Irrigation and Drainage for Food, Energy and the Environment

Fifth International Conference on Irrigation and Drainage

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November 3-6, 2009

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

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Preface

The papers included in these Proceedings were presented during the **USCID Fifth International Conference on Irrigation and Drainage**, held November 3-6, 2009, in Salt Lake City, Utah. The Theme of the Conference was ***Irrigation and Drainage for Food, Energy and the Environment***. An accompanying book presents abstracts of each paper.

Viewed from a global perspective, with proper insight and planning, the world's fresh water resources are sufficient to meet all the demands for agriculture, industry and domestic uses. However, at a local level, water professionals are facing new challenges related to increasing water scarcity and competing uses of water. These uses include water for food, energy and the environment. This Conference provided an opportunity for water professionals, managers, policymakers and others to share their experiences with balancing water demands.

Often water is viewed as a single use resource; however, given the increase in competition for water, opportunities may exist at the local level to use water for multiple purposes. Exploring these opportunities will require increased cooperation among local water users and even countries who share water basins.

The papers presented during the Conference focused on these issues. Technical sessions addressed the following topics: **Applications of Technology; Environment and Drainage; Water and Energy Efficiency and Policy;** papers presented during the **Opening Plenary Session** and a **Poster Session** are also included in the Proceedings.

The authors are professionals from academia; federal, state and local government agencies; water and irrigation districts; and the private sector.

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

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

Reed R. Murray
U.S. Department of the Interior
Provo, Utah

Conference Chairman

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SUBSURFACE DRAINAGE — WHAT'S NEXT?

James E. Ayars Ph.D.[1]

ABSTRACT

Subsurface drainage is a critical element in sustaining and protecting the investment in irrigated agriculture. There have been significant developments in the state of the discipline in the last 30 yrs. There has been a steady progression away from the basic elements of the system design and construction to developing management strategies that conserve water and contribute to the remediation of poor quality drainage water. In the past, the ecological impact of drainage was given little consideration but this has changed significantly in recent times. This manuscript will briefly discuss the current state of the art in drainage system design and management and speculate on what the future holds for this critical discipline.

INTRODUCTION

Drainage has been identified as the forgotten factor in sustaining irrigated agriculture (Scheumann and Freisem 2001). Surface and subsurface drainage provides the following functions: protects the resource base for food production; sustains and increases yields and rural incomes; protects irrigation investment; protects lives and assets against flooding and high groundwater levels; provides improved health conditions; protects water quality. These seven functions encompass both subsurface and surface drainage. Subsurface drainage is generally assumed to be required whenever irrigated agriculture is practiced. The emphasis in this paper will be to discuss the current state of the art in subsurface drainage design and management and consider what the future may hold. This is not to diminish the importance of surface drainage in providing a healthy ecosystem and environment but the author's experience has been in subsurface drainage.

Comparing the topics investigated in the Third Drainage Symposium and proposed for the Ninth Drainage symposium sponsored by the American Society of Agricultural and Biological Engineers provides insight into how the discipline as changed from 1976 symposium to the call for papers for the 2010 symposium. The topics considered in the call for papers have been categorized as follows; theory, design, soil properties, materials and construction, modeling, management, environmental impacts, and drainage institutions and policy. The number of sessions in each of these categories in 1976 and 2010 are summarized in Table 1.

The most apparent aspect has been the shift from theory and basic design to management over this period of time. The concept of drainage water management and environmental impacts has had a significant shift in the time frame from the very first drainage symposia to the 2010 call for papers.

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Table 1. Sessions allocated to specific topics in Drainage Symposia in 1976 and 2010.

Topic	1976	2010
Theory	1	
Design	1	1
Materials and Construction	1	
Modeling	1	1
Management		3
Soil Properties	1	1
Environmental Impact		3
Drainage Institutions		1

The objective for the remainder of this paper will be to briefly discuss the current state of the art in the individual topics highlighted in Table 1 and speculate on what the future might be with regard to each of these topics.

CURRENT STATE OF THE DISCIPLINE

Theory and Design

The theory of flow of water in porous media and specifically for flow to drains has been developed over the years based on the Bossinesq and Dupuit-Forcheimer theories. Most of the basic theory has been accepted and used as the basis for implementing designs for a subsurface drain system. Hooghoudt developed a steady state approach in the Netherlands that has been adopted for humid areas throughout the world (van der Ploeg et al., 1999). The drainage design in humid areas generally is based on the idea of a steady state system and the design criteria require the removable of a specified depth of water in a given period of time to ensure adequate aeration of the soil.

In arid irrigated areas rainfall is a minimal consideration in the design of a drainage system and the major source of excess water is a result of irrigation inefficiency. The design then incorporates the irrigation schedule and proposed irrigation system inefficiencies in the design. This has resulted in a transient analysis procedure developed by the US Bureau of Reclamation (USBR) called Dynamic Equilibrium (Reclamation, 1993). In this method the midpoint water table depth between two drainage laterals returns to the design depth at the end of the irrigation cycle. The water table position follows a succession of declining and then increasing increments as the irrigation season progresses. Design of transient systems has been implemented in the agricultural drainage planning program (ADPP) developed by Colorado State University (www.ids.colostate.edu). Donnan developed a steady-state procedure for design of subsurface drainage in irrigated areas as well (Reclamation, 1993).

Soil Properties

Successful design and implementation of subsurface drainage systems requires an accurate description of the soil properties including hydraulic conductivity, soil layers, soil types, saturated zones, and the specific yield of the soil. The USBR in the drainage manual (Reclamation 1993) has described the necessary field techniques to gather all the data needed for design and construction of subsurface drainage systems. This is a very labor intensive and costly process when large irrigation systems are being developed that require drainage. Natural Resource Conservation Service (NRCS) has developed many soils maps that cover most of the soils in the United States that can be used for initial reconnaissance and design (websoilsurvey.nrcs.usda.gov).

Despite the field studies outlined in the drainage manual there are still problems associated with characterizing soil properties that will impact flow to the drains. One particular problem is preferential flow from the soil surface to the drain that bypasses the soil matrix. This has the potential for rapid transport of pollutants from the soil surface to the drainage water without the benefits of remediation in the soil profile. An accurate description of the saturated zone above the water table and the aeration status is critical in the design and potential management of a drainage system.

The spatial variability of these parameters also represents a significant problem when considering the design of a system. Simple field testing for these parameters may not be adequate to characterize the variation in soil type, soil layering, hydraulic conductivity, salinity, and toxic elements.

The symposia topics show that the problem of the necessary inputs in the design in particular the soil properties is an ongoing problem and one that still requires much attention.

Materials and Construction

It appears based on Table 1 that materials and construction are no longer a major component for research. There have been significant improvements over the years in the construction of drainage systems and the drain “tile”. The drain tile has progressed from individual pieces of pipe made of wood, clay, or cement (Figure 1) to a continuous pipe of plastic. The installation process has evolved from a machine dug trench with hand laid tiles (Figure 2) to a continuous pipe that is trenched (Figure 3) or installed into the ground using a laser controlled plow (Figure4). Envelope materials have progressed from graded sand or soils to fabric “socks” that enclose the drain pipe.

Figure 1. Drain tile shapes.

Figure 2. Hand installation of drain tile.

Figure 3. Laser controlled trenching of plastic drainage lateral.

Figure 4. Laser controlled plow installation of plastic drain lateral.

Modeling

Modeling was part of the program in 1976 and continues into the latest drainage symposium in 2010. Over the years there has been extensive development of models for both the design and management of subsurface drainage systems (Skaggs, 1999). These models have become more sophisticated as the computer power has improved going from large mainframe computers to personal computers that have more power than the original mainframes.

DRAINMOD (Skaggs, 1982)(Figure 5) is the best known of the water balance models and is used extensively in the United States and throughout the world for designing and management of drainage systems in humid areas. This model has been adopted by the NRCS for use in designing drainage systems in the United States. Development on DRAINMOD has continued to include modules for nitrogen and salinity transport. Chang et al. (1983) tested DRAINMOD for application in irrigated agriculture and Wahba et al. (2002, 2005) and Wahba and Christen (2006) have used it for water management studies in irrigated areas of Egypt and Australia.

Models being used for drainage design particularly in arid irrigated areas include the Colorado State University irrigation and drainage model (CSUID) (www.ids.colostate.edu) and the Soil-Water-Atmosphere-Plant environment (SWAP) model (Kroes et al., 1998).

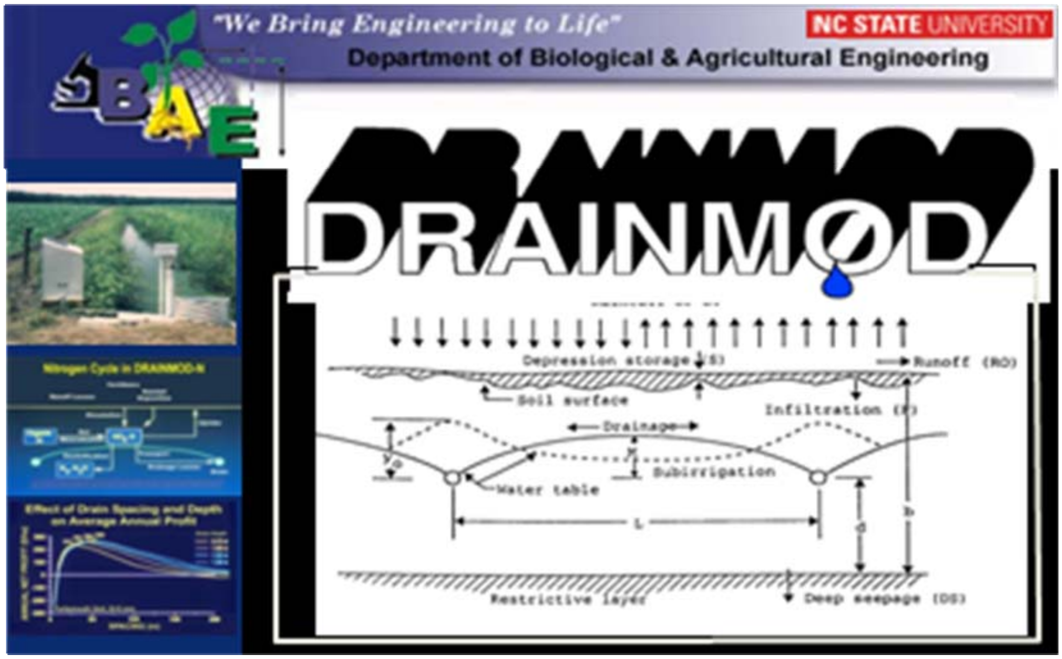

Figure 5. DRAINMOD characterization.

Management

Active management of subsurface drainage systems is a reasonably new concept and initial studies have been accomplished in the eastern United States in conjunction with the development of the DRAINMOD model. The information in Table 1 demonstrates that the idea of management is a developing concept and one that has much interest around the world. The goals for management include reduced drainage flows, improved water quality in drainage flows, and improved soil water conditions and in situ use of water by crops. Subsurface drainage system management in irrigated conditions is a new development since concerns with the accumulation of salt in the profile above the drains have limited this approach. Studies (Ayars et al. 2006a; Ayars 2007) have demonstrated that management of drainage systems in arid areas is possible without developing a salinity profile in the root zone that impacts production.

Figure 6. Drainage control structure in humid region.

Environmental Impact

Comparing the number of sessions between 1976 and 2010 it is apparent that the environmental impact of drainage has reached a significant crossroads and requires extensive research. In the past drainage systems were designed for continuous operation and very little consideration was given to the environmental impact of the drainage water on surface water quality. Continuous operation of drainage systems in arid areas results in over drainage of irrigated fields (Doering, Benz et al. 1982) with the resultant loss of water and an excessive load of salt being transported to surface water (Christen, Ayars et al. 2001) along with any dissolved agricultural chemicals The problem with accumulation of selenium in the Kesterson Reservoir highlights the environmental concerns associated with drainage from arid irrigated lands (San Joaquin Valley Drainage, 1990). Now not only salinity but toxic elements found in the drainage water are of concern. There are major concerns with nitrate pollution in the Gulf of Mexico and the discharge of phosphorus, and pesticides in drainage water in humid areas. In response to the environmental impacts of drainage water new research is being conducted on managing drainage water discharges to reduce the total load of nitrates in the drainage water and the salinity in drainage water. The Agricultural Drainage Management Systems (ADMS) task force was developed in the mid west to find solutions to the transport of nitrate in drainage water from agricultural land that was contributing to the hypoxic zone in the Gulf of Mexico (Figure7).

