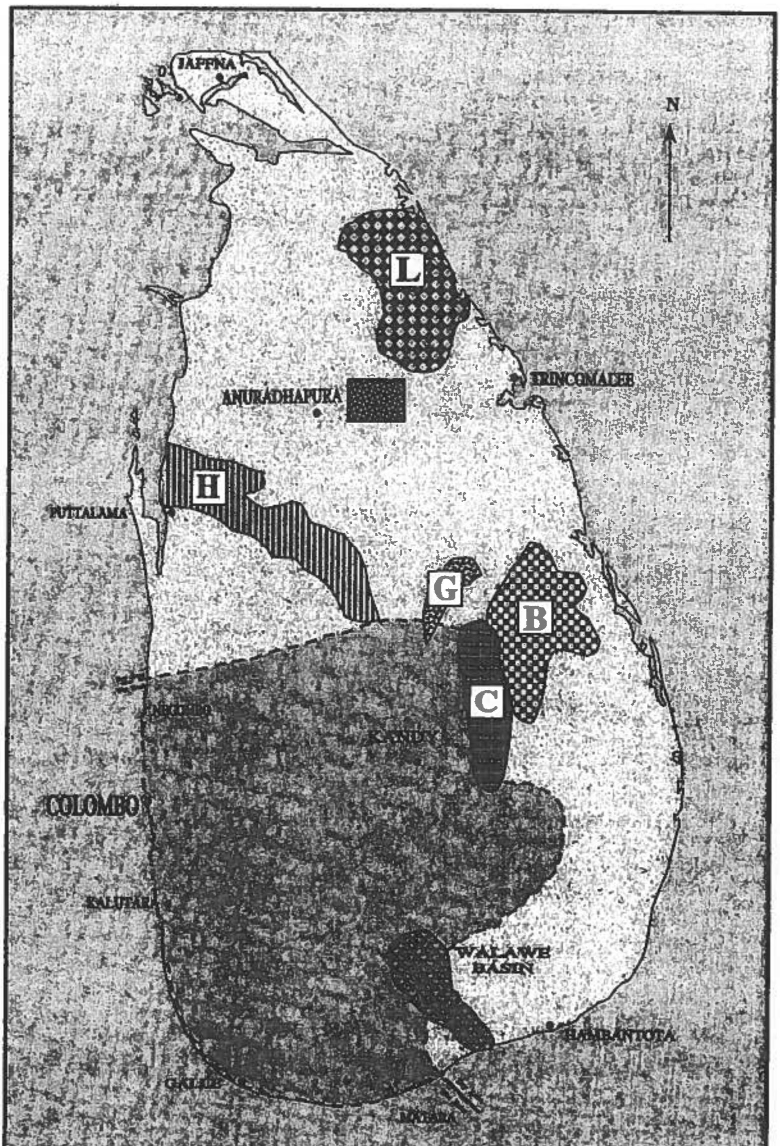


Fig. 5. Map of Sri Lanka Showing Development Areas

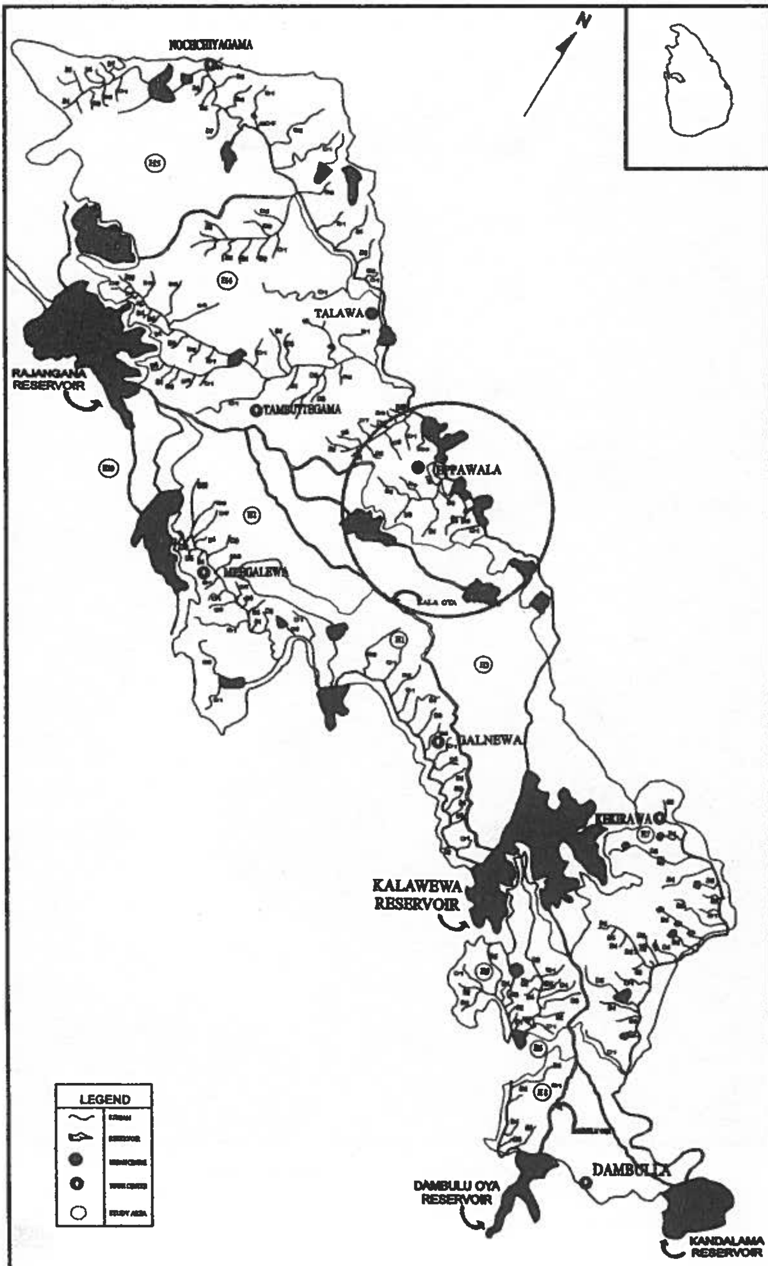


Fig. 6. Mahaweli Ganga Development Scheme (System - H)

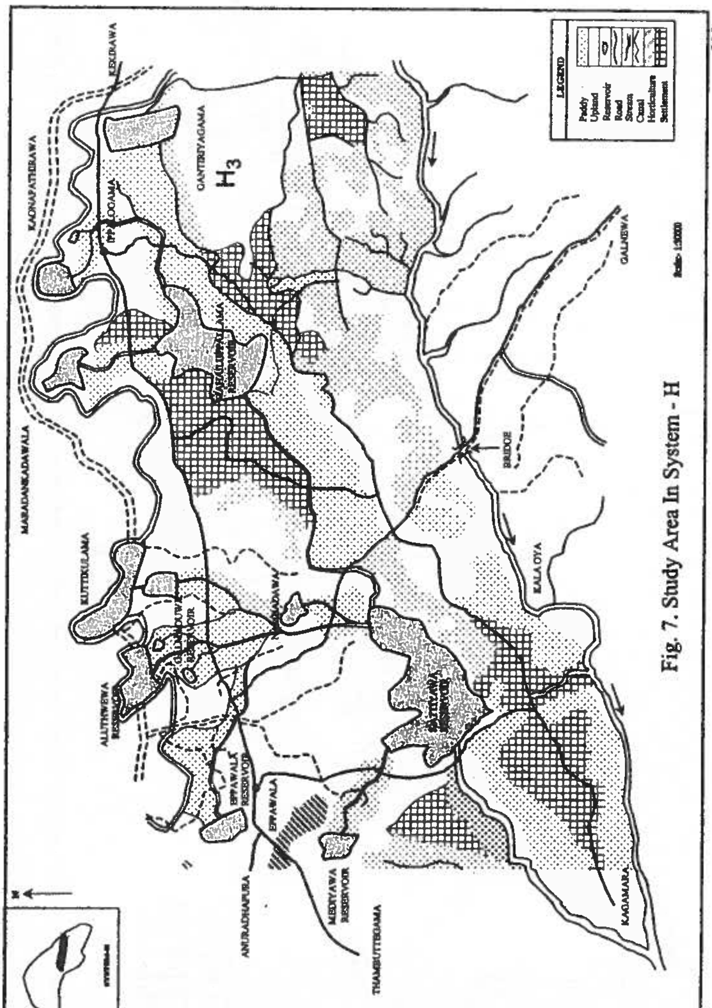


Fig. 7. Study Area In System - H

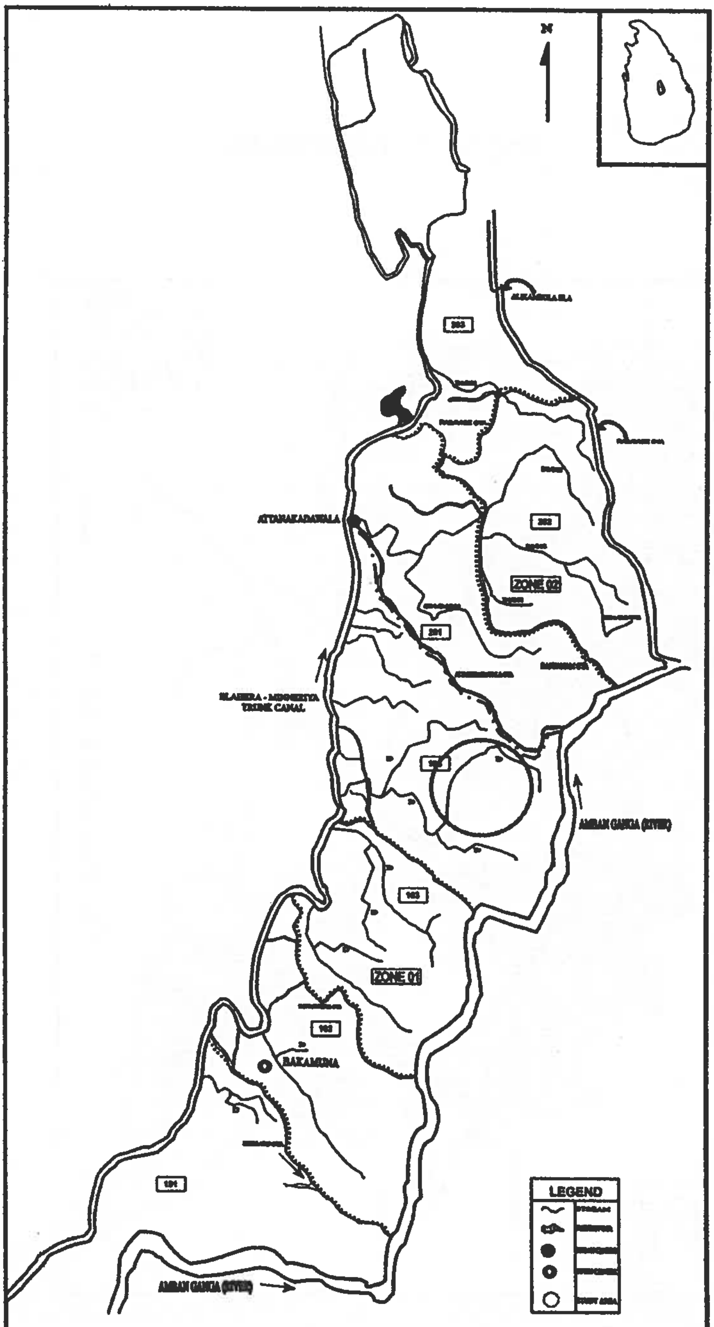


Fig. 8. Mahaweli Ganga Development Scheme (System - G)

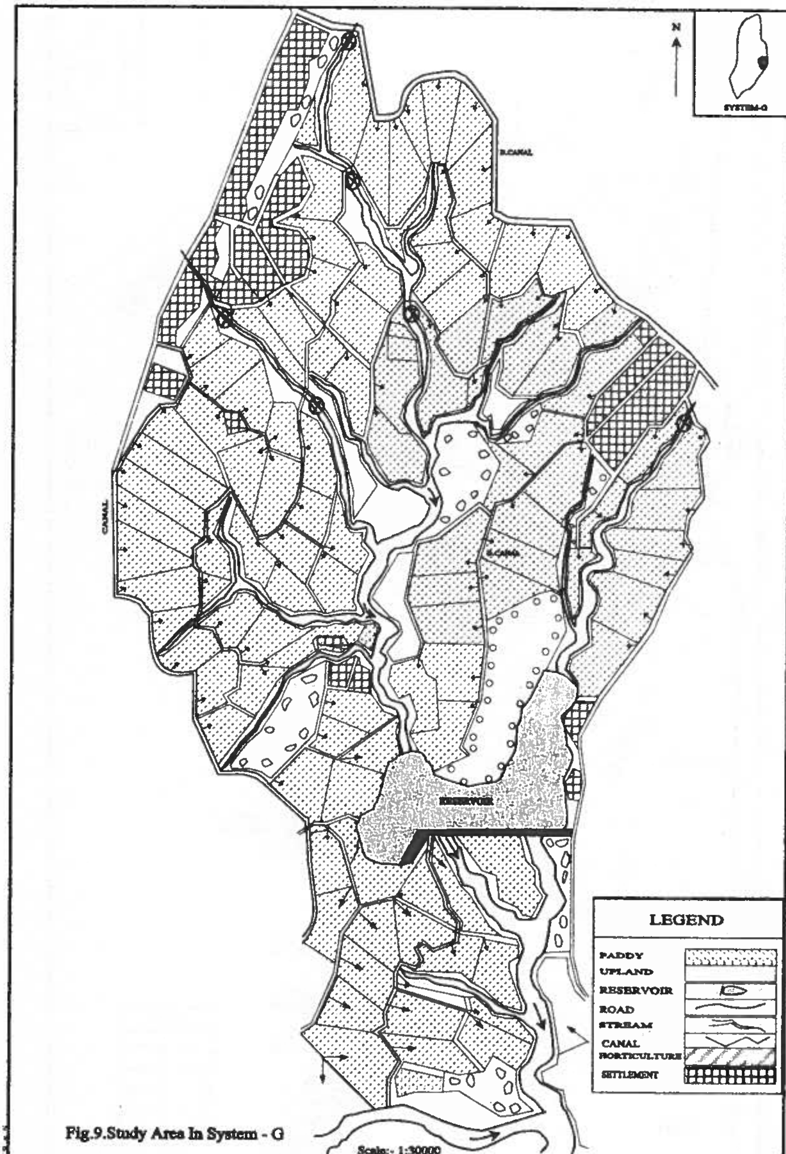


Fig.9.Study Area In System - G

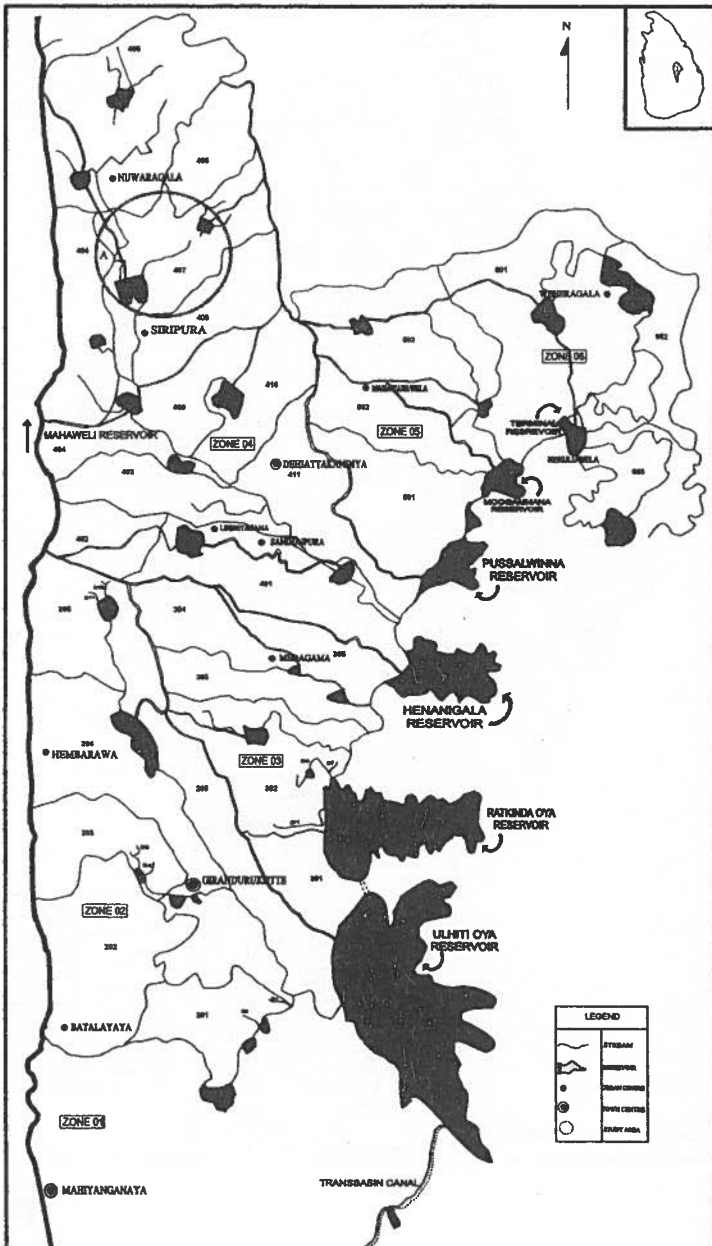


Fig.10. Mahaweli Ganga Development Scheme (System - C)

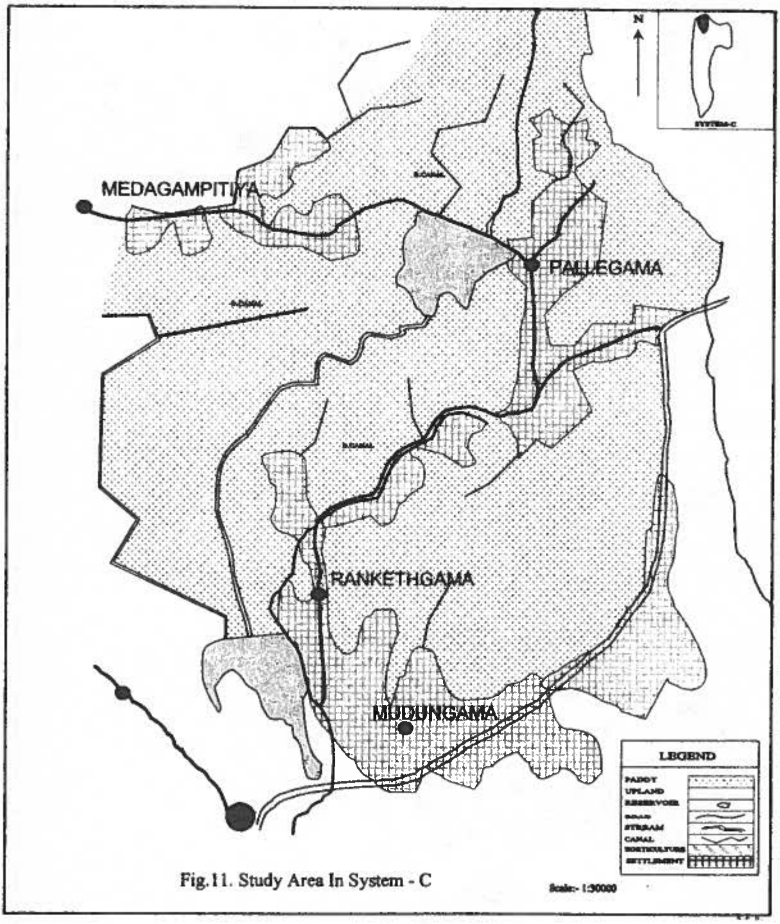


Fig.11. Study Area In System - C

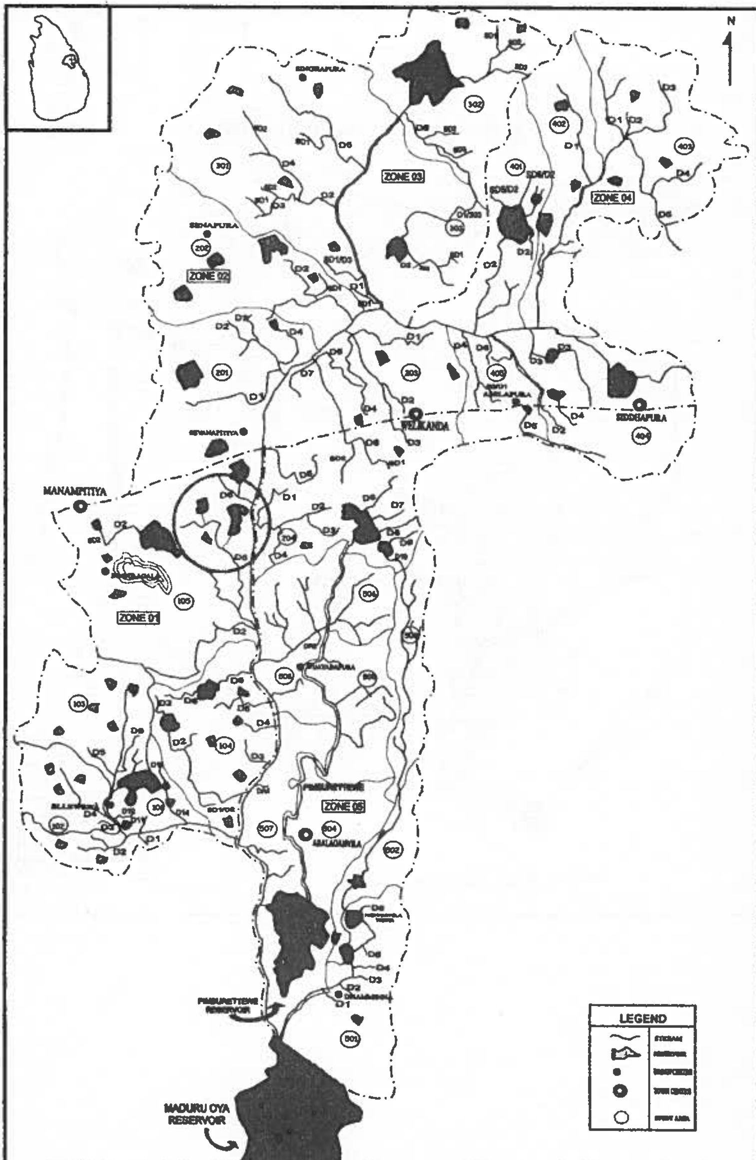


Fig. 12. Mahaweli Ganga Development Scheme (System - B)

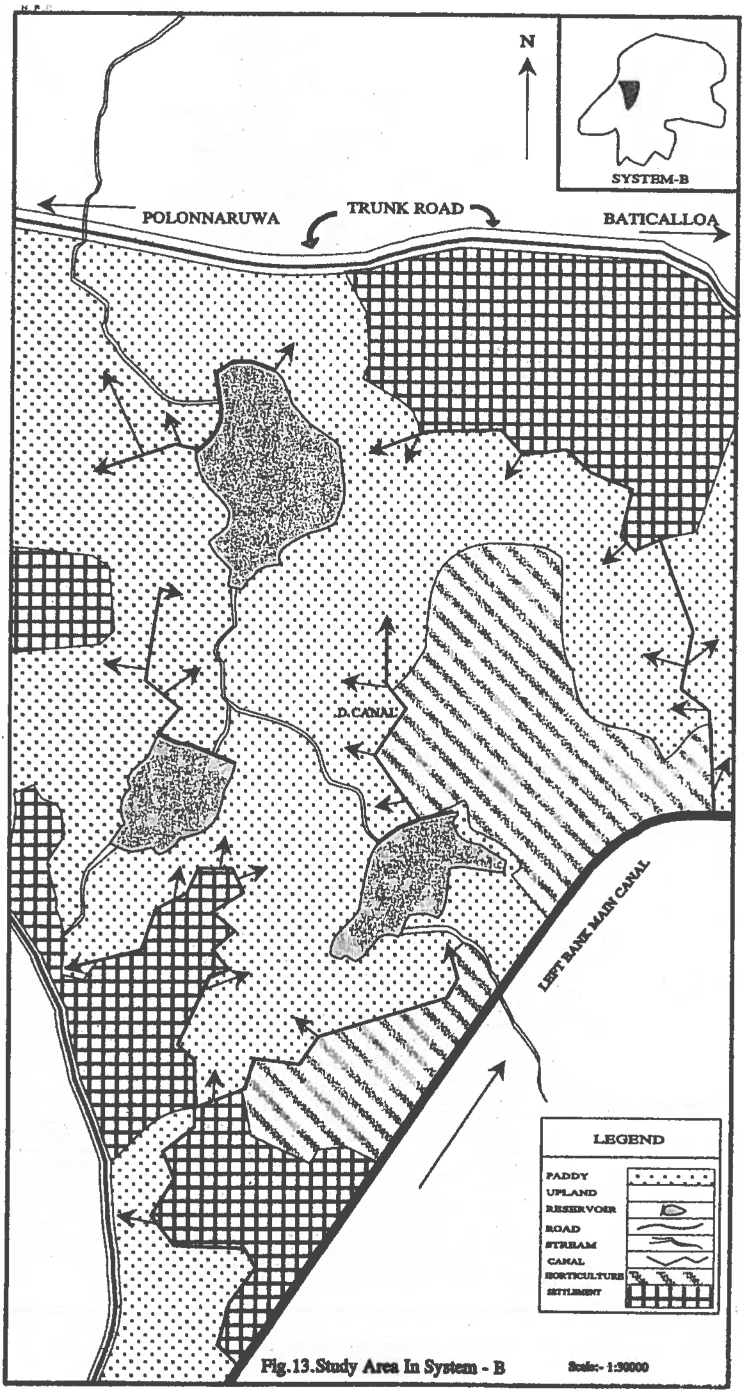


Fig.13.Study Area In System - B

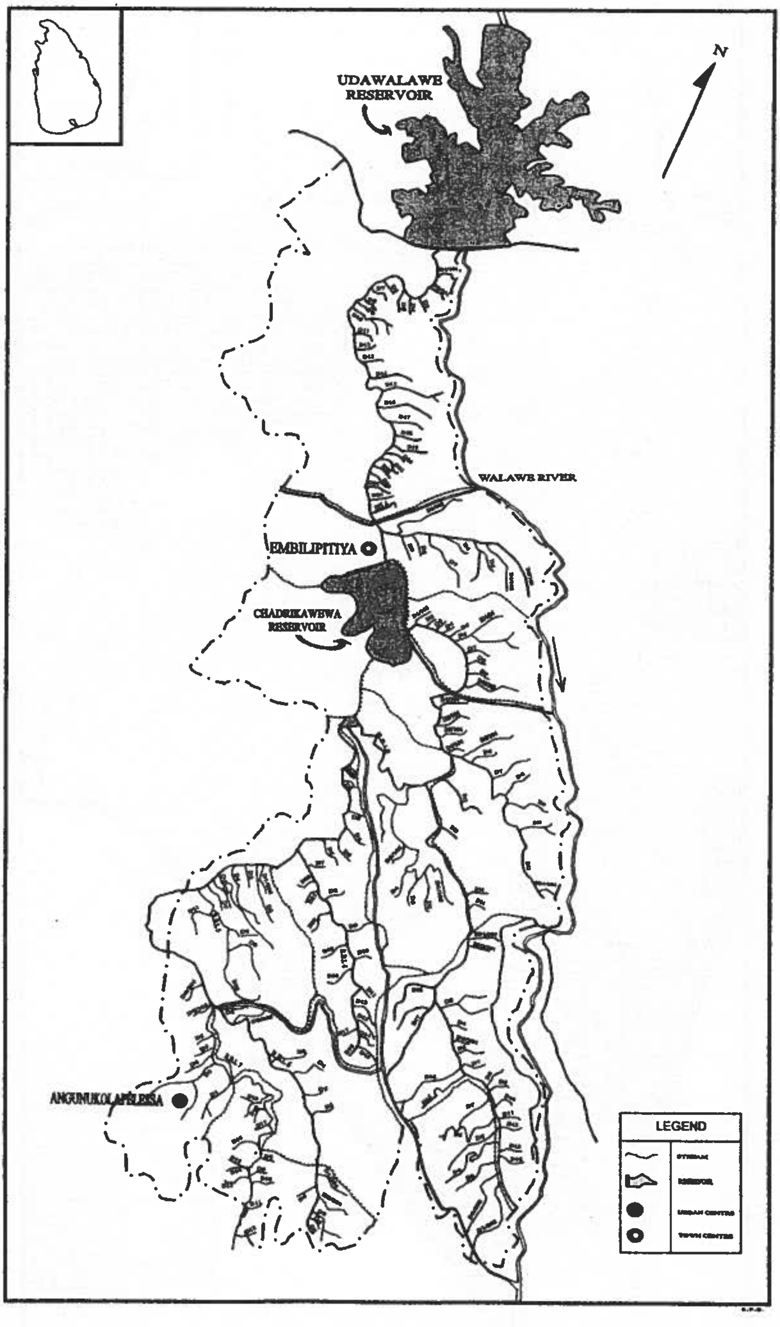


Fig. 14. Walawe Basin (Right Bank)

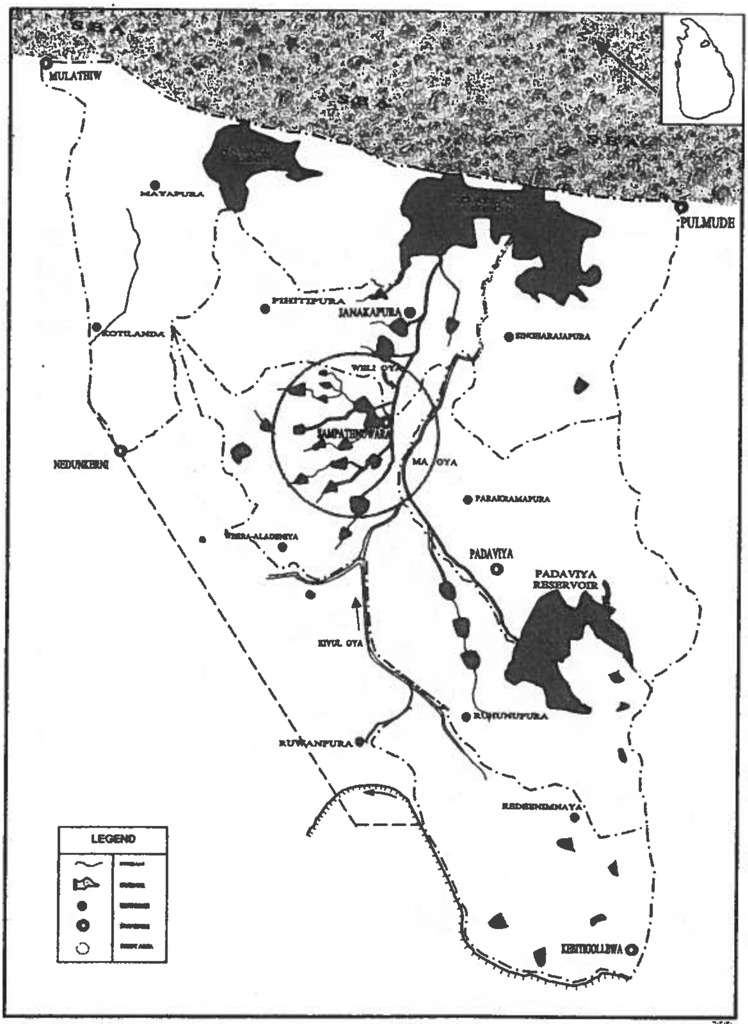


Fig. 15. Mahaweli Ganga Development Scheme (System - L)

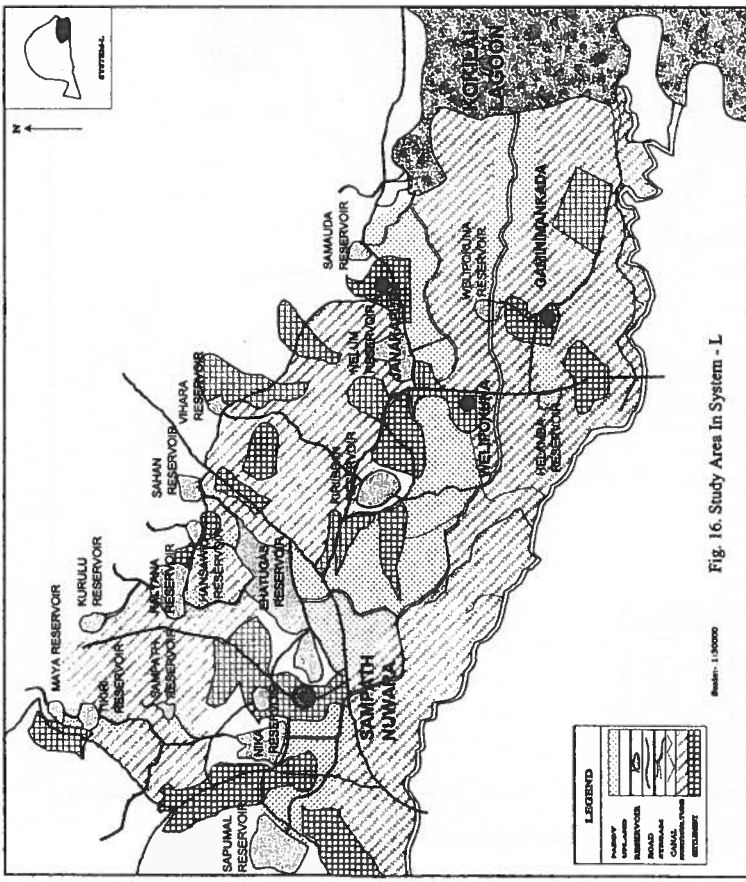


Fig. 16. Study Area In System - L

COMPETING INTERESTS IN WATER RESOURCES

MULTI-NATIONAL WATER USE - STRATEGIES AND AGREEMENTS

CASE STUDY - HUECO BOLSON GROUND-WATER STUDY

Rong Kuo [1]

ABSTRACT

Ground-water pumping for municipal water supply accounts for a majority of the withdrawals from the Hueco Bolson, the major transboundary aquifer located in El Paso, Texas/Juárez, Chihuahua area. Since the early 1900's pumpage from the Hueco Bolson has exceeded the annual recharge. In 1995, a total of 168,000 acre-feet (210 million cubic meters) was pumped from the Hueco Bolson, 60% was pumped by Mexico. As pumping increases with the anticipated population growth on both sides of the border, it is predicated that the Hueco Bolson will be depleted by 2030, unless some measures be taken.

The cities of El Paso and Juárez recognize the strain on the water supply that each city government is facing. In 1995, the water utilities that supply water to El Paso and Juárez sought information exchange on the Hueco Bolson through the International Boundary and Water Commission (IBWC).

The IBWC, following the traditional role of exchanging information on border water resources, held commission meetings in 1995-99 with various water resources agencies of the United States and Mexico. The information exchanged, included information regarding soil type, well construction data and use of wells, lithological descriptions, piezometric levels, results of ground-water quality analysis (major irons),and pumping records. As the result, a binational report entitled "Transboundary Aquifers and Binational Ground-Water Data Base, City of El Paso/Ciudad Juárez Area" was developed and published in January 1998. The

1 Civil Engineer, Ph. D., P.E., U.S. Section, International Boundary and Water Commission, El Paso, Texas

report summarizes and graphically integrates the information, and contains geohydrological maps and a bibliography.

Further, mathematical ground-water models for the aquifer on both sides of the border have been developed. The ground-water models will serve as supporting tools for the authorities in both countries charged with the planning for optimum utilization and administration of the ground-water resources of the region.

Hueco Bolson Aquifer

The Hueco Bolson extends from the New Mexico/Texas State line south to the Sierra Juárez to the west and to the Sierra El Presidio in Mexico and Sierra Guadalupe to the south in Texas. From the Sierra Juárez in Juárez, Chihuahua, Mexico, the Hueco Bolosn extends southeast to Indian Hot Springs, Texas (Fig. 1).

The Hueco Bolson is one of the major transboundary aquifers between United States and Mexico. The Hueco Bolson is the principal aquifer which provides the total water supply for municipal and industrial use in the Ciudad Juárez, Chihuahua, and a significant portion of the water supply for municipal and industrial use in the city of El Paso, Texas.

The primary occurrence of fresh ground water in the Hueco Bolson is in an irregularly shaped wedge of water bordering the Franklin and Organ Mountains and the principal water-yielding unit in the Hueco Bolson is the Santa Fe Group of Tertiary and Quaternary age (Kernodle, 1992). The Santa Fe Group consists of two units: the lower Fort Hancock Formation and the overlying Camp Rice Formation. The Fort Hancock Formation predominantly consists of interbedded clays and silts while the Camp Rice Formation generally is of sands and gravel with some interbedded clays.

Existing Problems

Ground-water pumping for municipal water supply accounts for a majority of the withdrawals from the Hueco Bolson. Since the early 1900's pumpage from the Hueco Bolson has exceeded the annual recharge which is estimated to be about 6,000 acre-feet (7 million cubic meters) per year from neighboring ground-water basins and 14,600 acre-feet (18 million cubic meters) per year from mountain-front recharge (Sayre and Livingston, 1945). In 1995, a total of 168,000 acre-feet (210 million cubic meters) was pumped from the Hueco Bolson in which 60% of the total volume, 100,000 acre-feet (123 million cubic meters) was pumped by Mexico. Recent trends indicate that municipal pumpage in Mexico increased about 13% between 1990 and 1994 while municipal and military pumpage in the United States decreased 24.0% during the same time interval (Fig. 2).

Pumping trends demonstrate increased dependance on ground water in this region of Mexico, and partial conversion from ground water to surface water use in this region of the United States.

In heavily developed parts of the Hueco Bolson, drawdowns have reached 150 feet (45 m) since 1940 (Fig. 3).

Most of the drawdowns are near municipal wellfields which vary between 50 and 100 feet (15 and 30 m). Some of the highest rates of drawdown have occurred beneath Ciudad Juárez, where over 100 feet (30 m) of drawdown has been recorded in less than 25 years. As a result, a major portion of the metropolitan El Paso/Ciudad Juárez area recorded land subsidence of as much as 0.41 foot (0.125 meters) between mid-1950's and the mid-1980's.

As pumping increases with the present population growth on both sides of the border, ground-water experts have repeatedly warned that the Hueco Bolson will be totally depleted in 2030, unless some measures are taken. These measures include finding new water sources and significantly improving the management of these scarce ground-water resources.

Exchange of Information

The cities of El Paso and Juárez recognize the severe future situation of the water supply that each city government is facing. In 1995, the water utilities that supply water to El Paso (El Paso Water Utilities) and Juárez (Junta Municipal de Agua y Saneamiento de Juárez (JMAS)) seek information exchange on the Hueco Bolson through the IBWC.

The IBWC, following the traditional role of exchanging information on border water resources, held commission's meetings in 1995-99 with various water resources agencies of the U.S. and Mexico which have an interest in this resource. The information exchanged, included information regarding soil type, well construction data and use of wells, lithological descriptions, piezometric levels, results of ground-water quality analysis, and pumping records.

Binational Report

There was a consensus that there was a need to integrate official ground-water data on the Hueco Bolson from the United States and Mexico into a single data base. A Binational Technical Group (BTG) was established to include personnel from both countries. From the United States representation was included from the U.S. Section of the IBWC, Texas Water Development Board, New Mexico Water Resources Research Institute, U.S. Geological Survey, and the U.S. Environmental Protection Agency; and from Mexico representation included the Mexican Section of the IBWC, National Water Commission (CNA), and the Ciudad Juárez JMAS.

As the result, a binational report entitled "Transboundary Aquifers and Binational Ground-Water Data Base, City of El Paso/Ciudad Juárez Area" was prepared and the final version was published in January 1998.

The binational report includes a data base on ground waters in the El Paso/Ciudad Juárez area utilizing information exchanged by the United States and Mexico during a series of official meetings coordinated by the IBWC. The report summarizes and graphically integrates the information, and contains geohydrological maps and a bibliography.

The binational report does not arrive at any conclusions, but rather seeks to establish a joint ground-water data bank, accessible to anyone interested in this type of information, validated by the two Governments for international distribution.

Mathematical Models

In order to find better ways to manage scarce ground-water resources, the BTG, working in a joint manner, developed mathematical ground-water models (Fig. 4 and Fig. 5) for the aquifer on both sides of the border.

The ground-water models will serve as supporting tools for the authorities in both countries charged with the planning for optimum utilization and administration of the ground-water resources of the region.

It was recommended by the BTG during the 1995-96 IBWC meetings that each country create its own ground-water mathematical model to develop simulation of the regional aquifer system. Such models will provide better knowledge of the aquifer and would support the various institutions charged with the management and planning of ground-water resources in both countries. For this reason both sides expressed an interest in knowing the functional aspects of the aquifer volumes of freshwater available and its distribution and to consider further development of each model for quality deterioration, salinity trends, and development of a suitable management plan.

In order to develop two compatible models, a common zone covering areas on both sides of the border (Fig. 6 and Fig. 7) was jointly identified to include the geographical boundaries corresponding generally to the Rio Grande alluvium.

Within this zone, similar parameters and characteristics were used to be for both models. The BTG discussed details on the data, parameters used, and boundary conditions in this zone. It was agreed that any country can extend its model's coverage in the other country to a distance greater than the common zone; however, that country would use only the information already exchanged through the IBWC. If necessary and proper, the BTG would be able to recommend the exchange of additional data though the IBWC for that area outside the common zone.

Results from both mathematical models under a steady state condition from 1903 to 1975 were compared and evaluated. Recommendations were made to improve the future transient model runs.

It is expected that the development of the mathematic models will serve as tools for the authorities in both countries for suitable and equitable utilization and administration of the ground-water resources of the region.

At the completion of the development of the simulation models a technical report will be prepared by each country on results obtained. The IBWC will then prepare a Joint Report summarizing and accepting the technical reports developed by each country. It is estimated that the models will be operational by 2001.

International Boundary and Water Commission (IBWC)

The IBWC was created more than a century ago by the governments of the United States and Mexico to apply the provisions of various boundary and water treaties, and settle differences arising from such applications through a joint international commission located at the border. The IBWC's jurisdiction extends along the United States-Mexico boundary, and inland into both countries where they may have international boundary and water projects.

For more than 100 years, the United States and Mexico have relied on the IBWC to apply their boundary and water treaties, and regulate and exercise the rights and obligations assumed under those treaties, along with resolving the differences that arise from such application. The IBWC exercises this responsibility along its 2,000-mile (3,000-kilometer) border jurisdictional zone, maintaining a relationship of mutual respect and understanding, and fostering a better international relationship so as to improve the health and well-being of the more than 10 million inhabitants in the border area.

Today, the IBWC continues to play a major role in the United States and Mexico border environmental cooperation relationship with a vision of providing to its border area customers, environmentally sensitive, timely and responsive boundary and water services to make the region a better place to live.

REFERENCES

1. International Boundary and Water Commission, United States and Mexico, Transboundary Aquifers and Binational Ground-Water Data Base, City of El Paso/Ciudad Juárez Area, 1998

2. Kernodle, J. M., Results of Simulations by a Preliminary Numerical Model of Land Subsidence in the El Paso, Texas, Area; U.S. Geological Survey, Water-Resources Investigations Report 92-4037, 1992

3. Land, L.F. and Armstrong, C.A., A Preliminary Assessment of Land-Surface Subsidence in the El Paso Area, Texas; U.S. Geological Survey, Water-Resources Investigations Report 85-4155, 1985

4. Frenzel, P.F. and Kaehler, C.A., Geohydrology and Simulation of Ground-Water Flow in the Mesilla Basin, Doña Ana County, New Mexico, and El Paso County, Texas; U.S. Geological Survey Professional paper 1407-C, 1992

5. Sayre, A.N. and Livingston P., Ground-Water Resources of the El Paso area, Texas; U.S. Geological Survey, Water Supply paper, 1945

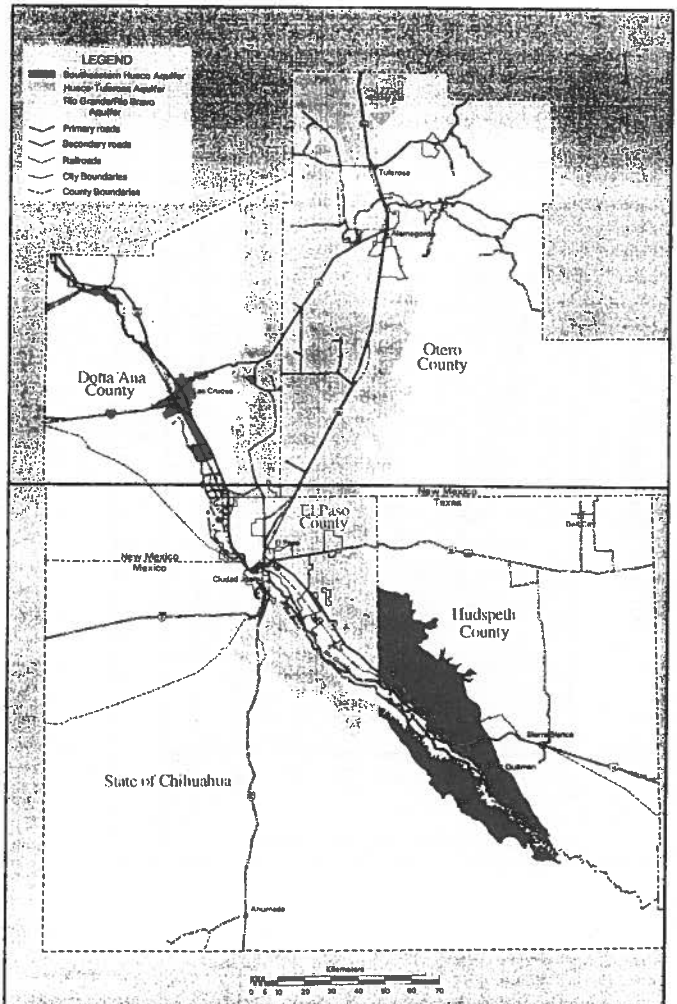


Figure 1 –Location of the Hueco–Tularosa, southeastern Hueco Aquifer, and Rio Grande Aquifer in the Regional Study Area

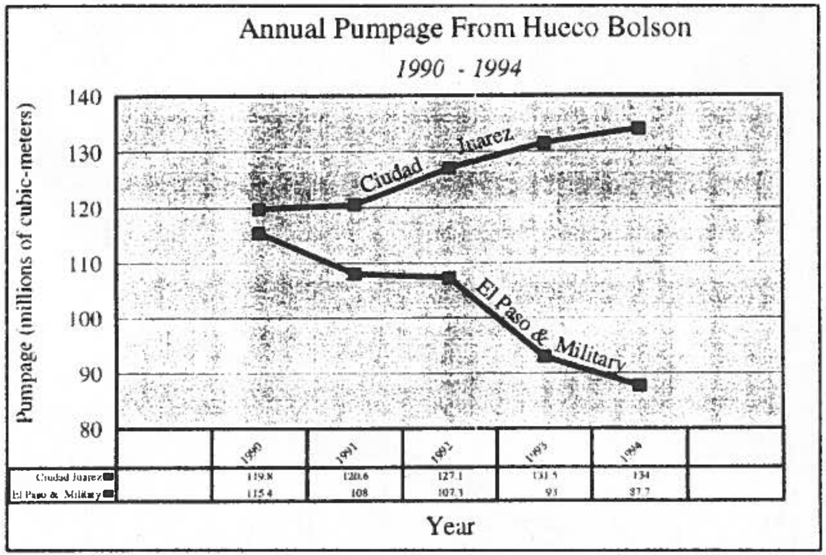


Figure 2 – Ground-Water Pumpage from the Hueco Bolson; 1990-1994 (source of data City of El Paso Public Services Board; Junta Municipal de Agua y Saneamiento).

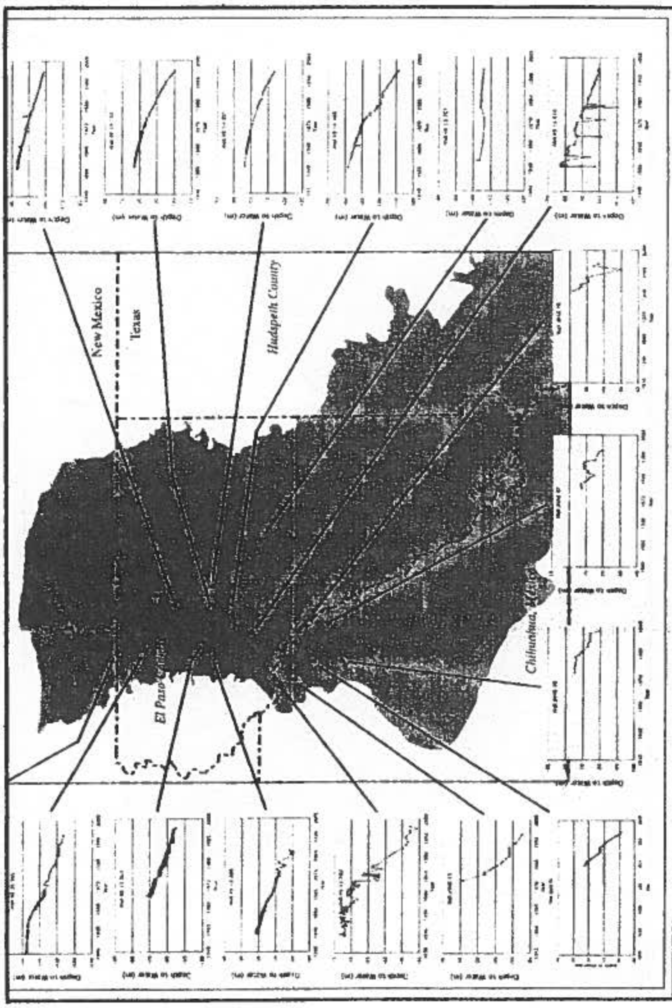


Figure 3. time series hydrographs for the Hueco aquifer (source of data, Junta Municipal de aguas y Saneamiento; Texas Water Development Board; Geological Survey).

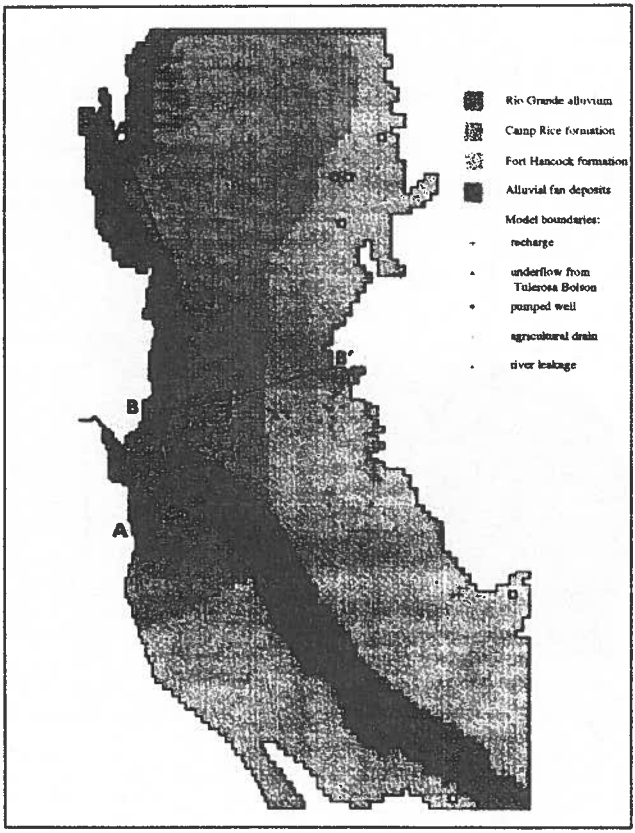


Figure 4 – U.S. Model Zonation and Boundary Conditions in Ground-Water Flow Model of Hueco Bolson

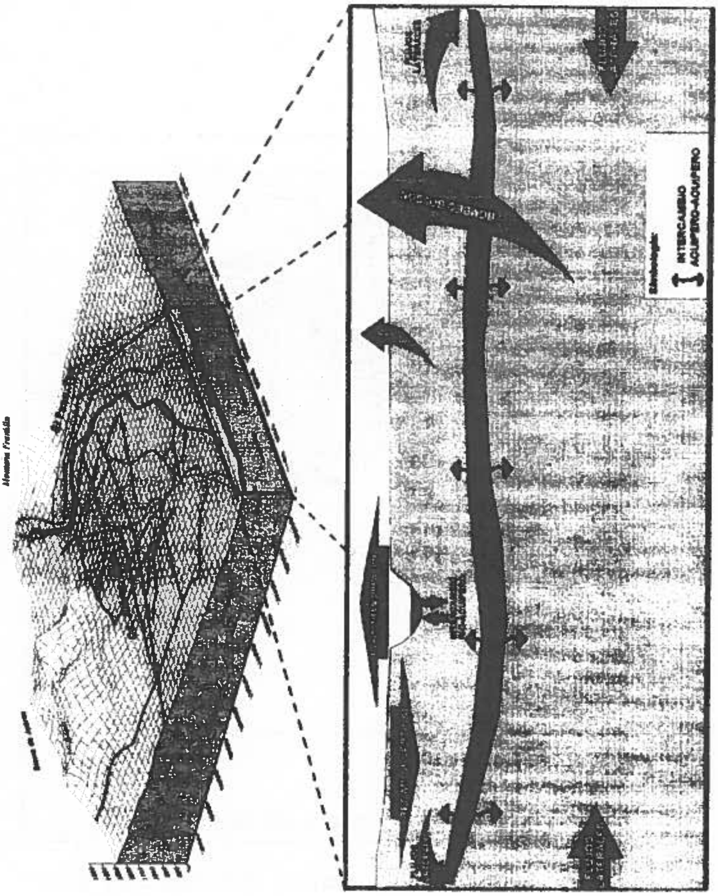


Figure 5 - Mexican Model of Hueco Bolson

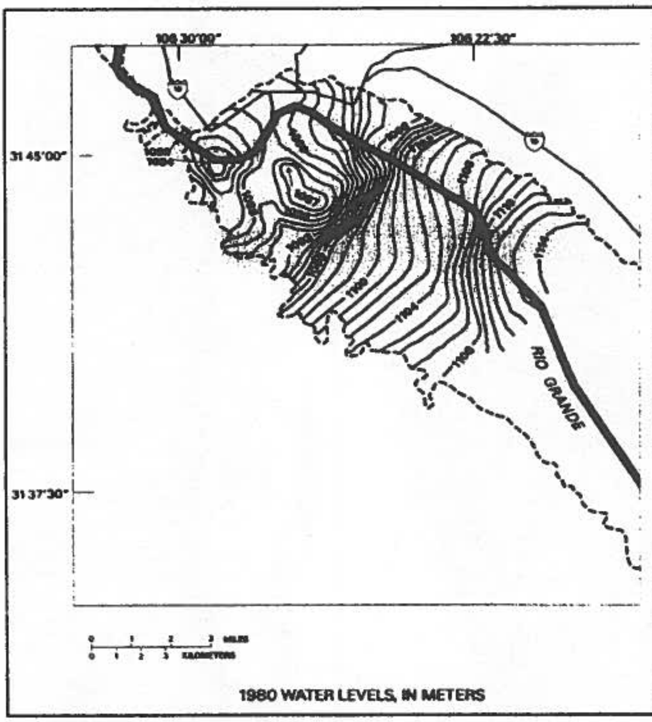


Figure 6 - U.S. Model Showing The Common Zone

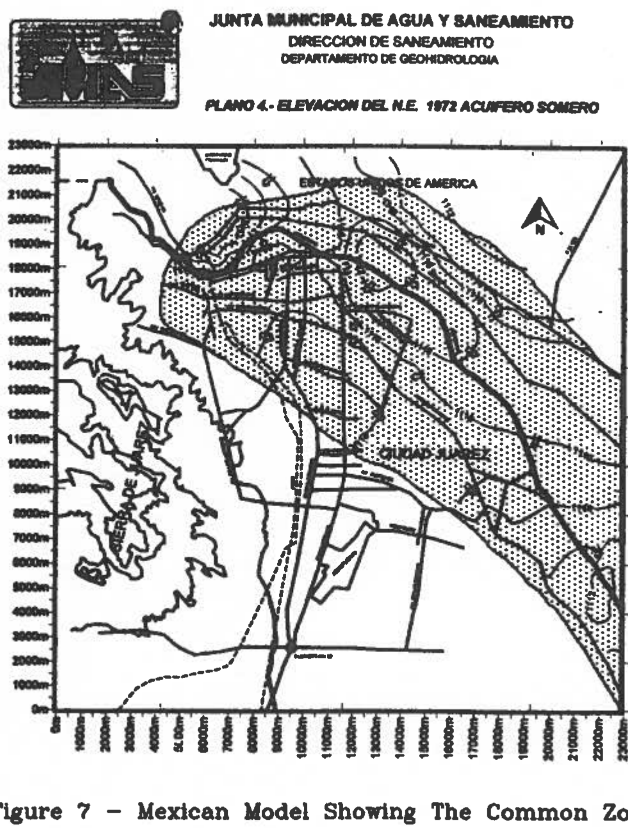


Figure 7 – Mexican Model Showing The Common Zone

DRAINAGE IN THE ARAL SEA BASIN: PAST AND FUTURE

Victor Dukhovny[1] Vadim Sokolov[2]
Ulugbek Ruziev[3]

ABSTRACT

The geography and climate conditions definite the importance of irrigation development for life and economic activity within the Aral Sea Basin. Irrigation in Central Asia was the basis for development, employment and welfare of populations in all its history. In the conditions of arid climate the large-scale utilization of land for irrigated agriculture depends on the artificial drainage. This problem deals with two major land quality problems in the Aral Sea Basin. These are the interrelated issues of salinity and waterlogging caused by high groundwater levels. Only about 60% of the irrigated land (1999) are classified as non-saline, according to the Central Asian standards (the main criterion is total amount of toxic salts in the soil). This paper describes current situation and possible solutions for soil salinity problems in the Aral Sea Basin.

INTRODUCTION

The Aral Sea Basin, which geographically coincides with boundaries of the biggest part of Central Asia, is located in the heart of the Euro-Asian continent. The Aral Sea Basin covers the whole territory of Tadjikistan, Uzbekistan, and part of Turkmenistan, three provinces of the Kyrgyz Republic, and the southern part of Kazakhstan (see Fig. 1). This territory covers an area about 1.55 million km^2. The population in the region was about 39.8 million inhabitants in 1998.

The western and the north-western parts of the Aral Sea Basin are covered by the Kara Kum and Kyzyl Kum deserts. The eastern and south-eastern parts are situated in the high mountain area of the Tien Shan and Pamir mountain ranges. The remaining part of the basin is the various types of alluvial and inter-mountain valleys, dry and semi-dry steppe. The landlocked position of Central Asia, within the Euro-Asian continent, determines its sharply continental climate, with low and

---

[1] Prof. In Land Reclamation and Water Management, Director, Scientific-Information Center, Interstate Commission for Water Coordination (SIC ICWC), 11 Karasu-4, Tashkent, 700187, Uzbekistan.
[2] Ph.D. in Hydrology, Deputy Director, SIC ICWC.
[3] Legal Specialist, Agency of the GEF Project, 5, A. Qodiry Street, Tashkent, 700128, Uzbekistan.

irregular precipitation. Large daily and seasonal temperature variations are characteristic of the region, with high solar radiation and relatively low humidity.

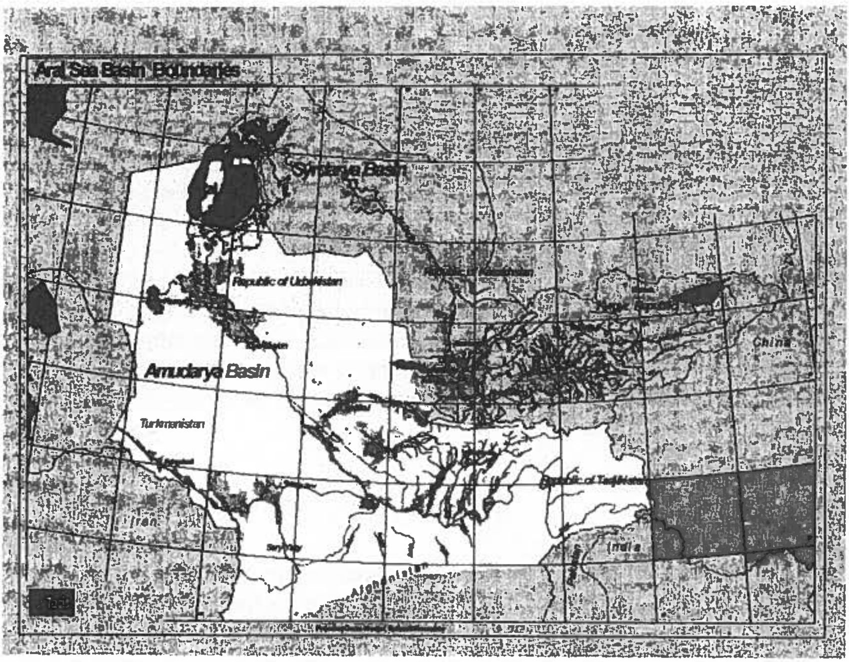


Fig. 1. Map of the Aral Sea Basin.

The rivers originate as a result of snow melt and rainfall in high mountains that reach up to 7,500 m to the west and south. The Amu Darya river originates in Afghanistan and Tadjikistan, and the Syr Darya river in the Kyrgyz Republic. Both rivers fall rapidly to the desert plains of downstream riparians: Uzbekistan and Turkmenistan on the Amu Darya; Uzbekistan , Kazakhstan and – to a small extent – Tadjikistan on the Syr Darya.

The geography and climate conditions define the importance of irrigation development for life and economic activity within the Aral Sea Basin. Irrigation in Central Asia was the basis for development, employment and welfare of populations in all its history. The age of irrigation is the same as in ancient civilization centers of the world - Egypt, Mesopotamia, India, China, Mexico. The Horezm in the beginning of the first millennium BC was known as one of the significant center of agriculture in the world, where the cultivated area was more than two million ha. By archeological investigations it has been identified as an Ancient Ariana. The population of the region has excellent traditions in the usage of water for irrigated agriculture.

The information of Russian geographers at the end of last century showed that irrigated area in old Turkestan within the Aral Sea Basin was estimated at 2.5 to 2.8 million ha. The large-scale expansion of irrigation in the region was promoted by the former Soviet Federal Government to develop the region as an agrarian appendage of the former Soviet Union. So-called "complex" development of irrigated agriculture started at the end of 1950-s. The growth of irrigated area over the region was tremendous: irrigated area was 4.5 million ha in 1960, 5.2 million ha - in 1970, 6.9 million ha - in 1980, and 7.5 million ha - in 1990.

Out of the total area of 155.4 million ha in the Aral Sea Basin, over 59.16 million ha (or 38.1%) are cultivable land. In 1998 the total cultivated area within the Aral Sea Basin was about 10 million ha. This amount includes 9 million ha under the annual crops and about 1 million ha under permanent crops. The suitable area for irrigation is estimated at 32.6 million ha, but economic feasible irrigation potential was estimated at about 10.2 million ha, of which actual irrigated area is 7,948,100 ha (or only 5.1% of total territory of the Aral Sea Basin).

The large-scale irrigation development has changed the hydrological cycle in the region and this has created serious environmental problems in the Aral Sea Basin. The most dramatic was the shrinking of the Aral Sea and disruption of its ecosystems. Other changes included: (1) soil degradation as a result of waterlogging and salinization of irrigated land in the catchment areas of the Aral Sea Basin, (2) crop diseases and insect infestation, due particularly to the cotton mono-crop agricultural development, and (3) adverse health effects from the poor water quality in the main and tributary rivers.

The unexpected collapse of the Soviet Union in 1991 added socio-economic problems to the Aral Sea Basin. With the collapse, prior sources of funds were cut off, and investments in water management, water supply, drainage, land reclamation, and the deltas were abruptly stopped.

DRAINAGE AS A KEY ELEMENT OF IRRIGATION DEVELOPMENT

The peculiarity of the arid zone is that the wide utilization of land for irrigated agriculture depends on the artificial drainage. Two major and interrelated land quality problems have resulted in the Aral Sea Basin. These are issues of salinity and high groundwater - induced waterlogging.

In the past, drainage was constructed only to protect land against waterlogging and to stop malaria. Drainage as a land reclamation measure was carried out on a small scale because of the lack of proper technical facilities. To drain the land, a network of open canals was usually dug. As a result, drainage was seldom sustainable for a long period. Large-scale drainage development in Central Asia began in mid of 1960-s. Drainage has become an inseparable part of the "complex" land reclamation measures aimed at sustaining the agricultural production. It was also raised to a high technical level.

The basic data on existing drainage in the Aral Sea Basin is presented in Tables 1 and 2. Actually 56.8% of the irrigated area (4,513,253 ha) has drainage. Out of the total drainage, about 59.6% is surface (open) drainage, 26.2% - sub-surface, and 14.2% is vertical drainage (tube-wells), mainly on the foothill slopes or in the area with clay soils. The vertical drainage is more commonly in Uzbekistan, Kazakhstan and Turkmenistan, but during the last seven years (1992-1998) sustainability of this type of drainage was reduced, because power cost increased, absence of spare parts and general shortage of funds for maintenance. In the new reclaimed area (Golodnaya steppe and Djizak steppe in the Syr Darya river basin, Surkhan-Sherabad steppe and Karshi steppe in the Amu Darya river basin (all within Uzbekistan), and also in the zone of the Garakum canal in Turkmenistan), drainage is mainly sub-surface. Advanced sub-surface and vertical drainage provided before the optimal reclamation regime of irrigation with minimum of water consumption rate at 7.5 to 9.0 thous. m^3/ha in comparison with 15 to 16 thous. m^3/ha with old types of drainage.

Table 1. Salinization and Drainage in the Aral Sea Basin (1998)

Country	Area under irrigation	Area salinized		Drained area		
	ha	ha	%	ha	%	% of total
1	2	3	4	5	100*5/2	
Kazakhstan*	742100	210000	28.3	332200	44.8	7.4
Kyrgyz Republic*	462100	21200	4.6	21200	4.6	0.5
Tadjikistan	719200	115000	16.0	328600	45.7	7.3
Turkmenistan	1744100	652290	37.4	1022253	58.6	22.7
Uzbekistan	4280600	2140550	50.0	2809000	65.6	62.1
Aral Sea Basin	7948100	3139040	39.5	4513253	56.8	100

* Only provinces in the Aral Sea basin are included

At present, the main task is to rehabilitate the drainage system to a good working conditions. Collector-drainage network is maintained by the Ministry of Agriculture and Water Management. The farms are in charge for on-farm collectors, vertical drainage and some closed horizontal drainage within farm boundaries. The Ministry make repairs on inter-farm collectors, using funds from the State budget, so their technical conditions is usually satisfactory. The drainage network within farm boundaries is usually not repaired. Due to the current maintenance difficulties, a large number of tube wells and part of the sub-surface horizontal drainage are operated contrary to their design. As more private farms appear in the future, further degradation of drainage systems can be expected unless preventive measures are taken.

Table 2. Types of Drainage in the Aral Sea Basin (1998)

Country	Total Drained Area	With Surface Drains		With Sub-surface Drains		Vertical Drainage (Tube wells)	
	ha	ha	%	ha	%	ha	%
1	2						
Kazakhstan*	332200	163700	49.3	15600	4.7	152900	46.0
Kyrgyz Republic*	21200	11900	56.1	9300	43.9	0	0
Tadjikistan	328600	191000	58.1	137600	41.9	0	0
Turkmenistan	1022253	614572	60.1	322962	31.6	84719	8.3
Uzbekistan	2809000	1709700	60.8	698300	24.9	401000	14.3
Aral Sea Basin	4513253	2690872	59.6	1183762	26.2	638619	14.2

* Only provinces in the Aral Sea basin are included

As it is clear from Table 1, the soil salinity issue is still one of the principal problems in the Aral Sea Basin. Only about 60% of the irrigated area (1998) are classified as non-saline, according to the Central Asian standards (the main criterion is the total amount of toxic salts in the soil). In the upper reaches of the Amu Darya and Syr Darya river basins less than 10% of the area has moderate or heavy salinity, while downstream about 95% of the area is heavy saline. The greatest soil salinity problem is in Uzbekistan, where about 25% of irrigated area are moderate or heavy saline. Salinity is, of course closely tied to natural drainage conditions. Moreover, since 1990, a growing water shortage, lower water quality, and the decay of enterprises responsible for the drainage systems maintenance (lack of repair and maintenance, lack of investments in drainage) has resulted in an increased secondary soil salinization. Losses of crop production due to soil salinization are the problem, since they can reach 30% of yield for cotton, but salinized areas are still cultivated to provide population employment.

RETURN WATER GENERATION AND SALT PROBLEMS

The drainage network is a basis for formation of return flow from irrigation, which together with wastewater from industry is a principal pollutant of the water eco-systems in the Aral Sea Basin. Variations of drainage and wastewater formation in the region during the last 25 years are shown on the graphs in Figures 2 and 3. Return water constitutes about 32.2 km^3/year, or 25% of natural river flow in the region. Wastewater constitutes only 7.8% of this amount. Remaining part is drainage water, collected from irrigated areas, which constitutes 30.7 km^3/year, or over 40% of water withdrawal for irrigation. About 4.7 km^3 or 14.2% of return water is re-used, mainly for irrigation. About 17.5 km^3 or 52.7% is a load to the rivers, and 11.0 km^3 or 33.1% are discharged into natural depressions.

Fig. 2. Drainage and Wastewater Variations in the Syr Darya River Basin

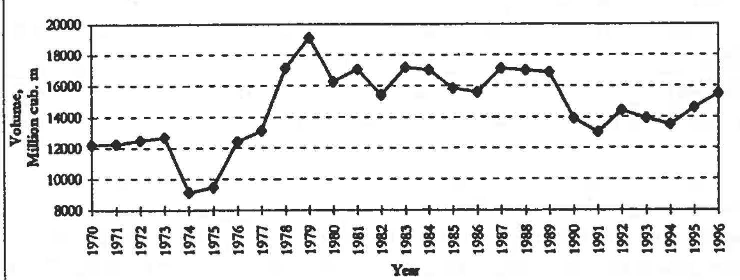
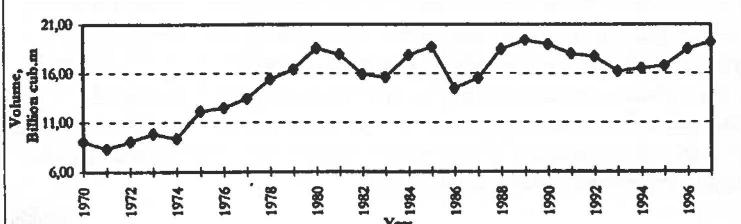


Fig. 3. Drainage and Wastewater Variations in the Amu Darya River Basin



The collector-drainage water has anthropogenic origin and consists of two components. The surface component of return flow is formed by the outfall from irrigated areas, losses from irrigation network, and also from water pumping by vertical drainage systems. Sub-surface components of these waters is formed as a result of infiltration from the irrigated fields and from the irrigation network where infiltrated water feeds the groundwater and then fully or partly discharges to the collector-drainage network.

The investigation of collector-drainage flow formation showed that there is a very close correlation between water withdrawal to irrigation and return of drainage flow by taking into account the lag in time of drainage water formation.

The return flow from irrigation (m^3/ha) is calculated on the basis of:

$$D+C = Oir\{\frac{B}{Ks} + 0.9[\frac{1-Ks}{Ks} + (1-Kir)]\} + (I-O)gw + A*Oc - (Et+U)gw - Wdis, \quad (1)$$

where :

D+C - runoff of drainage-collector waters;

Oir - irrigation water application rate;

B - leaching part of water consumption; water required to support the necessary degree of soil desalinization;

Ks - efficiency of irrigation systems;

0.9 - this coefficient shows the perfect irrigation scheme in use (losses = 10%);

Kir - efficiency of irrigation technique;

(I-O)gw - influx or outflow of groundwater in the irrigated area considered;

A*Oc - portion of infiltration of rainfall (Oc) below the zone of aeration;

(Et + U)gw - part of total consumption satisfied by groundwater (depends on the crop type);

Wdis - runoff dissipation.

Operational (monthly) forecast of collector-drainage runoff is calculated as:

$$(D + C)_t = A1*(D + C)_t -1 + A2*(Oir_{t-1} + Oir_{t-m-1}), \quad (2)$$

where:

(D + C) - runoff of collector-drainage waters;

Oir - irrigation water application rate;

t - index of a month (1,...,12);

m - the value of time lag shift between water diversion for irrigation and collector-drainage formation (in months);

A1, A2 - regression coefficients.

LEGAL ISSUES

Unfortunately, during the former Soviet Union command system the main principle was that a cubic meter of river water used for irrigation and other users would bring more value than the same cubic meter, delivered to the ecological needs. This is causing the degradation of irrigated lands, lower crop yields and additional human health risks. After collapse of the USSR, an integrated regional co-operation has been frustrating, and raises organizational, financial and technical problems. Generally, it has a significant impact on environmental situation and health problems as a whole.

Historically, from the first "Water Law of Turkestan" of 1910, water scarcity and water quality are increasingly seen as a cause of domestic and international conflicts, and therefore is a risk to national stability and security. Water scarcity could contribute to a weak national administration as water scarcity and quality becomes a major threat in developing countries trying to achieve their social development objectives.

First of all, we need to pay attention to the origin of the problems: transformation period to a market economy; raised market economic, social, environmental and health stress; rapidly growing population; insufficient funds and lack of sources of finance; weakness of institutional and legal framework; absence of staff training and brain drain of scientific and engineering staff. These factors lead to many problems in all sectors, including agriculture and water management.

It should be mentioned that at the present time, for most of the regional problems, institutional and international legislation is still lacking especially on transboundary water resources. Water relations needed a legal basis, because rivers in the region became transboundary. This required a new approach to inter-state negotiations in the sphere of water allocation and water use. The solution is to develop the relevant inter-state agreements and procedures in accordance with the international law and taking into account local historical traditions and experience.

The Central Asian states responded quickly to the need for a new legal basis for water allocation and management. Water ministries of these countries jointly declared on September 12, 1991, that joint water resources management would be based on equity and mutual benefits. In order to overcome inherent inter-regional water issues and minimize ethnic tensions, the five Central Asian countries established an inter-state agreement on February 18, 1992.

Each state has the right to manage on its territory by its own national resources and by part of the transboundary water as far as a quota agreed upon with other countries. The Aral Sea and its deltas had been defined as an independent water consumer and have its own quota for water. Transboundary water is the object of common ownership of the states and their development, protection and usage should be carried out on a basis of inter-state agreements by the inter-regional bodies according to the national requests and regional interests.

According to the Agreement on Water Resources Management in the Aral Sea Basin, water allocation should be based on existing uses of water resources. The two river basin agencies should continue to perform basin management under the control of the Interstate Commission for Water Coordination (ICWC) and Basin Water Management Organizations (BWO) of the two main transboundary rivers, Amu Darya and Syr Darya. This management includes transboundary water allocation, monitoring of water use and water quality, data collection and information exchange, analysis, management and forecasting.

Despite the fact that these institutions are working satisfactory, and they have a strong regional framework and mutual understanding on water management issues between themselves and water management bodies in each republic as the members of one "water team", they lack sufficient decision making and regulatory powers at the top level of political power. International agreements on transboundary water are urgently needed.

A strong commitment to address water quality and environmental problems exists and was confirmed by the five Central Asia Head of States in the January 11, 1994, "Plan of Action for Improving the Environmental Situation in the Aral Sea Basin" which includes among other projects, the Water Quality Assessment and Management sub-project that addressed these needs. Also, these issues were included in the scope of work for the Global Environmental Fund's Project "Water Resources and Environmental Management in the Aral Sea Basin" started in 1998.

Creation of a legal framework in the water management sector, combined with modern irrigation and drainage practice, socio-economic and ecological requirements, and suitable low-cost technology would provide an opportunity to coordinate a transforming period in regional joint water management.

Environment and water quality are the most sensitive areas of drainage impact. Therefore, such factors are concerned with solving problems related to drainage and environmental conditions in the Aral Sea Basin. This includes the need for development of a comprehensive scheme for collection and removal of drainage and wastewater in the basin: implementation of advanced and low-cost drainage technology; and support of pilot drainage and irrigation projects. Such actions will require the advanced engineering, institutional and financial measures as well as development of legal, juridical and regulative base for water, drainage, irrigation and environmental management.

Alongside engineering methods to improve water quality drainage including on-farm and inter-farm and national level practices, for sufficient drainage policy on the regional level and improvement of transboundary water quality as a whole, we need suitable legal basis – an inter-state agreement on water quality, including obligations and requirements of the parties on this matter, and general "rules".

Sufficient legal framework on the inter-state level requires new approaches in management, not only on the subject of water management and ecology, but on all sectors of economy and social being. Institutional (especially regional and NGO) and financial frameworks are absolutely essential. This is one of the main subjects of the Regional Water Resources Strategy being jointly prepared by the partners.

The Regional Water Resources Strategy must prepare a number of principal measures (institutional, political and technical) for sustainable development. The regional cooperation should be based on basic principles of international cooperation and international water law: rights of each basin country for equal and reasonable water use; spending not as much as possible, but as much as required; not causing harm and damage to other riparian parties providing democratic management and involvement to all water users; parity, equal responsibilities and rights; cooperating and regularly exchange data and information. The main methods and instruments by which Governments of the Aral Sea Basin can seek to achieve water and related environmental policy objectives according to the above mentioned principles can be classified as regulation on the economic level (market principles, water pricing, taxes, etc.) and on the legal level (legislation, licensing, inter-state agreements, etc.). Water law can be regarded as a link between water policy and water users.

At the present time the following set of draft agreements are being developed:

- Agreement on Institutional Framework of Transboundary Water Management in the Aral Sea Basin.
- Agreement on Transboundary Water Use.
- Agreement on Transboundary Water Planning.

- Agreement on Information Exchange and Development on the Interstate Database on Water and Land.
- Agreement on Protection of Transboundary Water Resources.
- Amu Darya and Syr Darya River Basin Agreements.

These agreements should support implementation of the regional water strategy and regional cooperation in the transboundary water management. These draft agreements are based on the international water law, with regard to the national strategies and laws, and have the objective to create the clear rules on allocation, pollution, water quality and biodiversity as well as a regional data bank. Drainage plans and developments require less data collection and less analysis than a regional water management strategy, yet they have to be included in the general database, like WARMIS[4]. For this reason there is a draft agreement on information exchange between the five participating republics.

Both the water users and decision-makers should develop a new approach to this problem. These agreements should be concluded on the basis of understanding their urgency and necessity. Otherwise, it will not be possible to use this instrument of regulating legal relationships.

FUTURE OUTLOOK

The necessary prospective land reclamation measures in the Aral Sea Basin should include:

- Eliminating the causes of excessive soil humidity and salinity (avoiding excessive supply water and improving water quality);
- Providing more effective drainage of irrigated land by raising the efficiency of current drainage network and rebuilding them where needed.

The drainage problems of the Aral Sea Basin are approached on the basis of actions needed in three principal components:

- completion of drainage facilities as required by design;
- reconstruction of the existing drainage facilities;
- proper maintenance of the existing drainage facilities.

---

[4] WARMIS – Water Resources Management Information System, which is under development by SIC ICWC with technical assistance from EU TACIS Program

To start these actions it is necessary to:

- develop a more complete understanding of the present characteristics of land use;
- improve the evaluation method assessment criteria of land melioration and fertility, considering the following: condition of irrigation and drainage networks, shortage of water resources and deteriorating quality or irrigation water. Assess lands in Central Asia using the new criteria and methods;
- develop a system to assess the state of drainage. Identify the operational state of existing drainage facilities and the need for rehabilitation measures;
- determine standards for the drainage system design with consideration of on-farm irrigation demands, water quality and the transition to new regulations on water and land use;
- develop design standards for the operation of drainage systems that will allow responsibility for operation and maintenance to be transferred to Water User Associations.

In principle, the proposed actions will minimize water losses in the irrigation network, but will require great capital investment. It will require the following steps:

- implement crop irrigation regimes in accordance with planned crop yields;
- sharply reduce leaching regimes by adoption of intensive methods of crop cultivation (chemical ameliorants and organic fertilizers, deep ploughing, crop rotation);
- secure uniform moistening and soil desalinization and minimize groundwater infiltration through optimization of the size of irrigated plots and land levelling;
- revise crop selection with regard to the environmental, economic and social conditions in the region;
- exclude highly saline lands from cropping;
- raise the efficiency of inter-farm and on-farm canals irrigation networks by installing watertight lining;
- organize the manufacture and large-scale introduction of better farm machinery and improve irrigation technology to achieve a uniform supply of water in furrows and consistent moistening of the root zone;
- organize regular cleaning and maintenance of inter-farm and on-farm collectors and water intakes to prevent further deterioration of primary drains and carry out the appropriate drainage of irrigated lands;
- initiate repair and rehabilitation works of on-farm drains, drainage collectors and tube wells, as well as expansion of the modern drainage technologies.

The next objective is to develop activities and principles for water disposal management. The goal should be to maintain total wastewater quality and quantity on an economically feasible and environmentally sound level, and provide negative balance of salts and other ingredients, irrespective of water availability. Proceeding from this objective, the following tasks should be carried out:

- identify locations, volumes and time of wastewater discharges along the two rivers, as well as qualitative characteristics thereof;
- define measures for addressing pollution of environment by wastewater on the formation sites;
- study and analyze drainage outflow schemes;
- define measures for protecting rivers from pollution by wastewater and collector-drainage effluent at the points of their formation;
- calculate discharge limits for salts and pollutants to the rivers to prevent the maximum allowable concentrations to be exceeded;
- identify the sanitation releases on various sites of the rivers to support minimum epidemiological medical and ecological river discharge.

To meet these tasks it is necessary to undertake the following steps:

- Conduct feasibility study for ecological requirements to the river water quality with consideration of different users' interest.
- Study the existing system of water disposal in the Aral Sea Basin for the following aspects:
- types of wastewater subject to withdrawal (industrial, communal, agricultural);
- water receivers (river, the sea, groundwater horizons, local depressions, etc.);
- types of pollutants (petroleum products, mineral fertilizers, bacteriological pollutants, biogenic substances, etc.);
- degree of wastewater treatment (without treatment, treated by mechanical, physical and chemical, and biological means).
- Inventory the non-point and point wastewater discharge into water sources according to water management districts.
- Prepare schematic mapping of irrigated lands by independent irrigation systems for identification of actual water supply, drainage water discharge, quantitative and qualitative characteristic of water delivered and discharged, assessment of salt and pollutant redistribution processes.
- Assess drainage capacities of irrigated areas in the basin, their efficiency and technical conditions.
- Assess present status of collector-drainage water and prospective to reduce its volume by introducing water saving irrigation technologies, inter-system utilization of drainage water, using it for soil recharge by means of groundwater level regulation (sub-irrigation).
- Study the possibility of circular water supply, secondary and sequential re-use of wastewater; replacing water-cooled systems by air-cooled ones in industry,

introduction of "dry" technologies in various branches of economy (discharging wastewater).

- Study the character of quantitative changes in the composition of collector-drainage water, which is presently disposed to local depressions.
- Assess the efficiency of various options for collection and evacuation of collector-drainage and wastewater to the Aral Sea in both river basins.
- Develop principles for wastewater management, including establishment of limits, regimes and schedules for wastewater disposal into the river.

CONCLUSIONS

Given the large area of the Aral Sea Basin, it's international character, population pressure, scale of irrigation developments, and extensive environmental degradation, the finalization and adoption of the draft agreements are vital. These agreements could then lead to the implementation of Regional Water Resources and Environmental Management Strategy, which has of utmost importance to all the riparian states. The implementation of such strategy would create conditions for ecologically stable socio-economic development of each of the five Basin States and the Basin as a whole. The international community via the World Bank is ready to assist the States of Central Asia in designing and managing such Project to the maximum extent possible.

IMPACTS OF AND SOLUTIONS TO URBANIZATION ON AGRICULTURAL WATER RESOURCES

Guozhang Feng[1]

ABSTRACT

Cross-boundary issues in water resources development and management are very popular throughout the world. One of the most notable cross-boundary issues facing irrigation is water resources allocation between urban and rural areas, and typically industrial and agricultural uses. In many areas in the world, agricultural water resources (typically irrigation) is severely impacted by urbanization, which has been one of the crucial restricting factors to sustainable agriculture of the world, especially that of developing countries. This paper presents the impact of urbanization on agricultural water resources. The general impact in China is briefly described. Some special solutions to the impact are recommended which include raising the design standards of irrigation projects, bestowing priority on farmland irrigation, and stipulating an upper limit to the water available per capita. More attention should be paid to the comprehensive solutions: to set up a water-saving society, to strengthen water pollution prevention and water resources protection, and to speed up capacity building. A strategic framework for sustainable water resources development and management for the new millennium is proposed for central Shaanxi, one of China's typical regions suffering from severe water shortage. Based on the analysis of basic demand for sustainable development and probable water resources available, an amount of 500 cubic meters of water per capita per year on average might be an upper limit to this region. A rough allocation of the water to agricultural, industrial, residential and environmental for the year 2020 is suggested based on the objective of self-sufficient food supply, continuous development of industry, persistent improvement of life quality, and safe environment. These solutions may also be appropriate for most developing countries and other countries with similar issues.

INTRODUCTION

Urbanization is an essential trend of the developing world, which is accompanied by rapid industrialization and population growth in persistently expanding urban areas. One of the most important characteristics of urbanization is rapid increase in water demand for residential and industrial uses in urban areas. The residential

[1] Professor of hydrology and water resources, College of Water Resources and Architectural Engineering, Northwestern Sci-Tech University of Agriculture and Forestry, Xinong (NWAU) Campus, Yangling, Shaanxi 712100, The People's Republic of China.

water use includes domestic and municipal uses. The increase in water demand in urban areas often causes chronic urban water shortages because the deficit between water supply and demand may result in severe conflicts between different water users. Water scarcity has become one of the crucial restrictions to further development of the urbanized and urbanizing areas.

There are two commonly acceptable approaches to meet the increasing water demand in the growing urban areas. The first approach is to exploit new water sources to heighten water supply capacity of urban water supply systems. The second one is to develop highly efficient water-saving techniques to reduce net water consumption in urban water utilization systems. However, this is difficult to accomplish due to natural scarcity, deficient availability and uneven geographical distribution of freshwater, as well as lack of advanced technology, sufficient investment and powerful management. It may be possible to plan and implement projects and programs to solve the conflicts and meet the needs in some regions or countries with relatively abundant water resources. However, it is difficult for most developing countries because of their relatively lower levels in development in water supply projects and water-saving techniques. In addition there may be a lack of sufficient technical and financial supports to further the development of new water sources, especially, those in arid and semiarid areas.

In some developing countries or regions, a commonly adopted approach in making up for the deficit between water supply and demand in urban areas is to share the water which was originally intended for farmland irrigation, domestic and livestock uses in rural areas (so-called agricultural water resources). This has become one of the most notable cross-boundary issues impacting sustainable development of agriculture, the socio-economy and the environment.

A direct consequence of urbanization to agricultural water resources is the severe impact on the security of water quantity for agricultural uses. Urbanization also induces severe impact on the security of water quality of agricultural water resources frequently caused by a large amount of urban wastewater and pollutants returned into water sources directly used for farmland irrigation, as well as air pollution-induced acid rain. Therefore, the impact of urbanization on agricultural water resources consists of two aspects: quantity and quality of the water resources. These factors could cause crucial socio-economic issues and become tremendous restrictions to food security, economic growth, social progress and environmental safety.

To investigate both aspects of the impact of urbanization on agricultural water resources and to seek appropriate approaches to solve the issues are of major concern and should be well dealt with in depth. The purpose of this paper is to present the current status on the impact of urbanization on agricultural water resources in China and offer strategic solutions to reduce the impact. The paper also provides a brief case study on central Shaanxi, one of China's typical regions suffering from severe water shortages, under the consideration of basic water demands for a sustainable agriculture and a safe environment.

IMPACTS OF URBANIZATION ON AGRICULTURAL WATER RESOURCES

Every event has its cause and effect, so has the impact of urbanization on agricultural water resources. To understand the cause and effect of the impact is a basic requirement for seeking rational solutions to the problems.

Driving Forces

Several forces drive the impact of urbanization on agricultural water resources. They are rapid population growth and concentration, high-speed industrialization and increasing number of cities and expanding urban areas.

Rapid population growth and concentration: The development of socio-economy in a given region or country often results in rapid growth and high concentration of population in its urban areas. A high ratio of urban residents to total population is one of the most notable characteristics of developed countries compared to that of most developing countries. In 1990, for instance, the percentage of urban population was 75.2% in the United States and only 26.4% in China (the State Statistical Bureau, 1997). The rapid growth of population in urban areas leads to high concentration of the population. The density of the population in urban areas is much higher than in the countryside.

People living in urban areas require more water for domestic and municipal uses to heighten their living standards. Therefore, rapid population growth in urban areas is a direct determinant to increasing water demand for domestic and municipal uses. For example, as the largest developing country of the world, China has made remarkable achievements in its economic development and modernization and received international acclaim since 1978 with the onset of reform (Elizabeth Economy, 1997). Correspondingly, the population in urban areas increased from 172 million by the end of 1978 to 370 million by the end of 1997 (the State Statistical Bureau, 1998). The population has doubled in the past two decades and the percentage of urban population increased from 17.9% to 29.9% during the period of the two given years. Figure 1 shows the accumulative population growth rate (ratio of annual to 1978's population) in urban areas where the growth rate in 1978 is assumed to be 100% and the ratio of urban to total population in China.

High-speed industrialization: Industrialization and urbanization are twin sisters. Industrialization causes urbanization, and urbanization accelerates industrialization. The reality of the world shows that the more the industrialization, the more the urbanization, and vice versa.

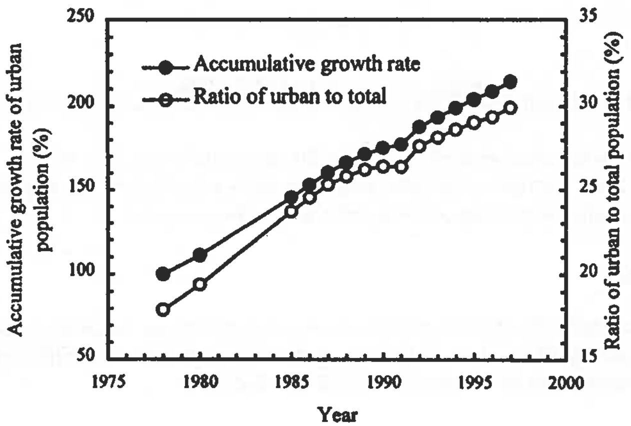


Fig. 1. Population growth in urban areas in China (data source: the State Statistical Bureau, 1998)

Regardless of the level of industrialization of a region or country, the key driving force to water resources is the speed of the industrialization. The higher the speed, the stronger the force. In particular, this could cause crucial industrial water shortages. China is also a typical example of severe water scarcity in industrial uses along with its high-speed economic industrialization. According to the State Statistical Bureau (1998), China's GDP (Gross Domestic Products) of industry increased 19.8 times during the period of 1978 to 1997. The average annual growth rate of industrial products was up to 10.5%, the highest in the world. Figure 2 illustrates the accumulative growth rate of industrial GDP (ratio of annual to 1978's GDP) where the growth rate is assumed to be 100% in 1978.

Increasing number of cities and expanding urban areas: On one hand, new cities continuously appear and grow. On the other hand, old cities are always under reconstruction and expansion. Within the past several decades, the number of cities in China dramatically increased to 668 in 1997, while it was only 191 in 1978 and 79 in 1949 (the State Statistical Bureau, 1998; Water Resources Bureau of the Ministry of Water Resources, 1995).

The most typical new city in China may be Shenzhen (see Figure 4), now called the window of reform and opening of China. It has become a worldwide famous modern metropolis. According to the Shenzhen Statistical Bureau (1998), the population of the city was 3.80 million by the end of 1997, which was 12 times the 0.31 million in 1979 when it was still an unknown small "fishing village". Its industrial products increased 233 times during the same period, which was approximately 12 times the national average.

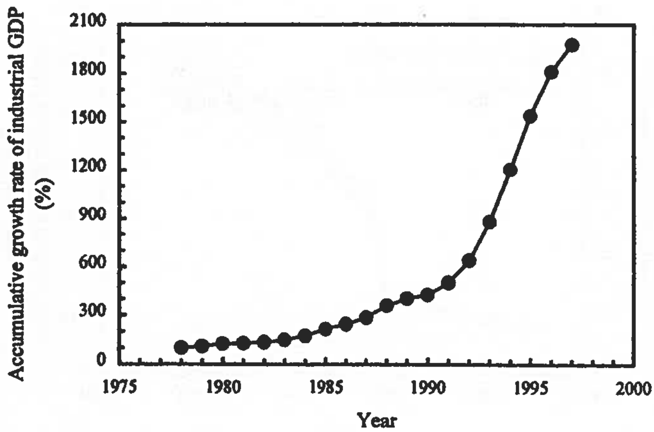


Fig. 2. Accumulative growth rate of industrial GDP (ratio of annual to 1978's GDP) in China (data source: the State Statistical Bureau, 1998)

At the same time, the constructed area of the cities in China was increased to 20,214 km^2 by the end of 1996. It was doubled in last ten years (the State Statistical Bureau, 1988, 1997).

Conflicts Between Urban Water Demand and Supply

Rapidly increasing water demand: In the process of urbanization, water demand for residential uses will inevitably increase with rapid population growth. On one hand, the people living in cities require persistent improvement of their living quality. In relation to water demand, popularization of piped water provides chances for wide uses of house showers and washing machines in cities. They are highly water-consumed compared to traditional living surroundings. On the other hand, with the improvement of living quality, the people living in cities desire more public water-related recreational facilities. It usually leads to rapid construction of municipal infrastructures, such as swimming pools, water amusement parks, water landscapes, green land irrigation and municipal sanitation.