Figure 7. Drained area that contributes to the hypoxic zone in the Gulf of Mexico.

Drainage Institutions

Drainage water management in the past has oftentimes fallen to the control of the irrigation districts providing the water service to the farms. In the humid areas drainage was the responsibility of the farmer who discharged drainage water into existing surface water bodies. Drainage on a large scale often involved controlling surface flow and was the responsibility of local political entities or districts formed for that purpose.

FUTURE CHALLENGES

Theory and Design

The basic theory for design of subsurface drainage systems has been well developed and is reasonably mature. There will probably be additional studies that may refine the theory and provide simpler methods of design but there will be few changes to the underlying processes. However, the design criteria need to be revised to implement additional criteria besides simply water table position and rates the recession of the water table. New criteria should include the effect of the design on water quality (Ayars et al. 1997; Guitjens et al. 1997), the potential for in situ use of shallow groundwater (Ayars et al. 2006a; Ayars et al. 2006b), and the oxygen status in the root zone above the water table. Figure 8 gives the outline of a proposed new drainage design procedure that includes consideration of water quality criteria and the use of controlled drainage and highlights the benefits of the new approach.

Soil Properties

This is an area that is critical to the design and installation of new drainage systems. As noted, data collection for characterization of soil properties needed in the design of drainage systems is an expensive and time-consuming task that does not necessarily completely characterize the site. New methods are needed to characterize the soil properties on a distributed basis such that these can be incorporated into new models and design programs. Techniques such as electromagnetic induction and ground penetration radar along with ground truthing may be the future for improved characterization of soil parameters needed in drainage system design and management (Allred et al. 2008).

Materials and Construction

The change from individual tile sections to continuously installed drainpipe is a significant improvement in the process of installation and construction as well as in material selection. It is not readily apparent what the future holds in this regard. With the new emphasis on water quality management there may be opportunities for changes in the construction that will incorporate materials that will be part of the solution to water quality issues. Filter materials are also an area that may provide opportunities for new materials and construction techniques.

Modeling

As long as there are Ph.D. candidates there will be models being developed and applied to the design and management drainage systems. There is real potential in this modeling effort to incorporate remotely sensed data into the designs of the system. This may include remotely sensed soil properties and salinity distributions. The design of a drainage system as part of an integrated water management system is an important goal to improve water productivity in humid areas and in irrigated areas and this will require models to evaluate the potential based on new designs and integrated water management strategies.

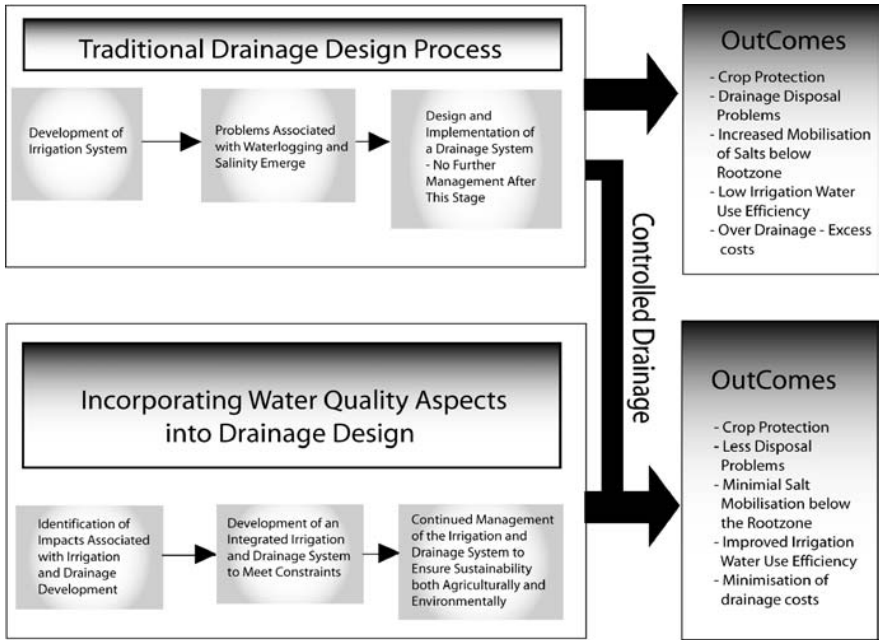

Figure 8. Schematic of drainage design methodology to include water quality criterion in subsurface drainage system design.

Management

Management of subsurface drainage systems is the next major area of research. This is being developed in the humid areas of the United States and other parts of the world and is yet to be fully developed in the arid and semi arid areas of the world. Extending our available water supplies will require that we minimize the drainage losses and improve water quality. Active management will be required to meet environmental quality goals. This is will present many challenges in humid areas subject to random rainfall events that require drainage discharge. In arid areas maintaining production sustainability and minimizing the impacts of salinity and toxic elements on the environment will be the critical consideration.

Environmental Impact

Moderating the environmental impact of subsurface drainage is critical for the sustained use of this practice. Future systems will have point of discharge structures that can be used to remediate drainage water by removing nitrates, phosphates, and toxic elements that may be present in the drainage water. This also provides an opportunity for developing distributed methods for remediation that may be included during construction. New design criteria should be developed to incorporate water quality as a criterion in the design. There is now an emphasis on the ecological restoration of previously drained areas particularly in wetland areas along the eastern seaboard of the United States. Studies also need to be developed to evaluate restoration of existing drainage systems to incorporate control structures or remediation structures needed as part of an environmental restoration.

Drainage Institutions

Drainage institutions will be faced with the challenge of providing the structure needed in ecological restoration. These will require significant cooperation between the farmer, the local governments, and the environmental community. In the developing world irrigation and drainage institutions need to be developed simultaneously as part of an integrated water management system.

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WATER MANAGEMENT POLICIES

Franklin E. Dimick[1]

ABSTRACT

Water user entities are usually governed by laws, regulations and policies. Although such entities may have input to laws and resulting regulations, they are not able to have full control of those aspects that govern how they do business. However, policies that govern these entities are totally within the control of the entity. Policies govern all aspects of the administration, operation and maintenance of a water user entity that are not dictated by laws and/or regulations.

Establishing sound, effective and defendable policies is essential to the viability of any water user entity. Good policies result in a water user entity being efficient, organized and successful. Failure to establish and put into effect such policies will result in chaos, legal battles, and failure for the entity.

Water user entities generally need to establish policies concerning five major areas of concern; 1) Administration; 2) Management; 3) Operation; 4) Maintenance; and 5) Rehabilitation and Improvements. Other areas of policy may be needed that are unique to each individual entity.

These five major areas are discussed below.

ADMINISTRATIVE POLICIES

Policy Making

One of the first policies an organization needs to make is how to establish other policies. The policy must include such things as who establishes policies, do policies have to be approved by the members of the organization or just by a governing board and how are policies changed or rescinded.

Personnel Matters

An organization that employs people must have policies on personnel matters such as how people are hired and fired, how wages are determined and set, what fringe benefits are employees entitled to, etc.

Safety

A policy that details the safety program and associated responsibilities is an essential element in the administration of a water user entity.

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Public Relations

A policy must be established on how the entity will handle public relations. This will include public relations with the news media as well as with the public and water users. It is important that an entity establish good public relations policies in order to gain support for actions they take or propose to take, especially during emergency situations and periods of stress such as drought, natural disasters, etc.

Funding

A sound policy on how the organization is funded is essential to the viability of the organization. A policy must be established that spells out where the organization's funds come from, how they are spent and who manages them. A policy must also be established as to how water charges and rates are set and collected. For example, are water charges based on an account charge plus a rate per acre foot, or are they based on the irrigable acres. The policy should also include provisions for special assessments for extraordinary maintenance or rehabilitation work.

Financial Management

Policies on how to manage the finances of the entity are needed to assure a smooth operation of the financial aspects of a water user entity. For example, policies are needed on when and how bills are to be paid, what size of a reserve account should be maintained, are separate accounts maintained for different activities, are reserve accounts invested or kept in savings accounts, etc.

Acquisition of Equipment, Supplies and Services

Acquisition of equipment, supplies and services can become a very burdensome task with significant problems if proper policies are not put in place. Acquisition policies for equipment should describe how much equipment is needed and whether new and/or used equipment should be purchased. Policies should also provide criteria for when it is appropriate to replace used equipment.

Policies on acquisition of supplies and services should describe the type of supplies or services to be acquired, how much inventory to carry, how the inventory is controlled or managed and provide some criteria on the quality of supplies and services to be acquired.

Protecting the Entity's Water Supply

Policies should be developed that describe actions to be taken by the entity to protect the water supply to the project. The policy should describe actions to be taken such as protests to proposed water right applications and response to proposed rules, regulations and laws.

Delinquent Payments

Delinquent payments is an issue that faces all water user entities at one time or another. Having a policy in place that spells out the action to be taken to collect delinquent payments will not only minimize the financial loss from these payments but will minimize conflicts between water users and the entity.

MANAGEMENT

Internal Management

Entities must develop policies on how the project is managed. Decisions have to be made on how much authority will be given to the manager and how much will be retained by the governing body (Board of Directors, etc.). The policy should also describe the organizational structure of the entity and the responsibilities of each subdivision of the organization to avoid any overlap of work assignments.

Emergency Management

A policy needs to be developed on who manages the project during an emergency situation such as a canal break or flood and what actions should be taken. Having this policy in place before the emergency could prevent serious problems from developing. The development of emergency management plans and adopting them as policy will greatly enhance the entity's capability to react to an emergency.

Training

A policy that describes the type, amount and frequency of training for various positions or individuals within the entity will be necessary to assure proper conduct of the entity's business.

Record Keeping and Reports

Any organization must keep records and utilize reports in order to operate efficiently and effectively. Policies governing what records must be kept, how they are kept and how they are protected must be developed and used. Likewise, policies governing preparation, use and retention of reports must be developed and used.

Conversion of Land and Water

One of the major concerns facing many water user entities at the present time is the conversion of agricultural land and water use to that of urban use. This conversion places many potential burdens on the water user entity and poses significant issues for them in maintaining a viable entity. Policies governing when, how and to what extent conversions of water and land within the boundaries of the entity can take place are mandatory for any entity facing this potential situation.

Water Transfers

Many conditions including drought, environmental requirements and urbanization are making it necessary and sometimes more profitable for water users and water user entities to transfer water to some other use or place of use. Policies governing the transfer of water between users within the entity, between users within and without the entity and between entities need to be in place to protect the viability of the organization and the remaining users within the entity.

Water Conservation

Diminishing water supplies and increasing costs of production make it necessary for a water user entity to develop and use water conservation policies. These policies should provide water conservation direction for both the individual users within the entity as well as the entity itself.

Coordination with Other Entities

In today's world, a water user entity can no longer operate in an isolated condition. Coordination of activities must occur with other water user entities as well as with government, commercial and private entities. Policies governing these coordination efforts will provide uniform and consistent efforts in this arena.

Water Offenses

Although it can be hoped that the situation will never arise, it is almost certain that a water user entity will have to deal with the situation of someone attempting to obtain water under illegal or fraudulent circumstances. In order to deal with these situations in a consistent and appropriate manner, policies must be in place that the water user organization's management can use. The policy should define what an offense is and what actions will be taken if such an offense should occur. The policy should also define what action will be taken for repeat or multiple offenses by the same water user.

Disputes

A policy that provides a process for handling disputes between water users and the water user entity or between the entity and another organization must be in place to quickly and efficiently resolve such disputes. The policy should also contain provisions for appealing the initial resolution of a dispute if either party to the dispute feels they were wrongly injured by the initial resolution.

OPERATIONS

Who Operates the System

Water user entities need to develop and implement a policy describing who operates what part or parts of the collection, storage, delivery and drainage systems. If individual water users or contractors are to operate part of any system, the policy should spell out their responsibilities in detail to avoid any misunderstandings.

Scheduling of Deliveries

Scheduling the delivery of water is a major factor in operating a water system. The manner in which water is ordered and scheduled for delivery needs to be described in a policy adopted by the water user entity.

Water Measurement

In order for a water user entity to be efficient and viable, it must measure the water which it manages. The entity must adopt a policy on when, where and how it will measure water. The policy should also contain provisions for verifying measurements in case of disputes that might arise.

Allocations During Water Shortages

As demands for water increase, water shortages become more common either through natural causes such as drought or through man-made shortages (due to such things as uses for fish and wildlife and for the environment). A water entity must have a policy in place for allocating water during periods of water shortage to avoid serious misunderstandings and conflicts with water users and other entities.

Environmental Considerations

Operations of any water delivery system must take into account the impact those operations may have on the environment. A policy that describes the relationship between the operation of the water system and the environment and the goals of the entity toward the environment is essential in preventing unwanted environmental conflicts and issues.

MAINTENANCE

Who Maintains the System

The water user entity must implement a policy on who operates what parts of the collection, storage, distribution and drainage systems. The standards to which each part is maintained should be included in the policy.

Preventive or Breakdown Maintenance

A policy detailing the type of maintenance that the water user entity intends to pursue should be implemented. This policy will determine the manner in which employees and/or maintenance contractors approach their maintenance activities.

Environmental Considerations

Maintenance activities will almost always affect the environment in some way. Therefore, it is necessary to develop a policy which relates maintenance activities to the environment. The policy should spell out the entity's goals in protecting the environment and reducing impacts on the environment by their maintenance activities.

REHABILITATION AND IMPROVEMENTS

When to Replace in Kind

A policy that describes the criteria for replacing, in-kind, a broken or worn part, piece of equipment, structure or facility will greatly enhance the entity's ability to react to breakdowns and maintenance activities in a timely manner.

When to Upgrade

Implementing a policy that provides information as to when a piece of equipment, structure or facility needs to be upgraded to improve its capability will assist those make that decision in the future.

When to Modernize the System

A policy which outlines the criteria for deciding when to modernize the entire collection, storage, distribution or drainage systems would be very beneficial in making this very critical decision.

Environmental Considerations

A policy on improving parts or all of a system in order to improve the environment or reduce the impact of the project on the environment would be beneficial to those making the decision as to whether or not such action should be taken. It would also be helpful in working with outside entities during environmental considerations.

SUMMARY

Establishing and implementing policies related to all aspects of managing, operating and maintaining a water system is essential to viability of that entity. An organization cannot function in today's world without these policies in place to improve efficiency, reduce conflicts and misunderstandings and protect the environment. Having policies in place will make life a lot easier for those who must manage any water management system.

USING REMOTE SENSING AND GIS TECHNIQUES FOR STUDYING IRRIGATION PERFORMANCE OF PALO VERDE IRRIGATION DISTRICT

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ABSTRACT

Managing water resources in western US has been a challenge for decision makers. In the last few decades, the rapid growth rates of population along with the alarming rates of global warming have added to the complexity of this issue. In this study, remote sensing techniques have been applied to evaluate the performance of agricultural irrigation, the largest consumptive user of water. The study area, "Palo Verde irrigation District" which is located in Riverside and Imperial counties, California, is an old irrigation district with a fairly heterogeneous cropping pattern. Landsat Thematic Mapper satellite images were used to estimate the actual ET using the SEBAL energy balance model. These estimates were integrated to obtain crop water demand for different periods throughout the growing season. The amount of diverted water was also estimated for the same periods, using flow measurements within the Palo Verde irrigation district. The results were analyzed within the ArcGIS environment in conjunction with water conveyance and field boundary layers to evaluate different performance indicators such as relative water supply, overall consumed ratio, depleted fraction, crop water deficit, and relative evapotranspiration. The results of these indicators can help irrigation managers to get a general idea of how the system performs and to identify possible ways of improving it.

INTRODUCTION AND BACKGROUND

Historically, western US has been best known for its arid climate, low precipitation, and long droughts. These inherent characteristics have made water availability a major issue in this part of the world. In recent years, some new challenges have added to the complexity of managing scarce water resources of the western states. Probably the most noticeable challenge is the rapid population growth rate. People are migrating to the west at a record rate, putting a lot of pressure on managers to supply required drinking water. Another important challenge for decision makers is that water should not only be available for human uses, but it should also protect ecosystems and critical habitat for

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flora and fauna. These issues make securing and managing water supplies far more complicated than what it was in the past.

In such a complicated situation, science plays an important role in helping resource managers to make the right decision. As authors of a recent USGS report (Anderson and Woosley, 2005) concluded: “The role of science in helping to meet water challenges will not likely involve finding undiscovered sources of water, but rather will be integral in developing a more comprehensive understanding of the consequences of each course of management action”. According to USGS, irrigated agriculture has been the biggest user of fresh water in the United States since 1950, accounting for about 65 percent of total water withdrawal – excluding thermoelectric power. Not surprisingly, 86 percent of all withdrawals and 75 percent of all irrigated lands were in the 17 conterminous western States (Hutson et al. 2004). Needless to say, a thorough management of water resources in western US is impossible without having a comprehensive knowledge of irrigation performance and the ways it can be improved.

Methods of quantifying irrigation performance have been significantly improved in last decades. A major advancement was the use of remote sensing and GIS techniques in estimating spatially distributed evapotranspiration (ET), a key input of many performance indicator models. Traditional methods of making point measurements cannot be extended to represent large irrigated areas, due to the dynamic nature of crop growth and regional variation of ET. Even if they are extended to cover large irrigation projects, the accuracy is usually low and the credibility of these studies is under question (Bastiaanssen and Bos, 1999). The advantages of space- and/or air-borne remote sensing over conventional methods are including, but not limited to: obtaining accurate and objective data, covering vast irrigated schemes with one or multiple scenes, and being able to spatially represent the results (Bastiaanssen and Bos, 1999). Nowadays, with the cost of satellite remote sensing being the lowest in its history, estimating accurate daily ET at regional scales is economically affordable by water users associations with limited financial resources. For a 15000 ha irrigation scheme, Bastiaanssen et al. (2001) estimated a cost of about US$ 1.00/ha to cover all the costs of carrying out a performance analysis using NOAA-AVHRR dataset, which is available online at no costs. Since then, Landsat high resolution imagery has also became available free of charges.

Although lots of studies have been carried out world wide, many decision makers are still not aware of the potential of remote sensing in addressing irrigation performance under different conditions. Bastiaanssen and Bos (1999) recommended more demonstration projects and pilot studies to show irrigation managers the possibilities of using remotely sensed data. This paper evaluates the performance of Palo Verde Irrigation District (PVID) in Southern California using remote sensing based indicators from satellite imagery.

Study Area

The Palo Verde valley is located in Southern California, on the west bank of Colorado River. With an average elevation ranging from about 88 to 67 meters above sea level, the valley is relatively flat. Alluvial soils of this area are mostly sandy loam in texture. The Palo Verde Irrigation District (PVID) was privately developed in 1925 to serve the valley's water users. Colorado River water is diverted through Palo Verde diversion dam to irrigate growing crops of the valley year round. PVID water conveyance system consists of about 244 miles of irrigation canals (23 percent of which are lined) and 141 miles of open drainage canals. Most dominant crops of this district are alfalfa and cotton with 68 and 23 percent of total cropped area, respectively. Grasses, grains, vegetables and orchards are planted in the remaining 9 percent of the lands.

METHODS AND MATERIALS

Two major types of input data are needed in remote sensing-based irrigation performance analysis: ground and remotely sensed data. Ground data include meteorological data and flow rates of diverted water, while remotely sensed data are used in estimating potential and actual evapotranspiration. In this case study, the USGS gauging station data at the intake of the PVID main canal was used for estimating the diversions from the Colorado River to the PVID.

All required meteorological data were downloaded from the website of "The California Irrigation Management Information System" (CIMIS). The data from two CIMIS stations within the PVID were averaged and used in calculations. These two stations were "Ripley" (33.53 N, 114.63 W) with more than a 90 meter fetch of alfalfa as reference surface and "Palo Verde II" (33.39 N, 114.73 W) with the same reference surface. In addition to several meteorological parameters, CIMIS also reports reference ET for every station based on different equations. Since the dominant crop in PVID is alfalfa, alfalfa-based reference ET (ET_r) estimated by modified Penman-Monteith method was used in this study. The modified version of Penman-Monteith is basically the equation described in FAO paper No. 56 (Allen et al., 1998), with the "bulk surface resistance (C_d)" is the one suggested by ASCE Task Committee of Standardization of Reference Evapotranspiration (Walter et al., 2000):

$$ET_r = \frac{\Delta(R_n - G)}{\lambda\{\Delta + \gamma(1 + C_d u_2)\}} + \frac{\gamma \frac{66}{T_a + 273.16} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)}$$

where ET_r is the alfalfa reference ET, Δ is the slope of saturation vapor pressure curve at mean air temperature, R_n is the net radiation, G is soil heat flux, γ is psychrometric constant, T_a is mean air temperature, u_2 is the wind speed at two meters height, e_s and e_a are saturated and actual vapor pressure, and λ is the latent heat of vaporization. C_d is 0.25 for daytime and 1.70 for nighttime.

Landsat 5 Thematic Mapper (TM) images (Path: 38, Row: 37) were acquired for nine dates between May and September 2007. This acquisition period was selected because cotton, the second dominant crop is planted in April and harvested in October, but the farmers stop irrigating cotton in September to allow the field to dry out and facilitate the operations of the harvesting machinery. The most dominant crop, alfalfa, is a perennial crop, so it grows year around, albeit at a slower rate in the winter months. Theoretically, the month of April was also important in evaluating irrigation performance, but both Landsat overpasses in April and even the second scene of March were cloudy and impossible to be used in this study. This is the most significant drawback of the TM satellite imagery. Higher spatial resolution images are available at lower temporal resolution and lower spatial resolution images such as from the MODIS sensor are available at higher frequency. Thus it is always a trade off between spatial and temporal resolutions. Table 1 shows the dates of Landsat images used in this study.

Table 1. Dates of available, cloud free satellite images (Path: 38, Row: 37)

No.	Julian Day	Date
1	128	05/08/2007
2	144	05/24/2007
3	160	06/09/2007
4	176	06/25/2007
5	192	07/11/2007
6	224	08/12/2007
7	240	08/28/2007
8	256	09/13/2007
9	272	09/29/2007

Potential Evapotranspiration

Almost all of the remote sensing-based methods of quantifying ET are based on simple form of energy balance equation at the surface:

$$R_n = G + H + LE$$

where R_n is the net radiation, G is the soil heat flux, H is sensible heat flux, and LE is the latent heat flux, all in W/m^2. These methods estimate R_n, G, and H from the reflectance of different spectral bands and then calculate LE as the residual of the energy balance equation. In this study it was assumed that potential evapotranspiration (ET_p) is equal to the sum of latent and sensible heat fluxes, so it was estimated by subtracting soil heat flux from net radiation. Since a well irrigated stress-free crop uses most of the available energy for ET, this assumption is valid. The results of energy partitioning models also show that the values of H are very close to zero for pixels with the mentioned characteristics. Bastiaanssen et al. (1996) used (R_n – G) as ET_p as well. Computed ET_p is an instantaneous value, due to the fact that the satellite image is a snapshot in time. But instantaneous ET_p can be scaled up to daily values, using ET_r values measured by CIMIS. In order to do so, instantaneous ET_r was identified, then the ratio of ET_p over ET_r was calculated and it was assumed that this ratio would be constant throughout the day. Daily ET_p can be readily estimated by multiplying this ratio by daily ET_r values. Since monthly ET_p is used in analysis of irrigation performance, daily ET_p needs to be scaled up further to longer period values. Considering that Landsat can provide two images per month (if cloud free), each month was partitioned into two periods, and it was assumed that the ratio of daily ET_p over daily ET_r for the day of satellite overpass is constant for that part of the month. The strength of this approach is that the effect of clouds or any other factor that might have an unexpected effect on evapotranspiration is reflected in ET_r value. However the weakness of this approach is that it is not taking into account the crop growth during the period. So it seems the reflectance based crop coefficient is a better method as it can be integrated in time, using the average K_{cb} curve.