Similarly, at the developing stage of urbanization in a region or country, rapid increase in industrial water demand is also inevitable. According to an urban water resources plan, 270 cities of China were water-short in 1990, which was 57.8% of the total cities (Water Resources Bureau of the Ministry of Water Resources, 1995). Residential and industrial water demand in 1990 was 23.03 Gm^3 (billion cubic meters) while predicted demands are 48.19 Gm^3 by 2000 and 71.37 Gm^3 by 2010, respectively. The number of cities is increasing, including the

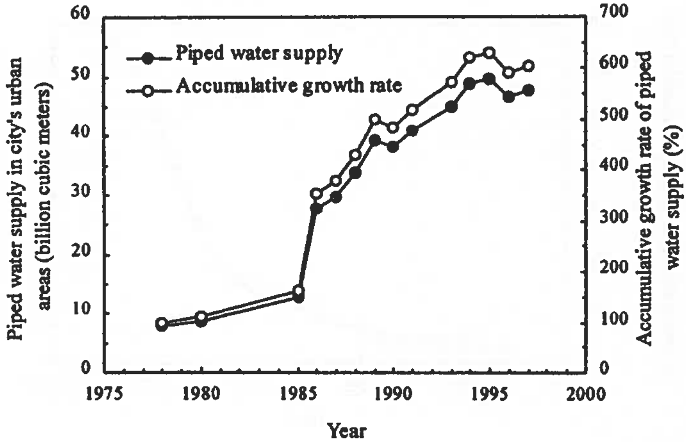


Fig. 3. Increase in piped water supply in recorded city's urban areas in China (data source: the State Statistical Bureau, 1981-1998)

water-short cities. An estimated countrywide water demand for residential and industrial uses in urban areas by 2000 is 152.12 Gm^3 (Institute of Water Resources and Hydropower Planning and Design of the Ministry of Water Resources, 1989).

Figure 3 presents the increase in piped water supply and accumulative growth rate of the water supply (ratio of annual to 1978's water supply) in city's urban areas in China, where the growth rate in 1978 is assumed to be 100%. In the city's urban areas with recorded piped water the pipes supplied 6.1 times water in 1997 and 6.3 times (the highest) in 1995 compared to the water supplied in 1978.

Slowly growing water supply capacity: Increased water demand needs correspondingly heightened water supply capacity. The Chinese government made the decision to promote the building of urban water supply systems. Some projects have been well planned and designed, some have been built and put into operation, and some are under construction. All cities of China have solutions to their water shortages. However, the speed of building urban water supply capacity has not yet kept pace with the increasing water demand due to relatively long construction periods of water projects, inadequate investments allocated to the projects, and some societal, economic, political and legislative reasons.

Deficit between water supply and demand: The unbalance between the water demand and supply will lead to water deficit in urban water resources systems. In the urban water resources systems of the aforementioned 270 water-short cities, the total water deficit of residential and industrial uses are estimated to be up to 12.12 Gm^3 by 2000 and 35.30 Gm^3 by 2010 if no new projects were put into service and only the currently available water supply projects of the year 1990 were used. Moreover, if all the planned new and reconstructed water supply projects for urban areas in the planning period were completed and put into full services, the deficit could not be completely filled and would still be in the range of 6.87 Gm^3 by 2000 and 10.25 Gm^3 by 2010 (Water Resources Bureau of the Ministry of Water Resources, 1995). In fact, the number of water-short cities may currently be counted at over 300 and up to 400. The countrywide urban water deficits in fact are much higher than the above figures.

Impacts on Quantity of Agricultural Water Resources

Although it is difficult for China to meet the increasing water demand for residential and industrial uses in urban areas, a surprising fact is that actual water supplied to urban areas has been steadily increasing. The total water supplied to all China's cities and towns in 1997 was reported to be 115.48 Gm^3, in which 24.68 Gm^3 for residential uses and 90.80 Gm^3 for industrial uses, respectively (the Ministry of Water Resources, 1998). This is very close to the predicted total urban water demand of 113.30 Gm^3 estimated from the total demands in 1980 and 2000 (Institute of Water Resources and Hydropower Planning and Design of the Ministry of Water Resources, 1989), using an average annual increment rate during the period. This implies that the estimated water deficit at the planning level has been filled though there were many reports about regional and seasonal water shortages in urban areas. The reported water scarcity indicates that the predicted water demand might be less than the real demand. In fact, a large part of the increased urban water supply has been the shared agricultural water resources including both surface water and groundwater.

As early as the beginning of the 1990s, the water supplied to urban areas by the projects controlled by the Ministry of Water Resources and its sub-agencies has been as high as 55.5 Gm^3 (Ren and Huang, 1992). Most of the water was supplied by former rural water supply projects.

Impact on surface water: In addition to the original and newly built urban water supply projects, the contributors to the urban water supply are projects originally built for rural water supply. In order to solve the current water scarcity in urban areas, a large number of surface water supply projects for rural uses are now required to be shared and transferred in part or whole to urban uses. This is partly based on the priority to domestic uses stipulated in the Water Law of the People's Republic of China (the State People's Congress of the PRC, 1988) and partly due to high output of industries.

Typical examples of sharing or transferring agricultural water resources for urban utilization are numerous. The notable example is Beijing, the capital of China.

Beijing has been facing severe water shortages for a long time and has become one of the most water-short cities in China. Because it is the capital, much more attention has been focused on its water supply security. A large-scale construction of water supply projects started in the early 1950s made considerable contribution to the city's safe water supply. The well-known two reservoirs, Miyun on the Yongding River and Guanting on the Bai River, the tributary of the Yongding River, once were major surface water sources of Beijing for both urban and rural uses, as well as for the uses of its neighbor city, Tianjin. The locations of the two cities are shown in Figure 4.

By 1980, annual total water used in Beijing was 4.92 Gm^3, in which 1.75 Gm^3 (35.5% of the total) for urban residential and industrial uses and other 3.17 Gm^3 (64.5%) for rural uses, mainly farmland irrigation. An estimated total water demand for 2000 is 52.7 Gm^3 and the portions for urban and rural uses are 23.6 Gm^3 (44.8%) and 29.1 Gm^3 (55.2%), respectively (Institute of Water Resources and Hydropower Planning and Design of the Ministry of Water Resources, 1989). Although the city operated under water shortages both the urban and rural had been steadily developing without acute conflicts in water challenges at that time.

Unfortunately, since 1980, with unprecedented development of the city and relevant regions, increased withdrawals on the upper reaches of the Yongding River and persistent droughts together induced significant reduction of the two reservoirs' inflows. This severely threatened the security of the city's water supply. Facing this crucial situation, the State Council of China made a decision to ensure the security of the water supply in the capital area through reducing its rural water supply and stopping the water supply to Tianjin (Institute of Water Resources and Hydropower Planning and Design of the Ministry of Water Resources, 1989). Since then, the conflicts in water allocations for urban and rural uses in Beijing have been acute. The problem could not be solved until the planned South-North Water Diversion Project (to be the largest interbasin water diversion project in China) is completed, and this is in spite of over-depletion of local groundwater for current uses.

Another typical case is the urban water supply systems in Liaoning province in northeastern China. A planned amount of surface water for industrial and residential use was 0.35 Gm^3 supplied by eight reservoirs on the Liao River, the Hun River, and the Taizi River in the province. The actual amount of the water supplied into the urban water supply systems was increased to 1.23 Gm^3 by the early 1980s. The increased water in urban areas was mainly obtained from rural uses (Institute of Water Resources and Hydropower Planning and Design of the Ministry of Water Resources, 1989). The situation has been getting worse. For instance, the annual average water for industrial and residential uses supplied by Dahuofang Reservoir on the Hun River, one of the eight reservoirs, was 0.26 Gm^3 in 1981 and increased to 0.45 Gm^3 by 1995. Meanwhile, the water for farmland irrigation was reduced from 0.88 Gm^3 to 0.48 Gm^3 (the Management Bureau of

Dahuofang Reservoir, 1986 and 1996).

Fig. 4. Map of China with locations of the cities, provinces and major rivers mentioned in the context

Impact on groundwater: Aforementioned are typical cities depending on use of agricultural water resources. They directly impact the surface water quantity of agricultural water resources. In addition, an impact of urbanization on agricultural water resources is over-abstraction of groundwater in both urban and near suburb areas for urban uses. It is seemingly an indirect impact but the consequence could be dangerous.

Similar to most of the world, in China, surface water is significantly affected by changing climate and human activities and has high variability in space and time. Moreover, groundwater has traditionally been major urban water resource and plays an important role in water supply in most cities. In some cities groundwater is the only water source. For example, Xi'an, the capital city of Shaanxi province, surface water was never diverted into the city to improve its water supply in spite of the severe geo-environmental hazards induced partly by over-pumping of groundwater until the severe water crisis during the early 1990s (Feng et al., 1999).

The over-withdrawal of groundwater caused chronic declines in groundwater tables, caused many large and deep cones of groundwater depression, and led to hazardous land subsidence and fissures, as well as saltwater intrusion. It was reported that in 1990 there were 56 regional huge cones of groundwater depressions in China. Most of the cones were centered near large water-short cites. Total area of these cones on the ground was up to 87,000 km^2 and was continually getting larger and deeper. In some cities groundwater tables had declined over a hundred meters with a continuing annual decline of 2 m to 4 m (Water Resources Bureau of the Ministry of Water Resources, 1995; the Ministry of Water Resources, 1998). Though they occurred in urban areas and/or water source zones of the cities, they seriously affected the quantity of agricultural water resources indirectly.

The heavy decline in groundwater tables implies that the aquifer is getting unwatered from cones' centers to the outer margins with steep hydraulic slopes. This can lead the groundwater to flow from rural areas outside the cones with higher water tables towards the cone center under the urban cities. As a result, the groundwater in the rural areas flows into urban areas, accompanied by a decline in the water tables in rural areas, which makes pumping more difficult and sometimes impossible for rural uses. Meanwhile, it may cause changes in soil water status on farmlands and further affects land productivity.

Impacts on Quality of Agricultural Water Resources

The impact of urbanization on quality of agricultural water resources mainly covers the following aspects.

Urbanization-induced water pollution and its impact: Urbanization contributes to consumption of a large amount of natural resources but also products a large amount of wastes. A large quantity of residential and industrial sewage is frequently directly discharged into surface water bodies without proper treatment. Most of the wastewater comes from urban areas and becomes main pollution sources in developing countries (Morcoux, 1994). It pollutes not only the urban environment but also the entire environment, as well as agricultural water resources.

In China, though the urban sewage effluents have been properly controlled and the amount of the sewage discharged into water bodies in some well-controlled typical regions was reported to be gradually reduced or properly treated, the total amount of the wastewater within the country is still large and enough to severely pollute the water involved. In some regions, water quality is getting worse. The water in rivers, lakes and reservoirs has been universally polluted, except for some remote inland rivers and individual branches of water resources systems. In 1997, the total amount of discharged wastewater was 41.6 billion tons, of which 22.7 billion tons was industrial liquid waste and 18.9 billion tons was residential sewage. With industrial wastewater, the county-level and above industries produced 18.8 billion tons and the Township and Villages Industrial Enterprises produced the other 3.9 billion tons. Because the large amount of the wastewater was discharged into water bodies, in a total length of 65,405 km of monitored river sections, the length of water quality was in Grades 1 and 2 of the national Quality Standards for Surface Water Resources (SL 63-94) (the Ministry of Water Resources of the PRC, 1994) was only 32.8% of the total length, 23.6% in Grade 3, 27.7% in Grades 4 and 5, and 15.6% above Grade 5. Particularly, in 138 monitored river sections flowing through urban areas, water was polluted above Grade 5 in 53 sections, Grades 4 and 5 in another 53 sections, Grades 2 and 3 in the other 32 sections, and no Grade 1 existed. Meanwhile, up to 50% of groundwater in urban areas was also polluted (the Ministry of Water Resources, 1998; the State Environmental Protection Administration, 1997 and 1998).

Economic losses of urbanization-induced water pollution include those resulting from the impact of water pollution on farm yields, livestock and fisheries, as well as human health. According to Xia (1998) total economic loss resulting from the impact of water pollution within the country was 21.86 billion RMB yuan (2.63 billion US dollars) excluding industrial loss. This loss includes 0.70 billion RMB yuan of wastewater irrigation caused farm yields reduction, 1.16 billion RMB yuan of water pollution damaged livestock and fisheries, and 20.00 billion RMB yuan of polluted drinking water and food caused human diseases (including urban residents' health loss).

<u>Urbanization-induced acid rain pollution and its impact:</u> Urbanization-induced acid rain pollution has an important and widespread impact on agricultural water resources as well as eco-environment. In China, the area receiving acid rain is now about one third of its territory. It is mainly distributed to the south of the Yangtze River and to the east of the Qinghai-Tibet Plateau. According to the data from 84 cities in the State-Controlled-Network, in 1997, annual average pH value of acid rain in 44 cities, i.e., 52.3% of the total monitored cities was less than 5.6 and varied among 3.74 and 7.79 in the entire acid rain covered region. In some cities the pH value was less than 4.5. The occurrence frequency of the acid rain was equal to or greater than 60% in 24 cities and greater than 90% in 5 cities in the State-Controlled-Network (the State Environmental Protection Administration, 1997 and 1998; Wang, 1999).

Most of the acid rain in China was caused by air pollution from industrial and residential waste gasses in urban areas. Inversely, acid rain heavily polluted the environment. In particular, the acid rain severely damaged crops and polluted the soils on farmlands as well as local water bodies in the acid rain covered region. According to a research carried out by an expert group organized by the State Environmental Protection Administration in 1994, annual total economic loss resulting from acid rain pollution in 1992 was approximately 14 billion RMB yuan (1.69 billion US dollars). The estimated loss was confirmed by the State Environmental Protection Administration and others (Xia, 1998). Most of the loss was due to acid rain-induced decline in agricultural products including crop yields, livestock and fisheries, as well as human health-related losses.

Urbanization-induced saltwater intrusion and its impact: This kind of urbanization impact occurred in coastal cities with over-withdrawals of groundwater. According to the Ministry of Water Resources (1998) the area which was intruded by saltwater was up to 1,433 km^2 along the coastal cities in only three northern provinces (Liaoning, Hebei and Shandong provinces, see Figure 4). It affected the security of drinking water of 90 million people and 24 million animals and resulted in the loss of 1.26 million tons of grain.

SOLUTIONS

China's water issues have been of long standing. Its water scarcity, in particular, and water-short-related problems concerning sustainable development have attracted worldwide attention and have been recognized as one of the most severe restricting factors to China's sustainable development in the forthcoming new millennium (the State Council of the PRC, 1994; the Sate Planning Commission and the State Scientific and Technological Commission, the PRC, 1994; Elizabeth Economy, 1994; Brown and Halweil, 1998).

Facing the severe restriction to the nation's sustainable development, China has made considerable efforts in solving water scarcity and achieved universally acknowledged successes (Institute of Water Resources and Hydropower Planning and Design of the Ministry of Water Resources, 1989; Qian, 1991; the Compilation Committee of Almanac of China Water Resources, 1988-1997). It was the successes in China's water issues' solutions that ensured China's high-speed economic development and food security in the past several decades.

In recent years, China conducted a series of researches on water resources and attempted to solve its water scarcity. Many strategies, approaches and measures have been proposed on current and long-term developing levels as part of socio-economic development plans and the agenda 21 (the State Council of the PRC, 1994; the State Planning Commission and the State Scientific and Technological Commission, the PRC, 1994). Water-saving agriculture, especially water-saving irrigation is now being popularized in water-short areas. Countrywide, water-saving cities are being establishment. The research results on China's water and water-related issues are thoughtful in both concept and reality. However, in relation to water scarcity, the current research seems to favor retaining many of the traditional models. For instance, in the current water resources plans, water demands and solutions are still based on the traditional "determine the supply according to the demand". Although the concept of "determining demand according to supply" has been introduced for a period of time it is still on the level of suggestion. This could lead to over reliance on the "inflow" or "passing through flow", and interbasin water diversion instead of making efficient utilization of local water resources under a target upper limit to the water available per capita. Meanwhile, the impact of urbanization on agricultural water resources seems to not be fair for rural water users in the currently available plans.

To reduce the impact of urbanization on agricultural water resources, China needs to (1) raise design standards of irrigation projects, (2) bestow priority on farmland irrigation, (3) stipulate an upper limit to the water available per capita in each given urban area, (4) set up and promote a water-saving society, (5) strengthen water pollution prevention and water resources protection, and (6) speed up capacity building. The first three solutions are directly concerned with agricultural water resources and the others are universal solutions. The three direct solutions are now described as follows.

To Raise Design Standards of Irrigation Projects

In China, farmlands have been irrigated for thousands of years. In the past several thousand years, the farmlands were irrigated without design standards for the concerned water supply projects in spite of advanced designs such as the famous 2255-year-old irrigation project, Dujiangyan in Sichuan province (Zhu, 1991). Since the concept of water supply reliability was introduced, China's irrigation projects were designed and built with given probabilities of water supply reliability. Since the 1950s, China has promulgated a series of regulations for water resources planning and water project design. The regulations include the probability of water supply reliability of water projects including irrigation, which should be guaranteed by design and pertinent techniques. Although the regulations have been revised several times and many techniques have been updated, the probability of meeting a full water supply is reduced instead of increased.

According to the regulations, each irrigation project should be designed and built using a given probability of water supply reliability, which is determined by scarcity or abundance of the water as well as the capacity of water resources development. However, in a recently revised regulation for water basin planning, the probability is reduced to 50% to 70% for dry-land crops, of which the lower limit is for water scarce regions and the upper limit is for water abundant regions or vegetable irrigation in suburbs. For paddy crops, the lower limit is 75% and the upper limit becomes 90% (the Ministry of Water Resources of the PRC, 1997). Some irrigation projects even have the probability less than 50% in design and some in operation. This is much lower than the probability of 95% to 97% for industrial water supply (the Ministry of Water Resources of the PRC, 1997).

The probability is an integrated indicator reflecting the importance of the water users and the capacity of water resources development. As the largest developing country with 22% of world population being fed by only 7% of the world arable land (EIU, 1998), China has to ensure its food security. It needs not only to enlarge the area of irrigated farmlands but also to raise the probability of water supply for farmland irrigation. Irrigation water supply should have the probability close to or equal to that of industrial water supply.

To raise the design standard or probability of water supply reliability of irrigation projects, the most important is to let those who are authorized to revise the regulations legislatively acknowledge the importance of agricultural water supply in the nation's food security, socio-economic development and the relationship between agricultural and industrial water uses. Only by revising the regulations legally can the probability be raised.

To Bestow Priority on Farmland Irrigation

Agriculture is the mainstay of China's rural economy (the State Planning Commission and the State Scientific and Technological Commission, the PRC, 1994) and the fundament of China's economy. It has been widely recognized that China has to produce enough food to meet its needs. To do so, the fundamental position of agriculture in the nation's economy could not be altered. China has to bestow priority on its farmland irrigation. This should not only be stipulated through legislation but also put into practice through the support of legislation, administration, science and technology.

According to China's Water Law (the State People's Congress of the PRC, 1988), in developing and utilizing water resources, water demands of agriculture, industry and navigation should be considered overall. It means that irrigation and industrial water uses have equal priorities. However, once the available water cannot simultaneously satisfy both agricultural and industrial uses, agricultural water supply may be reduced and even stopped. This is mainly due to increasing demands of industrial products and high output of industry compared to that of agriculture. At the initiatory stage of a country's industrialization, this may be unavoidable. But with the rapid development of industry which is capable of supplying sufficient products to meet the basic needs, and food production becomes pressing, the priority of water supply should be fairly balanced and might need to be transferred to irrigation.

To Stipulate an Upper Limit to the Water Available Per Capita

Water resources are limited. Total demand in a given area should not exceed a probable maximum. The maximum consists of local water resources obtained through appropriate water projects regulating the inflow or passing through flow and diverting water from other basins, i.e., interbasin water diversion. This should be specified as a target upper limit to the water available per capita in given areas.

The upper limit should be determined on either natural or administrative space-scales, such as watersheds and provinces. For practical purposes, on watershed scales, the limit should be specified at least on the first and second tributaries of large rivers and major river sections. On administrative scales, the limit should be specified at least on county-level administrative districts. The currently used divisions in the Water Resources Assessment of China (Hydrological Bureau of the Ministry of Water Resources, 1987) and those in the Water Resources Utilization of China (Water Resources Bureau of the Ministry of Water Resources, 1989) may be adopted as the basic districts for the limit stipulation on watershed scales. The current administrative districts should be adopted as the basic districts for the limit stipulation on administrative scales.

CASE STUDY

As a case study on the solutions to the urbanization impact on agricultural water resources, this section presents a brief description to the problems in Central Shaanxi, the core part of Shaanxi province of China.

Background

Central Shaanxi is located in the center of Shaanxi province and comprised of five prefectures. This region is not only the geographical but also political, economic and cultural centers of the province. Figure 5 shows the locations of this region in Shaanxi Province and geographical relationship of the province to the Yellow River.

The total area of Central Shaanxi is 55,384 km^2, which is 26.9% of the provincial territory. The population in this region was 20.48 million in 1995, which was 59.7% of the provincial population. The gross industrial and agricultural products were 74.5% and 67.1% of the provincial totals, respectively (Shaanxi Statistical Bureau, 1996). Also, 51.8% of arable lands and 86.6% of irrigation lands of the province are distributed in this region. However, the total amount of local water resources is only 8.96 Gm^3 (long-term annual average). It is 62 m^3 less than the "absolute scarcity threshold" of 500 m^3 per capita (OIEAU, 1998). In some areas the local water resources available per capita is even below the "extreme scarcity threshold" of 100 m^3 (OIEAU, 1998). With population growth, the water available per capita will gradually decrease. According to an acceptable estimate, the local water available for each resident in the region will decrease to 335 m^3 by 2020 and 248 m^3 by 2050 (Feng, 1999). It is obvious that there is tremendous contrast between the highly concentrated population, industry and agriculture, and the poor water resources in the region.

Water scarcity has become the "bottle neck" of the region's socio-economic development. Particularly, the scarcity in urban areas has resulted in severe economic losses, geo-environmental disasters, and some social problems. Having faced the water-short-induced problems, the provincial government and its water

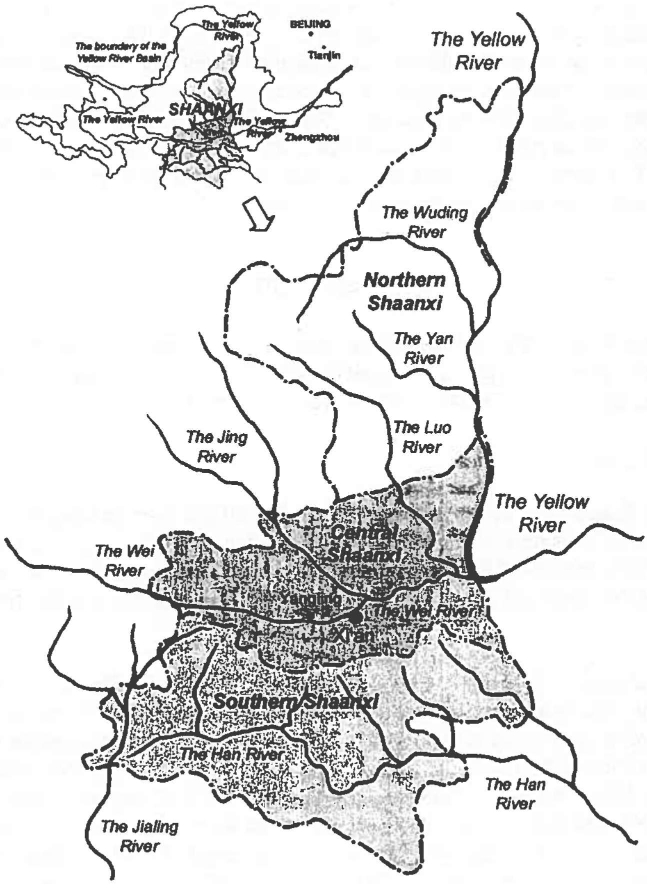


Fig. 5. Map of Shaanxi Province with locations of the main regions and places and distribution of major rivers and their relationship to the Yellow River

authorities as well as local governments have focused more attention on the solutions of the problems. For instance, in order to supply water for basic demand in urban areas, several water supply projects have been and are being built for the provincial capital and other cities. These are major water supply projects sharing water with agriculture for urban uses in this region. This significantly reduces agricultural water supply and severely impacts crop yields in spite of severe over-withdrawal of groundwater in irrigation districts.

The Solutions

To reduce the impact of urbanization on agricultural water resources for central Shaanxi, the basic solutions are similar to those mentioned earlier but noted here with more details. The following are some quantitative proposals to the problems for the region.

Based on the point of view of safe food supply and healthy environment, as well as overall sustainable development of the region, the author recognizes that in central Shaanxi, the target upper limit to per capita available water resources should be 500 m^3. It is, on one hand, basic requirement for improvement of living quality, sufficient supply of food products, continuing development of well-organized industries, and effective protection and amelioration of natural and artificial environments. On the other hand, it is based on the water resources for the region's uses. They consist of available local water resources, probable inflows and the allocated water of the Yellow River by the Ministry of Water Resources. The new projects include the provincial South-North Water Diversion Project (diverting water from the Han River and the Jialing River in the south to the center of Shaanxi province), Guxian Reservoir on the main stream of the Yellow River and local water projects (Zhao and Wang, 1999).

The annual quotas of the water allocated to residential, agricultural, industrial and environmental uses are 51 m^3, 163 m^3, 106 m^3 and 180 m^3 per capita in 2020, respectively, in which the quota for environmental uses includes inexploitable local water resources.

The water allocated for agricultural use is based on a reasonable improvement of efficient utilization rate of irrigation water, reliable crop yields per hectare and sufficient vegetable and fruit production. The crop yield could provide 400 kg of crop grain per capita annually which is about 100 kg higher than the current crop grain per capita.

In addition, the priority of agricultural water uses would be particularly important for the region's sustainable development.

CONCLUSIONS

The impact of urbanization on agricultural water resources has become a notable cross boundary issue facing farmland irrigation and a key factor restricting sustainable agriculture. It is mainly caused by urbanization-induced occupation and pollution to agricultural water resources.

In reality, the solutions to the impact are associated with the overall integrated water resources systems and their management and should be comprehensive. However, the solutions should emphasize specific aspects.

In view of the status of urbanization and its impact on agricultural water resources in China, efficient solutions directly concerning with the impact should be to raise design standards of irrigation projects, to bestow priority on farmland irrigation, and to stipulate an upper limit to the water available per capita. They may be also appropriate for most developing countries and other countries with similar problems.

Agricultural water resources itself is a complicated problem. In addition to the impact of urbanization, there are many other factors affecting the security of agricultural water supply. They should be solved together with the impacts of urbanization.

This paper mainly focuses on the impact of urbanization on agricultural water resources and its solutions in China. These are very notable cross-boundary issues that need to be jointly addressed comprehensively in overall water resources development and management. However, the issues are also worldwide and should be dealt with through international cooperation on sharing of potential solutions.

ACKNOWLEDGEMENTS

The author would like to express his grateful appreciation to Mr. William A. Price and Mr. Wayne O. Deason for their helpful comments on this paper. The author also would like to acknowledge Prof. Larry A. Stephens for his kind help in paper submission and conference information.

RFERENCES

Brown, L. R. and B. Halweil, 1998. China's Water Shortage Could Shake World Food Security. World Watch.

Dong, Fuxiang and Xindong Dong, 1995. Guidelines for Water-Saving Principles and Methods. China Construction Industry Press, Beijing.

EIU, 1998. China Mangolia: Country Profile. The Economist Intelligence Unit, London.

Elizabeth Economy, 1994. Reforms and Resources: The Implications for State Capacity in the PRC (Case Study of China).

Feng, Guozhang, 1999. Seeking After the Ways for Sustainable Water Resources Utilization for the Twenty-first Century in Shaanxi. In Water Resources Bureau of Shaanxi Province and Water Resources Society of Shaanxi Province: Proceedings of the Conference on Water Resources Development and Utilization in Shaanxi Province.

Feng, Guozhang and Peicheng Li, 1999. Optimal Water Regulation and Allocation in the Urban Water Resources Systems of Xi'an.

Hydrological Bureau of the Ministry of Water Resources (of the PRC), 1987. Water Resources Assessment of China. Water Resources and Electric Power Press, Beijing.

Institute of Water Resources and Hydropower Planning and Design of the Ministry of Water Resources (of the PRC), 1989. Water Resources Utilization of China. Water Resources and Electric Power Press, Beijing.

Morcoux, A. 1994. Population and Water Resources. FAO/UNFPA TSS.

OIEAU, 1998. Working Paper: General Consideration on the International Conference on Water and Sustainable Development, 19-21 March 1998, Paris.
Qian, Zhengying, 1991. Water Conservancy in China. Water Resources and Electric Power Press, Beijing.

Ren, Guangzhao and Yongji Huang, 1992. Water Resources Planning for Water Supply to Cities. In the Ministry of Water Resources: Almanac of China Water Resources. Water Resources and Electric Power Press, Beijing.

Shaanxi Statistical Bureau, 1996. Statistical Yearbook of Shaanxi. China Statistical Press, Beijing.

The Compilation Committee of Almanac of China Water Resources, 1988-1997. Almanac of China Water Resources. Water Resources and Electric Power Press, Beijing.

The Management Bureau of Dahuofang Reservoir, 1986. The Data of Dahuofang Reservoir Operation (1972-1985).

The Management Bureau of Dahuofang Reservoir, 1996. The Data of Dahuofang Reservoir Operation (1986-1995).

The Ministry of Water Resources (of the PRC), 1998. Water Resources Annals of China 1997.

The Ministry of Water Resources and Electric Power of the PRC, 1977. Design regulation of water resources and hydropower projects (SDJ 11-77).

The Ministry of Water Resources of the PRC, 1994. Quality Standards for Surface Water Resource (SL 63-94).

The Ministry of Water Resources of the PRC, 1997. Regulation for Compilation of River Basin Planning (SL 201-97).

The State Council of the PRC, 1994. China's Agenda 21 (White Paper on China's Population, Environment, and Development in the 21st Century).

The State Environmental Protection Administration (of the PRC), 1997. State of Environment, China'96.

The State Environmental Protection Administration (of the PRC), 1998. State of Environment, China'97.

The State People's Congress of the PRC, 1988. Water Law of the People's Republic of China.
The State Statistical Bureau (of the PRC), 1981-1998. China Statistical Yearbook. China Statistical Press, Beijing.

The State Planning Commission and the State Science and Technology Commission, the PRC, 1994. Priority Programme for China's Agenda 21.

Wang, Jianhua, Dong Jiang, Chuanyou Chen and Ming Ma, 1999. The State and Strategy of China's Water-Environment. Agro-Environment and Development, No.1, 1999.

Water Resources Bureau of the Ministry of Water Resources (of the PRC), 1995. A Brief Report to the Water Resources Planning for Water Supply to National Major Water-Short Cities.

Xia, Guang, 1998. An Estimate of the Economic Consequences of Environmental Pollution in China.

Zhao, Baiyou and Guangshe Wang, 1999. Framework for Middle-Long Term Development of water Resources for Resolving Water Scarcity of Shaanxi. In Water Resources Bureau of Shaanxi Province and Water Resources Society of Shaanxi Province: Proceedings of the Conference on Water Resources Development and Utilization in Shaanxi Province.

Zhu, Huiqin, 1991. History of Water Conservancy in China. In Zhengying Qian: Water Conservancy in China. Water Resources and Electric Power Press, Beijing.

MODEL AND FIELD STUDIES TO MANAGE SALINE SHALLOW WATER TABLES IN THE LOWER ARKANSAS VALLEY, COLORADO

J. Philip Burkhalter[1], Timothy K. Gates[2], and John W. Labadie[3]

ABSTRACT

Salinity and waterlogging problems plague the lower Arkansas River Valley in Colorado. Evaluating economic and environmental outcomes of best management practices (BMP's) to alleviate these problems is difficult because the system is hydrologically and legally complex; therefore, the problems previously have not been analyzed on a large scale. The goal of this project is to address this growing need and conduct an investigation that will fulfill, on a sub-regional scale, two main purposes: (1) *describe* the high water table and salinity problems within the basin through intensive data collection and analysis, and (2) *prescribe* solutions to the problems through detailed modeling of alternatives. This report presents preliminary results from a model of steady-state flow and salt transport in the shallow unconfined alluvial aquifer. The extensive field data collection effort, along with initial findings and analysis, are also discussed and presented.

PRELIMINARY MODELING

Recent changes within the Lower Arkansas River Valley system, such as the construction of Pueblo reservoir and subsequent modification of basin-wide system operations (winter water storage program), as well as decreased groundwater pumping have intensified long-term problems of high water table elevations and high salinity levels (Watts and Lindner-Lunsford 1992). Problems have increased to the point where some land has been taken out of production and significant crop yield losses are occurring (Valliant 1997). Within the Lower Arkansas River Valley, extending from Pueblo Reservoir to the Colorado/Kansas state line, water tables rose from 0.3 to 1.3 meters between the years 1969 and 1994 (Cain 1997). Additionally, according to the U.S. Environmental Protection Agency, portions of the valley have been classified with the highest salinity hazard rating.

To better define these problems and develop appropriate solutions, a representative study subregion of the valley within Otero County, Colorado, was selected that extends for around 40 kilometers from Manzanola to the Otero-Bent

[1] Research Assistant, Dept. of Civil Engineering, Colorado State Univ., Fort Collins, CO 80523
[2] Assoc. Professor, Dept. of Civil Engineering, Colorado State Univ., Fort Collins, CO 80523
[3] Professor, Dept. of Civil Engineering, Colorado State Univ., Fort Collins, CO 80523

County line (refer to Figure 1). The study subregion covers around 20,000 hectares (50,000 acres).

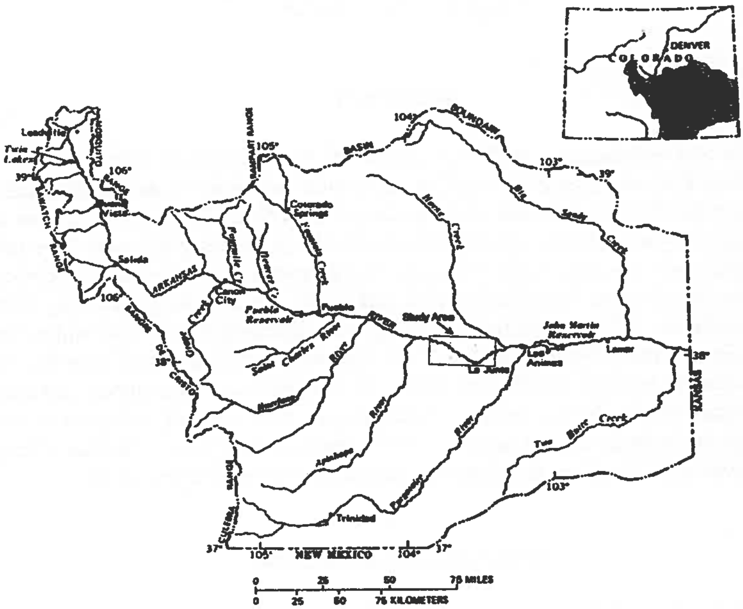


Fig. 1. Study Subregion (shaded) near La Junta, Colorado.

The study subregion is thought to be large enough to capture the variations of soil types, hydrogeology, irrigation and drainage infrastructure, and crops that are characteristic of the Valley upstream of John Martin dam, but small enough so that data collection is feasible.

Software Description

The Department of Defense *Groundwater Modeling System (GMS)* (Brigham Young University 1997) was used to create a flow and salt transport model of the study reach. Designed to serve as a comprehensive groundwater modeling environment, GMS acts as a graphical "GIS-style" interface for several different models. The GMS interface is divided into modules that allow the user to enter and analyze the various data types for the particular models being utilized. The two models within the GMS package employed in this investigation include: MODFLOW (McDonald and Harbough 1988), a modular three-dimensional finite-difference groundwater flow model, and MT3D (Zheng and Wang 1998), a modular three-dimensional contaminant transport model that uses MODFLOW results in its analysis. These two models are described in greater detail below.

MODFLOW: In the initial phase of this study, MODFLOW was applied to a condition of steady flow in the study subregion. There are two main reasons for opting to initially create a steady-state model. First, there were inadequate existing data to create a meaningful long-term transient model at the desired scale for this initial phase. Hence, an intensive data collection component of this study was initiated in the summer of 1999. This data collection effort is described subsequently and will, ultimately, provide the basis upon which a transient flow analysis can be conducted. The second reason is that the steady-state model is adequate to indicate the major effects of changes to the groundwater system. The preliminary modeling described in this paper investigates seven scenarios (including the "baseline conditions" scenario), the results of which are discussed later. The developed steady-state groundwater flow model simulates average conditions within the 33rd week of the year. This week was chosen because of data availability and because it is during a period when the water table is typically elevated.

The following MODFLOW options were used: The *Block Centered Flow 3 (BCF3)* option was used to define the basic hydraulic properties of the system. This option allows for rewetting of cells and provides alternative methods for calculating aquifer transmissivity between blocks. The *Preconditioned Conjugate-Gradient 2* solver was selected for use because it is well suited for cell rewetting calculations. The following sink/source packages were utilized:

- *Recharge* - used to model the areal aquifer recharge, which, in this case, results from downward flow of excess irrigation.

- *Evapotranspiration* - used to model losses due to groundwater upflux in response to evapotranspiration.

- *River* - used to model groundwater flow into and out of a partially penetrating river.

- *General Head* - used to model irrigation canals and ditches and associated seepage.

- *Well* - used to model the extraction of groundwater due to pumping.

- *Stream* - used to model groundwater flow into and out of the river tributaries.

The *Drain*, *Horizontal Flow Barrier*, and the *Time Varied Specified Head* packages were not used; however, the *Drain* package will be used in the future to investigate solutions to waterlogging problems involving subsurface drains.

MT3D: The MT3D model uses the groundwater flow output from the MODFLOW model along with four calculation packages to estimate contaminant transport. The packages used in the preliminary modeling were the *Advection* and the *Source/Sink Mixing* packages. The *Dispersion* and the *Chemical Reaction* packages were not used due to a lack of available data. Future incorporation of these packages is planned. MT3D was used to model the salinity transport under the same scenarios for which groundwater flow was modeled with MODFLOW.

GMS Model Application

The key steps involved in the application of the GMS model to the study subregion were:

1. *Selection and creation of a background image*. For our study, Landsat Thematic Mapper (TM) data were purchased from the EROS Data Center and an image was created using Idrisi GIS (Clark University 1997) software image processing functions.

2. *Description of the system by creation of a conceptual model*. The following coverages were entered to create the basic conceptual model of our study reach:
    - Surface Water System
    - Field Boundaries
    - Pumping Wells

3. *Creation of the finite-difference grid*. The finite-difference grid defines the cells in which MODFLOW and MT3D perform numerical calculations and, thereby, derive their outputs (Wang and Anderson 1982). The average field size within the study area was calculated to be 6.3 ha (15.5 acres); therefore, a square grid cell with a side dimension of 250 meters was used.

4. *Input of additional data sets into GMS*. To complete the conceptual model of the system, additional data sets not defined in the *Map Module* of GMS must be input into the model. The following data sets were input into GMS using the *Scatter Point Module*:
    - Ground Elevation
    - Hydraulic Conductivity
    - Water Table Elevation
    - Bottom Elevation

5. *Estimation of recharge and evapotranspiration (ET).* To arrive at estimates of recharge and ET, data were analyzed using an irrigation and fertilizer scheduling program *CropFlex98* (Broner 1998). The following steps were taken in this analysis:

    - *Analysis of crop types* - Utilizing data acquired from the FSA, the average percentages of each crop type grown within the study area were calculated (based on data from 1992 through 1997).

    - *Assigning crop types to modeled fields* - Based on the calculated average percentages, crop types were randomly assigned to each modeled field.

    - *Estimation of crop water requirements, crop ET, and deep percolation using CropFlex98* - Using meteorological data obtained from the CoAgMet on-line data center (Colorado Climate Center 1999) and crop coefficient data provided by Dr. Israel Broner (Colorado State University, 1999, personal communication), the soil moisture balance component of *CropFlex98* was used to estimate irrigation requirements for each crop type for years 1993 through 1998. Also, crop ET and deep percolation due to precipitation were calculated by *CropFlex98* and input into each field polygon based on the assigned crop type (Broner and Lorenz 1998).

    - *Calculation of recharge values* - Recharge values for each field were calculated using estimates of ET and leaching fraction estimates generated based on a truncated normal distribution developed from field data collected for a similar region (i.e. similar irrigation practices) in the South Platte River valley.

6. *Incorporation of salinity data into the conceptual model.* Three data sets were collected and used to estimate the salinity distribution within the modeled groundwater system. The data sets collected and incorporated into the model include the following:
    - Surface Water Electrical Conductivity (EC)
    - Groundwater EC
    - Soil Bulk EC

<u>Preliminary Modeling Results</u>

The GMS interface was used to translate all of the conceptual model data sets into MODFLOW and MT3D input file format. After a series of debugging procedures, the models were used to investigate the following scenarios:

- *Scenario 1: Baseline Conditions* - This scenario utilizes the data described above to simulate average conditions for the 33rd week of the year. The output from this scenario was used to evaluate the effects of changes to the system as described in the six other modeled scenarios.

- *Scenario 2: Increasing of Pumping Rates by 20%* - This scenario investigated the impacts of increasing the average pumping rate of all pumps within the study area by 20% and routing all of the additional pumped flow into nearby drains that flow to the river.

- *Scenario 3: Increasing of Pumping Rates by 30%* - This scenario investigated the impacts of increasing the average pumping rate of all pumps within the study area by 30% and routing the additional pumped flow into nearby drains that flow to the river.

- *Scenario 4: Reduction of Recharge Rates by 20%* - This scenario investigated the impacts of reducing the average recharge rates from overirrigation over the entire study area by 20%.

- *Scenario 5: Reduction of Recharge Rates by 30%* - This scenario investigated the impacts of reducing the average recharge rates over the entire study area by 30%.

- *Scenario 6: Increasing of Pumping Rates by 20% and Reduction of Recharge Rates by 20%* - This scenario investigated the impacts of increasing the average pumping rates by 20% and reducing the average recharge rates by 20%.

- *Scenario 7: Increasing of Pumping Rates by 30% and Reduction of Recharge Rates by 30%* - This scenario investigated the impacts of increasing the average pumping rates by 30% and reducing the average recharge rates by 30%.

The purpose of the preliminary modeling described in this document is to aid in directing the future course of data collection and modeling efforts and to provide a preliminary general indication of the sensitivity of the groundwater system to changes as described in the scenario descriptions. The results derived from these scenarios are presented below.

Table 1 summarizes the important information that was extracted from the preliminary modeling output. This table shows the statistics over all of the modeled fields for each scenario. Of key importance to this study is the reduction in water table elevation.

Table 1. Preliminary Model Output Summary.

Scenario No.	*Maximum Reduction in Water Table Elev. (meters)*	*Average Reduction in Water Table Elevation (meters)*	*Standard Deviation (meters)*	*Percent Reduction in Salinity from Groundwater Upflux*
1	-	baseline	scenario	-
2	0.482	0.012	0.032	0.6
3	0.749	0.017	0.045	0.9
4	0.410	0.045	0.063	1.9
5	0.632	0.068	0.093	2.9
6	0.954	0.058	0.081	2.6
7	1.562	0.086	0.125	3.8

From the MODFLOW modeling results, the following important conclusions were drawn about reducing the water table level:

- *The effects of increased pumping are localized.* The spatial distribution of the resultant decreases in water table elevation estimated in Scenarios 2 and 3 revealed that changes were localized around the pumping wells.

- *Changing irrigation practices to reduce aquifer recharge can have widespread effects.* The spatial distribution of the resultant decreases in water table elevation estimated in Scenarios 4 and 5 revealed that changes were widespread over the study region. However, the average net decrease was small for the scenarios considered.

- *Plans incorporating multiple solution alternatives will have significant cumulative effects.* It is important to observe, as can be seen in Figure 2 (which reflects Scenario 7), the relatively large effect that combining increased pumping and reducing recharge had in some regions.

Also of great importance to this study is the reduction of high salinity levels. The steady-state model yielded only limited information. Once a transient model has been established, the long-term effects of alternatives on salinity levels will become more evident. One interesting output parameter could, however, be extracted from this preliminary salinity model. The reduction of accumulated salinity deposited in the root zone, due to groundwater upflux, can be estimated from the MT3D output; although, this parameter is a bit misleading because it does not also reflect the salinity that would be removed from the root zone by the increased leaching that might accompany the lowering of the water table (only a transient model will quantify this effect). This parameter is shown in the far right column of Table 1 and is indicative of the extent to which upflux of salt can be reduced by lowering the water table.

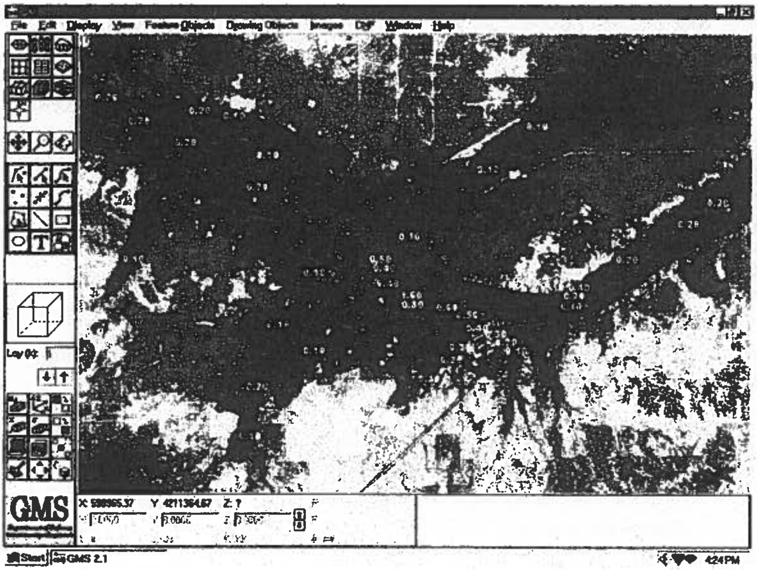


Fig. 2. Scenario 7 - Estimated Water Table Drawdown.

The preliminary modeling effort made another fact quite clear: there is a need for extensive, well distributed, time-varied data to support consideration of comprehensive solution alternatives. These data need to be collected at a frequency that will be adequate to capture any significant changes over the course of a year. Also, they must be of adequate spatial density to effectively describe the groundwater system. In response to these needs, a major data collection effort was initiated in the summer of 1999. This effort is described in the remainder of this paper.

COLLECTION AND ANALYSIS OF FIELD DATA

The objectives of the data collection effort are to accurately *describe* the high water table and salinity problems within the study area, and to support the implementation of a fully transient model to help *prescribe* solutions to these problems. A description is provided of on-going data collection activities and preliminary findings from the data that have been collected thus far.

Based on the knowledge gained from the preliminary modeling investigation described earlier, the major data needs were identified. Each data type is described below, and, if available, results are presented and discussed.

Water Table Depth and Salinity

Observation wells were installed in the spring (and early summer) of 1999 and used to collect water table depth and groundwater salinity data. The wells were installed using truck-mounted Giddings™ drilling rigs obtained from the USDA-NRCS Area Office in La Junta. The well casings consist of 6.35-cm (2½-inch) diameter perforated PVC pipe and extend to a depth of 3 meters below the ground surface.

Observation well locations were selected using a stratified random sampling technique. The study subregion was divided into five segments running west to east along the valley, each segment containing approximately the same number of fields. Each field within a segment was assigned a unique number, and ten fields were selected per region using a uniform random number generator, for a total of 50 selected fields. Additionally, 25 fields were selected to describe conditions near boundaries of the study area. In some cases (approximately 20%), observation well locations were shifted to nearby fields because of problems with field access or landowner preference. In a two or three cases, new fields were selected because the landowner did not want to participate in the study. Also, three existing observation wells and three abandoned pumping well casings are included within the total of 75 sites. Fields containing multiple well sites [five of these fields exist (each contains from seven to eleven wells) and are being used in other field-scale studies] were only counted once in this total.

The total of 75 observation sites provides a data density of approximately one well per 530 hectares of land area within the study region. The minimum distance between any two sites is approximately one kilometer, with the average distance being approximately two kilometers. A number of new wells will be installed before the 2000 season to increase data density and to extend the study region eastward into Bent County.

Measurements of water table depth and groundwater salinity began in early April, 1999, and have been ongoing since that time. Readings were taken biweekly until the end of May, 1999, when the frequency was increased to weekly. This weekly frequency was maintained through the peak of the irrigation period, reverted back to biweekly at the end of August, 1999, and continued through the middle of October, 1999. During the winter, data were collected at each site three to four times. Following the first complete year of data collection, the measurement frequency will be evaluated and adjustments will be made accordingly.

Water table depths were measured manually using a metal measuring tape and a float. Groundwater salinity was measured indirectly using electrical conductivity meters. Orion™ (Model 128 and Model 130) and Corning™ (Model 19450) EC meters were used to measure EC and were periodically calibrated using standard solutions. These meters utilize internally-programmed temperature adjustment algorithms (the reference temperature is 25° C) which are automatically reflected in the displayed EC readings. Three measurements of EC were made at each location for each reading - one shallow measurement just below the water table, one intermediate measurement, and one deep measurement near the bottom of the observation well. These measurements were averaged to come up with a representative EC value for the well. EC values were then converted into salinity using relationships developed by Cain (1986).

Preliminary Results: Only illustrative results and a summary from the water table depth and groundwater salinity data collection effort are provided within this report. Collected data indicate distinct rises in the water table over the course of the season in certain areas. Notably, the area in the southwestern part of the study region (i.e. near Patterson Hollow) shows a shallower water table depth as the season progresses. Other areas that show this trend include the south central (south of the town of Swink) and the east central (northeast of La Junta along Highway 194) parts of the study region. In much of the region, however, there was no evidence of substantial change in the water table depth. Plots of water table depth versus time for a set of representative wells are shown in Figure 3. A summary of the water table depth data statistical parameters for each measurement date is shown in Table 2.

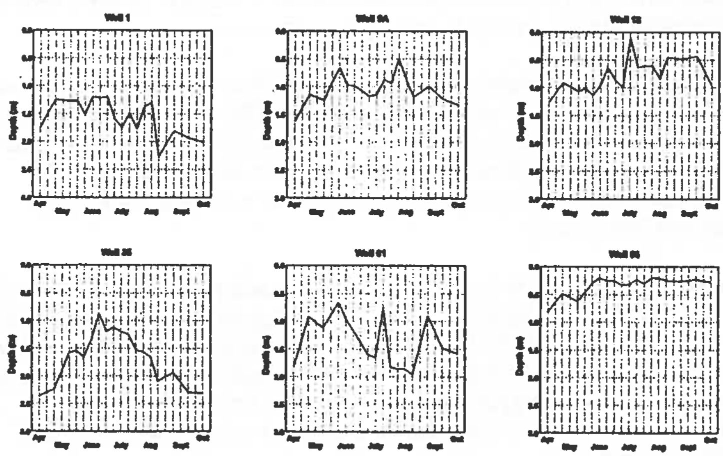


Fig. 3. Representative Water Table Depths - 1999.

Table 2. Water Table Depth Data (1999) - Statistical Parameters.

Date of Reading	*No. of wells read*	*Mean Depth (m)*	*Confid. Interval (-95%)*	*Confid. Interval (+95%)*	*Minimum Depth (m)*	*Maximum Depth (m)*	*Coefficient of Variation*
Apr 24	33	1.58	1.37	1.79	0.23	2.59	0.38
May 11	41	1.23	1.06	1.40	0.28	2.26	0.44
May 26	47	1.36	1.21	1.51	0.46	2.67	0.37
June 1	22	1.26	1.07	1.46	0.74	2.23	0.35
June 9	45	1.40	1.18	1.63	0.08	4.06	0.53
June 17	47	1.42	1.22	1.62	0.20	3.02	0.48
June 23	47	1.28	1.12	1.44	0.20	2.26	0.43
June 29	53	1.54	1.36	1.73	0.25	2.97	0.43
July 6	47	1.50	1.28	1.72	0.28	3.01	0.50
July 14	54	1.36	1.15	1.57	0.10	2.72	0.56
July 21	51	1.28	1.10	1.47	0.23	2.86	0.52
July 28	49	1.40	1.21	1.59	0.30	2.69	0.47
Aug 3	52	1.37	1.15	1.59	0.11	3.89	0.58
Aug 10	47	1.29	1.10	1.47	0.20	2.77	0.49
Aug 17	51	1.60	1.37	1.82	0.23	3.12	0.50
Sept 4	47	1.46	1.23	1.68	0.27	3.84	0.52
Sept 17	53	1.59	1.38	1.79	0.23	3.12	0.46

These data also were used, in conjunction with collected ground surface elevation data (using GPS survey equipment - discussed later), to generate water table elevation contour maps. Data for these maps were created by subtracting the interpolated water-table depth from the ground surface elevation (which incorporated the collected GPS data along with acquired USGS data). The early season contour map was subtracted from the late season map to create a data layer that represents the change in water table elevation between these two readings (Figure 4). From this figure, the areas where the water table rose are easily identifiable. Besides the areas discussed earlier, this figure shows an area directly east of Rocky Ford (north central part of study region) where the water table rose as much as 1.50 to 2.00 meters.

Data output similar to that for water table depth is given for the measured groundwater salinity. From these measured data, it is evident that the groundwater salinity decreased in some areas over the course of the irrigation season. This is likely due to the dilution effects as recharge filled the aquifer. Areas where a decrease can be seen include the northwest area (near the town of Manzanola) and the central area (east of Rocky Ford) of the study region. Interestingly, however, there were two areas (east central - near La Junta, and northeast - near the town of Cheraw) which show a noticeable *increase* in salinity. This is surprising and there is currently no recognized reason for these anomalous areas. The increased salinity might be due to dissolution of salts from the alluvial soil layers. Plots of salinity over the season for the set of representative wells are shown in Figure 5.

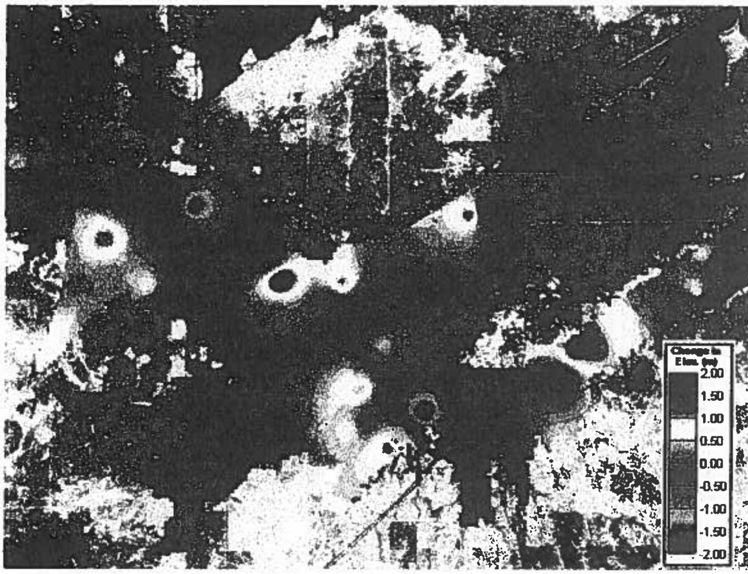


Fig. 4. Change in Water Table Depth - Early Season to Late Season (1999).

A summary of the groundwater salinity data statistical parameters for each measurement date is shown in Table 3.

Soil Salinity

Soil salinity was estimated by measuring the soil bulk EC at a number of locations within several field using a Geonics™ EM38 electromagnetic ground conductivity meter. For the purposes of creating the preliminary models, data that were collected on 30 fields in the summer of 1998 were adequate; however, to meet the needs of the transient model, it was necessary to expand the data collection effort to include 68 total fields (10 of which are in Bent County). Two sets of readings were taken at each field location, one representing early season conditions (data collected between May 31 - June 19, 1999) and one representing late season conditions (data collected between August 11 - 18, 1999). Fields selected (excluding the fields in Bent County) correspond to the observation well sites.

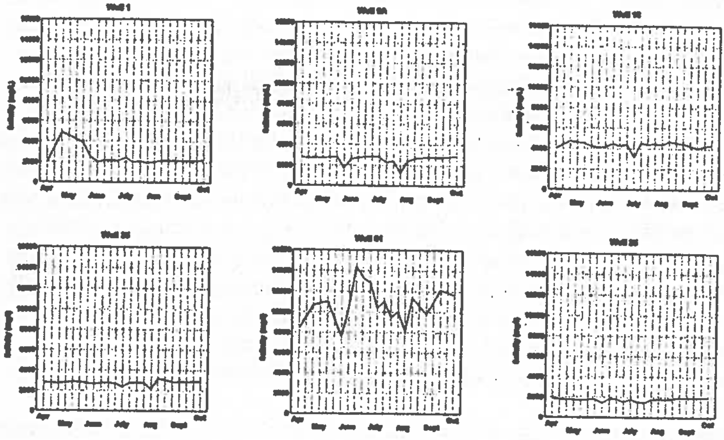


Fig. 5. Representative Groundwater Salinity - Summer 1999.

Within each field, horizontal and vertical EM38 measurements were taken at 50 - 80 locations (yielding a data density of around one point per 0.125 ha). The spatial distribution of these measurements was generally a grid pattern covering the entire field or, in cases where the field was large (> 20 ha), covering a portion of

Table 3. Groundwater Salinity Data (1999) - Statistical Parameters.

Date of Reading	*No. of Readings*	*Mean Salinity (mg/L)*	*Confid. Interval (-95%)*	*Confid. Interval (+95%)*	*Minimum Salinity (mg/L)*	*Maximum Salinity (mg/L)*	*Coefficient of Variation*
Apr 24	33	3,899	2,587	5,210	1,152	22,543	0.95
May 11	43	4,264	3,099	5,430	92	22,331	0.89
May 26	48	3,940	2,948	4,931	442	20,879	0.87
June 1	23	4,410	2,762	6,058	294	20,077	0.86
June 9	45	3,509	2,615	4,404	106	17,844	0.85
June 17	47	3,041	2,405	3,676	361	10,558	0.71
June 23	47	3,624	2,775	4,473	283	15,713	0.80
June 29	54	3,452	2,635	4,270	241	14,452	0.87
July 6	45	3,736	2,762	4,710	636	15,222	0.87
July 14	53	3,252	2,475	4,029	22	12,303	0.87
July 21	52	3,406	2,454	4,357	294	18,473	1.00
July 28	49	3,406	2,556	4,256	416	15,077	0.87
Aug 3	48	3,534	2,460	4,608	29	20,434	1.05
Aug 10	48	3,355	2,548	4,161	636	16,480	0.83
Aug 17	51	3,678	2,837	4,518	622	14,264	0.81
Sept 4	48	3,378	2,559	4,196	590	15,611	0.83
Sept 17	51	3,735	2,822	4,648	802	15,611	0.87

the field containing (or adjacent to) the observation well. The measured values were converted to EC_e for analysis and presentation within this report using the relationships mentioned previously; however, an analysis will be conducted to develop new relationships between EM38 readings and actual EC_e values. To accomplish this goal, a calibration site was selected in most fields where soil samples were collected. Samples were taken from the soil profile down to a depth of just over one meter at three points beneath the EM38 instrument - one at each end of the instrument and one in the middle of the instrument's longitudinal axis. The soil profile at each of these points was divided into five samples, yielding a total of 15 samples per calibration site. The *in situ* temperature for each sample was recorded, and each sample was analyzed for moisture content. Additionally, each sample will be analyzed in the laboratory to find EC_e and soil texture properties. The effects of each of these parameters in relation to the EM38 measurements will be investigated (Geonics Limited 1998).

Preliminary Results: Figure 6 shows the estimated EC_e values for the early season measurements (similar plots exist for the late season data). The dashed line (at an EC_e of 2.0 dS/m) indicates the approximate value above which typical crops (namely corn and alfalfa) will experience yield losses. In the early season reading, 55 fields had all or some portion of the measured sites that were above this threshold. The overall average for the study area was 2.74 dS/m for the early season. For the late season reading, 64 fields had all or some portion of measurements above the salinity threshold, and the overall average increased to 2.84 dS/m. This slight rise in average EC_e is likely tied to the prolonged high water table that was observed over the course of the irrigation season. High water table levels reduce the ability to leach salts out of the root zone and cause return flow of salts through upflux.

Water Table Depth and Soil Salinity: The relationship between water table depth and soil EC_e level for the early and late season readings was investigated. The water table depth values represent the average value at the particular location for the four weeks preceding the date on which the bulk soil EC was measured. The EC_e level represents the estimated average value for the particular location based on the bulk EC measurements obtained with the EM38 instrument.
For each data set, an equation was derived to approximate the relationship between the variables. In both cases, a power function gave the best approximation. For the early season data, the following equation was developed:

$$EC_e = 3.05D^{-0.71} \qquad (1)$$

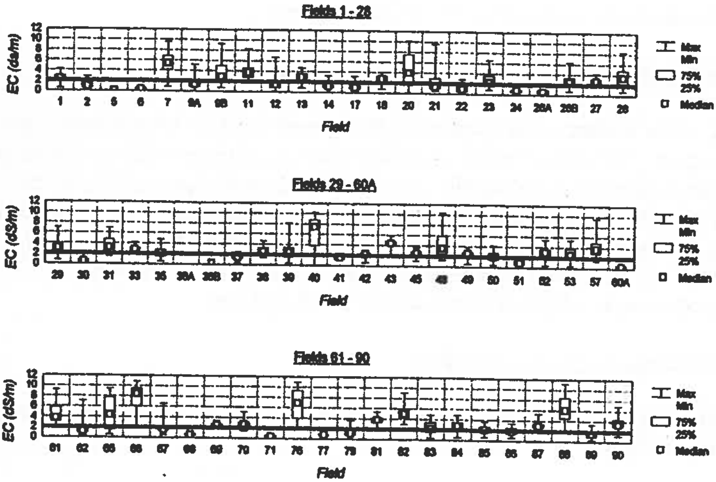


Fig. 6. Early Season EC_e - 1999.

where D represents the average water table depth as described above. The relationship described by this curve represents an r^2 value of 0.36, indicating that significant correlation exists. For the late season data, the equation developed is slightly different:

$$EC_e = 3.64D^{-0.65} \quad (2)$$

The r^2 value for the late season data relationship is 0.34, indicating a slightly lower, but still significant, correlation.

Water Surface and Land Elevation

Two separate Global Positioning System (GPS) receiver combinations were used to measure horizontal and vertical positions of several points of interest. Two Trimble 4600LS receivers were used in conjunction with a Trimble TSC1 Survey Controller, and two Ashtech Locus receivers were used with an HP-48GX serving as the Handheld Data Controller. Both systems utilize differential correction methods to arrive at point positions with an accuracy of ±1 cm (Trimble Navigation, Ltd. 1996 and Magellan Corp. 1998).

GPS data has already been collected to calculate positions for all observation wells, surface water levels at several locations, and numerous land elevation points. Ultimately, it is planned that the GPS surveying techniques will be applied to completely define the geometry of the physical system. The intent is to minimize modeling error due to ill-defined topology.

Surface Water Salinity

The EC of the surface water is currently being monitored at 164 sites within the study region. The measurements are being made at a frequency that corresponds to the data collection at the monitoring wells. As described previously, EC is measured using the Orion and Corning EC meters and the values are converted to salinity concentration using relationships developed by the USGS (Cain 1987, Ortiz et al. 1998). New relationships between EC and salinity are being developed as water sample data are collected and analyzed.

Additional Data Collection Activities

The following areas of data collection will be pursued in the future to enhance the modeling database:

- *Slug Tests* - Slug tests have been performed at 67 observation well sites to determine the average hydraulic conductivity of the surrounding soils. Analysis of these data is ongoing. The estimated values of hydraulic conductivity will be related to soil texture (obtained from analysis of the soil samples taken at observation well locations) and used to make estimations in areas where no direct measurements are possible. Discussion of the slug test technique and analysis method can be found in Chin (2000).

- *Crop Yield Estimates* - Estimates of crop yield will be made with the help of participating farmers. These estimates will help in determining the actual effect of soil salinity on the crops.

- *River and Tributary Geometry* - Cross-sections of the river channel and tributaries within the study area will be measured at several points at a spatial density that will allow for increased modeling accuracy.

- *Drainage System Inventory* - Existing records will be compiled and field investigations will be performed to locate existing subsurface drainage systems and their existing effectiveness. This will ultimately lead to incorporation of the *Drainage Package* into the transient MODFLOW model.

- *Water Samples* - Water samples are being collected at observation well and surface water measurement sites. Additionally, the State Engineer's Office is collecting samples at pumping well locations throughout the Lower Arkansas Valley. Currently, 24 observation well samples and 28 surface water samples have been analyzed in a laboratory for salinity (total dissolved solids) content. The results of the lab analysis will be used to develop new EC to salinity relationships specific to the study region. These relationships will refine those developed by Cain and should increase model accuracy.

Additionally, flow rate and water level data collected by the State Engineer's office and the USGS will be used, in conjunction with collected salinity and GPS data, to develop salt and water balances which will be applied to the GMS modeling. This data will be critical in the transient model calibration procedure and will reveal areas where further or more intense data collection is needed.

CONCLUSIONS

Field data confirms extensive and severe saline-high-water-table problems in the Lower Arkansas Valley. Salinity of overlying soils indicates levels that diminish crop productivity. However, though the salinity is serious, it seems recoverable through implementation of strategies developed by careful modeling.

The preliminary groundwater flow and salinity modeling of the study region indicates that the effects of increased pumping are localized, whereas the potential effects of changing irrigation practices to reduce groundwater recharge can be widespread. However, solution alternatives incorporating multiple BMP's including seepage control and subsurface drainage systems, and alternatives investigating the reduction of river levels should be considered in future modeling efforts. Additionally, the current steady-state model should be expanded to consider time-varied (i.e. transient) changes to the system so that the long-term effects of alternatives can be evaluated.

Critical to the need to develop transient models is the continuation of the described data collection activities. The current data collection methods including equipment used, observation well depth, measurement frequency, etc., need to be evaluated following the first full data period (year). Changes in these methods should be made if necessary. Also, improvements to existing calibration equations and to parameter estimation techniques should be possible following the analysis of all collected water and soil samples, the completion of the slug test analysis, and the collection of crop yield data.

REFERENCES

Brigham Young University (BYU), *The Department of Defense Groundwater Modeling System: GMS 2.1 Reference Manual*, Draft, Engineering Computer Graphics Laboratory, BYU; Provo, Utah, 1997.

Broner, Israel, and Jason Lorenz, *CropFlex: A Crop Management System User's Manual, Windows Version*, Department of Chemical and Bioresources Engineering, Colorado State University; Fort Collins, Colorado, 1997.

Cain, Doug, *Relations of Specific Conductance to Streamflow and Selected Water-Quality Characteristics of the Arkansas River Basin, Colorado*, U.S. Geological Survey Water-Resources Investigations Report 87-4041, 1987.

Cain, Doug. "U.S. Geological Survey Data Collection and Studies in the Arkansas River Basin", *Colorado Water*: August, 1997.

Chin, David A., *Water Resources Engineering*, pp. 568-571, Prentice Hall; Upper Saddle River, New Jersey, 2000.

Clark University, Clark Labs, The Idrisi Project, Clark University Graduate School of Geography; Worcester, Massachusetts, 1997.

Colorado Agricultural Statistical Service, *Colorado Agricultural Statistics*, Lakewood, Colorado, 1996.

Colorado Climate Center, CoAgMet Data Access, http://ccc.atmos.colostate.edu/~coag/, 1999.

Geonics Limited, *Applications of Electromagnetic Methods: Soil Salinity*; Mississauga, Ontario, Canada, 1998.

Magellan Corporation, Ashtech Locus Survey System, "The Easy-to-Learn, Simple-to-Use, Cable-free GPS Survey System for High-Accuracy, High-Productivity Applications"; Santa Clara, California, 1999.

McDonald, Michael G., and Arlen W. Harbough, *Chapter A1: A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model*, Techniques of Water-Resources Investigations of the United States Geological Survey, Book 6: Modeling Techniques, United States Government Printing Office; Washington, D.C., 1988.

McNeill, J. Duncan, *Rapid, Accurate Mapping of Soil Salinity by Electromagnetic Ground Conductivity Meters*, Soil Science Society of America, SSSA Special Publication No. 30; Madison, Wisconsin, 1992.

Nadler, Carl Theodore, Jr., *River Metamorphosis of the South Platte and Arkansas Rivers, Colorado*, Department of Earth Resources, Colorado State University; Fort Collins, Colorado, 1978.

Ortiz, Roderick F., and Michael E. Lewis, and Mary Jo Radell, *Water-Quality of the Arkansas River Basin, Southeastern Colorado, 1990-93*, U.S. Geological Survey, Water-Resources Investigations Report 97-4111; Denver, Colorado, 1998.

Sheets, Keith R., John P. Taylor, and Jan M. H. Hendrickx, "Rapid Salinity Mapping by Electromagnetic Induction for Determining Riparian Restoration Potential", *Restoration Ecology*, Vol. 2, No. 1, pp. 242-246; December, 1994

Trimble Navigation Limited, *GPS Surveying: General Reference*, Revision A; Sunnyvale, California, 1996.

Valliant, J. *Arkansas River Basin Seminar Notes - Colorado State University*; Fort Collins, Colorado, September 29, 1997.

Watts, K. R., and J. B. Lindner-Lunsford, *Evaluation of Proposed Water-Management Alternatives to Lower the High Water Table in the Arkansas Valley Near La Junta, Colorado*, U.S. Geological Survey Water-Resources Investigations Report 91-4046; Denver, Colorado, 1992.

Weist, William G., Jr., "Records, Logs, and Water-Level Measurements of Selected Wells, Springs, and Test Holes, and Chemical Analyses of Ground Water in Otero and the Southern Part of Crowley Counties, Colorado", *Colorado Water Conservation Board Basic-Data Report No. 11*, U.S. Geological Survey; Denver, Colorado, 1962.

Wilson, Woodrow W., "Pumping Tests in Colorado", *Colorado Ground Water Circular No. 11*, U.S. Geological Survey; Denver, Colorado, 1965.

Zheng, Chunmiao, and P. Patrick Wang, *MT3D MS: A Modular Three-Dimensional Multispecies Transport Model*, Departments of Geology and Mathematics, University of Alabama; Tuscaloosa, Alabama, 1998.

ARKANSAS RIVER SALINITY AND CONTAMINATION OF THE HIGH PLAINS AQUIFER

Donald O. Whittemore[1]

Ming-Shu Tsou[2]

Carl McElwee[3]

ABSTRACT

The Arkansas River in southeast Colorado and southwest Kansas is one of the most saline rivers in the United States. The primary sources of the dissolved constituents (mainly sodium, calcium, and sulfate) are from soils and bedrock in Colorado. The dissolved salt concentration in the river water greatly increases across eastern Colorado as evapotranspiration from ditch diversion and storage systems consumes water, while the dissolved salts remain in the residual water. The dissolved solids content of the river water now averages over 3,000 mg/L at the state line. The discharge into Kansas is saline during both high and low flow periods, although the salinity decreases with increasing flow. The major constituent, sulfate, reaches a maximum concentration of about 2,600 mg/L in low flows suggesting limitation by gypsum precipitation. The salinity has generally increased at the state line in greater than average river discharges during the last few decades. Although part of the increase could represent increased water use, a portion could represent a lag in the mass transfer of salinity to Kansas related to salt accumulation in soils and shallow ground waters of Colorado.

Shallow, saline ground water in the alluvium of the Arkansas River and under fields irrigated with river water has penetrated to various depths in the High Plains aquifer in southwest Kansas. Much of the saline water migration deep into the freshwater aquifer has occurred since the 1970's when the water level in the main aquifer declined below the alluvium and shallow parts of the High Plains aquifer. During many years since the mid-1970's essentially all of the salt mass has remained in southwest Kansas, i.e., there has often been little or no river flow exiting the area. Based on recent conditions and existing contamination, in about 50 years river water seepage has the potential to contaminate all of the High Plains aquifer underlying 500 mi^2 (1,300 km^2) of the corridor to a sulfate concentration over 1,000 mg/L (four times the level recommended for drinking waters). Management and protection of fresh ground waters in the region will be critical to maintain water quality for municipal, agricultural, and industrial uses.

---

[1]Senior Scientist and [2] Postdoctoral Research Fellow, Kansas Geological Survey, 1930 Constant Ave., Lawrence, Kansas 66047-3726

[3]Senior Scientist, Kansas Geological Survey, and Professor of Geology, University of Kansas, 1930 Constant Ave., Lawrence, Kansas 66047-3726.

INTRODUCTION

The Arkansas River flows from its headwaters in the Rocky Mountains in Colorado across the southeastern part of the state and then flows into southern Kansas (Fig. 1). Water has been diverted for irrigation from the Arkansas River for over 100 years in Colorado and Kansas. Soon after extensive irrigation systems were started in Colorado in the 1870's and 1880's, the river salinity increased as water was used and reused. The salinity has continued to increase such that the Arkansas River in southeast Colorado and southwest Kansas is one of the most saline rivers in the United States.

Before the development of irrigation systems, the dissolved solids loads in the Arkansas River derived from Colorado were carried through southwest Kansas and eventually discharged to the ocean. After the development of large diversion systems in Colorado and smaller diversions in Kansas, the average annual river flow decreased due to consumptive losses from evapotranspiration. This interrupted the natural process of draining salt loads out of the river basin to the sea. Development of irrigation from ground water in southwest Kansas increased appreciably starting in the 1950's. Resulting water-level declines near the river caused further losses in river flow from seepage into the underlying High Plains aquifer. Most of the saline water that now enters Kansas seeps into and contaminates the aquifer.

WATER QUALITY IN THE ARKANSAS RIVER

Water quality data presented in this paper are from analyses of the U. S. Geological Survey (USGS), Kansas Department of Health and Environment, and Kansas Geological Survey. The USGS collected and analyzed samples from the Arkansas River at the Coolidge gaging station near the Colorado-Kansas state line beginning in 1963 before discontinuing sampling in 1995 (U. S. Geological Survey, 1995). The Kansas Department of Health and Environment began periodic monitoring at the Coolidge station in 1967, although no samples were collected for a year and a half during the early 1980's. The Kansas Geological Survey (KGS) supplemented the periodic sampling starting in 1993, including collection during selected periods to characterize water quality along the river during different flow regimes. The Kansas Department of Agriculture collected many of the samples analyzed by the KGS as a part of cooperative studies; other state and local agencies have also participated in sample collection. Flow data are from the USGS program for stream gaging.

The primary sources of the dissolved constituents in the Arkansas River are from soils and bedrock in the watershed, especially the marine rocks of eastern Colorado. The dissolved salt concentration in the river water greatly increases across eastern Colorado as evaporation from reservoirs and irrigation ditches,

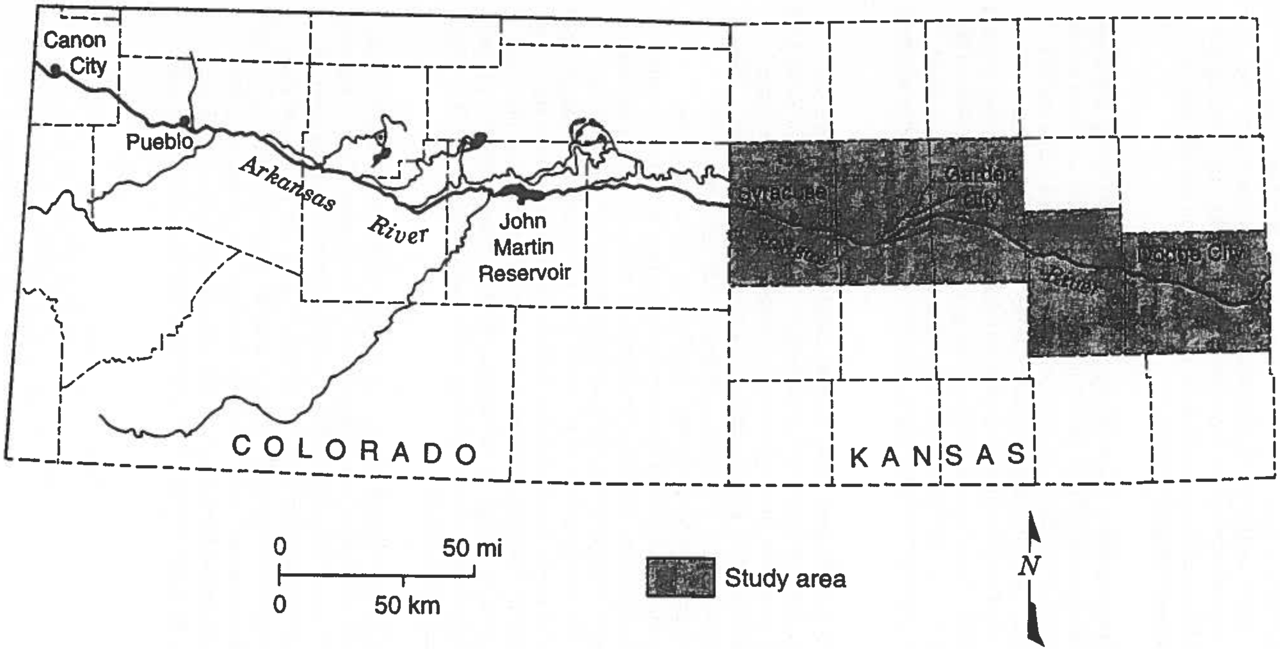


Fig. 1. Natural Drainage and Canals in the Arkansas River System in Southeast Colorado and Southwest Kansas. Only the major canals are shown.

evapotranspiration from irrigated fields, and transpiration by phreatophytes consumes water, while the dissolved salts remain in the residual water. The dissolved solids content of the river water often exceeds 4,000 mg/L during low flows (Fig. 2) and has averaged greater than 3,000 mg/L over the last couple decades at the Colorado-Kansas state line.

The salinity of Arkansas River water entering Kansas is greater during low flows (Fig. 2). At discharges near 100 cfs (2.8 m^3/sec) and below, the dissolved solids concentration reaches a maximum of about 4,200 to 4,500 mg/L. The salinity generally decreases with increasing discharge above 100 cfs (2.8 m^3/sec). The flows have been regulated by releases from John Martin Reservoir in southeastern Colorado since 1948, therefore most high discharges do not exceed 3,000 cfs (85 m^3/sec). High flows over the last couple of decades have contained dissolved solids contents of greater than 1,000 mg/L, the classification divide between fresh and saline water.

The dissolved solids in the river water include mainly sodium, calcium, and sulfate; typical analyses of recent low, moderate, and high flows are in Table 1. If the concentration of sulfate, the major dissolved constituent, is plotted versus discharge, the distribution of points appears very similar to that in Fig. 2. The sulfate concentration reaches a maximum of about 2,600 mg/L when the discharge falls to near 100 cfs (2.8 m^3/sec) and below. The cause of the maximum sulfate and dissolved solids contents during low flows is primarily related to gypsum solubility. Gypsum precipitates in soils and sediments when consumption of water concentrates the dissolved solids to over the gypsum saturation point. Chloride content, which is not limited by mineral solubility until orders of magnitude higher concentrations, does not reach a maximum limit as do sulfate and dissolved solids but continues to increase with decreasing discharge below 100 cfs (2.8 m^3/sec) (Fig. 3). Therefore, chloride concentration is a better representative of the degree of concentration of the salt content in the river water as a result of consumptive losses.

At discharges above 100 cfs (2.8 m^3/sec), the salinity of the Arkansas River has generally increased at the state line during the last few decades (Fig. 4). The data in Fig. 4 are for two periods in which flows ranged from less than 100 cfs (2.8 m^3/sec) to about 3000 cfs (85 m^3/sec). Conditions during the 1970's and early 1980's were drier and flows generally remained under several hundred cfs. Only the data for discharges greater than 100 cfs (2.8 m^3/sec) are plotted in order to examine the conditions of decreasing salinity with increasing flow. The two curves plotted in the figure are computer calculated fits based on the log-log equation

$$\ln y = b \ln x + a.$$

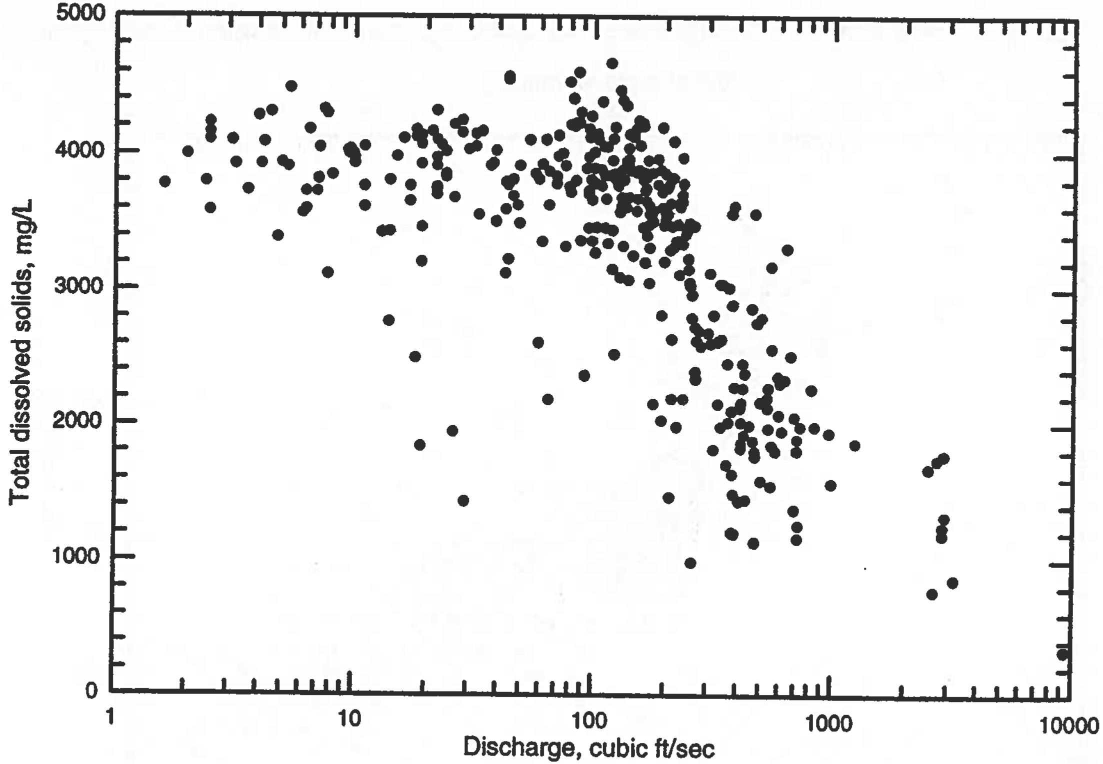


Fig. 2. Total Dissolved Solids Concentration versus Discharge for the Arkansas River near Coolidge, Kansas, 1963-1999.

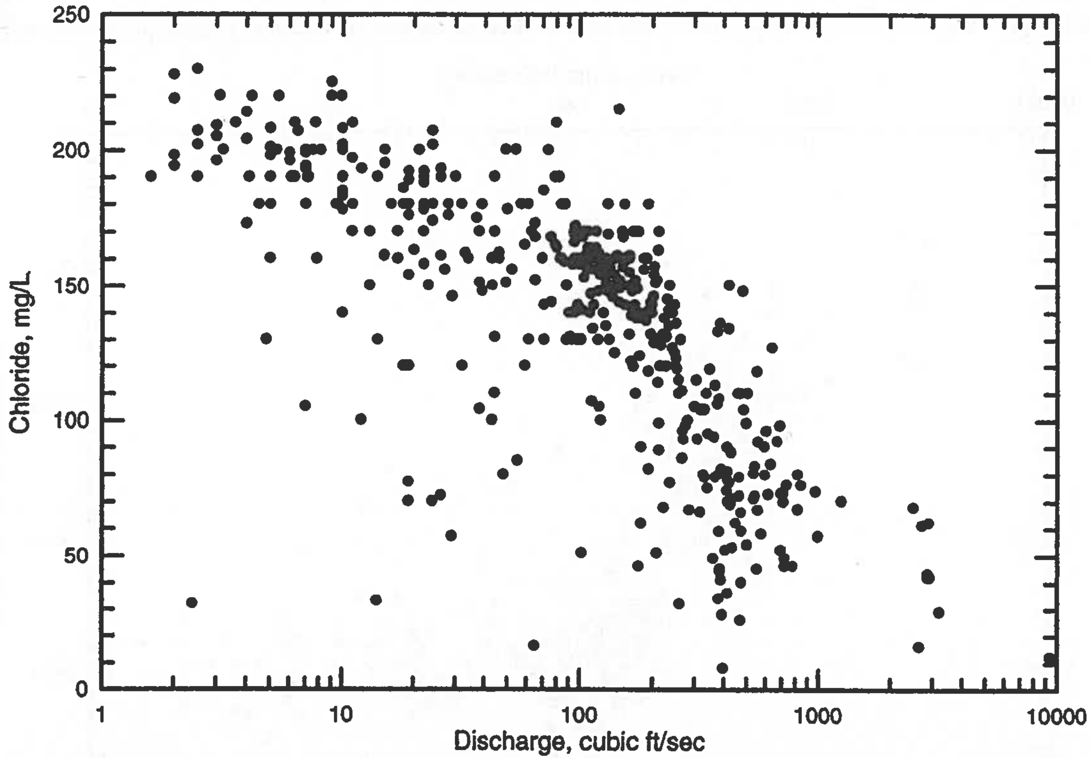


Fig. 3. Chloride Concentration versus Discharge for the Arkansas River near Coolidge, Kansas, 1963-1999.

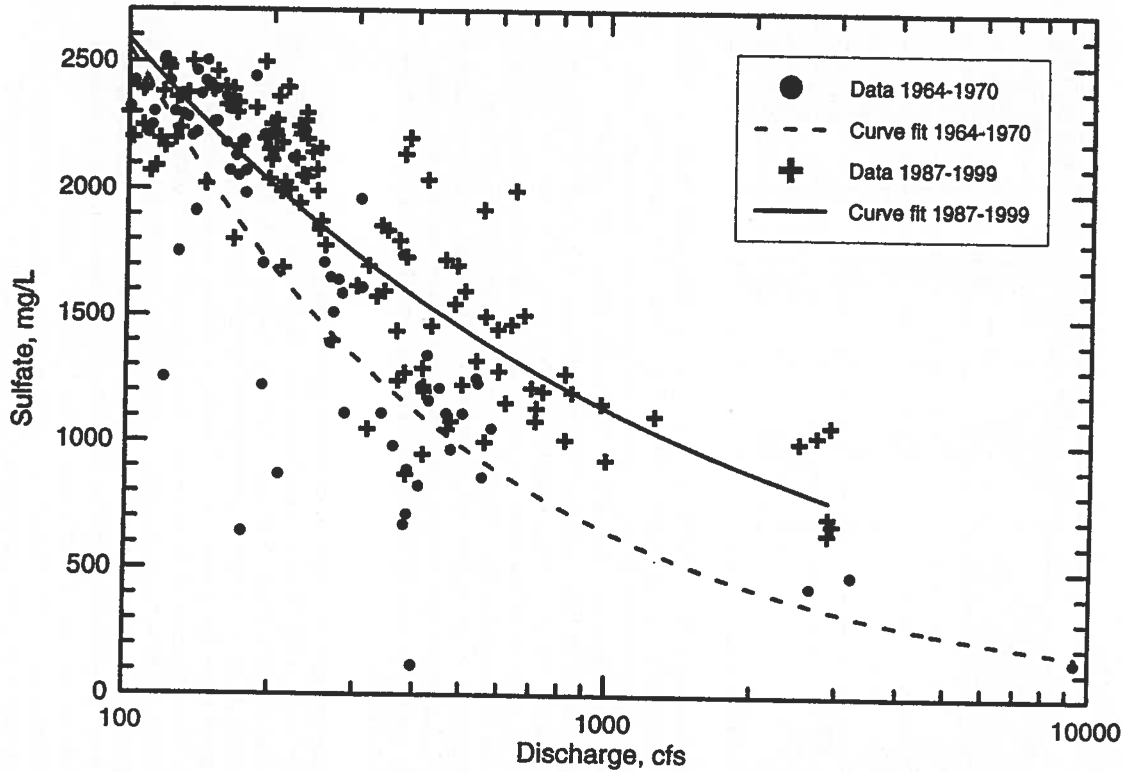


Fig. 4. Sulfate Concentration versus Discharge for the Arkansas River near Coolidge, Kansas.

Table 1. Typical chemical analyses of Arkansas River water near the Colorado-Kansas state line (at U.S. Geological Survey gaging station near Coolidge) for low, moderate, and high flows during the 1990's. All analyses are by the Kansas Geological Survey.

Date	Jan. 1, 1994	Oct. 16, 1997	May 20, 1999
Discharge, cfs (m^3/sec)	160 (4.5)	380 (10.8)	2900 (82)
Specific conductance, µS/cm	4510	3500	2260
Total dissolved solids, mg/L	4200	2890	1770
Ca, mg/L	377	300	197
Mg, mg/L	199	149	95.6
Na, mg/L	562	399	221
K, mg/L	10.5	8.9	6.5
HCO_3, mg/L	351	310	206
SO_4, mg/L	2330	1740	1070
Cl, mg/L	155	108	62.1
NO_3-N, mg/L	2.6	1.9	0.8

The fitted curves in Fig. 4 start at approximately the same sulfate value, between 2,500 and 2,600 mg/L, at a flow of 100 cfs (2.8 m^3/sec). With increasing discharge, the two curves diverge to greater differences in sulfate content with increasing discharge. At a discharge of 500 cfs (14 m^3/sec), the apparent difference in sulfate concentration indicated by the curves is about 450 mg/L or an increase of over 40% of the value for the period 1964-1970. At 1,000 cfs (28 m^3/sec) the apparent sulfate value and percentage increase are approximately 460 mg/L and 70%, respectively. The effect of removing the highest flow point {9,400 cfs (266 m^3/sec) within the period 1964-1970} on the apparent differences is small {the sulfate concentration difference decreases by only about 20 mg/L and the percentage increase falls by only a few percent at 500 and 1,000 cfs (14 and 28 m^3/sec)}.

There are two possible explanations for the apparent increase in river water salinity shown in Fig. 4: 1) increased water use and consumptive loss, and 2) a lag in the mass transfer of salts to Kansas. Increased use and consumption of water occurred in the river corridor in southeastern Colorado during the periods represented in the figure, especially of water pumped from wells in the alluvial valley. The magnitude of the salinity increase suggests that the second explanation might be the major cause. Although the discharge of the river and its tributaries in Colorado varies, over a long enough period the average annual salt load should be relatively similar for different periods. The diversion of water for irrigation in Colorado delays the movement of salt loads to Kansas by accumulating salts in soils and shallow ground waters. These delays began with the first surface irrigation system and continued with further development of diversion systems. The salt mass would be expected to build up until flushing by rain, higher diversion flows, and ground-water discharge carrying seepage from below irrigated fields and return flow canals finally re-establish the loads exiting Colorado to near their original average rate.

The variations in the salt loads of the Arkansas River entering Kansas are large. During dry periods, carbonate and sulfate salts can precipitate from irrigation water in soils. The salinities limited by mineral precipitation coupled with the low flows result in much smaller total salt loads entering Kansas than during large flushing events caused by particularly high rainfall and snowmelt. However, the lower flows with greater salinities that enter Kansas are as much of a contamination problem to aquifer water quality as high flows even though the rate of salt load is smaller.

WATER LOSSES IN THE RIVER CORRIDOR

Discharge records at stations along the Arkansas River in southwest Kansas indicate that the river has generally lost substantial flow from the state line to Garden City since the beginning of continuous flow measurements. In comparison, appreciable flow losses from Garden City to Dodge City began in the mid-1980's.

Continuous records of discharge measurements of the Arkansas River started in 1920 at Syracuse, 20.3 river miles (32.7 km) downstream of the Colorado-Kansas state line. Continuous flow records for the station near Coolidge, nearly 2 miles (3.2 km) downstream from the state line, began in 1950, and at Dodge City, 131 river miles (211 km) to the east, in 1944. The mean annual flows at Coolidge and Syracuse for 1951-1997 are within 1% of one another, thus, the record for Syracuse is an excellent substitute for budget calculations based on total annual flows. Gaging at Garden City started in 1922 but includes a period of only a flood hydrograph record from 1970 to 1986 without flow data. For several years during the middle of the 1970-1986 period, the river had very little or essentially no flow at Garden City. We estimated flows during this period based on the discharge records of the upstream and downstream gaging stations and the ditch diversion data. Errors in these estimates do not affect the total discharge differences in southwest Kansas because the Coolidge, Syracuse, and Dodge City stations were all recording during the period.