Actual Evapotranspiration

Actual evapotranspiration (ET_a) was spatially estimated using the Surface Energy balance Algorithms for Land, SEBAL (Bastiaanssen et al., 1998). This model is also based on the simple form of energy balance equation at the surface. SEBAL estimates R_n by subtracting outgoing from incoming short and long wave radiation (surface radiation balance). To estimate soil heat flux, first the ratio of G/R_n is calculated empirically for every pixel, and then this ratio is multiplied by R_n of that pixel. Finally, the H is approximated by selecting two anchor points, known as the cold and hot pixels. These pixels represent the boundary condition, where the former is a wet, well irrigated vegetation surface, and the latter is a dry, bare agricultural soil. Appropriate selection of these two pixels is dependent on operator experience and judgment and can affect the accuracy of estimated evapotranspiration. After estimating three out of four components of the surface energy budget equation, the forth component (LE) can be estimated as the residual of the equation. LE is then converted to ET_a by dividing by the latent heat of vaporization. Like ET_p, estimated ET_a is instantaneous and needs to be converted to longer period values. The same methodology (the ratio of ET_a over ET_r) was utilized to obtain daily and periodic ET_a.

Performance Indicators

Five different remote sensing-based irrigation performance indicators were estimated using the ground and space borne data. These indicators are relative water supply (RWS) (Perry, 1996), overall consumed ratio (e_p) (Bos and Nugteren, 1990), depleted fraction (DF) (Molden, 1997), crop water deficit (CWD) (Bastiaanssen et al., 2001), and relative evapotranspiration (RET) (Roerink et al., 1997). The first three indicators were estimated for the entire cropped area of the district, but CWD and RET were estimated for each pixel and then averaged over every field. All these indicators are dimensionless, so they can be easily compared over the time and/or space.

Relative Water Supply (RWS): RWS evaluates if the total water (irrigation and precipitation) supplied to the fields meets the demand of the crops or not. RWS is estimated as follows:

$$\text{RWS} = \frac{V_c + P_g}{ET_p}$$

where V_c is the volume of diverted water, P_g is the gross precipitation over study area, and ET_p is the potential evapotranspiration. The target value for RWS could vary from an irrigation system to another, based on system performance. Theoretically, a RWS of unity is desired, but the value gets bigger as the losses from diversion to application point increase. For an ideal irrigation scheme, target RWS could be considered unity. An ideal irrigation scheme could be described as an area with fertile soil in appropriate physical and chemical condition, under an efficient, well designed irrigation system and operated under an on-demand delivery scheme. On the other hand, the RWS should be greater than one in an irrigation scheme like PVID, where a fraction of water will be unavailable due to evaporation and seepage during water conveyance. In addition, extra water - over the consumptive use requirements of the crops - is usually applied in order to leach the salts out and to fill the whole root zone area until the next irrigation event.

Overall Consumed Ratio (e_p): Overall consumed ratio represents the fraction of total supplied water that can be used by crops, in the absence of any growth-limiting factor. This indicator is calculated as follows:

$$e_p = \frac{ET_p - P_e}{V_c}$$

where P_e is effective precipitation and the rest of parameters are as described before. Like RWS, e_p can also express the adequacy of supplied water. e_p greater than unity indicate under-irrigation, while values less than one implies adequate or over-irrigation. Due to the differences in system performance and soil/climate conditions, target e_p could differ from one system to another, thus it should be established for the specific scheme under study. Overall consumed ratio is inversely proportional to RWS, and the difference between these two indicators is in utilizing effective versus gross precipitation.

Depleted Fraction (DF): Depleted fraction is the fraction of supplied water that is used up by plants and can not be reallocated to another beneficial use. The following equation is used for DF computation:

$$\text{DF} = \frac{ET_a}{V_c + P_g}$$

Depleted fraction is very similar to e_p in nature, but it is based on ET_a rather than ET_p. Therefore, comparing these two indicators can give an idea about the presence of stress factors. However, next two indicators are better representatives for addressing sub-optimal evapotranspiration conditions.

Crop Water Deficit (CWD): Crop water deficit is the difference between potential and actual evapotranspiration. This indicator can be readily quantified as follows:

$$CWD = ET_p - ET_a$$

The optimal value of CWD is zero, which is almost unachievable under actual field condition. Thus, irrigation managers would want the CWD to be as small as possible. However, if deficit irrigation is economically viable, greater CWD's might be favorable.

Relative Evapotranspiration (RET): Relative ET identifies the fraction of potential ET that has actually happened under field condition. RET is defined as follows:

$$RET = \frac{ET_a}{ET_p}$$

Spatially distributed RET can give irrigation managers a thorough understanding on where they can improve. The fact that RET is a fraction is something that should be noticed before making any decision based on the results of this indicator, because a very small, disappointing RET might be the result of dividing a tiny ET_a by a small ET_p or a big ET_a by a very big ET_p. Each of these cases may require different actions to be taken. For example, at the early stages of crop growth, it is very hard to meet the crop demand when applying surface irrigation under a fixed-rotation water delivery scheme. But when the crops grow and establish good root system, it is much easier to supply most of required water. On the other hand, a farmer who takes advantage of sprinkler systems operated under on-demand delivery scheme is able to do a better job during the period right after crop emergence. Thus, a low RET at the beginning of crop growth is less surprising when surface irrigation is applied. One way to overcome the deceptiveness of RET is to look at it along with CWD.

RESULTS AND DISCUSSION

The results show that monthly actual and potential evapotranspiration values are almost constant for the first four months. The average ET_a and ET_p from May to August were 155.4 and 258.1 mm, respectively. Deviations from average are not significant during this period. But compared to August, ET_a and ET_p of the month of September showed a decrease of more than 28 and 30 percent, respectively. The reason behind this reduction in ET is the effect of atmospheric parameters such as lower average air temperature, reduced solar radiation, and higher relative humidity. Diversion of Colorado River water also dropped about 12 percent in September, mainly because farmers stop irrigating cotton in order to prepare the fields for harvest.

Performance Indicators

Relative Water Supply (RWS): The relative water supply was constantly increasing from 1.98 in May to 2.56 in September. A total average of 2.18 is reasonable for an irrigation scheme like PVID. Almost all of fields in this irrigation district are under surface irrigation systems, so a significant amount of water needs to be applied in each irrigation event in order to get the water to the end of field. In addition, a fraction of diverted water should be dedicated to leach the salts out of root zone and to account for the loss of water in conveyance (due to evaporation and seepage from irrigation canals).

Bastiaanssen et al. reported average RWS of 1.26 for Nilo Coelho irrigation scheme in Brazil, with fruits as dominant crops under pressurized irrigation system. They also defined benchmarks for different performance indicators. Based on their study, RWS values out of the acceptable range of 0.90 to 1.40 will result in more than 20 percent reduction in target yield (Bastiaanssen et al., 2001). Another recent study evaluated mean RWS of 1.10 (ranging from 0.14 to 2.77) for Lower Gediz Basin in Western Turkey (Karatas et al., 2009). Figure 1 demonstrates RWS values for each month of study during 2007 growing season. The coefficient of variation (CV) of monthly RWS was 0.10, which implies low temporal variation of this indicator.

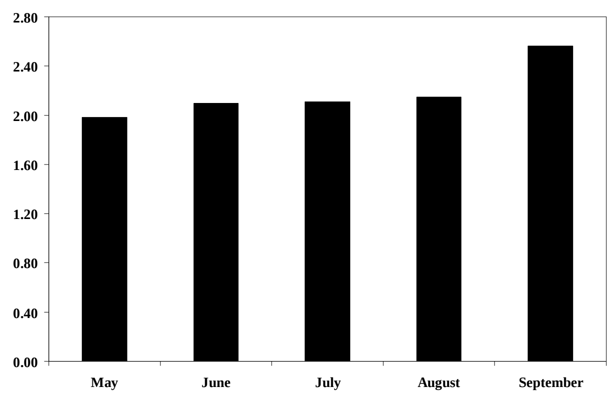

Figure 1. Monthly values of relative water supply (RWS) for PVID.

<u>Overall Consumed Ratio (e_p):</u> Overall consumed ratio is reversely proportional to RWS. As expected, this indicator showed decrease with the time, from 0.50 in May to 0.39 in September. The average e_p for the entire period of study was 0.46 with the CV of 0.09, which is a sign of low temporal variability of this performance indicator. The maximum e_p of 0.50 implies that even under an optimal agricultural condition, PVID crops will not be able to use more than 50 percent of diverted water. In other words, diversion of water is about two times larger than maximum crops water requirements. Hutson et al. (2004) mentioned that the risk of over-irrigating is greater in the arid West and the Mountain States, where surface irrigation is predominant and application rates are greatest. However, it is hard to conclude that PVID crops are over-irrigated, because part of diverted water spills back to the river at the end of canals. In addition, extra water is required to account for losses and leaching.

The range of 0.60 to 1.10 was considered as the benchmark for Nilo Coelho Scheme, and the average e_p (0.78) showed that irrigation managers have supplied adequate water to the crops (Bastiaanssen et al., 2001). In their study, Karatas et al. multiplied conveyance and application efficiencies of Lower Gediz Basin and defined 0.51 as the target value for e_p. The main crops of Lower Gediz Basin are cotton and grapes with some maize, vegetable, and fruits. In addition, the dominant irrigation system is furrows and borders, so this irrigation scheme is more comparable with PVID than Nilo Coelho. The researchers estimated an average e_p of 1.01, which indicates an overall under-irrigation in this case (Karatas et al., 2009). Figure 2 shows the estimated monthly e_p for Palo Verde irrigation district.

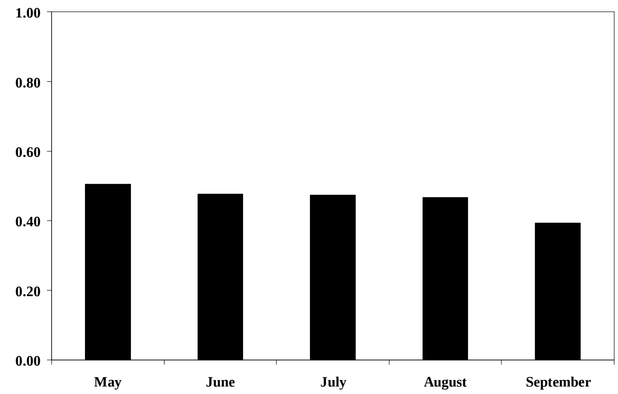

Figure 2. Monthly values of overall consumed ratio (e_p) for PVID.

Depleted Fraction (DF): Figure 3 presents the monthly variation in depleted fraction. Low temporal variation in DF can be seen in this figure, and a CV of 0.10 also confirms that. DF, in general, follows a pattern very similar to that of e_p. This is not surprising, since the main difference between these two indicators is the use of ET_a instead of ET_p as crop water demand in DF equation. ET_a can never exceed ET_p, so the values of DF are always lower than e_p values. The DF ranged from 0.37 in May to 0.28 in September, with the total average of 0.34. This is about half of the average DF estimated for Gediz basin, which was 0.69 (Karatas et al., 2009). However, it should be noticed that for Gediz basin, DF was highly variable among different months and different sub-basins (ranging from 0.28 to 3.79), so the estimated average may not be an appropriate statistical summary for comparison with DF values of PVID. Bastiaanssen et al. reported 0.61 as the average DF for pressurized irrigation system of Nilo Coelho scheme in Brazil (Bastiaanssen et al., 2001).

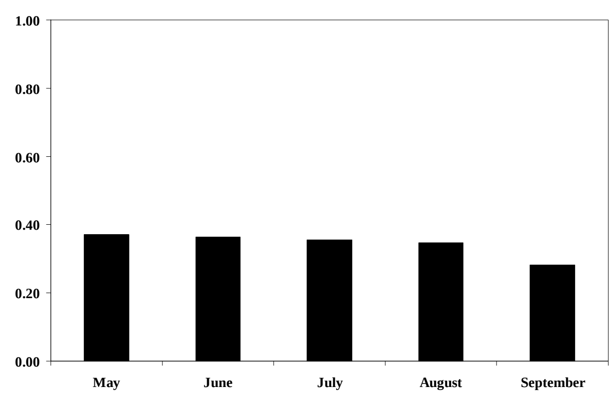

Figure 3. Monthly values of depleted fraction (DF) for PVID.

Crop Water Deficit (CWD): As it was mentioned before, CWD was estimated on a pixel by pixel basis and then it was averaged over every field in PVID. Figure 4 represents box plots of field's mean CWD for every month of the study. Ideally, irrigation managers want CWD to be as small as possible, unless deficit irrigation is selected as common irrigation practice. Studies carried out over Nilo Coelho and Gediz Basin show an average CWD of 30.30 and 41.50, respectively. Compared to these numbers, an average of 53.16 mm for PVID is not very high. The lowest CWD was 43.67 mm, belonging to the month of September. However, the decrease of CWD in September cannot be attributed to any improvement in water management or eliminating growth-limiting factors, but it is simply a result of lowered ET-deriving atmospheric parameters and biophysical changes of the crops (especially cotton) during final periods of growth. The temporal coefficient of variation was 0.12, which implies a low variability, but the mean spatial CV was higher (0.43), which is very close to the CV of 0.45, estimated for Nilo Coelho (Bastiaanssen et al., 2001).

The maximum observed CWD (60.31) is equal to about 2 mm/day difference between ET_a and ET_p. This difference could be due to the existence of stress factors such as elevated levels of soil salinity or inappropriate practice of irrigation (amount or timing). Some unofficial studies done in mid 1970’s revealed that the water discharged from PVID back to the Colorado River (drains and canal spills) is about half in volume and twice in salt concentration of diverted water. So the system is approximately salt balanced (Henning, 2009). The fact that the overall average of DF is 0.34 implies that the system is still successful in removing introduced salts. Therefore, salinity does not seem to be affecting crop growth, unless the initial salt level of the PVID soils was high, but this will not be clear without looking at the results of a thorough soil analysis. However, it should be noticed that a CWD of less than 2.00 mm/day is not really concerning. In addition, the median (47.95) may be a better representative than the mean, because the data distribution is skewed and median is more resilient to skewness and outliers. The maximum median CWD is about 1.8 mm/day.

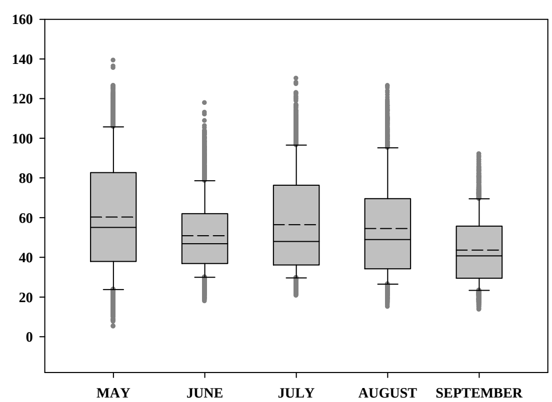

Figure 4. Monthly values of crop water deficit (CWD) in mm for PVID fields.

Relative Evapotranspiration (RET): With the temporal CV of 0.02, RET is the most uniform indicator over study period. Spatial variation of RET over PVID fields was about 0.26, which is two times the CV of RET over Nilo Coelho (Bastiaanssen et al., 2001). It should be noticed that the irrigated area of Nilo Coelho scheme is less than half of PVID in size, and achieving a uniform spatial distribution is more difficult as the area expands. In addition, water is applied through pressurized systems, which gives farmers more flexibility in meeting crop’s water demands. The average RET was 0.70 for all PVID fields over all five months. As mentioned before, the median (0.76) is statistically a better representative of the RET, due to the skewness of data distribution. In general, both numerical summaries indicate that on average, PVID crops transpire more than 70 percent of their potential. The results of other studies are highly comparable with our findings. Bastiaanssen et al. reported 0.76 as the mean RET for Nilo Coelho (Bastiaanssen et al., 2001). The value was 0.70 for Gediz basin with surface irrigation system (Karatas et al., 2009). Figure 5 illustrates box plots of monthly values of RET.

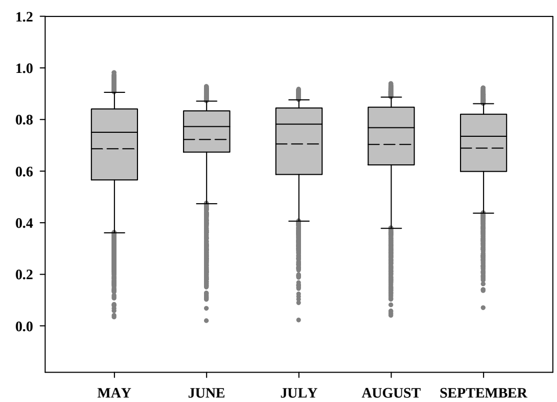

Figure 5. Monthly values of relative ET (RET) for PVID fields.

CONCLUSION

Different remote sensing-based performance indicators were studied over Palo Verde irrigation district in southern California. The relative water supply, an appropriate indicator for addressing irrigation water sufficiency, showed an average of 2.18 for the period of study (May to September). Since the surface irrigation method is widely practiced in PVID and only less than a quarter of the district's canals are lined, a value of more than 2 does not seem unrealistically high for PVID. However, irrigation managers may not be interested in reducing diversions. The main reason behind this lack of interest is financial issues. PVID farmers pay about US$ 55.00 per acre-feet, to cover operation and maintenance expenses. This fee is applicable just to the water they beneficially use, because the water that is not used goes back to river through canal spills. Therefore, a more accurate control on water diversion, which requires more staff and higher fees, is not really supported. The overall consumed ratio with an average of 0.46 also implies that demanded amount of water is most probably supplied. However, a target e_p should be defined before making any judgment about sufficiency of water diversion. Identifying such a target value is not possible without quantifying the efficiencies of irrigation sub-sections (conveyance, application, etc.), something which is not known for PVID. Average depleted fraction was 0.34, about 74 percent of mean overall consumed ratio. Mean and median RET of all fields in PVID were 0.70 and 0.76, confirming the observed difference between e_p and DF. These values indicate that PVID crops' evapotranspiration is more than 70 percent of their potential. Mean crop water deficit was 53.16 mm/month, or about 1.77 mm/day. Based on these indicators, it can be concluded that the overall performance of Palo Verde irrigation district is acceptable. Some of the indicators can be further improved by more accurately controlling water delivery, but the modifications are probably not economically viable.

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USING A SURFACE ENERGY BALANCE MODEL TO CALCULATE SPATIALLY DISTRIBUTED ACTUAL ET

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ABSTRACT

Remote sensing algorithms are currently being used to estimate regional surface energy fluxes [e.g., latent heat flux (LE) or evapotranspiration (ET)]. Many of these surface energy balance models use information derived from satellite imagery such as Landsat, AVHRR, ASTER, and MODIS to estimate ET. The remote sensing approach to estimating ET provides advantages over traditional methods. One of the most important advantages is that it can provide regional estimates of actual ET at low cost. Most conventional methods are based on point measurements (i.e., soil water sensors, lysimeters, weather station data, etc.), limiting their ability to capture the spatial variability of ET. Another advantage of remote sensing/surface energy balance ET models is that they are able to estimate the actual crop ET as a residual of the energy balance without the need of using reference crop ET and tabulated crop coefficients. This study focuses on the use of the energy balance-based model "Remote Sensing of ET" (ReSET) that uses an enhanced procedure to deal with the spatial and temporal variability of ET. ET was estimated for several years of data for the Arkansas River Basin, South Platte, and Palo Verde Irrigation District along with one day ET estimates for the Southern High Plains. Comparisons between the Remote Sensing ET values and ET values from more conventional ET methods [e.g., 2005 ASCE-EWRI Standardized Reference Evapotranspiration (Penman-Monteith) Equation] also are presented.

INTRODUCTION

Water resources management is especially important in regions of the world that are experiencing water scarcity. Evapotranspiration (ET) is the main consumptive use of irrigation in agriculture, and in most places the largest water use, therefore accuracy in ET estimation is needed for better irrigation management which can contribute to improving agricultural production and water conservation.

Solving Surface energy balance equations using satellite image based models has proven to provide good results in estimating ET. This approach captures the spatial variability between and within agricultural fields over traditional methods that use reference crop ET and a tabulated crop coefficient to calculate crop ET with the assumption that all fields have similar conditions of water availability and quality, pest issues, nutrient

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management, etc. Models based on a surface energy balance equation estimate the actual ET with a high level of spatial resolution. ET grids produced by these models can be used in other applications such as identifying unauthorized irrigations or detecting areas of a field that are not uniformly irrigated.

In this study, the objectives were: a) apply the ReSET model to several areas (Arkansas River Basin, South Platte, and Palo Verde Irrigation District along with one day ET estimates for the Southern High Plains) and b) compare between the Remote Sensing ET values and ET values from more conventional ET methods [e.g., 2005 ASCE-EWRI Standardized Reference Evapotranspiration (Penman-Monteith) Equation].

METHODOLOGY

Remote Sensing of ET (ReSET) Model

ReSET is a surface energy balance model built on the same theoretical bases of its two predecessors METRIC (Allen et al., 2007 a,b) and SEBAL (Bastiaanssen, 1998 a,b) with the addition of the ability to handle data from multi weather stations, which enhances the ET estimates by taking into consideration the spatial variability of weather data acquired from different weather stations. ReSET can be used in both the calibrated and the un-calibrated modes. The calibrated mode is similar to METRIC. Reference ET from weather stations is used to set the maximum ET value in the processed area, while in the un-calibrated mode it follows a similar procedure as SEBAL where no ET value is imposed on the model.

Models that use remote sensing images to model surface energy interpret radiation reflected on the satellites image bands into ground surface characteristics, such as albedo, vegetation indices (e.g., NDVI), surface temperature, and surface thermal emissivity. By adding the geographic information and the digital elevation map of an area the surface energy balance equation can be solved.

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

in which R_n is the net radiation calculated from the incoming and outgoing radiation (shortwave and long wave), G is the soil heat flux (rate of heat conducted and stored in soil and vegetation) calculated using an empirical equation by Bastiaanssen (2000), H is the sensible heat flux to the atmosphere or towards the surface. All units in Equation 1 are in energy units of W m^{-2}. Then, when all the previous terms have been calculated LE, which is the latent heat flux, is estimated as a residual of the energy balance (Equation 1) and the result is converted to an equivalent amount of water depth that was evapotranspirated in units of millimeters per hour or day.

Since R_n is calculated as well as G then what is left to estimate is H. The basic assumption to obtain the value of H for each pixel is that the air temperature gradient between near the ground surface and/or within the canopy and the adjacent screen level air layer changes linearly (i.e., is proportional) with the ground surface temperature (T_s, K). This is defined by a linear model represented by a "dT" function (i.e., dT = a T_s + b), Allen et al. (2007a). Based on this assumption a set of two points are selected to represent a maximum ET location and a minimum ET location. The point selected to represent zero ET is selected at a hot area (e.g., fallow/dry field) while the second point representing the maximum ET is selected at a well irrigated cropped field.

The assumption is that there is no ET at the hot pixel which can be translated using the energy balance equation as LE = 0, thus the equation just becomes R_n = G + H, which is solved for H at that hot pixel. This last case applies when using a model such as SEBAL; however if there has been a significant rainfall event a few days to a week before the remote sensing over-pass, then H should be calculated at that hot point by means of a soil water balance as proposed in METRIC. In terms of the cold pixel, it is assumed to be the point of maximum ET; therefore H is set to zero in the case of the un-calibrated model where no reference ET from weather stations is used for internal calibration such as SEBAL. In contrast, in the case that the model uses a reference ET for internal calibration such as in METRIC, any possible value of H will be calculated at the cold pixel as H = (R_n – G) – 1.05 λ_v ET_r, in which ET_r is the hourly alfalfa reference ET (mm hr^{-1}) at the time of the satellite overpass and λ_v is the latent heat of vaporization (J kg^{-1}, Equation 4). Further, the Monin–Obhukov similarity theory is used for correcting the calculations of sensible heat flux for atmospheric stability conditions. This is achieved through an iterative process where the aerodynamic resistance of heat transport (r_{ah}, s m^{-1}) at the cold and hot points are updated after each iteration until numerical stability is reached for the aerodynamic resistance (typically less than 5% difference between consecutive iterations of r_{ah}). Once numerical stability is reached, then H is calculated for the entire image using the dT function "a" and "b" coefficients and "r_{ah}" updated values. In the next step, the spatially distributed latent heat flux is calculated using the energy balance equation (Equation 1). Using the estimated distributed LE image the instantaneous "actual" evapotranspiration (ET_{inst}, mm h^{-1}) and the evaporative fraction is calculated. The entire day evapotranspiration can be calculated by assuming that the instantaneous evaporative fraction, calculated at the time of the satellite overpass, is constant over a whole day (24 hours), as follows:

$$EF(inst) = LE/(Rn - G) \tag{2}$$

in which R_n, G, and LE are all instantaneous values in W m^{-2}. ET 24-hour is calculated as shown in Equation 3, below:

$$ET24 = 86{,}400 * EF(inst) * (Rn24 - G24)/\lambda_V \tag{3}$$

Twenty four hour evapotranspiration is represented by ET_{24}, 86,400 is a time conversion from seconds to days, R_{n24} represents the 24-hour net radiation, 24-hour soil heat flux is G_{24}, L is the latent heat of vaporization that is used to convert energy to millimeters of evaporation calculated based on surface temperature. λ_v represents the energy needed to evaporate a unit mass of water, which is calculated using Equation 4 and was developed by Harrison (1963) and modified by Allen et al. (2007a), who instead of using air temperature used surface temperature un-calibrated for atmospheric interference (basically at sensor of brightness temperature).

$$\lambda_v = (2.501 - 0.00236(Ts - 273.16)) * 10^6) \qquad (4)$$

in which, *Ts* is the un-calibrated surface temperature in Kelvin.