Annual flows of the Arkansas River entering Kansas have been marked by a few years of particularly large discharge interspersed with periods of intermediate and low flows (Fig. 5). The largest discharge occurred in 1941 before regulation by the John Martin Reservoir began in 1948. The largest annual flows since then were in 1965, 1987, and 1998. Annual discharges at Dodge City parallel those entering Kansas but have been decreasing relative to the state input, especially since about 1980. Many years from the late 1970's to the early 1990's the river has been nearly or completely dry and flow loss is nearly 100 percent of the

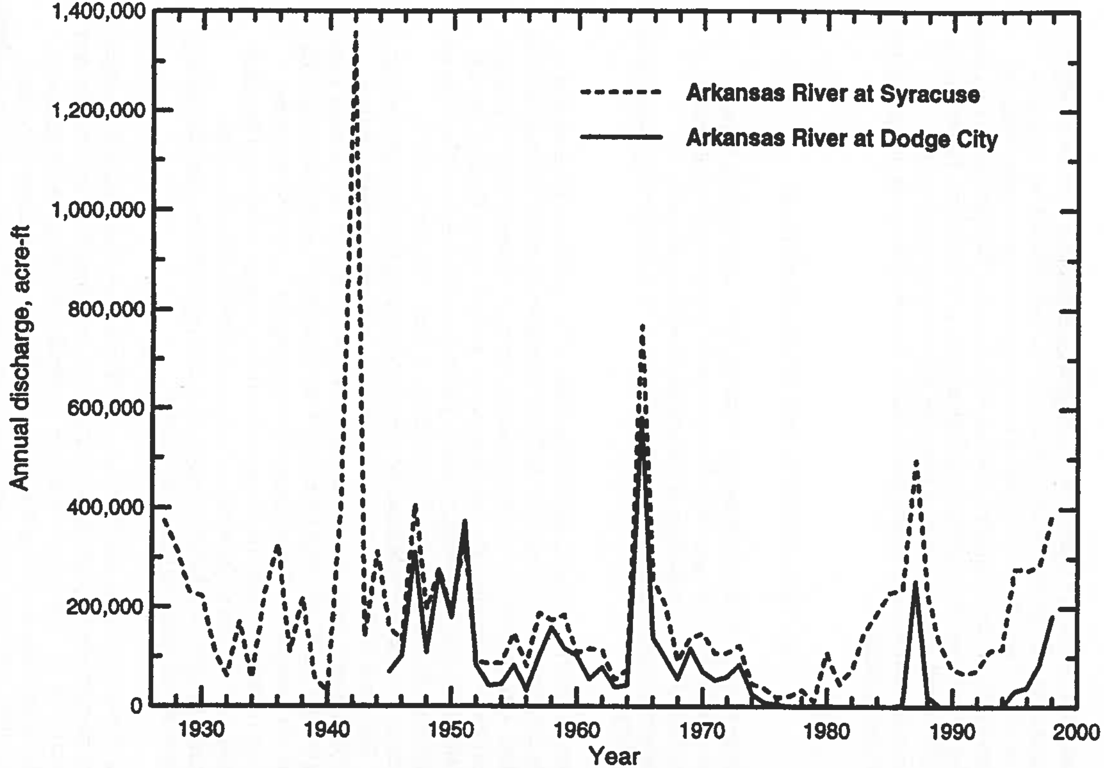


Fig. 5. Arkansas River Discharge at Syracuse and Dodge City, Kansas.

amount entering Kansas. Flow losses during the two highest recent discharge years (1987 and 1998) have been approximately 50% of the river volume crossing the state line. The total flow loss for the period 1975-1998 is 83% of the state-line discharge.

Annual flow differences between the state line and Garden City have fluctuated substantially but have all been negative except for one year, 1951, during which unusually heavy rains fell during May and June in southwest Kansas (Fig. 6). Most of the discharge difference has been due to diversions for irrigation in Kearny and Finney counties. The mean annual diversion for the main canals in the two counties for 1930-1995 is 70,700 acre-ft (8.7×10^7 m^3). For a few of the recent years, the flow loss between the state line and Garden City has been as high as about twice the total diversion for the particular year.

The river water lost from the state line to Garden City comprises a combination of evapotranspiration consumption and infiltration to the High Plains aquifer. Most of the water diverted for irrigation is consumed by evapotranspiration. Water-level and ground-water quality data indicate that substantial amounts of diverted water infiltrate to the aquifer. The combined soil moisture from rainfall and flood irrigation with diverted river water increases the degree and length of time for conditions during which recharge can occur. A small amount of return flow from the irrigated areas entered the river. In addition, some recharge from irrigated areas over the alluvial aquifer could have returned to the river. However, both of these mechanisms of surface return flow are accounted for in the flow loss differences because they would have primarily occurred upstream of Garden City. Substantial amounts of water were also lost from transpiration by phreatophytes, particularly tamarisk (salt cedar) and cottonwood trees, along the river and by evaporation from the surface of the broad, shallow river.

The recent large losses that substantially exceed irrigation diversions and phreatophyte consumption are infiltration from the river channel to the alluvium and thence to the underlying High Plains aquifer. The appreciable increase in ground-water withdrawals for irrigation from the High Plains aquifer during the 1970's caused water-level declines that allowed alluvial water to recharge the underlying aquifer. The recharge from the river is the main cause for discharge losses from Garden City to Dodge City (Fig. 7). Except for unusually large flow years, such as 1965, the Arkansas River gained flow between Garden City and Dodge City up to the mid-1970's. This would have also been true of the state line to Garden City section of the river before the onset of diversions within Kansas in the late 1800's because water levels in the High Plains aquifer prior to substantial pumping were higher than the river (McLaughlin, 1943; Latta, 1944). Most of the flow loss during 1965 (Fig. 7) would eventually have been returned from bank storage to the river during the years immediately following the high flow.

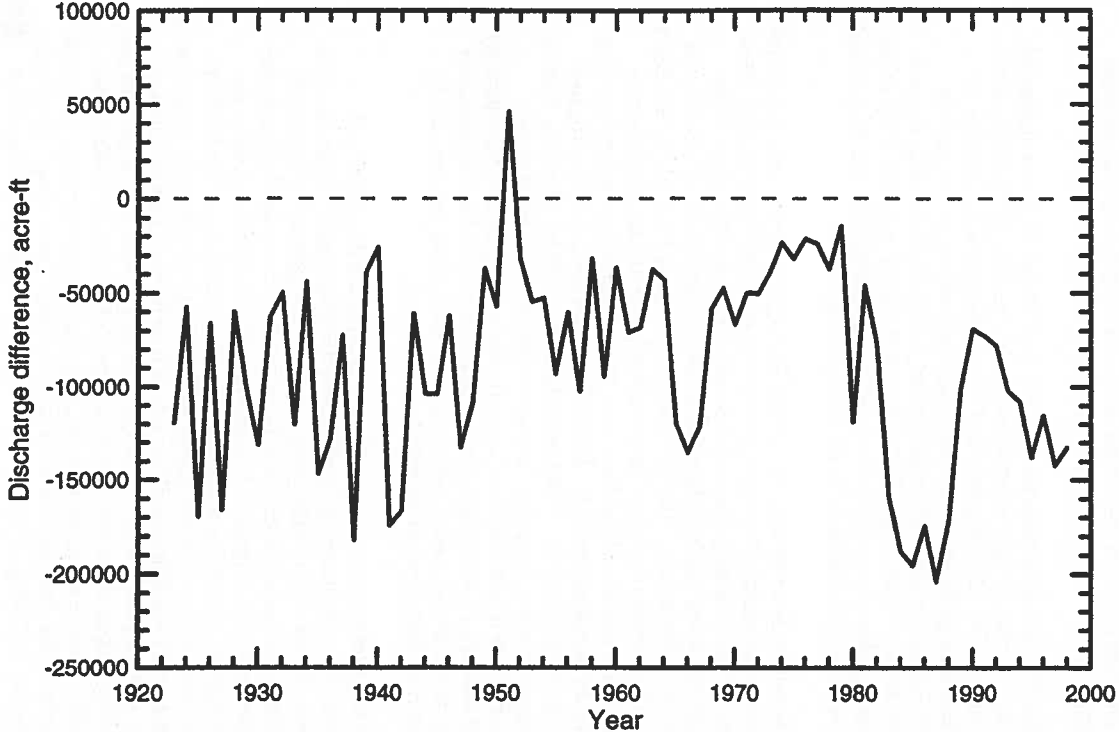


Fig. 6. Difference in Annual Discharge for the Arkansas River between the Colorado-Kansas State Line and Garden City, Kansas. Negative values indicate flow loss.

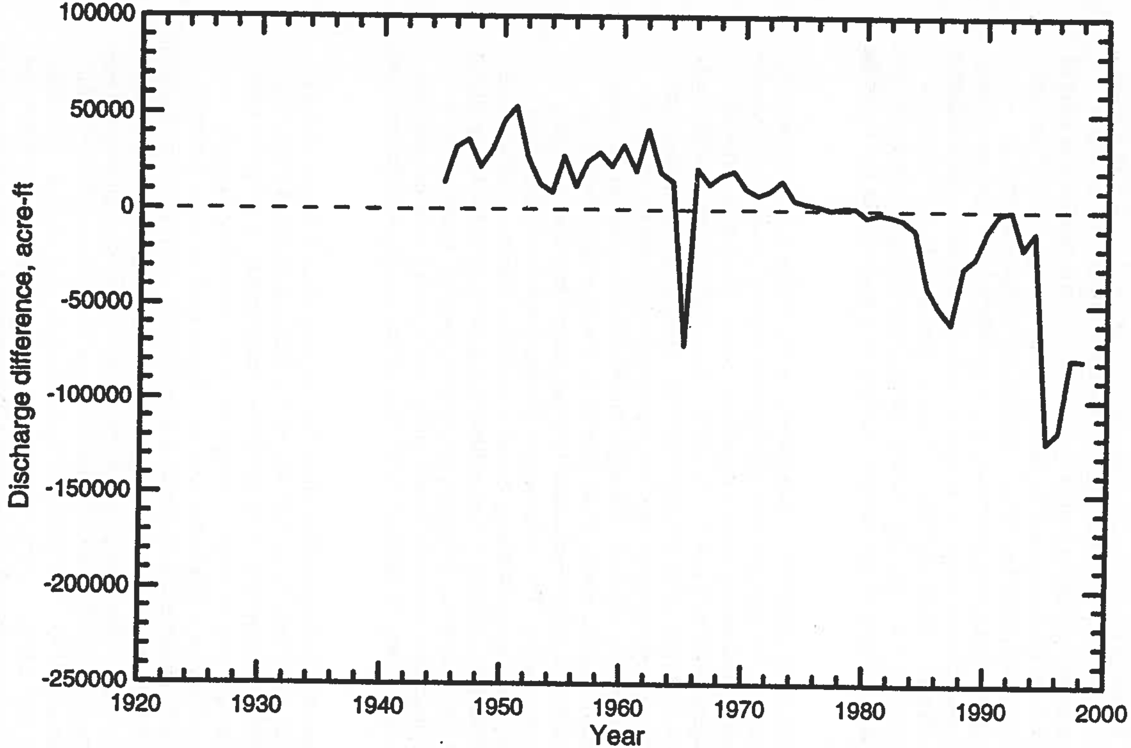


Fig. 7. Difference in Annual Discharge for the Arkansas River between Garden City and Dodge City, Kansas. Negative values indicate flow loss.

SALINITY BUDGETS AND AQUIFER CONTAMINATION

The total amount of sulfate mass accumulating in the Arkansas River corridor in southwest Kansas is the difference in the mass entering and leaving the system. The inputs include sulfate (or the sulfur equivalent to sulfate) in river water flowing across the state line, subsurface ground-water flow into the area, rainfall falling on the soil, gases extracted by plants from the atmosphere, fertilizer and other agrochemicals applied to the soil, animals and associated feed and chemicals (and associated animal waste) imported into the area, and transported miscellaneous chemicals related to human commercial, industrial, and residential activities. Outputs include the sulfate (or sulfur equivalent) in river water and subsurface ground water flowing out of the area, gases returned to the atmosphere by plants, and agricultural, commercial, and industrial products shipped out of the area.

The largest mass of sulfate that enters and leaves the system is in the river surface water. Ground water flow into and out of the corridor area in the alluvial aquifer approximately balances and is not a significant factor. The concentration of sulfate in rainwater is very low (on the order of one to a few mg/L) and the input mass is less than a percent of the mass difference in the river input and output. Atmospheric absorption and release by plants is also small and the input and output approximately balances. The high concentration of sulfate in the canal irrigation water and the ground water affected by the river water infiltration provide much more sulfur than needed by crops, therefore sulfur-containing fertilizer is not needed. The sulfur mass in chemicals brought in for animal production probably approximately balances the sulfur mass removed when the animal products are shipped; the mass difference is not expected to be significant relative to the river fluxes. Likewise, the sulfur in materials related to other human activities that could affect water quality are expected to be insignificant relative to river water. In addition, inputs and outputs would counterbalance each other.

Other than water, the largest mass of material entering and exiting the corridor area and that could enter the sulfate budget is probably agricultural crops. Grain grown in fields irrigated by river water would incorporate some sulfur from the water. Although some of the grain is used as animal feed within the river corridor, grain is also shipped out of the area. Plants draw up water through a semipermeable membrane in the plant roots and exclude most of the salt dissolved in the soil water. However, some of the salt does enter the plant, including sulfur, which is a nutrient. The average sulfur content of the grain from an irrigated acre of crops ranges from 7 lbs/acre (8 kg/ha) for wheat to 30 lbs/acre (34 kg/ha) for alfalfa (Lamond, 1997). The values for soybeans, corn, and sorghum fall within this range. The average for the 5 crops is 17 lbs/acre (19 kg/ha). The equivalent amount of sulfate dissolved in an acre-foot of water would give a concentration of 19 mg/L. This concentration is about 1% of the average sulfate content of

Arkansas River water entering Kansas during the last decade. In general, the higher the soil moisture salinity, the higher can be the amount of many elements drawn into the plant in the water. Even if the sulfur content of the plants irrigated with saline river water were two or three times the average, and all of the crops were removed from the corridor, the total mass would only be a few percent of that accumulating from river water losses.

Therefore, mass budgets for sulfate in the river water provide a good estimate of the sulfate mass accumulating in the river corridor in southwest Kansas. We computed the budgets for two areas: the state-line to the Garden City gaging station and from the Garden City to the Dodge City gaging station. We summed the net input for three periods: pre-1950, 1950-1975, and 1975-1997. The pre-1950 period approximately represents the first half of flow losses in the system since the start of river water irrigation. The 1950-1975 interval is for the transition period of increasing ground-water use and spans the data record for the 1964-1970 sulfate-discharge curve in Fig. 4. The 1975-1997 interval spans the data period for the second sulfate-discharge curve; the start of the interval is the beginning of little or no flows for several years at Dodge City and the transition to net annual flow losses within the Garden City to Dodge City corridor. We calculated the net loss for the Garden City to Dodge City area only for this 1975-1997 interval.

Although irrigation diversions from the Arkansas River started in the early 1880's in southwest Kansas, the systems did not become extensive until about 1910 when the sugar beet industry grew substantially. Since the mid 1900's, sugar beets have not been a crop irrigated by river water in the area but have been replaced principally by grain and forage crops. The large growth of phreatophytes along the river began after the turn of the century. We used a period of 50 years at the average conditions for the flow records of 1923-1949 available for both Syracuse and Garden City for the pre-1950 losses. Forty years at the average 1923-1949 conditions should represent reasonably well the period 1910-1949 based on the 1910 start of larger diversions. The additional 10 years at the average 1923-1949 conditions should be a conservative approximation of the total losses from the early 1880's to 1910. As indicated earlier, total annual flow at the Syracuse gage is a good approximation of the annual discharge near the state line. Losses for the other two periods are based on the Coolidge (except for 1950) and actual and estimated Garden City flow records. Volume losses for the two river segments are in Table 2.

Estimates of average sulfate concentrations in the river water are necessary to compute the mass accumulation. We computed the average discharge for each of the periods for the river segments (Table 2). We estimated the sulfate concentrations for the 1950-1974 and 1975-1997 periods from the two curves in Fig. 4. The estimate for the pre-1950's period is an approximation for somewhat less saline waters based on the observation that the salinity in the river water has

Table 2. Computations of flow losses, sulfate mass accumulated, and average sulfate concentration added to aquifer. The water volume in the aquifer includes that underlying a zone along the river, the diversion-irrigated area, and a ground-water mixing zone.

	Average annual flow loss 1923-1949	Total flow loss for 50 years at 1923-1949 average	Total flow loss for 1950-1974	Total flow loss for 1975-1997	
State line to Garden City	99,680 acre-ft/yr (1.230×10^8 m^2/yr)	4,984,000 acre-ft (6.148×10^9 m^2/yr)	1,501,000 acre-ft (1.852×10^9 m^2/yr)	2,419,000 acre-ft (2.984×10^9 m^2/yr)	
Garden City to Dodge City				550,700 acre-ft (6.793×10^8 m^2/yr)	
		Average sulfate content of river water 1923-1949	Average sulfate content of river water 1950-1974	Average sulfate content in river water 1975-1997	
		1050 mg/L	1600 mg/L	2000 mg/L	
		Sulfate mass accumulated for 50 years at 1923-1949 average	Sulfate mass accumulated for 1950-1974	Sulfate mass accumulated for . 1975-1997	Total sulfate mass accumulated from early 1880's to 1997
State line to Garden City		6.46×10^9 kg	2.96×10^9 kg	6.46×10^9 kg	15.39×10^9 kg
Garden City to Dodge City				1.36×10^9 kg	1.36×10^9 kg
					Water volume in aquifer
State line to Garden City					13,570,000 acre-ft (16.74×10^9 m^3)
Garden City to Dodge City –	Alluvial and main part of High Plains aquifer				3,264,000 acre-ft (4.026×10^9 m^3)
	Alluvial aquifer only				1,152,000 acre-ft (1.421×10^9 m^3)
					Average sulfate concentration added to aquifer
State line to Garden City					919 mg/L
Garden City to Dodge City –	Alluvial and main part of High Plains aquifer				337 mg/L
	Alluvial aquifer only				956 mg/L

been increasing. Use of the 1964-1970 curve in Fig. 4 for the pre-1950's estimate would give a greater sulfate mass. The average flows decrease and the sulfate concentrations increase for each of the successive three periods (Table 2).

An estimate of the average sulfate concentration in the ground water in the corridor is given by division of the total sulfate mass accumulated by the estimated volume of aquifer water into which the sulfate mass has migrated. The total area assumed for infiltration of the river water includes a zone along the river, the area irrigated by river water, and a mixing zone in the direction of ground-water flow. We estimated the zone along the river to be a 2 mile- (3.2 km) wide band representing migration up to one mile (1.6 km) on either side of the channel. The irrigated area includes all square mile sections (a section is a surveyed unit of the former U. S. General Land Office) within the irrigation company boundaries, even though not all of the area has been consistently irrigated, all sections with 20 acres (8 ha) or more irrigation outside the company boundaries as indicated in a 1942 survey, and all non-irrigated sections surrounded by these irrigated areas. We estimated that the mixing zone extends 3 miles (4.8 km) to the east of all sections that were indicated as irrigated by diversions in the 1942 survey. The 3-mile (4.8 km) distance approximately fits the observed distribution of sulfate in the aquifer outside the irrigation company boundaries. Some of the described areas overlap, such as where the irrigation company boundaries include the zone along the river.

There are two types of aquifer areas included in the state line to Garden City segment of the Arkansas River corridor. An alluvial trench in bedrock exists from the state line to southwest Kearny County. The two-mile (3.2 km) band along the river sums to 80 mi^2 (207 km^2) in this segment. The estimated average saturated thickness of the alluvial aquifer for this zone is 40 ft (12 m). The Ogallala portion of the High Plains aquifer is present to the east of this alluvial aquifer band and the combined saturated thickness of the alluvial and Ogallala portions of the aquifer exceed 300 ft (90 m) in some locations. The saturated thickness is less today than before development of extensive ground-water withdrawals for irrigation. The total surface area between the Coolidge and Garden City discharge gages, into which river water from the channel and diversion systems could have seeped and migrated in the subsurface, is 270 sections or mi^2 (699 km^2). The estimated average thickness of the currently saturated portion of the High Plains aquifer in this area is 250 ft (76 m).

The Garden City to Dodge City segment of the corridor does not include any extensive diversion systems; only one small ditch in the flood plain is active when river flows are sufficient. A two-mile (3.2 km) wide band along the river sums to about 100 mi^2 (260 km^2) for this segment. The average saturated thickness based on recent water level measurements for the High Plains aquifer is approximately 170 ft (52 m).

The quantity of water in the aquifer volume that can be affected by the saline recharge within the time frame of decades is primarily dependent on the average porosity of all the sediments but the thickest clay units. Although the initial quantity of aquifer water impacted by saline recharge is dependent mainly on the specific yield, dispersion of salinity into fine-grained sediments would occur over a longer time. Some of the water within the interior of the least permeable, thick clays could take multiple decades to reach the salinity in the more permeable sediments because the limiting transport mechanism would be diffusion.

The porosity of aquifer sediments is greater than the specific yield. The specific yield range used by the USGS in past models for the upper Arkansas River valley was 0.14-0.20 (Barker et al., 1981; Dunlap et al., 1985). This range is somewhat smaller than average for sediment textures such as listed in Fetter (1994) implying that there are many zones of fine-grained deposits and also that some of the coarser-grained sediments could be poorly sorted. Based on the above and porosity ranges for sediments in Fetter (1994), we used an average porosity of 0.3 for the High Plains aquifer to calculate the water volume. The resulting volumes calculated for the two river segments are listed in Table 2.

The mass/volume calculations indicate that, if all the sulfate mass added had time to mechanically disperse uniformly into the sediments, the average sulfate concentration added to the aquifers in the state line to Garden City portion of the corridor would be 920 mg/L. A calculation made for the major areas irrigated by river water in Kansas alone, based on a similar procedure as for the state line to Garden City segment of the corridor and using the amounts of water diverted, gives a similar average concentration for the aquifer underlying the irrigation systems and a ground-water mixing zone to the east of the irrigation area. These values should be added to the estimated sulfate content of the aquifer existing before the effect of Colorado irrigation systems on the river water quality. The two-mile (3.2 km) wide band of the alluvial aquifer along the Arkansas River from the state line to southwest Kearny County might have contained sulfate concentrations of up to several hundred mg/L in some locations during particularly dry years before the start of river diversions in Colorado. South of the Arkansas River, sulfate concentrations in the uncontaminated part of the High Plains aquifer are less than 50 mg/L. North of the Arkansas River, the aquifer just outside of the river-irrigated area contains water with a sulfate content generally within the range 50-200 mg/L; this range is expected to be the natural background before the impact of anthropogenically induced salinity.

The measured sulfate concentrations in well-water samples range widely depending on location and depth in the aquifer system. However, if the values were averaged, the concentration would generally fit the sum of the estimated naturally occurring and anthropogenically added contents based on the calculation above. Sulfate contents for alluvial aquifer waters along the Arkansas River in Hamilton and Kearny counties are greater than 2,000 mg/L in some locations.

Fig. 8 shows the sulfate concentration in samples from wells greater than 60 ft (18 m) deep (below the alluvial aquifer) in the Kearny and Finney county area of the Arkansas River corridor. There are large areas where the sulfate concentration exceeds 1,000 mg/L. Some of the wells yield waters with greater than 1,500 mg/L.

The calculated average concentration of sulfate in the entire aquifer underlying the river zone from Garden City to Dodge City is an appreciably smaller concentration. Water-level declines have not been as great along this stretch of the river and the river has been dry many of the years since the late 1970's. These factors, along with the presence of a less permeable zone underlying the highly permeable alluvium that slows downward migration to the main High Plains aquifer, have resulted in restricting the high sulfate concentrations primarily to the alluvial aquifer. For example, just to the west of Dodge City, multi-level observation wells 0.25 mile (0.64 km) south of the Arkansas River show a measured sulfate concentration of over 1,500 mg/L in the alluvial aquifer and about 50 mg/L from the top to the bottom of the underlying High Plains aquifer. A recalculation of the sulfate concentration for the Garden City to Dodge City segment, that would be appropriate for the alluvial aquifer, gives an average sulfate concentration of 960 mg/L added to the system if the aquifer thickness affected is only 60 ft (18 m).

FUTURE CONDITIONS

The saline water flowing in the Arkansas River from Colorado and accumulating in southwest Kansas has contaminated some of the ground waters supplying cities and towns along the river corridor. Some municipalities have drilled new wells farther from the river to obtain fresher ground water. The salinity of other water supplies is increasing as the accumulated sulfate migrates downward and in the direction of ground-water flow in the aquifer. Based on conditions during the last decade and the existing accumulation of salinity, in about 50 years river water seepage has the potential to contaminate all of the High Plains aquifer underlying 500 mi^2 (1,300 km^2) of the corridor to a sulfate concentration over 1,000 mg/L. This concentration is four times the recommended level for drinking waters.

The increase in sulfate concentration from river channel seepage is mainly dependent on the river water quality. In general, the higher the river discharge entering Kansas, the lower the salinity. The annual mean flow for the longest gaging record that reasonably represents state-line flows (Syracuse station, 1903-1906 and 1920-1998) is 295 cfs (8.4 m^3/sec). The annual mean for the station near the state line (Coolidge) is for the period 1951-1998 and is smaller, 215 cfs (6.1 m^3/sec). The estimated average concentrations of sulfate (based on Fig. 4) for the two mean flows at Syracuse and Coolidge are 1750 mg/L and 1930 mg/L, respectively, a difference of nearly 200 mg/L. Therefore, natural climatic

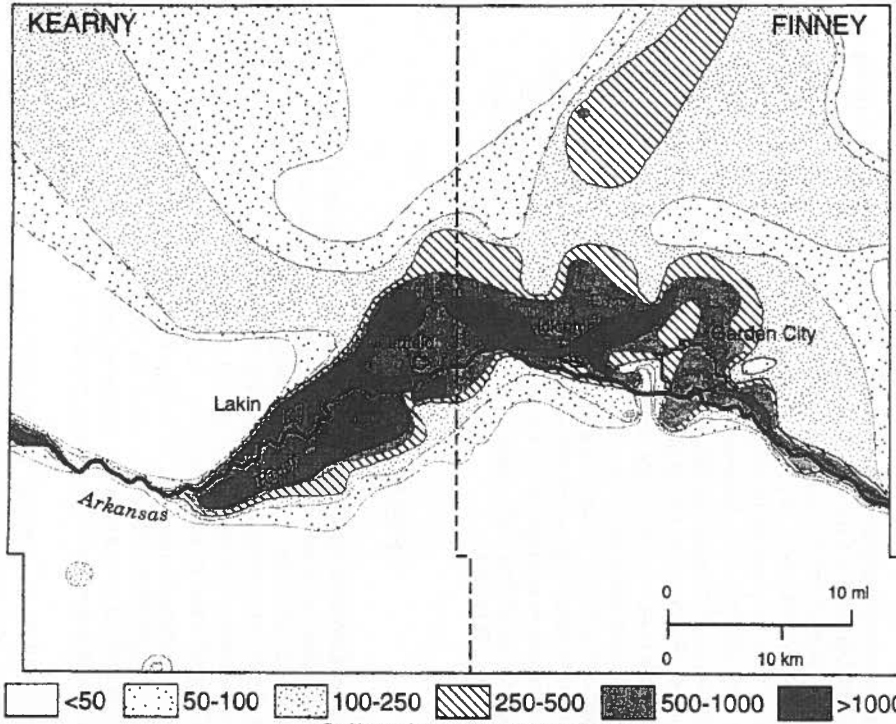


Fig. 8. Sulfate Concentration in Ground Water of the Arkansas River Corridor in Kearny and Finney Counties
The data used are for wells >60 ft (18m) deep for 1986 - 1995.

variations and the use of water in Colorado are very important to the quality of water received by Kansas.

In addition, there is a limited rate at which the water in the alluvial aquifer can migrate through the lower permeability zone, often present below the alluvium, to the underlying High Plains aquifer. Higher river discharge results in channel flow that extends throughout Kansas and carries substantial sulfate loads downstream out of the state. Extended low-flow periods can result in a dry river bed and the accumulation of all the salinity mass within southwest Kansas. Management of water storage and releases in Colorado are therefore also important to the amount of aquifer contamination in Kansas aquifers.

The river water that recharges the aquifer, even if saline, is a valuable resource. The recharge of the High Plains aquifer by river water seeping from the river channel and infiltrating below the ditch-irrigated areas is on a scale similar to other recharge projects in the United States costing many millions of dollars. As water treatment technologies become more cost efficient, desalinization of a local supply might become competitive with distant transport of freshwater if water-levels continue to decline at substantial rates in the High Plains aquifer. However, management and protection of the existing fresh ground waters in the corridor will probably be more economical for municipal, agricultural, and industrial uses.

CONCLUSIONS

Postel (1999), in her book "Pillar of Sand", has likened the salinity problems that can result from developing irrigation diversions in dry areas to a "Faustian bargain". She writes that "In return for transforming deserts into fertile fields and redirecting rivers to suit human needs, nature is exacting a price in myriad forms. Among the most threatening is the scourge of salt – the creeping, insidious menace that undermined the stability of several irrigation societies, and that now places ours in jeopardy as well." Although the salinity problems in southeastern Colorado and southwestern Kansas are not be as severe as in ancient Mesopotamia, and today in river plains of Pakistan, India, China, and the Aral Sea and Colorado River basins, they bear consideration for the future. Just as in many of the past and current areas of salinization where parts of the river systems lie in different countries, Kansas and Colorado will need to resolve cross boundary issues. The Arkansas River Compact of 1948 has been one mechanism that addresses water use in these two states but not salinity concerns. Sherow (1990) describes the history of the Compact and other "quarrel and rapport" between Colorado and Kansas in his book "Watering the Valley."

Irrigation companies and local, state, and federal agencies in Colorado and Kansas are working to understand the water-use and salinity issues and to develop possible management approaches to mitigate the salt impacts. We are developing mass transport simulations to examine the saline water migration under current conditions and to evaluate some of these possible management actions. The simulations involve recharge from the river and ditch irrigated areas, ground-water flow, and sulfate mass transport. The results will allow a more specific determination of the amounts and locations of saline recharge that are consistent with known patterns of aquifer contamination.

REFERENCES

Barker R.A., Dunlap, L.E., and Sauer, C.G., 1981, Analysis and computer simulation of stream-aquifer hydrology, Arkansas River valley, southwestern Kansas: U.S. Geological Survey Water-Supply Paper 2200, 29 p.

Dunlap L.E., Lindgren, R.J., and Sauer, C.G., 1985, Geohydrology and model analysis of stream-aquifer system along the Arkansas River in Kearny and Finney counties, southwestern Kansas: U.S. Geological Survey Water-Supply Paper 2253, 52 p.

Fetter, C.W., 1994, Applied Hydrogeology: Macmillan, New York, 691 p.

Lamond, R.E., 1997, Sulphur in Kansas, plant, soil, and fertilizer conditions: Kansas State University Agricultural Experiment Station and Cooperative Extension Service, Rep. MF-2264, Lawrence, KS, 4 p.

Latta, B.F., 1944, Geology and ground-water resources of Finney and Gray counties, Kansas: Kansas Geological Survey, Bulletin 55, Lawrence, KS, 272 p.

McLaughlin, T.G., 1943, Geology and ground-water resources of Hamilton and Kearny counties, Kansas: Kansas Geological Survey, Bulletin 49, Lawrence, KS, 220 p.

Postel, S., 1999, Pillar of Sand – Can the Irrigation Miracle Last?: W.W. Norton, New York, 313 p.

Sherow, J.E., 1990, Watering the Valley: University Press of Kansas, Lawrence, Kansas, 222 p.

U. S. Geological Survey, 1995, Water resources data, Kansas, Water Year 1995: USGS Water-Data Rep. KS-95-1, Lawrence, KS.

IMPROVING SUBSURFACE DRAINAGE DESIGN AND MANAGEMENT TO REDUCE SALT LOADS FROM IRRIGATION AREAS IN SOUTHEASTERN AUSTRALIA

Dr Evan Christen[1] Dominic Skehan[1]

ABSTRACT

A field investigation on a new vineyard in the Murrumbidgee Irrigation Area showed that improved subsurface drainage systems reduce salt loads in drainage water whilst providing waterlogging and salinity control. By only draining the rootzone the drainage volume and salinity were greatly reduced.

Improved design and management options were tested against the current practice of deep pipe drains (1.8 m depth) widely spaced (20 m apart) allowed to drain continuously. This drain configuration was managed to prevent flow when the water table was deeper than 1.2 m from the soil surface, and not during irrigations. This resulted in a 50 % reduction in the drainage salt load. Shallow (0.7 m depth) closely spaced drains (3.65 m apart) were also tested and reduced the drainage salt load by 95 % when compared to the unmanaged deep drains.

This improved design and management will significantly reduce the amount of salt that requires disposal. This work, together with other field and modeling studies, has been used to develop a set of guidelines for subsurface drainage with the aim of improving drainage water quality.

INTRODUCTION

The irrigation areas in southeastern Australia have developed shallow water tables to the extent that about 80 % of many irrigation areas experience water

[1] Respectively, Research Engineer and Technician, CSIRO Land and Water, PMB No.3, Griffith, New South Wales, 2680, Australia.

tables within 2 m of the soil surface. These water tables create serious problems of waterlogging and land salinisation.

In the past waterlogging has been controlled by the installation of subsurface drainage (tile drainage) which lowers water tables. This has been successful in horticultural farms of the Murrumbidgee Irrigation Area (MIA), Shepparton Irrigation Region and the Riverland along the Murray river. However, the nature of subsurface drainage is such that large amounts of salt are exported in the drainage water. At the time of installation the downstream consequences of salt export were not considered.

Subsurface drainage schemes have been targeted as areas for salt export reduction, since the drainage water is normally an order of magnitude more saline than surface drainage waters. In the MIA, the Land and Water Management Plan (LWMP)(DLWC 1998) identifies subsurface drainage as a major salt exporter from the area. About 30 % of the salt load leaving the area is from subsurface drainage, although only 7 % of the area has subsurface drainage installed. The MIA L&WMP set a goal of a 25 % reduction in the salt load from existing subsurface drainage.

In the MIA, new horticultural developments are to a large extent on the heavier soils that were previously used for annual crops such as rice and vegetables. These soils are quite different from those previously associated with horticulture, which were more freely draining lighter textured soils. Thus, new drainage design and management are required to reduce salt loads and provide effective drainage in heavy clay soils.

RESEARCH AIMS AND OBJECTIVES

The research aims were to investigate and develop new subsurface drainage design and management techniques to reduce the salt load from subsurface drainage in horticultural developments in the Riverine Plain of southeastern Australia, and provide a set of guidelines for water managers, installers and users of subsurface drainage. Specific objectives were:

1/ Develop and test improved subsurface drainage designs for clay soils that provide effective drainage of the rootzone whilst minimising salt mobilisation in the drainage water;

2/ Develop and test management practices for existing subsurface drainage systems to minimise salt export;

3/ Determine if deep drains with improved management are as effective as shallower drains in managing waterlogging and reducing salt mobilisation.

METHODOLOGY

Site Description

New subsurface drainage design and management strategies were tested in a replicated field trial on a newly established vineyard in the MIA, situated 30 km north east of Griffith, NSW, Australia. The vineyard was 2 years old, and was previously used for growing rice. The soil was a Griffith Clay Loam, Butler (1979). The top 0.3 m is a clay loam that becomes progressively heavier with depth down to about 0.9 m and then continues as a medium clay. The deep subsoil ranges from a light to heavy clay with soft and hard carbonate. Irrigation was applied down narrow furrows on both sides of the vines. Irrigations were about 8 hours in duration every 10 - 14 days. The irrigations were well managed with rapid advance times, about 4 hours to reach the bottom of the 400 m vine row, and only a small amount of run-off. The irrigation furrows were maintained in good condition.

Drainage Treatments

Drainage treatments installed in the experiment were:
1/ *Deep Drains* - Pipe Drains (100 mm slotted plastic pipe) at 1.8 m deep and 20 m apart, allowed to flow continuously. This represented current drainage design and management practices.

2/ *Managed Deep Drains* - Pipe drains configured as in treatment 1 above were managed to flow only when the water table was within 1.2 m of the surface, and not during irrigations.

3/ *Shallow Drains* - Shallow 'Mole' drains, 3.6 m apart and 0.7-0.8 m deep. A Mole drain is an unlined soil tunnel formed by soil compression.

4/ *No Drainage* - No subsurface drainage.

These treatments were chosen to:

1. Assess shallow closely spaced drains in providing effective drainage of the root zone, whilst minimising salt mobilisation, after work by Muirhead *et al.* (1995) and Deveral and Fio (1991).
2. Test the practice of managing existing drains to flow only when watertable levels are critical and not during irrigations, after work by Ayers (1996).
3. Determine if deep drains with improved management are as effective as shallower drains in reducing salt mobilisation, whilst managing waterlogging and rootzone salinity.

Experimental layout

The experiment was laid out in two blocks of equal area with complete randomisation in each block. Each treatment was 70 m long of varying width. Each individual drainage replicate had it's own sealed collector drain running to the pump sump where measurements of drainage quantity and quality were made, see Fig. 1.

Experimental Measurements

The experimental measurements aimed to quantify the drainage volume and salinity from each treatment and compare this with the effect of each treatment on water tables and soil salinity. Crop measurements were also made to ascertain the overall effect of the drainage treatments on vine growth and yield.

Irrigation applied to the vineyard was measured at the Dethridge wheel, which was calibrated using a Doppler ultrasonic flowmeter. Irrigation water salinity was sampled several times during each irrigation. Rainfall was measured at the sump and run-off was estimated at 10% of water applied.

Drainage discharge from individual treatments was measured manually at the pump sump. Measurements were taken at around half hourly intervals at times of peak flows after irrigation and at subsequently larger intervals as the flow rates declined. Drainage samples for electrical conductivity and chloride were taken in conjunction with the flow rate measurements.

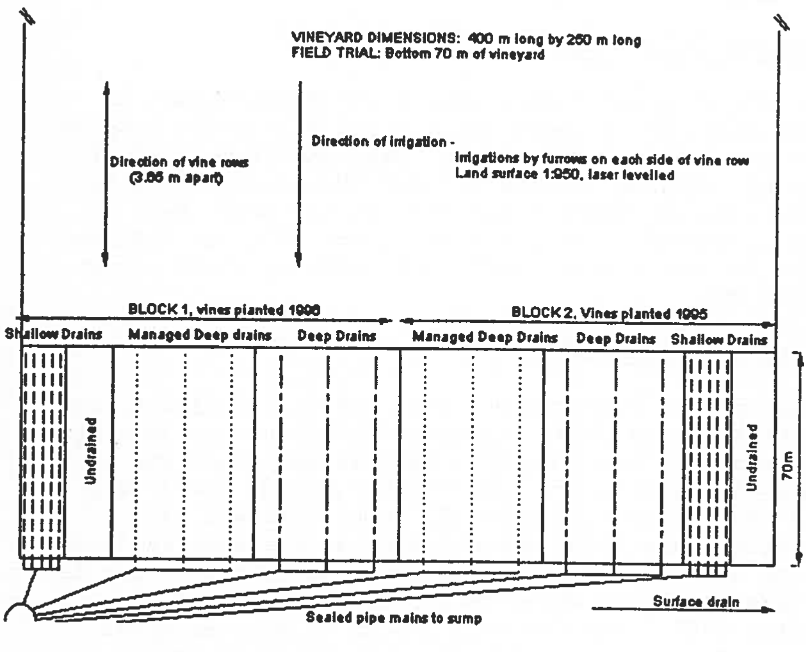


Fig. 1. Field Experiment Layout

Watertables and piezometric levels in each drainage treatment were measured using 1 m test wells and 3 m piezometers. These were situated in the vine row between drains in the shallow drainage treatments, and above and between the drains in the deep drainage treatments. These were logged at half hourly intervals.

Soil salinity was measured after each irrigation season by soil sampling to 2 m and EM38 survey and leaf chloride and yield measurements were undertaken at the end of the experiment. A detailed description of the site, treatments and measurements can be found in Christen and Skehan (1999).

Climatic Conditions

The MIA climate is described as 'Mediterranean' or semi-arid. The summers are hot and dry, while winters are mild with frosty nights. Mean annual rainfall is 418 mm, ranging between 140 and 700 mm. Rainfall is fairly evenly distributed through the year. Mean annual potential evapotranspiration (ETo) is 1800 mm. Only for the winter months does mean rainfall almost match ETo.

Seasonal Conditions

Experimental measurements were taken from January 1997 until February 1998, encompassing almost two growing seasons that are typically between September and February. During the experimental period there were few periods of high rainfall. Most rainfall was in small amounts which was absorped at the soil surface. There was only one rainfall event of 30 mm, on the 12th of January 1998, which caused the drains to flow. During 1997 there was only 336 mm of rain in total compared to the annual average at Griffith of 418 mm. The probability of exceedance of 336 mm of rainfall at Griffith is 70 %, when analysing the entire 121 year rainfall record.

RESULTS

Drain Flow

The different drainage treatments resulted in markedly different drainage volumes and salinities, and hence salt loads. The differences in flow resulted from the drain position in the soil profile and the management of the drains. The Deep Drains flowed continuously for the irrigation seasons, a small saline flow being sustained between irrigations and a large flow during and just after irrigation, Fig. 2.

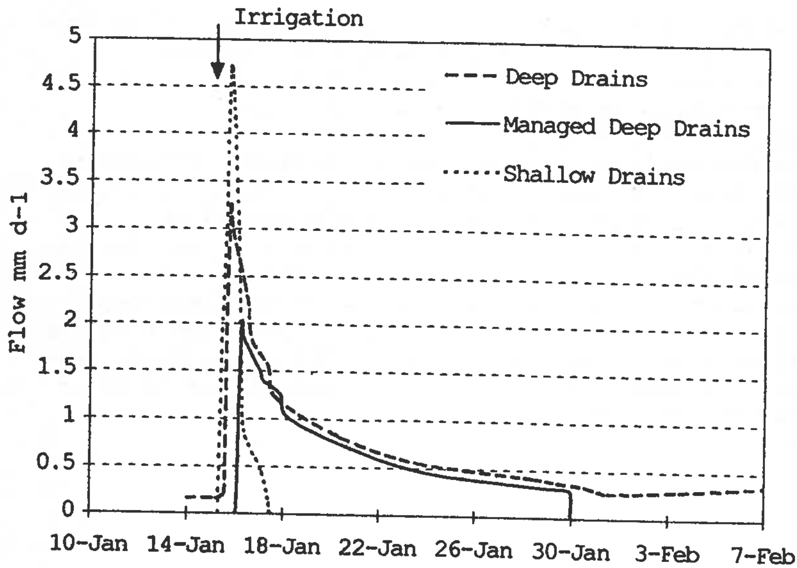


Fig 2. Treatment Hydrographs During and After an Irrigation

The Deep Drains continued to flow long after the Shallow Drains had ceased because they were draining a larger soil volume, down to 1.6-1.8 m, and they were influenced by regional groundwater pressures, Deverel and Fio (1991) also reported this effect. Regional groundwater effects were demonstrated by a 0.5 m rise in piezometric levels at the beginning of the irrigation season before any irrigations had been applied at the site.

The Managed Deep Drains were influenced less by these regional effects as they were prevented from flowing when the watertable reached 1.2m deep. The Shallow Drains had the shortest flow durations with the highest peak flows. This is due to only draining a shallow soil depth and the regional potentiometric level being below these drains.

Drain Water Salinity

Irrigation water salinity during the trial varied from 0.1-0.2 dS m^{-1}. There were significant treatment differences in the overall drain water salinity and in the variation in salinity over time, Fig. 3. Initially, the Deep Drains maintained a fairly constant salinity both during and between irrigations apart from a slight reduction in salinity at the time of the irrigation. This was probably caused by irrigation water flowing preferentially to the drains through the more permeable trench above the drain. In comparison, the managed drains had lower drain water salinities, with the lowest salinity drainage from the shallow drains. Muirhead *et al.* (1995) also found that discharge from shallow drains had much lower salinity than that from deep drains.

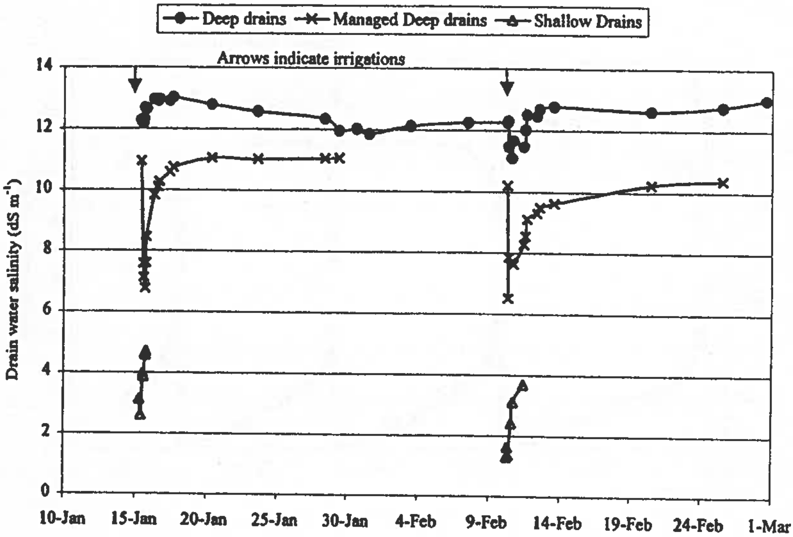


Fig. 3. Drain Water Salinity over the Period of the 3rd and 4th Irrigations

Watertable Depth and Drain Water Salinity

The watertable response under the Deep drains, Fig. 4, shows that a deep pipe drainage system, without major groundwater inflow from surrounding areas, only needs to be run for 2 to 7 days after an irrigation to lower the watertable below the root zone. After which turning off the pump can discontinue further drainage.

When the water table was shallow, during and just after an irrigation, the drainage water salinity was low, as the water table receded the drainage water salinity became more saline, Fig. 4. This is because drainage water salinity is a function of the depth of dominant water flow paths, Jury (1975) and in these soils the groundwater salinity is around 12 dSm^{-1} and soil salinity increases with depth.

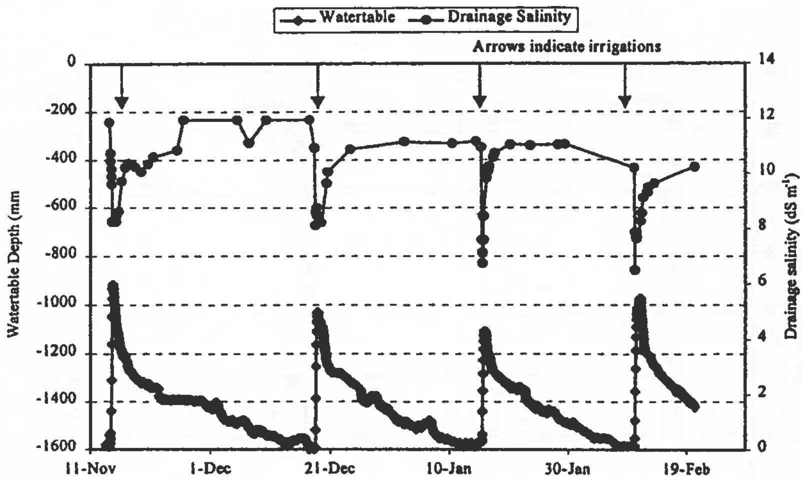


Fig. 4. Drainage Water Salinity and Water Table Depth for Deep Drains

Drainage Salt Load

The Managed Deep Drains removed 10-14 times the salt applied in the first three irrigations monitored (This additional salt is from that stored in the profile). This then declined to 0.3-4 times the salt applied. Overall the Managed Deep Drains removed 6 times more salt than applied, about half that of the Deep Drains, Table 1.

This was also the case for the rainfall event, where the Deep Drains removed 401 kg ha^{-1} compared to 223 kg ha^{-1} for the Managed Deep Drains.

Table 1. Salt Applied in Irrigation Water and Removed by Drains over Two Seasons (10 events)

Salt applied(kg ha^{-1})		Salt removed (kg ha^{-1})		
		Deep Drains	Managed Deep Drains	Shallow Drains
Total	508	5867	2978	319
Ratio*		11	6	0.6

* Ratio of salt removed to salt applied

The least salt removed was by the Shallow Drains, only about 0.6 of the salt applied in the irrigation water. This indicates that salt is accumulating in the profile with the Shallow Drains. This accumulation of salt is not necessarily a risk to the crop as the salt was not found to be accumulating in the root zone. Also the total amount of salt accumulated is relatively small, 189 kg ha^{-1}, which could be removed subsequently by irrigation or rainfall.

During the course of this trial there was only one significant rainfall event in a very dry period so the more normal effects of leaching by winter rainfall did not occur. Of the three drainage treatments the Shallow Drains were the closest to having a salt balance between salt applied and salt removed.

Watertable Control

The Deep Drains limited watertables less than 1 m deep to 8% of the time over the irrigation season, Table 2. The management changes used to control water flow from deep drains had little effect on the period watertables were above 1m. The Shallow Drains gave the best control of shallow watertables, but the watertable did build up beneath this treatment and was controlled at mole depth, which is consistent with results of Muirhead *et al.* (1995).

Table 2. Duration of Water Tables above 1 m

Treatment	Duration (% of season)
Deep Drains	8
Managed Deep Drains	10
Shallow drains	3
Undrained	42

Soil Salinity

There was a variation in the initial soil salinity's of the treatment plots, the Deep Drain plots having the highest salinity. After two seasons the salinity in the top 0.6 m had dropped in the Deep Drain treatment but had remained static for the other treatments, Fig. 5.

The Undrained treatment also experienced little change in salinity indicating that the drainage conditions were adequate to prevent salt accumulation. These results are only for a relatively short period and as such may not reflect the longer term effects of the treatments.

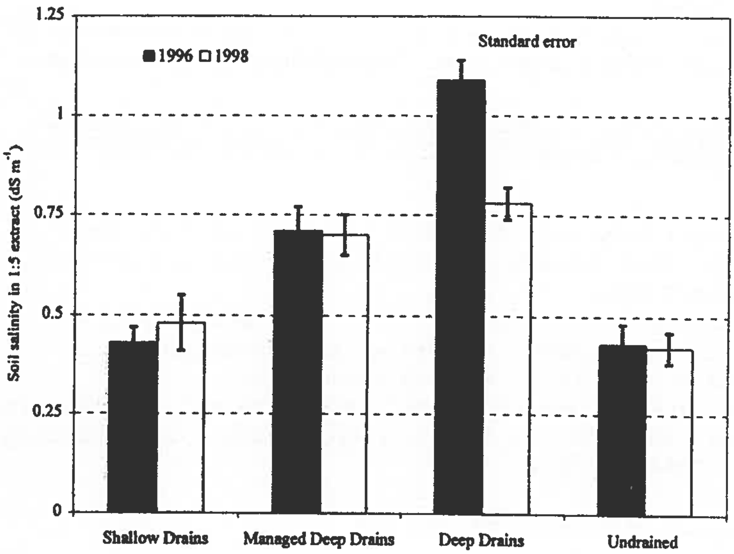


Fig. 5. Average Soil Salinity to 0.6 m (1996 sampling is before treatments were installed)

Vine Yield and Leaf Chloride

Leaf analysis found that the leaf chlorides in all treatments were similar, 0.57 - 0.69%, and well below the 1% toxic level. Vine yields taken at the end of the second season were found to be fairly uniform and quite high, 6.1-6.7kg/vine.

CONCLUSIONS

Changing drainage design from deep widely spaced drains to shallow closely spaced drains.

• Shallow drains removed less water than deep drains, thus potentially making more water available for plant use.

• Shallow drains have low drainage water salinity and remove smaller drainage volumes, thus reducing salt load, up to 95 % reduction compared to deep drains in this trial.

- Shallow closely spaced drains control watertables in the root zone better than deep widely spaced drains.

Managing deep drains by preventing discharge during irrigation and whenever the water table was below 1.2 m

- Managed deep drains removed less water than deep drains, thus potentially making more water available for plant use.
- Managing drains reduces drain flow compared to unmanaged drainage, resulting in a reduction in drainage salt load, 50 % in this trial.
- Deep drains, even when managed, were not as effective as shallower drains managing waterlogging and reducing salt mobilisation.

Impact of the drainage systems

An important outcome from this analysis is that the drainage treatments had only small effects on the root zone salinity over the experimental period and no measurable effect on vine health, but still drained water and salt from the area. Therefore, over the period monitored the water drained, salt removed, costs incurred, and downstream impacts of drainage water resulted in little direct productivity benefit to the farm.

A subsurface drainage system provides long term benefit to a farm in controlling waterlogging and salinity. However, there are periods when drainage is not critically required as occurred during this experiment. This can be due to changing land use, changing external hydrological impacts or dry climatic conditions. During these periods it is even more important that the drainage system incurs the least downstream impacts and least costs to the farmer.

This experiment showed that drainage systems for irrigated areas on clay soils in south eastern Australia can be designed and managed better than the currently accepted practices, so that detrimental downstream environmental effects due to excessive salt export are reduced, without affecting the productivity of the farm.

GUIDELINES FOR SUBSURFACE DRAINAGE DESIGN AND MANAGEMENT TO IMPROVE DRAIN WATER QUALITY

Using this work and results from other field trials and modeling not reported here guidelines for the Riverine plains, Australia have been developed.

New Drainage Systems

New drainage systems should consider the potential for salt mobilisation:

- Avoid sites where large volumes of drainage may occur from regional groundwater.
- Install drains as shallow as possible.
- Design drainage systems into management units aligned with irrigation units.
- Install drainage control structures to manipulate water tables
- Main drains and sumps that are installed at depth should be sealed to prevent entry of saline water.

Existing Drainage Systems

- Should have control structures installed so that drainage can be managed.
- Should be divided into management units with control structures aligned with irrigation units.

Management of Drainage Systems

- Drainage systems should be prevented from discharging during irrigation events.
- Drainage systems should be controlled to maintain water tables safely below the root zone, not left to drain uncontrolled where water tables may fall much deeper than required.

REFERENCES

1. Ayars, J. E. (1996). *Managing irrigation and drainage systems in arid areas in the presence of shallow groundwater: case studies.* Irrigation and Drainage Systems. 10:227-244, 1996.

2. Butler, B. E. (1979). *A soil survey of the Horticultural Soils in the Murrumbidgee Irrigation Areas, NSW.* Bulletin No. 289, CSIRO, Melbourne.

3. Christen, E. W. and Skehan, D. (1999). *Design and management of subsurface drainage for improved water quality: a field investigation.* CSIRO Land and Water, Technical Report 6/99.

4. Deverel, S.J. and Fio, J.L. (1991). *Groundwater flow and Solute movement to drain laterals, western San Joaquin Valley, California 1. Geochemical assessment.* Water Resources Res., 27(9), 2233-2246.

5. Department of Land and Water Conservation (1998) *Murrumbidgee Irrigation Area and Districts Community Land and Water Management Plan, Griffith NSW.*

6. Jury, W. A. (1975). *Solute travel-time estimates for tile drained fields: I. Theory.* Soil In: "Science Society of America Proceedings". 39:1024-1028, 1975.

7. Muirhead, W. A., Christen, E. W., and Moll, J. L. (1995). *Groundwater control using shallow subsurface drains.* CSIRO Division of Water Resources, Consultancy Report 95/23.

ACKNOWLEDGEMENTS

We would like to thank the Murray Darling Basin Commission for partial funding and Mr. D. Murphy for supplying the experimental site. Technical assistance was provided by J. Moll, J. Townsend and R. Sides.

EVALUATION AND UPDATE OF DRAINAGE WATER MANAGEMENT OPTIONS ON THE WESTSIDE SAN JOAQUIN VALLEY, CALIFORNIA

Manucher Alemi[1] Wayne Verrill[2]

ABSTRACT

Over one million acres of irrigated lands on the westside of the San Joaquin Valley are affected by shallow water tables, salinity, and toxic trace elements such as selenium. The San Joaquin Valley Drainage Program developed a management plan in 1990 to manage agricultural subsurface drainage and related problems. A review of the present status and information on the SJV drainage problem since adoption of the 1990 Plan is under way. Three subarea committees comprised of growers and water district staff representing the drainage problem area prepared reports on the implementation status of the 1990 Plan recommendations. Eight technical committees comprised of university scientists, government agency staff, water district staff, growers, and other stakeholders reviewed the latest information on drainage management options. The committee reports present detailed information on eight drainage management measures. The current status of knowledge on each of the eight measures is summarized in this paper.

---

1 San Joaquin Valley Drainage Implementation Program, Coordinator, Division of Planning and Local Assistance, Department of Water Resources, 1020 Ninth Street, Sacramento, CA 95814.

2 Associate Land and Water Use Analyst, Division of Planning and Local Assistance, Department of Water Resources, 1020 Ninth Street, Sacramento, CA 95814.

INTRODUCTION

California's San Joaquin Valley is one of the world's most vital and productive farming areas. The westside of the San Joaquin Valley is a fertile yet arid landscape where commercial agriculture is viable only with irrigation. A low permeability clay layer underlies most agricultural lands of the westside SJV. The clay layer does not allow for adequate percolation of leachate, causing the water table to rise toward the soil surface. Water logging of the crop root zone and evapotranspiration of soil water from the shallow water table results in the accumulation of salts and potentially toxic trace elements in the crop root zone. High concentrations of naturally occurring trace elements, such as selenium, in drainage water may pose a hazard to fish and wildlife when agricultural drainage waters are discharged to surface water bodies.

Salinization

The San Joaquin Valley Drainage Program Study Area on the westside SJV is about 2.3 million acres (Figure 1).

Using 1980-85 data to demonstrate the extent of salt accumulation in the Study Area, SJVDP estimated the annual increase in total dissolved solids in the upper aquifer to be about 6.115 million tons. The sources of this salt accumulation are shown in Table 1.

Table 1 - Estimated Salt Contributions

Source	Salt input (tons)
Native salt solubilization	2,825,000
Imported water from the Delta	1,766,000
Groundwater pumped from the confined aquifer	968,000
Local stream diversions	301,000
Lateral groundwater inflow and local stream inflow	155,000
Canal seepage and precipitation	100,000

Water Table and Water Quality

The depth of the shallow groundwater table below the ground surface in the Study Area is monitored at over 1,000 locations twice each year. The water table is shallowest in

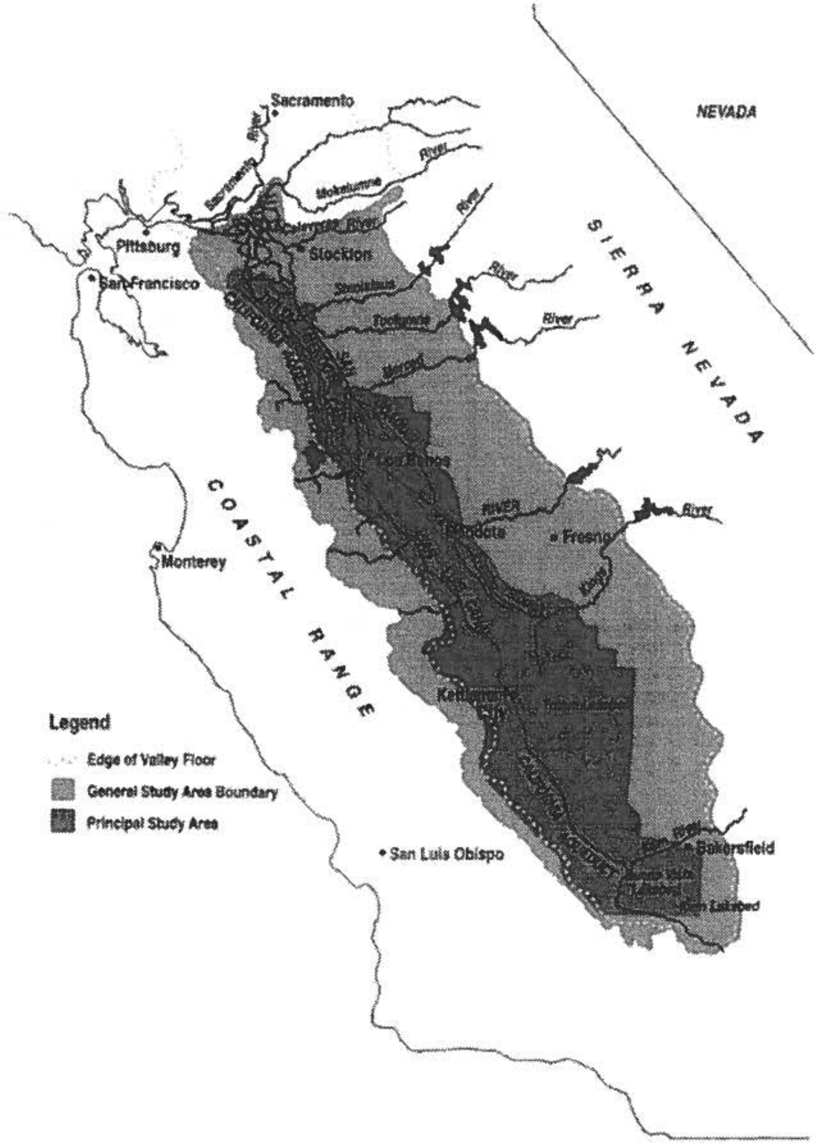


Figure 1
Program Study Area

early spring as a result of winter rainfall and preplant irrigations. In many areas, depth to the water table increases with time during the growing season due to reduced percolation (caused by decreasing infiltration rates), increased shallow groundwater use by crops, and limited natural and artificial drainage. Areas having shallow water depths from 0-5 feet during 1991-1997, varied from a minimum of 311,000 acres in 1991 to a maximum of 749,000 acres in 1997. SJVDP conducted a regional water quality evaluation of key constituent concentrations from 1984-1990 (Table 2).

Table 2. Areas with Shallow Water Table Between 0-5 Feet and Salinity, Selenium, and Boron Concentrations in Shallow Groundwater, 1984-1990 Data

Constituent concentration	Area (acres)
Salinity >2500 ppm	661,700
Boron > 2 ppm	882,200
Selenium > 5 ppb	553,800

In 1995, DWR conducted a one-time monitoring of electrical conductivity in shallow groundwater (Table 3).

Table 3. 1995 San Joaquin Valley Shallow Groundwater Area for Groundwater Electrical Conductivity Ranges

EC Range Microsiemens/cm	Area (acres)
0 to 2,000	188,800
2,000 to 4,000	337,300
4,000 to 10,000	257,200
10,000 to 20,000	50,600
greater than 20,000	31,000

Table 2 indicates that salinity is high in over 660,000 acres and boron and selenium are also present in significant concentrations in shallow groundwater. Table 3 shows the area and range over which salinity affects irrigated lands.

San Joaquin Valley Drainage Implementation Program

Four federal and four State agencies signed a Memorandum of Understanding in December 1991. The agencies agreed to use SJVDP's 1990 Plan as the guide to manage the Valley's subsurface drainage problems. They agreed to work together to identify specific tasks and associated responsible parties, seek needed funding and authority, and set schedules to implement all components of the 1990 Plan. Those signing the MOU recognized that the success of the program depended on local districts and irrigators to carry out effective drainage management measures. Key components of the SJVDP 1990 Plan are: source reduction, drainage reuse, land retirement, evaporation ponds, groundwater management, river discharge, water for fish and wildlife protection, and institutional changes. Recommendations were made for the various subareas.

SJVDIP Drainage Management Update Process and Results

In 1997, the SJVDIP in cooperation with the University of California and water and drainage districts in the Valley began to evaluate and update the 1990 Plan. This process is intended to remove the constraints to implementation of the 1990 Plan and foster cooperation among stakeholders in resolving long-term drainage problems for the benefit of both agriculture and the environment in the Valley.

This activity is being carried out in three phases by the SJVDIP. The first phase in updating the 1990 Plan consisted of two concurrent tasks. One task was formation of three subarea committees consisting of growers and district staff. The subarea committees' task was preparation of status reports that assessed the progress toward adopting the recommendations of the 1990 Plan. The three subareas were Grasslands, Westlands, and Tulare-Kern. The second task was a technical and economic evaluation of the management options proposed in the 1990 Plan, with the addition of salt and selenium utilization. In total, eight technical committees consisting of university scientists, government agency staff, and stakeholder representatives reviewed and evaluated information on eight separate drainage management measures. These two tasks were completed in early 1999(SJVDIP, 1999a-1999k).

The second phase is a synthesis of the information gathered in the first phase into a report that identifies interactions and trade-offs between drainage management options. The report also makes recommendations based on technical and economic considerations. This task was accomplished by an Ad Hoc Coordination Committee and was completed in January 2000.

The third phase will use the recommendations from the second phase along with input from stakeholders to formulate acceptable processes and means for further implementation of drainage management measures.

CURRENT STATUS OF KNOWLEDGE ON DRAINAGE MANAGEMENT MEASURES

Drainage Reuse

Demonstration projects to reuse drainage water on salt tolerant crops and halophytes and discharge brine to a solar evaporator at a rate equal to daily evaporation have been established. Substantial progress has been made in the development of these sequential reuse systems with an endpoint of salt separation in solar evaporators. Additional research is needed on selection and marketability of halophytic crops, and management of selenium and boron within the reuse system. Long-term sustainability has not been established.

Drainage Treatment

Opportunities exist to apply reverse osmosis membrane technology for the recovery of drinking-quality water and concentration of brine and selenium. Desalinization of drainage is now being considered for implementation. Biological treatments currently under development also hold promise.

Land Retirement

A 15,000-acre land retirement pilot project is being initiated by the USBR, and a corollary program is being initiated by the Westlands Water District. The 1990 Plan purpose for land retirement, environmental isolation of selenium, has been expanded to include habitat restoration for recovery of special-status species, and water transfers. Management techniques are needed to prevent soils from becoming salinized and seleniferous. Use of limited irrigation and rotational fallowing are alternatives to complete cessation of irrigation and permanent retirement. These alternatives could achieve the objectives of increased water conservation and reduced drainage volume while minimizing soil salinization.

Evaporation Ponds

Evaporation ponds play a major role as a terminal point for disposal of drainage water in closed basins. However, the impacts of selenium on water birds using the ponds have to be mitigated. Substantial reductions in bird use of ponds and bird impacts have been observed after pond configurations were modified and mitigation habitats were provided. For example, for 740 acres of evaporation ponds where average selenium concentration in drainage water was about 7 ppb, 145 acres of compensation habitat and 640 acres of demonstration habitat were established to mitigate adverse impacts. Continued research is needed to provide additional data regarding the effectiveness of mitigation measures.

Source Reduction

Improved irrigation systems and management plays a major role in the reduction of drainage water volume. Subsurface drainage can be reduced by shortening furrow lengths, installing drip and linear-move irrigation systems, modifying irrigation schedules and managing groundwater levels to encourage crop use of shallow groundwater, and generally improving management of irrigation systems.

Groundwater Management

Although groundwater continues to be pumped in portions of the Study Area, especially in years of limited surface supply, a systematic pumping plan to lower shallow groundwater tables, as recommended in the 1990 Plan, has not been implemented over concerns of poor water quality. The technical committee has determined that it is possible to reduce the volume of drainage water by managing groundwater tables. The drawback in lowering shallow groundwater tables by pumping from deeper aquifers is gradual degradation of the aquifers.

River Discharge

Discharge of drainage water containing conservative constituents to the San Joaquin River can be timed to coincide with periods of high flows and high assimilative capacities in the River. This requires a real-time management system for drainage discharge, and thus cooperation and coordination among water users, dischargers, and reservoir operators. Currently, discharge of drainage water containing selenium is subject to regulation of water column concentration of selenium as well as selenium load limits. Research should continue on the determination of site-specific ecotoxicity criteria for selenium, based on a better understanding of exposure pathways for at-risk biota. Such site-specific ecotoxicity criteria may allow for real-time management of selenium discharge.

Salt and Selenium Utilization

Industrial and commercial markets for salt and selenium, as well as human and animal health and nutrition uses for selenium, already exist. A research and development program is recommended for the separation, harvesting, purifying, manufacturing, and marketing of salt and selenium products made from San Joaquin Valley drainage salts.

IMPLEMENTATION ANALYSIS

The selection of a combination of drainage management options depends on the feasibility and applicability for specific conditions in the Valley. In this analysis we consider two regions, one with access for discharge to the River (Region A), and one without discharge to the River (Region B). In selecting a mix of options to meet regulatory requirements (for example, load limits), the cost of each option must be evaluated. The combination of options that meet the requirements at a minimum cost should be selected. Assuming that discharge to the River is subject to water quality objectives (SJVDIP, 1999g), and discharge to evaporation ponds is subject to Waste Discharge Requirements (SJVDIP, 1999d and 1999h), we offer the following strategy for in-valley drainage management.

Regions A and B

Initial Drainage Reduction: Source control, on-farm and district-wide drainage reuse, and active land management should be taken as the first step in managing drainage water in both regions. However, these actions alone may not be sufficient to eliminate the volume of drainage requiring management. Therefore the following further actions may be needed.

Region A

Discharge to the River: After initial drainage reduction measures have been taken, the remaining drainage water can be discharged to the River provided it meets river discharge requirements.

Discharge to Ponds: If discharge to the River exceeds the load limits or water quality objectives, then discharge to evaporation ponds (standard, modified, or accelerated rate) could be selected. When selenium in drainage is less than 2 ppb, standard evaporation ponds are sufficient. When selenium concentrations are high, modified ponds, and pond site-specific management measures, are necessary to reduce impacts to water birds. Compensation habitat is also necessary for unavoidable impacts. These additional management measures add to the costs of drainage management.

In an experimental study, drainage is used on halophytes and brine is discharged to solar evaporators at a rate less than daily evaporation. When managed properly, these evaporators have shown promise. Selection of solar evaporators versus evaporation ponds depends on site-specific conditions. For example, solar evaporators require installation of tile drains in halophytes, and dedication of agricultural land to halophytes as well as the evaporators. Since water can not be ponded in a solar evaporator, for a given amount of drainage water, more land is required compared to an evaporation pond. Evaporation ponds and mitigation habitat can be created on poor soils. Thus the economics of pond modifications, management, and compensation habitats vs. costs of solar evaporators have to be analyzed before selecting a drainage discharge system.

Secondary Drainage Reduction Measures: If evaporation ponds are not a viable option, drainage treatment, groundwater management, and land retirement should be considered in a mix of options with minimum costs.

Region B

In Region B, River discharge is not an option. After initial drainage reduction measures are implemented, remaining drainage can be discharged to evaporation ponds. If evaporation pond requirements reduce the feasibility of this option, secondary drainage reduction measures can be implemented.

CONCLUSIONS

Shallow groundwater, salinity, and selenium are three major drainage problems in the Valley impacting agriculture and the environment. Drainage management measures including source reduction, drainage reuse, evaporation ponds, and limited discharge to the River, as recommended in the 1990 Plan, appear to be effective in managing the drainage problem. Drainage treatment may still be limited by cost. Groundwater management may contribute to some water quality degradation, and may have limited potential. Salt separation and utilization is currently under development. Further research, monitoring, and field experiments are needed to develop an optimal mix of efficient, cost effective, and environmentally protective drainage management measures.

REFERENCES

California Department of Water Resources. 1992-1996. *Drainage Monitoring Reports.*

CVRWQCB, February 1998. Loads of salts, boron, and selenium in the Grasslands Watershed and Lower San Joaquin River, Volume I - Load Calculations.

San Joaquin Valley Drainage Program. September 1990. *A Management Plan for Agricultural Subsurface Drainage and Related Problems on the Westside San Joaquin Valley, Final Report.*

San Joaquin Valley Drainage Program, 1990. *Technical Information Record.*

San Joaquin Valley Drainage Implementation Program, 1999a. Drainage Reuse Technical Committee Report.

--------, 1999b. Drainage Treatment Technical Committee Report.

--------, 1999c. Land Retirement Technical Committee Report.

--------, 1999d. *Evaporation Pond Technical Committee Report.*

--------, 1999e. *Source Reduction Technical Committee Report.*

--------, 1999f. *Groundwater management Technical Committee Report.*

--------, 1999g. *River Discharge Technical Committee Report*

--------, 1999h. *Salt Utilization Technical Committee Report.*

--------, 1999i. *Grasslands Subarea Report.*

--------, 1999j. *Westlands Subarea Report.*

--------, 1999k. *Tulare/Kern Subarea Report.*

ACKNOWLEDGEMENTS

We wish to acknowledge the members of the technical and subarea committees who have contributed to development of the committee reports evaluating the various drainage management options. Special thanks to Professor John Letey of University of California, Riverside who with the senior author co-managed the update and evaluation of the 1990 Plan.

SIMULATION STUDIES ON USE OF SALINE WATER FOR IRRIGATION IN SEMI-ARID ENVIRONMENT

Satyendra Kumar[1] R.K.Jhorar[2]

ABSTRACT

Diagnosis in water management is being supported more recently with the help of physically based numerical models simulating the water and salt balance. This paper presents computer aided water management for interpretation of field experiments and for predicting future scenarios. An agro-hydrological model was first calibrated and validated for local conditions (Hisar, India) and subsequently used for predicting long term impacts. Various water management response indicators are used to interpret the impact of both medium (4 years experimented) and long term (next 10 years simulated) use of such saline waters on soil environment and sustainable crop production. The present simulation study showed that the prolonged use of high salinity waters (EC ≥ 7 dS/m) with normal irrigation (preplant with 8 cm canal and postplant with 6 cm saline water) in semi-arid areas should be restricted on medium to heavy textured soils because high salinity proved detrimental to relative transpiration and ultimately to the grain yield. Salinity hazard index was inflated by 92 to 146% and relative transpiration was suppressed by 40 to 60%. Consequently, simulated wheat and pearlmillet crop yields were down to 37 and 18 q/ha for 7 dS/m water and to merely 25 and 13 q/ha for 14 dS/m water during 15th simulated year, compared to 62 and 31 q/ha realized under canal water in the beginning in 1989-90. However, simulations showed that prolonged use of marginally saline water (EC = 3.5 dS/m) under normal irrigation and even of moderately saline water (EC = 7 dS/m) under heavier irrigation (12 cm canal pre- and 10 cm saline postplant water depths), on such medium to heavy textured soils, with a sub-surface drainage system, need not be forbidden. Reasonably good crop yields could still be obtained in the range of 46-48 and 21-22 q/ha for wheat and pearlmillet crops. Drainage effluent of 7.6 dS/m salinity from using 7 dS/m water continuously over 14 years indicates sustainability in using such moderate quality waters. But for highly saline waters (EC ≥ 14 dS/m) such long term usage needs to be restricted on such soils in semi-arid areas where even the heavier amounts of irrigation failed to depress salinity hazard and elevate crop transpiration to any noteworthy levels, grain yields remaining below 30 and 15 q/ha for the two crops.

[1] Senior Soil Physicist, Department of Soil Science,
[2] Assistant Professor, Department of Soil and Water Engineering,
CCS Haryana Agricultural University, Hisar-125 004, India

INTRODUCTION

The importance of irrigation in world's agriculture is well known. It is used on a large scale mainly in arid and semi-arid areas. All over the world where irrigation is being practiced, waterlogging and salinization are known phenomena. Approximately 25% of the world's total irrigated area is affected by such forms of land degradation and about 36% in India. In central and north-west Haryana (India), most lands have soils and ground waters often rich in salts. The consequent waterlogging and soil salinization pose immediate threat to the sustainability of agricultural production in this part of Haryana where the water table has risen at a rate of 10 to 30 cm annually during past three decades with 0.47 million hectare area already within 3 m from ground surface during June 1996. This area is further marked by inland drainage basin conditions with no natural outlets for drained and/or pumped water. Saline water was considered in the past as a non-usable resource. However, now the old standards are changing and new practices are being adopted (Oster,1995). Recent studies indicate a potential for the use of saline drainage/irrigation waters for crop production (Rhoades et al., 1989; Hamdy et al., 1993; Kumar et al., 1996, Kumar, 1998). Diagnosis in water management is recently being supported more and more with the help of physically based computer models simulating the water and salt balance dynamically. This paper presents computer aided water management for interpretation of field experiments and also for predicting future scenario. An agro-hydrological model was first calibrated and validated for local conditions by using the field observed data of 4 years and then simulations were extended for a period of over 10 years with waters (i) of actual field salinity 3.5 dS/m ($SW_{3.5}$) and of hypothetical salinities of 7.0 (SW_7) and 14.0 (SW_{14}) dS/m vis-a-vis canal water (0.3 dS/m = CW), (ii) with normal irrigation mode (IM_1): preplant irrigation with 8 cm of canal water and postplant irrigation with 6 cm of saline water and (iii) also with a heavier irrigation mode (IM_2): preplant irrigation with 12 cm of canal water and postplant irrigation with 10 cm of saline water.

WATER AND SALT BALANCE

Water balance clearly shows the existence of a close relationship between irrigation and drainage. In one dimensional unsaturated/saturated soil profiles, the water balance is accounted as:

$$\Delta W = P + I_{rr} + Q - T_{act} - E_{act} - E_i - R - D_r \qquad (1)$$

where ΔW is the water storage change in a vertical soil profile, P the gross natural precipitation, I_{rr} the man-induced irrigation, Q the flux through the bottom of the vertical soil profile (positive = seepage, negative = natural drainage), T_{act} the actual crop transpiration, E_{act} the actual soil evaporation, E_i

the precipitation intercepted by foliage, R the runoff and D_r the drainage.

In humid regions artificial sub-surface drainage D_r is required so as to remove excessive soil moisture arising from precipitation whereas in arid and semi-arid irrigated regions D_r is needed to control ΔW so as to keep the salt balance close to neutral. A small over irrigation ($I_{rr} >> T_{act}$) is usually preferred in order to maintain salinity within acceptable limits by leaching the soil profile. Therefore, both irrigation and drainage need to be considered simultaneously for improving water management systems. The salt balance of the soil profile can be accounted as:

$$\Delta C = I_{rr}\, C_{ir} + Q\, C_q - D_r\, C_{dr} \tag{2}$$

where ΔC is the salt storage change in the vertical soil profile, $I_{rr}\, C_{ir}$ and $Q\, C_q$ are the salt loads through irrigation and seepage, and $D_r\, C_{dr}$ the salt disposal through drainage system. The solute concentration has been expressed in mg/cm^3.

WATER MANAGEMENT RESPONSE INDICATORS

Yield has long been and is still perceived as the main indicator for evaluating the success of a water management strategy but is, however, unable to explain the long term changes in waterlogging and salinization induced from irrigation and drainage. Apart from yield, ΔW and ΔC, which describe a net drying/ wetting (ΔW) and salinization/desalinization (ΔC) effect, also need to be given due weightage in justifying a certain water management practice. The concept of classical irrigation efficiency (Wolters, 1992) is, no doubt, quite useful for evaluating the advantages/disadvantages of irrigation by describing the water losses through soil and plant root system but it does not address the response of the vadose zone to the soil profile moisture and salt storage changes. For systematic and fast assessment of a certain water management scenario, use of suitable water management response indicators have been proposed (Bastiaanssen, 1993, Kumar et al., 1996). Two of such indicators viz., relative transpiration (RT = T_{act}/T_{pot}) and salinity hazard index (SHI = Actual soil salinity/Critical soil salinity) have been used in this study. Actual soil salinity is in fact the weighted root zone soil salinity averaged over the growing season. The critical soil salinity is the salinity at which crop yield reduction manifests.

SWASALT: ON-FARM SIMULATION MODEL

One dimensional physically based model SWATRE (Feddes et al., 1978 and Belmans et al., 1983) was taken as basis for the numerical water flow experiments for present study. The working group at Hisar calls the model as SWASALT (Simulation of WAter and SALT). It is a versatile code and has proved its utility in various hydrological studies under widely varying climatic and agricultural conditions (The Netherlands: Feddes et al., 1988; Egypt: Feddes and Bastiaanssen, 1992; India: Kumar, 1994; Kumar et al., 1996; Kumar, 1998). It may be used for scheduling irrigation, designing drainage, assessing percolation, predicting long term waterlogging and/or salinization and transport of substances such as solutes, nitrogen and pesticides (Boesten and van der Linden, 1991).

SWASALT simulates soil water flow in the unsaturated/saturated zone, based on Richards' equation and includes water uptake by roots in the form of a sink term. The sink term is a function of the potential transpiration rate T_{pot}, rooting depth and the total suction head in the root zone h_{tot} (Feddes et al., 1978). The T_{pot} is obtained by bifurcating potential evapotranspiration ET_{pot} into potential soil evaporation E_{pot} and T_{pot} according to leaf area index LAI (Belmans et al., 1983):

$$E_{pot} = ET_{pot} \exp(-0.6\ LAI) \qquad (3)$$

$$T_{pot} = ET_{pot} - E_{pot} \qquad (4)$$

The h_{tot} is taken as a function of both matric pressure head (h_m) and osmotic pressure head (h_{osm}):

$$h_{tot} = h_m + \varepsilon\, h_{osm} \qquad (5)$$

where ε, an empirical crop dependent salinity sensitivity factor, has been included to reflect crop response to salinity (Bastiaanssen et al., 1996).

Finally T_{act} is estimated as:

$$T_{act} = \alpha(h_{tot})\, T_{pot} \qquad (6)$$

where $\alpha(h_{tot})$, a sink term variable, is a function of h_{tot} and have values from 0 to 1. Thus the effect of both water and salinity stress on ET is accounted.

The model outputs daily water and salt balances, profiles of: soil water content, solute concentration and pressure head, patterns of root water uptake and of flux divergence. The model simulations of the water and salt balances of the unsaturated zone can be used to support the field interpretations by: (i) quantifying the water and salt balances each day, (ii) predicting combinations of water and soil quality conditions for which field trials are not available/practicable, and (iii) studying the long term impact of variable irrigation and drainage regimes on soil environment.

FIELD EXPERIMENTS

Experiments on use of saline water with different combinations of canal and saline drainage water were conducted during 1989 to 1993 for the cereal crops of wheat and pearlmillet. These experiments were carried out at the research farm of the Haryana Agricultural University at Hisar (India), where a tile drainage system is installed at an average depth of 2.70 m and at spacing of 24 m. The irrigation water treatments selected were (i) Canal Water, CW (ii) Saline Water, SW (iii) canal water in Alternation with saline water, AW, and (iv) canal water Mixed with saline water in 1:1 ratio, MW. This paper discusses the complete annual cycles of wheat-pearlmillet rotations with various saline water treatments. The composition of the experimental loamy soil is presented in Table 1.

Table 1: Soil Texture, Bulk Density (ρ_b), Saturation (Θ_s) and Residual (Θ_r) Soil Moisture

Depth (cm)	Soil layer	Sand	Silt	Clay	Texture	Θ_s	Θ_r	ρ_b (gm/cm^3)
		----per cent----				(cm^3/cm^3)		
0-20	I	46.5	23.6	29.9	scl	0.52	0.01	1.45
20-80	II	37.9	45.8	16.3	l	0.42	0.00	1.46
80-200	III	13.3	59.7	27.1	sicl	0.42	0.01	1.44

wherein scl abbreviates for sandy clay loam, l for loam and sicl for silty clay loam.

The pF curves, estimated from van Genuchten et al. (1991) approach of the three loamy soil layers (Kumar, 1992) are presented in Fig.1. In the field preplant irrigation was applied with 8 cm canal water while postplant irrigation, with different irrigation water treatments, was scheduled at IW/CPE ratio of 0.9, IW being the depth of irrigation water fixed at 6 cm and CPE the cumulative pan evaporation.

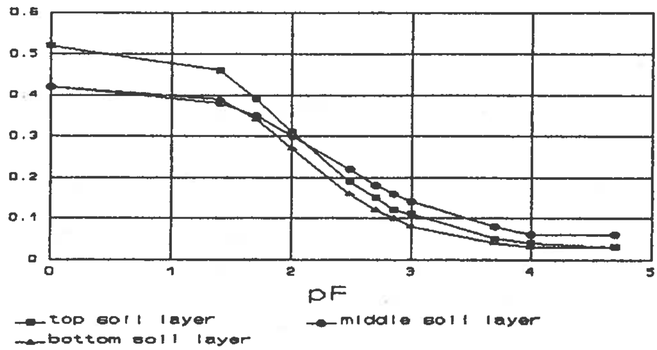


Fig. 1. pF Curve of the Reuse Experiment Soil Profile Layers

LONG TERM SIMULATION STUDY

Simulations for the extrapolation study were carried out, starting from the date of wheat 1992-93 harvest (day 110/1993) to over a decade, in order to observe and compare the long term performance of two extreme water quality management treatments of fresh (canal) water and saline (drainage) water. Simulations were also carried out for hypothetical high salinity waters, SW_7 (7 dS/m) and SW_{14} (14 dS/m), besides for the actual marginal salinity (3.5 dS/m) drainage water from the field, $SW_{3.5}$. Two modes of irrigation selected for present study were: i) Normal (IM_1) with 8 cm preplant canal and 6 cm postplant saline water depths and ii) Heavier (IM_2) with 12 cm preplant canal and 10 cm postplant saline water depths. The calibration and validation study between model predictions and field observations was realised using the 1989-93 reuse experiment data. The field observed water table depths, soil moisture content profiles, salinity profiles and crop yields could be compared satisfactorily with the model predicted values (Table 2). It may be noted that the yield was not simulated but estimated from the simulated relative transpiration values using crop response factors of 0.95 for pearlmillet and 1.1 for wheat (Doorenbos and Kassam, 1979). The soil and plant water relationships, thus calibrated during the 1st year (1989-90) and validated for the next three years (1990-93) of the reuse field experiment (Kumar, 1994; Kumar et al., 1996), were kept as such for the extrapolation study as per the norms of simulation process.

Table 2. Calibration and validation results for the experimental period of 1989-93

Treatment	Year/Crop	Water table		Soil moisture		Soil salinity		Yield difference (ton/ha)
		n	SEE (m)	n	SEE (cm^3/cm^3)	n	SEE (g/l)	
CW	WH-90	15	0.08	8	0.011	8	0.98	0.82
SW	WH-90	15	0.08	8	0.007	8	1.77	0.29
CW	PM-90	8	0.30	8	0.036	8	0.80	0.18
SW	PM-90	8	0.30	8	0.031	8	1.71	0.16
CW	WH-91	15	0.18	8	0.011	3	0.81	0.52
SW	WH-91	15	0.17	8	0.013	3	1.25	0.15
CW	PM-91	6	0.07	12	0.034	9	1.17	0.13
SW	PM-91	6	0.09	12	0.034	9	1.92	0.12
CW	WH-93	11	0.21	28	0.017	15	1.45	0.12
SW	WH-93	11	0.30	28	0.023	15	2.05	0.03
CW	PM-93	68	0.19	64	0.023	43	1.25	-
SW	PM-93	68	0.20	64	0.025	43	1.83	-
Average			0.18		0.022		1.42	0.25

where WH represent wheat, PM the pearlmillet, n the number of observations, SEE the standard error of estimate, CW the canal water and SW the saline drainage water of 3.5 dS/m.

INTERPRETATION OF THE RESULTS

The annual complete cycles for 15th year of simulation, comprising of wheat and pearlmillet rotation, have been considered for analysing and discussing the results obtained. Water management response indicators (WMRI) of relative transpiration, salinity hazard index and the grain yield have been presented in Tables 3 and 4 with both irrigation modes for wheat and pearlmillet crops. Results of 1989-90, the first year of experimentation, have also been included so as to facilitate comparison. The trend of different water management response indicators (Tables 3 and 4) foretell the danger of using saline water continuously over prolonged periods of over 14 years under normal irrigation (IM_1). The salinity hazard index was inflated by 92 to 99% and stood at unsafe and dangerous level of 2.1 for the wheat and pearlmillet crops during the final (15^{th}) year of simulation for 7 dS/m water, compared to the near target value of almost 1 for canal water (0.3 dS/m) in the first (reference) year of 1989-90. Consequently, relative transpiration registered a decline of about 40% for wheat and pearlmillet, resulting into quite poor grain yields of 37 and 18 q/ha for these crops, compared to 62 and 31 q/ha obtained from canal water in 1989-90. Continuous use of still poorer quality (14 dS/m) water further suppressed the crop transpiration by 20% over 7 dS/m water, culminating into very poor grain yields of 24.5 (wheat) and 13.3 q/ha (pearl millet) in the final year of present study. The salinity hazard index elevated to quite alarming value of 2.7 for these cereal crops with a phenomenal increase of about 150%. However, irrigation waters of marginal salinity ($SW_{3.5}$) could produce reasonable yields of about 46 and 22 q/ha for wheat and pearl millet despite being applied continuously for over 14 years since 1989-90 and need not be forbidden as such (Tables 3 and 4). These extrapolated results strongly suggest that the continued and prolonged use of waters of salinity 7 dS/m and greater should be forbidden on such medium to heavy textured soils under normal irrigation (preplant CW with 8 cm and postplant SW with 6 cm).

Table 3: Relative Transpiration (RT), Salinity Hazard Index (SHI) and Grain Yield (q/ha) for Wheat

Indicator	Irrigation Mode	Reference Year		Final 15^{th} year of Simulations			
		CW	$SW_{3.5}$	CW	$SW_{3.5}$	SW_7	SW_{14}
RT	IM_1	0.88	0.86	0.81	0.66	0.53	0.35
	IM_2	-	-	-	0.84	0.68	0.43
SHI	IM_1	1.08	1.14	1.28	1.67	2.07	2.66
	IM_2	-	-	-	1.28	1.68	2.33
Yield	IM_1	61.50	60.10	56.6	46.1	37.0	24.5
	IM_2	-	-	-	59.4	47.5	30.0

where IM_1 is preplant CW irrigation of 8 cm and postplant SW irrigation of 6 cm and IM_2 the preplant CW irrigation of 12 cm and postplant SW irrigation of 10 cm. Reference year refer to the first year of field experiments.

However, when irrigation applied was at greater depths under mode IM_2 with these varying salinity waters, both the relative transpiration and salinity hazard index were improved considerably because of improved salt leaching. Consequently, crop yields were also improved. Marginal salinity water ($SW_{3.5}$)

expectedly, affected largest improvement and the yields were enhanced by 31% (46.1 → 59.4 q/ha) and 23% (21.6 → 26.6 q/ha) for wheat and pearlmillet over those under normal irrigation, with 29 and 21% improvement in salinity hazard. Even with moderately saline water SW_7, leaching was quite satisfactory under heavier irrigation so as to cause a decline of 19 and 15% in SHI and an incline of 28 and 19% in RT for the two crops, with enhanced grain yields (37 → 47.5 q/ha: wheat and 17.6 → 21 q/ha: millet). Water of higher salinity (14 dS/m, SW_{14}), however, had little effect in reducing soil salinity and enhancing crop transpiration and yields (Tables 3 and 4) even under heavier application mode.

Table 4. Relative Transpiration (RT), Salinity Hazard Index (SHI) and Grain Yield (q/ha) for Pearlmillet

Indicator	Irrigation Mode	Reference Year		Final 15[th] year of Simulations			
		CW	$SW_{3.5}$	CW	$SW_{3.5}$	SW_7	SW_{14}
RT	IM_1	0.92	0.89	0.81	0.65	0.53	0.40
	IM_2	-	-	-	0.80	0.63	0.44
SHI	IM_1	1.05	1.14	1.28	1.70	2.09	2.70
	IM_2	-	-	-	1.35	1.77	2.46
Yield	IM_1	30.60	29.60	26.9	21.6	17.6	13.3
	IM_2	-	-	-	26.6	21.0	14.6

where IM_1 is preplant CW irrigation of 8 cm and postplant SW irrigation of 6 cm and IM_2 the preplant CW irrigation of 12 cm and postplant SW irrigation of 10 cm. Reference year refer to the first year of field experiments.

These long term simulations indicate the possibility of prolonged application of even moderately saline waters (upto 7 dS/m) on such medium to heavy textured but drained soils with heavier irrigations for achieving still reasonably good yields of about 48 and 21 q/ha for wheat and pearl millet crops even after over 14 years of continuous use (Tables 3 and 4). It may be recalled that almost similar simulated wheat and pearlmillet crop yields (46 and 22 q/ha) were realized from continuously applying marginally saline water (3.5 dS/m) for over 14 years under normal irrigation mode.

Thus, continued and prolonged application of marginally saline water (3.5 dS/m) under normal irrigation (IM_1) and even of moderately saline water (7 dS/m) under heavier irrigation (IM_2), on such medium to heavy soils but with a sub-surface drainage system, need not be forbidden since reasonably good yields (46-48 and 21-22 q/ha) could still be achieved for wheat and pearlmillet even in 15[th] year. For highly saline water of 14 dS/m such long term continuous use, however, need to be restricted on such soils where even the heavier irrigation failed to elevate crop transpiration and depress salinity hazard to any noteworthy levels, with crop yields remaining below 30 and 15 q/ha.

Table 5: Solute influx (through irrigation, I_{rr} C_{Ir}, and seepage, Q C_Q) and outflux (through drainage, D_r C_{Dr}) rates, drainage water salinity ($C_{Dr}=D_rC_{Dr}/D_r$), soil profile salinity in 0-100 cm (C_{100}) and water table depth (W T) during final 15[th] year of simulation

Parameters	Irrigation mode	CW	$SW_{3.5}$	SW_7	SW_{14}
I_{rr} C_{Ir}, (t/ha)	IM_1	0.9	7.6	15.3	30.3
	IM_2	-	12.6	25.4	50.5
D_r C_{Dr} (t/ha)	IM_1	7.3	11.5	17.2	30.1
	IM_2	-	18.7	30.3	54.9
C_{Dr}, (dS/m)	IM_1	3.6	4.5	5.7	8.5
	IM_2	-	5.6	7.6	11.6
C_{100} (dS/m)	IM_1	8.8	11.6	13.7	17.4
	IM_2	-	9.3	12.0	16.5
WT (m)	IM_1	2.2	2.1	2.0	1.9
	IM_2	-	2.0	1.9	1.7
QC_Q = 7.85 t/ha, average constant flux provided specified for all cases					

where IM_1 presents preplant CW irrigation of 8 cm and postplant SW irrigation of 6 cm, IM_2 preplant CW irrigation of 12 cm and postplant SW irrigation of 10 cm, and C_{100} and W T present the averaged values for the final simulated year

Average constant flux, provided as an input for calibrating and validating the model in order to closely compute the groundwater table, was kept as such during extrapolation studies (solutes seeping at steady 7.85 t/ha/yr, Table 5). The reason was that the present study fields, located at the edge of the sub-surface drainage system, were directly in contact with adjoining high water table fields without such drainage facility. Under such typical boundary effects, seepage influx plays crucial role in salt balance, compared to the situation where fields are located within a drainage system. That was why the solute influx (through irrigation and seepage) exceeded the outflux (through drainage) and even in case of canal water irrigation about 1.5 ton salts were added per annum per hectare. The mystery of the declining relative transpiration (0.9 down to 0.8) and crop yields (down by 4-5 q/ha) on prolonged use of even non-saline water is, thus, unfolded. Salt accumulation was at higher rates of 4, 6 and 8 t/ha/yr when saline waters of 3.5, 7.0 and 14.0 dS/m were used over 14 simulated years under normal irrigation. As the irrigation depth was increased under IM_2 mode, salt leaching became more effective, with rates of salt accumulation being reduced by almost half to 1.8, 3 and 3.5 t/ha/yr (Table 5).

Simulated use of highly saline water (14 dS/m) for over 14 years left behind a drainage effluent of 8.5 dS/m under normal irrigation which further aggravated to 11.6 dS/m under heavier irrigation mode. For less saline waters (7.0 and 3.5 dS/m) these values were 5.7 and 4.5 dS/m under normal irrigation (IM_1 mode), and 7.6 and 5.7 dS/m under heavier irrigation IM_2 (Table 5). The moderate quality (7.6 dS/m) of the drainage effluent from continuous application of the moderately saline water (7 dS/m) over 14 years indicates sustainability in its use, of course under heavier irrigation mode. During the 15th year of simulations, soil profile salinity C_{100} (averaged over 0-1 m) was quite high at 17.4 dS/m for 14 dS/m water even under greater irrigation depths of 12 cm whereas for other less saline waters SW_7 and $SW_{3.5}$, it was 12 and 9 dS/m. The water table stood at 2.2 m under canal water irrigation during 15th simulated year and at 2, 1.9 and 1.7 m for 3.5, 7 and 14 dS/m waters (under heavier irrigation) but still well below the root zone and safe for waters of marginal to moderate salinity ($SW_{3.5}$ and SW_7). It is interesting to note that the increased water application depth of 24 cm under heavier irrigation, over the normal, is only 4 cm in non-saline water but 20 cm in saline water. The scenario appears very attractive because it would help reduce the load both on the demand of decreasingly available fresh water and on the disposal of increasingly available saline water. But for effective leaching with heavy irrigations, good soil drainage, either natural or artificial, is however a must.

CONCLUSIONS

The performance of even good quality water did worsen a little because of the dominance of seepage term owing to the situation of the present study fields being on the edge of a sub-surface drainage system, directly in contact with adjoining high water table fields (without such a facility). The salt influx resulting from seepage proved quite crucial for the soil water-salt balance and affected all the water quality treatments. Thus the soil water and solute balance may behave less favourably for such edge-situated fields as compared to the fields lying within a sub-surface drainage system.

The present simulation study indicated that the prolonged use of high salinity waters (EC $\geq$ 7 dS/m) with normal irrigation should be restricted on medium to heavy textured soils in semi-arid areas because increasing salinity in these waters proved detrimental to the relative transpiration and eventually to the grain yield. Long term use of such saline waters, under normal irrigation, inflated the salinity hazard alarmingly (92 to 160%) and suppressed the crop transpiration critically (40 to 60%). Consequently, wheat and pearl millet crop yields were down to 37.0 and 17.6 q/ha for 7 dS/m water and to merely 24.5 and 13.3 q/ha for 14 dS/m water during the final (simulated) 15th year, compared to 61.5 and 30.6 q/ha realized form canal water application during the first (reference) year of field experimentation on reuse of saline (drainage) water.

However, the continued and prolonged use of marginally saline water (EC = 3.5 dS/m) under normal irrigation (8 cm canal water pre- and 6 cm saline water postplant depths) and even of moderately saline water (EC = 7 dS/m) under heavier irrigation (12 cm canal pre- and 10 cm saline postplant), on such medium to heavy soils but with a sub-surface drainage system, need not be forbidden since reasonably good crop yields could still be obtained in the range of 46-48 and 21-22 q/ha for wheat and pearlmillet crops. But for highly saline waters (EC ≥ 14 dS/m) such long term use needs to be restricted on such soils in semi-arid areas where even the heavier amounts of irrigation failed to elevate crop transpiration and depress salinity hazard to any noteworthy levels, the crop yields remaining below 30 (wheat) and 15 q/ha (pearlmillet). Besides low crop yields, another disturbing scenario is the alarmingly high salinity developed both in the drainage effluent (12 dS/m) and also in the root zone soil profile (17 dS/m) during the 15th year of present simulation study.

After continuous simulated application of moderately saline, 7 dS/m, water for over 14 years, moderate quality of the drainage effluent of 7.6 dS/m indicates the feasibility of its sustainable reuse under heavier irrigation. Interestingly, the increased water irrigation depth of 24 cm, in excess over the normal irrigation, is just 4 cm in fresh water but a good 20 cm in saline water, thereby utilizing less of highly competitive fresh water but more and more of the increasingly available saline water.

Similar long term simulations are being carried out further with irrigation depths of 10 cm (for the present 12 cm) of preplant fresh water and 12 cm (for the present 10 cm) of postplant saline water so as to explore the attractive potential of utilizing saline ground/drainage waters so as to help reduce the load on the disposal of drainage effluent and check water table rise and soil salinization in the areas underlain by saline groud water.

REFERENCES

Bastiaanssen, W.G.M., 1993. Interpretations of field experiments to arrest rising water tables using SWASALT model, Mission Report to Indo-Dutch operational research project. DLO-The Winand Staring Centre, International Activities Rep.29, Wageningen, The Netherlands: pp.77.

Bastiaanssen, W.G.M., R. Singh, S. Kumar, J.K. Schakel and R.K. Jhorar, 1996. Analysis and recommendations for integrated on-farm water management in Haryana, India: a model approach. DLO-Winand Staring Centre, Report 118, Wageningen, The Netherlands: pp.152.

Belmans, C., J.G. Wesseling and R.A. Feddes, 1983. Simulation of the water balance of a cropped soil : SWATRE, J. Hydrol. 63: 271-286.

Boesten, J.J.T.I. and van der Linden, 1991. Modelling the influence of sorption and transformation on pesticide leaching and persistence, J. Environ. Qual. 20: 425-435.

Doorenbos, J. and A.H. Kassam, 1979. Yield response to water, FAO Irrigation and Drainage Paper No. 33, Rome, Italy: pp. 193.

Feddes, R.A. and W.G.M. Bastiaanssen, 1992. Forecasting soil-water-plant-atmosphere interaction in arid regions, in Water Savings Techniques for Plant Growth, NATO-ASI Series. H.J.W. Verplancke et al., Editors: 57-58.

Feddes, R.A., P.J. Kowalik and H. Zaradny, 1978. Simulation of water use and crop yield. PUDOC, Wageningen, The Netherlands: pp.189.

Feddes, R.A., P.J.T. van Bakel, P. Kabat, J.H.M. Bronswijk and J. Halbertsma, 1988. Modelling soil water dynamics in the unsaturated zone, state of art, J. Hydrol. 100: 69-111.

Hamdy, A., S. Abdel-Dayem and M. Abu-Zeid, 1993. Saline water management for optimum crop production, Agril. Water Management 24: 189-203.

Kumar, S., 1992. Identification of soil hydraulic characteristics in Haryana state (India). Interne Mededeling 220, DLO-The Winand Staring Centre, Wageningen, The Netherlands: pp.9.

Kumar, Satyendra, 1994. Suitability of simulation techniques on reuse of drainage water, Proc. National Seminar on Reclamation and Management of Waterlogged Saline Soils, Karnal, India. Vol II: 64-76.

Kumar, Satyendra, 1998. Computational models to predict water quality impacts on soils and crops: Lead paper. Proc. National Seminar on Strategies for Management of Poor Quality Waters in Agriculture, CSSRI, Karnal: 46-65.

Kumar, S., R.K. Jhorar and M.C. Agarwal, 1996. Reuse of saline irrigation waters for cereal crops. CCS Haryana Agril. Univ., Hisar, India, Bulletin: pp.96.

Oster, J.D., 1995. Irrigation with poor quality water, Agril. Water Management, 25: 271-297.

Rhoades,J.D., P.T. Bingham, J. Letey, G.J. Hoffman, A.R. Dedrick, P.J. Pinter and J.A. Replogle, 1989. Use of saline drainage water for irrigation. Imperial valley study. Agril. Water Management 16: 25-36.

van Genuchten, M.Th., F.J. Jeij and L.J. Lund, 1991. Indirect methods for estimating the hydraulic properties of unsaturated soils, Proc. International Workshop, Univ. of California, U.S.A.

Wolters, W., 1992. Influences on the efficiency of irrigation water use, Ph.D. thesis, Technical University Delft, The Netherlands: pp.150.

HYDRODYNAMIC MODELING TO OPTIMIZE IRRIGATION EFFICIENCY

Jeffrey J. Anderson[1]   J. C. Guitjens[2]

ABSTRACT

The two-dimensional, hydrodynamic model HYDRUS-2D is used to simulate irrigation schedules for an alfalfa crop over the length of a growing season. The objective is to evaluate current practices in order to produce management alternatives that reduce irrigation drainage.

HYDRUS-2D uses a finite element technique that numerically solves the Richards equation for water movement in variably saturated media. The model is calibrated by comparing its output to actual field data collected from an instrumented plot at the Newlands Agricultural Research Center in Fallon, Nevada. The simulation's scope is applied to a vertical cross-sectional study area, 21.95 m in depth by 18.50 m in width, representing half of the spacing between two parallel drains. The soil profile contains one drain and three piezometers below it. An accurate model of the site's layered soil profile is developed by selecting soil parameters that produce acceptable agreement between actual and modeled drain discharge values, as well as, root mean square error between piezometric pressure heads.

The following ratio is used to determine what portion of the water leaving the soil profile is consumed by evapotranspiration,

$$D_{et} / (D_{et} + D_d)$$

where D_{et} is the depth of water used by evapotranspiration and D_d is the depth of drainage water. Optimal results are achieved as the ratio approaches one. Using short, 24-hour intervals indicates how the ratio behaves on a daily basis during irrigation cycles and provides insight into ways to modify standard irrigation practices to create a more efficient management alternative.

---

[1]Jeffrey J. Anderson, Graduate Student, University of Nevada Reno, 1000 Valley Rd. Reno, NV 89512-0013, email: jeferwho@hotmail.com

[2]J.C. Guitjens, Professor of Irrigation Engineering, University of Nevada Reno, 1000 Valley Rd. Reno, NV 89512-0013, email: guitjens@unr.edu

INTRODUCTION

Irrigation is the primary water consumer in Nevada, responsible for using as much as 83.2% of the state's water resources annually (Cobourn, 1992). A large portion of this water is not used beneficially by crops, but instead is lost to canal seepage and deep drainage in the field. Legislative reform, industrial growth, and a swelling population continue to increase the demands on water resources. Since agriculture is not only the largest water user but also returns irrigation drainage, it is critical that more efficient means of canal delivery and irrigation management be developed in order to spread the finite amount of water to an increasing number of concerns. The Bureau of Reclamation has a program aimed at reducing canal seepage, but irrigators receive no organized support to consider technologies that can advance water conservation through management (Guitjens, 1999). This paper is aimed at helping managers by explaining how the HYDRUS-2D software package can be used to quantify the hydrodynamics involved in the irrigation-drainage relationship. It is hoped that managers could utilize the protocol described in this paper to improve their own management decisions.

OBJECTIVES

The objectives are to illustrate the usefulness of HYDRUS-2D for: (1) developing a calibrated, hydrodynamic, irrigation-drainage model which can then be used to (2) evaluate a previous year's irrigation schedule and then employed (3) to generate management alternatives with reduced drainage.

BACKGROUND

The study site which was modeled is located at the Newlands Agricultural Research Center (NARC), part of the Newlands Project in Churchill County of West Central Nevada (Fig. 1). The Newlands Project is one of the oldest irrigation projects authorized under the Reclamation Act of 1902. Water is diverted from the Truckee and Carson Rivers to irrigate about 65,000 acres of the Carson Desert (Clark, 1995). It has been suggested that 35% of the diverted river water is lost to canal seepage before reaching the field, then another 35% of the remaining water is lost to drainage after irrigation (Guitjens, 1999). Early in the history of the project irrigation began raising the water table which eventually encroached on the root zone, decreasing yields. To maintain an unsaturated root zone it was necessary to install a network of ditch drains throughout the project; the drains conduct water from the fields, through a series of ditches to low lying wetlands which include the Stillwater National Wildlife Refuge.

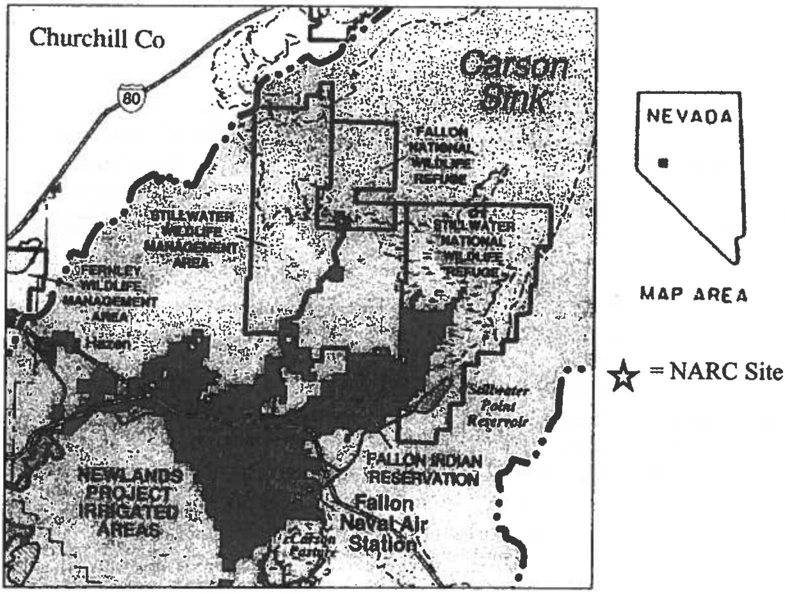


Fig. 1. Fallon Area with NARC Site (Trionfante and Peltz, 1994)

The infiltration through the saline soils of the Carson Desert fills the marshes with drainage water of poor quality. The water's concentration increases from 240 mg/L prior to irrigation to 600 - 3,000 mg/L after drainage, a 2.5- to 12.5-fold increase (Rowe et al., 1991). For comparison, water with concentrations greater than 1000 mg/L may be harmful to sensitive crops and is considered unfit for human consumption (Hoffman, 1994). To intensify the problem Operating Criteria and Procedures (OCAP) were implemented between 1977-88. The goal of these court ordered rules is to ensure the efficient management of water for the Newlands Irrigation Project by maximizing the use of the Carson River while reducing the contribution of the Truckee River. The execution of the OCAP increased project efficiency by decreasing the quantity of water delivered to the distribution system. Consequently the amount of water reaching the wetlands decreased, this ultimately led to a 50% reduction in wetland size, and a four- to seven-fold increase in average dissolved-solids concentrations in the drainwater (Hoffman, 1994).

The highly concentrated drainwater is believed to be responsible for the large loss of emergent and submergent vegetation in the Stillwater and Carson Lake wetlands. The loss of these primary producers, has had a negative effect on higher trophic levels, both in terms of loss in nesting and cover habitat, and in the loss of food supply. During the past three decades, Federal and State wildlife biologists have observed that migratory waterfowl have decreased in kind and number while disease has increased in the population (Hoffman, 1994; Clark, 1995).

In 1990 the Truckee-Carson-Pyramid Lake Water Rights Settlement Act was passed by Congress and enacted to restore wetland ecosystems, like the Stillwater National Wildlife Refuge. The act authorized the purchase of water rights from agriculture lands to be used to dilute the saline waters which had been created in the wetlands (WHSRN, 1999). By 1995, over 10,000 acre-feet of water had been purchased for transfer to the refuge, these purchases continue from willing farmers (Clark, 1995).

The purchase of agricultural water rights, coupled with the water needs of a growing population and industrial sector puts the future of farming in Churchill Country in question. Experience indicates that the Stillwater wetlands will flourish when supplied with adequate freshwater to dilute saline drainwater. Agriculture can survive and contribute to this goal by focusing on water conservation through drainage reduction. Ayers and Meek (1994) showed that the salt mass discharge decreased in rough proportion to decreased drainwater volumes, thus improving irrigation efficiency ultimately reduces the salt load reaching the wetlands. Improved efficiency will also conserve fresh water, which could be used for dilution if it is allowed to enter the wetlands directly.

METHODS

Study Area

Figure 1 shows that NARC is located in the Lahontan Valley, part of the Carson Desert of West Central Nevada. The region is a mid-latitude desert with cold winters and hot summers. Mean annual precipitation is roughly 13 cm per year with the majority falling during the winter months, temperature ranges from -32°C to 41°C with an average of 10.4°C and the elevation is approximately 1,190 m (Newton, 1998).

Hydrogeologic Setting: The Quaternary sediments (Fig. 2) in the Carson Desert were derived from the surrounding fault block mountains composed predominantly of Late Tertiary olivine-basalts, rhyolites, andesites, rhyodacites, many of which occur as tuffs (Willden and Speed, 1974).

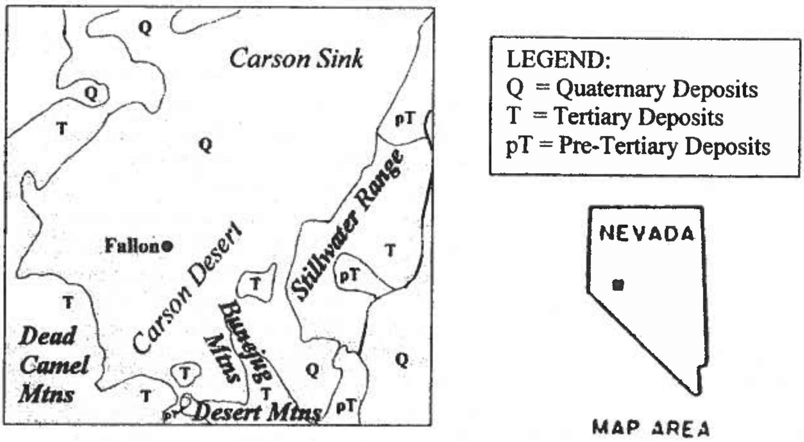


Fig. 2 Geologic Map of Fallon Area (modified from Willden and Speed, 1974 and Faulkner, 1996)

Glancy (1986) divided the subsurface into four distinct aquifers (Fig. 3) based on differences in water-chemistry and variations in the hydraulic properties of the aquifer materials. A shallow alluvial aquifer extends from the land surface to a depth of about 50 feet, an intermediate-depth alluvial aquifer extends from 50 feet to depths of between 500 to 1,000 feet, and a deep-alluvial aquifer underlies the intermediate aquifer. The fourth aquifer is a mushroom shaped basalt formation which exists within the alluvial aquifers and is exposed to the surface at Rattlesnake Hill. All four aquifers respond to stresses independently over the short term due to their varying hydrologic characteristics. Over the long term these units are hydrologically interdependent revealing an interconnected nature of their transmissive zones, thus the subsurface can be thought of as an aquifer system over the long term. Due to the lack of precipitation, recharge to the aquifer system is mainly accomplished by the infiltration of irrigation water and canal seepage.

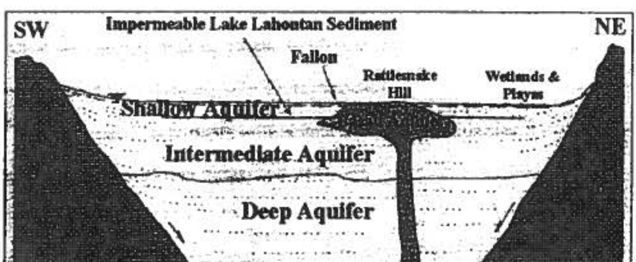


Fig. 3. Hydrogeologic cross-section of study area (Faulkner, 1996)

Site Description: Field data were collected at NARC from a 22-acre field equipped with a series of 15 lateral, tile drains installed two meters below the ground surface and 37 meters apart (Fig. 4). Raised dirt borders exist above each drain lateral and allow flood irrigation events to occur from north to south. Borders are absent near the main drain to allow excess water to runoff toward the east. During 1992 alfalfa was grown in the field and pressure head data were collected from piezometers near the midpoint of each drain. Flows were monitored from each of the lateral drains through an access hole. Bore logs from five locations across the length of the field show a layered soil profile containing various mixtures of sand, silt and clay (Mathis 1995). Guitjens (1992) described the soil's available water storage capacity as ranging in general from 9 to 13%, although in very sandy areas the capacity dropped to between 4 and 6%. Pohll (1993) conducted slug tests to determine the effective hydraulic conductivity of the profile to be approximately 3.23×10^{-3} m/day with a variance of 1.72×10^{-5} m^2/day^2. No information on the conductivity of individual layers is available to date. Pohll and Guitjens (1994) show that a small (0.001) regional gradient exists across the field, although it is dominated by the local gradient to drains in the time immediately following an irrigation event. Precipitation, irrigation amounts, Class-A pan evaporation, and wind data were also collected, however, no measurement of surface runoff between borders was made.

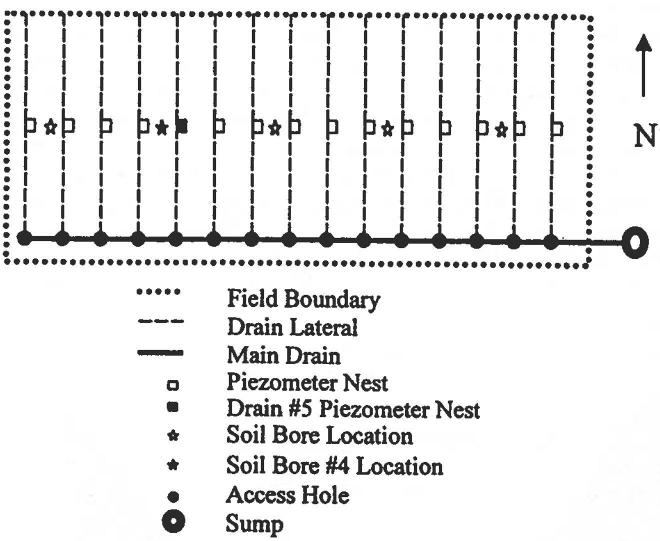


Fig. 4. Site Plan of NARC

Modeling Procedure

The modeling procedure requires the adoption of a systematic protocol; Fig. 5 illustrates the protocol used in this study.

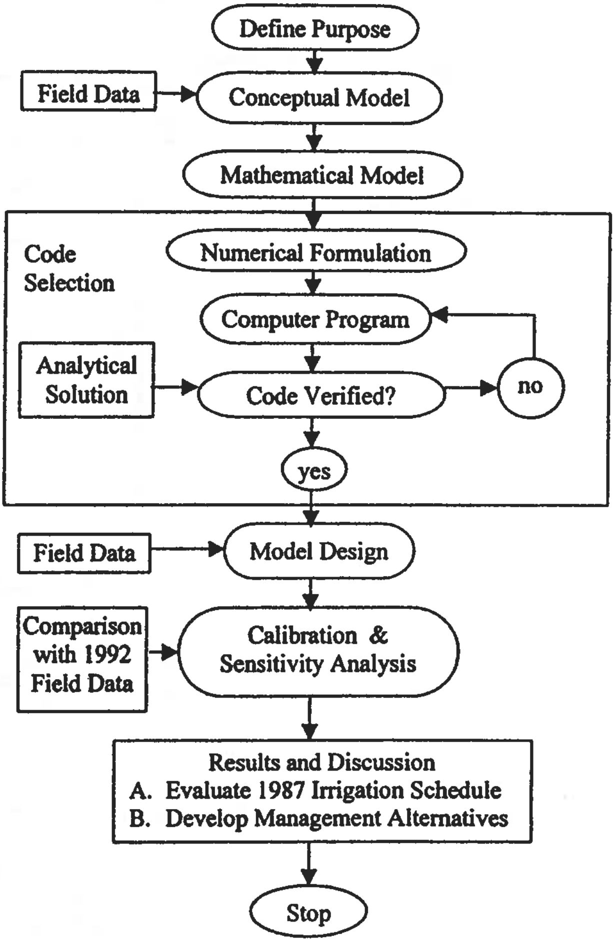


Fig. 5. Flow Chart of Modeling Protocol
(Adapted from Anderson and Woessner, 1992)

Conceptual Model: Once the purpose of the project is determined a conceptual model (Fig. 6) summarizes the key elements, present in the field and acts as a link to the computer model.

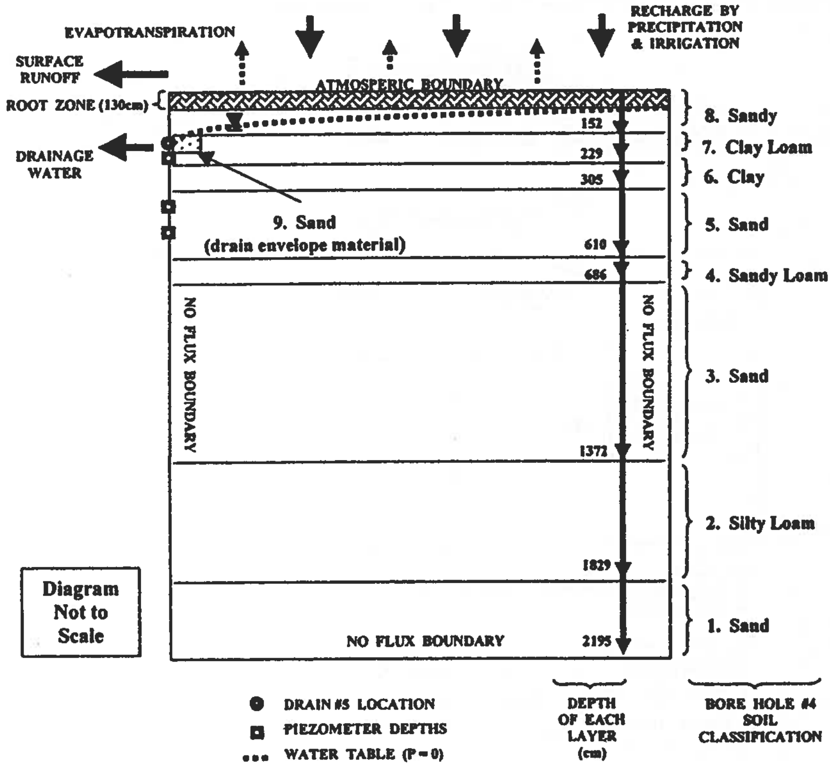


Fig. 6. Conceptual Model of the Area of Interest

The area of interest is limited to a vertical cross-section adjacent to drain #5 with the dimensions of 21.95 m in depth by 18.50 m in width. This cross-section represents a half drain spacing and assumes a mirror image to the left of the drain. Drain #5 extends from 190-200 cm below the surface. Below the drain there are three piezometers at the depths of 216 cm, 320 cm and 412 cm, respectively. Nine different subregions are included, the main horizons (1-8) match the materials and depths described in the log from bore hole #4 (Mathis, 1995). The ninth sub-region represents the drain envelope material that is commonly laid around tile drains at the time of installation. The alfalfa root zone is set to a depth of 130 cm.

Recharge is accomplished by precipitation and irrigation events. Water leaves the profile as either evapotranspiration (ET) at the atmospheric boundary or drainage through the tile drain. Surface runoff occurs when the HYDRUS-2D simulation is unable to accept the full precipitation-irrigation event within a 12-hour period of model time. The vertical sides and bottom are all no flux boundaries. Note that the small regional gradient described by Pohll and Guitjens (1994) has been left out of the conceptual model since HYDRUS-2D is not designed to handle this. This simplification is considered allowable since the local gradient towards the drain would dominate the regional gradient during the irrigation season. The local gradient during the irrigation season is towards the drain, and a local water-divide exists at the mid-point between drains. The slope of the local gradient increases when moving radially toward the drain (Schwab et al., 1996). ET is assumed to occur only during daylight hours, while drainage may occur 24 hours each day. The ET of the alfalfa crop is quantified by multiplying a variable crop coefficient (Rashedi, 1983) by the reference ET, which is derived from Class A pan evaporation data and pan coefficients which are a function of wind speed and relative humidity (Doorenbos and Pruitt, 1977).

Mathematical Model: The two-dimensional, isothermal Darcian flow of water in variably saturated rigid porous medium can be described using the following formulation of Richards' equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i} [K (K^A_i \frac{\partial h}{\partial x_j} + K^A_{iz})] - S \qquad (1)$$

where θ is the volumetric water content (cm^3/cm^3), h is the pressure head (cm), S is a sink term for evapotranspiration (cm^3/hr), x_i (i=1,2) are the spatial coordinates (cm), t is time (hrs), K^A_{ij} and K^A_{iz} are components of a dimensionless anisotropy tensor $\mathbf{K^A}$, and K is the unsaturated, hydraulic conductivity function (cm/sec) given by,

$$K(h,x,z) = K_s(x,z)\, K_r(h,x,z) \qquad (2)$$

where K_r is the relative conductivity and K_s the saturated hydraulic conductivity (cm/hr). HYDRUS-2D version 1.0 (Simunek et al., 1996), a finite element code which solves (1), was used for this project. This program has been verified widely and was not modified for this research.

Model Design: HYDRUS-2D includes a geometry module that was used to create the exterior and interior boundaries (Fig. 7). MESHGEN, the HYDRUS-2D finite element mesh generator, was used to create a grid with 3,989 points, 7,774 triangles and 11,762 edges (Fig. 8). The density of the grid was increased in the area near the drain, by increasing the number of points on the line defining the drain envelope (Fig. 9).

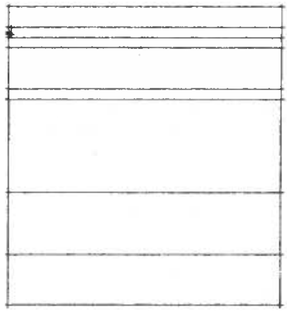


Fig. 7. Profile Showing Boundaries Created in HYDRUS-2D Geometry Module (1,850 cm wide x 2,195 cm deep)

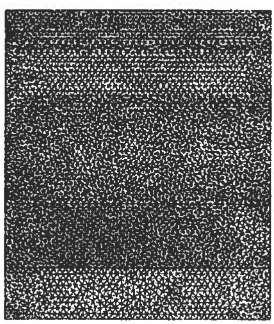


Fig. 8. Finite Element Grid Generated by the MESHGEN Module.

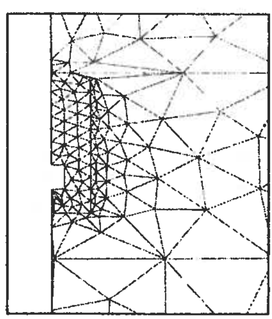


Fig. 9. Enlargement of the Grid in the Vicinity of the Drain (notice the increased density within the drain envelope boundary)

The boundary module was used to define the boundary types. The surface is an atmospheric boundary, the drain a seepage face, while the sides and bottom of the profile are no flux boundaries. The 130 cm root distribution of the conceptual model varied between 115-150 cm in the computer model due to the irregular way the mesh elements fit together. The initial pressure head was set to zero at a depth of 130 cm and increased linearly to 2,065 cm at the bottom of the profile. In order to obtain the gradient towards the drain, the profile was allowed to drain for 120 hours before any irrigation was simulated. The piezometer locations were made observation nodes in the mesh, this provided pressure head values to compare simulation output to field data.

<u>Calibration:</u> The model used for calibration implemented the irrigation schedule and ET field data from the 1992 growing season to create a time variable boundary table with 243 entries. All precipitation-irrigation events and daily ET amounts are entered in HYDRUS-2D as a unit width, hourly flux with the units cm/hour. Daily totals for recharge and ET were divided by 12 hours, to create an hourly flux which would apply, or remove, the correct amount of water during daylight hours only. If the HYDRUS-2D simulation was unable to accept the total amount of recharge in that 12-hour period, the difference was assumed to be surface runoff and the recharge amount was less than the application amount according to the irrigation schedule.

The 1992 season was selected for calibration since piezometer and drainflow data had been collected during that period. Modeled pressure heads were compared to field values, collected from the drain #5 piezometer nest using a root mean square error (RMSE) technique,

$$RMSE = [1/n\ \Sigma(h_m - h_s)_i^2\ ]^{0.5} \qquad (3)$$

where, n is the number of field piezometer readings, h_m is the field measured pressure head and h_s is the simulated pressure head. Simulation and field measured drain flows were also compared as part of the calibration process. The model simulated 3,000 hours, from April 13th to August 10th, which represents the time when piezometer and drain-flow data were collected. Table 1 summarizes how the model time was discretized, note the default settings were used for the time step control. The iteration criteria that were used are shown in Table 2, only maximum number of iterations was increased from the default settings, as this gave the program a greater flexibility in reaching convergence.

Table 1. Time Discretization Summary

Initial Time (hours)	0
Final Time (hours)	3000
Initial Time Step (hours)	0.1
Minimum Time Step (hours)	0.001
Maximum Time Step (hours)	1.0

Table 2. Iteration Criteria Summary

Maximum Number of Iterations	20
Water Content Tolerance	0.0001
Pressure Head Tolerance	0.1
Lower Optimal Iteration Range	3
Upper Optimal Iteration Range	7
Lower Time Step Multiplication Factor	1.3
Upper Time Step Multiplication Factor	0.7

Initial soil types, matching the descriptions used in the log for soil bore #4, were chosen from the entries in the HYDRUS-2D, soil catalog. Each soil type in the catalog has default values, within an accepted range, for its hydraulic properties. The model was calibrated by varying the soil type of the horizons until the RMSE for pressure head was minimized.

HYDRUS-2D incorporates the use of Feddes Parameters (Feddes et al, 1978) to determine root water uptake. Using the default Feddes' values the actual ET values did not match the values calculated by the conceptual model. Since the conceptual technique is specific to alfalfa, the Feddes' parameters were adjusted until the modeled ET equaled the conceptual figures. Changes in the Feddes' parameters are summarized in Fig. 10 and Table 3.

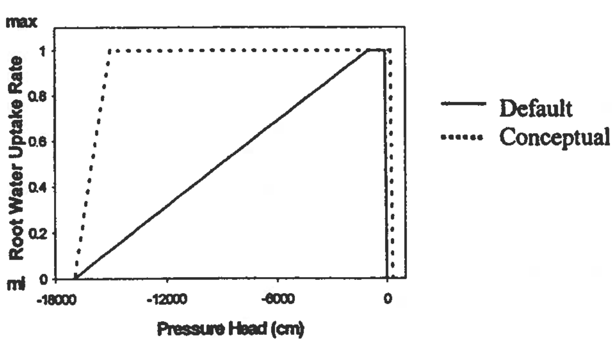


Fig. 10. Comparison of Default Feddes' Parameter Values with the Values which Allowed the Conceptual ET to be Obtained in the Model.

Table 3. Data Table Used to Create Fig. 10, where: P_0 is the pressure head below which roots start to extract water from the soil, P_1 is the pressure head value below which roots start to extract water at the maximum possible rate, P_2 is the pressure head below which roots can no longer extract water at the maximum rate, P_3 is the pressure head at which root water uptake ceases, also known as the wilting point. All values in cm.

	Conceptual	Default
P_0	300	0
P_1	200	-100
P_2	-15000	-1000
P_3	-17000	-17000

The calibration results are shown in Fig. 11 and Fig. 12. The average RMSE for pressure heads (15.0 cm) was obtained using the soils shown in Table 4, these match the soil bore log closely. The average of the 14 collected field drain flows was 4.2 L/min, within an order of magnitude of the modeled average of 8.7 L/min. Some error in flows was expected due to the difference in the way field values were derived, compared to the model. The field drainflow was measured from the access hole (see Fig. 4) at the end of a drain #5, which collected water over the entire drain-lateral length. In contrast, the two-dimensional model calculated the seepage face flux only along a unit drain length. To compare field data with the modeled results an assumption was made that the seepage face flux represented the average flux for a unit length. Soil heterogenuity makes it improbable that infiltration rates would be constant on a field-scale, hence the flow into the drain along each unit length would vary and it is possible that the modeled cross-sectional flux would not be representational of the average. Since the field measures 162 m from north to south a small deviation from the average seepage face flux would lead to a sizeable error in the modeled drain flow.

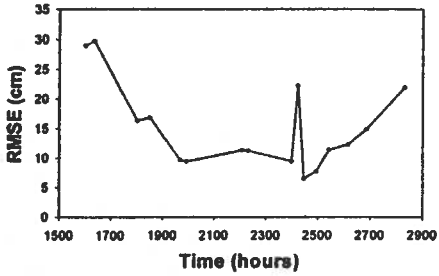


Fig. 11. RMSE comparing modeled & field pressure heads

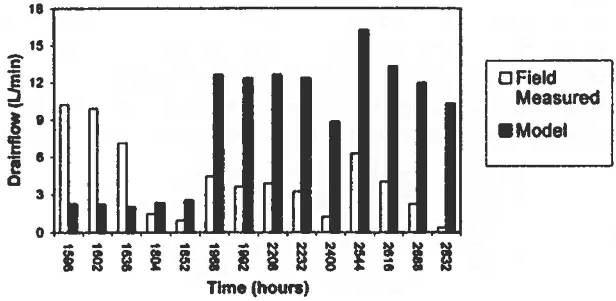


Fig. 12. Comparison of modeled and field drain flows

Table 4. List of Soil Material and Parameters Used in Calibrated Model. Q_r = residual water content, Q_s = saturated Water Content, K_s = saturated hydraulic conductivity

Layer	Soil Type	Q_r	Q_s	K_s (cm/hr)
1	Sand	0.045	0.43	29.7
2	Silt Loam	0.034	0.46	0.25
3	Sand	0.045	0.43	29.7
4	Sandy Loam	0.065	0.41	4.4208
5	Sand	0.045	0.43	29.7
6	Clay	0.070	0.36	0.02
7	Clay Loam	0.100	0.39	1.31
8	Sandy Loam	0.065	0.41	4.4208
9	Sand	0.045	0.43	29.7

Figure 12 shows the modeled drainflow is generally greater than the field flow, especially at later time. In water balance terms this indicates that either the ET schedule values were not large enough or that the modeled recharge was over estimated. The ET schedule is considered reliable since it was based on direct Class A pan measurements and alfalfa crop coefficients developed specifically for the study site (Rashedi, 1983). The weakness seems to be in the amount of water allowed to infiltrate within the model. The geometry of the field allows water to run off the south end of an irrigation border. Anecdotal evidence supports the notion that the entire amount of water that was applied according to the irrigation schedule would not have entered the profile, unfortunately no measurements of surface runoff exist to adjust the irrigation amounts. The sensitivity analysis (Fig. 15) shows that an average drainflow of 4.8 L/min can be obtained in the model when the irrigation amount is reduced to 90% of the original amount. A 10% reduction in the irrigation amounts only produced a slight increase in the RMSE for pressure heads (from 14.5 cm to 17.5 cm).

Sensitivity Analysis: Additional simulations were run to check the sensitivity of the calibrated model to changes in ET and irrigation amounts. Figures 13-16 show the effects of using 90%, 80% and 70% the original values for ET and irrigation.

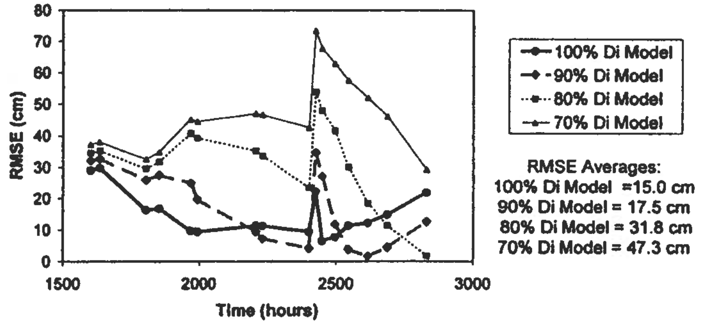


Fig. 13. RMSE for four D_i levels

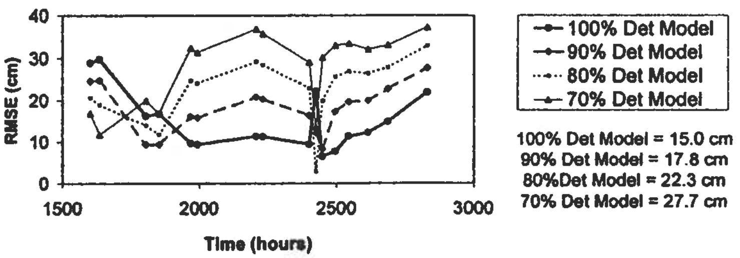


Fig. 14. RMSE for four D_{et} levels

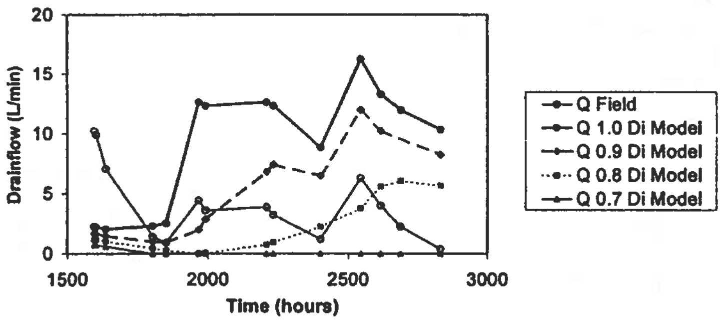


Fig. 15. Observed Drain Discharge Compared to Simulated Values for Four D_i Levels

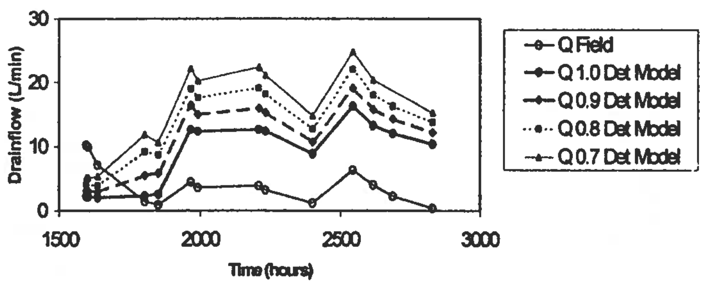


Fig. 16. Observed Drain Discharge Compared to Simulated Values for Four D_{et} Levels

Results and Discussion: Once a calibrated model is obtained it can be used to evaluate the efficiency of a previous year's irrigation schedule. This is done by inputting the appropriate time variable boundary information including an irrigation schedule, precipitation records and Class A pan based ET data. For this research 1987 was chosen because during that year half of the NARC field was sprinkler irrigated while the other half was flood irrigated. Simulating each of these schedules allows comparison between two common methods of irrigation. The simulations each modeled 5,316 hours, representing a full growing season from February 26th to September 30th. The actual atmospheric flux used in each simulation are shown in Fig. 17.

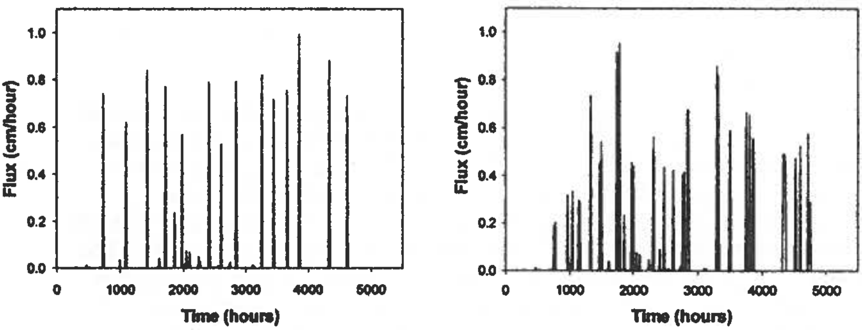


Fig.17. Atmospheric Fluxes for Simulations of the 1987 Flood (left) and Sprinkler (right) Irrigation Schedules.

For the purposes of this research, efficiency is judged with the following ratio,

$$D_{et} / (D_{et} + D_d) \tag{4}$$

where D_{et} is the depth of water used by evapotranspiration and D_d is the depth of drainage water. The ratio only is valid when no surface runoff occurs. The quantity D_{et} represents the water used beneficially by the plant, while $(D_{et} + D_d)$ delineates the total amount of water depleted from the soil. Optimal results are achieved as the ratio approaches one. Using short, 24-hour intervals indicates how the ratio behaves on a daily basis during irrigation cycles and provides insight into ways to modify standard irrigation practices to create a more efficient management alternative.

The cumulative atmospheric fluxes from the irrigation schedules were compared with the cumulative fluxes crossing the boundary within each simulation. The flood simulation accepted the entire amount (134.6 cm) of water that was applied. In contrast, at four separate times the sprinkler simulation profile did not accept all of the applied water and surface runoff occurred (Fig. 18). The total depth of water applied using the sprinkler schedule was 238.8 cm, of which 6.6 cm went to runoff.

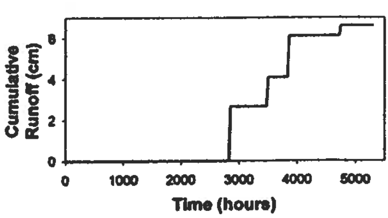


Fig. 18. Cumulative Surface Runoff Occurring During the 1987 Sprinkler Irrigation Simulation.

Before the efficiency of a simulation can be calculated and graphed on a daily basis the HYDRUS-2D output file *v_mean.out* must be modified. Using a spreadsheet program D_i, D_{et} and D_d for each iteration can be calculated by multiplying *vAtm, vRoot* and *vSeep* respectively by the time elapsed since the last iteration. Adding each D_i value to the ones before it provides a cumulative total of D_i for each time step. The same is done with D_{et} and D_d. To calculate the efficiency ratio on a daily basis the only values that are important are the cumulative totals for each 24-hour increment. Manually separating these values is time consuming, but a short FORTRAN program speeds the process greatly. The program used to sort the data for the irrigation efficiency graphs included in this paper follows in Fig. 19. The program requires an input file *24sort4* which includes the following columns: time, cumulative D_i, cumulative D_{et} and cumulative D_d. The output file *sort4* will contain the cumulative values of D_i, D_{et} and D_d for each 24-hour period. To find daily values for D_i, D_{et} and D_d take the difference between each day's cumulative total and use these daily values to calculate $D_{et}/(D_{et} + D_d)$. Daily $D_{et}/(D_{et} + D_d)$ for the flood and sprinkler irrigation simulations are shown in Fig. 20 and 21.

```
Real Time, CDi, CDet, CDd
        Open (10, File='24sort4.txt', status='old')
        Open (20, File='sort4.txt', status='old')
    P=1.0
    Do 100
    Read (10,*,end=101) Time, CDi, CDet, CDd
    Check = (P*24.0)-Time
    If (Check .LE. 0.2) then
        Write (20,*) Time, CDi, CDet, CDd
        P=P+1.0
    End if
    100 continue
    101 Close (10)
        Close (20)
    End
```

Fig. 19. FORTRAN Program Used to Sort Data

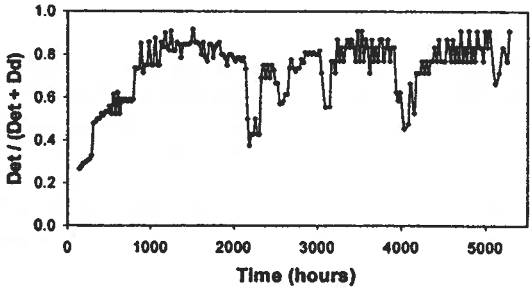


Fig. 20. Fraction of Removed Soil Water Going to ET for 1987 Flood Irrigation Simulation

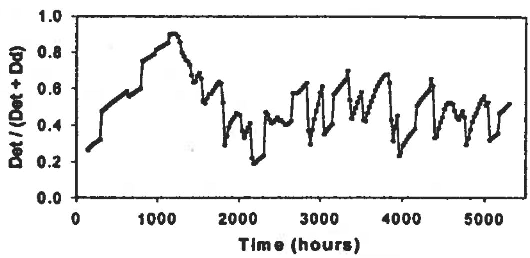


Fig. 21. Fraction of removed soil water going to ET for 1987 sprinkler irrigation simulation

The average value of $D_{et}/(D_{et} + D_d)$ for the flood simulation (0.73) was higher than for the sprinkler simulation (0.51), indicating that in this case the flood schedule was more efficient than the sprinkler schedule. Due to the surface runoff the sprinkler irrigation was actually less efficient than 0.51. A better measure of efficiency when runoff occurs is the water use efficiency (E_u),

$$E_u = W_u / W_d \qquad (5)$$

where W_u is the water benefically used and W_d is the water delivered to the area being irrigated (Schwab et al, 1996). Therefore, with W_u equal to D_{et} and W_d equivalent to $(D_{et} + D_d)$ plus the depth of runoff, the E_u for the sprinkler simulation equalled 0.48.

The aim of a management alternative is to increase the efficiency of an irrigation schedule without adversely affecting the plant's yield. Various strategies for increasing the efficiency have been tried, each one attempts to reduce the application of water in order to prevent drainage. To be sure that plant stress is not reducing yield the *cum_Q.out* file should be examined to be sure that *CumQRP* (cumulative potential root-water uptake) and *CumQRP* (cumulative actual root-water uptake) are equal, if they are than the model is allowing the calculated reference ET to occur.

The management alternative that has shown the greatest success is based on meeting the ET requirements of the plant. A weekly irrigation was applied to meet the ET requirements of the upcoming week. ET and natural precipitation values from 1987 were used. The natural precipitation was included in the model, but was in addition to the amount of water applied to meet the ET requirement. A second management alternative modeled a 90% efficiency based on the depth of weekly irrigation equal to $D_{et}/0.9$ for that week. The results of these management alternatives appear in Fig. 22.

The average value of $D_{et}/(D_{et} + D_d)$ for the simulation that matched the ET requirements was 0.85 while the D_{et}/90% simulation averaged 0.78. The natural precipitation reduced the expected efficiency of each simulation due to increased drainage. This drainage may be helpful for leaching salts out of the root zone. Figure 23 shows how the average efficiency of the D_{et}/90% simulation was increased from 0.78 to 0.84 when the natural precipitation was removed from the model.

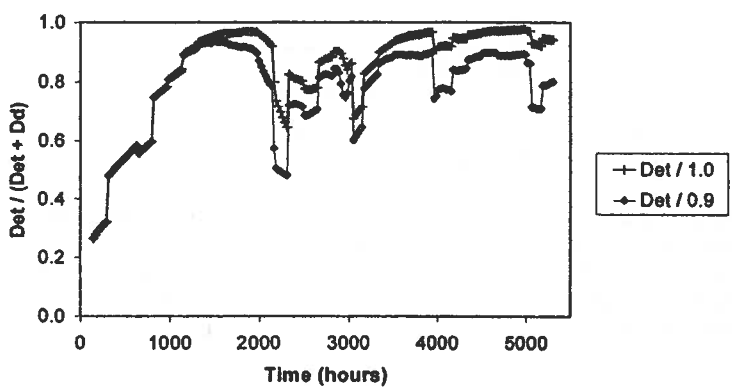


Fig. 22. Fraction of Removed Soil Water Going to ET for Two Management Alternatives. $D_{et}/1.0$ corresponds to a schedule that matches ET requirements, $D_{et}/0.9$ corresponds to a schedule with a 90% efficiency.

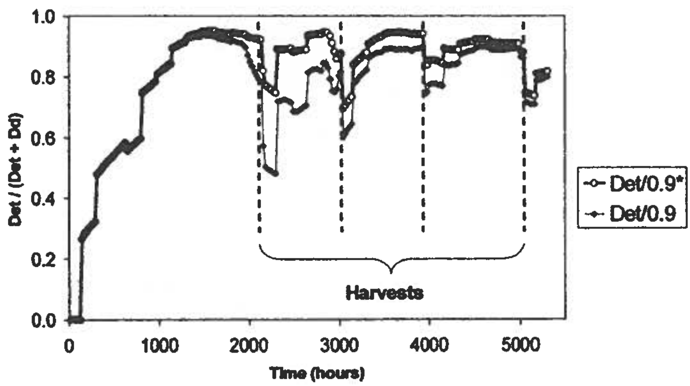


Fig. 23. Fraction of Removed Soil Water Going to ET for Two Management Alternatives. $D_{et}/0.9$ corresponds to a schedule with a 90% efficiency and natural precipitation, $D_{et}/0.9^*$ corresponds to the same schedule without natural precipitation.

Each management alternative shows a similar pattern of decreased efficiency, first during the initial hours of the simulation (t<1,600 hrs) and then after each alfalfa cutting. Cuttings occurred on May 21st (2,148 hours), June 26th (3,012 hours), August 3rd (3,924 hours) and September 18th (5028 hours). Figure 24 shows the daily drainage for the $D_{et}/1.0$ model. The greatest drainage occurs at the beginning of the simulation. This early drainage may be a remnant of the initial conditions imposed on the profile and the drainage that occurs while the initially flat water table takes on a sloped form. Therefore, it is possible that the early inefficiency may result from model limitations and may not be duplicated in the field where this sloping water table rises following irrigation rather than falling from a flat water table. After 1,600 hours the initial drainage is complete (Fig. 24) and the efficiency remains relatively high with the exception of short periods of inefficiency during four post-harvest periods (Fig. 23). The inefficiency after the first two cuttings matches closely with an increase in drainage. By reducing irrigation before harvest D_d may also be reduced. The same is not true about the third and fourth cuttings where drainage is minimal and continues to decline after harvest. Here the apparent inefficiency is the result of a small drainage term dominating a smaller post-harvest ET term.

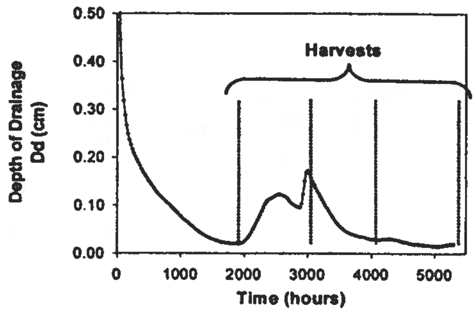


Fig. 24. Depth of Water Going to Drainage During each 24-hrs, Harvests are Shown as Vertical Lines.

CONCLUSION

A two-dimensional, hydrodynamic model of a half drain spacing was developed using HYDRUS-2D. The model was calibrated to pressure head and drainflow data collected in 1992 at the NARC. A RMSE of 15.0 cm was achieved between field and modeled pressure head by adjusting the soil type and hydraulic properties of layers in the profile. This RMSE is in close agreement with the values obtained in previous work (Newton, 1998 and Guitjens, 1999). The modeled versus field drainflow showed less agreement, due in part to modeled results being compared to the average across the length of the drain and in part to overestimates in the recharge due to lack of surface runoff measurements. Future work will attempt to calibrate drainflow by reducing the time allowed for infiltration to more closely approximate the hydrodynamics of an irrigation event. The calibrated model was useful for evaluating the 1987 flood and sprinkler irrigation schedules, showing that both schedules over watered. Management alternative schedules were developed based on the ET requirements of alfalfa and resulted in an increased efficiency of between 12-37%.

REFERENCES

Anderson, M.P. and Woessner, W.W. 1992. Applied Groundwater Modeling: Simulation of Flow and Advective Transport. Academic Press, San Diego, CA, 381 p.

Ayars, J.E. and Meek, D.W. 1994. Drainage load-flows relationships in arid irrigated areas. Trans. ASAE, 37: 431-437.

Clark, J. 1995. Stillwater National Wildlife Refuge, Refuge Reporter, Retrieved May 20, 1999 from the World Wide Web: http://www.gorp.com/gorp/resource/us_nwr/nv_still.htm

Coboum, J., Johnson, W., Ford, J., Reid, M., and Allen, N. 1992. Nevada's water future: making tough choices, A Guide for Public Policy Dialogue, Sponsored by University of Nevada, Cooperative Extension.

Doorenbos, J. and Pruitt, W.O. 1977. Crop water requirements. Irrigation and Drainage Paper No.24, FAO United Nations, Rome, 144 p.

Faulkner, B.R. 1996. Soil chemistry and hydrodynamics of irrigation with drainwater, Nevada, University of Nevada, Reno Masters Thesis, 78 p.

Feddes, R.A., Bresler, E., and Zaradny, H. 1978. Simulation of Field Water Use and Crop Yield, Simulation Monographs, Pudoc, Wageningen, The Netherlands, 188 p.

Glancy, P.A. 1986. Geohydrology of the basalt and unconsolidated sedimentary aquifers in the Fallon area, Churchill County, Nevada, USGS Water-Supply Paper 2263. 62 p.

Guitjens, J.C., 1992. Interpreting spatial yield variability of irrigated spring wheat. Trans. ASCE. 35(1):91-95.

Guitjens, J.C. 1999. Modeling management alternatives for efficient water use and drainage reduction. USCID 17th Congress, Spain Trans. 1B-Q48 (R3.06):79-94.

Hoffman, R.J. 1994. Detailed study of irrigation drainage in and near Wildlife Management Areas, West-Central Nevada, 1987-90, Part C. Summary of irrigation-drainage effects on water quality, bottom sediment and biota. USGS Water-Resources Investigations Report 92-4024C. 32 p.

Mathis, A.C. 1995. Influence of the subsurface distribution of salts and trace elements on the quality of irrigation drainage water at Fallon, Nevada, University of Nevada, Reno Masters Thesis, 185 p.

Newton, B. 1998. Simulating hydrodynamics of irrigation drainage. University of Nevada, Reno, Professional Paper, 68 p.

Pohll, G.M. 1993. Modeling regional flow and flow to drains, University of Nevada, Reno Masters Thesis, 120 p.

Pholl, G.M. and J.C. Guitjens. 1994. Modeling regional flow and flow to drains, Journal of Irrigation and Drainage Engineering. 120(5):925-938.

Rashedi, N. 1983. Evapotranspiration crop coefficients for alfalfa at Fallon, Nevada, University of Nevada, Reno Masters Thesis, 155 p.

Rowe, T.G., Lico, M.S., Hallock, R.J., Maest, A.S. and Hoffman, R.J. 1991. Physical, chemical and biological data for Stillwater, Frenley and Humboldt Wildlife Management Areas and Carson Lake, West-Central Nevada, 1987-1989. USGS Open-File Report 91-185.

Schwab, G.O., Fangmeier, D.D., and Elliot, W.J., 1996. Soil Water Management Systems, 4th ed., Wiley and Sons, New York. 371 p.

Simunek, J., Sejna, M., and van Genuchten, M.Th. 1996. The HYDRUS_2D Software Package for Simulating Water Flow and Solute Transport in Two-Dimensional Variably Saturated Media, Version 1.0, USSL, Riverside, CA, 167 p.

Trionfante, J. and Peltz, L. 1994. Hydrologic features of the Truckee and Carson River Basins and adjacent areas, Western Nevada and Eastern California, USGS, Open File Report 93-368, map.

WHSRN-USA. Stillwater Nevada, USA Hemispheric Reserve. Retrieved May 21, 1999 from the World Wide Web: http://wetlands.ca/wi-a/whsrn/stilwater.html.

Willden, R. and Speed, R.C. 1974. Geology and mineral deposits of Churchill County, Nevada, Bulletin 83 of Nevada Bureau of Mines and Geology, University of Nevada, Reno, 95 p.

CHARACTERIZATION OF THE CONDITION OF IRRIGATED LAND IN THE SEMI-ARID REGIONS OF SOUTHERN AFRICA

Michael A. Johnston[1] Meiring du Plessis[2]

ABSTRACT

Intensive irrigation in the semi-arid regions of southern Africa often leads to the degradation of soil properties and river water quality, and causes the development of high water tables. There is consequently a need to monitor the condition of irrigated land regarding its productivity so that problems can be identified and rectified timeously. Because comprehensive characterization of land is costly, it is seldom carried out, particularly in developing countries. A survey procedure is proposed which involves various field and laboratory measurements which will allow the establishment of critically important land characteristics on a cost-effective basis. Characterization of the soil salinity/sodicity status can be greatly enhanced by employing electromagnetic induction measurements, with the aid of GIS presentation, to rapidly delineate categories of problematic soils. This information, in conjunction with soil type, provides a rational basis for selecting a limited number of suitable sites for soil sampling. Sodicity in southern Africa is invariably an issue on the poorer quality soils, and the soil aggregate stability can be evaluated using rapid laboratory tests. A case study showed that by using the proposed procedure the cost can be reduced to about one fifth of that using a conventional approach.

INTRODUCTION

Irrigation agriculture in South Africa dates back at least 200 years, when small scale irrigation was practised by the European settlers in the present-day Western Cape province, at the southern tip of Africa, for the production of fruit and vegetables (Bruwer and van Heerden, 1991). Gradual expansion in the area under irrigation took place thereafter, but it wasn't until the early to mid nineteen hundreds that substantial development took place. Between about 1930 and 1950 a number of major state-financed irrigation schemes were developed across the country during this economically-depressed period, with a view to financial upliftment of the population. Expansion has continued subsequently, and to-day there are some 1.29 million hectares of land under irrigation (Water Research

[1] Associate Professor (Soil Science), School of Applied Environmental Sciences, University of Natal, Private Bag X01, Scottsville 3209, South Africa.

[2] Research Manager, Water Research Commission, P O Box 184, Pretoria 0001.

Commission, 1996). The size of individual schemes ranges between about 5 000 ha and 50 000 ha.

Irrigation development in relation to climate and land resources

Climatic conditions in southern Africa make irrigation an attractive option for farmers. Over 60 % of South Africa receives less than 500 mm of rainfall per annum, and the evaporative demand is high (Scotney and van der Merwe, 1991). Rainfall tends to be higher in the eastern regions, and becomes drier towards the west (Fig. 1). Most areas receive summer rainfall, with only the western Cape having a Mediterranean climate. Rainfall is, however, erratic and unreliable, and results in periodic droughts and floods. As a result, irrigation plays a vital role in stabilizing agricultural production. The major crops being irrigated in South Africa, ranked according to the total area under production for that crop, are: Small grain (wheat, barley, etc.), alfalfa, maize, fruit (deciduous plus citrus), vegetables, pasture and forages, grapes, sugarcane, oilseeds, potatoes, cotton and tobacco (Water Research Commission, 1996).

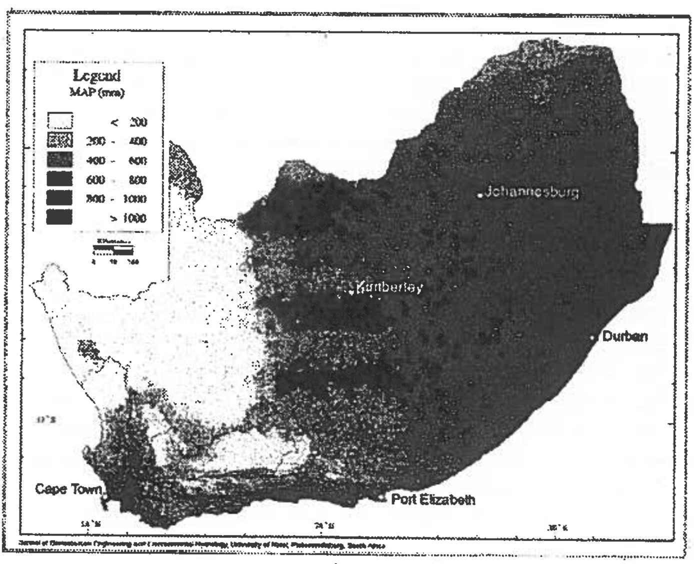


Fig. 1: Rainfall distribution in South Africa in terms of mean annual precipitation (after Dent, Lynch and Schulze, 1989).

Statistics provided by the Water Research Commission (1996) show that about 45 % of irrigated land has a rainfall of less than 500 mm, and 83 % less than 750 mm per annum. In the drier regions flood irrigation is the dominant method, whereas sprinkler irrigation is more common in the moister regions where the topography is steeper. Overall, sprinkler irrigation is the most common method (about 55%), and there is an on-going tendency to move away from flood (currently about 33%) towards sprinkler and micro methods. The quantity of water that is irrigated per annum varies widely according to climate and crop, but would typically fall in the range of 700 mm to 1300 mm.

The planning and establishment of the major irrigation schemes has generally been soundly done. The land selected for irrigation has been based on detailed soil surveys, and soils of poor quality excluded as far as practically possible. Traditionally, irrigation schemes were established on almost level alluvial soils along major river systems. While these soils are predominantly deep loams, there is often marked variability in textural and structural properties, internal drainage and salt status. Suitable soils are often spatially interwoven with those with severe limitations, and it is inevitable that some poor quality soils have been included in the irrigation development. These include shallow (<0.8 m) soils, "duplex" soils (large and abrupt textural change between A and B horizons), medium to coarse sands, and heavy clays. The proportions of soils of different suitability that are irrigated in the various South African provinces are shown in Table 1. On average, about 13 % of the soils were regarded as being of marginal quality for irrigation. This could represent a conservative estimate of the current situation, because expansion of the schemes has tended to encroach into areas of poor quality soils. However, a high proportion of the soils developed are deep sandy loams to sandy clays, and are very suitable for irrigation.

Drainage

In the development of the irrigation schemes, provision was generally made for a system of main drains, so that surface water could be effectively removed. Subsurface drains were not installed initially in order to keep capital costs to a minimum. The intention was to install subsurface drains if, and when, waterlogging problems arose. This has indeed occurred, and subsurface pipe drains have been installed to a greater or lesser degree on all of the schemes in order to control the water table. As much as 40 % of irrigated land in some regions is underlain by drainage (du Plessis, 1991).

Water sources and quality

Surface waters form the major water source in southern Africa, and virtually all of the large irrigation schemes are supplied from storage dams situated on the larger rivers. By normal standards of irrigation in semi arid/arid regions of the world, the quality of irrigation water is fairly good. While the electrical conductivity (EC) seldom exceeds 1.0 dS m^{-1} on average, on many schemes the EC is less than 0.5

dS m^{-1}. Table 2 shows some analyses that represent the typical quality of water used at some of the larger South African irrigation schemes. The quality is, however, deteriorating with more intensive use, and irrigation agriculture will need to adapt to the future scenario of producing crops with less water of a poorer quality (du Plessis, 1991).

Table 1: Areas under irrigation for various categories of land suitability in different provinces (Water Research Commission, 1996)

Province	Land						
	Very suitable		Suitable		Risky		Total
	Area ($x10^3$ ha)	%	Area ($x10^3$ ha)	%	Area ($x10^3$ ha)	%	Area ($x10^3$ ha)
Eastern Cape	34.6	22	95.0	61	25.3	16	154.9
Free State	39.1	39	41.1	42	18.7	19	98.9
Gauteng	16.9	63	6.9	26	2.9	11	26.7
KwaZulu-Natal	66.6	39	71.8	42	31.9	19	170.3
Mpumalanga	129.2	82	25.4	16	2.8	2	157.4
Northern Cape	81.0	50	71.3	44	9.6	6	161.9
Northern Prov	61.7	45	46.9	35	26.5	20	135.1
North West	83.6	81	16.3	16	3.4	3	103.3
Western Cape	100.9	36	128.0	45	52.6	19	281.5
Total	613.6	51	502.7	36	173.7	13	1 290

IMPACT OF IRRIGATION ON WATERLOGGING AND SOIL CONDITIONS

As in the rest of the world, waterlogging and salinity/sodicity problems have developed on virtually all of the major irrigation schemes in southern Africa. Experience has shown that most of the problems occur on land of poor suitability for irrigation (Dohse *et al.*, 1991). The problems have been exacerbated by flood irrigation methods that do not lend themselves to efficient water management, and also by a tendency by farmers to over-irrigate.

A number of surveys have been conducted to evaluate the extent of the problems. Estimates (Table 3) show that the areas affected in the different provinces vary between six and twenty six percent, which confirms that problems of significant magnitude exist. Associated with this is a progressive deterioration in the quality of irrigation water (du Plessis, 1991). While these aspects pose a threat to the long-term sustainability of some of the irrigation schemes, the situation is by no means out of control. In some regions large areas of waterlogged soils have been successfully reclaimed and brought back to high levels of production (Streutker, 1982).

Table 2: Typical chemical characteristics of irrigation water used at some major irrigation schemes in South Africa

Irrigation scheme	River	EC at 25° C (dS m^{-1})	pH	SAR (mmol $L^{-½}$)
Douglas	Vaal	0.8	7.5	2.0
Riet	Riet	0.6	7.6	2.6
Uppington	Orange	0.3	6.8	2.5
Robertson	Breede	0.3	7.2	1.3
Addo	Sundays	1.1	7.5	2.4
Loskop	Olifants	0.7	7.5	0.8
Pongola	Pongola	0.2	7.7	0.7
Heatonville	Mhlatuzi	0.3	7.3	1.6

Table 3: Estimated percentages of waterlogged or salt-affected irrigated land in the different provinces (Water Research Commission, 1996)

Province	Waterlogged or salt-affected		
	Severely %	Moderately %	Total %
Eastern Cape	6	13	19
Free State	6	18	24
Gauteng	5	15	20
KwaZulu-Natal	5	9	14
Mpumalanga	1	5	6
Northern Cape	4	20	24
Northern Province	12	14	26
North West	3	5	8
Western Cape	9	15	24

Negative impacts of irrigation are commonly expressed in terms of waterlogging, soil salinity and degradation of river water quality. However, other problems deserve attention. Soil sodicity is a major problem, and the vast majority of "salt-affected" soils are sodic (Scotney and van der Merwe, 1991). This has implications for soil structure and permeability (du Plessis and Shainberg, 1985). The associated problems of surface crusting, hardsetting (as a result of structural degradation; Mullins *et al.*, 1990), compaction and erosion tend to have been neglected.

THE NEED FOR MONITORING THE CONDITION OF IRRIGATED LAND.

Irrigated land is a valuable resource. Normally it is the highest potential land that is selected for irrigation. In South Africa, high potential, irrigable land is very scarce, and comprises less than 2 % of the total land area. Further, the large capital investment of an irrigation scheme demands that the irrigation scheme remain viable on a permanent basis. There is therefore a need to monitor the condition of the land in order to evaluate any degradation that is occurring and which might reduce the productivity in the long term. Identification of any problems will then allow remedial measures to be made timeously. While this makes logical sense, a proper characterization exercise is seldom carried out. A major obstacle is the cost of such an exercise.

While there is a large number of parameters that could be usefully measured in a land characterization exercise, it is aimed here to propose a monitoring programme that addresses the most critical "bottom line" issues. Appropriate techniques and procedures are suggested that help to reduce the cost of such an exercise. The proposals are made with regard to the conditions that generally pertain in southern Africa. In particular, soil types and the topography tend to be rather variable. This often results in the waterlogging/salinity problems tending to occur in rather isolated patches, separated by fairly large distances.

PROPOSED CHARACTERIZATION OF THE LAND AND WATER RESOURCES.

This proposal must be viewed as an exercise that should be carried out once every five to ten years in a resource monitoring programme, or as a once off exercise to evaluate the status of the resource. The following aspects are regarded as being of critical importance, and warrant characterization:

a) Irrigation water quality;
b) Soil salinity and sodicity;
c) Incidence and extent of waterlogging;
d) Soil aggregate stability (which has implications for surface crusting, hardsetting and erosion).

It is assumed that certain basic information would be available. This includes:

- Soil map, at a scale of 1:10 000 or larger;

- Orthophoto map at a scale of 1:10 000 (or larger) showing contours at, ideally, 2.0 m intervals.

If possible a recent colour aerial photograph should be obtained, since this will help considerably to provide a visual record of the *status quo* regarding the land and crop growth performance.

A procedure to characterize these land and water features on a cost-effective basis is presented below.

(a) Irrigation water quality

The chemical composition would normally require monitoring on a monthly, or perhaps seasonal (low/high river flow) basis. A periodic evaluation of these results corresponding to the land evaluation exercise would be appropriate. The major parameters that would require characterization are:
EC; pH; concentrations of Ca^{++},Mg^{++},Na^{+},K^{+},Cl^{-}, $SO_4^{=}$,alkalinity (i.e. $CO_3^{=}$ + HCO_3^{-}); and the calculated sodium adsorption ratio (SAR).

If drip irrigation is being practised, iron concentration should be measured, in view of the hazard of blockage of dripper nozzles. Concentrations higher than 1 mg L^{-1} are regarded by Hewson *et al.* (1995) as being problematic. If the particular water is subject to industrial pollution then the analysis of other elements (e.g. heavy metals) is warranted.

Evaluation of irrigation water is comprehensively discussed for South African conditions by the Department of Water Affairs and Forestry (1993). A point that should be made is that many soils are particularly susceptible to the adverse effects of sodium, and SAR levels as low as 2 can be harmful to the infiltration rate. A factor that plays an important role is rainfall, often of high intensity, on bare soil shortly after planting. In order to counteract the low electrolyte concentration/sodium effect, gypsum is widely used as a topdressing, particularly in horticultural crops.

(b) Soil salinity and sodicity

Characterization of the salinity and sodicity status of soil is most effectively achieved by analysis of the extract of a saturated soil paste (Rhoades *et al.*, 1999). The EC of this extract (EC_e) describes the salinity status and the SAR_e the sodicity status. These measurements ultimately need to be made on samples taken down to a depth of about 0.9 m. Conducting a survey using purely a soil sampling (and analysis) programme is, however, a very laborious and costly exercise. The procedure can be streamlined to a large degree by the use of the electromagnetic induction (EM) technique.

The EM method of evaluating soil salinity is well-established, and a detailed account of the principles and practices of the technique is given by Rhoades *et al.* (1999). The Model EM-38 (of Geonics Ltd., Canada) is particularly useful, and the instrument effectively measures the apparent EC of the bulk soil (EC_a) to a depth of approximately 1.50 m. It is sensitive to the conductive liquid phase, and is primarily influenced by the electrolyte concentration as well as the water content of the soil.

Quite a considerable amount of research work has been done in various countries in generating calibration relationships for interpreting EC_e values from instrument measurements. Most notable of these have been conducted in the United States at the U.S. Salinity Laboratory (Rhoades, 1990), in Canada (McKenzie *et al.*, 1989), in Australia (Slavich and Petterson, 1990) and in South Africa (Johnston *et al.*, 1996). In our experience, the prediction of EC_e from instrument readings using calibration equations is not highly accurate, due mainly to textural and water content differences that invariably exist down the profile. The real strength of the technique, however, is that measurements of reasonable accuracy can be made very rapidly without the need for direct contact between the sensor and the soil. The instrument can therefore be used as a screening tool, whereby areas of similar EC_a can be delineated. This helps considerably in selecting the most meaningful sites for soil sampling for salinity analysis. Far fewer soil samples are, as a result, required.

The EM technique can also be used to identify areas that are susceptible to salinity development by measuring the conductivity of the material below soil depth. The EM-34/3 model has a much deeper response depth than the EM-38, and this instrument has been used successfully for this purpose by Williams and Baker (1982).

The technique is not directly sensitive to soil sodium status, *per se*. However, in southern Africa (and elsewhere, Rhoades *et al.*, 1999) there is a general relationship between soil salinity and sodicity, and it is rather unusual for a sodic soil to have a very low salinity level. Using the survey procedure suggested here, the sodium status would be characterized within a particular salinity category.

It should be mentioned that substantial progress has been made in the U.S. and Canada in developing automated systems of mapping soil salinity, using a vehicle-mounted EM-38 sensor connected to a global positioning system (GPS) receiver (Cannon *et al.*, 1994). Such systems certainly have an important role to play in irrigation agriculture where soil salinity is a major, widespread problem. However, in southern Africa the problem is of a lower magnitude, and affected land tends to occur in isolated patches. This situation does not generally justify the expense of a sophisticated automated system.

Recommended survey procedure

While there is room for personal preferences in the system that may be followed in a survey, the following procedure is recommended. Conduct an EM survey on a two-stage basis whereby a reconnaissance investigation is carried out at more widely spaced points, recording the position from a GPS receiver. Once a general impression of the magnitudes of EC_a have been obtained for different categories of land, a strategy for more detailed measurements can be developed. This exercise should be conducted with regard to the soil type (using a soil map) and, if possible, from visual appearance using recent colour aerial photographs. For the most reliable interpretation of EM readings, the soil moisture status should be near field capacity when the survey is undertaken. Drier conditions result in relatively low EC_a (and EM) values (McKenzie *et al.*, 1989).

Problem areas that have been identified by the above procedure should then be studied in greater detail. The EM measurements should be made at spacings of between about 20 and 80 m, depending on the prevailing conditions. Each position can be established by using a system of reference pegs, or preferably from positions obtained from a GPS receiver. A GPS resolution of 5 to 10 m is regarded as satisfactory.

The data set of EM measurements with their respective positions should be plotted to provide a picture of the spatial distribution of salinity levels. Two options exist regarding the salinity parameter used. Either the EM reading can be used directly (after correcting to 25° C, McKenzie *et al.* 1989), or EC_e could be estimated using an appropriate calibration equation (Johnston *et al.*, 1996; McKenzie *et al.*, 1989; Rhoades, 1990) and that plotted. As a permanent record of the salinity status of the soil, it is appropriate, in our opinion, to use both options and plot both EM values as well as calculated EC_e values for the upper profile. In order to achieve the latter it is necessary to establish calibration equations for the particular soils involved. These can be developed from soil samples, taken at 0.3 m depth intervals down to 0.9 m or deeper.

c) Incidence and extent of waterlogging

While surface water accumulation can arise from inadequate smoothing of land, it is primarily high water tables (i.e. subsurface water) that require identification and delineation. Two types of monitoring "wells" should be considered, *viz.*:

- Deeper boreholes (20-30 m depth): For measuring, on a regular basis, the changes in groundwater level as a result of irrigation activities. By monitoring changes in the water level, it can be determined whether the general groundwater level is rising, and one can then evaluate the risk for the development of wide-spread waterlogging conditions.

- Shallow observation wells: Positioned within the irrigated land to detect the development of perched water tables in areas where topography and soil conditions indicate their likely development.

Installation of observation wells can most conveniently be achieved by augering to a depth of at least 1.2 m and, if necessary, lining the hole with a perforated plastic pipe. By positioning the observation wells at suitable intervals on transects across problem areas, the depth to the watertable can be quantified. Water table elevations, at perhaps 0.5 m depth intervals, can then be plotted on a map of suitable scale.

Artesian water is sometimes encountered on alluvial soils, whereby the shallow groundwater is confined below an impermeable clay layer in the lower soil profile. This situation is normally easily identified in the course of augering observation wells. The use of piezometers, i.e. non-perforated tubes sealed within the access hole, is warranted. The characteristics of the artesian water body (e.g. depth and distribution of the confining layer, location of recharge area) would influence the design of a suitable drainage system.

d) Soil structural condition

While the sodium status (SAR_e or exchangeable sodium percentage) describes the potential for instability of the clay fraction (dispersion and swelling), it is very desirable to measure directly the physical condition regarding structural coherence and permeability. Tests should ideally be done both on the topsoil (plough depth) as well as on the subsoil at a depth which is most restricting to permeability.

A test which is very simple, and yet yields very meaningful information, is the "Emerson test" (Charman and Murphy, 1991). This test uses a visual rating system that describes the degree of clay dispersion in soil. Basically, observations are made on the degree of dispersion (turbidity) in distilled water after subjecting a soil sample to three different levels of physical disruption *viz.* no disruption, a moistened sample physically worked with a spatula, and a suspension shaken for 10 minutes. The rating system produces an index on a scale of 1 (dispersive) to 8 (non dispersive/stable). Other useful tests which could also be used are the air:water permeability ratio (Hutson, 1982; Reeve, 1965a) and the modulus of rupture (Reeve, 1965b).

As with soil sodicity, aggregate stability should be characterized within salinity (EC_e) categories, and within soil types. In addition to the aggregate stability evaluation, the other structural problems such as surface crusting, hardsetting and compaction can be given particular attention, if it is warranted.

OUTLINE OF A CASE STUDY OF LAND EVALUATION

The condition of an area of land of 121 hectares (299 acres) on a sugarcane irrigation scheme at Heatonville (150 km north-east of Durban) was evaluated following a procedure similar to that described above, and using the EM-38 sensor. While the quality of irrigation water is good (Table 2), this scheme is known for its poor-quality duplex soils which tend to suffer from sodicity, unstable structure and low permeability.

The EM measurements, taken in both vertical and horizontal orientations, plus GPS positions were recorded at some 1 300 points by "walking" the area. Soil samples were taken down the profile at 28 selected points for calibration of the EM measurements, and evaluation of the salinity (EC_e) and sodicity (SAR_e) status. Soil properties in the problem areas were generally similar, and the main calibration equation used to translate EM to EC_e values was:

$$EC_e(\text{mean of 0-0.9m depth}) = 0.033EM(\text{mean of vertical+horizontal}) - 1.647$$
$$(r = 0.88 \text{ for 17 observations})$$

Aggregate stability was evaluated using the Emerson test on these plus 25 other surface (0-0.3 m depth) soil samples. The depth to the perched water table was established from 155 observation holes, augered to 1.2 m and sited at strategic positions in the problem areas. The ArcView 3.1 package (Environmental Systems Research Institute, Inc., CA) was used to plot the distribution of salinity in terms of both EC_e (Fig. 2) and EM values, as well as the distribution of the water table (Fig. 3).

It is clear that soil salinity on this irrigation scheme does not reach very high levels (Fig. 2), due largely to the low-salinity irrigation water. A comparison between Figs 2 and 3 confirm that the salinity problems are closely associated with waterlogging. It was also found that SAR_e was strongly related to EC_e (r of 0.82 for 44 observations) for the problem areas. The linear regression relationship obtained allowed a fairly reliable association of SAR_e with the EC_e ranges used in Fig. 2:

EC_e (dS m^{-1})	SAR_e
2.0 - 3.0	19 - 27
3.0 - 4.0	27 - 34

Clearly, a serious sodicity problem exists which needs to be treated.

The basic costs of the various elements of the exercise are given in Table 5. Also reported for comparative purposes is the estimated cost that would be incurred using a conventional procedure, without the EM sensor. The major difference

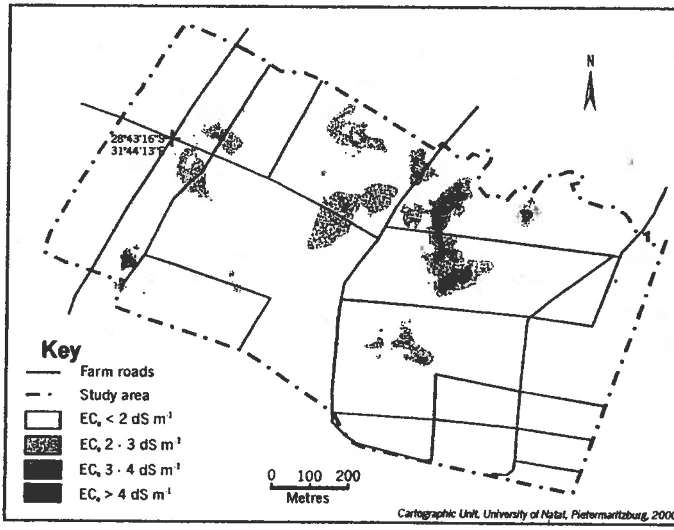


Fig. 2: The distribution of soil salinity in terms of EC_e for the 0-0.9 m depth predicted from EM measurements in the study area at Heatonville.

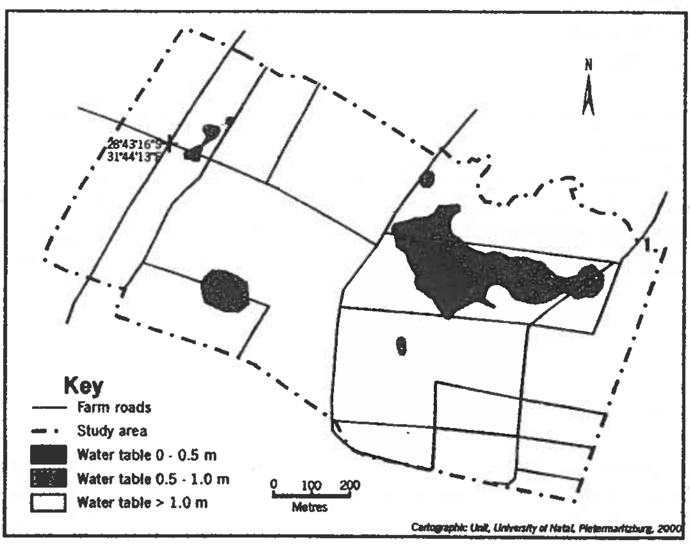


Fig. 3: The distribution of the high water table in the study area at Heatonville.

Table 5: Relative costs for conducting a soil evaluation of a 121 ha area at Heatonville using (a) the EM-38 sensor, as opposed to (b) the conventional procedure. Costs are given in South African rands, with an approximate exchange rate of R6.00 : US $1.00.

(a) Procedure using the EM-38 sensor:

Item	Cost (R)
Personnel	
Reconnaissance EM survey; technician for 2 days @ R350 day^{-1}	700
Detailed EM survey; technician for 3 days @ R350 day^{-1}	1 050
Water table survey; technician for 2 days @ R350 day^{-1}	700
4 field assistants for 1 day @ R80 day^{-1} each	320
Data processing/GIS work; technician for 1.5 days @ R350 day^{-1}	525
Equipment	
EM-38 (R43 000) + GPS (R41 000); expected life span 4 000 hours, 40 hours (Rhoades *et al.*, 1999) @ R21 h^{-1}	840
Motor vehicle for 5 days @ R300 day^{-1}	1 500
Photographs, maps, etc.	600
Soil analysis	
84 saturation extract analyses @ R30 $sample^{-1}$	2 520
50 aggregate stability tests @ R10 $sample^{-1}$	500
Overall cost ha^{-1}	76

(b) Conventional procedure (expected costs):

Item	Cost (R)
Personnel	
Field survey; sampling by auger; technician for 12 days @ R350 day^{-1}	4 200
1 field assistant for 10 days @ R80 day^{-1}	800
Data processing/GIS work; technician for 1.5 days @ R350 day^{-1}	525
Equipment	
GPS (R41 000); expected life span 4 000 h, 48 hours @ R10.25 h^{-1}	492
Motor vehicle for 12 days @ R300 day^{-1}	3 600
Photographs, maps, etc.	600
Soil analysis	
1 000 saturation extract analyses @ R30 $sample^{-1}$	30 000
50 aggregate stability tests @ R10 $sample^{-1}$	500
Overall cost ha^{-1}	337

between the approaches is that in the conventional procedure all of the salinity measurements would be done by augering, and then analysis of the saturation extract. Where the EM method is employed, the bulk of the salinity measurements is estimated from instrument readings, and the number of soil samples required would be less than 10 % of that for the former procedure.

The costing exercise showed that the use of the EM sensor allowed a substantial saving, and the overall cost amounted to approximately 22 % of that for the conventional procedure. Cost items having a major impact were sample analysis and salary for technical staff.

CONCLUSIONS

The information gathered in the proposed exercise serves to characterize effectively the condition of the land and water resources. The evaluation cannot be regarded as being highly detailed, but the critical issues would be described using cost-effective procedures.

The proposed procedure will serve to identify soil and water problems that exist on an irrigation scheme, describe the severity, and also delineate the extent of the problem. This information can then be used for comparison with future surveys conducted in a similar way, in order to assess whether any deterioration in the natural resources has taken place.

Characterization of the soil salinity/sodicity status can be streamlined by use of an electromagnetic induction sensor. A case study conducted on a 121 ha area showed that this instrument allowed a considerable cost saving.

REFERENCES

Bruwer, J.J. and van Heerden, P.S., 1991. Spotlight on irrigation development in the RSA: The past, present and future. Proceedings of the Southern African Irrigation Symposium, (Durban): 3-10. The Water Research commission, Pretoria.

Cannon, M.E, McKenzie, R.C. and Lachapelle, G., 1994. Soil salinity mapping with electromagnetic induction and satellite-based navigational methods. Can. J. Soil Sci. 74,.335-343.

Charman, P.E.V. and Murphy, B., 1991. Soils, their Properties and Management. A Soil Conservation Handbook for New South Wales (pp 158-160). Sydney University Press.

Dent, M.C., Lynch, S.D. and Schulze 1989. Mapping Mean Annual and Other Rainfall Statistics over Southern Africa. Water Research Commission, Pretoria. WRC Report 109/1/89.

Department of Water Affairs and Forestry, 1993. South African Water Quality Guidelines, Volume 4: Agricultural Use. Government Printer, Pretoria.

Dohse, T.E., Schoeman, J.L. and Turner, D.P., 1991. Changing approaches to the selection of land for irrigation development. Proceedings of the Southern African Irrigation Symposium, (Durban): 240-247. Water Research Commission, Pretoria.

Du Plessis, H.M., 1991. Researching and applying measures to conserve natural irrigation resources. Proceedings of the Southern African Irrigation Symposium, (Durban): 61-69. Water Research Commission, Pretoria.

Du Plessis, H.M. and Shainberg, I., 1985. Effect of exchangeable sodium and phosphogypsum on the hydraulic properties of several South African soils. S.Afr. J. Plant Soil, 2, 179-186.

Hewson, S., Ridge, R. and Willcox, T., 1995. Reference Manual on Drip Irrigation for Sugarcane. Bureau of Sugar Experiment Stations, Bundaberg, Australia.

Hutson, J.L., 1982. Structural stability of diagnostic horizons in South African soils. South Afr. J. Science, 453-454.

Johnston, M. A., Savage, M.J., Moolman, J.H. and du Plessis, H.M., 1996. Calibration models for interpretation of soil salinity measurements using an electromagnetic induction technique. S.Afr. J. Plant Soil, 13, 110-114.

McKenzie, R.C., Chomistek, W. and Clark, N.F., 1989. Conversion of electromagnetic inductance readings to saturated paste extract values in soils for different temperature, texture, and moisture conditions. Can. J. Soil Sci. 69, 25-32.

Mullins, C.E., MacLoed, D.A., Northcote, K.H., Tisdall, J.M. and Young, I.M., 1990. Hard-setting soils: Behaviour, occurrence and management. Advances in Soil Science, 11, 37-99.

Reeve, R.C., 1965a. Air-to-water permeability ratio. In C.A. Black (ed.). Methods of soil analysis, Part 1. Physical and mineralogical properties. Agronomy 9, 520-531. Am. Soc. of Agron., Madison, Wis.

Reeve, R.C., 1965b. Modulus of rupture. In C.A. Black (ed.). Methods of soil analysis, Part 1. Physical and mineralogical properties. Agronomy 9, 466-471. Am. Soc. of Agron., Madison, Wis.

Rhoades, J.D., 1990. Determining soil salinity from measurements of electrical conductivity. Commun. Soil Sci. Plant Anal. 21, 1887-1926.

Rhoades, J.D., Chanduvi, F. and Lesch, S., 1999. Soil salinity assessment - methods and interpretation of electrical conductivity measurements. FAO Irrigation and Drainage Paper 57. Food and Agricultural Organization of the United Nations, Rome.

Scotney, D.M. and van der Merwe, A.J., 1991. Irrigation: long term viability of soil and water resources in South Africa. Proceedings of the Southern African Irrigation Symposium, (Durban): 50-60. The Water Research Commission, Pretoria.

Slavich, P.G. and Petterson, G.H., 1990. Estimating average root zone salinity from electromagnetic induction (EM-38) measurements. Aust. J. Soil Res. 28, 453-463.

Streutker, A., 1982. Present situation of irrigated soils in South Africa with regard to sustained crop production. Trends in water use efficiency, waterlogging and salinisation (in Afrikaans). Presented at the workshop on Soil Aspects of Irrigation. Water Research Commission, Pretoria.

Water Research Commission, 1996. Discussion paper on: Policy Proposal for Irrigated Agriculture in South Africa. Prepared by G.R. Backeberg, T.J. Bembridge, A.T.P. Bennie, J.A. Groenewald, P.S. Hammes, R.A. Pullen and H. Thompson. Report number KV96/96, Water Research Commission, Pretoria.

Williams, B.G. and Baker G.C., 1982. An electromagnetic induction technique for reconnaissance surveys of soil salinity hazards. Aust. J. Soil Res. 20, 107-118.

IMPROVING IRRIGATION AND DRAINAGE POLICIES TO ACHIEVE WATER QUALITY GOALS IN THE NEW MILLENNIUM

Dennis Wichelns[1]
Shannon Fretwell[3]
David Cone[2]

ABSTRACT

Irrigation and drainage activities can generate off-farm impacts when constituents in surface runoff or subsurface drain water degrade the quality of receiving waters. Efforts to improve water quality in rural areas have increased in recent years in both industrialized and developing countries. The goals of those efforts, the parameters of concern, and the policies implemented vary among countries according to the initial water quality conditions, the technology of agricultural production, and the level of economic development. In the industrialized countries, current efforts to achieve incremental improvements in water quality may, in some cases, generate costs that exceed incremental benefits. However, the benefits may accrue to a large number of residents in non-farm areas, while the direct costs are imposed on a smaller number of farm residents. In developing countries, the potential gains from water quality improvements often exceed incremental costs, but financial and political constraints may limit the implementation of effective programs. We provide in this paper an economic perspective regarding efforts to improve water quality in areas where irrigation and drainage activities generate off-farm impacts. We include examples from California and Egypt that illustrate some of the pertinent issues.