MODEL APPLICATIONS

South Platte Basin

Seasonal ET Estimates for Corn

The South Platte Basin (Colorado) is covered by two Landsat 5 scenes (33/32 and 32/32) (Figure 1). In this paper, eleven 2006 Landsat images were used to calculate the seasonal ET. The images used corresponded to six images from path 32/32 for 2006: May 11 (DOY 131), May 27 (DOY 147), June 28 (DOY 179), July 14 (DOY 195), July 30 (DOY 211), Sept. 16 (DOY 259) and five images from path 33/32 for 2006: April 16 (DOY 106), May 18 (DOY 138), June 19 (DOY 170), July 21 (DOY 202), Aug. 22 (DOY 234).

By selecting images from two different satellite paths (same row) the potential number of images per month, covering the study area, doubled. Instead of having one image every 16 days, for the particular study area, it was possible to have the potential for one image every 8 days. This advantage provides additional flexibility in selecting the cloud free images while still having images fairly frequently. Normally an image per month is recommended for seasonal estimates for crops that grow over a period of 4 or 5 months such as corn. For crops that have a shorter growing season the error increases if additional images are not used given the rapid change in the crop phenology and the fact that one image per month would represent a significant portion of the growing season for that crop (e.g. some vegetables).

The concept of seasonal ET calculations is based on calculating ET grids for the individual dates when the images are available for an area, then an interpolation is carried out between scenes to calculate an ET grid for every day. The sum of those daily grids is the seasonal ET for the area, for details about the interpolation technique you are referred to Elhaddad and Garcia (2008).

To evaluate the accuracy of the remote sensing-based ET estimation and the seasonal interpolation technique used in this study, a comparison between the seasonal estimates developed by the ReSET model and the seasonal ET calculated using the 2005 standardized ASCE reference ET (ASCE-EWRI, 2005) equation for alfalfa fields was conducted. An excellent agreement is not expected since the ASCE method assumes ideal crop growing/agronomic conditions, which are rarely encountered in the “real” world.

Seasonal Comparisons

Seasonal estimates of ET were calculated for corn fields (identified by using a crop classification map generated by Northern Colorado Water Conservancy District) in the South Plate basin using two approaches, the ReSET approach and the ASCE-EWRI (2005) ET approach using the Integrated Decision Support Group Consumptive Use model (IDSCU) (http://www.ids.colostate.edu/index.html?/projects/idscu/) with average corn crop coefficients.

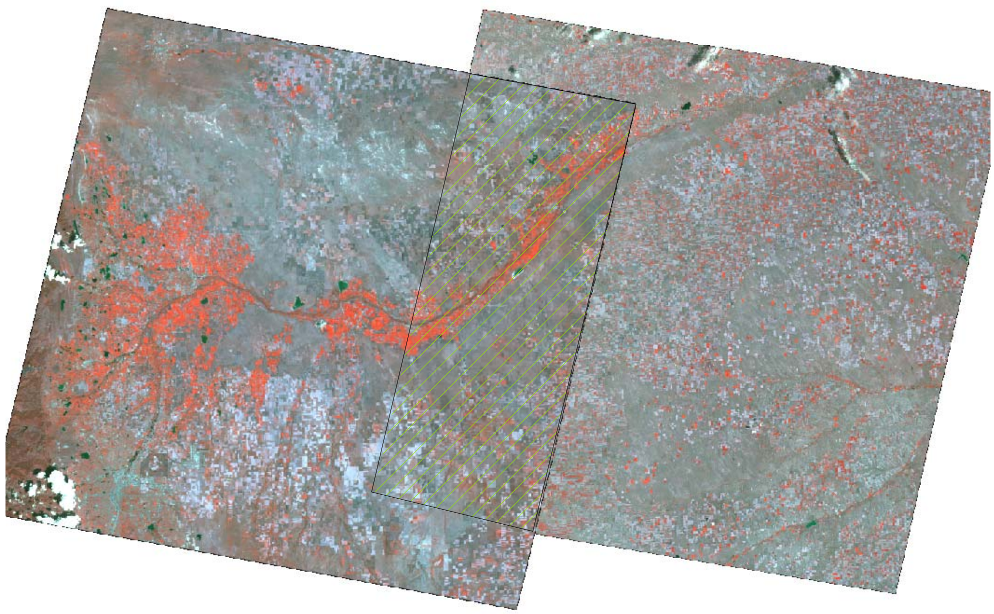


Figure 1. Overlap area for Landssat 5 scenes path/row 33/32 and 32/32 in the South Platte River Basin, CO.

To compare the seasonal ET calculated by ReSET against a traditional method such as ASCE a ratio was created by dividing the calculated ASCE-EWRI corn seasonal ET for each field by the estimated corn seasonal ET from the ReSET model for the same field. The seasonal ET of a field was calculated by taking the arithmetic mean value of all pixels in the field. However, to avoid edge effects (pixel contamination) a buffer of 60 meters (two pixels) around the edge of the field was implemented. For each field, since the ASCE method is calculating ideal seasonal ET values then it should be compared to the best part of the field meaning the maximum ET reported. Therefore, the maximum ET value for each of 418 corn fields was extracted. The ratio (ASCE/ReSET maximum pixel) ranged from 0.9 to 1.25 as shown in Figure (2), the average of the ratio was 1.07. Corn fields that had normal growing conditions (no crop damage, early harvest (silage) or water stressed) fall within 5 percent difference from the ASCE seasonal estimates (see Figure 3).

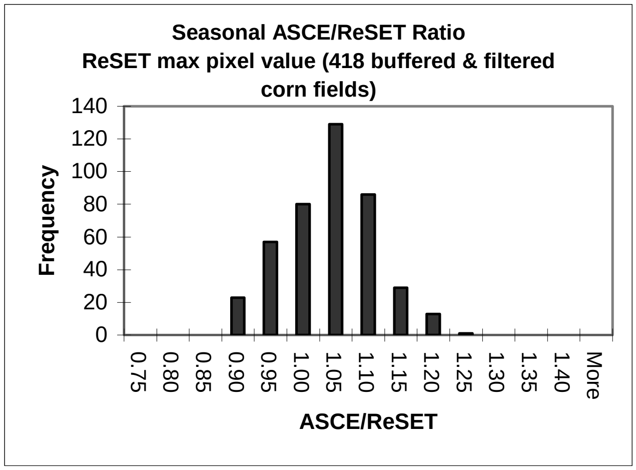


Figure 2. Ratio of ASCE/ReSET maximum pixel value for each field.

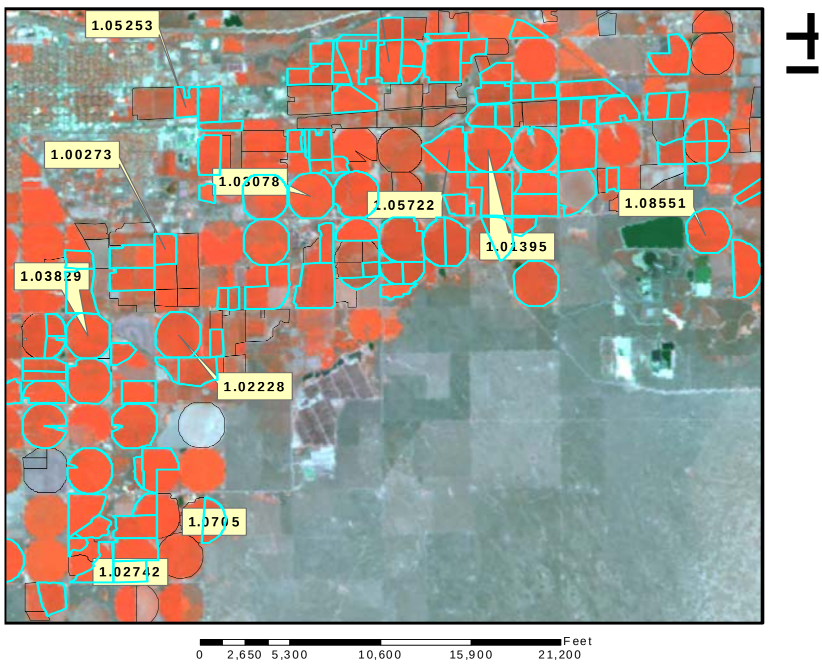


Figure 3. ASCE/ReSET corn seasonal ET ratio around 1 – (background image 7/14/2006)

Model application in the lower Arkansas River Basin region in Colorado.

The ReSET model can be used to calculate the total amount of water consumed by fields in a region, the model was applied to the lower Arkansas River Basin in Colorado. The study region contains a large agricultural area. This region grows a variety of crops, most commonly corn and alfalfa, with a variety of other crops including onions and melons. Seven Landsat 5 images were obtained for the area, using the ReSET model, ET grids were developed for the 2007 growing season starting in late April and ending in early October. Seasonal estimates of ET were developed using the ReSET seasonal tool (Elhaddad and Garcia 2008) which calculates ET for a specific period using individual ET grids processed from single Landsat scenes and interpolating between them. The ET grids for days between the scenes are created based on temporal and spatial interpolation between actual Landsat image dates using the daily reference ET from weather stations in the region as an interpolation index.

The seasonal ET results of ReSET were combined with a Geographic Information System (GIS) to determine the total water consumption per pixel (900 mts^2) which were aggregated to a field and then to a canal service area. The actual water consumption can be compared to the water requirements of the crops and this information can be used to identify areas of water stress. This information can also be used to help farmers or water managers improve their irrigation management.

Single ET Grids Estimated by ReSET from 4/28/07 to 10/5/07

Figure 4 below shows the individual ET scenes and the original Landsat 5 imagery. As can be seen from the processed images the ET is low at the beginning and end of the season (as expected) while it goes to the highest value during the middle of the season. Some of the images show an increase in ET in the non-irrigated areas and this is most likely due to rainfall prior to the image date or due to upward flux from a shallow water table or seepage during the middle of the season due to irrigation activities.

Seasonal Evapotranspiration Grids

When developing a seasonal Evapotranspiration grid, the main crop of interest determines the start and end date of the seasonal grid. Figure 5 shows two seasonal estimates of water consumed by different types of crops, on the left is the ET estimated from April 28, 2007 (DOY 118) and Oct. 5, 2007 (DOY 278) which targets crops such as alfalfa. The grid shows ET values up to 1,200 millimeters for the growing season. The grid on the right covers the ET for the period from May 30, 2007 (DOY 150) and October 5, 2007 (DOY 278) which targets crops such as corn. The grid shows ET values up to 900 millimeters for the growing season.

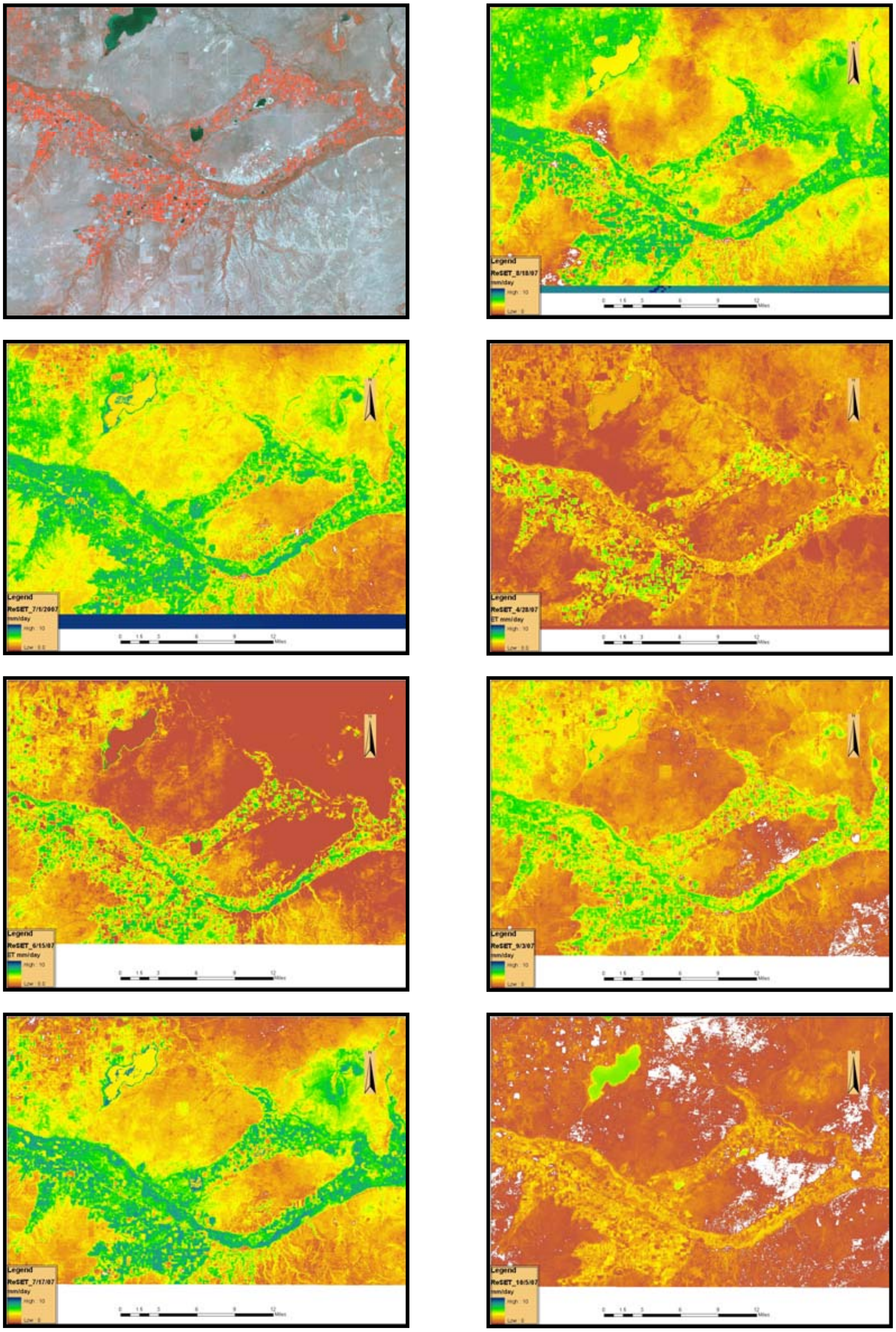


Figure 4. ReSET images for 2007

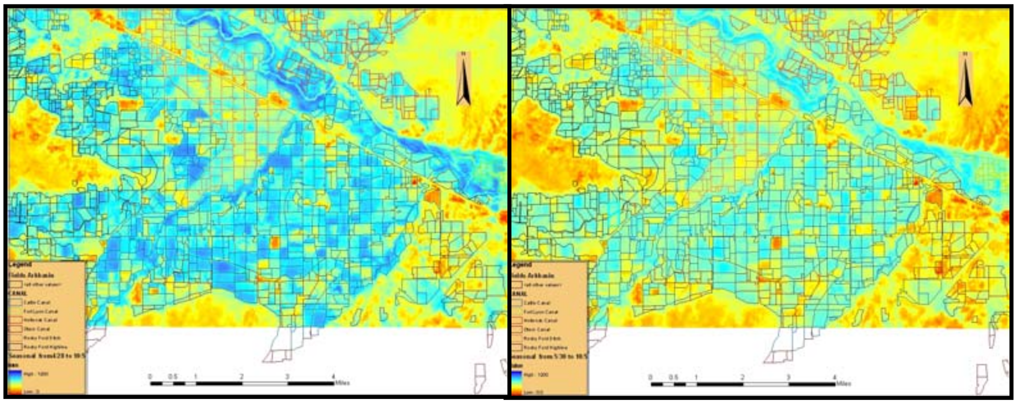


Figure 5. Seasonal Evapotranspiration grids for alfalfa (left) and corn (right).

<u>Seasonal ET for Canal Service Areas</u>

When evaluating the performance of a canal one important issue is the water conveyance efficiency of the canal. What are the losses? Are the fields at the lower end of the canal getting enough water, similar to the fields located at the head of the canal? What is the actual amount of water consumed by the crops in the canal service area? All these questions can be answered fairly accurately by the remote sensing-based approach. The Catlin canal in the Lower Arkasas River Basin in Colorado was selected using GIS and Figure 6 shows some spatial information for this canal; such as the sum of the water consumed by the fields in this canal service area. For the Catlin canal the model estimated the ET to be 57,525x10^3 m^3 (46,636 acre feet), this number represents the actual water used by the crops in all the fields in the Catlin canal service area during the period from April 28, 2007 (DOY 118) and October 5, 2007.

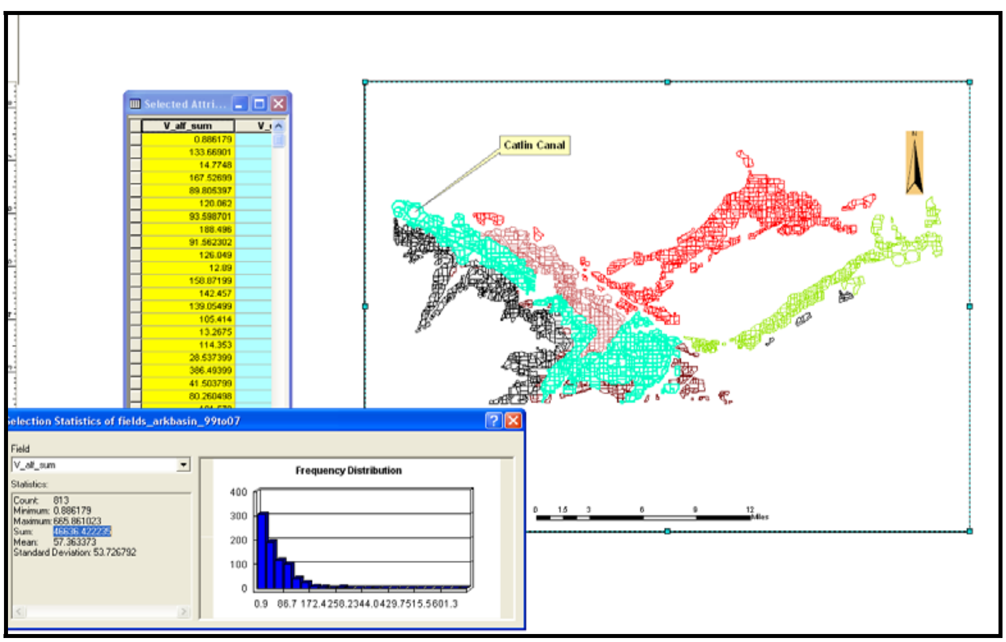


Figure 6. Seasonal evapotranspiration for the Catlin Canal service area

Model Application in Palo Verde Irrigation District (PVID)

The Palo Verde Irrigation District service area falls on the overlap between two Landsat scenes (39/37 and 38/37), which made it possible to collect over 30 usable images for the area in the year 2002 (a combination of Landsat 5 and 7 scenes). Seasonal estimates were calculated from single ET grids processed using both the un-calibrated for atmospheric effects and the calibrated for atmospheric effects ReSET models. The alfalfa fields in the area had a maximum ET value of 1,748 mm/yr when estimated using the calibrated process. The alfalfa ET for the Blythe weather station from the California Irrigation Management Information System (CIMIS) is 1,774 mm/yr which is 1.5% more than the annual ET estimated by the calibrated ReSET model. Figure (7) shows the seasonal ET using the un-calibrated ReSET ET grids where the seasonal alfalfa ET estimates resulted in a maximum annual ET of 1,612 mm/yr which is 9.1 percent lower than the CIMIS estimates.

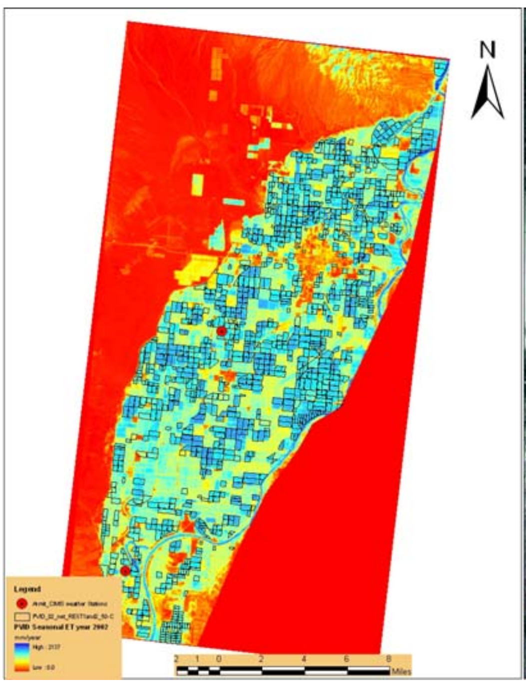
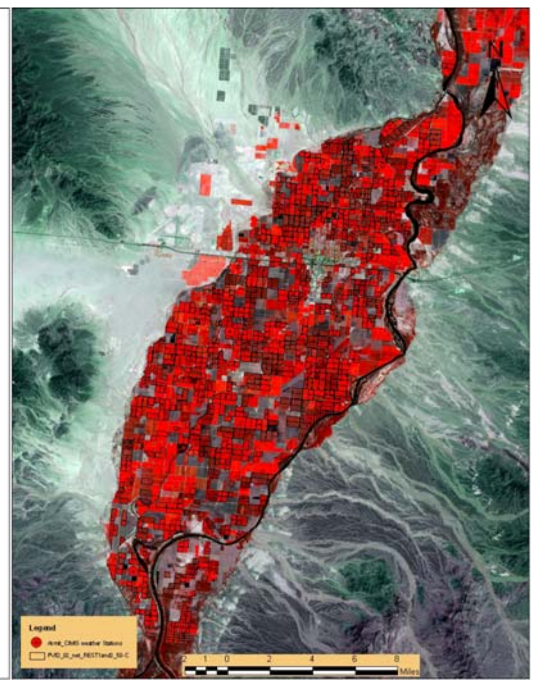


Figure 7. Seasonal ReSET ET



Landsat 7 image for the study area

ReSET Model ET Comparison to Lysimetric ET

Lysimeters provide accurate measurements of actual ET. The ReSET model ET estimates were compared with ET derived from the USDA-ARS Lysimeters at Bushland, Texas.

The Conservation and Production Research Laboratory (CPRL) of the USDA-ARS located in Bushland, Texas is located at 35° 11’ N, 102° 06’ W, and its elevation is 1,170 m above mean sea level.