AN ECONOMIC FRAMEWORK

The off-farm impacts of irrigation and drainage activities have gained importance in recent years as many state and national governments have increased their efforts to enhance water use efficiency and improve water quality. In developed countries, water quality issues largely involve efforts to enhance the environmental amenities and recreational opportunities provided by rivers, lakes, and wetland areas. The demand for those amenities has

---

[1] Associate Professor, Univ. of Rhode Island, Kingston, Rhode Island.
[2] Manager, Broadview Water District, Firebaugh, California.
[3] Assistant Engineer, Stoddard & Associates, Los Banos, California.

increased over time with rising incomes and greater demand for recreation and leisure activities. There is also an increased awareness and greater concern regarding the potential impacts of pesticides, nutrients, and other constituents in surface runoff and subsurface drain water.

The total benefit derived from improvements in water quality can be described as an increasing function of some measure of water quality, such as dissolved oxygen or the inverse of the concentration of a harmful constituent. The total cost of achieving improvements in water quality can also be described as an increasing function in the same dimension. For most constituents of concern, it is likely that the total benefit increases at a declining rate over some range of water quality improvements. Within such a range, the incremental benefits obtained from further improvements in water quality are positive, but declining. It is also likely that the total cost of achieving improvements in water quality increases at a rising rate over some range of water quality improvements. Examples of plausible total benefit and total cost curves are shown in Figure 1.

Provided that all pertinent costs and benefits are included when estimating the functions shown in Figure 1, the socially optimal level of water quality would be WQ^*, where the vertical distance between the total benefit and total cost curves is maximized. Any other level of water quality would generate a smaller net benefit. This optimal level of water quality occurs precisely at the point where the incremental benefit is equal to the incremental cost, as shown in Figure 2.

The concepts described in Figures 1 and 2 suggest that policy makers should consider both the incremental benefits and incremental costs when defining water quality goals and choosing policy alternatives to achieve those goals. As noted above, it is possible in industrialized countries that current water quality efforts regarding some constituents in some locations may be seeking to achieve water quality levels that exceed the social optimum. This can occur when the benefits of water quality improvements accrue largely to individuals or groups who are not required to pay the direct costs of achieving those improvements. In many developing countries, current water quality efforts often fall short of WQ^* due to financial constraints or to a similar divergence between those who benefit from water quality improvements and those who would be required to pay for them.

Figure 1. Total Costs and Benefits of Water Quality Improvements

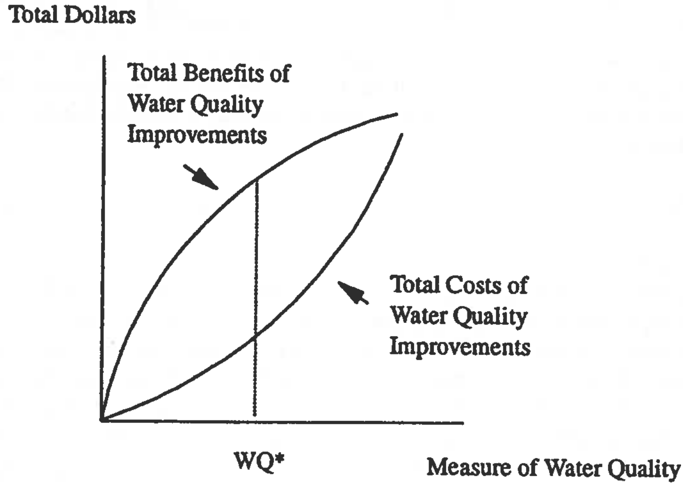
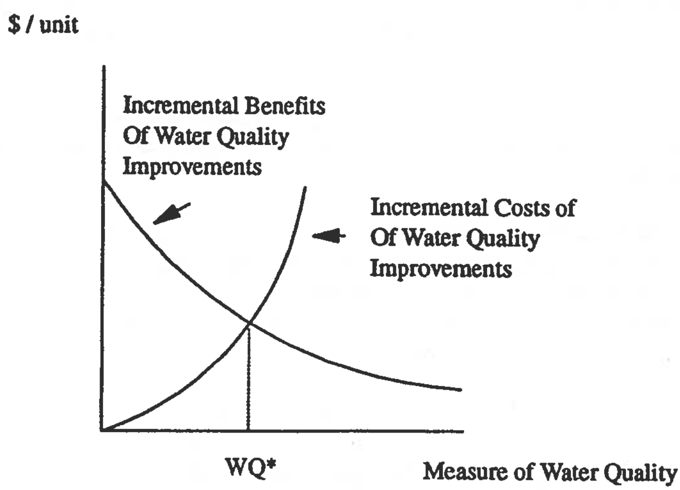


Figure 2. Incremental Costs and Benefits of Water Quality Improvements



The conceptual cost and benefit curves shown in Figures 1 and 2 provide a useful framework for evaluating water quality goals and policies. However, to implement this framework appropriately, policy officials must obtain accurate empirical estimates of the cost and benefit curves, and all pertinent costs and benefits must be included in those estimates. The curves may change over time with changes in public preferences and technology, such that some degree of flexibility in policy choices may be appropriate. We examine some of these issues in settings pertaining to both industrialized and developing countries.

WATER QUALITY EFFORTS IN INDUSTRIALIZED COUNTRIES

The goal of current policy efforts regarding the water quality impacts of irrigation and drainage activities in developed countries might be described as seeking incremental improvements in water systems that have already been improved substantially by regulatory policies implemented in earlier years. In the United States, for example, many state and national programs have been implemented since the original Clean Water Act was passed in 1972. Compliance activities implemented in both the public and private sectors have improved water quality in many of the nation's waterways. Incremental improvements may enhance water quality further and may improve the quality of life for those who derive direct or indirect benefits from rivers, lakes, and wetlands. However, the incremental costs of achieving further improvements in water quality may be substantial for some waterbodies, particularly when improvement requires reducing the concentration or load of a constituent for which a low-cost treatment or removal process is not available.

The pertinent policy questions regarding the water quality impacts of irrigation and drainage in developed countries might be described as the following:

- What are the constituents of concern in surface runoff and subsurface drain water, and what are the appropriate water quality standards for those constituents? Input from scientists and other specialists should be given appropriate weight when seeking answers to this question.

- How might appropriate water quality standards vary with location or with differences in pertinent land and water characteristics? In what situations might site-specific water quality standards be appropriate?

- What policies and programs can be implemented to achieve the desired water quality standards at minimum cost?

- What is the optimal policy strategy, given the inevitable uncertainty regarding the potential costs and benefits of water quality improvements, the farm-level responses to policy measures, the impact of rainfall and storm events on water quality conditions, and long-term changes in public preferences regarding agriculture and the environment?

- Will the incremental improvement in water quality be sufficient to justify the incremental costs, when all appropriate costs and benefits are considered?

Consideration of these policy issues is particularly important in developed countries where the incremental costs of further improvements in water quality may be substantial. One such example is found in California's San Joaquin Valley, where efforts to reduce the load of selenium entering the San Joaquin River in agricultural drainage water have generated substantial farm-level and regional costs in recent years. An appropriate question at this time is whether the incremental benefits of further reductions in selenium loads will exceed the incremental costs.

Reducing Selenium Load in
The San Joaquin River

In earlier papers we have described the farm-level and regional efforts that have been implemented since 1986 to reduce the volume of subsurface drain water entering California's San Joaquin River (Wichelns and Cone, 1992; Wichelns et al., 1996). The drain water contains selenium, boron, and other elements that are found naturally in local soils and are leached from the profile during irrigation and drainage activities (Letey et al., 1986; Deverel and Gallanthine, 1988; Gilliom, 1991).

The U.S. Environmental Protection Agency has established a national water quality criterion for selenium of 5 parts per billion (ppb), when measured as a 5-day moving average concentration. The California Regional Water Quality Control Board for the Central Valley Region has adopted a Basin Plan Amendment designed to achieve the national selenium concentration standard over time. That amendment includes a set of monthly and annual selenium load targets that are expected to generate acceptable selenium concentrations in the near term, while farm-level and regional efforts are implemented, over time, to achieve the national water quality standard. The selenium load targets require substantial reductions in the volume of subsurface drain water discharged to the San Joaquin River each year, as an affordable technology for removing selenium from drain water is not yet available.

Seven irrigation and drainage districts in the region have formed the Grassland Basin Drainage Activity Agreement to construct and operate regional drainage facilities and coordinate efforts to achieve the selenium load targets. The group has constructed a new channel that carries drainage water from all seven districts around a wetland habitat area to an existing portion of the San Luis Drain, which carries the water to a tributary of the San Joaquin River. That program, known locally as the Grassland Bypass Project, began operations in September of 1996.

We have estimated the costs of farm-level, district, and regional efforts to achieve the selenium load targets (Wichelns et al., 1999). Activities include farm-level improvements in irrigation methods, greater recycling of saline, commingled drainage water within irrigation districts, and formation of a regional drainage entity to coordinate district efforts and participate in policy discussions with staff members of state and national agencies. The estimated costs are the following:

Cost Category	Estimated Cost
	(dollars/acre)
Farm-level irrigation improvements	92.74
District efforts	11.22
Regional coordination	13.82
Total	117.78

The estimated total cost of $118 per acre generates an estimated annual cost of about $11 million throughout the 94,000-acre area included within the Grassland Bypass Project. This sum does not include some of the long-term costs of efforts to reduce drain water volume, such as the yield reductions and changes in cropping patterns that will likely occur in future, due to increasing soil salinity caused by persistent recycling of saline drainage water.

Estimating the costs of achieving selenium load targets is easier than estimating the potential benefits. However, one approach to evaluating current and future policy efforts is to ask whether the total benefit of current improvements in water quality exceeds $11 million per year, and whether the incremental value of further reductions in selenium loads will exceed the incremental costs.

Policy Implications

The selenium load targets pertaining to the Grassland Bypass Project are currently being reviewed by policy officials, as the agreements required to continue the project are scheduled for renewal. It is likely that the selenium load targets will be made more restrictive in future, requiring greater farm-level and district efforts to reduce the volume of subsurface drain water entering the San Joaquin River. Conceptually, more restrictive selenium load targets correspond to a higher level of WQ on the horizontal axis of the graph in Figure 1. If the current level of WQ is already beyond WQ^*, further efforts to improve water quality will reduce net social benefits.

Given the uncertainty regarding the impact of low concentrations of selenium in the San Joaquin River, policies that allow greater flexibility in farm operations may generate greater net social benefits than policies requiring strict adherence to restrictive load targets. Appropriate policy measures include allowance for storm events and periods of high rainfall when the volume of drainage water discharged to the River is increased naturally. Farmers and drainage districts have little control over the discharge of drainage water during those times and the volume of water in the River is usually increased by the same storm events. Hence, it may be socially optimal to allow greater discharges of agricultural drainage water during those periods.

The opportunity costs of administrative and research personnel should also be considered when evaluating water quality policies and programs. At present, the policy process for implementing selenium load targets, monitoring compliance, and determining the size of financial penalties consumes thousands of hours of administrative and research staff time each year. The direct costs of that time are reflected in salaries and travel expenses, while the opportunity costs include other endeavors that the administrators and researchers could be pursuing, if less time were required to administer and monitor the Grassland Bypass Project. These costs are often not trivial and they should be included when estimating the total and incremental costs of policies to improve water quality.

WATER QUALITY EFFORTS IN DEVELOPING COUNTRIES

Efforts to improve the quality of agricultural drainage water in developing countries may generate substantial benefits for farmers and other residents of rural areas. In many irrigated areas, farmers at the tail ends of canals use drainage water to augment their limited surface water supply. The salts in drainage water used by tail-end farmers will accumulate in soils, over time, and may eventually cause reductions in yields or changes in cropping patterns. In some areas, other harmful constituents in drainage water, such as pathogens from household effluent or metals from municipal and industrial effluent that enter agricultural drains may present more immediate hazards to tail-end farmers.

In areas where efforts to improve drainage water quality have been limited by financial or political constraints, the incremental gains from such improvements may be larger than the incremental costs. To the extent that current levels of water quality are less than WQ^* in Figures 1 and 2, net social benefits can be enhanced by improving water quality. In some developing countries the potential gains may be quite large, particularly in regions where agricultural drains receive effluent from non-agricultural sources and where the drains pass through many towns and villages in rural areas. A useful example of potentially large net gains to water quality improvements is provided by current irrigation and drainage conditions in the Nile Delta.

Improving Drainage Water Quality in the Nile River Delta

Agricultural drainage water is currently viewed as an important resource for irrigation in the Nile Delta. The Egyptian Ministry of Public Works and Water Resources operates a series of pumping stations that lift drainage water from main drains into delivery canals for blending with fresh water supplies. The Ministry currently recycles about 4 billion cubic meters of drainage water annually and is planning to expand pumping operations in future. Drainage water is also conveyed through a new canal to provide irrigation water for a portion of the Sinai Peninsula.

In some portions of the Nile Delta, the salinity of agricultural drainage water is less that 1,500 parts per million (ppm) in total dissolved solids (TDS) and the blended irrigation water is not directly harmful to crops (Zhu et al., 1998). In other areas, the salinity exceeds 1,500 ppm TDS and continuous use of the blended irrigation water will cause soil salinity to increase over time.

Drainage water quality is also impaired by metals and pathogens in municipal and industrial effluent discharged into agricultural drains. In some areas of the Nile Delta, the Ministry has stopped pumping agricultural drainage water for blending with irrigation supplies due to concerns regarding metals and pathogens (Zhu et al., 1999). However, many farmers withdraw water directly from drainage ditches to supplement their limited surface water supply.

Agricultural drainage water polluted with municipal and industrial effluent may pose a health risk to residents of towns and villages located along open drainage ditches. Some of the ditches discharge into Lake Manzala in the northern Delta, where water quality has been degraded substantially over time. Hence, efforts to improve the quality of water in agricultural drains may generate benefits for several groups of residents in the Nile Delta. These groups include farmers who use drainage water to supplement irrigation supplies, residents of towns and villages located along the drains, and those who live near Lake Manzala.

The incremental benefits of improvements in water quality may be larger than the incremental costs, given the current degradation of water quality in agricultural drains. Removing metals and pathogens may generate important health benefits, while also making more water available for use in irrigation. While the fixed costs of installing treatment facilities and re-directing municipal and industrial effluent may be substantial, the initial variable costs of removing effluent from agricultural drains should be relatively small at current concentrations.

Efforts to improve water quality in agricultural drains in the Nile Delta should include removal of municipal and industrial effluent from drains, as long as the Ministry and farmers continue to use agricultural drainage water to augment surface water supplies. Policies designed to reduce the volume and improve the quality of effluent generated by municipalities and industries would also be helpful in solving water quality problems. It is often less costly to reduce pollution before it is generated, rather than treating degraded waters or accepting the damages, particularly when initial levels of treatment may generate relatively large improvements in water quality.

Reducing the discharge of municipal and industrial effluent into agricultural drains would be consistent with efforts to improve farm-level water management in the Nile Delta. As farmers improve irrigation practices there will be less surface runoff in drains that collect both surface runoff and subsurface drain water. Operational spills into drains are also being reduced as the Ministry installs downstream control structures in secondary canals. Reducing the volume of surface runoff and operational spills will cause the average concentrations of salt and other constituents in agricultural drainage water to increase. Hence, the volume of effluent entering drains must also be reduced to prevent an increase in the concentrations of metals and pathogens.

Policy Implications

The Government of Egypt has already implemented water quality standards for effluent discharged by municipalities and industries, although enforcement is not complete. Law 48, passed in 1982, includes standards for BOD, COD, NH_4, pathogens, and total suspended solids (Zhu et al., 1998). However, due to lack of compliance with Law 48, the effluent discharged into several agricultural drains is not in compliance with those standards.

Efforts to achieve compliance will impose costs on municipalities and industries that will be required to reduce effluent volume and to treat the effluent that is discharged into agricultural drains. Firms and municipalities will be encouraged to implement low-cost alternatives for reducing effluent, such as changing production technology or adopting affordable treatment measures. At present, the incentive for innovation regarding municipal and industrial effluent reduction and treatment is less than it would be if the standards established in Law 48 were enforced.

The social costs of reducing municipal and industrial effluent may be substantial, as firms and towns are required to change production practices, invest in costly treatment programs, and seek alternative methods for disposing treated effluent. Conceptually, however, the social benefits of water quality improvements will exceed the social costs if the current level of WQ is less than WQ^* in the graphs in Figures 1 and 2. Successful efforts to improve the quality of water in agricultural drains in the Nile Delta could improve the quality of life for many Egyptians living in both rural and urban settings.

ACKNOWLEDGMENTS

This paper is Rhode Island Agricultural Experiment Station Publication 3753. The comments of Dr. Zhongping Zhu regarding irrigation and drainage in the Nile River Delta are appreciated.

REFERENCES

Deverel, S.J. and S.K. Gallanthine, 1988. Relation of salinity and selenium in shallow groundwater to hydrologic and geochemical processes, Western San Joaquin Valley, California. Open-File Report 88-336, U.S. Geological Survey, Sacramento, California, 23 pages.

Gilliom, R.J., 1991. Overview of sources, distribution, and mobility of selenium in the San Joaquin Valley, California. In: Dinar, A. and D. Zilberman (eds.), The Economics and Management of Water and Drainage in Agriculture. Kluwer Academic Publishers, Boston.

Letey, J., C. Roberts, M. Penberth, and C. Vasek, 1986. An agricultural dilemma: drainage water and toxics disposal in the San Joaquin Valley. Special Publication 3319, Division of Agriculture and Natural Resources, University of California, 56 pages.

Wichelns, D. and D. Cone, 1992. Tiered pricing motivates Californians to conserve water. Journal of Soil and Water Conservation, 47(2):139-144.

Wichelns, D., L. Houston, and D. Cone, 1996. Economic incentives reduce irrigation deliveries and drain water volume. Irrigation and Drainage Systems, 10:131-141.

Wichelns, D., D. Cone, S. Fretwell, and K. Ward, 1999. Estimating the costs of farm-level and district efforts to achieve selenium load targets. In: Contemporary Challenges for Irrigation and Drainage, Proceedings of the 14th Technical Conference on Irrigation, Drainage, and Flood Control, USCID, Phoenix, Arizona, June 3-6, 1998, pages 173-186.

Zhu, Z., I. El Assiouti, A.F. Khattab, and R.A. Azim, 1998. National Policy for Drainage Water Reuse, Report Number 8 of the APRP Water Policy Reform Activity, USAID, Cairo, Egypt.

Zhu, Z., A.F. Khattab, I. El Assiouti, and R.A. Azim, 1999. Intermediate Drainage Reuse in Bahr Bagar Drain Basin, Report Number 20 of the APRP Water Policy Reform Activity, USAID, Cairo, Egypt.

PLANNING TO MEET FUTURE WATER NEEDS

George H. Hargreaves[1] Eric R. Olsen[2]

ABSTRACT

Conservative projections foresee world population growing from approximately six billion to over eight billion people by 2050. During that same period, per capita food grain production, irrigated area, and the income of the poorest 20% are expected to decline. As a result, much of the world's population faces a future of poverty and hunger. These people, forced to the economic margins, often engage in harmful agricultural practices-fanning steep slopes, slash-burn agriculture, overgrazing-which increase soil erosion and flooding. In the context of growing population and poverty, this paper discusses several water-related issues: irrigation, depletion of groundwater, drainage, and flood control. Also discussed are the roles of government and the private sector in water resource management. Finally, it discusses the question of resource conservation or development, concluding that before conservation becomes a viable choice (especially for the poor), development is necessary. To help plan sound water projects in the future, this paper advocates the development of a global water resource inventory. It describes a start toward such an inventory-the IWMI "World Water and Climate Atlas"-and how it can be used.

INTRODUCTION

Thomas Malthus published his *Essay on the Principle of Population* in 1798. In it he argued that without the checks of disease, war, and famine, humankind was doomed to eventually outgrow its ability to feed itself. Simply put, the geometric nature of unrestrained population growth would literally eat up any conceivable increase in agricultural production. His pessimistic vision destroyed the optimism of his age. After Malthus it seemed that the advances of modem science and technology no longer heralded a future of increasing and unbounded prosperity for everyone (Heilbroner, 1986).

---

[1]Research Professor Emeritus, International Irrigation Center, Department of Biological and Irrigation Engineering, Utah State University, Logan, Utah 84322-4105.

[2] Lecturer, Department of Computer Studies, University of Maryland University College, In Bosseldorn 30, D-69216, Heidelberg, Germany; E-Mail: eolsen@faculty.ed.umuc.edu.

Today, in spite of enormous increases in agricultural productivity, the Malthusian vision continues to haunt the world. Current world population is approximately six billion. By 2050, conservative estimates predict that it will exceed eight billion; a simple extrapolation of the present rate of growth predicts that it will exceed ten billion. What makes this alarming is that, while agricultural production will undoubtedly increase, it is unlikely to keep pace. For example, 80% of the world's nutritional needs are met by the major food grains: wheat, rice, and maize. At current rates of growth, the production of these grains per capita can be expected to drop to 71 % of current levels; irrigated area per capita can also be expected to drop to 80% of current levels (Brown, et al., 1997; Brown, et al., 1998). Note that these numbers do not include the long-term effects of many current agricultural practices which deplete groundwater, pollute the environment, erode steep slopes, and create flood damage. If continued, such practices will push these numbers even lower.

Further complicating this scenario is the fact that 98% of population growth is in the developing world (National Geographic Society, 1998b). Unfortunately, some developing countries do not have the institutional and legal frameworks needed for planning and implementing sound long term agricultural and environmental policies. Others lack the political will to ensure that their populations are fed (Reid, 1998). Even where food supplies are plentiful, extreme poverty leaves many people without the means to feed themselves (Sen, 1981). Today, such problems have left about 20% of the world's population chronically undernourished and nearly the same amount without a reliable source of safe drinking water (Reid, 1998).

Escaping a Malthusian future is possible. To do so, it will be necessary to work on a global scale to expand the food supply, to reduce reliance on non-renewable resources, to decrease pollution, to control climate change, to increase economic prosperity, to promote stable and responsible governments, and, ultimately, to stabilize the population. This paper addresses only a small part of the solution: meeting future water needs.

In 1997 the International Water Management Institute (IWMI) and the Utah Climate Center at Utah State University (USU) set out to develop and publish an atlas of water and climatic data. With support from the governments of Japan and the United States an atlas for Asia was developed. This atlas provided an initial inventory of Asian water resources: reference evapotranspiration (ETo), 75% precipitation probabilities (P_{75}), an index of the relative adequacy of rainfall for crop production ($MAI = P_{75} / ETo$), an estimate of the surplus or deficit of rainfall in meeting crop requirements ($NET = ETo - P_{75}$), and the basic climatic information needed to use this information in simple crop models. IWMI has continued to expand and refine the atlas and data products with various partner organizations (IWMI, 1999a).

To deal with the water resource issues facing the world between now and the year 2050, it is recommended that the IWMI atlas be supplemented with other land and water resource inventories, including: surface water availability, possible reservoir sites, and potential areas for irrigation. In addition, the development of the tools needed to make the best use of this information is suggested. By helping assess probable costs and benefits, such inventories and tools would enable developing countries to plan and develop irrigation, drainage, hydropower, and flood control projects that are both economically and ecologically sound.

WATER RESOURCE MANAGEMENT

Managing a Scarce Resource

Considered on a global scale, the fresh water resources of the planet are more than adequate to meet all foreseeable future needs for agricultural, industrial, and domestic uses. However, considered on regional and local scales, the ability to meet water demands in some areas is limited. Geographic and seasonal variations in weather patterns create surface water shortages that have forced the development of ways to survive in desert regions and to cope with periodic droughts.

In excessively arid areas and seasons, groundwater has often helped meet shortfalls in water demand. Unfortunately, this is frequently a non-renewable resource and many areas of the world have become excessively dependent upon it for irrigation. In China, nearly all river basins depend on the over-pumping of aquifers. In India, seventeen districts have seen aquifers permanently depleted. Chronic over-pumping and aquifer depletion for irrigation also continues in central Mexico, California, the Great Plains of the United States, the Arabian Peninsula, and North Africa. Of the approximately 250 million hectares of irrigated land in the world, some 50 to 60 million are now irrigated from non-rechargeable groundwater; these will probably be forced out of production by 2050 unless adequate surface water supplies can be developed (Brown, et al., 1998). Sound resource conservation policies would reserve this non-renewable resource for making up serious deficits in surface water supplies during drought years.

Damming and diverting surface water to meet shortfalls is generally preferable to over-pumping aquifers. Unlike much groundwater, surface water is a renewable resource. With careful planning and management, water use can be balanced with the amount of surface water available on a one-year, ten-year, or longer basis. Still, there are serious problems to be resolved.

Of these, the most intractable are the political conflicts over water in the arid regions of the world. In more than two hundred river basins, water is shared by two or more countries. Some twenty-two countries depend upon the flow of water from another country. Frequently, the season of maximum water demand is also the season of minimum water availability. Conflicts over who gets water and how much are almost inevitable. There is a need to come up with, and implement, practical solutions for providing enough agricultural, industrial, and domestic water for everyone. Unless this can be done, political tensions over water will only build over the next half century for, by the year 2050, some four billion people will live in regions that suffer severe water shortages (Simon, 1998).

Most recommended solutions are stopgap measures at best. Implementing policies to encourage water conservation and to reduce water pollution will, in the short term, ease demand by encouraging more efficient use of existing water supplies. While currently too expensive for agricultural and industrial uses, desalinization of seawater would increase the supply of available water. However, by themselves, these measures will not meet the demands of a growing population. Projected agricultural needs alone dictate that new water supplies must be developed.

Irrigation for agriculture in arid regions (about one-third of the inhabited area of the world) or during a dry season (often three or more months even in otherwise wet areas) is the principal consumptive use of water. In the United States, this amounts to an average annual application of irrigation water of 570mm. About half of this amount is from surface water. This is only 11% of the average annual flow of the Mississippi River and only 14% of the average annual surface runoff of the rainiest one-eighth of the continental U.S. Other areas of the world have a similar situation. Clearly, a major part of present and future water needs could be met by taking better advantage of existing surface water resources.

By creating a systematic inventory of global water resources, the countries of the world can more easily identify solutions for local water shortages. Developing regional water storage and transportation systems requires knowing where and when the excess runoff occurs; knowing how much occurs; and, determining where it is both technically and economically feasible to site such systems. This kind of information exists-although in a fragmented and non-systematic form-for much of the United States and other developed areas of the world; it needs to be created for those underdeveloped areas where most of the water shortages in the next half century will, most likely, occur.

Managing an Over-Abundant Resource

Somewhere between one-third and one-half of most continents suffer from excessive precipitation. This frequently results in significant reductions in land use or in damages due to flooding. In Colombia, about nine percent of the land area floods annually, rendering much of it unsuitable for agriculture. In China, record-breaking floods in the spring of 1998 affected more than 300 million people and killed tens of thousands (Binyan and Link, 1998).

In areas afflicted by too much rain, as well as in low-lying areas where surface runoff tends to collect for long periods, artificial drainage systems are often beneficial. Adequate drainage, whether artificial or natural, provides the soil aeration needed for crop root development and health. It also helps control the spread of disease. For instance, swampy areas have long been associated with malaria and yellow fever; drainage of these areas helps reduce the population of mosquitoes, the vector for transmitting these diseases.

Constructing dams for flood control can also be beneficial. Controlling the release of water down a watershed can reduce or eliminate flooding. As well as preventing deaths, this helps stop much of the damage to land, agriculture, and infrastructure that floods periodically cause. In addition, there are the obvious side benefits of generating hydropower, storing water for use during a dry season, and preventing the spread of water-borne diseases like cholera.

Still, dams are not a solution in all areas. Sometimes local ecosystems require periodic flooding to regenerate; in others, floods would not have occurred without a history of human damage to the environment. Many of the problems associated with excess precipitation, especially flooding and soil erosion, are caused by improper agricultural practices; in some developing countries this amounts to approximately 50% of the rain-fed agriculture. Farming steep slopes, slash-burn agriculture, and deforestation all destroy the capacity of the land to absorb precipitation and ease the flow of water down mountains and hills. Over-grazing destroys the plants whose root systems hold soil in place. Eliminating these problems would seem to be more ecologically sound-and, in the long run, less expensive-than building and maintaining dams. However, that may not be possible without a rapid rate of water resources development.

A global inventory of water resources would make it possible to assess the benefits and costs of drainage and flood control projects. Knowing how much precipitation generally occurs would help estimate hydropower potential. Flood prone areas could be identified. In turn, this would allow planning for the most ecologically sound and cost-effective ways to prevent or reduce flood damage.

Again, it is in the developing world where this information is most needed and would be most useful.

Conservation or Development?

Although sometimes framed this way, addressing the world's present and future water needs is not a simple question of whether resources should be conserved or whether they should be developed. Conservation and development are not so easily separated. Conserving groundwater requires developing the surface water resources to replace it. Preventing various environmentally harmful practices, like farming on steep slopes and slash-burn agriculture, requires providing the poverty-stricken people who generally engage in these practices with some other, less destructive, means of feeding themselves. Land, water, and other resources need to be developed to the point that conservation becomes a viable economic choice for everyone.

Consider, for example, the case of Greece. In the late 1940s, the country was an environmental disaster. Most of the forests had been destroyed, the trees cut down to provide fuel. The mountains were eroded, torn apart by hillside farming, extensive overgrazing, and the resulting increase in flooding. Then, starting in 1947, large dams were constructed, new flood channels were excavated, rural electrification was provided, and private irrigation development was promoted. By 1968, the Greek gross domestic product (GDP) had quadrupled. Over those same twenty years, vast areas had been reforested and overgrazing was virtually eliminated. Farming on irrigated alluvial lands (and providing farmers with various goods and services) proved far more profitable than cutting firewood, overgrazing, or growing crops in mountainous areas.

In underdeveloped areas where population pressures-growth, poverty, migration-have led to or will lead to environmental destruction, there is a need to promote a rapid pace of resource development. Only if development can get ahead of population pressures and increase everyone's level of prosperity, will the survival of people at the economic margins no longer depend on making uneconomic and environmentally harmful choices. If this can be done, perhaps many economic and environmental travesties can be prevented; for instance, in Central America, poor people may not be compelled by their desperate situation to burn mahogany forests on steep slopes, to create an open patch of ground, to plant corn, to feed a starving family.

Institutional Considerations

The world is rapidly developing a global economy in which everyone is interdependent. How one nation chooses to use or manage its land, water, and energy resources can affect other nations; negative effects from poor choices are international, if not global, problems. As a result, there is an increasing need for international guidelines, agreements, and institutions to ensure cooperation on a global scale.

Historically, most governments have been poor managers of natural resources. Although many have created institutions to develop their resources, they have often been hampered by their focus on a single problem: controlling floods, or improving agriculture, or preserving the environment. Almost inevitably, various single-purpose agencies end up having opposing goals and competing with each other for scarce funds. Multi-purpose organizations, chartered to balance the costs and benefits of all purposes, have seldom been established.

Another frequent problem is that few governments have the institutional capacity and expertise required for resource development and use. In those that do, this capacity has sometimes eroded over the years. For instance, in 1902 the United States created the Bureau of Reclamation (USBR) to develop land and water resources on a river-basin-wide scale in the sixteen western states. By 1951 more than 100 dams and 33 power plants had been constructed. Internationally, the USBR provided its expertise in river-basin studies and planning in Asia, Africa, and Latin America. Unfortunately, the planning, design, and construction activities have largely ceased; emphasis is now on management and conservation.

Consequently, governments -- whether national or international -- should promote private-sector development of natural resources, including water. Private efforts would help ensure that projects are economically sound, as well as likely to last beyond the next change of government. To do so, governments need to create the legal and institutional framework that will encourage responsible private development projects. They need to pass and enforce laws which: provide private access to land and water resources on a competitive basis; prevent the destructive exploitation of those resources; and, promote multiple-purpose development efforts. In addition, they should develop, support, and use international institutions that will serve as the long-term repositories of the expertise and information needed for making sound resource development and conservation decisions.

In 1999, the Worldwatch Institute noted that the world's three richest people had assets that exceed the combined gross domestic product of the world's forty-eight poorest nations (Brown, et al., 1999). To end their needlessly inevitable cycles of poverty and hunger, these countries need to develop their land and water resources in an economically and environmentally sensible fashion. Perhaps, if these forty-eight poorest nations were to create the favorable circumstances outlined above, they could attract sorely needed investments from the three richest people (and others).

WATER RESOURCE ATLASES

The IWMI "World Water and Climate Atlas"

International organizations like the International Water Management Institute (IWMI)-working with universities such as Utah State University (USU), the University of East Anglia (UEA), and the Australian National University (ANU)-are already working toward developing global resource inventories and the expertise to use them. With the development of the IWMI "World Water and Climate Atlas" (IWMI, 1999a), a start can be made to address-on a global and international basis-some of the technical, economic, and environmental issues involved in increasing irrigated area per capita, balancing available surface water with demand, improving agricultural potential in areas with poor drainage, and preventing flood damage.

For instance, this atlas provides the basic information needed for simple crop modeling. Minimum and maximum temperature data can be used to identify regions which meet the temperature requirements for specific crop cultivars. This information, combined with reference evapotranspiration and crop coefficients, enables the estimation of seasonal water requirements for the crops. Planners can then determine whether existing water resources are adequate and, if not, potential areas for their development.

As this atlas is refined -- with added and improved data, better analysis software, and more experience using the data -- it could become an important planning tool. By using a standard and readily accessible base of information, solutions that have proven beneficial in some areas can be evaluated for application in other similar situations. After all, given the current rate of population growth and barring some Malthusian disaster, there is a pressing need to better manage world water resources over the next half century. The information in this atlas provides a firm foundation upon which preparations for that future can be made.

A Climate Classification Atlas

Since plant adaptation and the potential for rainfed agricultural production depend principally upon temperatures and water availability, a world atlas of climate classification for agriculture would be very useful as well (note that much of the base information is included in the IWMI atlas, but needs to be extracted and coupled with crop-specific information). To be useful, this atlas need not be complicated. In fact, two climate classifications-one based on temperatures and the other based on water availability-would serve most planning needs (Hargreaves, 1977).

Table 1 shows the first of these climate classifications. This classification is based on monthly average temperatures and the length of the growing season. An atlas classifying the world on this basis, ideally combined with a comprehensive database of crop temperature requirements, would allow local planners to identify specific cultivars suitable for projects in their area.

Table 1. Temperature-Based Climate Classification

Climate Type	Temperature Criteria
Polar	All months below 10°C
Boreal	1 to 3 months above 10°C
Subtemperate	4 to 5 months above 10°C
Temperate	6 to 9 months above 10°C
Subtropical	10 to 12 months above 10°C
Tropical	All months at 17°C or above

The second climate classification, shown in Table 2, reflects water availability. This classification divides climates into seven classes based on a moisture adequacy index (MAI) which measures the water constraints on agricultural productivity for that climate.

MAI (sometimes used as A_{75}) is easily derived from the 75% probability rainfall amount (P_{75}) and reference crop evapotranspiration (ETo):

$$MAI = P_{75} / ETo \quad (1)$$

In turn, P_{75} is most conveniently derived from mean precipitation (P_m) and the standard deviation in the amount of rainfall (SD):

$$P_{75} = P_m - 0.74\ SD \quad (2)$$

The 75% probable streamflow Q_{75} can be calculated from Eq. 2 by substituting Q for P. Note, however, that Eq. 2 is less accurate for use when P_m is less than 30%

of ETo; when this is the case, calculating P_{75} with a ranking distribution or other similar technique may be preferable.

Table 2. MAI-Based Climate Classification

Climate Classification	MAI Criteria	Water Constraints on Productivity
Very Arid	All months with MAI ≤ 0.33	Not suited for rainfed agriculture
Arid	1 or 2 months with MAI ≥ 0.34	Limited suitability for rainfed agriculture
Semi-Arid	3 or 4 months with MAI ≥ 0.34	Suitable for crops requiring a 3 to 4 month growing season
Wet-Dry	5 or more consecutive months with MAI ≥ 0.34	Suitable for crops requiring a 5 or more month growing season
Somewhat Wet	1 or 2 months with MAI > 1.33	Natural or artificial drainage required
Moderately Wet	3 to 5 months with MAI > 1.33	Good drainage required
Very Wet	6 or more months with MAI > 1.33	Very good drainage required

The criteria for the climate classes and the water constraints were based on research which used various crop trials to develop an empirical equation for relative yield (Y) as a function of water availability (X):

$$Y = 0.8\,X + 1.3\,X^2 - 1.1\,X^3 \tag{3}$$

Note that Y = 1.0 for maximum yield under prevailing conditions of fertility and management and that X = 1.0 for the water required to produce that maximum yield. In the trials, the majority of data for X was in the range of 0.30 to 1.20. The research showed that with X = 0.30, Y was about one-third of potential; for X = 1.20, Y was about 93% of maximum; and, for X = 1.33, Y was about 78% of maximum. Essentially, Y falls off rapidly with increasing values of X (Hargreaves, 1975). Consequently, regions and time periods with MAI > 1.33 need drainage to maintain production levels.

IWMI (1999b) used Eq. 3 and a modified classification to map agricultural potential for South Asia. The modified classification uses MAI of 0.38 replacing 0.34, and consists of the first four classes.

MAI is also relevant in terms of the application of fertilizer. Experience with dry farmed wheat in Iran indicated that fertilization was usually profitable when all months during the period of actual growth had MAI values above 0.33. In another case, a mass fertilization project in El Salvador financed by USAID failed because MAI values on many of the farms were too low during the pollination period. For fertilizer to be worth applying to increase yields, there must first be a minimum of moisture.

A Surface Runoff Atlas

To identify areas for irrigation, drainage, flood control, or hydropower projects, planners need to know how much surface runoff to expect and when to expect it. Consequently, a resource atlas of surface runoff would also be extremely useful. Since runoff is determined principally by rainfall and evapotranspiration, it is possible to estimate surface water flow from these two parameters (both are included in the IWMI atlas). This is particularly valuable since measuring actual runoff levels can be difficult. Obtaining reliable data requires good equipment, well-trained personnel, adequate measuring site selection, and diligent field inspection. In addition, flood flows are hard to measure: frequently the rating curve must be extended significantly above measured data points; over-bank flow is difficult to estimate. Consequently, in areas lacking the resources and expertise to make actual measurements, it is often easier and cheaper to estimate runoff.

For a rough estimate of runoff, suitable for planning purposes, where extensive streamflow data are not available, the MAI climate classification can be used. For instance, Table 3 shows the average annual depth of runoff for the seven climate classifications derived from a study of 110 climate stations in the United States (Hargreaves and Samani, 1986; and, Geraghty, et al., 1973).

Table 3. MAI-Based Runoff Estimations

Climate Classification	Average Annual Runoff Depth (mm)
Very Arid	15
Arid	35
Semi-Arid	120
Wet-Dry	200
Somewhat Wet	290
Moderately Wet	440
Very Wet	935

By classifying the local climate, reasonable typical runoff values can be obtained. More accurate local estimates can be made by regressing the 75% probability stream flow (Q_{75}) with the average monthly MAI occurring 15 days earlier (Hargreaves and Merkley, 1998). In a study of eight watersheds this yielded the following empirical equation (with an r^2 of 0.92):

$$Q_{75} = 3.45 + 12.0\ \text{MAI} \tag{4}$$

If reliable streamflow data can be obtained for a nearby area, together with the climatic data for calculating MAI, a similar empirical equation can be developed which can be used to extend streamflow estimates to surrounding areas as well as to estimate local responses to severe storms.

A resource atlas which provides worldwide values of MAI coupled with reliable streamflow data is needed. This information, with the tools to analyze it, would enable planners to estimate typical local runoff as well as plan for extreme weather.

<u>Other Resource Atlases</u>

Several other land and water resources atlases are needed. These include: extreme rainfall, soils, and topography. Much of the data needed for such atlases exist in dispersed form, or collected without the tools to use them. For instance, a topographic atlas with a simple means of calculating slopes for a local area and, thus, identifying potential erosion problems would enable planners to select better sites for development projects and identify the potential costs associated with development there. An atlas of extreme rainfall possibilities would allow developers to calculate minimum parameters for various construction projects: the minimum capacity for a canal, the minimum strength of bridge pilings, etc. A soils atlas, using standardized soils classifications, would be useful for both irrigation and construction.

Ideally, publicly funded international organizations (FAO, for example) would take on two tasks. First, they need to compile, maintain, and regularly update the data needed for these atlases; most importantly, these data need to be gathered on a consistent and world-wide basis. Furthermore, they need to make these data available in open, standard formats that will allow anyone to make use of the data (i.e., no proprietary data formats designed to force users to use a specific software package); in the world of the internet this would probably best be done with online databases, with published table structures and definitions, which could be accessed by anyone over the network with standard SQL database queries. Second, these organizations need to act as a clearing-house for the techniques used for analyzing the data. There should be approved, standard methods of analyzing the data for estimating extreme rainfall events, forecasting typical surface runoff, calculating evapotranspiration, etc. This way planning for various parts of the world, both costs and benefits, can be more easily compared. However, the software to apply these methods can and should be developed in the private sector, where market forces will encourage competition, resulting in cheaper software, the continued adoption of new technology, and rapid responses to changing user needs.

SUMMARY AND CONCLUSIONS

The need for increasing water resource development is urgent. Without an accelerated rate of development, poverty, hunger, insecurity, and the degradation of the natural environment will increase. By 2050, if present trends continue, the world will be a place where severe droughts create intractable political conflicts in dry areas and severe floods destroy farms, infrastructure, and lives in wet areas. Groundwater supplies will have been pumped disastrously low and remain unreplaced. Potential irrigable lands will continue untilled and unproductive. Steep slopes will have been denuded, farmed, and abandoned to erosion. Forests will have been burned to open clearings, to plant crops for a year or two, and then vacated in favor of newly burned tracts of forest. In fact, through lack of use and support, the world may have lost the institutional capacity to develop our water resources. The ability to feed the world's population will have been severely damaged.

Unlike Thomas Malthus, the world need not peer blindly into a bleak future. In the two centuries since he published the *Essay on the Principle of Population*, the number of people in the world grew six-fold, from one billion to six billion

(National Geographic Society, 1998a). Nevertheless, over that period, the human race did not experience a worldwide Malthusian crisis of spiraling population, dwindling resources, and, as a result, declining levels of prosperity. Instead, there were immense increases in agricultural yields, industrial production, and, more importantly, populations in the developed nations of the world were stabilized. The lesson to be learned from the past two hundred years is that, although basically correct, Malthus did not see some of the subtleties in the connection between population and prosperity. Most notably, he did not realize that rapid and widespread economic development could tame population growth. If prosperity can be extended to the developing nations of the world quickly enough, their populations will stabilize and the poorest people will no longer be forced to the economic margins. With this process completed, there is every reason to believe that the world will face a future with enough resources to provide everyone with healthy, productive, and meaningful lives. Certainly, there are many complex obstacles blocking the way to world-wide prosperity. None is insurmountable. A concerted effort to inventory global resources-land as well as water-and to manage them in a careful, responsible fashion would be a beneficial first step.

REFERENCES

Binyan, L. and P. Link. 1998. "A Great Leap Backward?" Review of He Qinglian, *Zhongguo de xianjing [China's Piffiall]* (Mingjing chubanshe, Hong Kong: 1998). *New York Review of Books,* 8 October 1998, 19-23.

Brown, L. R., M. Renner, and C. Flavin. 1997. *Vital Signs 1997: the Environmental Trends that are Shaping Our Future.* Worldwatch Institute. W. W. Norton & Company, New York.

________. 1998. *Vital Signs 1998: the Environmental Trends that are Shaping Our Future.* Worldwatch Institute. W. W. Norton & Company, New York.

________. 1999. *State of the World.* Worldwatch Institute. W. W. Norton & Company, New York.

J. J. Geraghty, et al. 1973. *A Water Atlas of the United States.* Water Information Center. Port Washington, New York.

Hargreaves, G. H. 1975. "Moisture availability and crop production." *Transactions ASAE* 18 (5): 980-984.

________. 1977. *World Waterfor Agriculture.* Agency for International Development. Washington, D.C.

Hargreaves, G. H. and G. P. Merkley. 1998. *Irrigation Fundamentals.* Water Resources Publications, LLC, Highlands Ranch, Colorado.

Hargreaves, G. H. and Z. A. Samani. 1986. *World Waterfor Agriculture.* International Irrigation Center, Department of Agricultural and Irrigation Engineering, Utah State University, Logan, Utah.

Heilbroner, R. L. 1986. *The Worldly Philosophers: The Lives, Times, and Ideas of the Great Economic Thinkers.* 6th ed. Simon and Schuster, New York.

IWMI (International Water Management Institute). 1999a. *World Water and Climate Atlas.* Available on the internet at www.iwmi.org or www.cgiar.org/iwmi/Atlas.htm or on CD-Rom.

________. 1999b. *Mapping Agricultural Potential Using the IWMI* Atlas, Personal Communication from IWMI. P.O. Box 2075, Colombo, Sri Lanka; E-Mail: iwmi@cgiar.org

National Geographic Society. 1998a. "Millennium Moments." *National Geographic* (October 1998).

________. 1998b. "Population." *National Geographic* (October 1998), map supplement.

Reid, T. R. 1998. "Feeding the Planet." *National Geographic* (October 1998), 56-75.

Sen, Amartya. 198 1. *Poverty and Famines: An Essay on Entitlement and Deprivation.* Clarendon Press, Oxford.

Simon, P. 1998. "Tapped Out". In "Are We Running Dry?", *Parade Magazine, Herald Journal* (Logan, Utah), 23 August 1998, 4-6.

TRACING THE HISTORY OF THE DEVELOPMENT AND MANAGEMENT OF TWO IRRIGATION SYSTEMS IN THE TERAI OF NEPAL

Krishna C. Prasad[1] Bryan P. Thoreson[2]
David J. Molden[3]

ABSTRACT

Significant effort has been placed on increasing irrigated area, agricultural performance and improving overall irrigation system performance. Sometimes, these efforts are successful, but often frustrations are met. A wide variety of experiences have been gained, but unfortunately many of these experiences are not well documented. These are lost learning opportunities.

The purpose of this paper is to trace the history of two irrigation systems in Nepal to help fill this gap in recording experiences. The two study systems are the Khageri system serving about 3,900 ha and the West Gandak system serving about 10,300 ha. Both systems are located in the terai, the plains of Nepal, and were originally constructed in the 1960s and 70s. They are run-of-the-river systems, originally designed to provide supplemental water to paddy during the monsoons. Main and secondary canal systems were provided for both, and farmers were expected to construct the tertiary system. Both systems have undergone significant modernization of infrastructure and institutions to provide better flow control for paddy irrigation and, at West Gandak, for winter crops. Recent efforts have been to increase the involvement of farmers in managing the irrigation system through a management transfer program. While partial success has been achieved, sustainability remains uncertain.

This presentation tracks the development history of the systems, showing significant changes and their consequences on performance. We demonstrate that a balance between institution and infrastructure development must be achieved for success. We show the need for effective institutions to support local managing agencies. Future development paths are suggested. The experiences of these two systems, while in many ways unique, are also in many ways typical of irrigation development.

---

[1] IWMI Nepal Research Coordinator, International Water Management Institute (IWMI), GPO 8975 EPC 416, Kathmandu, Nepal.
[2] Project Manager, Davids Engineering, 1772 Picasso Avenue, Suite A, Davis, CA 95616-0550.
[3] Research Leader, Irrigation and Water Resources Program, International Water Management Institute (IWMI), PO Box 2075, Colombo, Sri Lanka.

IRRIGATED AGRICULTURE DEVELOPMENT IN NEPAL

Nepal's agricultural sector contributes about 40% to the total gross domestic product (GDP) and 81.2% of the total population (about 22 million) is engaged in agricultural activities (HMG/N, 1999). The agricultural sector has experienced an annual agricultural production growth rate of 1.7% over the last two years and per capita growth of agricultural GDP of 0.5% (HMG/N, 1998). Nepal continues to emphasize agricultural development to increase food security (HMG/N, 1998).

Irrigation is vital for achieving higher returns from agriculture. Run-of-the-river surface water schemes irrigate about 861,580 ha (82%) of the total 1,055,617 ha of irrigated area in Nepal (HMG/N, 1998, p 520). Optimal performance and sustainability of these irrigation schemes are crucial to increased agricultural productivity and increasing farmer income.

Farmers in Nepal have a long tradition of constructing and managing irrigation systems under their own collective initiatives. In the 17th century, an edict of King Ram Shah stated that irrigation and its management were the responsibilities of the community (Pradhan, 1989a). Thus, Nepal has a strong tradition of community-directed irrigation development and management.

These systems number in the thousands, serving about 75% of the total irrigated area in the country (Prasad, et. al, 1998). They are typically are run-of-the-river systems diverting water by means of temporary brushwood diversions or earthen dams. The canal networks are unlined with few water control structures. These systems require frequent maintenance by the farmers.

Historically, the state also has been associated with the task of irrigation development, albeit the number of systems has been much less. It is only in the last 40 years that the state has become a major player in irrigation development. During this time, Nepal's Department of Irrigation (DOI) has undergone numerous administrative changes, along with changes in development philosophy.

As we trace the history of Khageri and West Gandak irrigation systems, we can see the effects of these changes on irrigation system performance. The difficulties that both the farmers and the government have had adapting to the changes will also become evident.

KHAGERI AND WEST GANDAK IRRIGATION SYSTEMS

Khageri was built by DOI with the farmers expected to develop the tertiary level canal system (Table 1). Under the management transfer program, all of its secondary canals have been turned over to water users association (WUA) for their regular operation and maintenance (O&M). The average area of transfer unit is 142 ha. The main system is under joint management of Narayani Lift Irrigation Office of DOI and the Khageri WUA.

Table 1. Salient features of Khageri and West Gandak.

Details	*Khageri*	*West Gandak*
Location	Central Plains	Southwestern Plains
Construction	1961-68	1976
Design Discharge	8 cumecs	8.5 cumecs
Design Area	6000 ha	10300 ha
Source	Khageri River	Narayani River
Average Annual Rainfall	1832 mm	1463 mm
Annual Water Diversion	62 million cubic meters	64 million cubic meters
System Type	Run of the river, weir with side intake,no storage	Run of the river, barrage with side intake, seasonal storage
Length of Main Canal	23 km	32 km
Total Canal Length	90 km	740 km
Turnout Type	Gated Outlets	Gated Outlets
Water Measurement	Along Main Canal	Main and Secondary Canals
Measurement Type	Structures calibrated gages	Structures calibrated gages
Farm Families	5578	7500
Land Owners	90%	80%
Average Farm Size	0.7 ha	1.4 ha
Water Rights	At System Intake, within system farmer rights not legally established	At System Intake, within system farmer rights not legally established
Water Distribution	Roughly in proportion to area	Roughly in proportion to area

Prior to construction of the West Gandak Irrigation System, some farmer-managed irrigation systems were taking water from small drains and rivers lying within the present service area (Mishra and Molden, 1996). The Indian government constructed the main, branch and minor canals greater than 620 l/s. Farmers were expected to develop infrastructure with smaller capacities. The system, except the intake, was fully transferred to the WUA in November 1997. Accordingly, the WUA is carrying out operation and maintenance. Before the transfer, Nepal West Gandak Canal Irrigation Office of DOI managed the system.

CHANGES IN MANAGEMENT INSTITUTIONS AND INFRASTRUCTURE

Early Years (Construction to 1991)

During this time, both systems were under agency management. DOI was responsible for the collection of water use fees from the farmers, and operation and maintenance of the main and secondary canals. Although the farmers did not concern themselves with the O&M of the main and secondary systems, they did mobilize labor to make repairs in some extraordinary situations. Also, although

DOI was to be collecting water use fees, the total collection was nearly zero (Prasad, et al, 1998).

Operation and maintenance at the tertiary level and below was the responsibility of the farmers. Also, the agency did not take an active role in assisting the farmers to organize.

A change in philosophy occurred in the 1980s when it was felt that the major constraint to irrigation performance was lack of development and farmer management of tertiary infrastructure[4]. The West Gandak system experienced a transformation from 1982 through 1989, due to the Command Area Development Project (CADP) implementation. The purposes of CADP were to increase: 1) water utilization, 2) farmer involvement in construction of tertiary structures and system management, and 3) the living standards of farmers. The project designed and built farm ditches serving 7–12 ha and developed water user groups to facilitate system management.

Although farmers were expected to participate in O&M as part of the CADP, most water user groups were not formed until near the end of the project. Thus, during the years of the project and also after the project O&M was mainly performed by DOI.

Joint Management (1992 to 1994)

In 1992, the DOI initiated a Joint Management (JM) program in both the Khageri and West Gandak irrigation system to allow the farmers to play a greater role in system management. The JM program was expected to reverse the deteriorating conditions in the systems (Laitos and Shakya, 1992). It involved the creation of system-wide water users associations (WUA) at both systems. The program focused on structural improvements in the physical system, and efforts to build up the farmers' institutional capacity for effective participatory irrigation management. The WUA was also given a legal status through registration with the government's administration office under the prevailing law.

As part of capacity-building efforts, various kinds of training programs were organized by the DOI for farmers, farmer leaders, and DOI personnel on different aspects of irrigation system management. Farmer participation was sought at all levels of system management. The main activities carried out jointly by the agency and the farmers included preparing operational schedules and limited conflict management.

---

[4] Tertiary infrastructure includes canal conveyance, regulation and control structures to deliver water to farms, as opposed to main and secondary canals that deliver to the tertiary system.

Farmers participated in the maintenance and system improvement construction management and contributed labor, or fees to these activities. However, the final O&M decision remained with DOI during this program.

Irrigation Management Transfer Project (1994 to 1998)[5]

In 1994, both systems were selected to be part of the Irrigation Management Transfer Project (IMTP) of DOI. The project emphasized transfer of irrigation management responsibilities over to the organized farmers while improving the system's physical condition (CADI, 1995). The aim was to gradually transfer the management of canal networks up to the secondary level to the WUA. The headwork and main canal were to remain under the joint management of the irrigation agency and the WUA. The WUAs were allowed to retain a portion of the collected fees for covering the O&M costs of the part of the system they were managing.

Again, the paths of these two irrigation systems diverge. At Khageri, the WUA has assumed the full management responsibilities of the canal networks up to secondary level and the headwork and the main canal are being canal jointly managed with the irrigation agency. The WUA fixes the operational schedules in the branch canals and has a greater voice in operational decisions at the main canal level. The WUAs are maintaining the secondary canals and also contributing more resources to the main canal maintenance. The WUAs also contributed to the cost of system rehabilitation.

At West Gandak, the farmers were eager to take over the management of the main canal also. Based on the past performance of the West Gandak WUA, DOI decided to hand over the main canal in November 1997. Since then, the WUA has been managing the entire system by itself with the exception of the intake gate. DOI operates the intake gate to match the WUA's water allocation schedule. The WUA mobilizes farmer labor for maintenance. It also uses income from fees, penalties, land rental and canal bank trees and service road tolls.

Both WUAs are expected to receive technical and some financial support, especially in case of emergency, from the government in the future. Farmers often give feedback that government support systems are weak.

Major changes in legislation and the events that have taken place in these two systems are summarized in Table 2. The table shows the shift from construction to management and the government's response in changing legislation.

---

[5] Phase I of IMTP. Beyond this, only post transfer supports would be extended in these systems. Phase II of IMTP will concentrate on the other eight systems.

Table 2. Major events at Khageri and West Gandak

Year	Changes in Legislation	Major Events in	
		Khageri	West Gandak
1961	-	Construction begins	-
1963	Irrigation Act 2018 providing legal provisions concerning water use, construction and maintenance of canals, distribution of water, collection of water charges, etc.	-	-
1967	Irrigation, Electricity and Related Water Resources Act, 2024 with legal provisions related to irrigation, electricity production, and other matters concerning water resources	Construction ongoing	-
1968	-	Construction completed	-
1974	Introduction of Canal Operation Regulation to govern water use for irrigation	-	-
1976	-	-	Construction completed
1979	-	-	India handed over the system to Nepal
1982	-	-	Commencement of CADP
1988	New working policy on irrigation development through participatory approach and enactment of Irrigation Regulation, 2045 to provide legal provisions for formation of water user groups, water distribution, water charge collection, etc.	-	-
1989	-	-	Conclusion of CADP
1992	Adoption of Irrigation Policy, 2049 clarifying the government's policy on participatory irrigation development and management	- Commencement of Joint Management program - Formation of WUA and its registration	- Commencement of Joint Management program
1993	-	- First WUA election - Various training programs	First election of WUA and registration - Start of gradual turnover of secondary canals
1994	-	- Conclusion of JM - Commencement of IMTP - Household surveys	- Conclusion of JM - Commencement of IMTP - Household surveys

Table 2. Major events at Khageri and West Gandak (cont.)

Year	Changes in Legislation	Major Events in	
		Khageri	West Gandak
1995	-	- 2nd WUA election - Joint walk-thru for identifying the rehab needs	- 2nd WUA election - MOU signing for management transfer - Rehab work started
1996	First amendment of Irrigation Policy, 2049 giving a bigger thrust on participatory irrigation development and management	- MOU signing for management transfer - Rehab works started	- Gradual turn over of secondary canals started
1997	-	3rd WUA election gradual transfer begins	- Complete turn over of all secondary canals - Turn over of the main canal
1998	Discussions for revising the Irrigation Regulation started to make it more practical	-	- O&M by WUA - Post transfer support by the agency
1999	-	All secondary canals transferred to WUA - O&M of the secondary canals by the WUA - Main canal under joint management	-

RESULTS AND PERFORMANCE

Khageri Irrigation System

Service Area: Khageri was originally designed to serve 6,000 ha (ICON, 1995). An impact assessment study conducted in 1978 indicates that the system served only 3,714 ha (APROSC, 1978). Several studies (ICON, 1993; GITEC, 1993; IWMI and RTDB, 1998) show that the irrigated area has been far below the design area (Figure 1). However, the service area has slightly improved with the joint management program and IMTP.

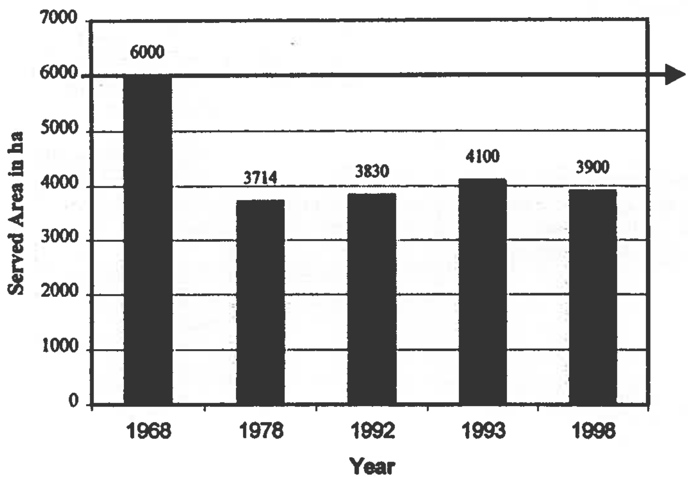


Figure 1. Change in Khageri Service Area.

Resource Mobilization for O&M: Table 3 compares the amount of resources mobilized by the WUA including labor mobilization during last few years to the government's O&M budget allocation.

Table 3. Resource Mobilization for O&M in Khageri

Year	Govt. O&M Expense	Resource Mobilization by Farmers
1991	254,000	-
1992	158,000	-
1993	213,000	-
1994	404,000	481,660
1995	300,000	117,048
1996	300,000	438,074
1997	300,000	73,990

Source: DOI and WUA records. Amounts are in Nepali Rupees unadjusted for inflation (in 1994, $1 = Rs 47, in 1999, $1 = Rs 69)

The WUA, thus, has been able to mobilize on an average of 40.4 % of the incurring total O&M costs compared to nothing before IMTP. The figure includes farmers' contribution to the rehabilitation works under IMTP. Nevertheless, from sustainability point of view, the resource mobilization by farmers needs to be further increased.

Agricultural Productivity: The Khageri irrigation system has experienced continuous increases in agricultural productivity of major crops grown in the service area (Table 4). Although rice varieties grown and management practices have also changed some over this period, much of the rapid yield increase in the past few years is likely attributable to improved irrigation management.

Table 4. Yields of Major Crops in Khageri (t/ha)

Year	Paddy	Wheat
1977/8	2.0	1.2
1992/3	2.5	1.1
1994/5	2.5	1.4
1995/6	2.8	1.5
1996/7	3.4	2.1
1997/8	3.9	2.1

Source: DOI records.

West Gandak Irrigation System

Service Area: The West Gandak irrigation system was handed over to the Government of Nepal in 1979. At the time of hand over, the main canal system covered about 4,300 ha as against the targeted area of 8,700 ha. A socioeconomic study conducted in 1982 indicates that the total service area reached 13,200 (APROSC, 1982). Irrigation Master Plan prepared in 1988 mentions that the developed service area in 1988 was 13,400 ha. Another study reports that in 1992, the system served only 4,000 ha (GEOCE, 1996). Yet another study just before IMTP mentions its service area as 10,100 ha (GITEC, 1993). This indicates quite a variation in the assertion of the service area (Figure 2).

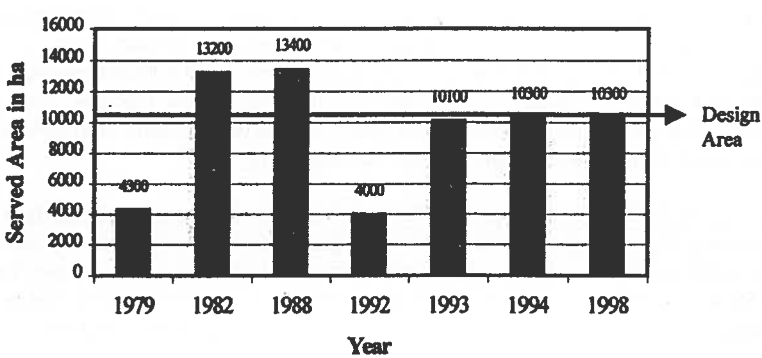


Figure 2. Change in West Gandak Service Area.

At the time of system hand over to Nepal the system was not fully developed and served only about half the targeted area. With the CADP, the system was able to serve more than the designed command area. But the area decreased drastically after conclusion of CADP to 4,000 ha. Again with joint management program, the service area increased to 10,100 ha. Later with IMTP, it was further increased to 10,300 ha.

Resource Mobilization for O&M: Encouraged by the labor mobilization in the desilting works of the main canal, farmers in West Gandak became more willing to contribute toward O&M of the system. More and more farmers became members of the WUA and paid membership fees, share fees, and irrigation service fees (CADI, 1996). The resources required for O&M of the system are now coming from three sources: 1) the agency as transitional financial support after the management transfer, 2) the farmers as various fees and penalties, and 3) land rentals, trees on the canal banks, canal service road tolls, etc. The resources in NRs. allocated by the government and mobilized by the WUA in West Gandak have varied tremendously over the last few years (Table 5).

Table 5. Resource Mobilization for O&M in West Gandak

Year	Govt. O&M Expense	Resource Mobilization by Farmer
1994	2,366,732	184,086
1995	2,352,329	479,730
1996	971,806	111,164
1997	1,040,229	253,712

Source: DOI and WUA records. Figures are in Nepali Rupees, unadjusted for inflation (in 1994, $1 = Rs 49. In 1999, $1 = Rs 69)

The figures include cost incurred during the rehabilitation and labor contributions made by farmers in the deferred maintenance works and income from other sources. The WUA has been able to mobilize an average of 13.5 % of the total O&M cost of the system compared to almost nothing in the past. However, the figures still are much below the required level of resource mobilization by farmers for giving it continuity under the farmers' management.

Agricultural Productivity: In general, West Gandak also has experienced notable increases in the agricultural productivity of major crops in the service area (Table 4). In addition, some cash crops like sugarcane and oilseeds are becoming popular (IWMI and RTDB, 1997). Similar to Khageri, increases in yield are likely due to improved management, although other factors could have led to the increase.

Table 6. Agricultural Productivity of Major Crops in West Gandak (t/ha)

Year	Paddy	Wheat
1982/3	1.3	0.7
1992/3	2.0	1.7
1993/4	3.7	2.0
1994/5	3.4	2.4
1995/6	3.7	1.5
1996/7	4.0	2.9
1997/8	4.5	3.0

Source: DOI records.

Sustainability: Changes in management have not yet proven to be sustainable. The WUAs are changing and adapting, but it is still not clear whether they will survive. Resource mobilization is insufficient. There is a dependency on cash generation from non-irrigation service related sources such as tree cutting and collecting road tolls. Thus there is not a good link between service provision and resource mobilization. The strength of WUAs is often challenged by political influences. Politicians try to get popular by promising free government services. The government has been slow in their transformation to a service-oriented agency, thus support services to WUAs are lacking. In spite of this, the WUA at Khageri is most likely to be sustainable[6] as indicated by the mobilization of 40% of the O&M costs. Although at West Gandak, the WUA has been able to undertake management of the main canal, the mobilization of only 13% of the O&M costs raises sustainability questions.

LESSONS

We can identify three periods in Nepal's irrigation development.

1. A pre-modern period where Nepali farmers were largely responsible for development and management of irrigation.
2. A construction period between 1960 and 1990 where huge investments were made in infrastructure development. Construction of new facilities in Nepal is still in progress.
3. A period from 1990 to present where more efforts were placed on better management of infrastructure.

From the relatively short 1960s to 1990s, there have been many changes in views on development and management of irrigation. Traditionally, farmers were

[6] At Panchkanya, another IMT site, the WUA is progressing very well and is likely to sustain (Starlkoff et al, 1999).

expected to build, operate and maintain irrigation. Thousands of systems built with this philosophy are still functioning well, although there is certainly scope for improvement.

During the construction period, the responsibility for construction and management shifted to the government agency. Beneficiary farmers were expected to pay for services received from the government. During this period, there was considerable expansion in irrigated area country-wide. There were over-optimistic estimates of area that could be irrigated, and results that could be achieved. As characterized by Khageri and West Gandak, maintenance proved to be difficult because of insufficient funding. The area served by these systems rapidly declined due to poor maintenance. Rehabilitation programs aimed at modernizing infrastructure and management were no help, as area and production would go up, then drop again soon after rehabilitation. There appeared to be an endless cycle of construction, decline, then rehabilitation, decline, and then rehabilitation.

Meanwhile, during the early years of the construction phase, farmer managed irrigation systems were not even recognized as irrigation by irrigation officials. Later, important studies re-discovered these systems and found them to be vibrant, with farmers making decisions, and covering costs of operation and maintenance. It was increasingly recognized that farmers could and should play a more important role in managing irrigation. As characterized at both Khageri and West Gandak, in the 1980s, farmers were given a minor role in managing irrigation in primarily agency run schemes. In the 1990s, more radical experiments took place where farmers assumed significant responsibilities for running irrigation systems.

Approaches to infrastructure design has also changed during that period in modern systems, first from development of main canals delivering water to deliver supplemental irrigation water, to intensive development of infrastructure to deliver water directly to farms (called tertiary or command area development). Within various rehabilitation programs other experiments took place. Some infrastructure allowed for changes in timing and amount of water deliveries by relying on gated outlet systems. Others focused on simpler, but supposedly easier to manage infrastructure, with proportional flow dividing devices. Some irrigation systems in Nepal indeed look like large testing grounds for a variety of infrastructures.

Since the 1960s, policies for development and management have shifted course in large ways. Policies shifted from farmer management to agency management, then back. Infrastructure designs changed, sometimes within one system in very drastic ways. Irrigation officials trained in one manner of development and management were expected to make important changes in their attitude and implementation. Farmers had to adjust to an uncertain environment in development. How could they know what would happen next? It is no wonder that expected gains from irrigation have been less than expected. It is also likely that these cycles of trial and error will be repeated unless we can learn from lessons of the past.

The experiment in the 1990s with turnover of agency schemes to farmers can be rated as a partial success. There has been an increase in productivity that is likely due to improved management by farmers. With resource mobilization still far less than required to run these irrigation systems, it is questionable whether gains can be sustained. Progress to sustainable and productive management at these turnover sites has been much slower than expected. Perhaps this is not surprising when farmers have passed a period where there have been so many changes in policies and philosophies of management.

Some lessons derived over this time period are that:

- Development efforts focusing on infrastructure can easily lead to expensive and non-productive cycles of construction, decline then rehabilitation, decline then rehabilitation. This is a cycle that needs to be broken.
- Farmers of Nepal clearly have the capability of developing and managing irrigation. While this was ignored in the past, it provides an important component of Nepal's development. Right now finding the right mix of farmer management and government support is important.
- Recovering from the cycle of construction and rehabilitation has been positive, but much more difficult than perceived. It is vital to get new irrigation development started right. It is also important to continue efforts to improve management – of both farmers and government – in these systems.

Clearly, development of Nepal's water resources is critical for the country's development. It should be expected that there is much trial and error to get the development process right. Somehow we have to reduce the time it takes to reach the potential for managing these systems. One important part of the process is to document and understand trial and error and success and failure to make sure we improve how development takes place.

REFERENCES

Agricultural Projects Services Centre, APROSC, 1978. Impact Evaluation Study of Khageri Irrigation System, Kathmandu, Nepal

Agricultural Projects Services Centre, APROSC, 1982. Socio-economic Study on Command Area Development Project (Western Gandak, Banganga, Manusmara and Jhaj), Final Report, Asian Development Bank, Kathmandu, Nepal

Agricultural Projects Services Centre and John Mellor Associates, Inc., 1995. Nepal Agriculture Perspective Plan. HMG/N, Kathmandu, Nepal.

Canadian International Water and Energy Consultants, 1998. Master Plan for Irrigation Development in Nepal, Master Plan First Cycle – Detailed Framework, Kathmandu, Nepal

Computer Assisted Development Inc, 1995, Annual Progress Report, Ft. Collins, CO.

Computer Assisted Development Inc., 1996, Annual Progress Report, Ft. Collins, CO.

Department of Irrigation, 1990. Provisional Impact Evaluation Study of West Gandak Irrigation Sub-Project. Vol. II. Kathmandu, Nepal

Department of Irrigation, 2052 (1995). Information Sheet of Operation and Maintenance Projects. DOI, Kathmandu, Nepal

Department of Irrigation, 1996. Monitoring of Irrigation Systems under O & M, Kathmandu, Nepal

Department of Irrigation (DOI), 1999. *Department of Irrigation: From the Past to Present*. Nepali version. System Management and Training Program, DOI, Kathmandu, Nepal

EVEREC, 1993. Baseline Study of West Gandak Irrigation System, Department of Irrigation, Nepal

GEOCE Consultants, 1996. Study on Socioeconomic and Irrigated Agricultural Aspects in the West Gandak Irrigation System. Kathmandu, Nepal

GITEC Consult, 1993. Irrigation Management Transfer Project, Main report. Department of Irrigation, Nepal

His Majesty's Government of Nepal, 1989. Master Plan for Irrigation Development in Nepal, Working Papers – Sixth Issue, CIWEC and East Consult (P) Ltd., Kathmandu, Nepal

His Majesty's Government of Nepal, 1995. Project Administration Memorandum. Irrigation Management Transfer Project, Kathmandu, Nepal

His Majesty's Government of Nepal, 1998. The Ninth Plan 1998. HMG/N, Kathmandu, Nepal

His Majesty's Government of Nepal, 1999. Economic Survey 1999. HMG/N, Kathmandu, Nepal

Institute of Animal and Agricultural Science, IAAS, 1994. Proceedings of the workshop on Irrigation Management Transfer held at Rampur, Chitwan on June 1-2, 1994, Nepal

Integrated Consultants Nepal, ICON, 1993. Baseline Study of Khageri Irrigation System. Department of Irrigation, Nepal

Integrated Consultants Nepal, ICON, 1995. Diagnostic Study of Tertiary System for Khageri and Panchakanya Irrigation System, Vol. I and II. Department of Irrigation, Nepal

IWMI and RTDB, 1998. Comparative Performance Assessment in 7 selected schemes in Nepal, International Water Management Institute (IWMI) and Research and Technology Development Branch (RTDB), Nepal

Laitos. R. and C. B. Shakya, 1991. Guidelines for Turnover and Joint Management in Nepal. Computer Assisted Development, Inc., Ft. Collins, CO.

Mishra, V. S. and D. J. Molden, 1996. Management turnover in the West Gandak Irrigation System, Nepal. Colombo, Sri Lanka: International Irrigation Management Institute (IIMI). V, 19. (Short report series on locally managed irrigation no. 14).

Mishra, V. S. et. al., 1999. Effect of Gate Operation on Performance of Irrigation Systems: A case study of Khageri Irrigation System, Nepal (unpublished paper).

Pradhan, N. C. et. al. 1995, Benefit Monitoring and Impact Evaluation of West Gandak and Khageri Irrigation Systems under the Joint Management Program, Department of Irrigation, Kathmandu, Nepal.

Pradhan, P., 1989. Increasing Agricultural Production in Nepal: Role of Low-cost Irrigation Development Through Farmer Participation. IIMI, Sri Lanka.

Pradhan, P., 1989a. Patterns of Irrigation Organization in Nepal: A Comparative Study of 21 Farmer-Managed Irrigation Systems, IIMI, Sri Lanka.

Prasad, K. C. et. al., 1998. Irrigation Service Fees in Nepal, RTDB and IWMI, Kathmandu, Nepal.

Starkloff, R., H. Hemchuri, S. Upadhyaya, K. Prasad, 1999. Functional status assessment of Panchakanya Irrigation System, IWMI/RTDB, Kathmandu, Nepal.

SECONDARY WATER SUPPLY MANAGEMENT FOR IRRIGATION DISTRICTS AND CANAL COMPANIES

John Wilkins-Wells[1]

ABSTRACT

One of the more important business practices over the years in larger multipurpose water districts has been the delivery of untreated water for lawns and gardens. This is generally in addition to traditional irrigation water deliveries. With rapid urbanization occurring in many rural agricultural counties, even smaller irrigation districts and canal companies are beginning to provide such service to small acreage subdivisions and a variety of other non-agricultural water users (golf courses, parks, etc.). It is a business innovation stemming from urbanization in traditional and, for the most part, prime irrigated lands throughout the West. This paper presents two case studies of untreated water delivery for lawns and gardens by such enterprises. It discusses some of the issues surrounding the development of this practice, the costs and benefits of engaging in this kind of water service, and what opportunities and constraints lay ahead for this business practice in the future.

SECONDARY WATER SUPPLY SYSTEMS

Secondary water supply management, or raw water delivery through open ditches or small pipelines for non-potable domestic use, such as for lawns and gardens, is an old tradition in the West. Irrigation

[1] Assistant Professor, Senior Research Scientist, Department of Sociology, Clark B258, Colorado State University, Ft. Collins, CO, 80523. Much thanks is owed to the following for information on these case studies: Floyd Baham, Manager, Davis and Weber Counties Canal Company, 138 West - 1300 North, Sunset, UT 84015; Lee Cammack, Area Manager, J-U-B Engineers, Inc., Kaysville, Utah; Monty Nelson, Operations Manager, Kennewick Irrigation District, 214 West 1st Avenue, Kennewick, WA 99336.

districts and canal companies in California and Utah were providing lawn and garden water on a limited basis as early as the turn-of-the-century, in addition to their normal service of supplying water for irrigated agriculture (Hutchins, 1936).

In the face of declining irrigated farm income in many areas, this type of water service has the potential to prolong the viability of prime irrigated lands in areas experiencing virtually uncontrolled urban growth. This will be shown in the two case studies. At the same time, secondary water supply management provides much needed revenue to improve current irrigation facilities (canals, headgates, etc.), and water conservation through better record keeping, computerized water accounts, billing and other day-to-day business practices. Secondary water supply management appears to enhances the business operation of these traditional enterprises.

Local municipalities are greatly benefitted by secondary water supplies of this nature, by not having to build as many expensive water treatment facilities to meet what are generally brief peak demands for urban outdoor needs during the relatively short summer growing season, particularly in the Rocky Mountain region. Some community education in the use of untreated water for outdoor use is implied. However, it is often a win-win situation if irrigation enterprises and municipalities can cooperate with each other to develop such systems, if start-up capital can be secured, and there is an appreciation among municipal and county leaders about how this kind of water delivery helps maintain diverse land uses in urban corridors.

At the same time, interviews with canal company and irrigation district representatives indicate some mixed feelings about this secondary supply concept (Wilkins-Wells, 1999). Some argue that it may promote even faster urban sprawl onto irrigated lands. Yet, urban growth onto irrigated lands may have more to do with county and municipal land use policies and codes than it does with any kind of innovative raw water service provided by traditional irrigation enterprises. Let us briefly review the issue of urban sprawl before examining our two case studies of secondary supply systems. It has a bearing on the value of these systems.

IRRIGATION ENTERPRISES AND URBAN SPRAWL

Urban sprawl has importance to the two case studies because it is believed to be contributing significantly to the cost of operating an irrigation enterprise today (Wilkins-Wells and Coulter, 1999). Control of urban sprawl continues to be a major issue for county and municipal governments throughout the nation (American Farmland Trust, 1999). Although long an issue for the more populous West Coast states, many prime irrigation counties in the Rocky Mountain region are now facing rapid urbanization onto priceless irrigated lands. Nelson (1990), in an important theoretical discussion of farmland preservation techniques and their effectiveness in slowing urban sprawl, concluded that such practices as tax incentives, right-to-farm legislation, acquisition and/or transfer of development rights, agricultural zoning and various combinations of such policies, although suggestive, still lacked real empirical evidence as to their effectiveness. More recently, Geisler (1999) argues that urban sprawl may be more a function of who owns agricultural land than anything else. Transfer of farm ownership out of the hands of farmers and into the hands of corporate (non-agricultural) owners can lead to more rapid urban sprawl.

One of the issues that links urban sprawl not only to the loss of prime irrigated land, but to the increased costs of operating irrigation districts and canal companies, is the amount of farm income that is believed to be subsidizing urban sprawl. Although rarely researched, we may examine for a moment how this works with irrigated agriculture. It is a troubling trend for irrigated farm income and the preservation of prime irrigated lands in the West.

Irrigation enterprises can be said to have four kinds of operating costs today. We may refer to these as: 1) bond, loan or federal repayment contracts for infrastructure development and/or major improvements; 2) annual costs borne by these enterprises on their own account, which generally includes direct administrative, operation and maintenance costs associated with delivering water to farms; 3) pass-through costs represented by costs imposed on irrigation enterprises as a result of urbanizing trends in the vicinity of these enterprises, but for which these enterprises are effectively reimbursed through one-time service fees and special water rates they charge for provisioning subdivisions and other non-agricultural water users, and; 4) non-pass-through costs that are imposed on these enterprises by urbanization, but for which they are generally not reimbursed.

Examples of the third category of costs, pass-through costs, are typically represented by what secondary supply systems do for irrigation enterprises in their adaptation to urbanization. More on this in a moment.

Examples of the fourth category of costs, non-pass-through costs, and where farm income is actually drained off to subsidize urban sprawl, include those for increased irrigation enterprise liability associated with subdivision development, and problems of maintaining, protecting and ensuring routine access to canal rights-of-way. Other costs in this fourth category include removing urban trash from canals, damage to canal systems from urban storm runoff, urban-related vandalism to irrigation enterprise equipment and facilities, and demands to bury open ditches in pipeline to accommodate subdivision needs.

Still other examples of these non-pass-through costs include a growing percentage of irrigation enterprise employee time (and therefore salaries) going to address problems and complaints from subdivision dwellers, and city and county requests for special action such as maintaining vegetation along canals at some specific height to accommodate urban dwellers, or requiring these enterprises to assess potential drainage and crossing issues affecting subdivision development; generally with little or no compensation for the time spent by enterprise employees in assessing these issues.

These and a host of other costs--by and large absent from irrigation enterprise budgets twenty years ago--are now routinely borne by irrigators, in whole or in part, through the water assessments, or in the case of irrigation districts, district land taxes, that these irrigators annually pay to operate and maintain their irrigation facilities. In short, farm income is subsidizing urban sprawl.[2]

Non-pass-through costs borne by these traditional irrigation enterprises are growing at an alarming rate.[3] Valuable farm income is lost to these urbanizing influences. One of the principal causes of this trend appears to be county and municipal land use codes that provide little protection to irrigation district and canal company lands and rights-of-way. Development plans submitted to county planning offices frequently affect irrigation enterprises very negatively, and without any real means of compensating irrigation enterprises for impacts associated with subdivision development and other externalities created by urban sprawl onto previously established irrigated lands.

Urban sprawl is a complex social, economic and political issue (Daniels and Bowers, 1997). However, when it comes to irrigation districts and canal companies, urban sprawl is clearly subsidized by farm income through these non-pass-through costs. It is true that urbanization around irrigated lands can clearly improve the equity of farms in many instances through increased land values, and this is desirable to many farmers. However, lowered farm income due to the many subtle affects of urbanization on the farm operation, such as increased non-pass-through costs associated with water allocation, may encourage somewhat more land speculation on the part of irrigators, to the exclusion of capital improvements to farms. Current research is underway to assess these relationships. However, what is important here is that this process may be, in part, ameliorated by these traditional irrigation enterprises entering into secondary water supply management.

---

[2] A current follow-up study to the Irrigation Enterprise Management Practice Study recently completed for the U.S. Bureau of Reclamation by Colorado State University is examining this cost in more detail. This cost to farmers is estimated to be in the tens of millions of dollars in lost farm income annually in the Rocky Mountain region alone.

[3] Why the irrigation community has not reacted to this trend more assertively, demanding compensation for lost farm income, is puzzling, although many enterprises are now beginning to assert their concerns to local county commissioners and municipalities.

Two enterprises are informative in this regard. Both are predominately agricultural in the traditional sense of the word, but they are attempting to accommodate urban sprawl in the best way possible. They do so, in effect, by ensuring that costs associated with urban sprawl are pass-through costs (category three above), rather than non-pass through costs (category four). This will become apparent in discussing how these secondary supply systems are set up, financed, and operated. The first is the Davis and Weber Counties Canal Company of Sunset, Utah. The second is the Kennewick Irrigation District of Yakima, Washington. Again, both of these are predominately agriculture water providers.

THE DAVIS AND WEBER COUNTIES CANAL COMPANY[4]

The Davis and Weber Counties Canal Company (D&WCC) was officially established in 1894. A predecessor organization goes back to the early 1870s. The company was conceived and constructed with one purpose in mind, to provide reliable water supplies to farmers. It has been fulfilling this goal for over 100 years. Approximately 18,000 of the original 40,000 acres of prime irrigated land under the canal company still continues to be served, despite rapid urbanization in Davis and Weber counties.

Davis and Weber counties have always been important diary, fruit and grain producing counties in the intermountain region. However, things have been changing in recent years. Since the late 1970s, these counties have become largely urbanized. Yet, there is still important agriculture in the area, as well as a highly valued rural life style on the outskirts of Ogden and Salt Lake City.

Prior to 1940, almost 100% of D&WCC water supplies were used for irrigation purposes. However, the transition from agricultural land to residential subdivisions began after the war. In 1985 the canal company's board of directors and management began to investigate the potential for alternative uses of irrigation water in its service area. This was partly driven by the need

[4] Adapted in part from Davis and Weber Counties Canal Company annual reports.

to find additional sources of revenue to improve the agricultural water delivery system.

Special water rates for residential areas would be developed to finance a secondary water supply system, while at the same time financing the upgrade of the larger irrigation system that served both agricultural and residential water users. Clearly, first and foremost in the minds of farmers was to keep water attached to the canal company service area. However, providing raw water delivery for lawns and gardens could produce valuable new sources of revenue for the canal company to upgrade its aging irrigation system.

In April of 1985, a local firm that provided D&WCC engineering services for many years was hired to prepare a feasibility study on raw water delivery for lawns and gardens within the canal company's service area. After this study was completed, a series of meetings were held with local cities. These meetings were designed to acquaint cities with possible new options in coping with their growing demand for expensive treated water.

To place lawn and garden watering under non-potable sources would greatly relieve the cities of the increasing cost of using treated water for the same purpose. Municipal water treatment systems were often designed to accommodate the peak demand for outdoor water use during the summer months, and at a great cost to the cities. The idea of a canal company providing raw water to alleviate the need to design potable water systems for this peak summer usage looked like a win-win situation for everyone.

During 1986 and 1987, the D&WCC Board of Directors and its management staff continued to investigate avenues available to the canal company. Interest from the cities continued to grow. In February 1988, a special canal company stockholder's meeting was held in which 66% of the total voting shares of stock were represented. At this meeting, 65% of the company stock voted in favor of D&WCC entering into a loan with the Utah Division of Water Resources to a maximum amount of $35,000,000. This loan was needed by the canal company to finance the up front basic infrastructure required to begin providing secondary supply service to local municipalities. This included building small, one acre, reservoir storage facilities to pressurize portions of the secondary system. In return, D&WCC pledged up to one-half acre foot of water per share of company stock for use in developing the secondary water system. Only one percent (1%) of those present voted against this 1988 board resolution. It was a very popular idea.

In April 1988, D&WCC officially applied to the Division of Water Resources for funding. In August of the same year, the agency approved funding for the D&WCC secondary water project in the amount of $38,000,000, including the first phase of the project that would serve Kaysville City, Utah. An agreement was signed with Kaysville City, and contracts were awarded in September of 1989 for a small reservoir east of Highway 89, along with the secondary supply pipelines to serve Kaysville City.

In December 1989, land was purchased in Layton, Utah for another small reservoir site, and in May 1990 D&WCC purchased property in the City of Sunset to construct another small one acre reservoir. Additional construction was completed through 1992. In summary, three surrounding communities now receive some secondary water supply service from D&WCC.

An agreement was entered into by D&WCC with each of these cities spelling out ordinances, mutual covenants, canal company maintenance procedures, city obligations, fees and assessments, and rate adjustments for future users. Presently, the city collects and remits fees to the canal company by first billing the secondary supply water user (homeowner) an initial connection fee, then the annual water fee. The city also collects a nominal fee per homeowner account for administrative costs. The canal company does not have to bill the secondary supply water users. It just receives a check for the annual fees collected by the City for the service.

These secondary water supply fees are used not only to pay back the loan from the state agency, but also to continually upgrade the canal company's agricultural water supply system. In the process of developing this new service, and to relieve the burden of local municipalities expanding their own domestic water service for lawn and garden water, the canal company has fallen upon a new source of revenue to help finance a much needed rehabilitation of its irrigation system.

Again, Davis and Weber still provides agricultural water service to more than 17,000 acres of prime irrigated land. This land is being kept in production despite considerable urban sprawl in the county. Farmers continue to farm and the irrigated lands are much valued for their production, open space qualities, and the mixed economy they provide to the counties.

SECONDARY SERVICE CONNECTIONS

A typical secondary supply service connection consists of a pipeline being constructed down the middle of the residential street serving a small housing subdivision. An extension is then tapped into this street pipeline from the planter strip along the curb. One-inch pipelines are then extended from this planter strip water connection to individual households. A ¾-inch riser, painted red and tagged as non-potable water, is the service connection for the household. Education programs in the use of outdoor raw water connections are organized by the cities.

Cities cooperating with D&WCC have passed local ordinances governing the overall management of the secondary water supply system. These ordinances protect the canal company from liability. The developers of subdivisions receiving secondary water supply are largely responsible for acquiring the water to develop their subdivision. Developers convey to the Davis and Weber County Canal Company, upon payment of fair market value for such water rights, a minimum of three (3) acre feet of water per gross acre of newly developed land to be served by the secondary supply system (e.g., the total area of the subdivision lot prior to any improvements or development).

New service must be pre-approved in writing by the canal company prior to a city issuing a building permit to the developer. All construction and drawings of the secondary supply system must be in accordance with the canal company's standards and approval. Finally, the pressure irrigation facilities constructed for delivery of raw water to new subdivisions or developments are transferred to the canal company with a twelve (12) month warranty by the developer.

Rules and regulations, and a community education program in the use of raw untreated water, have been developed in cooperation with the canal company and the cities now being served. Guidelines for property owners have been carefully designed to protect the water user as well as the property of the canal company and irrigated farms from non-pass-through costs (category four costs).

THE KENNEWICK IRRIGATION DISTRICT[5]

Irrigation in the area now served by the Kennewick Irrigation District (KID), Yakima, Washington began in the late 1800s. The district was officially organized in 1917. Farmers are still the primary customers in the irrigation district operations plan.

The district has 88 miles of canal, four ditch riders, and a maintenance crew of 6. There are 19,171 water accounts in the district. Household water is normally from wells, and some water is pumped directly from the Columbia River. However, KID draws its main water supply from the Yakima River, as do 7 other neighboring districts. Like a typical irrigation district, KID delivers only raw water. It is not involved in managing a potable domestic water supply system for anyone in its service area.

Water users who have been managing small amounts of raw water for lawns and gardens at an old irrigation turnout or lateral, approach the Kennewick Irrigation District about forming a Local Improvement District. These are referred to locally as "LIDS." A local improvement district is like a small incorporated lateral or homeowners association, but in this case it is organized for the purpose of obtaining a reliable raw water supply for irrigating lawns and gardens. In reality, it is a subdivision that is organized into a LID.

Upon a subdivision or homeowner's request to consider the organization of a LID, a determination is made by the Kennewick Irrigation District (the "mother" district if you will) as to the feasibility and desirability of such a small improvement district within its service area. A vote is then taken of the people affected by the proposed improvement district.

---

[5] Adapted in part from Kennewick Irrigation District reports and newsletters.

The "voting public" in this case might consist of a small subdivision of 50 households.

If the resolution passes among the water users affected (e.g., homeowners), Kennewick Irrigation District then assists the small improvement district in finalizing its membership. However, the newly proposed LID must be approved by the Kennewick Irrigation District board of directors for the cost, because the mother district (Kennewick, that is) finances the cost of developing the LID. In one example, the Kennewick Irrigation District lent $100,000 to a new local improvement district to develop its secondary supply system, amortizing the cost for the LID homeowners and charging some interest.

The development costs and annual operation costs of the secondary supply system for the local improvement district is obviously tied to the number of members in the LID. These operation costs are prorated across all members. Generally, the more people there are in a LID, the cheaper the raw water for each homeowner. Thus, the cost of untreated water service varies from one LID to the next.

The Kennewick Irrigation District system comes right into the local improvement district with a ¾-inch valve from the mother district's main line. The local improvement district can have this connection installed above or below the ground. Changes or breakage are billed back to the local improvement district, not to the individuals within the improvement district. Again, these local improvement districts are like small affiliated homeowners associations, or incorporated laterals in irrigated areas. The Kennewick Irrigation District only interacts with the LID as an association, not with single individuals in the association. The LID also pays for its own street cutting and road repairs. If a line breaks in the road, the local improvement district pays for those repairs too.

CONCLUSION

In summary, canal companies and irrigation districts are entering into many new forms of agreements with cities to make more efficient use of water and to accommodate urban growth in innovative ways. Farmers express a strong desire to remain in business as long as their water supply can be guaranteed, and as long as their irrigation district or canal company can effectively work with county planners, developers and new homeowners. Pressurized secondary water supply systems represent a major new form of business venture for traditional irrigation enterprises that can be used to address these challenges. In addition, these systems are capable of generating new revenue to upgrade existing irrigation facilities for agricultural water use and to meet new environmental concerns.

The entry of traditional irrigation districts and canal companies into secondary water supply management has been a revenue generator in most instances. It is financing the upgrading of irrigation systems in a way that could not be achieved otherwise. It often allows the agricultural water district or canal company to have more control over its water rights too. However, it also raises new concerns and new demands for water service which are not common in irrigation districts and canal companies. It is certain that secondary water delivery to subdivisions and other fractional water users for non-agricultural purposes is not possible for all irrigation enterprises. However, it is clear that the potential is there for additional revenue sources to meet future agricultural water delivery needs for some time to come.

Most of all, secondary water supply management provides a means of formalizing the responsibilities county and municipal government have toward the irrigation facilities, and in a way that allows the irrigation enterprise to be reimbursed for most non-pass-through costs. In fact, the process really converts or upgrades non-pass-through costs into pass-through costs, as well as improving the liability protection of these enterprises. The down side to this practice is the continued urbanization of the irrigated area, an almost inevitable process today. However, at least in these instances, the irrigation enterprise is a role-player and stakeholder in the urbanization process, rather than a bystander. To the degree that control over the enterprise's destiny is minimally guaranteed, secondary water supply management has its distinct benefits to irrigated agriculture in the face of the urbanization juggernaut.

AFTERWORD

In July of 1999, a major break occurred in the main canal of the Davis and Weber Counties Canal Company system, seriously damaging seventy residential homes under the canal. Contrary to the advice of the canal company, and despite the service it provided in meeting the costs of inexpensive municipal supplies for lawn and garden use, and thereby saving county and municipal taxpayers the cost of building more extensive water treatment facilities, the canal company was facing a lawsuit for its supposed negligence in managing the canal.

Like mud slides, earthquakes and other natural disasters, nature can take its toll on aging infrastructure. The problem is exacerbated by inadequate and often short-sighted county and municipal land use codes that place homeowners in harms' way through unrestricted urban sprawl into flood plains and under or near man-made water ways. A recently passed county land use code in a neighboring state, and one designed with all of the current state-of-the art practices of conservation easements, development transfer credits, and the like, showed only one sentence in a 258 page document pertaining to the business needs, liability concerns and interests of irrigation districts and canal systems. It is a testament of the times.

Meanwhile farm income continues to decline, and water supplies to the farm represent a major crop production cost leading to this decline in farm income. Not only does farm income subsidize urban sprawl through a growing number of non-pass-through costs not addressed by county and municipal land use codes, but the overall process leads to an impermanency syndrome on the part of farmers to sell when the price is right, rather than face continued costs and liability concerns.

Secondary water supply management can certainly lead to the strengthening of partnerships between traditional irrigation enterprises, and counties and municipalities, and in a way that allows continued multi-purpose land use and open agricultural space. However, counties and municipalities must be committed to protecting the economic interests of farmers and the traditional irrigation enterprises that serve them.

REFERENCES

American Farmland Trust. Saving Open Space: Public Support for Farmland Protection (1999). Center for Agriculture in the Environment, See also their website at http://www.farmland.org/

Concerned Citizens Resource Association: A Member Group of Western Colorado Congress. Various published materials.

Daniels, T., and Bowers, D., Holding Our Ground: Protecting America's Farms and Farmland. Island Press, Washington, D.C. (1997).

Geisler, C.C., *Fallowing Our Bliss: The Receiving End of Sprawl*. Paper presented at the Rural Sociological Meetings, Chicago, Ill, August 4-8, 1999.

Hutchins, Wells A., Mutual Irrigation Companies in California and Utah. Farm Credit Administration, Cooperative Division, Bulletin No. 8, Washington, D.C. (1936).

Nelson, A.C., *Economic Critique of U.S. Prime Farmland Preservation Policies*, in Journal of Rural Studies (6:2:119; 1990)

Wilkins-Wells, J., et.al., Irrigation Enterprise Management Practice Study. Final Report. Research and Technology Transfer Division. U.S. Bureau of Reclamation (see website: http://socaddr244.soc.colostate.edu.

Wilkins-Wells, J, and Coulter, T., *The Affect of Urbanization on the Cost of Operating an Irrigation District or Canal Company*, in Contemporary Challenges for Irrigation and Drainage. Proceedings 14^{th} Technical Conference - 1998. U.S. Committee on Irrigation and Drainage.

ROLE OF CANAL AUTOMATION AND FARMER'S PARTICIPATION IN MANAGING WATER SCARCITY: A CASE STUDY FROM ORISSA, INDIA

Dr. B.P. Das[1]

Dr. J.M. Reddy[2]

ABSTRACT

The Derjang irrigation project, initially planned and constructed to command 6000 ha, experienced serious shortage and inequity in water distribution (between 1967 to 1993). Distress of the system resulting from unauthorized tampering by the beneficiaries, to a large extent, led to significant deficiency in water conveyance. A complete rehabilitation of the distribution system with structured zones below which distribution is unregulated, and formation of Water Users associations (WUAs) has resulted in increased crop production and farm income. The hydrological data from 1967 to 1980 indicated an additional yield of 1000 ha-m annually which led to creation of increased live storage by installation of gates on open crested spillway. This has led to a Stage II extension for creating an additional potential of 1800 ha. With a healthy system and WUAs functional, it has been possible to irrigate an additional 1400 ha in 1998. But a major concern continues to be the abstraction of 10 to 15% over the authorized withdrawal, where mechanically operated shutters are provided. To obviate such a contingency, canal automation in a pilot scheme for the entire command is being formulated and will be implemented in a 2-year time frame. This scheme would be a training ground for 250,000 ha of command area being rehabilitated in Orissa through a World Bank assisted Water Resources Consolidation Project (WRCP). Preliminary assessment shows that a good system with automation and farmers participation can irrigate an additional command area of 10% with minimal investment.

INTRODUCTION

The Derjang irrigation project, in the State of Orissa, was constructed in 1967 to provide irrigation water to a drought prone command area of 6600 ha in which monsoon crops are grown over an area of 5951 ha. A reservoir, formed by an

[1] Chief Advisor, Projects, Department of Water Resources, Government of Orissa, India.

[2] Professor, Department of Civil Engineering, Colorado State University, Fort Collins, Colorado; and Int. Training Consultant for the Water Resources Consolidation Project, Orissa, India.

earthen dam, was built across the river Ningra, intercepting a drainage area of 399 sq km, and has a live storage capacity of 4640 ha-m.

The average monsoon rainfall over the basin is 1000 mm, but varies in a range of 700 to 1400 mm with considerable erraticity in the months of July, September and October (Table 1).

Table 1. Typical distribution of rainfall

Month	Rainfall Variability, mm		Average Rainfall, mm	Useful Rainfall, mm
	minimum	**maximum**		
June	100	250	130	30-100
July	200	400	300	100-300
August	250	400	350	120-300
September	75	250	150	50-130
October	50	150	70	0-50

As the predominant crop grown in the monsoon is rice (long duration), which needs at least 150 mm of effective rainfall in July for transplantation and 150 mm in September and October for flowering and maturity, scarcity is invariably experienced in drought years (total monsoon rainfall less than 800 mm) which have a recurrence interval of 1 in 3 years. The problem of equitable distribution of water particularly to meet the crop water need in the tail area (30 % of the command area) gets affected with the head of the command area (70%) utilizing 90 to 95% of the available water. Identification and delineation of the most needy areas in the command is not addressed by any well-defined mechanism. Consequently the water requirement for the crops at different stages of crop growth in the command, in space and time, is neither realistically assessed nor effectively met. The cropping pattern at the project design stage was based on the soil characteristics (Table 2).

The scarcity has become obvious due to the increased coverage of heavy duty crops (rice) in both cropping seasons of Kharif and Rabi. It is pertinent to mention that due to occurrence of two to three cyclonic storms per year (with a precipitation of 200 to 250 mm in a 3 day period), non-rice crops even on highlands suffer from impeded drainage and consequently provide poor remunerative yield leading to diversification to rice.

Table 2. Cropping Pattern at Project Formulation Stage

Cropping Period: Kharif (June to October)		
Rice Groundnut Sugarcane Others	64% 13% 3% 18%	Out of a total of 31%, almost 25% is currently covered with medium and long duration rice
Cropping Period: Rabi (November-May)		
Pulses Rice Others	18% 5% 5%	Rice coverage has gone up to 25% to 30% and overall Rabi coverage is 40%

WATER DISTRIBUTION NETWORK

A 13.2 km long main canal (Angul main canal) with a design capacity of 6.8 m^3/s at the head feeds the command area principally through five laterals (total withdrawal of 4 m^3/s) and a branch canal (Balaram Prasad branch) at the tail that draws 2.02 m^3/s (Figure 1). This tail branch feeds a major lateral canal, the Barasinga distributary which draws 0.72 m^3/s from the branch canal.

The project also provides drinking water supply to the district headquarters town of Angul (population 1,00,000) and for industries by allocating 500 ha-m of the live storage for these purposes.

The undulating command area has good slope of 1 in 1000 for 70 % of the area, but is flat (1 in 4000) for 15 to 20% of the command where rice is necessarily grown in the Kharif and Rabi seasons. The soils are of silty clay type and have an infiltration capacity of 20 to 40 mm per day. The overall assessment of supplementation by irrigation for the entire command area based upon consumptive use study is 600 mm for the principal cropping season, June to October. Depending upon the quantity of surplus water available at the end of the monsoon (31 October), the cropping pattern and coverage for the Rabi crops (November to May) are decided.

MANAGEMENT PROBLEMS EXPERIENCED

Starting in 1967 when the system became operational, inequity in distribution became evident because of the following factors:

(a) Actual seepage loss over the 13.2 km long main canal and 76 km of medium and minor channels was 20 to 50% more than the assumed value of 2 m^3/s for one million sq km of wetted area. The overall conveyance efficiency was in the range of 60-65% (not exceeding 70% for well maintained channels) against the value of 75% assumed in the design.

(b) The design assumption for conveyance capacity for main/laterals was somewhat deficient. The channel could not carry more than 90 to 95% of their capacity under design conditions.

(c) Normally canal capacities were decided for the worst meteorological conditions to meet full crop water need. This necessarily meant that conveyance capacity was actually in excess in good years but needed careful regulation in average/bad years so that the release from the reservoir in any 10 day spell (normally releases are decided based on 1-day rainfall data) does not exceed the overall crop demand for the entire command.

(d) At the design stage, the laterals were planned to draw their authorized discharge when the parent channel is running at half supply (40 to 70 % of design capacity) when there is overall reduced crop water need. The individual outlets for laterals were therefore so positioned that they draw full supply when the parent channel is conveying partial discharge. With the regulating shutters operated manually becoming worn (sometimes non-functional), over-withdrawal occurred in all the off-taking channels in the head and middle reaches.

(e) An appropriate water management technique for varying crops over the command has neither been formulated nor practiced effectively. Consequently, undependable and inequitable distribution resulted in over-withdrawal in the head reach (over 40% of the command) and the middle and tail reaches getting as low as 50% of the authorized discharge intermittently, particularly during drought spells. Over-withdrawal in the head reach resulted in breaches, overtopping and damage to structures (outflanking), whereas the short supply down below made the farmers obstruct flow, cut canal banks, and operate and damage the structures in the tail reach in particular. The system, in summary, went into distress progressively and the conveyance capability of the system was significantly reduced.

(f) By 1985, within two decades, the project was incapable to irrigate even 5000 ha. Consequently, over the entire command, the productivity was skewed and the overall production/farm income was considerably lower than envisaged.

INTERVENTION CALLED FOR

Immediate need was felt for (a) rehabilitation of the system, (b) adoption of an appropriate cropping system with farmer's participation, and (c) flexible, but firm water management practice linked with crop water demand from hydro-meteorological considerations.

The OWRCP, financed by the World Bank (apprised and negotiated between 1992 to 1995 with a credit of $291 million) that followed the Bank-assisted National Water Management Project (NWMP) in India, addressed the issues comprehensively by including Derjang project for rehabilitation and improved water management and agricultural practices. Almost $1 million (forty million Rupees) has been spent on the System Improvement and Farmers Turnover (SIFT) activities for this project between 1993 through 1999.

DERJANG STAGE II PROJECT: EXPANSION OF THE COMMAND AREA

Interestingly, prior to formulating the NWMP proposal, it was revealed that the actual water yield of the basin based on reservoir operation studies (1965-1980) was higher by 15% over the design figure (1958). With increased availability of 1000 ha-m during the monsoon, two crucial decisions were taken: i) to install radial gates on the open crest of the spillway to store 1200 ha-m, augmenting the live storage to a total 4640 ha-m. This work was completed by 1984, and ii) the rehabilitation of the main canal in 1993-94 period indicated increased availability of water to the tail area, which dictated that the command area of 6000 ha can be extended in the tail by 1800 ha. In conjunction with the World Bank-assisted WRCP, the National Bank for Agricultural and Rural Development of India (NABARD) financed the extension project ($0.75 million or Rs 30 million) between 1996 through 1998.

STRATEGY AND ACTION PLAN FOR INTEGRATED DEVELOPMENT

System improvement under NWMP and WRCP enabled (a) restoration of the conveyance capacity of the entire network by desilting, raising of low banks, rehabilitation of damaged structures (1993-1995) which resulted in increased withdrawal of 50 to 60% in the laterals particularly in the lower reaches (Table 3), and (b) as experienced in two bad drought years of 1996 and 1998, the conveyance efficiency was close to 75% over the entire command, including the Stage II command area, where 1400 ha was the additional coverage in Kharif (June-October, 1996). The highest discharge drawn from the reservoir in September-October (1998) was 8 m^3/s for the overall covered area of 7400 ha (against the previous maximum of 4.8 m^3/s and 4500 ha up to 1993).

Table 3. Gain in Discharge and Area after Rehabilitation

Name of Lateral	Discharge, m^3/s			Command Area, Ha		
	Original Design	Pre-Rehab	Post-Rehab	Original Design	Pre-Rehab	Post-Rehab
Raniguda Dstributary @ head	0.64	0.38	0.60	548	366	530
Raniguda Distributary @ middle	0.34	0.21	0.30	310	219	300
Nuapada Distributary	0.51	0.30	0.50	431	258	400
Khalari Distributary @ head	0.84	0.55	0.80	631	425	600
Khalari Distributary @ middle	0.38	0.23	0.35	338	216	310
Balaram Prasad Branch	2.02	1.21	*3.50*	1847	1160	*3500*
Barasingha Distributary	0.72	0.41	*2.30*	695	404	*2400*
Angul Main Canal	6.80	4.80	*8.80*	5950	4500	*7500*

(Italic numbers--by resectioning and lining to feed Stage II area of 1800 ha)

PARTICIPATORY IRRIGATION MANAGEMENT

With uncertainty and undependability of flow in the network, and low reservoir levels in drought years, it was obvious that farmers participation in the system management was crucial to conservation and optimal utilization in general and during droughts in particular. The key to participatory approach was to share the surplus and shortage over the entire command rather than over an individual channel. This necessarily meant that operation and management of minor channels over relatively small areas (say 300 to 400 Ha) involving farmers was an essential pre-requisite, by formation of Water Users Associations (WUAs). Again the key issue was to ensure availability and equitable distribution of water by relatively simple, robust and unregulated operation of all minor channels over the entire command area. In essence the Bank assisted NWMP and WRCP stipulated the re-organization of the distribution network into ***structured zones*** each serving up to a maximum of 2000 ha, below which all the off-taking channels will have no regulating shutters. At the head of the structured zone, the design flow would be maintained for a 3 day/7 day/10 day spell depending upon the crop need, with the entire zone receiving ON and OFF irrigation. Each turnout will be so designed and constructed that during the ON period, the farm area served will receive its authorized discharge and volume. The parent channels (main canal and major distributaries) will have regulators to supply the allocated quantity to the structured zones. Such dispensation would obviate the inequity significantly.

A necessary adjunct to this proposition was the formulation and operation of Water User's Associations that would fully operate and distribute water, do routine maintenance, leaving the operation and maintenance of main channels up to the structured zones to the Water Resources Department. With success stories of WUAs in developing and developed countries (Philippines, Mexico, Turkey, Italy, Japan and the USA), it was decided to cover the Stage I command area of 5951 ha. Annex I and II describe the philosophy of Participatory Irrigation Management (PIM) concept, and the structure of WUAs in Derjang Project. Four more WUAS have also been formed informally for the Stage II command since 1998. The WUAs were actively involved during system rehabilitation and decided that intervention was needed primarily for better water management by modifications from regulated conditions to unregulated turnouts at suitable locations and of suitable size.

An Apex Committee regulated a few (6 to 8) WUAs by periodic review meetings with Water Resources and Agriculture Departments officials. A typical setup is shown below.

APEX COMMITTEE

President of WUA

Vice-president | **Secretary** | **Assistant Secretary** | **Treasurer**

To promote and accelerate formation of WUAs (between August 1996 to January 1997) a Non-Governmental Organization (NGO), the Youth Service Center of Angul, was selected. The NGO deployed Social Organizers in the locality for motivation of farmers. The NGO selected was earlier involved for four years in the locality to implement literacy and health programs. The benefit that accrued from system rehabilitation and constitution of WUAs can be typically described for WUA No.7 with a command area of 473 ha.

(i) *Benefit in Kharif Cropping Season*

Shorter duration rice was slowly adopted (June 15 to October 15th) to replace long and medium duration rice (June 15th to November 15th). Water shortage due to uncertain monsoon was not to affect the crop yield. Long duration (400 ha) and medium duration (53 ha) was replaced by short duration (200 ha) and medium duration (100 ha) and long duration (150 ha). Fertilizer input increased from 20 kg/ha to 35 kg/ha (1997), which along with better water availability resulted in almost 40% increase in crop yield from 880 metric tons to 1150 metric tons from the pre-rehabilitation to the post-rehabilitation stage with WUAs.

(ii) *Canal Automation*

The decision to extend the system at the tail-end was taken in 1994 primarily because the entire distribution network was rehabilitated under World Bank assisted NWMP (1993 to 1995) and WRCP (1995 to 1999), which inter-alia provided for constitution of Water Users Associations (WUAs) over the original command area of 5951 ha. As of 1999, thirteen (13) WUAs have been constituted and are functioning satisfactorily. There has been improvement in the farm yield and farm income in this project area.

With cross-regulators and head regulators having regulated gates feeding structured zones, abstraction from the parent canal was higher (10 to 30%) in the head reach. For example, the main canal of 13.2 km feeds the initial 3800 ha until branching out to Balaram Prasad Branch which is now required to command an area of 3700 ha including the Stage II. With a drought situation that prevailed in 1998, the main canal was drawing a maximum of 8 m^3/s for the overall command of 7400 ha as against the design capacity of 8.8 m^3/s. The head- reach with a command area of 3800 ha consumed 4.7 m^3/s leaving only 3.3 m^3/s for the tail 3600 ha (actually irrigated). It was estimated that the seepage loss in the head command was 0.85 m^3/s, and 0.6 m^3/s in the tail. Thus the overall duty at the head of field application was 987 ha per 1 m^3/s and 1270 ha per m^3/s for the head and tail command areas, respectively. Because the tail area was more compact (with 50% less channels than the head), seepage loss was less and with active support of WUAs and strict monitoring the tail area was by and large satisfactorily irrigated. Only 1 cumec was provided to the tail-end of the system- 1800 ha of area under Stage-II Santri distributary- by difficult and time consuming manual operation as against the demanded requirement of approximately 2 cumec.

Even after the almost complete rehabilitation (between 1993 and 1998) and formation of WUAs (1996 to 1998), the need for additional operational/structural improvements for ensuring/restricting the supply to each structured zone to the authorized quantity was felt. The lesson learned is that canal automation has to be introduced to obtain equity, particularly with the extension of the command area. A comprehensive scheme for remote operation of the entire system by a centralized control center at the reservoir, getting feedback in real-time from the regulators for the laterals and ensuring a proportional withdrawal is being formulated with the technical guidance provided by Colorado State University. The Department of Civil Engineering at Colorado State University, through the 2nd author, is a constituent of an International Lead Consultant Body for the Orissa WRCP. The automation scheme would essentially consist of:

- Developing an operational plan for the system
- Developing an outlet scheduling algorithm
- Developing a feedback control algorithm
- Software Integration
- Installing data acquisition/communication system
- Flow measurement at cross-regulators and head regulators for structured zones.

The hardware components of the scheme would be:

- Construction of additional cross-regulators and minimum rehabilitation of structures to enable installation of remote control operation of gates.
- Installation of equipment for data acquisition, transmission and operation of regulating structures.

The automation scheme is likely to cost $500,000 (Rs 2 million) to improve irrigation efficiency by at least 10 to 15% and primarily to assure the beneficiaries of the earnestness of the Department of Water Resources to maintain equity. In addition, this pilot scheme is undertaken to act as a demonstration and training site for the engineers of the Department.

SUMMARY AND CONCLUSIONS

The Derjang medium irrigation project was initially planned and constructed to command 6000 ha experienced serious shortage and inequity in water distribution (between 1967 to 1993). Distress of the system resulting by unauthorized tampering by the beneficiaries to a large extent led to significant deficiency in conveyance. With World Bank assistance, a complete rehabilitation of the distribution system with structured zones below which distribution is unregulated, and formation of WUAS that resulted in Participatory Irrigation Management, have already been done and have resulted in significant increase in production and farm income. The farm income has gone up substantially by adoption of cash crops in the winter and has shown 250% increase over half the command (from Rs 4000 in 1992 to Rs 10000 in 1998). The hydrological data from 1967 to 1980 indicated additional yield of 1000 ha-m annually which led to creation of increased live storage by installation of gates on open crested spillway. This has led to a Stage II extension for creating an additional potential of 1800 ha. With a healthy system and WUAs functional, it has been possible to irrigate an additional 1400 ha in 1998. But a major concern continues to be the abstraction of 10 to 15% over the authorized withdrawal, where mechanically operated shutters are provided. To obviate such a contingency, canal automation in a pilot scheme for the entire command is being formulated and will be implemented in a 2-year time frame. This scheme would be a training ground for 250,000 ha of command area being rehabilitated in Orissa through the World Bank assisted WRCP. Preliminary assessment shows that a good system with automation and farmers participation can irrigate an additional command area of 10% with minimal investment.

ANNEX-I. WHY IRRIGATION MANAGEMENT TRANSFER TO FARMERS

- Make farmers conscious of the price and utility of water. A government managed system delivers water on-demand irrespective of the merit of the demand, such as crop water need related to the growth stage; more important whether irrigation can be damaging to the crop yield. This is particularly true under Indian conditions where small holdings of 200 or more farmers receive water concurrently over a small command of 200 - 300 Ha. The possibility of different variety of crops grown all over the command in a staggered manner between holdings exists.

- Farmers pay for the water delivered quantitatively and hence economic water use.

- Distribution network at a minor level is usually in poor condition when the government (under Indian condition) maintains the entire system. The water inequity is significant from the head to the tail in a minor channel, which is primarily due to loss of conveyance capacity (even minor channels/water courses become non-existent after 10/20 years of use). Farmers through WUA will have to ensure minor preventive maintenance for ensuring equity.

- Infrastructural improvement done such as provision of unregulated turnouts prior to transfer ensures equitable distribution provided the Association is totally responsible for operation/water management.

- Appropriate cropping practice/diversification becomes possible to generate optimal farm income.

- The Farmers Association necessarily gets better access to government aided technology demonstration/extension programs as well as access to credit for better seed, fertilizer, pesticide and storage cum marketing facility. Use of farm equipment to cut down labor time and cost can be significant with associations trying to cover large compact farm areas.

- A downstream benefit is that, in addition to farm income, incremental family income is generated through a community approach covering dairy, poultry, piggery, horticulture, pisciculture and even commercial activities like weaving, painting, handicraft, etc. In addition community facilities related to health, education and rural connectivity can be better realized.

- A sense of belonging of the irrigation system prevails and grievance redressal is much faster.

- Worldwide experience shows management transfer to farmers to be cost effective and a sustaining development process.

Specific functions assigned to the Water Users Associations and objectives to form the Associations are:

a) to demonstrate and make the farmers conscious of the need of equitable distribution to ensure increased agricultural production
b) to increase consciousness for ensuring economy in water use
c) to develop and adopt appropriate cropping pattern
d) to advise the DOWR on minor level improvements
e) to operate and maintain the distributary/minor canals and structures that will be improved under WRCP
f) to collect irrigation fees on behalf of the DOWR
g) to ensure equitable water distribution among the WUA members; and
g) through the apex council, to advise the DOWR on main system operations as these affect operations within the WUA's management perview.

ANNEX II. DERJANG IRRIGATION PROJECT PROFILE OF WATER USERS ASSOCIATIONS

WUA No.	Ayacut Area (Ha)	Total Number of Farmers	Villages Involved
1	339	420	4
2	271	457	5
3	324	383	3
4	480	410	4
5	558	425	5
6	212	270	2
7	473	575	6
8	720	475	5
9	46	502	11
10	635	619	11
11	630	620	5
12	176	400	3
13	598	505	6
Total	5951	6060	70

All WUAs were registered during August 1996 to January 1997. Average land holding = 5951 / 6060 ~ 1.00 Ha / Family

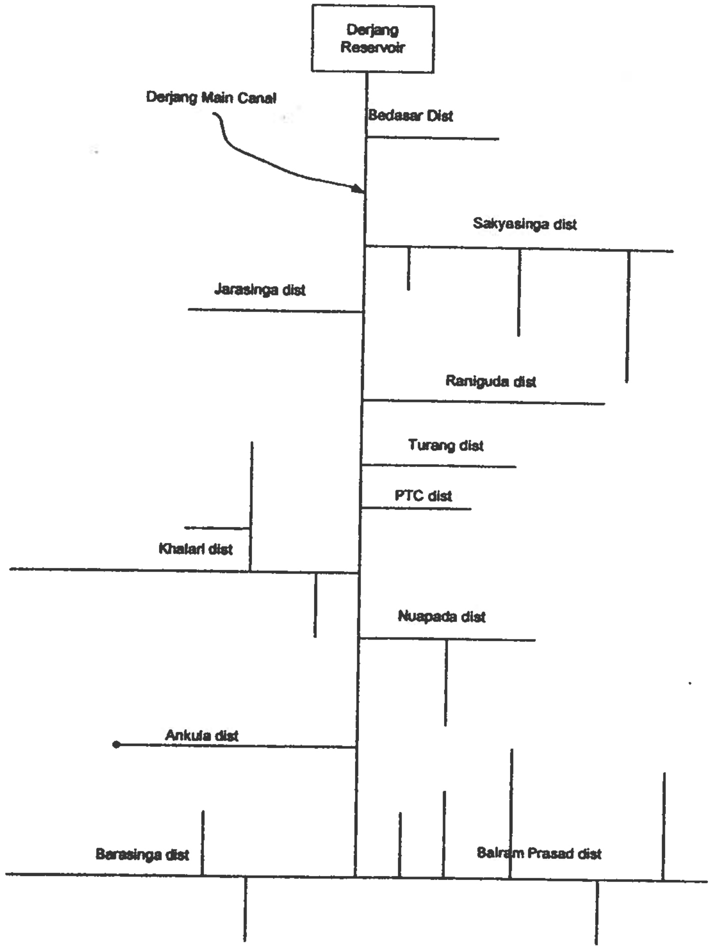


Figure 1. Index Map of the Derjang Irrigation Scheme

WOMEN'S PARTICIPATION IN IRRIGATION DEVELOPMENT PROJECTS

Azza Abdel-aziz[1] Ramchand Oad[2]

ABSTRACT

This paper reports the results of a field study of irrigated agriculture in Egypt. Specifically, it investigates the factors that determine women's participation in irrigation development projects. It is hoped that such analysis will help formulate strategies that can increase involvement of women in rural development efforts.

A review of literature on women's participation shows that gender aspects are often not included in the design and implementation of irrigation development projects. As a result, women involuntarily do not use the improved facilities, and consequently lose their fair share of the project benefits.

Necessary data and information for this study was obtained from the Irrigation Improvement Project (IIP) in Egypt. Findings of the study indicate that social barriers discouraged participation of young and married women in rural development projects. Older women and widows participated more in all project stages. There was no clear correlation between the level of education and participation, perhaps due to the high illiteracy rate among rural women.

1. INTRODUCTION

1.1 Perceived Benefits of Women's participation

The Ministry of Public Works and Water Resources (MPWWR), in Egypt, is responsible for managing all irrigation resources. However, farmers have always participated, informally, in the operation of the irrigation system and on-farm management. Recently, governments of many developing countries and financing agencies have made efforts to involve farmers in development projects' stages. This approach helps the planners to design projects that address the beneficiaries' needs. Whereas male farmers are increasingly involved in various phases of these projects, women are still left out. Not many systematic efforts have been made to encourage women's participation. Moreover, the gender aspect is still not included in the mainstream of irrigation and agriculture projects.

---

[1] Irrigation Engineer, Ministry of Public Works and Water Resources, Egypt.

[2] Professor at Agricultural Engineering Department, Colorado State University, Fort Collins, CO 80523.

The general belief that the development project's benefits will automatically trickle down to women and families leads development agencies to ignore women as direct beneficiaries. Further, in Middle Eastern and Islamic societies, rural women do not take the initiative to participate in new development projects. Their activities are usually limited to their households. Women have to be specifically approached to encourage their participation in new projects.

The planning, design, and implementation of development projects should be customized to the needs and capabilities of the beneficiaries. The participation of all beneficiaries, both men and women, is necessary for appropriate design, implementation, and management of improved facilities.

A careful study of the social, cultural, and technical barriers to women's participation is necessary to design optimal methods for improving irrigated agriculture. The lack of knowledge about problems of rural women and the impact of development projects on them and their families makes it difficult to design successful projects.

In a World Bank operations evaluation study, Murphy J. L. (1995) stated that insufficient attention to the roles of women was detrimental to project efficiency and sustainability. As a result, the visibility of gender issues in the World Bank activities has increased in recent years.

Many studies show that promoting women's participation and increasing their benefits from development projects will improve the living standards of their families. Women tend to devote more time and money to household and family needs, while men spend a higher potion of their income on goods for their personal consumption (M. Zwarteveen, 1996 and L. Brown, 1995). The increase in women's income, time and labor savings, and other project benefits are often directly used for household and family care.

1.2. The Study Objectives

The overall goal of this research is to study the extent of women's participation in irrigation development projects and its impact on the household and the family well-being. This research also provides guidelines, whereby women can participate effectively in irrigation and agricultural development projects. The direct participation of women should help them capture their fair share of the benefits for greater welfare of the household.

The specific objectives of this research are:

1. To determine the extent to which women are participating in irrigation improvement projects.

2. To analyze the significance of women's participation and its effect on their families' welfare.

3. To identify ways to improve women's participation for greater benefits to women and families.

4. To provide guidelines, for implementing and financing agencies, for effectively involving women in the future irrigation development projects.

1.3 Background of the Irrigation System in Egypt and the IIP

The Irrigation Improvement Project (IIP) is one of the largest irrigation projects in Egypt. It was initiated in 1988 by an agreement between the Egyptian government and the United States Agency of International Development (USAID) with a budget of $80 million. The feasibility study of the project included a description of the project area, identification of the problems, formulation and analysis of the alternative solutions, and an implementation plan. Women needs were not addressed in the project goals and objectives.

The irrigation water delivery canals supply water to the branch canals. The branch canals supply the meskas[3] at a level below the irrigated land. Most of the irrigation in Egypt, including the IIP project area, is carried out by pumping water from meskas to the adjoining fields.

With the wide use of diesel pumps, some farmers pump water directly from the branch canals, which causes a drop of the water level below the designed level. This results in inadequate and uneven distribution of the water supply and low irrigation efficiencies. Water supply to the meskas, from the main irrigation canals, is on a rotation basis[4].

The fundamental changes introduced by the IIP are:

- Single point water lifting from the branch canal to the head of each meska. The traditional low level meskas are replaced by either raised lined open meskas or buried pipelines.

- Continuous flow in the meskas, for effective operation.

The MPWWR's strategy is to turn over the improved meskas to farmers after construction. Also, the IIP staff will train farmers to operate and maintain the improved micro-irrigation system. This requires a high organizational level to operate and manage irrigating from a single point. For this purpose, the MPWWR has introduced the Irrigation Advisory Service (IAS). The IAS is a

---

[3] The meskas in Egypt are earth low level open channels (ditches).

[4] * Two-turn rotation: 7 days on and 7 days off, or 4 days on and 4 days off for rice.
 * Three-turn rotation: 5 days on and 10 days off, or 4 days on and 8 days off.

new cadre in the MPWWR formed to assist farmers in the changeover to the new system. The IAS staff is trained to organize farmers in the Water Users' Associations (WUAs) and assist them in operating and maintaining the new meskas and on-farm water management practices. They will also provide the link between the farmers and the Irrigation Department staff. To ensure the sustainability of the new systems, IAS staff will be concentrating on a service-oriented delivery system, which responds to farmers' needs.

The Water Users Association (WUA) include all farmers in a meska command area. The members elect their own leaders and meska committee (chairman, treasurer, and pump operator). The WUA committee participates in the project design, development of the operating plan and rules, and resolves any problems on the meska. The improved meska is turned over to the WUA after implementation; the WUA is responsible for the meska operation and maintenance. The IAS group provides the WUA with the technical assistance needed in the operation and maintenance of the improved facilities.

The IIP main goals are to improve overall efficiency of water use and to remove water supply constraints to achieve high irrigation efficiency and optimum crop production.

IIP also has the following institutional objectives:

- Forming and strengthening Water User Associations (WUAs) to assist in designing, implementing, operating and maintaining the improved meskas.

- Establishing an Irrigation Advisory Service (IAS) to assist WUAs in group management, water management, conflict resolution, etc.

The project is divided into four stages: *Introductory stage*, where the project staff explains the goals and stages of the project to the beneficiaries and form WUAs. The *Design stage*, where the improved system is designed and the IAS staff gets the approval of the WUAs on the design. In this stage farmers suggest any desired changes. The *Implementation stage*, where some changes could be added to adapt the design to farmers needs. The *Operation stage*, where the improved meskas are turned over to the WUAs for operation and maintenance, after training them.

Some of the recognized benefits of the IIP were time and labor savings, increase in yield and income, increase in crop variety, and decrease of the chance of getting infected with water-born diseases.

2. METHODOLOGY

2.1 The study Hypothesis

H1 Although, governments and financing agencies are adopting the participatory approach[5] in the irrigation development projects, women are not specifically addressed in the Irrigation Improvement Project plans. They are not considered as direct beneficiaries and not involved in the project stages.

H2 Women's participation is related to their age, education, marital status and whether they are farmers or house women. Social and cultural norms also have a strong impact on women's participation.

H3 The Irrigation Improvement Project technology has significant impact on time, labor, yield, incomes, crop variety, and environment. The participation of women in the Irrigation Development Project will have a significant impact on the project benefits to women and their families. The increase of women's benefits would have a significant positive impact on family welfare, since women and men use the resources and capture the project's benefits differently. Women tend to devote more time and money to household and family needs, while men spend a higher potion of their income on goods for their personal consumption (M. Zwarteveen, 1996 and L. Brown, 1995).

H4 Having more female engineers within the development agencies' staff could help increase female participation. Women's education, family and farm size, social influence, and gender of the head of household are also important factors, which might affect female participation.

2.2 Selecting the Study Variables and Identifying Relationships

The variables used for testing the study hypothesis are divided into dependent and independent variables. The independent variables are: gender, age, marital status, occupation, and education. The dependent variables are: women's participation in the IIP stages, the project benefits for women and men, and the factors affecting women's participation and decision making.

To test the first hypothesis, a comparison between women's and men's participation in the project stages is used.

To test the second hypothesis, the relationship between women's participation in the project stages and their age, education, occupation, marital status, gender of decision making, and social influence is analyzed. Also, the relationship between the participation of women and the social and cultural norms is examined.

To test the third hypothesis, the project benefits are divided into economic,

---

[5] The participation of the beneficiaries in the project stages

environmental, and social benefits. Economic benefits would be increase of income, yield, crop variety and quality. The environmental benefits would be improved water conservation, decreased dead storage, which decreases water born diseases, decreased health hazards from the old open channels running through the villages, and the providing of better roads. The social benefits would be fewer conflicts between farmers over water and better education for children. The relationships between the gender and project benefits will be examined. We will also shed some light on the difference in interests and concerns between men and women when evaluating development projects. Also, the relationship between the gender of the beneficiary and money and time allocation will be analyzed.

The fourth hypothesis will be evaluated, along with other strategies to increase the involvement of women in rural development projects, studying previous projects and the IIP staff questionnaire, as well as the beneficiaries' questionnaire.

2.3 Data Collection and Analysis

The study area is chosen from one of the Irrigation Improvement Projects (IIP) areas: Saydia Command area. The study sample is chosen from the first portion implemented in the Saydia area.

Four sources were used for data collection. The first was reviewing similar studies related to the significance and impact of female participation in rural development projects, factors that affect their participation, and how to deal with them to increase women's participation. The second was interviewing farmers and staff using a structured questionnaire. The third set of data was from studying the available documents from the studied project, IIP. Finally, participatory observation was used, from my experience working with the Irrigation Improvement Projects.

The beneficiaries' survey data were collected through private interviews, due to the illiteracy of some of the surveyed individuals. The population for the beneficiaries' survey was randomly selected, depending on the availability of the interviewees. The interviewer reached farmers and house women either in the field or in their homes. These interviews, and the limited resources, limited the size of the sample replying to the beneficiaries' questionnaire. Forty farmers and house women responded to questionnaire; 25 women and 15 men. The interviews were conducted in Arabic by one of the Irrigation Improvement Projects engineer working in the study area.

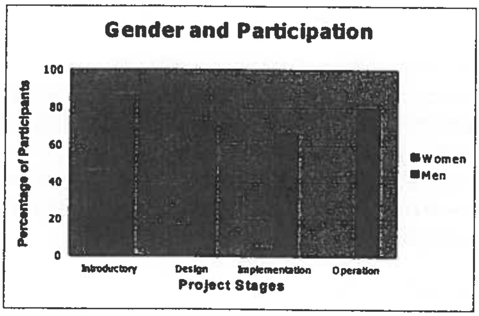
For the Irrigation Improvement Project staff survey, the questionnaires were mailed to 15 of the project engineers. The staff questionnaire was replied by 13 of the project engineers.

The limited sample size makes it difficult to generalize the results over the whole IIP area in Egypt. Also, the small sample size limited the power of statistical analysis.

3. RESULTS AND DISCUSSIONS

3.1. Extent of Women's participation

The extent of women's participation in the Irrigation Improvement Project varied according to the project's phase. Presvelou (1980), Zwarteveen (1995), Johnson (1996), Okeyo (1988), Chaney (1987), and Jiggins (1986) documented the tendency of the development agencies to ignore women in the planning and implementation of development projects. They also pointed out the lack of women's participation in these projects due to the lack of information on women activities, needs, and considering women as passive recipients of technology. The results of the IIP staff survey showed that 9 out of the 13 engineers, who replied to the questionnaire, confirmed that women were not considered as direct beneficiaries in the project formulation. The other four engineers said that women were indirectly included, through male members of the family and they should directly participate only if they are farmers.



During the introductory stage, the Irrigation Advisory Service (IAS) staff reaches farmers in their fields. Working with the IIP and participating in forming the WUAs, it is often observed that some women were accessible to the staff in the field, performing farming activities. During this stage, women often show their interest to learn about the new project and in many cases, they approached the IIP staff seeking information. The results of the beneficiaries' questionnaire showed that the project objectives and stages were explained to 46 percent of women, compared to 87 percent of men.

During the introductory stage, the IAS staff begins the process of forming WUAs, by conducting initial meetings with the water users, usually in farmers' houses. Since it is not culturally acceptable, women do not attend those meetings and are therefore excluded from the WUAs. In subsequent meetings, WUAs are formed and leaders are elected from the water users who attend the meetings. After the WUA establishment, the WUA leaders are responsible for checking designs, supervising implementation, and meska operation and maintenance. And since women do not participate in any of the initial WUAs activities, they are not members of the WUAs. They also do not participate in any of the design, implementation, and operation stages.

The results of the beneficiaries' survey showed that only 17 percent of women, compared to 73 percent of men, were able to participate in the design stage by sharing their ideas and suggestions with the IIP staff, either directly or through a male family member.

In the implementation stage, only 4 percent of women, versus 67 percent of men, participated in this stage.

Excluding women from the WUAs is the main reason for their low participation in the design and implementation.

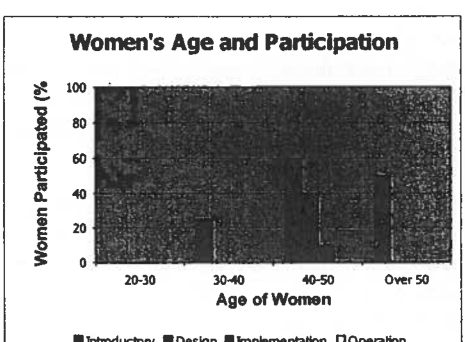
In the operation stage, the improved meskas are turned over to the WUAs for operation and management, after receiving the appropriate training. Since women were not members of the WUAs, they are excluded from participating in the operation and management of the improved system.

3.2. Factors Influencing Women's Participation

Age, Marital Status, and Occupation:

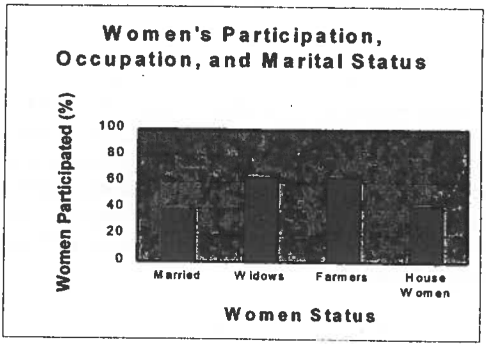
The United Nations statistics (1995) showed that 55 percent of Egypt's population were living in rural areas and females represented 49 percent of Egypt's population. Also, the statistics showed that there were 119 women per 100 men over the age of 60; 68 percent of these women were not married (single, divorced, or widows). These women were more likely to be the heads of their households since statistics showed that 91 percent of widows in Egypt were the heads of their households.

The results of the IIP survey confirmed the results of previous studies by Cloud (1984) and Warner (1997) that seniority and marital status are important factors for formulating policies to increase involvement of different sections of the rural society. The IIP beneficiaries' survey results show that older women participate more in the



project stages. Of the women's groups that were informed about the project objectives, the information was explained to 56 percent of the women over 40 years old and to 25 percent of women under 40. Furthermore, all women who participated in the design and implementation stages were over 40 years old. These results should be considered in the context that 75 percent of the women interviewed were over 40 years old.

The study results show that women's participation is also related to their occupation and marital status. About 63 percent of the widowed women, compared to 39 percent of the married women, participated in the IIP project. Also, 64 percent of women farmers participated in the project, compared to 42 percent of the household women.



Older women participated more since they have more time to devote for farm management, social activities and new projects. Younger women are more occupied with childcare and household activities. They usually do not have the time to directly participate in the farming activities. Also, it is more socially acceptable for older women to participate in what are traditionally considered as male activities -- farm management and participation in development projects.

Widowed women participate more than married women, perhaps because widowed women are usually older and therefore socially free to do so. Another reason is that widowed women are usually the heads of their households and in many cases manage their farms. This reasoning is supported by the fact that 81 percent of the widowed women interviewed were farmers, over 40, and the heads of their households.

Education:

The World Bank publications (1994 and 1995) stated that women's education has a strong positive impact on the management of their farms, the yield and their participation in development. In the IIP beneficiaries' survey, it was hard to detect relationship between women's participation and education, perhaps due to the limited participation and the high illiteracy rate of the interviewed women.

However, the results showed that none of the educated women interviewed participated in the IIP projects; all women who participated were not educated. Seventy five percent of the women interviewed had no formal school education, even though the interviewed population was randomly selected. This is supported by the United Nations statistics (1995) which show that, in 1990, 46 percent of women of age 14-25, and 78 percent of age 25 and older, are illiterate.

Social Barriers:

In Egypt, the society expects women to be especially careful about their virtue and reputation. These social norms limit women's ability to associate with non-related males. Consequently they can not participate in events and meetings which are mostly attended by men. In the projects where women are addressed as direct beneficiaries, such as population planning, women are addressed separately and certain strategies are developed to encourage women's participation.

Agriculture, in Egypt, is a male dominant field. In most cases, the rural community does not understand the necessity of women's participation in agricultural and irrigation projects, and consequently do not support it. The research results confirmed previous findings by Cloud (1984) and Brown (1995) that culture and social customs govern women's opportunities to participate in development. All women interviewed for the beneficiaries' survey identified culture and social customs as the main reason for their non-participation in the project. However, the results also showed that 38 percent of these women wanted to participate more.

Presence of Female Staff in Implementing Agency:

Confirming the previous studies by Brown et al. (1995) and Murphy (1995), 12 out of 13 IIP engineers agreed on the significance of the presence of females and individuals experienced in gender activities within the rural development project staff. They also pointed out that these females should work in close contact with all beneficiaries, males and females, to explain the significance of women's participation. They also agreed that the presence would have a positive impact on women's participation and the acceptance of this participation by the male water users.

3.3 Women's Benefits From The IIP Project

During an evaluation of the IIP progress by members of the USAID staff, a farmer's wife expressed that the people in the village could gain more benefits if the environmental aspects were taken into consideration during the formulation and design phases. She pointed out that consulting the beneficiaries, especially women, about the meskas design could lead to better environmental surroundings by covering the portion of the canal which runs through the villages, or in the areas of obvious danger to people's health and life.

The study results show that men recognized increases in income, crop yield, and the time and labor saving as important benefits of IIP. Women emphasized the positive environmental impacts, in addition to the once mentioned.

The reported environmental benefits of the project included the decrease of the chance of being infected with waterborne diseases and getting drowned in the old open channels going through the villages.

A direct relationship between women's participation and the benefits could not be determined because of the low participation of women. However, the results of the beneficiaries' survey showed that women farmers and widows recognized more benefits than married women and household women. Since women farmers and widows participated in the project stages more than other women, this could support the hypothesis that women's participation has a positive impact on their benefits from the project.

The results of the staff questionnaire showed that 12 out of 13 engineers agreed that women's participation would increase their benefits from the project.

3.4 Women's participation and family welfare

Murphy (1995) and Brown (1995) stressed that women's participation and access to resources are critical determinants of a sustainable agriculture, social and economic development, and diffusion of new technologies. Studies by Cloud (1984), Guyer (1980), and Tripp (1985) have confirmed that women's benefits have a more positive influence on the family welfare, since the women tended to allocate more of their time and resources towards the family, especially the children. Confirming these previous studies, the results of the beneficiaries' survey showed that 94 percent of the women invested the saved time and labor in household and child care activities and only 20 percent of them used it in farm management. On the other hand, 33 percent of men used their saved time and labor in child and household care; 87 percent used them in farm management, 12 percent used them in sports activities, and 17 percent use them in resting. These results confirm that women devote more time and labor to child and house care. They also confirm the growing belief that increasing women's benefits from the development projects and integrating gender issues within the mainstream of these projects would increase family welfare.

[illegible]	[illegible]	[illegible]
[illegible]	94	33
[illegible]	20	87
[illegible]	0	12
[illegible]	0	17

Ignoring women as direct beneficiaries and not taking their activities into consideration will have a negative impact on them, their families, and sustainability of the new system. Most women use water delivered through irrigation facilities differently than men. They use the canal water for washing clothes, watering and bathing cattle. Since most women were not consulted regarding the IIP design, their activities were not taken into account when designing the improved irrigation system. With the improved system (raised meskas, buried pipelines, and lined meskas), women would have to travel longer distances to fetch water, which will consume more of their time and labor. Often, their cattle cross the raised meskas resulting in damage to the structures. Designing small areas for women to water the cattle and building crosswalks would protect the improved system, and save women's time and labor, which will be more likely used for child and house care.

4. CONCLUSIONS AND RECOMMENDATIONS

The following strategies are recommended to enhance women's participation in the rural development projects, generally, and the Irrigation Improvement Project specifically.

1. The role of women and the significance of their participation in rural development should be very clear to the development projects planners and staff. The development project staff should also be trained to integrate gender into the project development stages.

2. For continued participation of women in the projects, it is very important for all the beneficiaries, both males and females, to understand the significance of women's participation in the development project and support it.

3. Women should be specifically addressed in the initial stage of the project. Conducting special " Women-Only Meetings", at the early stage of the project, to explain the project objectives, how they can participate in the project stages and how their participation would benefit them and their families. Women-only meetings should be held where the women would feel comfortable to devote their time and share their ideas with the IIP staff. Women-only meetings can overcome the cultural and social barriers, which discourage women from participating in the meetings attended mostly by males (Hulsebosch et al, 1995).

4. Women should also be encouraged to attend the Water User Associations meetings and participate in the meska council election and the other activities of the WUAs. The place where these meetings are held should be planned carefully. Meetings should be held in neutral places such as: schools and community centers. In the IIP project, identifying a required percentage of women to attend the WUAs meetings could help increase women involvement in the project.

5. Women staff in government agencies, who combine the skills provided by modern education with an understanding of the social aspect of women's

participation, would enhance the integration of gender into development projects. Having more females within the project staff, who are in closer contact with beneficiaries and understand the significance of women's participation, will encourage women to participate and share their ideas.

6. As recommended by Cloud (1984) and Warner (1997), seniority and marital status should be taken into account when targeting policies to increase women's participation in rural development. Socially influential women, older women, women farmers, and widows should be identified and contacted in the initial project stages. Since they have more influence and their participation is more socially acceptable, they could encourage other women to participate.

REFERENCES

Brown, Lynn R., et al, "Gendering Food Security: Women as Producers, Gatekeepers, and Shock Absorbers." International Food Policy Research Institute, March 1995.

Brown, Lynn R., and Haddad, L., "Time Allocation Patterns and Time Burdens: A Gender Analysis of Seven Countries." The Gender CG Newsletter, International Food Policy Research Institute, vol.1 no.2, March 1995.

Chaney, Elesa M., "Women's Components in Integrated Rural Development Projects." Rural Women and State Policy: Feminist Perspectives on Latin American Agricultural Development, 1987.

Cloud, Kathleen, "Women's Productivity in Agricultural Systems: Considerations for Project Design." Gender Role in Development Projects, 1984.

"Enhancing Women's Participation in Economic Development." A World Bank Policy Paper, 1994.

"Equality: The Role of Public Policy." A World Bank Publication, July 1995.

Guyer, Jane I., "Household Budgets and Women's Income." African Study Center, Boston University, 1980.

Hulsebosch, Joitske ,and Ombara, Doris, "Towards Gender Balance in Irrigation Management: Experience in Kenya South West Kano Project." Irrigation and Drainage Systems. Vol. 9: 1-14, 1995.

Jiggins, J., "Gender-Related Impacts and the Work of the International Agricultural Research Centers." CGIAR Study Paper no. 17, 1986.

Johnson, Ruth E. and Ayala Perdue, Mitzi, "American Women Involved in

Agriculture." 16th International Congress on Irrigation and Drainage, ICID.CIID, vol.1B, 1996.

Murphy, J.L., "Gender Issues in World Bank Lending." A World Bank Operation Evaluation Study, 1995.

Okeyo, Achola-Pala, "The Role of Women in Eastern Africa Rural Development." Regional Development Dialogue, vol. 9 no. 2, Summer 1988.

Presvelou, C., and Spijkers-Zwart, S., (Edits) "The Household Women and AgriculturalDevelopment." paper 17, Landbouwhogeschool Wageningen, The Netherlands, 1980.

"The World's Women 1995: Trends and Statistics." United Nations, 1995.

Tripp, Robert, "CIMMYT's Experience with the Users' Perspective in Technology Development." Women and Agriculture Technology: Relevance for Research, vol.2, Report from the CGIAR Inter-Center Seminar on Women and Agriculture Technology, July 1985.

Warner, M.W., R.M. Al-Hassan and J.G. Kydd, "Beyond Gender Roles? Conceptualizing the Social and Economic Lives of Rural Peoples in Sub-Sahara Africa." in development and Change, vol.28 no.1, January 1997, pp143-168.

Zwarteveen, M., "Gender Issues, Water Issues: A Gender Perspective to Irrigation Management.", 1996.

PIM: A REALITY IN ASIA?

Sheel Bhadra Sinha[1] Raman Kumar[2]

ABSTRACT

Agricultural sector has been the largest beneficiary of aid world over and the lions share has gone to irrigation but the benefits have not matched the investment. Water is wrongly treated as a free and inexhaustible commodity. The consumption of water has been doubling every 21 years and seventy percent of all water used is utilized for irrigation though half of it only, reaches the crops. Coupled with increased demand from industry and urbanization, there is severe pressure on water now. As signs of "water stress" is becoming more pronounced, and issues relating to water are assuming political overtones, water has to be treated as an economic commodity and ways and means have to be found for increasing the performance of the irrigation systems. Among the various reasons for the non-performance or under-utilization of the created irrigation potential, non-participation of the beneficiaries and poor upkeep of the system by the administrative and development machinery of the government at the various levels, deserve special mention and attention. "Participatory Irrigation Management" (PIM), where the beneficiaries share responsibility in partnership with the governmental agencies has now become indispensable for efficient running of a system. It may be pointed out that this approach is not a new one. From time immemorial, the natural resources, in all the civilizations, were treated with respect and there were rigid laws governing their use. It appears that over the passage of time the beneficiaries became indifferent to the use and management of natural resources, causing the government agencies to step in. PIM has taken off in the last two decades in South East Asia where Philippines has been the trailblazer and also in Latin America. The success in Mexico can be attributed to political will at the highest level. Different approach, have been adopted for PIM, but no single model can be adopted as a role model to succeed unless it takes into care the local conditions as well. PIM is not an exact science where, the formulae would be applicable in all conditions. Socio-economic and cultural backgrounds have to be taken into consideration. Applicable pre conditions in general are:

1. Improvement in irrigation delivery system,
2. Legal rights to farmers,
3. Economic viability of the system as well as the farmers organization,
4. Ensure viable returns of the agricultural produce, and
5. Inculcate sense of responsibility in farmers towards the system.

[1] Systems Manager, Water & Land Management Institute, WRD, Govt. of Bihar, Patna, 801 505, India

[2] Assistant Engineer, Central Design, WRD, Anisabad, Patna 800 002, India

BACKGROUND AND PROBLEMS FACING IRRIGATION SECTOR

Most of the water related problems stem from the fact that the value of water has never, even remotely, been close to its true worth. Even today, when "free economy" is being advocated in the developing countries, it is highly under priced commodity leading to the illusion that it is available in plenty and need not be conserved. With the ever growing population and increasing demand on water from different sectors, more and more countries are marching towards water stress zone.

In India as elsewhere, irrigation took its shape as a small community project developed by local groups. Natural flowing streams were diverted for irrigating the land. Management of small tanks and dug wells for irrigation has been in practice from centuries. The importance of the irrigation need not be emphasized. It may be pertinent, to point out that irrigation sector has been the largest beneficiary of aid in the post war era but its performance has not been commensurate with the investment. Due to various reasons, the performance of this sector, in the developing countries specially, began declining though it would be erroneous to assume that irrigation from canals has always been a losing proposition. Economic History of India, (CUP) states that in 1846-47, a surplus of 19% over total expenditure was generated in this sector. In earlier times i.e. ancient and medieval, there were rigid rules governing the usage of natural resources and they were strictly enforced. In the 6th century BC, Megasthenese observed that "the sluices by which water is let out from the main canals into other branches so that every one may have equal supply of it." In the 2nd century AD the Chola dynasty in southern India built anicut in the Cauvery River. In the 13th to 16th century AD the Vijaynagar empire built many irrigation schemes and all of these were locally managed. This does not mean that in those times the situation was absolutely perfect, even Buddha is reported to have mediated in a water dispute in the ancient Patliputra! Canal irrigation in India had always been a profitable enterprise in old times. The Western Jamuna Canal, in India, constructed during the Mogul period and later remodeled by Warren Hastings in 1817, yielded a net return of 13% on the capital invested. Lord Curzon, in his budget speech in 1905, observed "The Government of India, have spent 31 million sterling pound upon state irrigation works in all the above classes. With it they have dug nearly 50,000 miles (80,467 km) canal and distributaries, they have irrigated an area of 21½ million acres (8.6 million ha) out of a total irrigated area in the British India of about 47 million acres (18.8 million ha) and they derive from it a net revenue of £2,700,000 per annum, or a net revenue of on capital outlay of approximately 7 percent. If we capitalize the net revenue at 25 years purchase, we obtain a total of 67½ million sterling, or considerably more than double the capital outlay." Almost similar situation existed every where, and as the pressure was not much on water, because of less demand on it from other sectors there was not much concern for its better management. Navalawala, has estimated that in India, the total losses in the irrigation sector between 1985-86 to

1989-90 amounted to Rs. 88927.8 million. The losses were due to many reasons, chief amongst them being,

- budget constraints for operation and maintenance due to uneconomic pricing of the water,
- inadequate response from the staff responsible for O & M, and
- to some extent inappropriate design of the structure and highly centralized form of governance leaving no role for the beneficiaries and NGOs.

This malady became so deep rooted in India, that irrigation coverage started declining so much so, that the water rate collection was not enough even to meet the cost of establishment kept for its collection. The revenue collection was found to be satisfactory only in those states where the revenue collectors were given a fixed amount as percentage of the total amount collected, like Haryana and Uttar Pradesh. In other states like Bihar and West Bengal the situation was alarming, while the cost of collection in Bihar varied from 55 percent to 210 percent, in West Bengal it varied from 95 percent to more than 600 percent. Even in those states where the revenue collection was not a costly proposition the cumulative arrears of the revenue were mounting up. Almost similar situation prevailed in all the Asian countries where PIM in its different flavor has been adopted. One may ask whether the Governments of these countries embraced PIM because they found it hard to set things right because of socio-political reasons. Whatever may be the reason PIM came in as a handy tool and was thought to be panacea for these shortcomings. So far it has eluded the desired results. Some of the countries where PIM is being practiced are Mexico, Columbia, Turkey, Sri Lanka, Philippines, Indonesia, Japan, Italy and Taiwan besides India. The situation in Japan, Italy and Taiwan can not be taken as indicative of its success because these are developed nations.

Case Studies of a Few Countries

A brief discussion about the status of PIM in Columbia and Mexico has been furnished because in the former country the farmers voluntarily embraced PIM while in the latter, it was a part of the economic reforms and was backed by a strong political will for its implementation. A passing reference has been made about other countries, before in depth analysis of the case study at Paliganj is taken up.

Colombia: The situation leading to adoption of PIM in this country is unusual in the sense that the farmers themselves initiated it. Since 1976, 16 out of 24 large and medium schemes stand transferred to Federation of Water Users Association of Irrigation Districts (FEDERRIEGO). The area covered by these associations is about two-third of quarter million hectares of cultivable land. The remaining schemes are expected to be difficult to transfer. In 1991 a federation of the water users association was formed. This association looks after the interest of the water users and has a seat in the top land development council of policy making, of the country, but it has not been able to provide much assistance to its members association. Over the years the main areas requiring corrective actions according to Luis E .Quintero Pinto are:

- social issues,
- institutional presence,
- administration, and
- finance and budget.

The recovery of water charges has not been very consistent. An interesting factor that emerges is that the highest fee collections are from those irrigation districts (Coello/Salda) where the users have made substantial contribution for the system, and is the lowest, in those irrigation districts where only the government, has made investments. Out of the twenty-four, water districts only seven are self reliant and others receive subsidy from the government to the tune of 5 percent to 100 percent of their budget. This subsidy is also not sufficient in some of the cases for the operation and maintenance, as it is determined on the basis of past collection. The water rates, has two components. One is the basic or fixed fee, which represents cost per hectare of land for creating infrastructures like road, drainage etc. and the other is usage fees, based upon volumetric supply to the users. The volume of water supplied to the user is calculated on purely estimated basis; as most of the time the water is delivered without actual measurement. The employee delivering the water guesses the flow and records the time. On the basis of these two parameters the volume is determined. The associations are non-profit entities, and can not therefore distribute the profits amongst the members. Vermillion and G-Resterpo (1999), have reported that after the transfer, high priority was given to improve cost efficiency, but majority of farmers reported no change as far as "administration and communication" was concerned. Though there was significant reduction to the government in cost of irrigation, but this resulted in an upward trend of irrigation cost to the farmers. No significant change was reported in agricultural productivity and no clear pattern has emerged so far as total cost of irrigation is concerned.

<u>Mexico:</u> The transfer program in Mexico was initiated in 1988, which was a part of the sweeping economic reforms. The topography and climatic conditions of the land precludes rainfed agriculture hence there is a need for irrigated agriculture. The reform process, which was initiated in 1988, led to the creation of National Water Commission (CNA) in 1989 and a new water law in 1992. 87 percent of the area under major/medium irrigation districts were transferred to the water users association for management of irrigation by 1996. Before the process of handing over the irrigation system began there was a series of meetings with the farmers exhorting the benefits of participation in the management of water. During these meetings, with the ejitarios and small landowners, it was also promised that the Government, will assist with the rehabilitation of the system

and provide fund for purchase of machinery. This was partially fulfilled. As a measure of fostering goodwill between the ejitarios and the small landowners it was decided that the post of the President and Treasurer of the Water Users Groups will alternately, be held by their representatives. The problems being faced can be broadly classified as:

- social issues,
- conflicts due to poorly specified water rights,
- insufficient revenue to support O & M, and
- poor accounting and book keeping practices.

Enrique Placios has reported that, there have been dramatic savings, to the Government by way of lowering of its share of O & M component. Earlier it was in the region of 80 percent but now it stands reduced to 25 percent. 80 percent of the farmers felt that the irrigation services have improved after transfer of the system, but the systems are generally in poor condition, partly because the government did not fulfill its commitment about restoring the system before its transfer. Another serious malady was noticed, which is not part of the physical system. In reality it is a social problem i.e. indiscriminate hiring and firing of staffs when the directors change, nepotism in staff hiring and the use of "director's position as political spring board." Duplication of efforts and poor co-ordination between the CNA and the Water Users Associations has been cited as "second generation" problem. Water Users Associations are exempt from paying for the rights to use water. They are supposed to pay the cost incurred by CNA for bulk delivery of water to modules or districts. However in practice the Water Users Association's directors negotiate with the users, the amount they will pay and it varies. In some of the modules it is based upon the area irrigated, yet in another it is based on crop and the area planted, and in fewer cases it is on the basis of volumetric supply.

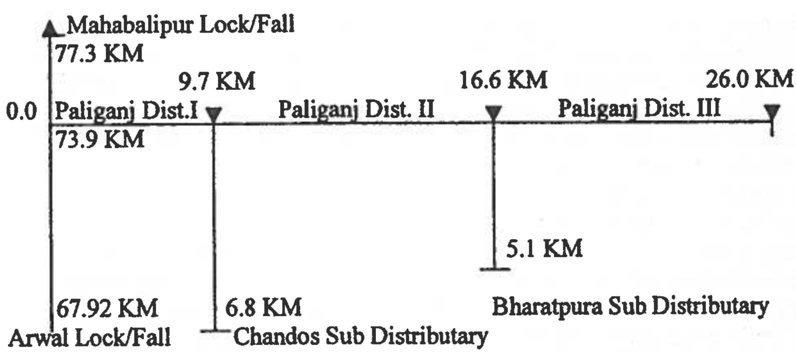
<u>Philippines:</u> To the die-hard supporters of PIM it may sound archaic, but Namika Raby opines that "the immediate objective of forming irrigator associations in the national irrigation system was the cost recovery, through collection of irrigation service fees." During 1983-87 the cost of O & M per hectare stood at US$ 16.40, out of which the major portion, US$ 13.10 was spent on salary and wages of staff. The per hectare cost, of O & M rose to US$ 30.00, with the ratio of salary and O & M charges almost remaining same. PIM in Philippines has worked best in smaller areas, best performance has been reported in systems having homogeneous social unit and having a command of 50 hectares and the optimum has been rated as 200 hectares. Strong leadership quality for mobilizing groups of people for construction, operation and maintenance, and conflict management has been attributed as reasons for the success of the communal system. The present impasse has been attributed as "this direct transfer of communal PIM model without taking into account the social, technical and managerial requirements of a

national system." The main bottleneck in success of PIM has been described as the inability to secure voluntary compliance from its members.

Sri Lanka: Sri Lanka has been experimenting with PIM since 1977. An important factor, which must not be overlooked, is that historically the farmers have been managing tank irrigation according to well-defined ethical values of the traditional Sinhalese Community. The model of PIM, adopted was that of Philippines. In 1984 the Government decided to charge 50 percent of the O & M cost from the beneficiaries and subsequently this was to increase, gradually over a period of 5 years to 100 percent, but there has been very low level of collection. This is attributed to "political lobbies discouraged farmers" from paying and when some farmers did not pay, others followed suit, because neither the farmers organization nor the Government could initiate corrective measures. In order to strengthen the farmer's organization, amendments were made in 1994. It has a important provision-in such inter-provincial systems, where the farmers organization have taken over the whole or part of a distributary canal, it exempts them from paying revenue to the Government, and instead empowered them to levy and collect amount from the farmers for O & M of the canal. The levy can be collected from both the tenant-cultivator as well as the owner-cultivators, unlike previously, when it was collected only from the owners. According to the National Development Council's report Sri Lanka intends to hand over all systems below 400 hectares to farmers and for the systems bigger than 400 hectares, the distributary level management will be handed over.

India, Paliganj (Bihar): a Case Study

Paliganj Distributary, (Culturable Command Area, 12197 Ha) is a subsystem of Main Eastern Low Level Canal of Sone Canal System in the State of Bihar, India. Schematic diagram of the system is given below.



Schematic Drawing of Paliganj Distributary System.

The river Sone, originates, from Amar Kantak plateau in Madhya Pradesh and then passes through Bihar. A sizeable population of the Bihar, 17.43% falls under its command covering about 13% of the total area of Bihar. The Sone Canal System is one of the oldest canal systems in the country; dating back to the times of East India Company. In 1853, an army engineer, Lt. Dickens, while visiting the Sahabad district conceived the idea of irrigating the land of the district by tapping several streams in the Kaimore range of hills. The actual construction was started in the year 1868-69 and was completed in 1875. In the original project report it was envisaged that the collection of revenue, will offer a net return of 8.75 percent on the outlay. From the very beginning the project was treated as a commercial enterprise. Initially the Government of India decided that the execution of the Sone Canal System should be left to private entrepreneurs and its execution was entrusted to East India Irrigation & Canal Company, which subsequently, was bought by the Government. The system over the years has undergone changes, and the process is still continuing, but as a whole it has been performing well as would be evident from the Table 1.

Table 1, Irrigation Achievement of Sone Canal System

Period	Average irrigation in Ha.	Coefficient of variance (%)
1875-1883	60358.85	50.44
1883-1891	129001.55	11.32
1891-1901	171420.76	14.91
1901-1911	221657.00	11.16
1911-1921	229611.08	9.85
1921-1931	226450.56	4.60
1931-1941	234638.72	4.84
1941-1950	252890.80	5.26
1950-1958	289661.30	11.73
1958-1968	353446.92	24.70
1968-1979	523419.08	6.84
1979-1989	541816.24	2.39

(Cropping Pattern and Operation Schedule in Sone Irrigation System, Basawan Sinha, 1992, WALMI, Bihar)

The different groupings of the year has been done taking into account certain factors, viz. in the year 1950-1958 augmenting the canal flow by tubewells was started, in 1968-1969 the Sone barrage was commissioned and the canals were remodeled, while the Action Research Program in Paliganj, was started in 1988. It would be evident that there has been gradual but steady increase in the irrigated area, but the collection of the revenue in the State, has been far from satisfactory, as would be evident from the Table 2.

Table 2, Cost of Expenditure Incurred in Revenue Collection. (in million Rs.)

Year	Expenditure on the revenue collection establishment	Demand raised	Actual collection
1987-88	954.53	122.80	73.50
1988-89	969.51	147.30	59.00
1989-90	1417.98	143.50	67.82
1990-91	Not available	155.50	48.42
1991-92	do	120.50	173.42
1992-93	do	200.00	204.16
1993-94	do	150.00	152.20
1994-95	do	170.00	170.64
1995-96	1814.78	190.00	281.42
1996-97	2071.83	400.00	285.50
1997-98	2308.42	400.00	181.12
1998-99	2300	450.00	221.96

(Water Resources Department, Govt. of Bihar, Programme and Achievements Reports for the years, 1998-99 and 1999-2000.)

The reason for low collection could be to due to the fact that earlier, a distinct system of revenue collection existed, known as *satta* system. It was a form of lease agreement between the farmer and the Department of the Government. In this system the farmer had to procure the right to use canal water. They had to apply for getting water every year and permission was accorded by the canal officer on the basis of the condition of the canal, village channel and clearance of the dues of the previous years. There was provision of long term lease also, say from 2 years to 15 years. When due to certain reasons there was shortage of water the long term lease holders got preference over the annual-lease holders. For implementing the *satta* system, there was a hierarchy of officers. The entire system hinged on *Lambardars* also called *sattadars* who were farmers having say in the village matters. *Patrol,* the lowest government functionary of the Department, used to inspect the land in his daily inspection and note the progress of water in the field. He never interfered in the operation and management of *Lambardars,* who had the sole responsibility of operation and management at the microlevel, even though he i.e.; *patrol* was instrumental in assessing the area irrigated. Over the passage of time due to certain changes in the concept of the irrigation, the *satta* system was abolished. But the abolition of the *satta* system could neither bring about any improvement in irrigation nor in the rent collection. Difficulties in irrigation increased further. Revenue collection arrears started mounting up and the cost of collection continued to be more than the amount collected. This situation seriously compelled the government to start looking for alternatives of water management and, PIM, appeared prima facie to be the solution.

Description of the Paliganj System: An action research program, in Paliganj distributary was taken up in the year 1988, under US AID, by Water & Land Management Institute, Bihar. It was finally handed over to the farmer's organization in the year 1997. Paliganj distributary is part of Patna canal, which in turn is a part of the Main Eastern canal of the Sone Canal System. Paliganj distributary offtakes from 46.2 miles (67.92 Km) of Patna canal between Arwal and Mahabalipur locks. Patna canal in this reach has a full supply depth of 6.5 feet (2 m), width of 60 feet (18.6 m) and bed slope of 1:7000 and a capacity of 905 cusecs (26 cumecs). The total length of the Paligunj distributary is approximately 26 km and has two sub-distributaries, Chandos offtaking at 9.7 km and Bharatpura at 16.6 km. The designed discharge of the Paliganj distributary is 180 cusecs (5.14 cumecs). The details of the area under the action research program was as follows:

Table 3, Area Under Paliganj Water Users Association.

S N	Name of channel	Length of channel in miles (km)	Capacity in cusecs (cumecs)	Culturable command area in acres (ha)
1	Paliganj reach I	6.06 (9.70)	178.5 (5.10)	5770 (2308)
2	Chandos sub-dist.	4.25 (6.80)	24.5 (0.70)	6075 (2430)
3	Paliganj reach II	4.31 (6.90)	109.2 (3.12)	4910 (1964)
4	Bharatpura sub-dist.	3.18 (5.10)	24.5 (0.70)	4360 (1744)
5	Paliganj reach III	5.87 (9.40)	54.6 (1.56)	9377.5 (3751)
	Total			30492.5 (12197)

(Bench Mark Survey Report, Technical Publication No. 51, WALMI, Bihar)

In the bench mark survey carried out by the action research team they had identified the following reasons for poor performance of the system:

- complete absence of micro level planning,
- lack of proper and adequate control structures in the canal,
- inadequacy of water courses, and
- unauthorized withdrawal of water by bank cutting.

In the above report the Action Research Programme team had spelled out several measures to be adopted for the situation to improve, but the following are more important ones:

- modern scientific water management techniques,
- suitable and equitable distribution of water, and
- evolving effective water scheduling for the entire distributary command.

Basawan Sinha in his seminal study "Cropping pattern and Operation Schedule in Sone Irrigation System" 1992, has carried out a very thorough sampling of farmers regarding adequacy, timeliness. Their perception regarding the whole system amongst other parameters and the sample survey for the Patna canal system, of which Paliganj distributary is a part of the tail end system, is revealing. In the tail end system, only the large farmers appear to be comfortable as far as the canal efficiency is concerned. As far as timeliness of water supply is concerned the same story is repeated. About framer's perception for non-availability of timely and adequate irrigation by canal every one decried the poor conditions of the canal and negligence of the canal operators. It should therefore have been desirable to rehabilitate the canal system to its original condition before handing it over to the beneficiaries. The new managers of the system could hardly be expected to improve the long neglected canal system overnight. Little that could have been done was to ensure that the structures were at least rehabilitated before the system was handed over.

Since the start of the Action Research Program till September 1992, the government had spent approximately Rs. 57,00,000.00, an amount that does not include the salary and other expenditure of a large number of staff engaged in this program. Audited figures for the subsequent years are not available. The performance of the water user's group too has not been encouraging, keeping in view that this program has been going on since last 11 years. The farmer's organization of the Paliganj, after it was transferred to them, could collect only 30 percent of the total revenue over last three years. The revenue due is piling up, as was the case before the turnover. The most sad part is that it has not been replicated anywhere in the State so far. There is a program of replicating it in 40 other systems but the majority of the farmers of these 40 systems complain about the poor condition of the structure and behavioral attitude of the staffs. They cited lack of co-operation amongst themselves, bad condition of the canal and its structure, lack of resources after the turnover to carry out O & M and non willingness to pay the water rent (a legacy of the past), as main impediments in managing their affairs. Except the constraints of the fund to carry out O & M activities after turnover all are social problems.

CONCLUSION

There is no single model of PIM, which can be replicated everywhere because to make PIM a success it has to be viewed with a socio-cultural angle. It would be evident from the case studies of Columbia and Mexico that "social issues" have been cited as requiring corrective measures. The per hectare cost on staff is a major issue of concern for the government in Philippines and PIM has been successful in smaller areas of 50 to 200 hectares and strong leadership quality has been attributed for its success. Sri Lanka had a long tradition of community management of irrigation system. So is the case with Turkey. But in Asia, where the rural masses are a heterogeneous conglomeration can it succeed? Probably, only if there are rules clearly defined and they are rigidly enforced. This takes us to the next logical question. Can the rule be enforced? If so, then what was the need to introduce PIM? The canal system as a whole was delivering the required results say three to four decades earlier. Only when the system started developing cracks and no remedial measures were taken, the present situation developed.

Water has also to be treated as economic good, and sooner it is done the better. As every country has its own unique water- pricing problem due to socio-political reasons, it appears that it is an elusive goal. Those who put forward arguments that increased prices will make water un-economical are not entirely correct. For example Mexico raised the water prices by almost 400 percent at the time of turn over, and even in Sone Canal System in India there was increase in water rates but the demand for the irrigation did not fall. In the age of international funding it should also be obligatory on the part of the donor agencies to insist upon economic pricing of the water. Subsidies must be done away with, because it leads to wastage of water and there should be realistic pricing of agricultural produce. The Governments in the less developed countries also do not want to make the water users agencies more independent because it gives the government an opportunity to exercise discretion. Duane is of the view "to keep such agencies firmly in the political domain where there is maximum opportunity to exercise discretion and minimum constraints from the rules of the commercial undertakings."

Management of human resources i.e.; capacity building is a very important factor and it should be coupled with performance requirements that means accountability, both by the government and by the farmers, as Chamber has observed that there is incentive for bad management. There have been many instances where the conflict of interest, of different Water Users Groups has hindered its functioning in the social and political environment, which favors "grabbing any thing one can get away with".

The most important part is that case studies by people, who advocate, or oppose the water users group are highly biased. Some of the notable successes like Sri Lanka's Gal oya system is highly projected and though it has been implemented in many countries since then, its replication has, not been so successful elsewhere. One can not wish away the water users group, they are necessary, at least theoretically, but to make them successful the Water Users Groups should be given executive power and authority (if the Governments are willing to lose their control). In USA and France, where the farmers own the irrigation systems, they can influence the transfers, promotions of the staffs. Mass and Anderson, have rightly observed about solution to frictions amongst the cultivators of a distribution system regarding equity of supply "no irrigation community has been able to settle except by long and costly experience."

As mentioned earlier, the donor agencies have a crucial role to play. Levine has observed that World Bank's National Water Management Projects and US AIDS's training program in India left the questions of organizational and infrastructure changes to other programs. The donor agencies must insist on performance indicators and aid should not be a part of bigger political game. For PIM, to succeed the first and foremost pre-requisite is political will at the highest level as is the case in Mexico. It is too premature to comment on Andhra Pradesh, India, where it has the support of the highest political executive of the State.

Participation can be termed as conscious involvement. In the Asian context, it seems to be elusive. The rural masses lack community character and it is heterogeneous mass of conflicting interests. Social factors like religion, caste, gender bias further add to this woe. Lack of legal rights to the farmers and poverty, is another impediment in participation. This leads us to the challenges facing the millenium. What is to be done? One option could be "ostrich" like situation. Just imagine that it does not exist. The other option could be to let the matter drift, with donor agencies pumping funds for "action research" studies, training, seminars etc. After a decade or so there would be discussions on "third generation" problems based upon highly biased case studies, put forward by protagonists and antagonists of the PIM. In the prevailing Asian context, we feel that one of the options to improve the situation is will at the highest level. For example the Act Number 11 of 1997, Chapter II, clause 14.5, governing the PIM in Andhra Pradesh, India, lays down that "A person having more than two children shall be disqualified for election or for continuing as a Chairman or a President or a Member of the Managing Committee." Such rules may not have to do any thing with PIM, but it sends down a strong signal to all concerned that business is intended.

Emerging social changes have raised many new issues in water management. The state has always played a leading role in water resources management, but the inefficient use, poor recovery of revenue and widespread malaise of corruption has forced the governments to look for alternative methods of management. It is an accepted fact that user based allocation is more effective than that practiced by the state, but participatory action is also not equally effective everywhere and it will succeed only where there is strong demand of water coupled with a history of cooperation amongst the users.

REFERENCES

1. A Management Perspective on the Performance of the Irrigation Subsector, Charles Nijman, IIMI.
2. Bench Mark Survey Report of Paliganj, Technical Report 51, WALMI, Bihar.
3. Benefits and Second Generation Problems of Irrigation Management Transfer in Colombia, Louis E Q-Pinto, EDI Participatory Irrigation Management Case Studies Series.

4. Benefits and Second Generation Problems of Irrigation Management Transfer in Mexico, Enrique Palacios V, EDI Participatory Irrigation Management Case Studies Series.
5. Cambridge Economic History of India, CUP, Cambridge, UK.
6. Chandragupta Maurya and his times, Sir William Meyer Lecture, 1940-41, Madras University.
7. Conflict, Growth and Justice in Arid environments, Mass & Anderson, R E Krieger Publishing Co. Florida, 1986.
8. Cost recovery in Irrigation Projects: Perceptions from World Bank operations evaluation, expert consultation on irrigation water charges, P. Duane, paper no. 5, FAO, 1986.
9. Cropping Pattern and Operation Schedule in Sone Irrigation System, Basawan Sinha, 1992, WALMI, Bihar, India.
10. Economic Aspects of Irrigation and Pricing of Water, B N Navalawala, Water Management Forum, 1992, Seminar on Irrigation Water Management.
11. From Participatory Irrigation Management to Irrigation Private management Transfer: The Process and progress in Sri Lanka (draft), Namika Raby, EDI, The World Bank.
12. Impacts of Colombia's Current Irrigation Management Transfer Program, Research report no. 25, Vermillion and G-Resterpo, 1999.
13. Managing Canal Irrigation: Practical analysis from South Asia; R Chambers, Institute of Development Studies, UK, Oxford and IBH Publishing Co., India.
14. Participatory Irrigation Management in the Philippines: National Irrigation Systems, Namika Raby, EDI, Participatory Irrigation Management Case Studies Series.
15. The Marchioness of Bute (ed.), The Private Journal of the Marquees of Hastings, K.G; Governor-General and Commander-in-Chief in India.
16. The World Bank and India's Irrigation reforms, R Wade, the Journal of Development Studies, vol. 18, 1982.
17. Transferring Irrigation Systems from the State to Users: Question of Management, Authority and Ownership, David Groenfeldt, EDI, The World Bank.
18. Water Resources Department, Govt. of Bihar, Programme and Achievements Reports for the years, 1998-99 and 1999-2000.

[Note: The views expressed herein are of the authors and not of the organization to which they belong.]

PRIVATE GROUP IRRIGATION PROJECTS IN MANITOBA CENTRAL MANITOBA RESOURCE MANAGEMENT LTD.~ A CASE STUDY

B. Shewfelt, M.Sc., P.Eng.[1]

D. Smallwood[2]

ABSTRACT

Irrigation projects in Manitoba have historically been developed by individuals, exploiting water sources close to their land base. In the 1990s private *group* irrigation companies have emerged. This paper explores the management issues of one such company, *Central Manitoba Resource Management Ltd.*

Central Manitoba Irrigation Association Inc., acting for its 45 producer members, prepared an irrigation development strategy for South Central Manitoba. An operating company, Central Manitoba Resource Management Ltd. (CMRM Ltd.), was established in 1999 to own and operate the off-farm infrastructure resulting from the strategy. CMRM Ltd. developed seven projects in 1999, involving 15 shareholders and supplying 6,000 acres (2 400 ha) of irrigation.

CMRM Ltd.'s management structure retains local autonomy. The capital, operating, maintenance and administrative costs are prorated to each shareholder at the project level. The single operating company allows for streamlining of administrative requirements while shareholder agreements ensure protection of the individual producer's equity. To protect the share value, the operating company applies for and retains the Water Rights and Environment Act licences. Furthermore, group liability insurance is provided to the company's shareholders.

The operating company provides Government resource managers with a single contact for licencing, environmental monitoring and channel maintenance issues. Environmental licences issued to the operating company increase accountability in resource utilization, monitoring and protection. The irrigated agricultural sector benefits from the enhanced sustainability and increased potential to attract and support further value-added industry.

For the producer, the operating company is not a complicated concept, but does require cooperation. Producers benefit from peer interaction and coordinated environmental initiatives. The operating company structure allows for participation of both irrigating and non-irrigating landowners in joint projects. On the negative side, the cost of licencing, monitoring and maintenance of channels is being downloaded towards the producer. This along with increasingly stringent regulations, makes development times unacceptably long and alternative investments more attractive.

---

1 District Manager, Prairie Farm Rehabilitation Administration, PFRA, 200-101 Route 100, Morden, MB, Canada, R6M 1Y5.

2 Manager, Association of Irrigators in Manitoba Inc., Morden, MB, Canada.

INTRODUCTION

This paper describes *Central Manitoba Resource Management Ltd. (CMRM Ltd.); a private group irrigation company* in South Central Manitoba. The paper documents issues of management structure, benefits and costs and operational issues.

Central Manitoba Resource Management Ltd. is the second private group irrigation company developed in Manitoba within the last decade. The other, *Agassiz Resource Management Ltd. (ARM Ltd.)*, formed in 1995, resulted from a need to share and manage the limited water resources on intermittent streams (PFRA, 1997). ARM Ltd. now owns and operates, or is in the process of transferring in, 14 reservoirs (Fig. 1) and associated pipelines. ARM Ltd.'s projects serve approximately 5,000 acres (2 000 ha) of irrigation, or close to 15,000 acres (6 000 ha) of land base (in rotation) for 21 shareholders.

Central Manitoba Resource Management Ltd. was incorporated in 1999. CMRM Ltd. is in the process of finalizing agreements with 16 shareholders for ownership, operation and management of seven irrigation projects (Fig. 1). These projects service up to 6,000 acres (2 400 ha) of irrigation in rotation (1:3 years typically), or a total land base of close to 18,000 acres (7 300 ha). The projects include 6 reservoirs, 60 miles (100 km) of pressurized pipes, and pumps capable of delivering 20,000 USgpm (1 250 l/s) to on-farm distribution systems (e.g., pipes, pivots, traveling guns).

For the year 2000, a third operating company is poised to take hold. *Souris Valley Resource Management Ltd. (SVRM Ltd.)*, will operate in Southwest Manitoba. SVRM Ltd. is currently designing and licencing four projects (Fig. 1), involving about 7 shareholders, and totaling over 2,000 acres (800 ha) of irrigation.

HISTORICAL IRRIGATION IN MANITOBA ~ 1970s TO EARLY 1990s

The agricultural industry in Manitoba has adopted irrigation in a market-driven fashion, requiring a return on investment equal to or greater than alternative investments (AIM, 1999). As a result irrigation development in Manitoba has largely been associated with higher value crops. For example, in 1997, approximately 75 % of irrigation development involved horticultural crops (Gaia, 1997). Potatoes represent 91% of the horticultural cropping mix with vegetables (e.g., carrots, onions) representing 7%, and nursery and fruit the other 2% by acreage (Gaia, 1997). Figure 1 shows the spatial distribution of existing irrigation in Southern Manitoba.

The frost free period in the southern agricultural zone of Manitoba, ranges from 100 to 125 days (MB Potato Council, 1994). Growing season precipitation in southern Manitoba averages from 9 to 11 inches (180 to 280 mm) (MB Agriculture, 1998). For southern Manitoba the average water deficit for potatoes is between 2 to 5 inches (50 to 115 mm) and the deficit at 10% risk[3] is between 4 to 9 inches (100 to 180 mm) (MB Agriculture, 1998). Irrigation makes up this small deficit in moisture, increasing on-farm yields and ensuring a consistent quality product demanded by processors.

---

[3] 10% risk refers to the water deficit for potatoes equaled or exceeded 1 in 10 years

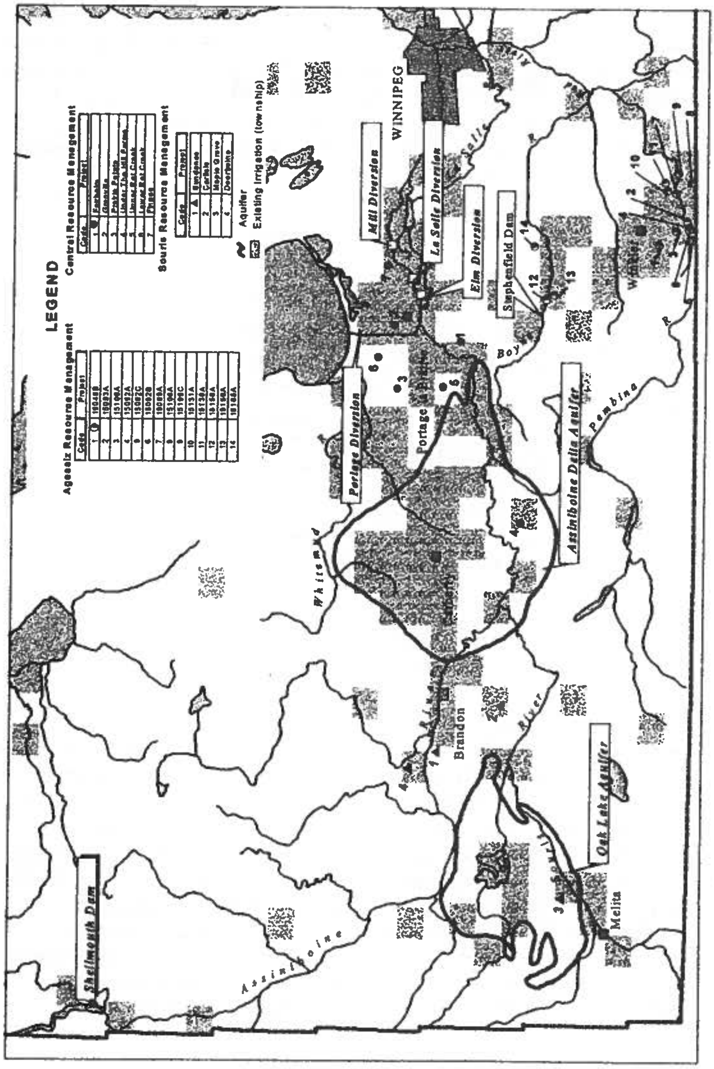


Fig. 1 - Irrigation in Southern Manitoba and Location of CMRM Ltd. Projects

Virtually all irrigation infrastructure in Manitoba is privately owned. Large Government funded group irrigation projects have been proposed for Manitoba in the past. Most recently, the Assiniboine-South Hespler Area Study, completed by the Federal and Provincial Governments in 1987, proposed to deliver water to 300,000 + acres (120 000 ha) at a capital cost of close to $500 M (1999 $Cdn.).[4] The project failed to garner public financial support and did not proceed. In contrast in the decade since 1987, private individual and group irrigation development have accounted for an increase of approximately 33,000[5] acres (13 400 ha) (AIM, 1999). The current rate of development is approximately 5,000 acres (2 000 ha) per year (Fig. 2).

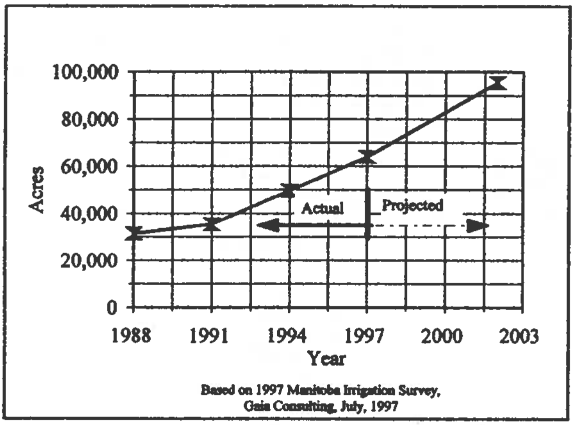


Fig. 2 - Irrigated Acres in Manitoba - Actual/Projected

Prior to the late 1980s, a perception of unlimited water resources prevailed in the irrigation industry in Manitoba. The major *water* infrastructure projects had been largely built and operated by the Government, and were a significant "hidden" reason for the success of individual irrigation developments in Manitoba. The Shellmouth Dam, the Elm, Mill and La Salle River Diversions, the Portage Diversion and Stephenfield Reservoir (Boyne River), were all put in place with Government financing decades ago (Fig. 1). The Shellmouth Dam and Portage Diversion were developed as flood control projects, but generate firm flows and water distribution required for irrigation developments. The Elm, Mill and La Salle River Diversions and the Stephenfield Reservoir augment intermittent streams for municipal water supply, providing irrigation water as a side benefit at no cost to the producer. Similarly, the costs of resource monitoring programs on the Assiniboine Delta and Oak Lake Aquifers and the Assiniboine River (Fig. 1) are a Government responsibility, but benefit irrigators.

---

[4] Capital cost escalated at a factor of 1.34 from 1987$ to 1999$; also approximately $350 M (1999 $US).

[5] The land base would be a minimum of double to triple this due to the nature of irrigating the horticultural crops in rotation.

As a result of the existing water infrastructure, local irrigation water supplies were readily available and cheap at the farm gate. Firm base flows on the Assiniboine River and on the augmented intermittent streams and channels allowed for irrigation development on land directly bordering the waterways. On the Assiniboine Delta Aquifer and other smaller aquifers, water was developed from under the owner's land base.

Accordingly, prior to 1992 the concept of *group* irrigation projects was given little consideration in Manitoba. Projects tended to service only a single sprinkler system. Small developments were consistent with the desire of traditional Prairie farm operations to keep the production infrastructure under family ownership. This kept the complicating factors of dealing with others to a minimum and allowed focus to remain on primary production, or the "bottom" line.

The criteria for environmental impact assessment also made smaller projects more desirable. Individual developments diverting less than 160 ac-ft (e.g., adequate for 1-2 pivots) do not require an environmental licence and neither do water impoundments of less than 40 ac-ft. These Provincial Environment Act triggers were rarely exceeded, especially for storage. This allowed development to proceed with little consideration of more complex factors such as soil, water and habitat protection, and cumulative impact assessment. Producers with small projects avoided the complications of the Environment Act process and the $2,500 application fee.

GROUP IRRIGATION DEVELOPMENTS IN THE 1990s

The concept of private group irrigation projects in Manitoba was spearheaded by the Agassiz Irrigation Association Inc. (AIA Inc.). In 1992, producers in the Winkler area (Fig. 1) proposed to develop group irrigation projects, and formed Agassiz Irrigation Association Inc. to promote their ideas (AIA, 1992). In contrast to the individual developments, the Agassiz Irrigation Association (AIA Inc.) faced issues that made group projects desirable. The intermittent streams in the Agassiz area presented a finite water source with an associated risk of drought. AIA Inc. was seen as vehicle for producers to share the risk and for joint resource management with the Government (PFRA, 1997).

AIA Inc. also recognized the importance of addressing environmental impact issues. Environmental licencing was required for storage in excess of 40 ac-ft (50 dam^3), whereas Agassiz was planning to develop more than 2,000 ac-ft (2 400 dam^3) of water storage. The Association provided an economy of scale in planning and licencing of projects, addressed cumulative impacts and coordinated resource monitoring and mitigation efforts (PFRA, 1997).

Part of the AIA Inc. strategic plan was to form an operating company which would manage the group assets of the irrigators. This operating company was incorporated in 1995 as Agassiz Resource Management Ltd. (ARM Ltd.). AIA Inc. and ARM Ltd. formalized their water management and business plan in 1998 (AIA, 1998). Securing Government technical and financial support was easier with a management plan that dealt collectively with development and environmental issues.

In 1997, the Surplus Water Irrigation Initiative was developed jointly with industry and the Provincial and Federal Governments, to help release constraints to privately owned *group* irrigation development in Manitoba. The rate of irrigation development and the lack of organizational structure was a concern to prospective industries looking at locating in Manitoba. An incentive to form group investments, similar to the Agassiz model, seemed desirable from the point of view of industry expansion. It also became clear there would be a need for emphasis on environmental sustainability that could be addressed more effectively within the framework of group development. The Surplus Water Irrigation Initiative promoted the development of organizations similar to AIA Inc. and ARM Ltd.

As part of the Surplus Water Irrigation Initiative, Central Manitoba Irrigation Association Inc. (CMIA Inc.) prepared an irrigation development strategy for South Central Manitoba and solicited projects from its 45 producer members (CMIA, 1997). The plan promoted group projects along the Portage Diversion and Assiniboine River, as well as supplementing the Rat Creek with water from the Assiniboine River. Storage reservoirs were promoted on other tributaries to the Whitemud and Assiniboine River. The plan also highlighted public issues in the areas of inter-basin transfer of water, cumulative environmental impacts, best management approaches to protection of ground and surface water and soil resources, and maintenance of channels used to convey water.

The CMIA Inc. vision took hold in 1999. CMIA Inc. established an operating company, Central Manitoba Resource Management Ltd. (CMRM Ltd.) to own and operate the off-farm infrastructure resulting from the strategy. CMRM Ltd. provided management and operational structure for group developments, and negotiated with other agencies to use natural and man-made channels to convey irrigation waters. Seven projects were developed in 1999 (Fig. 1), all requiring Environment Act licences, which CMRM Ltd. obtained on behalf of the shareholders. The formation of CMRM Ltd. signaled a significant shift away from smaller individual developments towards larger privately owned group irrigation developments.

OPERATING COMPANIES~MANAGEMENT STRUCTURE

ARM Ltd. and CMRM Ltd. retain a similar management structure. The companies are run by a board of directors, elected from the shareholders in the company. Shares are issued for projects on the basis of acre-feet developed, and percentage of the individual assets owned. The assets are limited to the off-farm infrastructure required to deliver the water to the farm gate. In Manitoba, irrigation projects are designed to service multiple locations since the on-farm irrigation systems are often rotated with the horticultural crops[6], which are typically grown in a 1:3 year rotation.

---

[6] The CMRM Ltd. projects largely involve irrigated potato production in rotation with dryland production of oilseeds (canola, sunflowers, flax), grain (wheat, corn) and pulse (beans). There is a small acreage of irrigated special crops including carrots, horseradish, garlic and hybrid seed production.

A shareholders agreement is issued defining:

- shareholder's company name;
- asset location and nature (i.e., pipelines, pumps, reservoirs);
- % ownership of the asset in question;
- acre-feet developed and therefore shares (e.g., 1 share per ac-ft);
- responsibilities of the shareholder and CMRM Ltd., namely:
  - liability insurance to be obtained by CMRM Ltd.;
  - shareholders loan (if any);
  - default conditions;
  - maintenance agreement; and
  - user privileges and responsibilities.

The shareholder companies often have multiple business partners. In addition, shareholders can be irrigators or dryland producers. This is important since the land base for the irrigation systems often includes rented or leased land. Some potato producers rent their own land for dryland production in turn for access to an expanded land base. This allows them to concentrate capital and management on the higher value potato crop. The dryland farmer can capture an increased land value (i.e., rent) in return for becoming a shareholder in the operating company.

Land control and regulatory licences secure the asset for CMRM Ltd. Reservoir ownership is transferred to the operating company (e.g., CMRM Ltd.), which involves legal subdivisions. For pipelines and wells, the operating company (e.g., CMRM Ltd.) takes an easement or lease on the property the asset is located on. In the case of public property (e.g., road allowances) a municipal approval for the utility location and maintenance is required. Any other utility crossings, such as highways or railways, are covered in separate agreements with the regulating agencies. Water Rights and Environmental Act licences are held by the operating company (CMRM Ltd.), in order to secure the share value. CMRM Ltd. may also obtain financing for individual projects, on the basis of the shareholders agreements, the asset value and licences held.

Day to day project management and maintenance is done by the shareholders in the specific project. Maintenance can be payed directly by the managing shareholder, or hired out to a contractor. Where the project assets are jointly owned and operated, specific agreements on sharing of maintenance, operating and capital costs are required. Typically these are based on delivery capacity (e.g., gpm for pipelines and pumps) or volumetric requirements (e.g., ac-ft for storage), or at agreed to hourly rates.

Administration of the operating company is the responsibility of the Manager of CMRM Ltd. The CMRM Ltd. administrative functions include: posting of asset valuations, accounting of expenditures and depreciation, annual financial reports, arranging easements and land transfers, submitting documentation for water rights licences, liaising with Government and the public on issues of the environment, arranging for monitoring equipment and sampling, reporting on water use and environmental monitoring, and applications for Government assistance.

THE ROLE OF THE IRRIGATION ASSOCIATIONS

Agassiz and Central Manitoba Irrigation Associations continue to hold a broader membership base than their sister operating companies (i.e. CMRM Ltd., ARM Ltd.). This provides for discussion of issues relevant to all producers, including individuals not part of the operating company. The managers of the Associations (AIA Inc., CMIA Inc.) also manage the operating companies (ARM Ltd., CMRM Ltd.). Producer memberships are collected to cover operating costs of the Associations.

Broad based planning and pre-feasibility studies can be carried out by the Associations on behalf of all members; often resulting in specific projects which are thereafter turned over to the operating company for development. CMIA Inc. is currently involved with planning, research, monitoring and consultation in the following areas either directly or through the provincial irrigators association (Association of Irrigators in Manitoba Inc.):

- groundwater table reservoir sustainability (North Portage);
- EM38 mapping of selected irrigated soils (i.e. salinity);
- Portage Diversion operation study;
- healthy river discussions (e.g., instream flow needs);
- infrastructure planning studies; and
- development of Best Management Plans for irrigators.

RETURN FROM IRRIGATED PRODUCTION

The benefits of irrigated crop production accrue at several levels, including the producer, the industry and the Government. This section attempts to list these benefits, albeit in a qualitative manner. The Surplus Water Irrigation Initiative recently approved a study by the Association of Irrigators in Manitoba Inc. into the "Economic Impact of Irrigation in Manitoba". This study, to be completed in the year 2000, will attempt to quantify the benefits of irrigation in Manitoba and to whom they accrue.

In the years since the drought of the late 1980s, the potato processing industry in Manitoba has made irrigation a requirement for existing and new producers. Of the 6,000 acres (2 400 ha) to be developed by CMRM Ltd., about 50% was in potatoes prior to irrigation and 50% is 'new' potato growers who obtained contracts on the basis of developing irrigation projects to secure production. Thus, net benefits to the irrigation crop accrue from either the conversion of dryland potato production to irrigated potato production or from conversion from dryland grain and oilseed production to irrigated horticultural crops.

To estimate the net benefits of the irrigation projects to the producer, a couple of methods are available. Firstly, irrigated production allows for contracting a higher net yield with the processing company, requiring fewer acres to deliver the contract. As a result, the net unit cost of production has been estimated to be approximately $1.11 per hundredweight (cwt) (1991 $ Cdn.) less for irrigated production than dryland production (AIM, 1999). Using a net yield of 220 cwt/ acre (Manitoba Agriculture, 1999) the net return of converting from dryland potatoes to irrigated potato production can be estimated to be

$250 per acre ($620 per ha) per year.[7] Depending on producer's specifics this increment could be larger than that associated with conversion from dryland grain and oilseed production to irrigated potato production. AIM (1999) estimated net return for conversion from dryland canola and wheat to irrigated potato production at about $200 per acre ($500 per ha) per year.

Another method to estimate the value of irrigation to the producer is to look at the net incremental yield per acre resulting from irrigation. Shaykewich et al. (1997) indicate an return of about 16 cwt per acre per inch of total precipitation.[8] Manitoba Agriculture (1998) presented average water deficit maps to maturity for potatoes in Manitoba; the deficit varied from 2" to 3" (50 to 75 mm) in the CMRM and ARM areas to 4" to 5" (100 to 125 mm) in the Assiniboine Delta Aquifer and South West Manitoba areas (Fig. 1). At a contract price of $7.00 /cwt this amounts to a potential increased income of from $280 per acre ($690 per ha) to over $500 per acre ($1200 per ha).[9]

The additional potato production associated with the CMRM Ltd. projects is contracted to the two french fry processing plants in Manitoba. Recent expansion of these plants has resulted in a continued need to expand the irrigated potato production. The processing plants benefit from the security of supply which allows them to remain competitive for contracts.

The Governments of Manitoba and Canada benefit from irrigated production through reduced unemployment and through sales, business and income tax revenues. In 1997, the two processing plants in Manitoba spent approximately $300 M with suppliers, of which $240 M was spent in Manitoba. The plants employ between 1,500 and 2,000 people in Manitoba. Approximately 90% of the product is exported out-of-province bringing net trade surplus to Manitoba and Canada (AIM, 1999). The construction and operation of the irrigation projects also creates jobs and tax revenue. While the majority of the irrigation equipment (sprinklers, pipe and pumps) are purchased from United States manufacturers, local construction companies and equipment suppliers have installed the systems and constructed the major works (e.g., reservoirs). The 1999 CMRM Ltd. project works will cost close to $3 M ($500 per acre, $1200 per ha), not including on-farm sprinklers, pumps and pipes. On the farm, the increased employment from conversion of 3,000 acres (2 400 ha) from dryland cereal production to irrigated potato production amounts to about 17 person years of employment.[10] Assuming an additional 100 acres of vegetables associated with the projects adds another 12 person years.[11] The net value of these benefits to the Government has not been quantified.

---

7 The incremental return from premiums paid for quality resulting from irrigation was not included in the study (AIM, 1999).

8 Total precipitation is the sum of irrigation and rainfall.

9 $7.00 per cwt x 16 cwt per inch x number of inches average moisture deficit.

10 Cereals @ 1000 acres (400 ha) per person year and potatoes at 150 acres per person year (60 ha), vegetables at 8 acres (3 ha) per person year (AIM, 1999).

BENEFITS AND COSTS OF GROUP PROJECTS

Group irrigation projects have incremental benefits over and above the direct measurable monetary return to irrigation. At the Government level, the following benefits accrue:

- group projects require environmental impact assessment, which ensures monitoring and implementation of Best Management Practices for soil and water resource protection;
- water use data collected by the operating company aids the Government in operation of their water structures (e.g., Shellmouth Dam, Portage Diversion);
- environmental mitigation measures can be negotiated on an industry-wide basis;
- empowering local agencies to deliver environmental mitigation leads to better producer understanding and reduced environmental impacts (Shady, 1997)[11];
- large producer organizations make it increasingly feasible for Government agencies (e.g., PFRA), to educate producers in resource management issues (e.g., soil, water and habitat conservation); and
- Water Rights licencing will become more streamlined with knowledgeable advocates filing the applications. The number of resulting licences will be reduced. Turnaround time should improve.

In a similar fashion, group projects benefit the producer in certain "intangible" ways, accruing the following benefits:

- project planning experience is available to new growers (e.g., licencing, engineering design, tendering, installation standards); resulting in higher standard projects with better longevity and safety[12];
- group project operation and management experience is available to new growers and landowners;
- Environment Act and Water Rights licences have a value to the producer with respect to securing financing and protecting their investment value;
- larger and more complex projects (delivering water further from the source) are identified for study and can be considered for implementation (e.g., KGS, 1999); and

---

11 Under the Hill Farms (PFRA, 2000) have implemented Best Management Plans and provide peer leadership within CMRM Ltd. ARM Ltd. monitors stream flows on three streams below the escarpment and has a soil resource project which documents groundwater fluctuations and salinity flux (PFRA, 1997).

12 ARM Ltd. is currently renovating several reservoirs to current design standards.

- resource monitoring projects provide real data to producers making management decisions (e.g., nutrient and water scheduling, drainage improvements (e.g., tile), soil monitoring) (PFRA, 2000).

The trade-off for group projects is the increased cost to the Government and the producer, neither of which have been accurately measured. The change to group projects has triggered an increase in Environment Act Proposals (i.e., five in 1999). Although no additional staff has been hired by the Government as a result of this workload, there has been a noticeable delay in the review period. At this point, the Surplus Water Irrigation Initiative has financed the environmental assessments which are costing in the order of $50 to $100 per acre ($125-$250 per ha). In addition the cost of filing Water Rights licencing applications has been funded by the Government. Producers must pay an additional $2 per acre ($5 per ha) environmental application fee and the operating costs for CMRM Ltd. of $1 to $3 per acre ($2.5 to $7.5 per ha) per year (e.g., insurance, management, accounting). The cost of the environmental monitoring programs has yet to be determined, as they are still under negotiation with the Government.

In addition to the monetary costs, the environmental approval process has a potential opportunity cost. The environmental review process is open-ended, reacting to public involvement and is not yet well defined relative to some issues (e.g., fisheries requirements). As a result the process is data intensive (e.g., detailed soils surveys; well and creek water qualities; production issues) and has lead to increasing consulting costs. Overlapping of jurisdictions result in duplication of applications and increase the cost of licencing (e.g., Provincial water licences, municipal permits, Provincial and Federal environment impact analysis). Relative to the time frame for licencing small individual projects, the licencing process for larger group projects can be lengthy (e.g., 1 year) due to time to undertake the required studies. The net result is to make alternative investments more attractive.

FUTURE OF CENTRAL MANITOBA RESOURCE MANAGEMENT LTD.

The future of CMRM Ltd. appears promising. Currently planning and licencing is underway for another 2,000 acres (800 ha) in the year 2000. Furthermore, CMRM Ltd. will be busy in partnership with CMIA Inc., with issues of importance to all irrigators, including:

- planning and promotion of group infrastructure developments;
- industry leadership in sustainable development;
- streamlining licence applications to reduce cost;
- monitoring and reporting on water and soil resources;
- cultivating stronger partnerships with regulatory and municipal agencies;
- producer education, setting operational guidelines, and negotiating policies (e.g., BMPs, fuel handling guidelines, fish screens policies).

CONCLUSIONS

The formation of the CMRM Ltd. has signaled a shift in irrigation development in Manitoba towards group developments. The change, relative to smaller individual projects, has potential to accelerate development by delivering water to land further away from the available sources. CMRM Ltd. provides structure and management expertise required for group projects which involve the development and maintenance of conveyance systems and intense consideration of environmental sustainability.

The benefits to group irrigation development in Manitoba are substantial. Producers increase their net returns. Industry secures the supply of quality produce. Governments accrue monetary benefits from increased taxes and employment, both on and off-farm, and benefit from industry responsibility for environmental monitoring. The magnitude of these benefits need to be quantified in order to rationalize support to CMRM Ltd.'s licencing, operating and monitoring costs.

The future of the company will require that producers see value in CMRM Ltd. They are challenged to look beyond the farm gate to the industry and public benefits of this approach. Government, producers and prospective new industries will have a focal point to discuss expansion possibilities. New producers won't have to relearn the wisdom in irrigation development acquired by CMRM Ltd. Empowerment, education and training of CMRM Ltd.'s personnel and producers should lead to better water management and more environmentally sustainable projects.

REFERENCES

Agassiz Irrigation Association Inc., 1992, " Sustainable Irrigation for Manitoba - A Project for the 90s", March, 61 pp., Winnipeg, MB.

Agassiz Irrigation Association Inc., PFRA, 1996, " Environment Act Proposal, Irrigation Reservoirs - 1996", June, 37 pp., Morden, MB.

Agassiz Irrigation Association Inc., 1998, " AIA Inc.- Area Water Management Plan and Business Plan", Winkler, MB.

Association of Irrigators in Manitoba Inc., Gaia Consulting, Werner Research, 1999, "Irrigation Strategy", March, 31 pp., Morden, MB.

Central Manitoba Irrigation Association Inc., Gaia Consulting, 1997 "CMIA Inc. - Water Management Plan", Portage la Prairie, MB.

Gaia Consulting, 1997, "Manitoba Irrigation Survey", July, 18 pp., Portage la Prairie, MB.

KGS Group, 1999, "Upper Rat Creek Irrigation Project; Environment Act Proposal", June, 57 pp., Winnipeg, MB.

Manitoba Agriculture, 1998, " Soil Resource and Climate Information - An Assessment of Long-Term Precipitation, Crop Water Demand, and Moisture Deficit for Potatoes at Maturity in Manitoba", 10 pp., Carman, MB.

Manitoba Agriculture, 1999, "Guidelines for Estimating Irrigated Processing Potato Production Costs", April, Carman, MB.

Manitoba Potato Council, 1994, "Manitoba Comercial Potato Production Guide - 1994", 88 pp., Portage la Prairie, MB.

PFRA, AIA Inc., Werner Research, 1997, "Co-Management of Water Resources", USCID Water Management Conference, July, 14 pp., Fargo, ND.

PFRA, 2000, "Sustainable Irrigation in Manitoba - Under the Hill Farms - A Case Study", USCID International Conference, June, 15 pp., Fort Collins, CO.

Shady, 1997, "Irrigation in the World, From the Green Revolution to the Blue Revolution", CWRA 1997 Conference Abstracts, Lethbridge, AB.

Shaykewick et al., 1997; " Yield Estimation in Irrigated Potatoes", Manitoba Crop Diversification Centre 1997 Annual Report, Carberry, MB.

EVALUATION OF DIELECTRIC SOIL MOISTURE SENSORS FOR IRRIGATION SCHEDULING ON FARMS

Blaine R. Hanson[1]   Douglas W. Peters[2]

ABSTRACT

Seven dielectric soil moisture sensors were evaluated for their response to changes in soil moisture content and their appropriateness for irrigation scheduling on farms. The devices were the Sentry 200-AP, TRIME, TRASE, Aquaterr moisture meter, Enviroscan instrument, Hydra Soil Moisture Probe, and ThetaProbe. Results showed the TRASE and ThetaProbe devices to be relatively accurate compared to the other instruments. Calibration of the other instruments may be necessary under some conditions. In the fine-textured soils, the TDR devices sometimes would not operate. The Enviroscan has the advantage of high-frequency measurements, but tended to overestimate soil moisture contents.

INTRODUCTION

Recently, dielectric sensors have been developed that determine the soil moisture content based on measurements of the dielectric constant of the soil. Dielectric devices include time-domain-reflectometry (TDR) sensors and capacitance sensors, also called frequency-domain reflectometry sensors.

Numerous studies have been conducted on using the TDR and capacitance methods. Because of space limitations, however, the literature review is omitted. A comprehensive review of both techniques is in White and Zegelin (1995).

Field use of several dielectric instruments revealed readings that were unrealistic and contrary to reported laboratory calibrations. Thus, a project was initiated to investigate the response of dielectric methods to changes in soil moisture content and their appropriateness for irrigation scheduling on farms.

---

[1] Extension Irrigation and Drainage Specialist, Department of Land, Air and Water Resources, University of California, Davis,CA 95616

[2] Staff Research Associate (former), Department of Land, Air and Water Resources, University of California, Davis, CA 95616

PROCEDURE

Two approaches were used for this project. The first approach evaluated three dielectric soil moisture sensors at six locations in the San Joaquin Valley. Soil texture at the six locations ranged from silt clay to loamy sand. The sensors evaluated were the Sentry 200-AP, TRIME TDR, and TRASE TDR. The Sentry 200-AP is a capacitance device that requires installing a plastic access tube such that no air gap exists between the tube and the soil. A probe containing two electrodes separated by a dielectric is lowered into the access tube to the desired depth and a measurement is made. The TRIME TDR device requires a fiberglass access tube installed in the soil. A depth probe 7.9 in (200 mm) long containing two waveguides is lowered into the access tube to the desired depth, and a measurement is made. The TRASE TDR device involves driving two steel rods or waveguides into the soil parallel to each other. Two sets of rods were used with one set measuring over a 1-foot (0.3-m) depth interval and the second set measuring over a 2-foot (0.61-m) depth interval.

In addition, an Enviroscan instrument was evaluated at four other locations containing fine-texture soil. The Enviroscan system is a capacitance device consisting of a series of electrodes installed in a plastic access tube. The sensors are connected to a data logger. For this study, measurements were made at 4 in (0.1 m), 12 in (0.3 m), 20 in (0.64 m), 28 in (0.71 m), and 36 in (0.91 m) depth. Two of the locations corresponded to two of the above mentioned sites.

With the exception of the TRASE device, these devices require carefully installed access tubes. Because the installation and removal of the access tubes is time-consuming and difficult and because of the large number of measurements, it was not practical to collect volumetric soil samples each time measurements were made. This would have disrupted the soil adjacent to the access tubes and would require frequent removal and reinstallation of the tubes. Thus, soil moisture contents were measured with a neutron moisture meter (NMM) calibrated for each site. These NMM moisture contents were compared with the dielectric instruments' readings to evaluate their accuracy and their response to changes in soil moisture. In spite of concerns about different zones of influence between the NMM and dielectric sensors and possible errors due to the NMM calibration and its random counting rate, the results showed that the NMM data provided a reasonable description of the performance of the dielectric sensors.

All instruments were installed along a 6-foot (1.8-m) long transect at each site with the NMM access tube installed at the middle of the transect. The sensors were located as close together as possible to minimize any small-scale variability in soil moisture content, yet not interfere with each other.

The second approach consisted of comparing readings of an Aquaterr Moisture Meter, Hydra Soil Moisture Probe, and a ThetaProbe with volumetric soil moisture contents determined from soil samples. These devices are highly portable, thus allowing them to be easily moved. Soil textures used for this approach ranged from sandy loam to clay loam. The soil samples, each 59.5 cm^3 in volume, were taken about one inch (25 mm) from the dielectric instrument. The Aquaterr meter is a capacitance meter with a steel rod containing two electrodes at its tip. The rod is pushed into the soil to the desired depth and a reading obtained. A color-coded chart relates the instrument's reading to a qualitative indicator of soil moisture content. The ThetaProbe is a plastic cylinder 4.9 in (125 mm) long and 1.6 in (40 mm) in diameter with four steel rods, each 2.4 in (60 mm) long, attached to one end. The sensor is connected to a hand-held meter that reads in volumetric soil moisture content. The design of the Hydra Soil Moisture Probe is similar to that of the ThetaProbe. Both the ThetaProbe and Hydra Probe require a hole augered to the desired depth of measurement.

Linear regression equations were developed relating instrument readings to soil moisture contents. A single equation was developed for each site by combining the data of each depth of measurement. The coefficients of these equations were statistically compared to those of a one-to-one (1:1) line (slope =1, intercept = 0). Root mean square errors were also calculated between the actual and measured values where appropriate. A level of significance of 0.05 was used for all statistical tests.

RESULTS

Sentry

Figures 1a and 1b show the response of the Sentry instrument to changes in soil moisture content for two soil textures. For the coarser texture soils, a strong linear relationship existed between Sentry readings and soil moisture contents, but deviated from a 1:1 line (dashed line). For the fine-texture soils, the Sentry readings sometimes greatly overestimated soil moisture contents. Values exceeded 50 percent at a silt loam site, while for the silt clay site, moisture contents ranged between about 45 percent and nearly 120 percent, clearly unrealistic.

Coefficients of the linear regression equations showed the slopes of the regression equations to be less than one for the coarser texture soils, while for the fine-texture soils, slopes were between 1.76 and 3.00 even though the unrealistically high values were excluded from the statistical analysis. Coefficients of determination ranged between 0.54 and 0.73. Slopes and intercepts of the regression equations were statistically different from those of a 1:1 line.

TRASE

The TRASE values represent an average reading over depth intervals of 0 to 1 foot (0.30 m) and 0 to 2 feet (0.61 m), thus soil moisture contents were averaged over the same depth intervals. For the coarser texture soils, measurements showed a strong linear relationship between instrument readings and soil moisture contents for both depth intervals (Fig. 1c). At one of the silt loam sites, little correlation occurred between TRASE readings and soil moisture contents, reasons for which are unknown. For the other fine-texture sites, linear relationships were found such as shown in Fig. 1d. For all finer texture soils, measurements could not be made for the 2 foot (0.61 m) interval.

Coefficients of determination ranged from 0.85 to 0.98 except for the previously mentioned silt loam site ($r^2 = 0.02$) and the loamy sand site ($r^2 = 0.64$). Slopes of the linear regression equations ranged from 0.68 to 0.74 for the coarse-texture sites and between 0.78 and 1.47 for the two fine-texture sites. Slopes were not statistically equal to that of the 1:1 line for all sites except for the slope of the 0.61-m interval for sandy loam 1. The slopes of the coarse-texture soils were statistically equal to each other.

TRIME

Measurements were made only at one coarse texture soil because of a limited number of access tubes. In a sandy loam, TRIME readings nearly equaled soil moisture contents for moisture contents greater than about 25 percent (Fig. 1e). For moisture contents less than about 25 percent, TRIME readings exceeded soil moisture contents. This behavior occurred at all depths of measurement. Relatively little scatter occurred about the trend in the data.

At the silt loam site, TRIME readings greatly overestimated soil moisture contents although a linear relationship occurred. The sensor would not read at the 18 in (0.45 m) depth. The instrument underestimated soil moisture content at the two silt loam sites (Fig. 1f).

Coefficients of the regression equations showed slopes ranging between 0.55 and 1.41 and intercepts ranging between -22.01 and 21.63. Coefficients of

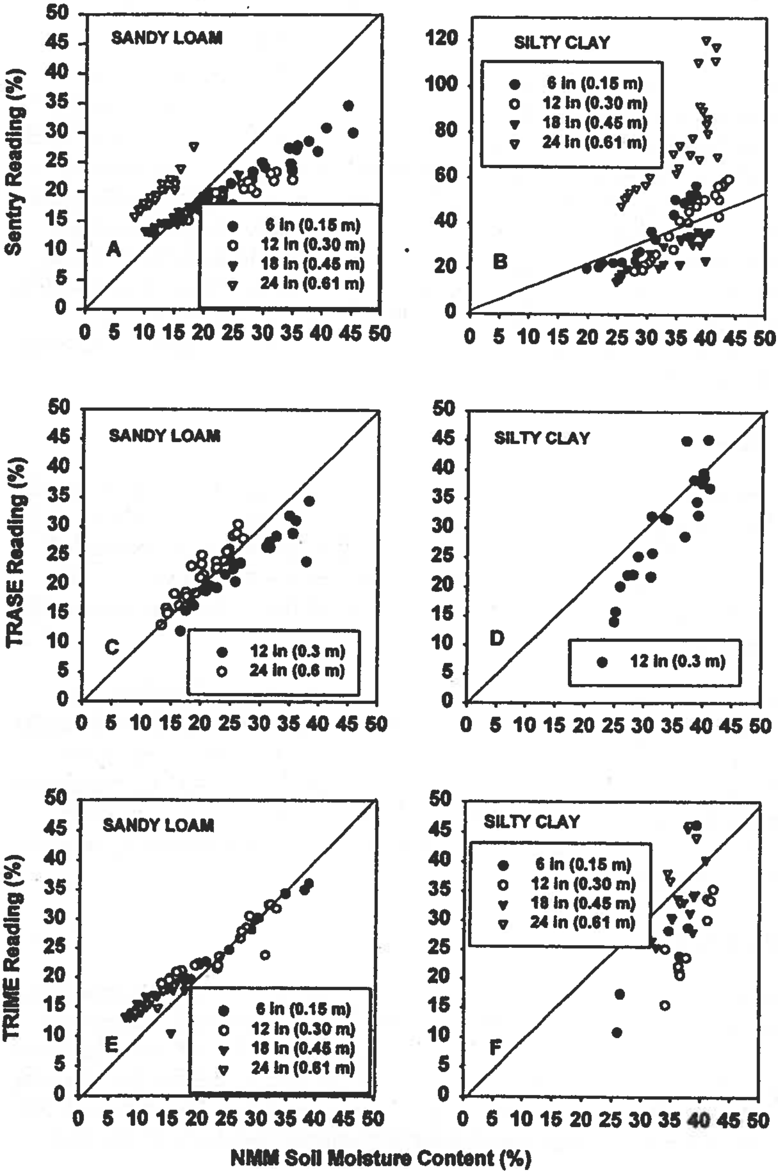


Fig. 1. Response of Sentry, TRASE, and TRIME sensors.

determination ranged between 0.35 and 0.91. Slopes of these equations were statistically different from those of a 1:1 line except for one of the silt loam sites.

Enviroscan

Figures 2a and 2b show NMM and Enviroscan readings with depth for two different measurement dates at the silt loam and silty clay sites. This approach was used because Enviroscan readings could not be directly compared with NMM readings due to different depths of measurements. Each set of data consists of readings in a relatively wet soil and in a relatively dry one. These data show that the Enviroscan readings generally were much greater than the NMM readings. Most of the Enviroscan readings were at least 1.5 times greater than the NMM values. The ratio of Eviroscan reading to NMM reading increased as soil moisture content decreased. However, at each location, the ratio for the shallowest measurement depth only ranged between 0.9 and 1.16. Similar behavior occurred at a silt loam site.

ThetaProbe

ThetaProbe readings plotted against soil sample volumetric soil moisture content are shown in Fig. 2c and 2d for a sandy loam and a clay loam sites. Data of the seven sites sampled showed a strong linear response of ThetaProbe readings to changes in soil moisture content with data points relatively close to a 1:1 line. Data of the sites with sandier soil tended to better fit the 1:1 line than the data of the other sites.

Regression coefficients showed similar slopes and intercepts among the finer-textured soils, but these coefficients were statistically different from the slope and intercept of a 1:1 line. Similar regression coefficients were found among the sandier sites, which were statistically similar to those of a 1:1 line. Coefficients of determination ranged between 0.68 and 0.91 with all but one site greater than 0.79. Regression equations of the fine-texture soils were not statistically equal to those of the sandier soils.

Aquaterr Meter

Aquaterr meter readings plotted against soil moisture contents are shown in Fig. 2e and 2f for three sites. In general, Aquaterr readings responded to changes in soil moisture content although considerable scatter occurred in the data. However, outliers appeared to exist over the dryer values of soil moisture at a clay loam site, while for a sandy loam site, little change in Aquaterr reading with changes in soil moisture content was found. Reasons for this behavior are unclear at this time.

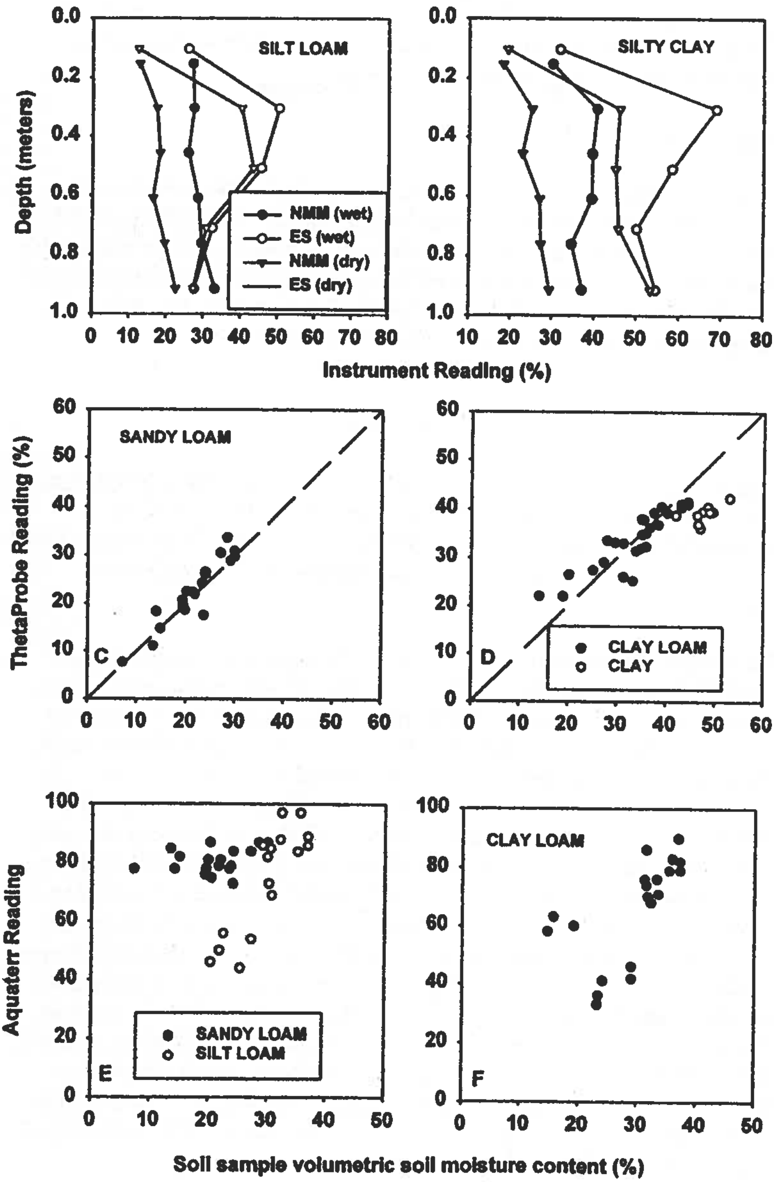


Fig. 2. Response of Enviroscan (ES), ThetaProbe, and Aquaterr sensors.

Regression coefficients and coefficients of determination show considerable variation between the sites. Coefficients of determination ranged between 0.18 and 0.77 indicating that much of the variation in the Aquaterr readings is not explained by the variation in soil moisture content.

Hydra Soil Moisture Probe

The Hydra Soil Moisture Probe readings were much larger than soil moisture contents for the three sites evaluated thus far (not shown) with RMS errors of 8.4 (sandy loam), 11.6 (silty clay), and 12.9 (silt loam). However, a linear relationship was found between soil moisture contents and probe readings with coefficients of determination ranging of 0.50, 0.80, and 0.91 for the three sites. All of the regression equations were statistically different from the 1:1 line.

DISCUSSION

It should be emphasized that these results are specific to these soils. While factors affecting the performance of dielectric sensors are not well-identified, some factors appear to be soil salinity, soil texture, and type of clay. These sensors used in locations with little soil salinity and a different type of clay may respond differently.

The ThetaProbe was the most accurate of the instruments over a wide range of soils with RMS errors ranging from 2.5 to 4.9. The TRASE instrument was also accurate over these soil types with RMS errors ranging from 1.8 to 5.6 with the exception of the silt loam site (Table 1). However, it would not read over the 0.6 m depth interval in the fine-texture soils. The TRIME instrument was relatively accurate in the coarse-texture soil, but accuracy was marginal at the sites with fine-texture soils with RMS errors greater than 8.3 (Table 1). Accuracy also was marginal for the Sentry in the coarse-texture soil with RMS errors ranging from 5.3 to 6.3 and was poor in the fine-texture soils with errors ranging from 8.9 to 36.2 (Table 1). The errors of the TRASE and TRIME instruments in the coarse-texture soils were similar to the RMS errors of the NMM, thus suggesting that the error in the NMM calibration curve might contribute significantly to differences between NMM and TRASE readings. (The RMS error of the NMM is based on the difference between calibration soil sample moisture contents and the predicted moisture contents from the calibration equation.) Accuracy of the Enviroscan system in these fine-texture soils was poor. Aquaterr readings were relative, and thus RMS errors were not calculated. Accuracy of the Hydra Soil Moisture Probe was poor for the three sites evaluated thus far.

Instruments with poor accuracy can be used for irrigation scheduling, but field observations and measurements will be necessary to interpret the instruments' readings relative to irrigation needs. The Aquaterr meter provides a qualitative reading only and will require field calibration.

The TRASE, ThetaProbe, and Aquaterr meter are relatively easy to install in a wet soil, but were difficult to use in relatively dry conditions. The Sentry, TRIME, and Enviroscan instruments require carefully-installed access tubes, which increases their difficulty of installation. Special installation equipment supplied by the manufacturers is recommended. Technical support is also required to set up the Enviroscan system.

An advantage of the ThetaProbe and Aquaterr meter is their portability, which allows many measurements to be made throughout a field. An advantage of the Enviroscan system is its ability to make very frequent measurements and to rapidly display the data on manufacturer supplied software.

The Aquaterr meter is the least expensive (about US$500) followed by the ThetaProbe (US$850 for a minimum kit). Minimum costs for the other instruments ranged between US$8,000 and nearly US$14,000.

REFERENCES

White, I. and Zegelin, S. J. 1995. Electric and dielectric methods for monitoring soil-water content. In: Handbook of Vadose Zone Characterization and Monitoring (ed: L. G. Wilson, L. G. Evertt, and S. J. Cullen). Lewis Publishers.

Table 1. Root mean square errors (percent) of the NMM and dielectric instruments at the six sites.

Site	NMM	Sentry	TRIME	TRASE
Sandy Loam 1	2.9	6.3	4.1	3.5
Sandy Loam 2	2.8	5.3	*	1.8
Loamy Sand	2.8	5.5	*	1.8
Silt Loam 1	3.1	29.8	14.1	8.7
Silty Clay	3.3	8.9	9.6	5.6
Silt Loam 2	3.7	36.2	8.3	4.8

SENSITIVITY OF MICRO IRRIGATION EMITTERS TO PLUGGING USING TREATED MUNICIPAL WASTEWATERS

R. Chica[1]
M. Alcaide[2]
J. Roldán[2]
E. Camacho[2]

ABSTRACT

Treated municipal wastewater can be used in trickle irrigation methods, but if we want to have a high application efficiency a good management is required. Clogging of emitters is one of the most important problems directly associated with the quality of irrigation water. This problem is increased when poor quality waters like wastewaters are used.

The sensitivity of different commercial emitters was studied when they were working continously during 620 hours. The objective was to find a relationship between emitter type and partial or complete plugging. A lateral with six different emitters was placed in a controlled experiment in laboratory. Municipal wastewater with a primary treatment was used. Later, this water was also filtered.

Results showed that pressure compensating emitters have a high sensitivity to clogging. Small pressure increments can help to clean plugged emitters. Plugging can also be decreased if wastewater with primary treatment is filtered. Non compensating pressure emitters showed a best behavior versus poor quality water.

INTRODUCTION

Drip irrigation systems have a large number of emitters that are easily clogged due to small flow paths they have. The quality of water is one of the main causes of plugging. The problem is furthermore increased if wastewater is used to irrigate. Clogging produces a poor irrigation uniformity.

Although previous works have been mainly devoted to study procedures to fight against clogging, several authors have also analysed the influence of emitter geometry. In this way, Lesavre and Zairi (1988) selected emitters resistant to clogging using wastewaters. Gamble (1986) and Nakayama and Bucks (1991) considered self-cleaning emitters to decrease clogging problems. Massoud et al. (1994) gave a classification of emitters sensitivity to plugging as a function of the minimum flow path.

[1] Department of Rural Engineering. University of Almería. Cañada de S. Urbano, s/n. 04071 Almería. Spain
[2] Deparment of Agronomy. University of Córdoba. Avda. Menéndez Pidal, s/n. 14071 Córdoba. Spain

The quality of irrigation water has been more widely considered. Nakayama and Bucks (1991) provided a table given the risk of emitter clogging depending on plugging factors: suspended solids; biological growths or chemical reactions. Gilbert et al. (1982) studied the clogging of eight different emitters using Colorado river water with several treatments. As a conclusion, the water treatment affects the normal operation of emitters. In this way, several authors (Bucks et al., 1979; Gilbert and Ford, 1986; and Nakayama and Bucks, 1986) give practical recommendations about treatments depending on specific water quality.

Although filtration and water treatments reduce the potential of clogging, Massoud et al. (1994) conclude that the problem can't be avoided in some conditions. Lau et al. (1981) also conclude that any chemical product can totally control clogging.

The main goal of this work is to study the sensitivity of different models of trickle irrigation emitters to plugging. Two types of treatments applied to wastewaters were considered. Finally, we present some recommendations about the most adequate emitter to decrease the risk of clogging.

MATERIAL AND METHODS

Experimental Procedure

Figure 1 shows an experimental bench used for emitter tests. Six different emitters were analysed. They are placed in each of the four laterals (16 mm of diameter) we have in a random way. Then, four repetitions of each emitter were considered. Separation between emitters is 0.2 m. Lateral length is short enough to accept that pressure distribution along lateral is uniform. Besides this, each lateral is supplied with water by both ends.

Filtration equipment consist on a disc filter (equivalent to 120 mesh) and sand filter (particle size of 1.2 mm of diameter). Due to the fact that water is recirculated through the experimental bench, the total suspended solids are disminished with time.

Emitters

Six commercial types were selected. The parameters (k and x) of the emitter discharge equation are shown in table 1 (Chica, 1999):

$$Q = kp^x \qquad (1)$$

Where Q represents flow rate ($L\ h^{-1}$) and p is the operating pressure (kPa). That table also includes the characteristic of emitters.

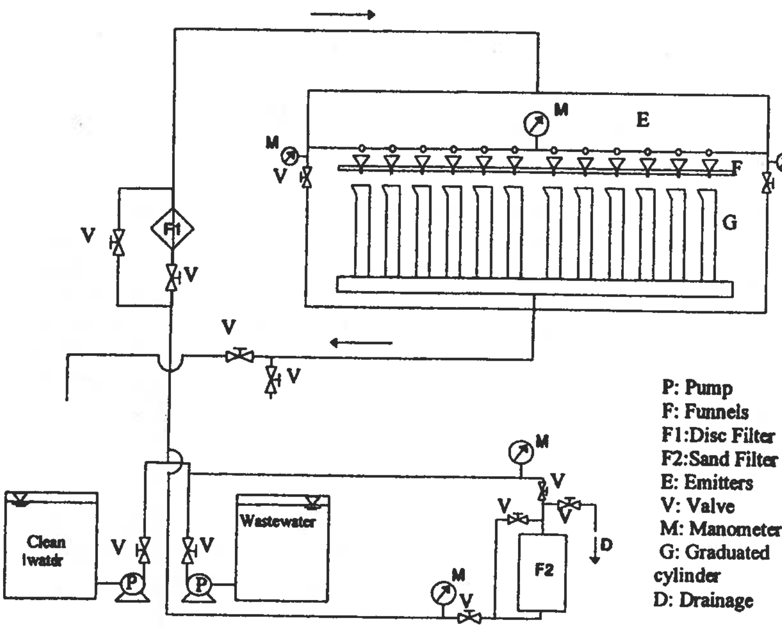


Fig. 1. Experimental Bench for Emitter Test

Table 1. Characteristics of Emitters and Parameters of Emitter Discharge Equation

Emitter	Parameters of discharge equation		Q_n (L/h)	Type
	k	x		
A	2.79	0.08	4	Pressure compensating on line
B	0.38	0.49	4	Labyrinth inserted (non compensating)
C	0.41	0.48	3.8	Labyrinth on line (non compensating)
D	4.61	-0.02	4	Pressure compensating on line non draining
E	0.44	0.48	4	Labyrinth in line detachable (non compensating)
F	0.54	0.44	4	Labyrinth in line non detachable (non compensating)

Wastewaters

Wastewater we have used in this work comes from the wastewater regenerated municipal station of the city of Córdoba (Spain). Two different types of wastewater have been used:
1. Wastewater with primary treatment (WPT).
2. The same water that once before has passed through the disc and sand filters (WPTF).

Some of the average physics and chemistry characteristics of the wastewater are shown in table 2. Those values were analysed each time we took water from the wastewater station. The first column shows the values of wastewater with primary treatment. The second column has the values of the same type of water once the wastewater has passed through the filters the first time. The third column shows the values after four hours of recirculation through the experimental bench. In the last case, only the suspended solids were analysed because it is the characteristic most affected by the filters.

Table 2. Characteristics of Wastewaters Used in Laboratory Tests

	Primary treatment	**Primary treatment + Initial filtering**	**Primary treatment + total filtering**
Suspended solids (mg/L)	109	45	6
BOD[3] (mg/L)	264	235	-
COD[4] (mg/L)	567	500	-
PH	7,64	7.88	-
Conductivity (dSm^{-1})	0.96	1.10	-
Fe (µg/L)	2000	-	-
P (mg/L)	9	-	-
Nitrates (mg/L)	<5	-	-

[3] Biological Oxygen Demand
[4] Chemical Oxygen Demand

A problem we found in this type of test was that the wastewater station was very far from the experimental laboratory. Then, wastewater was carried out in small tanks with a capacity of 25 liters. Although the water was changed very frequently (each four hours), we need to recirculate it during that time and characteristics of wastewater were modified mainly in the case that filters were installed (see table 2). However, it appears that only suspended solids decreased their values in a significant way. In another experiment, we studied the deposits in the emitters and pipes after four hours of recirculating water. The analysis demostrated that they were mainly constituted by organic matter (Chica, 1999). Therefore, the influence of filters does not affect other parameters in table 2.

Methodology and Experimental Procedure

The experimental test was conducted for 620 hours, that is, the current duration of the irrigation season. First, we worked with a type of wastewater and, once the experiment concluded, we started with the other type of water. In order to simulate, as exact as possible, the field irrigation practices, the system operated four hours each day up to reach the 620 hours.

Each four hours, flow discharge at the nominal operation pressure (100 kPa) was measured. Each 100 hours, the flow discharge was also measured at 60, 100, 140 and 180 kPa, to determine the flow discharge equation. Temperature was measured with a mercury termometer with precision ±1°C.

The sensitivity to plugging was studied computing two parameters:

1. The decrease of flow discharge (D_q), after 620 hours, in relation to the nominal discharge expressed as a percentage:

$$D_q = \frac{\overline{Q}_f - Q_n}{Q_n} \times 100 \qquad (2)$$

where Q_n (L h^{-1}) is the nominal discharge, and $\overline{Q}_f$ (L h^{-1}) is the average emitter discharge after 620 hours.

2. The level of clogging (LC) after 620 hours expressed as a percentage:

$$LC = \left(1 - \frac{\overline{Q}_f}{\overline{Q}_i}\right) \times 100 \qquad (3)$$

where $\overline{Q}_i$ (L h^{-1}) is the mean discharge of each emitter when the test starts.

Results were statiscally studied by means of a variance analysis (VA). Means were separated using a least significant difference (LSD) test at a significance level of 95% (González and Ollero, 1997).

Values of emitter discharges with time were fitted through a regression analysis to several types of curves: lineal; potential; polinomial; exponential and logarithmic.

Emitter discharge equation was determined from the discharge values obtained at the pressures of 60, 100, 140 and 180 kPa, by a regression analysis as well.

The variation of emitter discharge in drip irrigation is the result of several factors: hydraulic variation; manufacturing variability; emitter plugging and water temperature changes. At a given operating pressure, as in our case (100 kPa), there is no hydraulic variation. The importance of each of the remaining three factors can be evaluated through a factorial variance analysis (Cooper, 1969). The contribution of each factor is expressed by the coefficient of variation. The variance analysis permits us to write:

$$CV^2 = \frac{\sigma^2}{\overline{Q}^2} = CV_m^{\,2} + CV_t^{\,2} + CV_c^{\,2} \tag{4}$$

where σ is the standard deviation of emitter discharge, CV is the total coefficient of variation for emitter discharges, CV_m is the variation coefficient of the manufacturer, CV_t is the variation coefficient due to temperature and CV_c is the variation coefficient due to clogging.

CV_c can be obtained from equation 4 once the other CV have been experimentally measured. CV_t can be neglected because temperature variation in laboratory is very low (22-29 °C) and hydraulic regime of emitter is turbulent (Rodríguez-Sinobas et al., 1999).

RESULTS AND DISCUSSION

Deviation of emitter discharge from nominal discharge (D_q) and level of clogging (LC)

Values of D_q and LC obtained after 620 hours of system operation with the two types of wastewater (WPT and WPTF) at nominal pressure (100 kPa) are shown in table 3.

Table 3. Flow Discharge Deviation and Level of Clogging of Emitters after 620 Hours at 100 kPa

Emitters	Q_n (L h^{-1})	WPT				WPTF			
		Q_i (L h^{-1})	Q_f (L h^{-1})	D_q (%)	LC (%)	Q_i (L h^{-1})	Q_f (L h^{-1})	D_q (%)	LC (%)
A	4	3.04	0.02	-99.5	99.3	4.54	3.90	-2.5	14.1
B	4	3.73	3.18	-20.5	14.8	3.74	3.25	-18.7	12.9
C	3.8	3.79	2.98	-21.6	21,4	3.74	3.25	-14.5	13.1
D	4	4.11	4.21	-52.5	53,0	4.03	4.18	-5	8.6
E	4	4.31	4.32	-31.5	37.4	4.37	4.23	-1	10.8
F	4	4.13	3.70	-7.5	10.4	4.12	3.75	-6.3	9.0

A negative value of D_q in table 3 means that flow discharge has decreased and, therefore, clogging has increased. Order of emitter according to its level of clogging is:

- For the WPT: A-D-E-C-B-F
- For the WPTF: A-C-B-E-F-D

The pressure compensating emitter A was the worse in both cases. However, the other pressure compensating emitter D had the best performance when the water was filtered.

A variance analysis taking into account the two different types of used wastewaters and several emitters was done and the means separated (LSD). From the results (see table 4) it can be deduced that there is a significant difference between the two types of wastewaters. When the emitters are compared, a significant difference in the level of clogging was found between emitter A and emitters C, B, and F.

TABLE 4. Test of Means Comparison for the Level of Clogging of Emitters

Emitters	Homogeneous groups		Type of wastewater	Homogeneous groups	
A	I				
D	I	II	WPT	I	
E	I	II	WPTF		II
C		II			
B		II			
F		II			

Emitter Discharge Variation with Time at Nominal Pressure

Figures 2 and 3 show emitter flow discharge with time using WPT and WPTF respectively. In the first case, emitter A was quickly clogged. For emitter D the flow discharge recovered as the pressure was increased. Then, this raise of pressure is recommended as a method to prevent clogging once the irrigation is finished. In the second case all emitters have the same behavior.

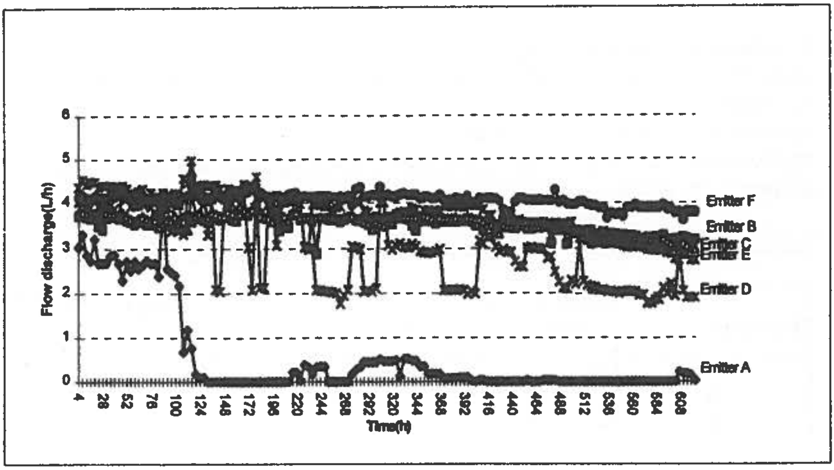


Fig. 2. Flow Discharge Variation with Time at Nominal Pressure Using WPT

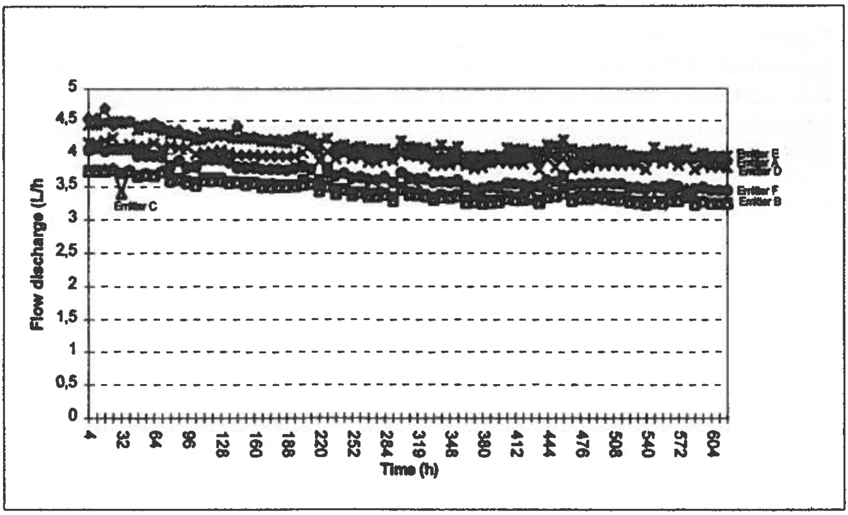


Fig. 3. Flow Discharge Variation with Time at Nominal Pressure Using WPTF

A regression analysis has shown that the general trend of flow discharge along time is best described by a polynomial curve for all emitters. Fitting equations (where y is discharge in L h^{-1} and x is time in hours) and correlation coefficients are in table 5.

Table 5. Equations Q-t for Each Emitter at Nominal Pressure Using two Different Wastewaters

Emitter	WPT		WPTF	
	Equation	R^2	Equation	R^2
A	$y=0.003x^2-0.0609x+2.93$	0.72	$y=0.0002x^2-0.0232x+4.58$	0.88
B	$y=-4E-05x^2+0.0033x+3.58$	0.69	$y=8E-05x^2-0.0123x+3.77$	0.92
C	$y=-5E-05x^2+0.0033x+3.68$	0.81	$y=9E-05x^2-0.0133x+3.76$	0.85
D	$y=-4E-05x^2-0.0205x+4.19$	0.56	$y=7E-05x^2-0.0099x+4.18$	0.81
E	$y=-5E-05x^2-0.0022x+4.38$	0.85	$y=0,001x^2-0.0141x+4.48$	0.87
F	$y=-4E-05x^2+0.0038x+4.07$	0.53	$y=2E-05x^2-0.0041x+4.0365$	0.78

<u>Variation of Emitter Discharge Equation (Q-p) with Time</u>

Parameters of emitter discharge (k, x) were calculated for all emitters and for the two types of wastewaters at the beginning of the test and at the end after 620 hours. Results are shown in table 6.

Table 6. Comparison Between Parameters of Emitter Discharge Equation at the Beginning of the Test and after 620 Hours Using two Different Wastewaters

Emitters	Phases	WPT			WPTF		
		k	x	R^2	k	X	R^2
A	Q_i	0.76	0.32	0.85	1.47	0.24	0.97
	Q_f	-	-	-	1.53	0.20	0.95
B	Q_i	0.53	0.42	0.99	0.60	0.40	0.99
	Q_f	0.47	0.42	0.99	0.41	0.45	0.99
C	Q_i	0.57	0.41	0.99	0.49	0.44	0.99
	Q_f	0.33	0.48	0.98	0.40	0.46	0.99
D	Q_i	0.58	0.003	0.02	0.70	0.006	0.02
	Q_f	0.33	0.33	0.60	0.47	-0.02	0.32
E	Q_i	0.58	0.44	0.99	0.70	0.40	0.99
	Q_f	0.33	0.47	0.99	0.47	0.46	0.99
F	Q_i	0.57	0.43	0.99	0.77	0.37	0.98
	Q_f	0.75	0.35	0.98	0.39	0.48	0.99

Except for emitters A and D, the correlation coefficient (R^2) tends towards 1. Then, the potential form of the discharge equation is adequate. For emitter D, and in some cases for emitter A, R^2 tends to zero and, therefore, their discharge equation is best represented by a constant function because they are pressure compensating emitters.

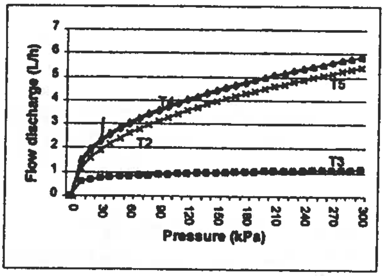
A variance analysis of the characteristics parameters of the discharge equation was done. The comparison between means of those coefficients for each emitter showed no significant differences between parameter *k* and significant differences for coefficients *x* between compensating pressure emitters (A and D) and non compensating pressure emitters (C, E, F, and B) (see table 7).

Table 7. Test of Means Comparison for Coefficients of Discharge Equation k and x

k coefficient		**x coefficient**	
Emitters	**Homogeneous group**	**Emitters**	**Homogeneous group**
D	I	**C**	I
A	I	**E**	I
F	I	**F**	I
E	I	**B**	I
C	I	**A**	II
B	I	**D**	II
Treatment	**Homogeneous group**	**Treatment**	**Homogeneous group**
T1	I	**T3**	I
T4	I II	**T2**	I
T2	I II	**T1**	I
T3	II	**T4**	I
T5	II	**T5**	I

The comparison between means of those coefficients for each treatment is also shown in table 7. In this table we have called:
T1: coefficients (*k*, *x*) of the nominal emitter discharge equation
T2: coefficients of the discharge equation at the beginning using WPT
T3: coefficients of the discharge equation after 620 hours using WPT
T4: coefficients of the discharge equation at the beginning using WPTF
T5: coefficients of the discharge equation after 620 hours using WPTF
In this case, we can distinguish two homogenous groups for coefficient *k*, and there are significant differences between the values of *k* in the nominal discharge equation and in the expression obtained after 620 hours using WPT. However, there were no significant differences for coefficient *x*.

As an example, figure 4 shows the discharge equation *Q-p* for all the above conditions in the case of two emitters: one non compensating pressure (B) and other compensating pressure (D).The trend for all curves is the same except for the discharge equation obtained after the system has been operating for 620 hours with WPT.



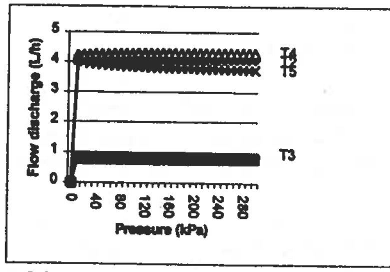


Fig. 4. Discharge Equations in the two Stages of the Test and for the two Types of Wastewaters

Calculation of the Coefficient of Variation Due to Clogging (CV_c)

As we have mentioned before, the CV_c was obtained from expression 4 neglecting previously the coefficient of variation due to temperature (CV_t). The values of the different coefficients of variation (total CV; manufacturing CV_m and CV_c) are shown in table 8. In most cases, CV_c is greater than CV_m when WPT is used. On the contrary, CV_c is lesser than CV_m when the wastewater is filtered (WPTF). Then, the quality of water influences the coefficient of variation.

Table 8. Coefficients of Variation of Emitters after 620 Hours Using the two Types of Wastewaters

Waste water	Coefficient of variation	Emitter					
		A	B	C	D	E	F
WPT	CV^2	4	0.010	0.00480	1.3628	0.01431	0.00034
	CV_m^2	0.00116	0.0012	0.00015	0.0036	0.00094	0.0009
	CV_c^2	3.998	0.0087	0.00358	1.3616	0.01399	0.00055
WPTF	CV^2	0.00054	0.00394	0.00047	0.0019	0.00014	5.8E-05
	CV_m^2	0.00116	0.0012	0.00015	0.0036	0.00094	0.0009
	CV_c^2	0.00061	0.00272	0.00031	0.0016	0.0008	0.00086

CONCLUSIONS

The type of emitter affects significantly the level of clogging. With all types of wastewaters we have used, a compensating pressure emitter (A) has the worse performance. However, we cannot conclude against this type of emitter because emitter D has the best performance when the wastewater is filtered.

The variation of emitter discharge with time is best fitted with a second order polynomial equation.

A pressure increment is recommended after the irrigation has finished in order to prevent clogging. A complementary study is necessary to look for the limits of that increment to avoid the system results very expensive.

The coefficients (k, x) of the emitter discharge equation show significant differences depending on both the type of emitter and wastewater comparing their values at the beginning of the test and after 620 hours. Those differences appear for coefficient x when emitters are considered and for coefficient k when we works with different types of wastewaters.

The coefficient of variation due to the manufacturer is the main factor of variability when the wastewater with primary treatment is filtered. If that water is not filtered, the coefficient of variation due to clogging is the main cause of poor behavior of emitters.

The quality of wastewater influences significantly the level of clogging of the emitters. Plugging can be decreased if wastewater with primary treatment is filtered because the amount of suspended soils is lowered until values quite similar to those obtained with a secondary treatment.

REFERENCES

Bucks, D.A.; F.S. Nakayama; and R.G. Gilbert. 1979. Trickle irrigation water quality and preventive maintenance. *Agric. Water Managmt*, 2: 149-162.

Chica, R. 1999. *Uso de agua residual depurada en sistemas de riego por goteo.* Tesis doctoral. Departamento de Agronomía. Universidad de Córdoba.

Cooper, B.E. 1969. *Analysis of variance.II Factorial analysis. Statistics for experimentalist*. Pergamon, New york, pp: 144-170.

Gamble, J. 1986. A trickle irrigation system for recycling residential wastewater on fruit trees. *Hort. Sci.*, 21(1):28-32.

Gilbert, R.C. and H.W. Ford. 1986. *Operational principles emitter clogging. In: Trickle irrigation for crop production.* F.S. Nakayama and D.A. Bucks (Eds). Elsevier, Amsterdam, pp:142-163.

Gilbert, R.C.; F.S. Nakayama; D.A. Bucks; O.F. French; K.C. Adamson; and R.M. Johnson. 1982. Trickle irrigation: predominant bacteria in treated Colorado river water and biologically clogged emitters. *Irrig. Sci.*, 3:123-132.

González, A. and J. Ollero. 1997. *Análisis estadístico con Statgraphics*. Grupo Editorial Universitario, Granada, Spain.

Lau, L.S.; R.H. Young; and G.P. Young. 1981. *Post-secondary treatment of effluent for drip irrigation.* Tech. Rep.n° 135. Water Resour. Res. Center, University of Hawaii at Manoa. Hawaii.

Lesavre, J. And A. Zairi. 1988. Epuration des eaux residuaires par epandage souterrain sous pression: conception et evaluation de la filiere de traitement. Agence de l'Eau Seine-Normandie. Centre de Recherche et d'Essais Appliqués aux Techniques de l'Eau.

Massoud, A.; D. Tajrishy; J. Hills; and G. Tchobanoglous. 1994. Pretreatment of secondary effluent for drip irrigation. *J. Irrig. Drain. Eng.*,120(4): 716-731.

Nakayama, F.S. and D. A. Bucks. 1986. *Trickle irrigation for crop production.* Developments in Agricultural Engineering 9. Elsevier, Amsterdam, 383 p.

Nakayama, F.S. and D.A. Bucks. 1991. Water quality in drip/trickle irrigation: a review. *Irrig. Sci.* 12: 187-192.

Rodríguez-Sinobas, L.; L. Juana; and A. Losada. 1999. Effects of temperature changes on emitter discharge. *J. Irrig. Drain. Eng.*, 125(2): 64-73.

NCWCD IRRIGATION SCHEDULING PROGRAM - CONVERTING TO A WEB-BASED ACCESSIBLE PROGRAM

James E. Draper[1]

ABSTRACT

In an effort to assist residents with conserving water, Northern Colorado Water Conservancy District (NCWCD) established an Irrigation Management Services Department. One of the goals is to promote increased efficiency during an irrigation event. In agriculture, NCWCD assists the farmer, through an irrigation scheduling program, by monitoring their soil moisture and providing a report of the moisture status. NCWCD provides soil moisture content and ET data relative to their crops along with suggested days until the next irrigation is needed. This allows the farmer to adjust their irrigation sets to maximize the use of their irrigation water and better utilize beneficial rainfall. NCWCD is presently integrating a web-based interface to their irrigation scheduling program.

IRRIGATION SCHEDULING PROGRAM

NCWCD has chosen the moisture depletion monitoring method for irrigation scheduling over the checkbook method, because of the difficulty in accounting for every drop of water entering and leaving the fields, including deep percolation. In addition, with the checkbook method, it is difficult to reestablish a calibration point or a starting point without saturating the soil profile or actually measuring the moisture content when calculations are off. Irrigation scheduling by the moisture depletion monitoring method is based on measured moisture level readings and crop water use data. The program is structured around the

---

[1] Directs the irrigation scheduling program at NCWCD and is a certified crop consultant. Northern Colorado Water Conservancy District 1250 North Wilson Ave. Loveland, Colorado 80537

analysis and relationship of the water holding capacity of the soil and the water needs of the crops. Four parameters determine the amount of water available within the soil profile, to the crops before stress occurs. The first is the effective depth of the root profile at the time of the reading. The second is the allowable depletion level for the growth stage of the crop, in percent of total available water. The third is the ET of the crop. Forth is the total holding capacity of the soil based on its profile and texture.

The District provides assistance with monitoring the soil moisture within agriculture fields. At the beginning of the season farmers subscribe to the irrigation scheduling program which include the use of tensiometers, readings once a week, and a printout of the status of the moisture within the field at each reading. At the time farmers' register with the program, the district enters their name, address, telephone number and password. Each field is assigned a weather station, usually within 25 miles. From soil maps or soils analysis, soil water storage capacities, soil types, texture, horizons, and parameters are defined and entered. The crops grown, along with depletion levels based on crop needs, soil texture or laboratory analyses are entered. A planting date or a green line date is also entered with the expected maturity date.

From the data entered at registration, the crop root growth is calculated and tracked throughout the growing season. The second parameter is provided from historical crop growth curves for northern Colorado. A weather station network provides the necessary Data to calculate ET parameters for the crops grown. The weather station network comprises ten alfalfa and three grass referenced-based weather stations plus two additional stations located at local golf courses. Each station reports twice a day via cellular telephone to the NCWCD headquarters.

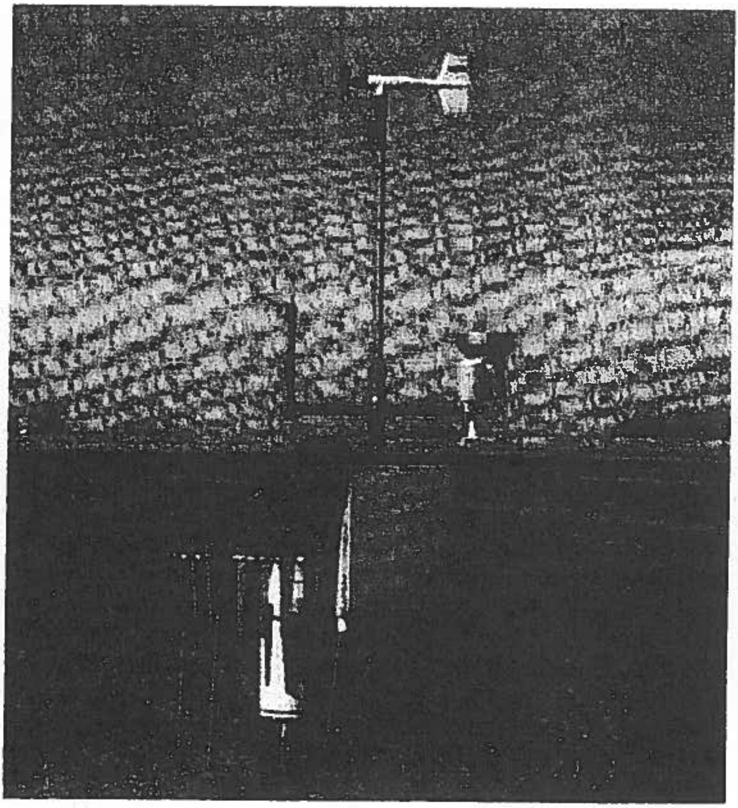


Fig.1. Typical Alfalfa Reference Weather Station.

Each station collects wind speed and direction, precipitation, relative humidity, air temperature, soil temperature, and solar radiation. Each station is solar powered with battery backup. Data derived is then processed and made available through a touch-tone dial system, Satellite subscription service (Data Transmission Network:DTN) and a web site. Information is also available through mailings and local newspapers. From data collected, NCWCD calculates an ET value for each weather station based on its alfalfa or grass reference. At the beginning of each day, the results of the previous week and the previous day are calculated, and based on historical data, a prediction for the next weeks water use is calculated and displayed for every crop for each weather station. The forth parameter, Total water holding capacity of the soil is determined from soil charts or laboratory analysis.

After these four parameters are established, tensiometers are used to determine the amount of moisture available, within the root zone to the crop.

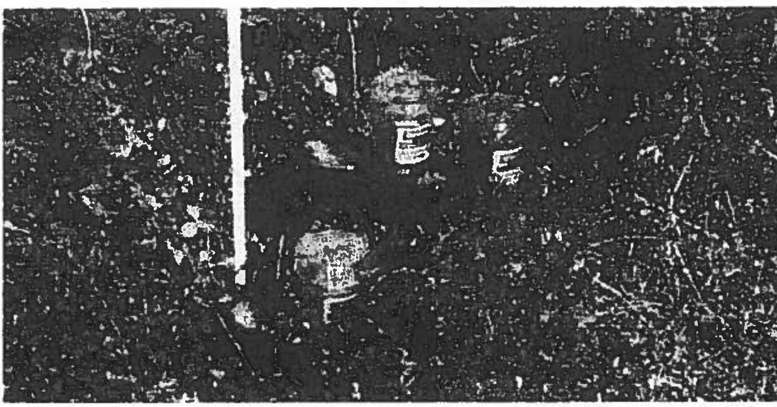


Fig 2. Typical Tensiometer Installation Site

As growing degree-days accumulate, crop water use curves are adjusted based on growth stage observations. The data entered at registration, with tensiometer readings, ET data, and crop water use curves are compiled and processed to produce the reports delivered to the farmer. The program determines how many days the crop will take to reach the pre-determined depletion level assigned to that crop and field.

Due to the quantity of farmers signed-up for this program, the district has been unable to address all the request of the farmers. With approximately 100 fields each year, one intern can read and report each field once a week. When the crop requirements and the farmers' irrigation needs do not correlate with the scheduled day to read the tensiometers, the farmer receives an inadequate report and cannot make the most intelligent irrigation decisions. In an attempt to address these deficiencies and to extend the reach of our services to the eastern areas of our district, NCWCD is integrating their present irrigation scheduling program with a web-based interface. The web-based interface will also allow farmers the ability to access the program at any time, and enable them to receive the services at a greater frequency than once a week. This allows farmers the capability to read their own tensiometers, run the irrigation scheduling program via the internet, download their results, and immediately receive a printout of the moisture status and an historical graph of the moisture levels.

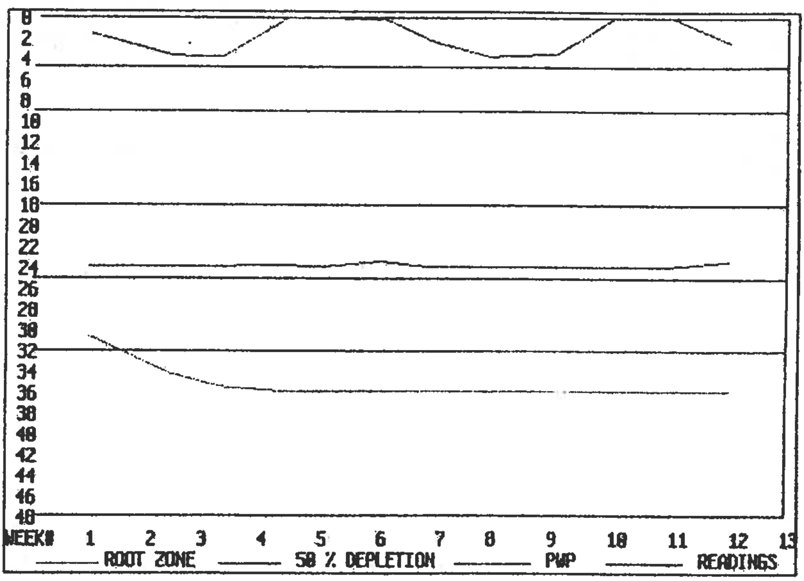


Fig 4. Historical Graph of Moisture Status within Soil Profile. (Provided to the farmer color coded)

NCWCD IRRIGATION SCHEDULING PROGRAM

FARMER'S NAME: Scott Meining
FARMER'S ADDRESS: Gilcrest

737-2928

DATE: 0 / 0 / 0
FIELD I.D. NUMBER 33
READING ENTRY NUMBER 12

CROP: CORN
PLANTING DATE: 111
ALLOWABLE DEPELTION % FOR THIS CROP: 50%
PRESENT AVERAGE ROOT DEPTH: 36 IN

	SOIL DEPTH	FIELD CAPICITY H2O	AVAILABLE H2O
1ST HORIZON:	18 IN	3.25 IN/FT	1.60 IN/FT
2ND HORIZON:	30 IN	3.27 IN/FT	1.54 IN/FT

	TOTAL FC	AVAILABLE H2O	PWP POINT
1ST HORIZON:	4.87 IN	2.39 IN	2.48 IN
2ND HORIZON:	8.19 IN	3.86 IN	4.33 IN

TOTAL AVAILABLE H2O 6.25 IN
TOTAL ALLOWABLE DEPLETION 3.12 IN

H2O AVAILABLE > PERMENANT WILTING POINT----IN & % REFERENCE TO DEPLETION LEVEL
TENSIOMETER READING FOR 1ST LAYER: 36 AVAILABLE H2O 1.83 IN +0.64 IN +53%
TENSIOMETER READING FOR 2ND LAYER: 63 AVAILABLE H2O 2.39 IN +0.46 IN +24%

AVAILABLE MOISTURE GREATER THAN ALLOWABLE DEPLETION WITHIN ROOT ZONE. 0.90 IN
CROP E.T. YESTERDAY (1 DAY) .11
CROP E.T. SINCE LAST READINGS .9
PROJECTED E.T. FOR NEXT WEEK 1.04
DAYS UNTIL NEXT IRRIGATION 6 DAYS

TENSIOMETER READINGS --------REMAINING AVAILABLE MOISTURE @ 50% DEPLETION

READING	1ST LAYER	2ND LAYER
4	1.20	1.93
7	1.20	1.93
10	1.20	1.93
13	1.20	1.93
16	1.20	1.93
19	1.09	1.79
22	0.98	1.62
25	0.89	1.46
28	0.81	1.33
31	0.74	1.22
34	0.68	1.11
37	0.62	1.02
40	0.57	0.93
43	0.52	0.86
46	0.47	0.78
49	0.43	0.72
52	0.39	0.65
55	0.36	0.60
58	0.32	0.54
61	0.29	0.49
64	0.26	0.44
67	0.23	0.40
70	0.21	0.35

Fig 3. Moisture Status Report Provided to Farmers Once a Week.

THE WEB BASED INTERFACE

The language selected to write the software was Microsoft Visual Basic in conjunction with Crystal Reports for the outputs. To run a software package with multiple inputs such as the irrigation scheduling program described, a properly designed database is necessary. Microsoft Access is the software language selected to handle the database chores. Customer information, crops, soils, and weather data tables were designed. Tables to hold data for each field and for the tensiometer readings were designed. In addition, links to the crop water use guide processed from weather data collected by the weather station network were created.

Concerns

1. The district wanted the ability to log all the soil moisture readings into a database while providing security and privacy to each farmer: By designing the district database to hold all the information and allowing the farmers access at the time they log on to the web, the district can update the interface, monitor the performance of the program, and make change accordingly. Password access will provide the security desired.

2. The district also wanted the ability to integrate the data from the weather station network into files that can be accessed by the farmers when they log-on to the web: The design and structure of the database again solves this problem.

3. And NCWCD wanted to provide a way for the district to monitor the status of the fields (a watchdog), oversee program use, and detect potential problems: Having the program run from within the district's web site, will facilitate troubleshooting the program, repairing corrupted or damaged files and avoiding erroneous inputs.

SUMMARY

The past four years, the program has scheduled three hundred fifty fields with one hundred seventy farmers. The past two years, the goal of attaining one hundred fields per year was not reached because of the lack of interest due to increased rainfall. The crops covered were alfalfa, both new seeding and established stands, barley, dry edible beans, corn, onions, potatoes, pasture, sugarbeets, winter and spring wheat, and watermelons. A variety of nursery grown cut flowers were added in 1999. The Irrigation scheduling program has been popular with farmers when drier seasons are experienced and less popular when adequate rainfall is encountered. The soil moisture content within the root zone of fields monitored and the calculated ET has tracked within expected deviations. This indicates that the soil moisture parameters have been properly selected and responses of soil moisture to crop use can be accurately predicted.

The Internet interface portion of the program has been delayed due to problems coordinating Microsoft Access, Microsoft Visual Basic and Crystal Reports. As my expertise and experience in writing code progresses, these issues should be resolved.

ON-FARM ACTIVITIES TO PROMOTE IRRIGATION SCHEDULING THE SOUTH CENTRAL KANSAS IRRIGATION MANAGEMENT PROJECT

Dr. Danny H. Rogers[1] Dr. Gary A. Clark[2] Dr. Dale L. Fjell[3]
Dr. Victor L. Martin[4] Robert Stratton[5]

ABSTRACT

Irrigation scheduling has been promoted as management tool to minimize irrigation water application, however, few irrigators regularly followed any rigorous scheduling methodology. Kansas State University Research and Extension in conjunction with an irrigation association, Water PACK, began a long-term project to promote ET based irrigation scheduling and other management technology. Area irrigators serve as the focal point of the project and over time have been asked to assume responsibility of scheduling the project fields. A long-term commitment and on-farm activities such as variable water application tests and center pivot uniformity tests seems to have generated confidence and acceptance of ET-based irrigation scheduling.

INTRODUCTION

The South Central Kansas Irrigation Management Project (SCKIMP) is a cooperative effort between K-State Research and Extension (KSRE) and irrigation farmers of South Central Kansas to refine, promote, and transfer the use of

---

[1]Extension Engineer, Irrigation, KSU Extension Research & Extension, Extension Biological & Ag. Engineering, 237 Seaton Hall, Manhattan, KS 66506

[2]Professor, Kansas State University, Biological & Ag Engineering, 147 Seaton Hall, Manhattan, KS 66506

[3]Professor, Kansas State University, Department of Agronomy, 2014 Throckmorton Hall, Manhattan, KS 66506

[4]Associate Professor, Kansas State University, Department of Agronomy, Sandyland Experiment Field, Box 247, St. John, KS 67576

[5]Project Coordinator, Sandyland Irrigation Field, Sandyland Experiment Field, Box 247, St. John, KS 67576

irrigation scheduling and water management technology. The primary partnership between KSRE and Water PACK (Water Protection Association of Central Kansas; members primarily consist of irrigation farmers in the area), has an overall goal of improving irrigation water application and water use efficiency to the fullest extent possible to maintain a sustainable irrigated crop production base. The thirteen county service area of Water PACK has an irrigated acreage base of over one-half million acres and adds millions of additional dollars to the area's economy. Although localized areas have groundwater decline problems, in general, the south central Kansas aquifer system is being managed at a safe yield as compared to the more well known Ogallala aquifer in western Kansas. However, this region has a great diversity of water use types. Muncipal and industrial water use from the Equus Beds near Wichita, is approximately equal in volume to agricultural uses, whereas state-wide agricultural water accounts for over 80% of the total water use. Other areas, especially along several stream corridors, have substantial and critical surface water needs for wildlife and recreational areas. Any reduction in irrigation demand through either improved system efficiency or management procedures without crop yield impact could have a positive water resource impact without irrigation economic consequences. This was one of the motivations that lead south central Kansas area irrigators, through their irrigation association (Water PACK) to request establishment of an area based irrigation scheduling and water management project.

The primary focus group of SCKIMP involves thirteen irrigator field partner sites whose operators have made a commitment to allow access to their fields for monitoring of production activities, to serve as educational sites for tours, to enhance project publicity, and to learn and adopt, as appropriate, improved irrigation scheduling and water management procedures.

Partner field information is then used to educate other area irrigators through in-field tours, and winter irrigation seminars. Information and experiences are also published in written educational materials. Each field site displays a large project sign to provide year round publicity. During the irrigation season, the signs are updated with approximately weekly and seasonal information on in-field values of evapotranspiration (ET or crop water use), rainfall and irrigation. Project newsletters featuring project activities and results are also used to transfer information. The newsletters are targeted to KSRE agents and other local water-related agency personnel for their programming use.

Co-sponsoring agencies for this extensive project include the Kansas Water Office, through State Water Plan Funds, and the Kansas Corn Commission. Senninger and Nelson Irrigation Corporations have also provided irrigation supplies used in field research and demonstration activities. Automated weather stations in south central Kansas established and maintained by the Equus Beds and Big Bend Groundwater Management Districts (GMD's) are also essential components for the project's success.

IRRIGATION SCHEDULING USING ET

ET, short for evapotranspiration, is a measure of crop water use. Reference ET is based on the measured climatic conditions from a weather station for a "standardized" crop. The reference ET value is a reflection of the atmospheric demand placed on the reference crop. This value is then modified by coefficients specific to each type of crop. The GMD's in that area of Kansas use a grass-based Penman-Monteith reference ET (ET_r). The ET_r estimate is modified by crop coeffients to estimate crop ET (ET_c) and then used to develop a water budget or irrigation schedule specific to a given field or crop. Irrigation scheduling is a process used to determine when and how much water needs to be provided to prevent yield limiting water stress or to apply limited water resources at the most beneficial times. Unlike most crop production management decisions, irrigation scheduling requires daily data, making it a somewhat tedious management procedure to implement at the farm level. Climatic based reference ET estimations and computer software (available through both public and commercial sources) allow the daily collection and processing of data in a more viable management manner. Field partners have been asked to assume more of the irrigation scheduling responsibility for their project field during the course of the project. Over half of the partners are now scheduling.

Figure 1 shows the daily evapotranspiration (ET) for irrigated corn grown in Pratt county in 1998 which was planted May 10 and reached physiological maturity on September 1. In June, which was abnormally hot and dry, daily crop water use rates were approaching and exceeding 0.40 inches per day. However, this high ET period was followed by July and August with relatively low to moderate corn ET values. Cumulative daily ET, rainfall and irrigation amounts are shown in Figure 2 for the period. The cumulative rainfall line shows the long periods without rainfall. Rainfall at that site was below normal for in-season rainfall amounts.

A field soil water balance is shown in Figure 3 and illustrates the essence of irrigation scheduling. This chart is part of a spreadsheet package provided to the partners by the SCKIMP project managers. The partners enter information to characterize the field, crop and irrigation system. Daily inputs of reference ET, rain, irrigation or a measured field soil water content value are used to update the balance sheet and output charts. The upper and lower horizontal lines on Figure 3 represent the soil field capacity (FC) and permanent wilting point (PWP) levels, respectively. The middle dotted line is the management allowed deficit (MAD) soil water value. The goal of the irrigation scheduling procedure is to maintain the field soil water content between the field capacity and the management allowed deficit values. Rain amounts (dots) and irrigation applications (squares) are also displayed. During June, the modeled field soil water content was depleted below the MAD, in spite of the applied irrigation. This means that the crop ET rate was greater than the irrigation capacity to replenish water use by the crop. Fortunately the early crop stress was primarily during the vegetative growth stages and severe yield losses did not occur. However, earlier irrigation would not have been beneficial since the field soil water content was near the field capacity level at that time. Thus, the soil profile for that site could not hold additional water. Most fields in south central Kansas are very sandy and have very low water holding capacity values.

FIELD VERIFICATION OF THE ET WATER BALANCE

Part of the process of getting ET based irrigation scheduling implemented involves building irrigator confidence in the information. One way to accomplish this is to apply varying amounts of water to parts of a field and measuring the effects on yield. Four partner center pivot sprinkler systems were modified in 1997 by adjusting sprinkler nozzle sizes to apply 25% less, 25% more, and "normal" irrigation amounts to test zones on narrow strips (approximately 50 ft. wide). These test zones or rings were placed near to the pivot point to minimize the number of acres affected by the test. The test zone sprinklers were pressure regulated and metered to assure the desired application, however uniformity tests on two of the sites showed that there was more variability in the application depths than expected. As a consequence of the uniformity test, the size of the test zones were increased in 1998 to minimize the effect of adjacent un-modified sprinklers on the test zone area.

Rainfall was higher than normal in 1997, minimizing the potential yield impacts of the variable water application amounts. Rainfall and irrigation amounts for the four sites are shown in Figure 4. All sites had similar crop water use and relatively good corn yields, although sites 4 and 8 with 236 bu/ac and 247 bu/ac (hand harvest) were the highest (data not shown). Field water use efficiency (FWUE) defined as the bushels of grain produced divided by a water depth, which was either irrigation plus seasonal rainfall or irrigation only, is shown in Figure 5.

The 1998 variable water rate study was modified so that the three zones applied approximately 50, 75, or 100% of the amount applied by the partner. Three of the sites were in corn and the application amounts and yields resulted in a confusing mixture of yield versus applied water results. The fourth field was cropped with soybean. Yield, applied irrigation, and field water use efficiency (FWUE) for that site are shown in Figure 6. The yield trend shows the response of increasing irrigation with the highest yield at the 100% water application level. However, FWUE decreased slightly for the 100% level as compared to the 75% zone.

IN-FIELD PIVOT UNIFORMITY EVALUATION

Irrigation efficiency and water distribution uniformity for full sized systems are also being examined as part of the scheduling project. Adoption of irrigation scheduling techniques, especially ET based scheduling, increases the importance of good uniformity since an underlying assumption of scheduling is that each plant has an equal opportunity for access to applied water. Figure 7 shows the plot of water application catch depth from the outer three spans of a field partner center pivot system. The outer half of the center pivot represents over two-thirds of the irrigated field area and allows for efficient collection of representative water application data. The uniformity coefficient for this system was 91%, which meets the accepted industry guideline. However, reduced application depths were measured in the 1100 feet to 1250 feet distance range. The applied depth in that zone was 15 to 20% less than the system average, so in the course of an irrigation season, when eight to twelve application events might occur, that portion of the system would apply a 1 ½ to 3 inches less total water than the field average. Irrigation WUE efficiency for corn can be 10 to 20 bushels per inch of applied water. Therefore, the "underirrigated" portion of the field could have yield losses as much as 50 bushels of corn per acre due to the irrigation system water application non-uniformity. The area under this center pivot represents about 25 acres which could translate into substantial financial losses. Sprinkler package nonuniformities have been identified in almost every tested system and have increased interest of other farmers in uniformity evaluations for their systems.

1998 FIELD SUMMARY

Table 1 is a summary of yield, irrigation, and irrigation water use efficiency from 1998 and shows there is considerable variance between partners. However, examination of individual field records is required to determine if the irrigation schedule followed was appropriate to the field conditions. Rainfall amounts and distribution, and soil type also have a large influence on the amount of irrigation

water needed. Furthermore, yield is also dependent on other production factors that are not discussed here.

CONCLUDING REMARKS

The South Central Kansas Irrigation Scheduling Project began its third full year in the summer of 1999 and will continue through the summer of 2001.

SCKIMP has provided an excellent opportunity to develop and maintain a long-term relationship with irrigation farmers in south central Kansas, resulting in positive progress in establishing acceptance of ET-based irrigation scheduling as a water management tool. The in-field information measurements and observations largely been complimentary to experimental field plot and laboratory based research which increases acceptance of irrigation information from those sources.

Table 1: FIELD PARTNER WATER USE AND YIELD SUMMARY FOR 1998

Partner	Crop	Irrigation inches	Production bu/ac	Area acres	June-August Rainfall inches
1	Corn	14.1	162	133	5.3
2	Corn	15.5	180	126	6.34
4	Corn	10.8	180	138	9.2
5	Corn	7.3	142	125	10.01
6	Corn	8.4	177	136	8.33
9	Corn	16.1	175	163	6.52
13	Corn	15.6	143	112	5.93
8	Soybeans	14.4	54	123	7.57
10	Soybeans	19.9	55	122	4.71
11	Soybeans	17.7	62	130	4.72
7	Alfalfa	21.7	8.1*	130	4.87
3	Wheat/ Alfalfa	11.8	62	169	4.84
12	Wheat/ Milo/Oats	17.2	57	125	4.88

* tons per acre

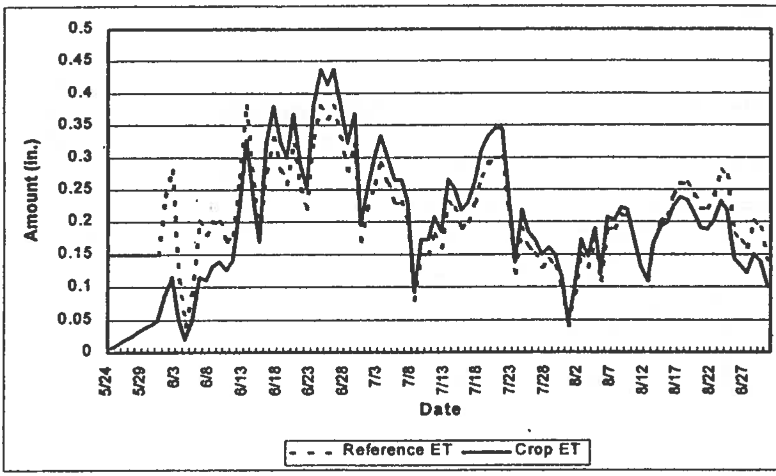


Figure 1. Daily Crop Evapotranspiration

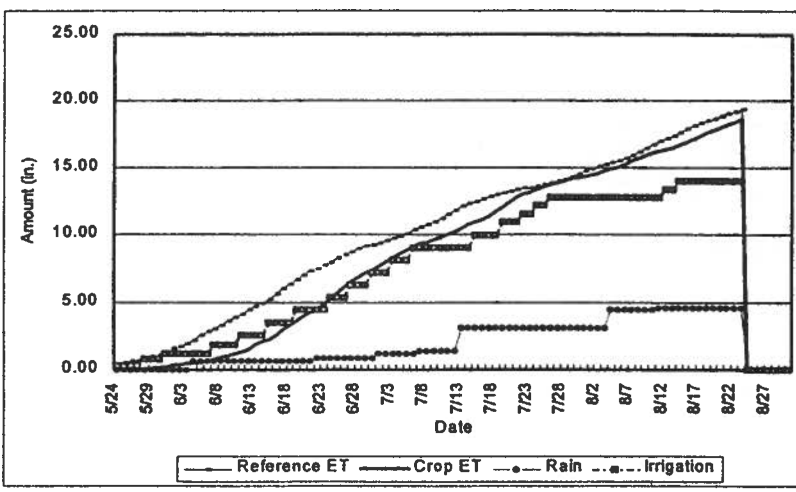


Figure 2. Cumulative Field Water Budget

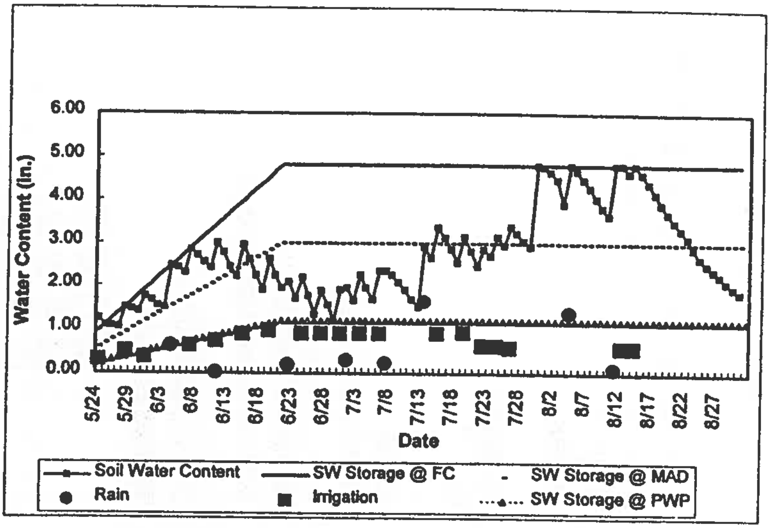
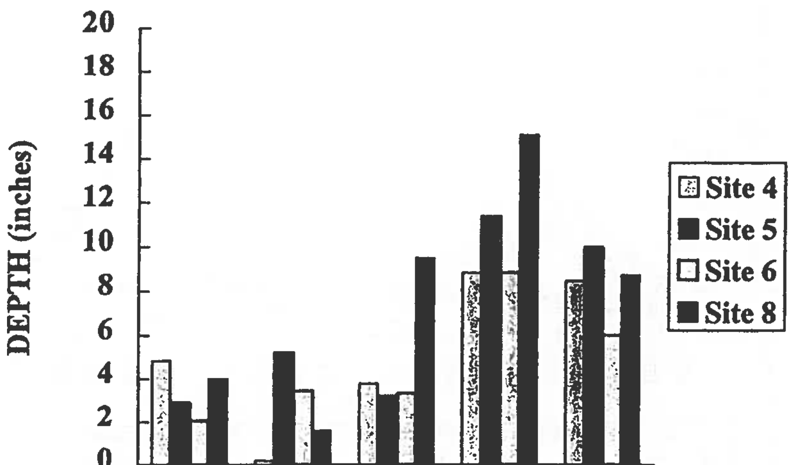
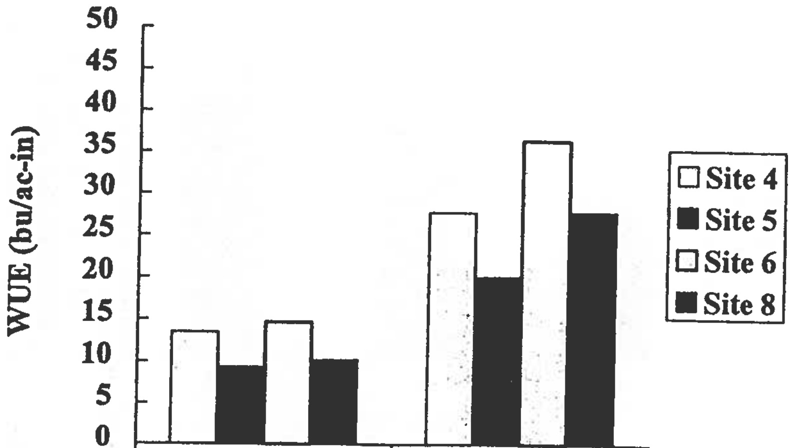


Figure 3. Field Soil Water Content, Rain, & Irrigation



	June	July	August	Total Rain	Irrigation
Site 4	4.85	0.18	3.78	8.81	8.46
Site 5	2.96	5.2	3.24	11.4	10
Site 6	2.05	3.42	3.35	8.82	6
Site 8	4.01	1.6	9.5	15.11	8.75

Figure 4. Site Rainfall and Irrigation - 1997



	Irr+Rain	Irrig
Site 4	13.6	27.8
Site 5	9.4	20.1
Site 6	14.7	36.4
Site 8	10.3	28

Figure 5. Field Water Use Efficiency - 1997

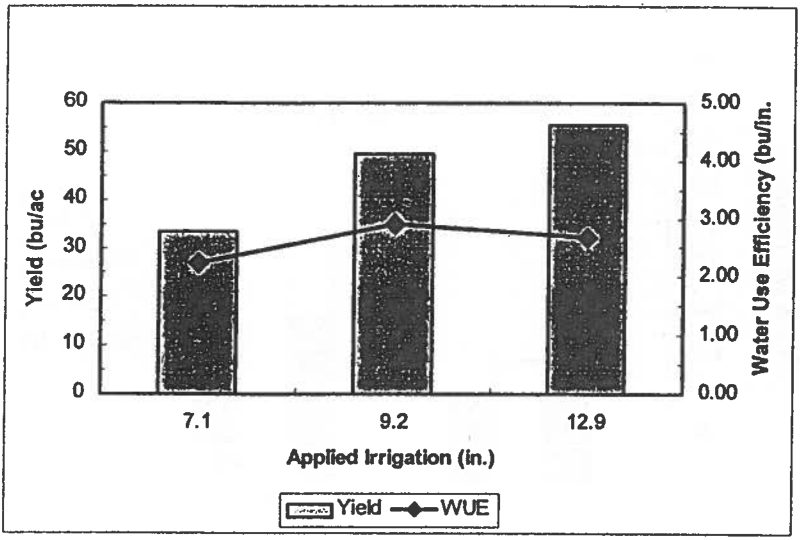


Figure 6. Yield and Water Use Efficiency - Site 8
Soybean (1998)

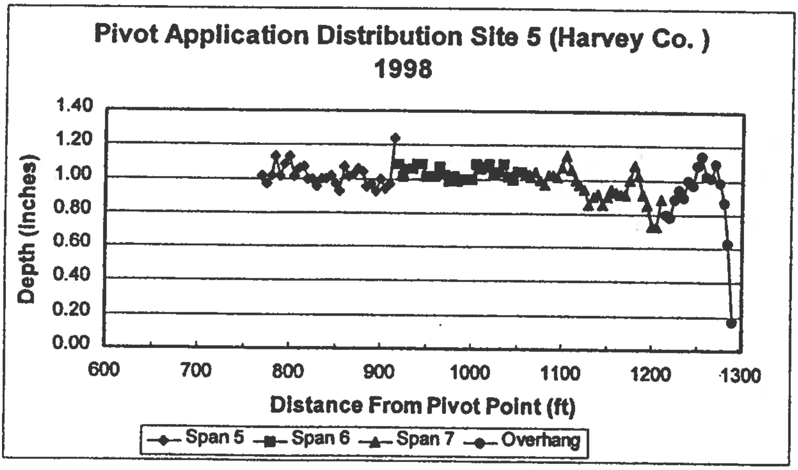


Figure 7. Pivot Application Distribution Site 5
(Harvey Co.) 1998

MANAGING IRRIGATION AND DRAINAGE FACILITIES WITH A SERVICE ORIENTATION

Hector M Malano[1]

ABSTRACT

The performance and sustainability of irrigation and drainage infrastructure worldwide in general and in developing countries in particular has been disappointing. It is argued in this paper that the main cause of poor performance is a lack of service orientation in the management of irrigation and drainage systems. Irrigation systems management with a service orientation entails clear and transparent accountability between managing agencies and customers and a clear delineation of and agreement on the level of service to be provided. An essential aspect of this agreement is the ability to link the level of service to the cost and price of service. An asset management program is the process that enables the managing organisation to formulate a long-term strategy for managing the infrastructure assets and provide this vital information. Two case studies with contrasting service characteristics are compared. The La Khe Irrigation Scheme in Vietnam, and the Goulburn-Murray Irrigation District in Australia. In both cases, the essential aspects of irrigation and drainage service provision are analysed including the cost and price of service, accountability to customers, and main features of their asset management programs.

INTRODUCTION

Poor performance of irrigation and drainage systems worldwide has been widely documented in the past two decades. The most common manifestation of the problen has been the lack of infrastructure and environmental sustainability often leading to low agricultural productivity.

Development of new irrigation areas is likely to continue to decrease in future as the cost of new development and competition for funding with other water subsectors increases. Many irrigation systems worldwide however are reaching the end of the infrastructure life; often prematurely as a result of poor infrastructure management practices. It is envisioned that up to 70% of the existing irrigation and drainage infrastructure will need renewal over the next 2-3 decades (IPTRID, 1990 Plusquellec, 1988)

---

[1] Associate Professor and Director of International Technologies Centre, Department of Civil and Environmental Engineering, University of Melbourne, Parkville, Vic 3052. Australia. Email: h.malano@devtech.unimelb.edu.au

Past experience shows that irrigation and drainage performance and sustainability have been poor with irrigation projects falling well short in areas of environmental and infrastructure sustainability targets. While there many immediate causative factors responsible for low performance, a common underlying reason can be found in the lack of service orientation in the management of irrigation schemes. Responsibility for managing irrigation and drainage systems has been historically the domain of Government instrumentalities with more *administrative* emphasis than *management* emphasis in their operation. The end-result of this type of operation is typically:

- A lack of responsiveness to the needs and desire of customers (users)
- A lack of clear identification of the level of service between the service provider and customer, and as a result;
- A failure to clearly identify the cost associated with the provision of this level of service.

THE CONCEPT OF IRRIGATION AND DRAINAGE SERVICE

The supply of irrigation water and the disposal of excess drainage water involve the conveyance of irrigation water from the source to the cropland or the evacuation of excess drainage water from agricultural and urban areas. In both cases, water -an economic good- is involved; although while the value attached to irrigation water is often substantial, drainage water is considered to have negligible or even a negative value associated with damages. The conveyance function is typically a service activity, which must be provided by an irrigation and drainage organisation.

Irrigation and drainage organisations must rely on substantial infrastructure for the provision of service which is often dispersed over large areas. This feature together with the fact that irrigation and drainage are support functions to agricultural production, itself generally an activity of low value economic output, entails low financial turnover for the provision of these services.

Traditionally irrigation and drainage management organisations have evolved from construction oriented organisations that have overseen the development of most of the irrigation schemes in the world today. More often than not however, these organisations have not managed to reorient their operation to the new environment that is primarily one of managing the existing systems. Malano & Hofwegen (1999) defined the management of irrigation and drainage systems as "*.....the process by which resources are allocated and used to provide irrigation and drainage services in a sustainable and cost-effective manner.*" Implicit in this definition is the concept of infrastructure sustainability and provision of a defined service standard at the lowest possible cost; two typical aims of the management function in any service organisation.

Implementing management with a service orientation in any irrigation and drainage system implies a number of characteristics normally absent in many existing organisations such as accountability to customers, due diligence compliance (safety of operation and work place and environmental), and above all, establishing a clear link between the desired standard of service and the cost of providing this service.

In recent years, much emphasis has been placed on transfer of responsibility for the management of irrigation and drainage to farmers. While the type of institutional arrangements vary from country to country, the main goal of this change is to relieve treasuries from the recurrent financial burden arising for the operation and maintenance of irrigation and drainage facilities. The principles outlined here however, are applicable to Government, corporatised or privatised agencies. Corporatised or privatised organisations may provide as environment more conducive to implementing a service orientated operation as users are in a better position to demand more direct accountability from service providers. Nevertheless, government organisations can also incorporate these attributes in their management activities.

THE ROLE OF ASSET MANAGEMENT

The level of funding for O&M often bears no relation with the age, condition and nature of the works required to sustain the infrastructure. Additionally, no mechanism is implemented to ensure that appropriate provisions are made for future investment in infrastructure renewals or a change in the level of service that may require upgrade of the hydraulic infrastructure. Rather all these activities are often tailored to budgetary allocations that are not commensurate to the actual cost incurred in the provision of a desired level of service. In other words, expenditure on infrastructure is determined by *inputs,* e.g. the availability of money and other resources. As budget allocations are usually insufficient to meet the expenditure requirements for maintenance and renewals of the infrastructure, this approach often results in insufficient expenditure in maintenance and renewals of the infrastructure and therefore lack of sustainability.

An alternative approach to managing infrastructure is to implement an *output* based budgetary process which considers the actual cost of providing irrigation and drainage service. The key element of this approach is a clear definition of the level of service to be provided to customers from which the infrastructure requirements and costs can be clearly identified.

Full cost assessment of the irrigation and drainage infrastructure involves life cycle costing of assets. Life cycle cost of irrigation and drainage assets can be 4-5 times the cost of construction (Moorhouse, 1999). It is therefore imperative that life cycle costing considers all the infrastructure events occurring over the life of the infrastructure including maintenance, renewals, modernisation and retirement that are consistent with the provision of an agreed level of service (Lindley E. 1990). This process has been termed *asset management*. Hofwegen &

Malano (1997) defined asset management as "...*A strategy for the creation or acquisition, maintenance, operation, rehabilitation, modernisation and disposal of irrigation and drainage assets to provide an agreed level of service in the most cost-effective and sustainable manner.*"

The main aims of the asset management program are to ensure the provision of a specific standard of service in a sustainable manner and at the lowest possible cost. By determining the long-term actual cost of running the hydraulic infrastructure, management can become aware of the level of revenues necessary to guarantee the long-term sustainability of the infrastructure and also of the eventual inadequacy of current funding.

An asset management program comprises a strategic and integrated analysis of the life cycle of the infrastructure as part of the continuous management review of the organisation. The ultimate outcome of an asset management program is to bring into focus the actual cost of owning and operating the infrastructure assets to provide a defined level of service. As such, it provides a clear picture for the organisation and for users of the financial implications of providing this level of service.

Fig 1 provides an illustration of the main elements that form part of an asset management program (Malano & Hofwegen, 1999). This is a comprehensive process that embodies the entire life cycle of the assets and consists of analysing all the options both structural and non-structural that are available to provide and sustain an agreed level of service. The process differs slightly depending on whether the program is implemented on a new irrigation scheme or an existing one. In a newly commissioned irrigation or drainage system the process begins with a new set of assets in the same condition whereas in an existing system the condition of assets usually varies across the system. The creation or acquisition of new assets however may take place both in new and existing schemes. In existing schemes, it usually forms part of an asset augmentation plan.

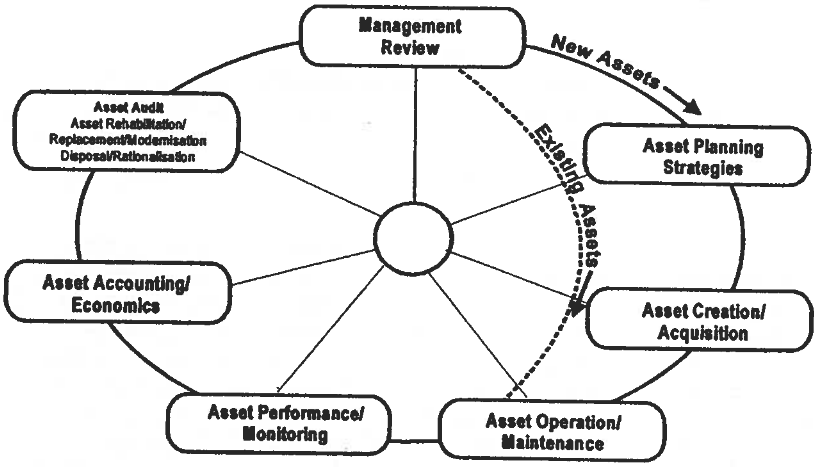


Figure 1. Elements of an asset management program

COMBINING HARDWARE AND MANAGEMENT TO ACHIEVE A SPECIFIC LEVEL OF SERVICE

Service oriented irrigation and drainage is based on developing and implementing a set of specifications that will govern the operation of the system. These specifications serve two purposes:

- provide a set of rules against which the operational performance of the system can be measured; and,
- provide a set of rules to govern the conditions for service delivery.

A typical set of service specifications includes operational parameters such as *rate, duration and frequency of supply, height of supply, supply monitoring, security of supply and quality of supply.* Typical conditions of service delivery are *payment for supply, points of supply to the farm, water ordering requirements, etc.*

The quality or level of service provided can be measured by indicators such as:

- *Adequacy:* This is a measure of the water supply ability to meet the water demand for optimal plant growth. It is often expressed as the ratio of the amount supplied to that required by the crop.
- *Reliability:* This is a measure of the confidence in the irrigation system to deliver water as specified by the level of service. It is defined as the

temporal uniformity of the ratio of the amount of water supplied to the required or scheduled supply.

- *Equity:* This is a measure of the access to a fair share of the water resource according to the amount specified by the water right. In general, it can be defined as the actual supply of water to users in relation to the allocated share.
- *Flexibility:* This is the ability of users to choose the frequency, rate and duration with which irrigation water is supplied.

The ability to deliver a specific level of service depends primarily on the water control hardware and the management inputs. A certain amount of substitution can occur between these two factors (Hofwegen & Malano, 1997). One type of flow control system can provide different levels of service depending on the quantity and quality of management inputs – staff & skills – although some flow control systems impose severe restriction on the flexibility (level) of service. For instance, typical upstream control systems can be used to provide on-request water supply where users may be able to specify the timing, discharge and duration of the delivery. However, the level of management inputs – staff & skills – needed are far greater than if the same level of service is provided by a centrally controlled supervisory system. Moreover, water resource use would be reduced, as the managing agency may have to run additional water in the canal system to meet eventual water orders from users to overcome the lack of ability of the system to respond to rapid changes in the demand. Nevertheless, the decision between alternative types of flow control must be made on the basis of appropriate economic analysis that includes the cost of service provision and the willingness of users to pay for it.

ASSET MANAGEMENT STRATEGIES: CASE STUDIES

An asset management program is the key element in the formulation of the organisation's strategy for the implementation of service orientated management. It is the link element between the operational objective designed to satisfy an agreed level of service and its financial implications. Asset management programs are also dynamic in nature in line with the changing business environment and objectives of the organisation.

The formulation and implementation of an asset management program must form part of a long-term strategy to satisfy specific objectives. As such, the development and implementation of an asset management program is always a long-term endeavour of the organisation. The level of financial and management commitment needed for the implementation of an asset management program is often quite substantial and varies between organisations. Two case studies are described below to illustrate the differences due to irrigation policies and objectives of irrigated agriculture in each case. The case studies selected are the La Khe Irrigation Scheme, Vietnam, and the Goulburn-Murray Water, Australia.

The two cases also highlight the differences in the level of maturity of these asset management strategies.

Case Study 1: The La Khe Irrigation Scheme, Vietnam

The La Khe irrigation scheme is located some 25 km south of Hanoi and services a gross drainage area of 13,000 ha, whilst providing irrigation to 8650 ha. 5615 ha is supplied by gravity from the main canal, which takes water from a spur channel off the Nhue river, via the main pumping station, with a total capacity of 12 m^3/s. The remaining 3000 ha obtain water directly from the Rivers Nhue and Day, which border the service area, and from drainage return water, originally supplied by the main canal.

Irrigation schemes in the Red River Delta (RRD) are characterised by a high reliance on pumping facilities both for irrigation supply and drainage service during the monsoon season. Typical electricity usage in the RRD was calculated to be about 300 kW-hr/ha but have been found to vary from 210-260 kW-hr/ha at LKIS over the research period, which indicates that LKIS is among the more energy-efficient pumped irrigation systems. The LKIS and other schemes in the Red River Delta are characterised by:

- Dilapidated infrastructure resulting from insufficient maintenance
- Poor hydraulic control that prevents a flexible and equitable irrigation service
- High reliance on pumping for water supply
- Poor defined operational rules and specifications

As part of a program aimed at improving the performance of irrigation schemes in the RRD, a methodology for changing the institutional and management arrangements of irrigation schemes was developed. As part of this effort, an asset management program was developed for the La Khe Irrigation Scheme. The main aims of the program are:

- To develop a strategy for maintenance, rehabilitation and modernisation of the irrigation infrastructure
- To develop a financial model to determine the actual system cost to ensure sustainability of the hydraulic infrastructure
- To develop a software tool that can be integrated with the IMSOP model to assist in the day-to-day management of the irrigation infrastructure

Management responsibility for the La Khe Irrigation Scheme and other districts in the RRD lies with the La Khe Irrigation Management Company. Irrigation management companies in Vietnam have traditionally been responsible for managing irrigation from the system intake – usually a pumping station – through to the farmer's fields. This type of arrangement is changing in accordance with Government policy aimed at reducing the company's responsibility to managing the main system while devolving the managing of the secondary and tertiary system to users

Costing Irrigation and Drainage Services: The asset management program is designed to identify all the costs associated with the systems infrastructure.

In addition, there are other cost items incurred in the administration and operation of the systems. Figure 2 shows the composition of the full cost of operation derived from detailed cost analysis for the period 1992-96 assuming asset annuity calculated on a renewals basis[2]. The cost figures provided by the irrigation company were aggregated into the following categories:

- Power cost for irrigation
- Power cost for drainage
- Maintenance
- Bulk water fee: Fee paid to Nhue agency for bulk water supplied to LaKhe Company.
- Personnel: This item includes full time staff, casual wages and staff on-costs
- Overheads: This item includes administration expenses, collection of water fees, taxes and miscellaneous expenses.
- Asset annuity cost

---

[2] Renewals asset annuity is based on the residual life of assets and indicates the cost of making appropriate provisions for renewing assets and the end of their useful life.

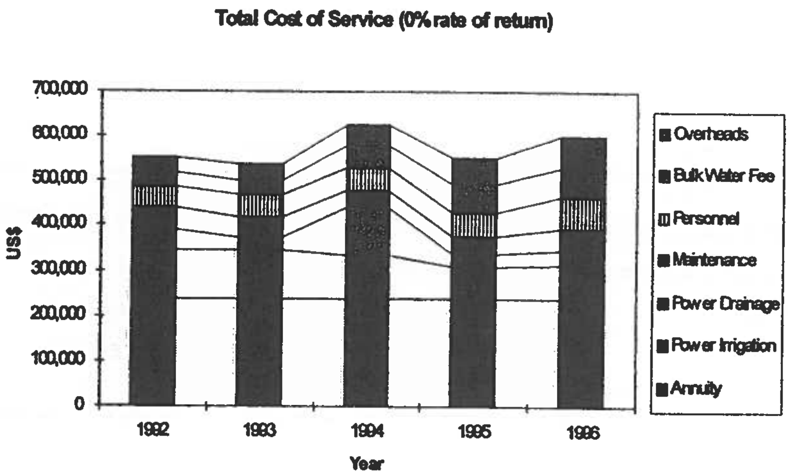


Figure 2. Composition of renewal based system operation cost for La Khe Irrigation scheme.

The asset management program developed for the La Khe Irrigation Co is still in its early stages. Consequently, it was considered premature to include risk costs in the analysis because of the lack of appropriate data to carry out a risk management assessment associated with the system assets. The asset management program at La Khe comprises the main system infrastructure that is used by the company to provide both irrigation and drainage services to farmers. A separate analysis is carried out for secondary and tertiary system assets which will become the responsibility of farmers organised in water users groups under a program of irrigation management transfer promoted by the Government.

Power cost and asset annuity are the more significant cost elements. Power cost accounts for between 25% to 40% for the period analysed which includes 1994, a year of high power use for drainage due to high summer rainfall. It can also be observed that irrigation and drainage are almost of equal importance in this system because of the heavy reliance on pumping for flood control.

An audit of the main system assets was conducted to determine the adequacy of the existing infrastructure to adequately supply the water demanded by the users. Hydraulic simulation of the operation of the main canal revealed capacity constraints in the main canal imposed either by the condition of the canal embankment, the siltation of the canal bed or the capacity of the cross regulators. Implicit in this audit was the assumption that the desired level of service would involve the capacity to supply water to the entire area during the peak demand period occurring during land preparation for rice. Table 1 presents a summary of the rehabilitation works and costs.

Table 1. Summary of main canal upgrade works and costs at La Khe.

Item	Quantity	Cost
Widening cross section	3,670 m	US$3.4/m
Raising embankment	834 m	US$1.7/m
Offtakes	59	US$280.00 each
Total		**US$30,415**
Cost per ha[3]		**US$3.45**

The La Khe Company refurbished the main canal during the 1998 Spring irrigation season. The additional depreciation charge incurred in relation to the current water price would be negligible given that the life of earthen canals can be considered indefinite. Conversely, canal maintenance cost will be substantially higher if the canal is to be maintained to meet the new hydraulic specifications.

Secondary and Tertiary System Costs: As indicated above, new institutional arrangements are intended to be implemented at La Khe whereby the Irrigation Management Company will become a wholesale water supplier to Water Users Groups organised in each secondary canal. These will in turn become responsible for the water distribution (retail) and maintenance of the secondary and tertiary infrastructure. The current asset management program does not include the secondary and tertiary system infrastructure. Nevertheless, a preliminary reconnaissance survey of secondary and tertiary system assets was conducted to develop guidelines to assist Water Users Groups with the management of the infrastructure, especially the assessment of water fee charges to be levied to individual farmers.

Water level in secondary canals is maintained largely by discharge control. There is a diversity of offtake configurations along secondary canals as a result of repairs and replacements made over the life of the system which makes any attempt to control, distribute and measure water distribution equitably very difficult. Future replacement of offtake structures along secondary canals must consider the possibility of standardising the design, possibly using precast concrete structures which would enable proper measurement of discharge into the tertiary canals.

The new institutional arrangements were tested on the three largest secondary canals at La Khe to evaluate the performance of the new model. This provided the opportunity to conduct a full asset audit for a secondary canal and identify the existing constraints to proper water management along the canal. On the basis of the survey, a preliminary design for the upgrade of the canal was carried out. The objectives pursued in the new design were:

- to modify the current design in order to provide sufficient canal capacity and water level control that enables an equitable and simple distribution of water along the canal; and,
- To achieve this in the most cost-effective way.

Table 2 summarises the main structural components and costs for the upgrade of secondary canal N5.

Table 2. Cost summary for refurbishment of N5 secondary canal.

Structure Type	**Number**	**Cost**
Duckbill weir	1	24 mil VND (US$1,714)
Gated cross regulator	1	36 mil VND (US$2,285)
Tertiary offtakes	16	32 mil VND (US$2,285)
Improvement lined section		20 mil VND (US$1,428)
	Total	**112 mil VND (US$8,000)**

The N5 secondary canal provides service to 773 ha of irrigated land. The estimated cost of upgrade of 12.00 $/ha represents an additional charge to the users of 1.60 $/ha annually assuming an economic life of 30 years and interest rate of 13%. This is clearly a small cost for the operational and productivity benefits to be derived from the upgrade.

Pricing of Irrigation Services: Historically, the price of irrigation and drainage service in Vietnam bears little relation with the actual cost of service provision. This can be ascribed to various factors including the prevalence of an *input* budgetary process instituted by Government and inappropriate identification of actual costs which in turns lead to inappropriate budget allocations even under subsidisation schemes

Figure 3 shows the comparison system operation costs with actual revenues assuming no rate of return on the infrastructure investment. The average revenue for the period analysed was US$49.00/ha while the average cost of operation was US$50.00/ha. These figures were calculated including the annuity component based on full economic life of assets. Presently, there are no formal provisions made for actual depreciation payments. The average cost over the period of study if provisions for depreciation must be made over the residual life of the present infrastructure is US$60.00 which leave a significantly greater gap between revenue and actual overall cost.

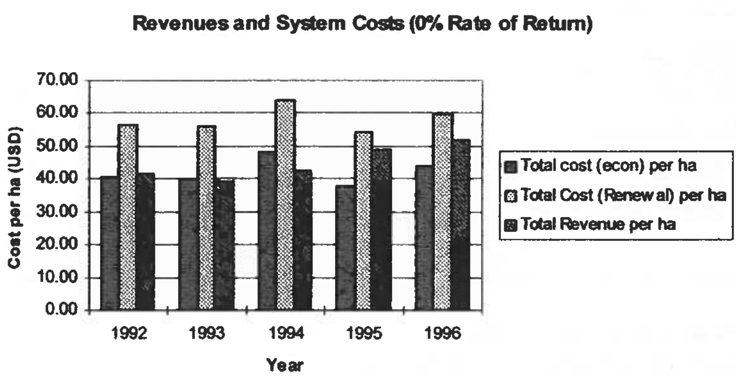


Figure 3. Comparison of system costs and revenues assuming no return on assets

Case Study 2: Goulburn-Murray Rural Water Authority, Australia

The Goulburn-Murray water authority is one of the authorities created under the water reform program and within the provisions of the Victorian Water Act of 1989. The authority is responsible for providing irrigation and drainage service to over 500,000 ha in north-east and central Victoria. It is also responsible to the operation of headworks to deliver bulk water supply.

Agriculture in the region is based on dairy production (52%), horticulture (23%) and cropping and grazing (25%). The breakdown of water use by the same industries is 55%, 3% and 42% respectively of the 2,500 GL of water distributed by the authority. The authority serves a customer base of 24,000 properties gravity and pumped irrigation, sub-surface and surface drainage, surface and ground water diversion and stock water supply.

To provide this range or services, the authority relies on a large network of mature assets spread over a wide area including 6,756 km of irrigation channels, 394 km of domestic and stock channels, 249 km of pipeline, 2,931 km of drains, 25,244 structures and 24,492 water meters.

Most of the authority's asset base was developed early this century and have undergone periods of under investment in maintenance and replacement, particularly in the 1970's and 1980's.

The hydraulic infrastructure consists of a typical upstream manually controlled system that relies on a combination of undershot and overshot regulators. Water distribution to farmers is carried out via Dethridge meter wheels that enable volumetric metering of deliveries. As part of the modernisation effort undertaken by the Authority, cross regulation structures in the main distribution system are progressively being brought under SCADA control technology.

Level of Service: Irrigation and drainage service specifications have been developed by the Authority and form part of the Customers Service Agreements. The irrigation standard services include 4-days notice for all orders with day 1 being the day after the order is placed. The agreements also include clauses related to percent of delivery targets, flow variation during delivery, and conditions for changes in start and finish times.

The tariff structure consists of two parts: A fixed component which is attached to the actual water allocation, and a variable component which is charge volumetrically according to the amount used.

Drainage services are provided according to variable ratings depending on the ability of the Authority to provide drainage to each property. Thus drainage rating factors depend on factors such as whether the property drains directly into the Authority's drains, the distance to the Authority's drains or whether the property is drained by community, private or other drains.

Asset Management Program: The development of the agency's asset management program was started in 1992/93 by the authority's predecessor organisation –The Rural Water Corporation – The program was initiated in response to the need for operating and maintaining the asset base in a financially sustainable manner and properly identifying the future cost of service provision and asset renewal. The stated objective of authority's asset management program (Moorehouse I, 1999) is "*...to ensure that agreed service and integrity standards of the distribution assets can be met over the long term whilst minimising life cycle costs.*"

The authority's asset management program is based on a comprehensive strategy which includes several key elements, including:

- Agreed levels of service
- Asset information
- Total life cycle approach
- Renewals pricing
- Cost effectiveness
- Risk management
- Statutory and due diligence compliance

Levels of service needed to be defined and agreed in order to identify the infrastructure interventions and costs of service provision. To address this, the authority relies on seventeen Water Services Committees that represent the rural customers. These are distributed in six irrigation areas, ten river basins and other waterworks districts. Relations between Water Services Committees and the authority are guided by Customer Service Agreements for each type of service, levels of service, pricing policy and billing arrangements. The overall performance is evaluated according to key performance indicators written into the agreements.

The cornerstone of the asset management program is the asset register. Vital physical and financial analysis relies on accurate information on the authority's asset base. The computerised asset register contains location, condition and other financial data that easily stored and retrieve by the organisation and is fully integrated with authority's information management system.

Pricing of Irrigation Services: As indicated above, the level of expenditure on asset maintenance and replacement prior to the implementation of the asset management program was not consistent with the long-term sustainable provision of services by the authority. The asset management program has enabled the authority to link transparently the provision of the adopted level of service with the price of service. The authority has adopted a renewals pricing policy which assumes that the infrastructure system is intended to be maintained indefinitely at a particular service level by continuing maintenance, replacement and refurbishment. The renewals annuity is set aside to enable the authority to meet the future capital expenditure required to sustain the level of service. The renewals annuity strategy consists of :

- Appropriate forward planning period, e.g. 20-year rolling planning;
- Cash flow forecasts based on technical assessments and financial estimates,
- Calculation of net present values and annuities
- Refurbishment and replacement financed from annuity reserve

At present, water pricing policy is continually revised according to renewal rolling plans. Currently, the cost of renewal annuity can constitute up to 30% of the total price of service. Water prices in the six areas supplied by the authority range between A$17.50/ML and A$22.00/ML (US$11.50-US$14.30). Reflecting the cost of asset renewals in the price of water has focussed the organisation and customers on achieving productivity improvements to restrict price increases and still meet the Government's requirement to achieve financial self sufficiency by 2000/01.

CONCLUSION

It is argued in this papers that managing irrigation and drainage facilities with a service orientation entails the ability to link the provision of a well defined level of service with the cost and price of service provision. Two case studies are contrasted to illustrate different degrees of evolution towards the implementation of service orientation: The La Khe Irrigation Scheme in Vietnam, and the Goulburn-Murray Water Rural Water Authority in Australia.

The La Khe Irrigation Company is one of the typical organisations managing irrigation and drainage systems in the Red River Delta of Vietnam which has begun to undergo management changes in parallel to the Government economic reform policies introduced in 1988. An asset management program was developed for this scheme to ascertain the long-term cost of service provision and its relation to the current water pricing policy. It revealed that there exists a substantial gap between cost and price of service (US$11.00/ha/annum). This shortfall has resulted in under-spending in maintenance and renewal of assets and the progressive deterioration of the system's infrastructure base

The Goulburn-Murray Water Authority is a public corporation with responsibility for managing irrigation and drainage services provided to over 500,000 ha in Northern Victoria. Despite technological constraints, the Authority has traditionally been able to provide a high (flexible) level of service to farmers. The authority relies on an upstream manually controlled flow system which is progressively being upgraded to improve the efficiency and effectiveness of service provision. This effort is part of an asset management program that began as early as 1992 in response to a Government policy to reduce subsidies. The program is designed to ensure that the full cost of service provision including full renewals annuity is reflected in the price of service. This accounts for 30% of the current A$20.00/ML average water charge.

REFERENCES

Hofwegen P. V.M. van & H. M. Malano. 1997. Hydraulic Infrastructure under Decentralised and Privatised Irrigation System Management. In: Decentralisation and Privatisation in Irrigation, DVWK Bulleting No 20. Pp 188-216, German Association for Water Resources and Land Improvement.

IPTRID. 1990. Irrigation and Drainage Research – A proposal for an internationally supported program to enhance research on irrigation and drainage technology in developing countries. Volume 1. 21 pages.

Lindley E., 1990. Asset Management Planning: Theory and Practice. Journal of Water and Environmental Management, Vol 6, 621:627.

Malano H. & P. V. Hofwegen. 1999. Management of Irrigation and Drainage Systems: A Service Approach. IHE Monograph 3. Balkema, Rotterdam, Brookfield. 149 pages.

Moorehouse, I. (1999). Asset Management of Irrigation Infrastructure. Irrigation and Drainage Systems: An International Journal. Kluwer Academic Press. **13:** 165-187.

Plusquellec, H. 1988. Improving the Operation of Canal Irrigation Systems, The Economic Development Institute of the World Bank, Washington D. C. 155 pages.

AN ECONOMIC APPROACH TO IMPROVING WATER MANAGEMENT IN WATERLOGGED AND SALINE AREAS

Dennis Wichelns[1]

ABSTRACT

Waterlogging and salinization arise in arid areas largely because two essential resources, irrigation water and the assimilative capacity of unconfined aquifers, are not priced or allocated correctly to reflect scarcity values and opportunity costs. Farm-level decisions regarding irrigation methods and water volumes will not be socially optimal when such values are not communicated to farmers in the prices they pay for irrigation and drainage resources, or in allocations that define their water supply or drainage capacity. Modifying farm-level prices and allocations may be helpful in reducing the rate of increase in waterlogged and saline areas in many regions.

This paper describes why farm-level irrigation and drainage strategies often differ from those that would be considered socially optimal. In the absence of appropriate economic incentives, farmers are not encouraged to consider the off-farm and long-term impacts of their decisions regarding irrigation and drainage inputs. Policies that can be implemented to provide such encouragement include volumetric water pricing, water markets, tradable water allotments, adjustments in area-based cost recovery programs, and incentives for farmers to use irrigation methods that reduce deep percolation.

WATERLOGGING AND SALINIZATION

Waterlogging and salinization have reduced the productivity of agricultural land in arid regions since the rise and fall of Mesopotamia, even though the irrigation-induced causes of these conditions have been known for nearly as long (Jacobsen and Adams, 1958; Kovda, 1983; Szabolcs, 1987; Ghassemi et al., 1995). Known also as the "twin menace" of irrigated agriculture, waterlogging and salinization affect most of the world's large-scale irrigation systems and they continue to impose farm-level and public costs in the form of lost production and efforts to reduce the rate of increase in affected areas.

---

1 Associate Professor, Univ. of Rhode Island, Kingston, Rhode Island.

Waterlogged and saline soils are found naturally in many areas, but inappropriate irrigation also causes waterlogging and secondary salinization, resulting in economic losses when crop yields are reduced by high water tables and soil salinity (Barrow, 1987, 1991; Szabolcs, 1987; Rhoades, 1990; Smedema, 1990; Dregne, 1991; Abdel-Dayem, 1997). The primary irrigation-induced causes include leakage from poorly lined irrigation canals and reservoirs, excessive water application, and inadequate drainage of agricultural land (Barrow, 1991; Scott, 1993). Seepage from irrigation facilities and deep percolation from farm fields enter unconfined aquifers that have become saline after many decades of irrigation. When a water table rises within 2 m of the soil surface, the root zone available to plants becomes restricted, salts rise to the surface by capillary action, and the resulting salinization can render land unsuitable for agriculture (Stone, 1984, p. 141; Arnon, 1987 p. 147; Abernethy and Kijne, 1993; Abrol and Sehgal, 1994; Hillel, 1994).

Some deep percolation is required in arid regions to remove salts from the root zone and sustain productivity, over time (Oster, 1984; Hoffman, 1990; Rhoades and Loveday, 1990). However, actual leaching fractions often exceed leaching requirements, because the non-water costs of irrigation rise with farm-level efforts to increase irrigation efficiency (Letey et al., 1990; Dinar and Zilberman, 1991). In addition, many water allocation and pricing policies do not motivate farmers to use water efficiently (Abrol et al., 1988; Prasad and Rao, 1991; Sampath, 1992; Meinzen-Dick and Mendoza, 1996; Rosegrant and Meinzen-Dick, 1996). Excessive deep percolation occurs in rotational water delivery systems in which farmers irrigate according to calendar-based schedules that do not match crop water requirements (Dhawan, 1989; Qureshi et al., 1994). In many systems, water prices are too low to encourage farm-level improvements in water management or to justify investments in irrigation methods that minimize deep percolation (Mageed, 1994; Hillel, 1994, p. 217).

AN ECONOMIC PERSPECTIVE

From an economic perspective, irrigation-induced waterlogging and salinization in arid areas arise largely because irrigation water and the assimilative capacity of unconfined aquifers are not priced or allocated correctly to reflect scarcity values and opportunity costs. Volumetric water prices are lower than optimal or non-existent in many irrigated regions, and allocation procedures are often based on rotational schedules that do not provide the flexibility or certainty required for farmers to optimize water use. In most irrigation systems, farmers may "discharge" deep percolation to unconfined aquifers at no charge and with no restrictions, even though assimilative capacity is often limited. As a result, the scarcity values of irrigation water and unconfined aquifer capacity are not communicated to farmers in resource prices or allocations, providing them with little incentive to consider the opportunity costs or the off-farm effects of irrigation and leaching activities.

Some Useful Economic Concepts

Opportunity cost is the incremental value of a resource or input in its next best alternative use. For example, when a farmer's water supply is limited, the opportunity cost of water used to irrigate a tomato field is the value that could be generated if that water were used instead to irrigate a cotton field.

Scarcity value is the implicit value of a limited resource that may or may not be priced in a market setting. For example, the scarcity value of water on a farm with a limited water supply is the value that could be generated with an additional acre-foot of irrigation water.

A socially optimal allocation of resources maximizes the net benefits generated in production, minus any costs that are not generally considered by firms or consumers, such as the environmental or off-farm effects of irrigation and drainage activities. The socially optimal combination of inputs and outputs will differ from the farm-level profit-maximizing combination when farm activities generate external costs. The social optimum will vary, over time, with changes in society's preferences regarding resource allocation.

External costs and benefits are the off-farm effects of agricultural activities. These generally are not considered by farmers when choosing profit-maximizing input and output combinations. Economic incentives such as effluent fees and cost-sharing programs for improving irrigation technology are designed to encourage farmers to consider external costs and benefits.

A discount rate can be used to describe the preference of an individual or society for receiving net returns or net benefits in the near term, rather than receiving those returns or benefits in future years. Higher discount rates describe stronger time preference. For example, an individual with a discount rate of 6% would prefer to receive net returns more quickly than an individual with a discount rate of 4%, if all other characteristics of the individuals are the same. The discount rates of individual firms and consumers will be higher than social discount rates if society places greater emphasis on net benefits available to future generations.

Off-farm effects are considered external costs in economic models of farm production because they are not paid by farmers when selecting crops or choosing irrigation inputs (Young and Horner, 1986; Chisholm, 1987; Upstill and Yapp, 1987; Ellis, 1992, p. 264; Izac, 1994; Strojan, 1995). Economic incentives and other policies that encourage farmers to internalize external costs can be identified by examining the farm-level and public goals regarding irrigation, and noting the differences in optimizing criteria that describe how farm-level and societal net benefits are maximized. Appropriate policies will provide farm-level incentives that are consistent with the criteria for maximizing societal net benefits.

Farm-Level Goals and Criteria

The farm-level irrigation objective can be described as maximizing the present value of net revenue, over time, while maintaining the quality of productive resources. The standard optimizing criterion for farmers in a humid region where soil salinity is not a problem is to equate the incremental value of water in crop production with its incremental cost, or price (Upton, 1996, Ch. 9). Incremental values are determined by crop-water production functions and crop prices, while water cost may be an explicit price for surface water delivery or the unit cost of pumping groundwater (Howell, 1990; Dinar et al., 1991). As water price or cost increases, farmers will reduce the volume of water applied, often by increasing the use of labor or technology to maintain crop yields, while irrigating more efficiently.

In arid regions, farmers must also consider the long-term impacts of irrigation and leaching on soil salinity. The net change in salinity is usually positive following irrigation events because plants use the water, while leaving salts in the soil. Leaching events displace salts from the profile by flushing soils with relatively good quality water. The farm-level optimizing criterion for saline areas includes the long-term impact of adding salts and the long-term benefit of moving salts through the soil profile when applied water exceeds crop water requirements.

Farmers in arid regions will achieve their profit maximizing goal if they equate the incremental value generated with irrigation or leaching water, plus the value gained by removing salts from the soil, with the price paid for water and the long-term, incremental damage caused by adding salts. Farmers will consider similar issues when selecting irrigation methods and water management practices. Surface irrigation methods (furrows, borders, and basin) are less expensive than sprinklers or drip systems, but they can also be less efficient and can generate more deep percolation during irrigation and leaching events. Farmers using more efficient methods can achieve irrigation goals with a smaller volume of water and they can achieve greater distribution uniformity that may enhance crop yields (Barrow, 1987, Ch. 7; Letey et al., 1990; Agnew and Anderson, 1992, Ch. 6).

Public Goals and Criteria

The public's goal regarding a publicly funded irrigation project may be described as maximizing the present value of societal net benefits generated, over time. Societal benefits include the value of farm products and other agricultural and non-agricultural benefits provided by an irrigation project, while costs include farm-level production costs, operation and maintenance of irrigation facilities and any off-farm impacts of irrigation and leaching. Societal costs also include the opportunity costs of water resources in regions where demand for water exceeds supply.

The net social benefit of an irrigation project is maximized when the incremental social benefit is equal to the incremental social cost. In particular, the sum of incremental agricultural and non-agricultural benefits must be equal to the incremental cost of water delivery, plus the long-term cost of adding salt during irrigation and leaching, the opportunity cost of water, and the long-term cost of rising water tables.

Farm-level decisions regarding water use will not be socially optimal unless water prices reflect incremental delivery costs, opportunity costs and the off-farm impacts of irrigation and leaching activities. In addition, farm-level discount rates used to calculate the present value of the long-term costs and benefits of irrigation and drainage activities must be the same as social discount rates. In practice, farm-level rates will likely exceed those used by the public to evaluate returns from irrigation projects, as individuals often place greater relative values on near-term net revenues than public agencies, which may assign greater relative value to the welfare of future generations (Sen, 1984, p. 175). When this occurs, farm-level choices regarding irrigation water and other inputs may result in a faster rate of waterlogging and salinization than is socially optimal (Quiggin, 1987; Greiner, 1997). This effect, in combination with inappropriate water prices and allocation methods, may explain why many large-scale irrigation projects encounter problems of waterlogging and salinization sooner than expected by project planners (Abul-Ata, 1977; Kapoor and Kavdia, 1994; Ramanathan and Rathore, 1994).

POLICY IMPLICATIONS

Differences in the criteria for maximizing the present value of farm-level or societal net benefits explain why farm-level choices of irrigation and leaching inputs are not socially optimal. Farmers have no economic incentive to consider the external effects of deep percolation on a regional water table and farm-level discount rates may exceed the social rate. In addition, farm-level water use will exceed the social optimum when the price of water is less than the incremental cost of delivery or when farmers are not presented with opportunity costs. Farm-level choices of water management inputs will also differ from societal optima when prices do not reflect off-farm effects. Policies that modify the farm-level price or availability of water and other inputs may be useful in closing the gap between farm-level and socially optimal input choices. We examine the potential role of water pricing and allocation policies, water markets, land assessments, and subsidies to encourage improvements in water management practices.

Water prices

Economic theory suggests that if the farm-level price of water includes the incremental delivery cost, the opportunity cost, and the long-term impact of rising water tables, farmers will choose the socially optimal levels of water use. In theory, the optimal water price should vary among farms according to differences in delivery costs and the impacts of irrigation and leaching on regional water tables. However, in most irrigated areas farm-specific water table effects cannot be estimated accurately, and farm-specific water prices are either very costly to implement or politically infeasible. A uniform water price, or a price that varies by region, is more likely to be implemented. In those situations, an estimate of average water table effects can be obtained using hydrologic data that describe irrigation water deliveries and rising water tables, over time, or technical coefficients that describe the proportion of applied water that becomes deep percolation when using various irrigation methods. The estimated average value could be used in place of farm-specific values when determining a uniform water price.

The opportunity cost of water can be estimated by considering the increase in regional net revenue that could be generated with additional water supply. In regions with an active water market, this may be estimated using water market prices, as these would reflect a major component of the opportunity cost of water. The incremental cost of water delivery includes operation and maintenance costs for the water delivery system. The portion of those costs that should be included in water prices may vary with public goals and the distribution of benefits from irrigation projects (Sampath, 1992).

Implementing a uniform water price in place of farm-specific prices will negate some of the efficiency gains implied by optimal water prices, but this should not dissuade public officials from considering a uniform pricing policy. In many irrigated regions, any effort to implement or enhance volumetric water prices will likely motivate farm-level improvements in water management that will improve the productivity of scarce water resources and reduce deep percolation. The societal value of this result may be substantial, even if water prices are not precisely the optimal prices prescribed by theory.

Volumetric water prices may also provide an economic incentive for public water agencies to improve delivery service and to reduce seepage along main and secondary canals, particularly if agency budgets are made dependent upon the collection of revenue from water sales (Moore, 1989; Small and Carruthers, 1991, pp. 52-53; Ellis, 1992, p. 271). Water agency personnel in regions where water is delivered at no charge to farmers and water rights are not assigned have little incentive to spend limited funds on canal improvement projects (Repetto, 1986). Placing a value on water at the agency level may reduce waterlogging and salinization caused by seepage from main and secondary canals.

Water markets and water rights

Formal and informal water markets are effective in communicating scarcity values among potential buyers and sellers, by providing farmers with an opportunity to lease or sell a portion of their water supply for a specific time interval or in perpetuity (Dudley, 1992; Rosegrant and Binswanger, 1994; Rosegrant and Meinzen-Dick, 1996; Dinar et al., 1997). Markets also encourage farmers to consider opportunity costs explicitly when they choose cropping patterns and irrigation methods (Dinar and Letey, 1991; Weinberg et al., 1993). Farmers with attractive market opportunities may choose to improve water management practices to make water available for sale or lease. Farm-level efforts to "convert" surface runoff or deep percolation into marketable water volume will reduce pressure on regional water tables. In areas where surface runoff or deep percolation is used by downstream farmers, it may be necessary to compensate those farmers for reductions in their water supply.

Water markets eliminate the need for public agencies to determine the opportunity cost or scarcity value of water, as market participants will express their desire to purchase or sell water at prices that reflect prevailing perceptions of scarcity. However, markets do require that property rights to water, or water use rights, are defined and enforced (Hearne and Easter 1995; Anderson and Snyder, 1997, pp. 22-25; Perry et al. 1997). In many regions, this will require improvements in water measurement and control capability, but those improvements would also support volumetric water pricing and may enable water agencies to provide farmers with greater flexibility in scheduling water deliveries.

Describing international experience with water markets, Briscoe (1997) concludes that "from a conceptual, practical and political perspective, the appropriate approach for ensuring that the scarcity value of water is transmitted to users is to clarify property rights and to facilitate the leasing and trading of these rights." Svendsen and Meinzen-Dick (1997) include a "net shift of authority for allocating water use rights from public agencies to the use right holders themselves through private transactions and arrangements" in their list of themes regarding future water management policies and institutions. Rosegrant (1997) suggests that the most important water policy reforms will involve changing the institutional and legal environment in which water is supplied to one that enables individuals to make their own decisions regarding water use, while at the same time presenting them with the true scarcity value of water.

Many examples of water markets have been described in the literature, including those in California (Cummings and Nercessiantz, 1994; Howitt 1994), Chile (Gazmuri 1994; Gazmuri and Rosegrant, 1996), India (Janakarajan, 1993; Shah, 1993; Saleth, 1996; Shah and Ballabh, 1997), and Pakistan (Chaudhry, 1990; Meinzen-Dick, 1994). In many cases, markets have improved the productivity of water resources while providing farmers with income-enhancing opportunities.

Water allotments

Some of the world's largest irrigation systems are operated by central government agencies that control the release and delivery of water along main and secondary canals, and determine how much water will be delivered to farmers or water user associations (Upton, 1996, pp. 200-201). There may be little or no formal experience with water markets or water rights in those systems, and the political desire to implement such programs may be limited. A potentially useful alternative is a program of water allotments that define how much water or delivery capacity is available to individual farmers or water user associations, each year, as a function of water supply or an environmental goal, such as reducing deep percolation. Allotments would provide farmers with clear information regarding water availability, without assigning ownership, as is usually implied in a system of formal water rights. The economic efficiency of an allotment program can be enhanced by allowing farmers to trade their allotments, either individually or as members of water user associations.

A program of water allotments can be designed to achieve specific program goals, while minimizing distortion of farm-level crop choices. For example, if the goal is to reduce deep percolation in a region where the aggregate water supply is not limiting, crop-specific allotments defined according to crop water and leaching requirements would provide farmers with sufficient water to irrigate crops they choose, provided they apply only the required water. Alternatively, if the aggregate water supply is limiting, and waterlogging problems are due to uneven distribution of water among farmers, a program of uniform water allotments defined according to the available supply may be more effective in reducing deep percolation, while improving aggregate production. Such a program would encourage farmers to consider the scarcity value and opportunity costs of water when choosing crops and irrigation methods.

Examples of crop-specific and uniform water allotments are compared in Table 1. A farmer with 3 ha of land planted in equal portions of alfalfa, cotton, and sugarbeets would be allotted 31,350 m^3 of irrigation water in a crop-specific program, while a farmer with the same land area would be allotted 27,000 m^3 in a uniform program. The second farmer may be able to produce the same crops by improving water management practices and, possibly, by allowing a shallow aquifer to provide a portion of crop water requirements. This would further enhance efforts to reduce the rate of increase in waterlogged areas. In this example, the uniform program may cause farmers to discontinue growing sugarcane, but that result may enhance societal net benefits in a region with a limited water supply or delivery capacity, uneven distribution of water among farmers, or problems with waterlogging and salinization.

Some of the farmers receiving 9,000 m^3 per ha in the uniform program may choose to sell or lease a portion of their allotment to other farmers for appropriate compensation. Farmers selling allotments may choose to grow crops with smaller water requirements and improve water management practices, while earning revenue from the sale or lease of allotments. Voluntary market transactions would determine the appropriate prices of allotments, and those prices would likely change, over time, with changes in crop prices and the cost of water, labor, and other inputs.

Land Assessments

Public water agencies in India, Pakistan, and other countries with major irrigation projects charge farmers for water delivery services using area-based assessments intended to recover the costs of operation and maintenance (Puttaswamaiah, 1994, p. 187; Kemal et al., 1995; Tsur and Dinar, 1997). The charges are usually higher for crops with higher crop water requirements and in regions with higher costs of service. These programs are less costly to implement than volumetric water pricing (Small and Carruthers, 1991, p. 141), but do not provide an economic incentive to use water efficiently because the farm-level cost of additional water within a season is zero.

An economic incentive to reduce deep percolation can be incorporated in area-based assessment programs by enhancing the crop-specific price structure to reflect the deep percolation objective. In particular, an area-based

Table 1. Examples of crop-specific and uniform water allotments to encourage reductions in deep percolation

Crop	Estimated Crop Water Requirement	Estimated Leaching Requirement	Crop-Specific Water Allotment	Uniform Water Allotment
		(m^3 per hectare)		
Alfalfa	12,000	1,200	13,200	9,000
Cotton	10,000	1,000	11,000	9,000
Sugarbeets	6,500	650	7,150	9,000
Sugarcane	20,000	2,000	22,000	9,000
Wheat	5,500	550	6,050	9,000

Notes: Crop water requirements are the midpoints of ranges in crop water requirements reported by Doorenbos and Kassam (1979, pp. 6-7).

Leaching requirements are estimated as 10% of crop water requirements, as recommended for irrigation water with an electrical conductivity (EC) of 0.75 mmhos/cm and drain water with an EC of 8.0 mmhos/cm (Doorenbos and Pruitt, 1975, p. 127).

Uniform water allotments describe an example in which the total water supply or delivery capacity in a canal command area is limited to an average delivery of 9,000 m^3 per hectare.

surcharge can be imposed on fields that receive larger water deliveries than crop-specific targets determined by the water agency, in consultation with farmers and water user associations. The targets could be established at levels that enable farmers to satisfy crop water and leaching requirements without generating excessive deep percolation, such as the crop-specific water allotment volumes shown in Table 1. Farmers exceeding those volumes could be required to pay an area-based surcharge determined by estimating the external cost of deep percolation, which is the present value of future reductions in regional net revenues due to rising water tables. The estimated opportunity cost of water also could be included in the surcharge to provide an additional incentive for farmers to achieve the targets.

Water Management Inputs

Improvements in water management practices can generate farm-level benefits by reducing the volume of water applied to soils and, thus, reducing the rate of salt accumulation. This provides an economic incentive to implement such practices, which include using sprinkler and drip systems, laser leveling, and hiring additional labor to improve the management of surface irrigations. Delivering water with greater precision enables farmers to reduce deep percolation, while maintaining or improving crop yields. However, farm-level expenditures for irrigation increase with the use of higher technology systems and a long-term cost may arise if the reduction in deep percolation reduces the rate at which salts are removed from soils. Farmers selecting irrigation methods will evaluate near-term and long-term effects, but will not consider the off-farm benefit of increasing regional water table depth.

The societal benefits of improvements in irrigation methods may be sufficient to justify public policies that motivate farm-level adoption, such as subsidizing the hiring of additional labor or the purchase of selected irrigation systems. Providing small farmers with access to credit and offering low-interest loans may encourage them to purchase new irrigation systems or install private tubewells to pump water from shallow aquifers. In regions with area-based water service charges, lower rates might be offered to farmers using irrigation methods that generate less deep percolation.

Transaction Costs

Some of the economic gains achieved by implementing volumetric water prices or establishing water markets will be offset by transaction costs that include efforts to measure water deliveries, collect revenue from water sales, record market transactions, and protect water rights. Transaction costs of market activity include the costs of identifying viable purchase and sale opportunities, negotiating terms of agreements, and mitigating or compensating for any third-party impacts (Rosegrant and Binswanger, 1994). The transaction costs of implementing water rights and pricing programs may be particularly high in developing countries where large irrigation systems deliver water to many small farms (Rosegrant and Binswanger, 1994). Public agencies can reduce private transaction costs by collecting and sharing water market information, and providing an efficient and secure procedure for transferring water rights.

The administrative costs of water pricing, allocation, and marketing programs can be substantial, particularly in countries where improvements in delivery channels, measuring devices, and operational procedures are required t o enable better control and measurement of water deliveries. Institutional enhancements may also be required to support volumetric water pricing and trading of water rights or allotments. However, administrative costs can be reduced by choosing the appropriate level at which to implement innovative programs and by adopting technologies that support program goals. For example, Small (1989) and Meinzen-Dick and Rosegrant (1997) describe volumetric "water wholesaling" in which a public agency sells water to a water user association at some point in the delivery system where volumetric measurement is feasible. The association is then responsible for recovering water costs from individual members. Measurement capability might be extended to lower levels of the delivery system by designing and installing new metering devices that provide volumetric measurement at a reasonable cost (Martinez et al., 1994).

CONCLUSIONS

Economic incentives and other policies that motivate farmers to improve water management may enhance resource use and sustainability in arid regions, and reduce the rate of increase in waterlogged and saline areas. Several engineering, administrative, and political issues will require attention in some countries to enable implementation of such policies, and transaction costs may not be trivial. Public investments may be required to improve irrigation systems to support better control and measurement of water deliveries before volumetric pricing, water allotments, or water marketing can be implemented successfully. The administrative costs of water delivery will likely increase when incentive programs are implemented and political support may be needed to gain approval for any changes in farm-level expectations regarding water supply when rights or allotments are defined and traded.

Public officials often describe the potential engineering and political costs of system improvements as binding constraints on policy enhancements, particularly in developing countries and in regions where water scarcity is not yet receiving national attention. However, in many arid countries, competition for land and water resources, and the value of output from irrigated agriculture, will continue to increase with rising populations and income levels. Therefore, it may be useful to begin improving water delivery systems and enhancing the policy environment in the near-term, while pressure on resources is not yet severe. This may enable public officials to implement economic incentives successfully in future, when water scarcity and the losses from waterlogging and salinization become ever more costly.

Economic incentives may also provide a valuable complement to engineering efforts that address waterlogging and salinization. For example, the cost of regional subsurface drainage systems, public tubewell programs, or tree planting efforts could be funded partially with revenues collected from water sales or land assessments designed to reduce deep percolation. This would reduce public expenditures for drainage relief programs, while providing farm-level incentives that may reduce the size and extent of facilities needed to collect and manage subsurface drain water. An appropriate combination of economic incentives and engineering efforts may enable farmers and the public to sustain the benefits derived from agricultural production in arid regions, despite the perpetual threat from waterlogging and salinization.

ACKNOWLEDGEMENTS

The helpful comments of three reviewers have improved the paper and are certainly appreciated. This paper is Rhode Island Agricultural Experiment Station Publication Number 3754.

REFERENCES

Abdel-Dayem, S. 1997. Waterlogging and salinity, pp. 99-116 in A.K. Biswas, (ed.) Water Resources: Environmental Planning, Management, and Development, McGraw-Hill, New York.

Abernethy, C.L. and Kijne, J.W. 1993. Managing the interactions of irrigation systems with their environments, pp. 75-103 in Ecologically Sound Resources Management in Irrigation, German Association for Water Resources and Land Improvement, Verlag Paul Parey, Hamburg, Germany.

Abrol, I.P. and Sehgal, J.L. 1994. Degraded lands and their rehabilitation in India, pp. 129-144 in D.J. Greenland and I. Szabolcs (eds.) Soil Resilience and Sustainable Land Use, CAB International, Wallingford, UK.

Abrol, I.P., Yadav, J.S.P. and Massoud, F.I. 1988. Salt-affected soils and their management. FAO Soils Bulletin 39, Food and Agriculture Organization, Rome.

Abul-Ata, A.A. 1977. The conversion of basin irrigation to perennial systems in Egypt, pp. 99-105 in E.B. Worthington (ed.) Arid Land Irrigation in Developing Countries: Environmental Problems and Effects, Pergamon Press, Oxford.

Agnew, C. and Anderson, E. 1992. Water Resources in the Arid Realm, Routledge, London.

Anderson, T.L. and Snyder, P. 1997. Water Markets: Priming the Invisible Pump,. Cato Institute, Washington, DC.

Arnon, I. 1987. Modernization of Agriculture in Developing Countries: Resources, Potentials and Problems, Second Edition, John Wiley & Sons, New York.

Barrow, C.J. 1987. Water Resources and Agricultural Development in the Tropics, Longman Scientific & Technical, Harlow, England.

Barrow, C.J. 1991. Land Degradation: Development and Breakdown of Terrestrial Environments, Cambridge University Press, Cambridge.

Briscoe, J. 1997. Managing water as an economic good, pp. 339-361 in M. Kay, T. Franks and L. Smith (eds.) Water: Economics, Management and Demand, E & FN Spon., London.

Chaudhry, M.J. 1990. The adoption of tubewell technology in Pakistan. The Pakistan Development Review 29(3,4), 291-303.

Chisholm, A. 1987. Abatement of land degradation: regulations vs. economic incentives, pp. 223-247 in A. Chisholm and R. Dumsday (eds) Land Degradation: Problems and Policies, Cambridge University Press, Cambridge.

Cummings, R.G. and Nercessiantz V. 1994. The use of water pricing to enhance water use efficiency in irrigation: case studies from Mexico and the United States, pp. 79-95 in G. Le Moigne, K.W. Easter, W.J. Ochs and S. Giltner (eds.) Water Policy and Water Markets, Technical Paper 249, World Bank, Washington DC.

Dhawan, B.D. 1989. Water resource management in India: issues and dimensions. Indian Journal of Agricultural Economics 44(3), 233-241.

Dinar, A. and Letey, J. 1991. Agricultural water marketing, allocative efficiency, and drainage reduction. Journal of Environmental Economics and Management 20, 210-223.

Dinar, A. and Zilberman, D. 1991. The economics of resource-conservation, pollution-reduction technology selection: the case of irrigation water. Resources and Energy 13, 323-348.

Dinar, A., Rhoades, J.D., Nash, P., and Waggoner, B.L. 1991. Production functions relating crop yield, water quality and quantity, soil salinity and drainage volume. Agricultural Water Management 19, 51-66.

Dinar, A., Rosegrant M.W. and Meinzen-Dick R. 1997. Water allocation mechanisms: principles and examples. Policy Research Working Paper 1779, World Bank, Washington, DC.

Doorenbos, J. and Pruitt, W.O. 1975. Guidelines for predicting crop water requirements. Irrigation and Drainage Paper 24, FAO, Rome.

Doorenbos, J. and Kassam, A.H. 1979. Yield response to water. Irrigation and Drainage Paper 33, FAO, Rome.

Dregne, H.E. 1991. Arid land degradation: a result of mismanagement. Geotimes 36(6), 19-21.

Dudley, N.J. 1992. Water allocation by markets, common property and capacity sharing: companions or competitors?. Natural Resources Journal 32(4), 757-778.

Ellis, F. 1992. Agricultural Policies in Developing Countries, Cambridge University Press, Cambridge.

Gazmuri, S.R. 1994. Chile's market-oriented water policy: institutional aspects and achievements, pp. 65-78 in G. Le Moigne, K.W. Easter, W.J. Ochs and S. Giltner (eds.) Water Policy and Water Markets, Technical Paper 249, World Bank, Washington DC.

Gazmuri, S.R. and Rosegrant, M.W. 1996. Chilean water policy: the role of water rights, institutions and markets. Water Resources Development 12(1), 33-48.

Ghassemi, F., Jakeman, A.J. and Nix, H.A. 1995. Salinisation of Land and Water Resources, Center for Resource and Environmental Studies, Canberra, Australia.

Greiner, R. 1997. Optimal farm management responses to emerging soil salinisation in a dryland catchment in eastern Australia. Land Degradation & Development 8, 281-303.

Hearne R.R. and Easter W.K. 1995. Water allocation and water markets: an analysis of gains-from-trade in Chile. World Bank Technical Paper 315. Washington, DC.

Hillel, D. 1994. Rivers of Eden: The Struggle for Water and the Quest for Peace in the Middle East, Oxford University Press, Oxford.

Hoffman, G.J. 1990. Leaching fraction and root zone salinity control, pp. 237-261 in K.K. Tanji (ed.) Agricultural Salinity Assessment and Management, American Society of Civil Engineers, New York.

Howell, T. 1990. Relationships between crop production and transpiration, evapotranspiration, and irrigation, pp. 391-434 in B.A. Stewart and D.R. Nielsen (eds.) Irrigation of Agricultural Crops, American Society of Agronomy, Madison, Wisconsin.

Howitt, R.E. 1994. Empirical analysis of water market institutions: the 1991 California water market. Resource and Energy Economics 16, 357-371.

Izac, A-M.N. 1994. Ecological-economic assessment of soil management practices for sustainable land use in tropical countries, pp. 77-96 in D.J. Greenland and I. Szabolcs (eds.) Soil Resilience and Sustainable Land Use, CAB International, Wallingford, UK.

Jacobsen, T. and Adams, R.M. 1958. Salt and silt in ancient Mesopotamian agriculture. Science 128, 1251-1258.

Janakarajan, S. 1993. Economic and social implications of groundwater irrigation: some evidence from south India. Indian Journal of Agricultural Economics 48(1), 65-75.

Kapoor, A.S. and Kavdia, P.S. 1994. Drainage and salinity problems in Indira Gandhi Canal Project Area, pp. 104-116 in R. Hooja and P.S. Kavdia (eds.) Planning for Sustainability in Irrigation, Rawat Publications, New Delhi.

Kemal, A.R., Bilquees, F. and Mahmood, Z. 1995. Case study on the economic valuation of the salinization and waterlogging as a result of inappropriate irrigation in Pakistan. Pakistan Institute of Development Economics, Islamabad.

Kovda, V.A. 1983. Loss of productive land due to salinization. Ambio 12(2), 91-93.

Letey, J., Dinar, A., Woodring, C. and Oster, J.D. 1990. An economic analysis of irrigation systems. Irrigation Science 11, 37-43.

Mageed, Y.A. 1994. The central region: problems and perspectives, pp. 101-119 in P. Rogers and P. Lydon (eds.) Water in the Arab World: Perspectives and Prognoses, Harvard University Press, Cambridge, Massachusetts.

Martinez, P., Mundo, M. and Carrillo, M. 1994. Measurement devices for irrigation water. Water Resources Development 10(3), 339-350.

Meinzen-Dick, R. 1994. Private tubewell development and groundwater markets in Pakistan: a district-level analysis. The Pakistan Development Review 33(4), 857-869.

Meinzen-Dick, R. and Mendoza, M. 1996. Alternative water allocation mechanisms: Indian and international experiences. Economic and Political Weekly 31(13), March 30, A25 to A30.

Meinzen-Dick, R. and Rosegrant, M.W. 1997. Water as an economic good: incentives, institutions, and infrastructure, pp. 312-320 in M. Kay, T. Franks and L. Smith (eds.) Water: Economics, Management and Demand, E & FN Spon., London.

Moore, M. 1989. The fruits and fallacies of neoliberalism: the case of irrigation policy. World Development 17(11), 1733-1750.

Oster, J.D. 1984. Leaching for salinity control, pp. 175-189 in I. Shainberg and J. Shalhevet (eds.) Soil Salinity Under Irrigation: Processes and Management, Springer-Verlag, New York.

Perry C.J., Rock M. and Seckler D. 1997. Water as an economic good: a solution, or a problem? pp. 3-11 in M. Kay, T. Franks and L. Smith (eds.) Water: Economics, Management and Demand, E & FN Spon., London.

Prasad, K. and Rao, P.K. 1991. On irrigation water pricing in India. Water Resources Development 7(4), 274-280.

Puttaswamaiah, K. 1994. Irrigation Projects in India: Towards a New Policy. Indus Publishing Company, New Delhi.

Quiggin, J. 1987. Land degradation: behavioral causes, pp. 203-212 in A. Chisholm and R. Dumsday (eds) Land Degradation: Problems and Policies, Cambridge University Press, Cambridge.

Qureshi, S.K., Hussain, Z. and Zeb-un-Nisa. 1994. An assessment of warabandi (irrigation rotation) in Pakistan: a preliminary analysis. The Pakistan Development Review 33(4), 845-855.

Ramanathan, S. and Rathore, M.S. 1994. Sustainability of Indira Gandhi Canal and the need for correct responses: a social scientist's perspective, pp. 277-299 in R. Hooja and P.S. Kavdia (eds.) Planning for Sustainability in Irrigation, Rawat Publications, New Delhi.

Repetto, R., 1986. Skimming the water: rent-seeking and the performance of public irrigation systems. Research Report 4, World Resources Institute, Washington, DC.

Rhoades, J.D., 1990. Soil salinity - causes and controls, pp. 109-134 in A.S. Goudie (ed.) Techniques for Desert Reclamation, John Wiley & Sons, New York.

Rhoades, J.D. and Loveday, J. 1990. Salinity in irrigated agriculture, pp. 1089-1142 in B.A. Stewart and D.R. Nielsen (eds.) Irrigation of Agricultural Crops, American Society of Agronomy, Madison, Wisconsin.

Rosegrant, M.W. 1997. Water resources in the twenty-first century: challenges and implications for action. Food, Agriculture, and the Environment Discussion Paper 20. IFPRI, Washington, DC.

Rosegrant, M.W. and Binswanger, H.P. 1994. Markets in tradable water rights: potential for efficiency gains in developing country water resource allocation. World Development 22(11), 1613-1625.

Rosegrant, M.W. and Meinzen-Dick, R.S. 1996. Water resources in the Asia-Pacific region: managing scarcity. Asian-Pacific Economic Literature 10(2), 32-53.

Saleth, R.M. 1996. Water Institutions in India: Economics, Law, and Policy, Commonwealth Publishers, New Delhi.

Sampath, R.K. 1992. Issues in irrigation pricing in developing countries. World Development 20(7), 967-977.

Scott, S.F. 1993. Water and sustainable agricultural development, pp. 19-50 in Ecologically Sound Resources Management in Irrigation. German Association for Water Resources and Land Improvement, Verlag Paul Parey, Hamburg, Germany.

Sen, A.K. 1984. Resources, Values and Development, Harvard University Press, Cambridge, Massachusetts.

Shah, T. 1993. Groundwater Market and Irrigation Development: Political Economic and Practical Policy. Oxford University Press, Bombay.

Shah, T. and Ballabh, V. 1997. Water markets in north Bihar: six village studies in Muzaffarpur District. Economic and Political Weekly 32(52), Dec. 27, A-183 to A-190.

Small, L.E. 1989. User charges in irrigation: potentials and limitations. Irrigation and Drainage Systems 3, 125-142.

Small, L.E. and Carruthers, I. 1991. Farmer-Financed Irrigation: The Economics of Reform. Cambridge University Press, Cambridge.

Smedema, L.K. 1990. Irrigation performance and waterlogging and salinity. Irrigation and Drainage Systems 4, 367-374.

Stone, I. 1984. Canal Irrigation in British India: Perspectives on Technological Change in a Peasant Economy, Cambridge University Press, Cambridge.

Strojan, S.T. 1995. The economics of salinization, pp. 188-204 in C.J.C. Phillips and P.C. Chiy (eds.) Sodium in Agriculture, Chalcombe Publications, Kent, UK.

Svendsen, M. and Meinzen-Dick, R. 1997. Irrigation management institutions in transition: a look back, a look forward. Irrigation and Drainage Systems 11, 139-156.

Szabolcs, I. 1987. The global problems of salt-affected soils. Acta Agronomica Hungarica 36(1-2), 159-172.

Tsur, Y. and Dinar A. 1997. The relative efficiency and implementation costs of alternative methods for pricing irrigation water. The World Bank Economic Review 11(2), 243-262.

Upstill, G. and Yapp, T. 1987. Offsite costs of land degradation, pp. 99-107 in A. Chisholm and R. Dumsday (eds) Land Degradation: Problems and Policies, Cambridge University Press, Cambridge.

Upton, M. 1996. The Economics of Tropical Farming Systems, Cambridge University Press, Cambridge.

Weinberg, M., Kling, C.L. and Wilen, J.E. 1993. Water markets and water quality. American Journal of Agricultural Economics 75, 278-291.

Young R.A. and Horner G.L. 1986. Irrigated agriculture and mineralized water, pp. 77-116 in T:T. Phipps, P.R. Crosson, and K.A. Price (eds.) Agriculture and the Environment, Resources for the Future, Washington, DC.

IRRIGATION PERFORMANCE AND MANAGEMENT IN TAIWAN

Ming-hua Tsai[1] Wen-jung Hu[2]

ABSTRACT

Paddy is the important crop to be grown in Taiwan. There are two paddy may be grown in a year, wherever irrigation water is available. It maintains the self-sufficiency in food-crop products so as to ensure the security of food supplies and raises farmers income in Taiwan for a long time. This paper is to introduce the aspects dealing with irrigation performance and management prevailed in Taiwan. Due to the recent socio-economic changes, the water demand has been increasing with the expansion of industrialization and urbanization. The acquistion of new water supplies for agricultural irrigation has become more difficult and costly. Besides, the existing irrigation water sources face the pressure of competition use of other purposes. Irrigation encompasses social, economic, policy and institutional aspects, such as irrigation science, ecological fuction, entry into WTO challenges, etc. As a result, a great effort to ensure efficient utilization and sustainable use of irrigation water through improvement in irrigation system and water management is being made and also discussed in this paper.

INTRODUCTION

The climate of Taiwan is comparatively warm, which provides a long growing season and permits diversified cropping. There are two or more crops can be grown in a year, wherever water is available. The average annual rainfall is 2,515 mm. Rainfall is abundant, but its distribution throughout the year is different locally and timely. This uneven annual rainfall is not quite in accordance with the growing seasons of crops. Therefore, irrigation is indispensable for crop production, which depends on the available water sources and adequate irrigation facilities as well as proper management. The total area of Taiwan is about 36,000 km^2 , of which 24% or 8,760 km^2 are cultivated lands including about 60% of irrigated land and 40% of non-irrigated land. In 1996, the total water used in Taiwan amounted to 18.1 billion m^3 , of which about 10.2 billion m^3 or 56% of the total was used for irrigation as shown in Table 1(WRB,1997). River off-take, reservoir/pond storage water and ground water are the three major water sources to be developed for irrigation. They are operated individually or conjunctively during the irrigation season with various irrigation systems, which can be

[1]Chief, Irrigation and Engineering Division, Forestry Department, Council of Agriculture, Executive Yuan, Taipei, Taiwan,100.
[2]Associate Professor, Department of Hydraulic and Environmental Engineering, Tamkang University, Taipei, Taiwan,251.

classified as(1)irrigation system directly diverting water from natural stream, (2)irrigation system with a reservoir, (3)irrigation system with irrigation ponds, (4)irrigation system with water supplied from irrigation wells, and (5)irrigation system with two or more of the aforementioned water sources. The total irrigations area in Taiwan is about 456,000 ha in 1997, of which 381,000 ha or 76% are under the jurisdiction of 17 Irrigation Assoiations(IA) and the rest are managed by private farmers and Taiwan sugar corporation`s farmers. These irrigation areas are served by 1,797 irrigation canal systems, 2,000 shallow and deep irrigation wells, and 18 reservoirs(TJIA,1998).

Table 1. Water use of Taiwan in 1996

Unit: $10^6 m^3$

Area □□□□□□□□	North	Central	South	East	Total	(%)
Agricultural water use	2,020	5,557	3,650	2,271	13,498	(74.5)
(1)Irrigation	1,654	4,828	1,548	2,170	10,200	(56.3)
(2)Fish-culture use	353	671	2,025	97	3,146	(17.4)
(3)Livestock use	13	5	77	4	152	(0.80)
Domestic water supply	1,524	619	660	59	2,862	(15.8)
Industrial water use	625	426	663	51	1,765	(9.7)
Total water use	4,170	6,602	4,973	2,380	18,125	(100)

Source : Water Resources Bureau, Ministry of Economic Affairs,1996

Taiwan had developed irrigation chiefly for rice cultivation for more than 300 years. As paddy rice consumes a large amount of water and water becomes more and more limited in Taiwan, economical and efficient utilization of the limited irrigation water resources is essentially important. For this point of view, water saving irrigation method and high irrigation efficiency management are developed for irrigation. This paper is to introduce the aspects dealing with irrigation performance and management prevailed in Taiwan, and some improvements due to the recent environmental and socio-economic changes.

IRRIGATION DEVELOPMENT HISTORY OF TAIWAN

Since rice is the staple food in Taiwan, irrigation has been essentially developed for rice cultivation. It began in the seventeenth century when immigrants came from mainland China. The early development of the irrigation systems were small scale with purpose mainly for rice production. Most of the irrigation systems were built and managed by the farmers themselves without any assistance from the government. By 1895, a total area of about 350,000 ha had been developed for farm land, of which about 200,000 ha were under irrigation.

During the period from 1896 to 1947, Taiwan was occupied by Japan, a set of regulations calling for the registration of those private irrigation systems were promulgated by the Japanese government in order to put them under government supervision for well management and maintenance, and 181 public canal cooperatives were founded to take in charge for irrigation operation and management. In the meantime, the government canal cooperatives were also established for operation and management of those canals which were constructed by government. Later on, the Japanese government further reorganized the public canal cooperatives and government canal cooperatives into irrigation cooperatives. In this period, the existing systems were remodelled, consolidated, and enlarged, and a number of new systems such as Tao-yuan Canal, Chia-nan Canal, etc. were constructed. The irrigation area was increased to about 560,000 ha.

After World War II, irrigation development in Taiwan had been carried out in a great efforts since 1945. First of all, rehabilitation of the damaged irrigation systems were the important works to be done, and about 260,000 ha of irrigation area were rehabilitated.

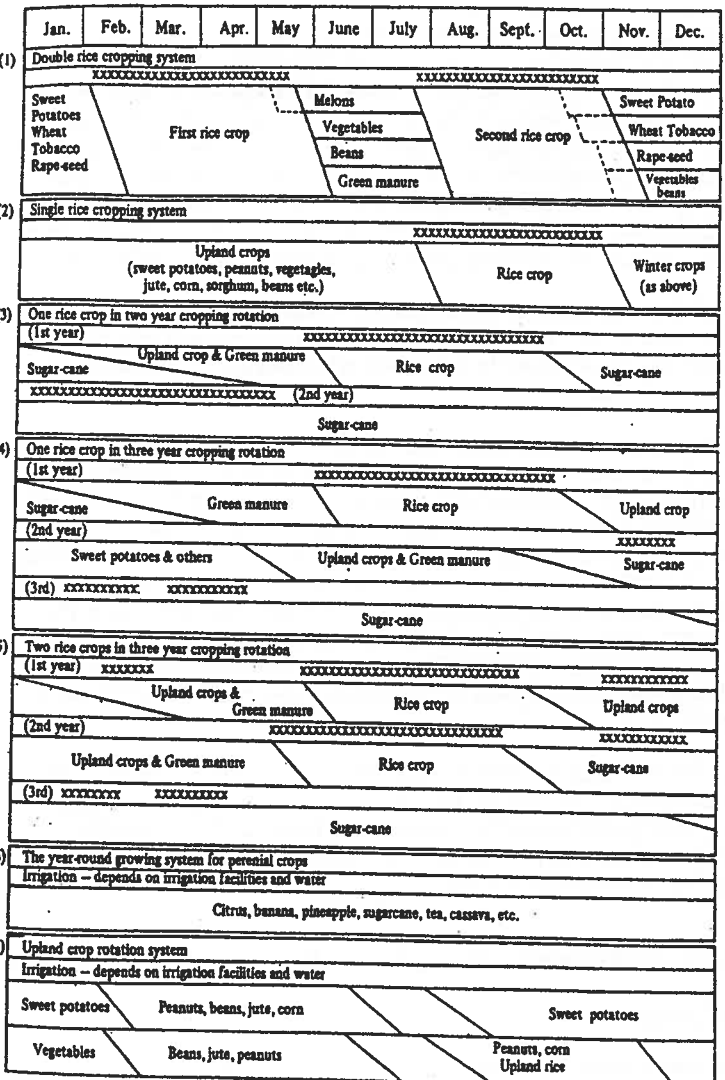
Since 1956, some new development for economical utilization of water resources projects related to irrigation for agricultural production were conducted. The new development projects covered: (1)large-scale irrigation, such as Shih-men Canal irrigation system, Kuan-shan Canal irrigation system, Lu-yeh Canal irrigation system etc., (2)multi-purpose reservoirs, such as Shih-man Dam, Tseng-wen Dam, Min-teh Dam, Pai-ho Dam, etc., (3)ground water development, mainly developed in Yun-lin and Ping-tung area,(4)tidal land and river-bed land reclamation. By 1962, the irrigation area was increased to 676,384 ha, which was the highest record in Taiwan. For the efficient utilization of the existing water resources, rotational irrigation practice, canal lining project, land consolidation projects were implemented.

At present, the total irrigation area managed by 17 IAs is 381,000 ha, the total length of the leading, main, lateral, and sub-lateral canals and farm supplying ditches is 44,466 km (TJIA,1998). Especially, the length of farm supplying ditches is 30,353 km, or 68% of the total(TJIA,1998). The average length of supplying ditches per hectare is 80 m.

CROPPING PATTERNS AND TYPICAL FARM-LEVEL IRRIGATION SYSTEMS

Cropping Patterns

Since rice is the predominant crop in Taiwan, it is usually used for the determination of the most common cropping patterns according to the availability of irrigation water. The cropping patterns to be adopted in Taiwan may be classified into seven groups as shown in Fig. 1(Wen,1980). Of the total service area of 381,000 ha in the 17 IAs, the double rice-crop area is 261,000 ha, the single rice-crop area, 24,000 ha, the rotation cropping area (including two and three year rotations),83,000 ha, and the upland crop area, 13,000 ha(TJIA,1998).



Legend: xxxx indicates irrigation period

Fig.1. Various Cropping Patterns Adopted in Taiwan(after Wen,1980)

Continuous Irrigation

Taiwan was a barren island in the old day. When immigrants came from mainland China and settled, agricultural activities started and canals were built to convey water from streams for irrigation. During this period, the population was spare and the water was plentiful, there was no need to restrict water use. The irrigation practice in those days was of the continuous method. Starting with the transplanting of rice, the paddy field is continuously supplied with water of 50 mm to 60 mm in depth through the period of rice plants except weeding, fertilizer application and harvesting. Water is applied day and night flowing into the paddy field at one end and out at the other end without any control. Such practice results in high use of water. In general, the irrigation rate was as low as 330 ha/(m^3/s) in most area.

Rotational Irrigation

Due to the rapid growth of population and rapid development of industry in Taiwan after World War II, the use of cultivable lands and existing water resources for irrigation and other purpose is approaching to a limit. To develop new water resources is not only costly but also time consuming. In this respect, an attempt was made to improve the conventional continuous irrigation method in order to reduce the unnecessary waste of irrigation water. A promotion of rotational irrigation was, then, initiated. There are three different methods of rotational irrigation may be done (Chow,1960 and JCRR,1968):

A. Rotation by sections in the main canal,
B. Rotation by sections in the laterals or sub-laterals,
C. Rotation by farm ditch.

In case A, the water will be conveyed in turn to different sections of the main canal. In case B, the main canal will have continuous flow while water will be conveyed to the various sections of laterals or sub-laterals successively. In case C, the water flow in the farm ditch will be intermittent while the flow in the main, laterals and sub-laterals will be continuous. In this case, the irrigation water is applied in appropriate quantity at the right time and in proper order so that all paddy fields may get the needed amount of water. In order to facilitate this method of irrigation, the whole area is divided into several rotation areas, and the irrigation systems are to be designed that irrigation water can be simultaneously be delivered into each individual rotation area of about 50 ha, the use of water is rotated in sub-divisions of a rotation area, called "rotation units". For example, a certain rotation area is divided into 4 rotation units, and the rotation interval is 4 days, each rotation unit will get its share of time of irrigation application in proportion to its area(Fig. 2). In the aforementioned three types of rotational irrigation, case A or B is mostly used in drought period, while case C is used in practical irrigation. Experiment had shown that rotational irrigation can achieve a saving of about 20-30% in water without producing any bad effect on rice growth and harvest. By this method, the irrigation rate was increased to 800 ha/(m^3/s). Furthermore, rotational irrigation is in favor of plant growth, saves fertilizer eliminate water disputes.

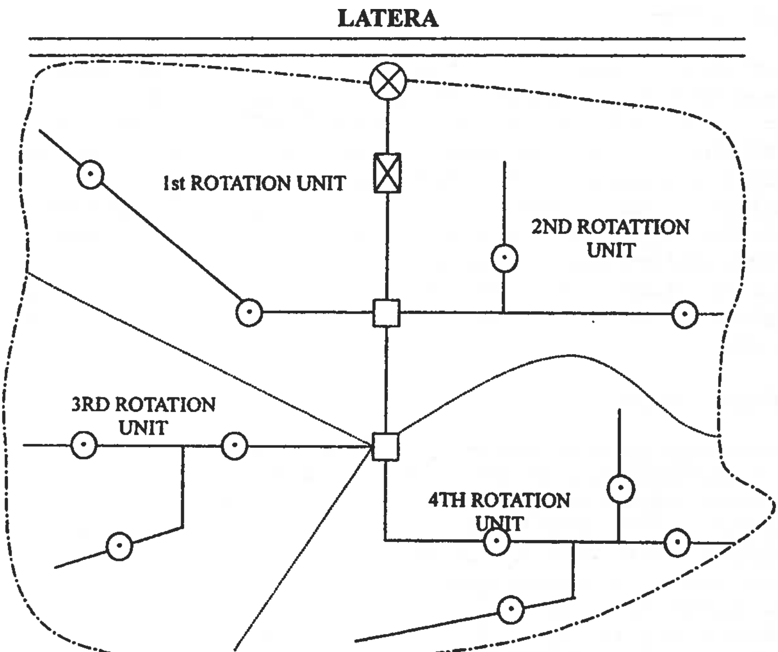
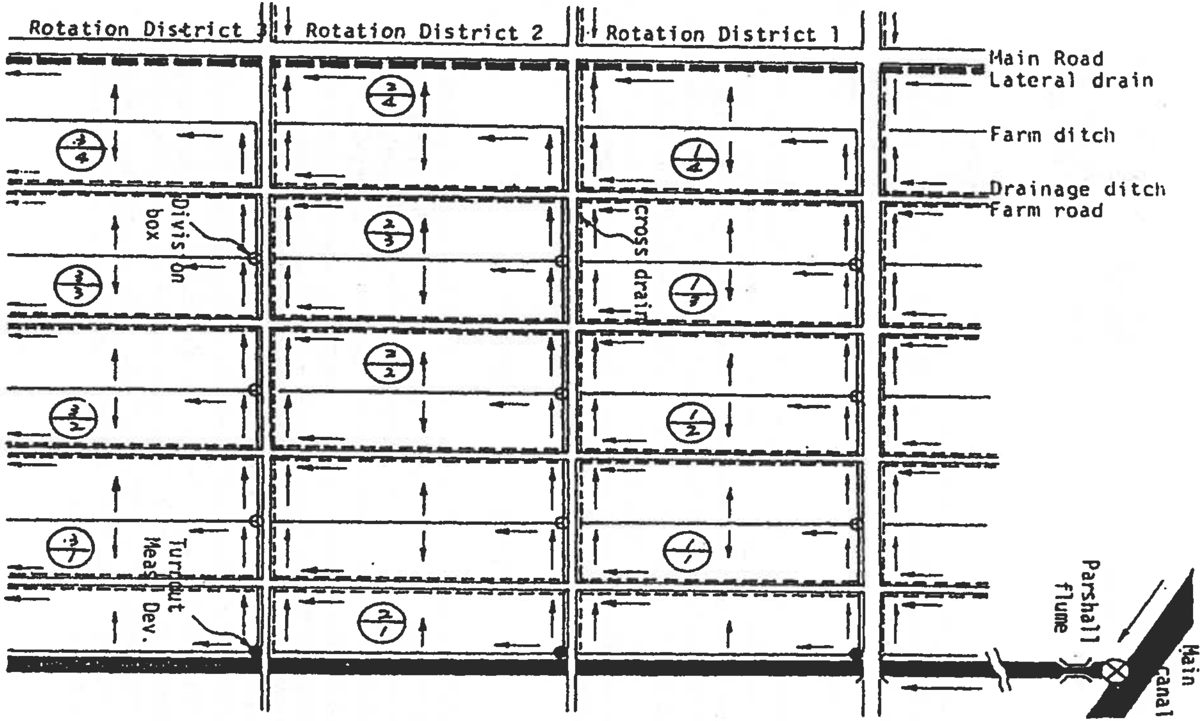


Fig.2. Typical layout of Rotation Area

Land Consolidation-Improved Farm Level Structures

Since land holdings in Taiwan have been very small and fragmental, the irrigation operation and management is inconvenient due to the inadequate and insufficient irrigation and road systems. A land consolidation program was started in 1958 to amalgamate the small and irregular farm plots and consolidate them by exchange and redistribution of farm roads, irrigation and drainage systems were made for better transportation, direct irrigation and effective drainage. A typical rotational area and water distribution system through land consolidation program is shown in Fig. 3.

As to the water distribution on paddy fields with land consolidation, irrigation water flows continuously through the turnout gate and controlled by the measuring devices into the rotation area, and irrigation is rotated among rotation units. In the land consolidation area, each block area of about 10-14 ha is regarded as a rotation unit, and each rotation unit is subdivided in several plots with area of 0.2 ha –0.4 ha (100-120 m long and 20-40 m wide). Irrigation water is delivered to each plot from the farm supply ditch directly, while in the rotational area without land consolidation, the water is supplied to the plot passing from field to field. Up to 1998, the total completed area is about 380,000 ha.



Remarks: Upper number in the circle --"Rotational Area"
Lower number in the circle --"Rotational Units"

IRRIGATION MANAGEMENT

In order to manage and utilize the irrigation water effectively, the Irrigation Association (IA) is organized by farmers according to water regions. The major functions of IA are construction, improvement and maintenance of irrigation/drainage facilities as well as water management. The total service area of the 17 IAs in Taiwan is 381,000 ha, and the typical organization of IA is shown in Fig. 4.

The IA has a management division at its head office to handle irrigation management policy, water planning and scheduling, and irrigation supervision. In a typical IA , it has local regional management offices, called "working station". The irrigation working station operates and maintains the irrigation system. Besides, some IAs have water source and canal working station to control and supply the water.

Field water distribution planning and execution are the main responsibilities of an irrigation working station. The station supervises and assists five to ten irrigation groups to carry out the water distribution and maintenance work of irrigation groups at the farm level. The irrigation groups are organized by the IA members themselves on the basis of farm-level irrigation systems without salary from the association. A group consists of an area of 50 to 150 ha and several teams, each with 10 to 15 members. The main work of a irrigation group is to maintain irrigation and drainage ditches, to distribute irrigation water, etc.

IRRIGATION OPERATION

Prior to the irrigation season, a preliminary water distribution plan is to be worked out by the management division at the head office according to the government policy, production goals, the existing reservoir/ponds storage and water release, water flows at diversion weirs, other available water sources, past records of irrigation requirements, canal conveyance losses, rotational irrigation intervals, and time of irrigation etc. The prepared plan is handed through regional management offices or directly to the working stations for further study and discussions with irrigation groups, and finalization. The finalized water distribution plan is to be strictly carried out by the working stations. The canal operators of stations are in charge of regulation and controlling water flows along main canal, laterals, and sub-laterals. The irrigation supervision are in charge of water control and measurement at turnout gates on laterals or sub-laterals, and of inspection on farm-level water distribution which are undertaken by irrigation groups in their individual irrigation areas.

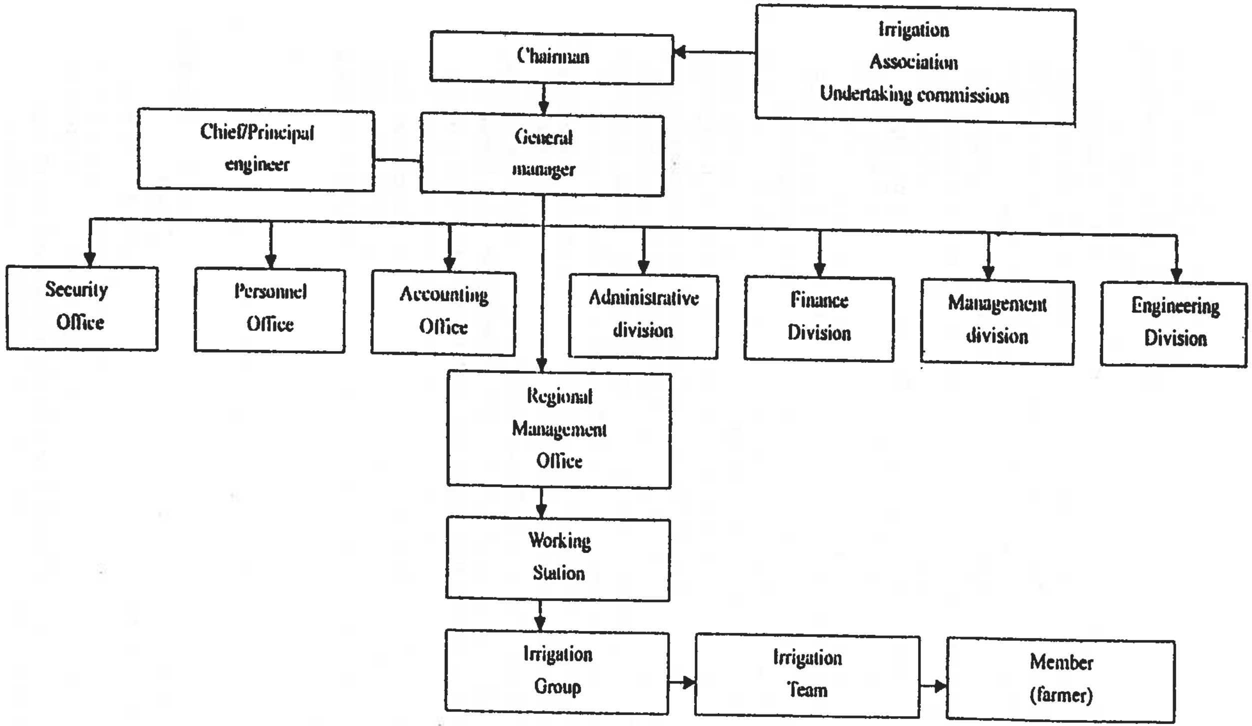


Fig.4. Organization Char of Typical Irrigation Association

PROBLEMS RECENTLY ENCOUNTERED

As rice is the predominant crop in Taiwan in the early stage, paddy is grown wherever possible, so, there had been a surplus crop of rice production year after year. For example, the paddy harvested area was 502,018 ha with an annual brown rice production of 639,000 t in 1945, increased to a high record of 786,343 ha with a maximum production of 2,712,000 t in 1976(COA,1994). Moreover, consumption patterns have been changing with increasing wealth, the average year consumption of rice per person has fallen from 134 kg in 1974 to 59 kg in 1996(DF,1998), in addition, the international price of rice has been low, and there has never been a fixed export market for Taiwan's rice. In order to balance out production and marketing of rice, a paddy diversion program was initiated on 1984 to divert the use of paddy field from the production of rice to alternative crops. The total diversified paddy field (including set-aside field) was from 43,700 crop-ha in 1984, increased to 260,000 crop-ha in 1997(DF,1998). Under this program, theoretically, there should have a large amount quantities of irrigation water to be saved for other use. Actually, about 76% of the irrigation water is river off-take with local and time difference, and has been seriously polluted, which is very difficult to be used by other users. Besides, the diversified paddy field is not concentrated, and irrigation is still needed for those paddy field which has not been diversified, and for the upland crops field, so a certain amount of discharge in canal is necessary for canal conveyance loss. As a result, not only no more water can be saved for other users, but also the irrigation management becomes more complicated. At the present stage of economic growth in Taiwan, water demand has been increasing and the production of additional new water sources has become more costly. No new irrigation projects can be implemented for rice production due to economic feasibility factors. However, in order to maintain paddy field with area of about 350,000 ha for self-sufficiency in food-crop products so as to ensure the security of food supplies and raise farmer's income so as to narrow the income gap between farmers and nonfarm workers, irrigation is still necessary. A certain amount of water is needed to be used for irrigation, but the percentage is decreased year after year. For example, the total amount of irrigation water used in 1996 was about 10.2 billion m^3 or 56% of the total water used in Taiwan, which was much lower than the amount of 13.6 billion m^3 or 81% in 1971.

MEASURES OF IMPROVEMENT

As mentioned above, due to the recent socio-economic changes, the water demand has increased with the increasing of population and the expansion of industrialization and urbanization. The acquisition of new water supplies for agricultural irrigation has been become more difficult and costly, and growing no more. Besides, the existing irrigation water faces the pressure of competition use of other purposes because of its lower production value per unit use of water. However, irrigation water resources are not only essential for agricultural production but also maintaining the ecological functions. In order to incorporate with Taiwan's future long-term agricultural policy, and to maintain the paddy field functions, the following measures are made(Tsai,1998).

1. In order to incorporate the dry and wet crops rotation plan, investigation of the existing irrigation water use is needed. Rasing the water use efficiency for first paddy in dry season is necessary. The paddy field protection and ecological maintaining is implemented on the ceased cultivation of the second paddy field in wet season.

2. The "Appropriate quantity of irrigation water and dependable water sources investigation and evaluation "project is implemented for establishing the reasonable irrigation water adjustment and utilization.

3. Strengthening improvements in irrigation management and operation techniques, repairing and improving the old existing irrigation system facilities, promoting the water saved pipe-line sprinkler irrigation are the measures for rasing the effective use of water resources.

4. Strengthening the monitoring system on the irrigation water quality, implementing management of the water quality monitoring in the heavy(or serious) polluted areas and studying the degradation tendency in general polluted areas are continued to carried out.

5. Automatic remote observing, transmission and processing of irrigation operation data, and system control systems are installed on the major canals for real-time irrigation operation and management.

6. Computer programming application to water distribution plan and irrigation scheduling, and irrigation systems' design are also conducted.

7. The functions and achievements of paddy field on production, living and ecology is investigated and evaluated. The reasonable water use model in different areas and different seasons are established.

CONCLUSIONS

Paddy is the important crop to be grown in Taiwan. It maintains the self-sufficiency in food-crop products so as to ensure the security of food supplies and raises farmer's income and to narrow the income gap between farmers and nonfarmers for a long time. Irrigation plays a very important role for rice production. Due to the recent socio-economic changes, the water demand has been increasing with the expansion of industrialization and urbanization. The acquisition of new water supplies for agricultural irrigation has become more difficult and costly. Besides, the existing irrigation water sources face the pressure of competition use of other purposes. Irrigation development is no longer merely a problem of engineering. It encompasses social, economic, policy and institutional aspects, such as irrigation science, soil improvement, ecological functions protection, entry into WTO challenges, ect. As a result, a great effort to ensure efficient utilization of the limited irrigation water through the improvement of existing irrigation systems and intensive management should be made.

REFERENCES

1. Wen, Li-jen, 1980, Improvement of Irrigation System and Water Management in Taiwan. Proceeding of ICID, 11th Congress, Grenable, France.

2. Chow, Lee, 1960. Development of Rotational Irrigation in Taiwan. Journal of the Irrigation and Drainage Division, American Society of Civil Engineers, Proc.86 (IR 3,2588):1-12, September.

3. Joint Commission on Rural Reconstruction(JCRR), 1968. Rotational Irrigation Development in Taiwan, Taipei, R.O.C.

4. Taiwan Joint Irrigation Association(TJIA), 1998. FY1997 Data Book of Irrigation Associations, Taichung, Taiwan, R.O.C.

5. Council of Agriculture (COA), 1994. COA General No.8, Taipei, Taiwan, ROC.

6. Water Resources Bureau(WRB), 1997. FY1996 Working Year Book of WRB, Ministry of Economic Affairs, Taipei, Taiwan, R.O.C.

7. Tsai, Ming-hua, 1998, Agricultural Water Conservancy Policy and Application Strategies for the future in Taiwan. Scientific Agriculture Vol. 46 No.1-2, 28-33, January 1998.

8. Department of Food(DF), 1998, Taiwan Food Statistics Book, Taiwan provincial Government, Taipei, Taiwan.