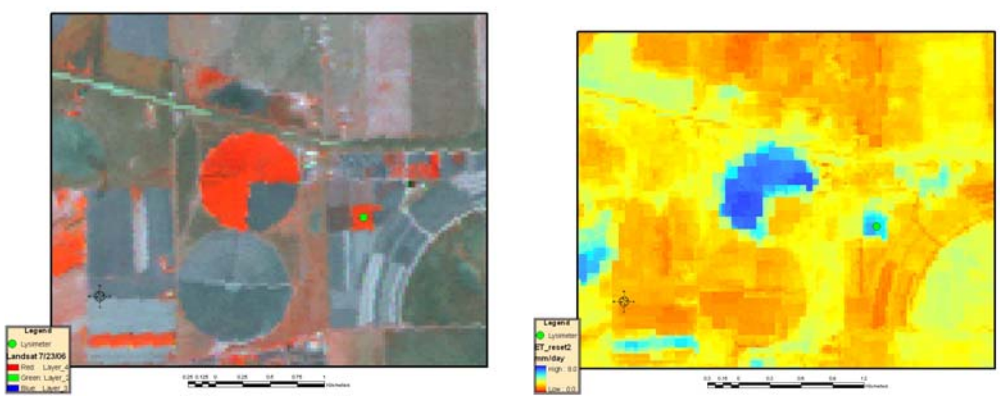
Estimates of ET for a Landsat 5 Thematic Mapper ™ image acquired on 7/23/06 were evaluated. The scene path/row was 31/36 and was acquired at 17:20 GMT [11:20 am

Central Standard Time (CST) in the US], DOY 204. The TM band 6 image was captured at a coarser resolution of 120 m, and was re-sampled to 30 m by the image supplier.

There were four lysimeter fields, each planted to clumped grain sorghum (northwest dryland field), row grain sorghum (southwest field), silage corn (northeast irrigated field), and silage sorghum (southeast irrigated field) respectively. Each lysimeter was located in the middle of approximately 4.5 ha fields.

The satellite image was processed using the ReSET model in its two modes (un-calibrated and the weather station calibrated mode), the weather station used in the model calibration was the Bushland-ARS station. The daily ET from the sorghum planted in the southwest Lysimeter was (ground data) 7.79 mm/day for that day. The selected cold pixel had a UTM coordinates of (3,897,719 N, 763,374 W), the hot pixel UTM coordinates was (3,878,382 N, 799,004 W).

The daily ET value for the Lysimeter estimated by the un-calibrated model was 6.73 mm/day (Figure 8) with a difference of -13.6 percent from the daily estimate of the Lysimeter, with the reference ET calibrated run the difference goes to -11.16%. The Lysimeter had sorghum grown for forage. A center pivot next to the Lysimeter was selected as our well irrigated field in the modeling process, it had an ET of 7.29 mm/day and 8.02 mm/day in the un-calibrated and the calibrated modes respectively. In the calibrated mode the reference ET used was 7.62 mm for the 24 hour ET and 0.76 mm for the hourly ET from the ARS-Bushland weather station. The field selected as a well irrigated field in the un-calibrated mode was 96 percent of the weather station reference ET and 105 percent of the reference ET in the calibrated mode.



Landsat imagery 7/23/06, Lysimeter location Calibrated ReSET ET (7/23/06)

Figure 8. Lysimeter Landsat 5 image and ReSET ET estimates.

CONCLUSION

The ReSET model was used to estimate daily and seasonal ET for several regions in the USA (South Platte river basin, CO; Arkansas river basin, CO; Palo Verde Irrigation District, CA; and Bushland, TX), for the daily estimates the model was compared with ET measured by lysimeters in Bushland, TX, showing only 5 percent difference from the daily ET recorded by the lysimeter. Seasonal estimates for the South Platte river basin were compared to the ASCE seasonal estimate for corn, the ratio of ASCE divided by the ReSET seasonal estimates for 418 corn fields had an average for ratios of 1.07, a similar application was done in the PVID to determine seasonal estimates of alfalfa ET in that area. The maximum yearly ET for reference alfalfa estimated by the calibrated ReSET model was 1,748 mm/yr while the estimated ET from the Blythe weather station was 1,774 mm/yr which represents a 1.5 percent difference. The results presented support the idea of using the ReSET model as a tool for water management, such as the example from the Arkansas river valley in Colorado where the model was used to estimate the ET for a group of fields based on the service area for a canals. This information can be used to calculate canal efficiency and irrigation system efficiency. The applications presented in this paper show that remote sensing of ET provides a valuable tool for water management.

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ESTIMATION OF SPATIAL EVAPOTRANSPIRATION OVER NON-IRRIGATED AGRICULTURAL AREAS USING A TWO-SOURCE ENERGY BALANCE MODEL

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ABSTRACT

Spatial estimation of evapotranspiration (ET) from satellite imagery is important in agricultural studies because it provides information about the spatial variability of crop growing patterns and health, as well as for crop water requirements.

The two-source energy balance model is one of the techniques used successfully in estimating ET spatially, through the estimation of surface energy fluxes such as sensible heat flux H, soil heat flux G, net radiation Rn, and latent heat flux LE, the latter being extrapolated to daily ET.

The current study applies the two-source model to rain fed agricultural field located in the Walnut Creek watershed south of Ames, Iowa. Landsat TM images used to perform the analysis with the support of ground based data were acquired during the SMACEX project conducted in the summer of 2002. A visual basic interface called SETMI was programmed to interact with ArcGIS and perform the analysis spatially.

A footprint model was used to compare the estimates of the different fluxes with measurements from eddy covariance flux towers. Two different closure methods were used to overcome the lack of closure problem in the eddy covariance measurements. Generally, the results show good agreements between the measurements and the estimates. The results show an underestimation of sensible heat flux with RMSE of 30 (Wm^{-2}) and latent heat flux with RMSE of 45 (Wm^{-2}). The net radiation and the soil heat flux shows RMSE of 17 (Wm^{-2}) and 29 (Wm^{-2}), respectively. The daily ET resulted in a RMSE of 0.71 (mm/day) and BIAS of -0.29 (mm/day).

INTRODUCTION

Evapotranspiration (ET) is an important component in hydrology, climatology, and water resource management. The spatial estimation of ET is required because of the inherent spatial variability of different factors affecting ET, such as soil and weather factors. It also provides information about the variability of the growing pattern of crops in the agricultural studies. Spatial ET over large areas can be estimated using satellite imagery.

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In irrigated agriculture, reliable estimates of spatially distributed ET can aid in the detection of water stress in cropped fields as well as seasonal ET, providing improved crop water demand estimates.

The following study applies the two source energy balance model (TSM) originally developed by Norman et al. (1995) with the consideration of the series resistance formulation approach in estimating the sensible heat flux over the surface. It is proved to have a better description of the interaction between the surface and the near-surface atmosphere (Anderson et al. 1997, Li et al., 2005). It deals with the surface energy fluxes over the bare soil and the vegetation canopy separately and then combines them at a level above the ground surface called air-canopy interface. The TSM with its recent modifications (Anderson et al. 1997, Li et al., 2005) has been used to provide estimates of different surface energy fluxes over a wide range of land surface covers. In order to perform the analysis, the TSM was programmed using ArcGIS as the modeling interface and Visual Basic 6 as a programming language to estimate ET spatially within a larger framework called Spatial EvapoTranspiration Modeling Interface (SETMI).

The model was tested over rain fed fields of corn and soybean crops located in the Walnut Creek watershed south of Ames, Iowa. Landsat TM5 and TM7 satellite images were the main sources of the remotely sensed data. SETMI requires only three spectral bands RED, NIR, and thermal IR for the analysis. The ground flux data were acquired through the Soil Moisture Atmosphere Coupling Experiment SMACEX project during the summer of 2002 (Kustas et al., 2005, Prueger et al., 2005). The required ground data for analysis and verification were wind speed, surface temperature, incident solar radiation, reference ET, height of flux measurements, net radiation (Rn), soil heat flux (G), and sensible heat flux (H) and latent heat flux (LE).

In addition to the output of the spatial LE image, the model can also produces spatial estimates of the net radiation Rn (Wm^{-2}), the soil heat flux G (Wm^{-2}), and the sensible heat flux H (Wm^{-2}). All the output images are instantaneous estimates for the energy fluxes and the LE was then converted to daily ET (mm/day). For verification purposes, a footprint model was used to obtain the flux source area and integrate the spatial fluxes to compare the estimated spatial surface energy fluxes with the ground based measurements of the different fluxes from eddy covariance.

METHODOLOGY

Description of the Two-Source Model

The two source energy balance model used in this study was originally developed by Norman et al. (1995) with the considerations of the series resistance formulation in the estimation of the sensible heat flux. General description of the model formulation is shown in Figure 1. The energy balance equation is described in Equation1.

$$Rn = H + LE + G \tag{1}$$

where Rn is the net radiation (W m^{-2}) which represents the available energy on surface to do work, H the sensible heat flux (W m^{-2}), LE the latent heat flux (W m^{-2}), and G the soil heat flux (W m^{-2}).

The two source model in its series formulation treats the bare soil and the vegetation surfaces separately and combines the effects at the canopy-air interface. For the estimation of the sensible heat flux it assumes that

$$H = H_c + H_s \tag{2}$$

where H_c and H_s are the canopy and soil components of sensible heat flux, respectively. These components can be estimated using Equations 3 to 5.

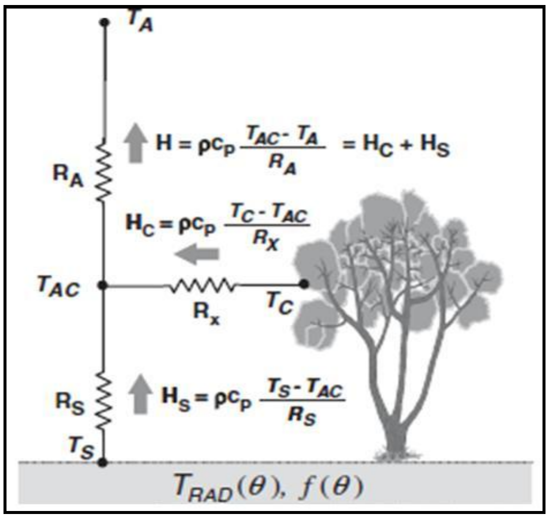

Figure 1. Schematic diagram describing the two-source model TSM approach, (from Anderson et al., 2007).

$$H = \rho C_p \frac{T_{ac} - T_a}{R_a} \tag{3}$$

$$H_c = \rho C_p \frac{T_c - T_{ac}}{R_x} \tag{4}$$

$$H_s = \rho C_p \frac{T_s - T_a}{R_s} \tag{5}$$

where R_a is the aerodynamic resistance to heat transfer and can be estimated using Equation (6), ρ the air density taken as 1.24 (kg m-3), C_p the specific heat of air taken as 1005 (J kg^{-1} K^{-1})and T_s, T_a, and T_{ac} the surface, air, and air-canopy interface temperatures, respectively.

$$R_a = \frac{\left[\ln\left(\frac{z_u - d_o}{z_{om}}\right) - \psi_M\right]\left[\ln\left(\frac{z_t - d_o}{z_{om}}\right) - \psi_H\right]}{k^2 u} \tag{6}$$

where z_u and z_t are the measurement heights for wind speed and air temperature, respectively, d_o the displacement height estimated as a fraction of canopy height h_c , $d_o = (2/3)\times h_c$, and z_{om} the roughness length for momentum taken as a fraction of canopy height, $z_{om} = (1/8)\times h_c$ (Garratt and Hicks, 1973). The stability correction factor for atmospheric heat and momentum transfer are ψ_H and ψ_M, respectively (Brutsaet, 1982).

The total boundary layer resistance of the complete canopy leaves R_x is estimated using the equation described by Norman et al. (1995). The resistance to heat flow in the boundary layer immediately above the soil surface R_s is estimated using Equation 7.

$$R_s = \frac{1}{a + bu_s} \tag{7}$$

where *a* and *b* are constants equals to 0.004 and 0.012, respectively. The parameter u_s represents the wind speed at height above the soil surface where the effect of soil surface roughness is minimal and estimated by the equation described by Norman et al. (1995). Recent modification to Equation 7 shows that R_s can be updated by the knowledge of T_s and T_c, in which it replaces the constant *a* by $c\times(T_s\text{-}T_c)^{(1/3)}$, where c = 0.0025, (Li et al, 2005), (Norman et al, 1995), (Kustas and Norman, 1999a, 2000).

For the estimation of the soil and canopy components of the latent heat flux estimates the TSM assumes that

$$LE = LE_c + LE_s \tag{8}$$

where LE_c and LE_s are the canopy and soil components of the latent heat flux, respectively. LE_c is estimated using Priestly-Taylor formulation described in Equation 9 (Norman et al, 1995).

$$LE_c = \alpha_{PT} f_G \frac{\Delta}{\Delta + \gamma} Rn_c \tag{9}$$

where α_{PT} is Priestly-Taylor constant taken as 1.26, f_G the fraction of the LAI that is green (f_g =1), Δ the slope of the saturation vapor pressure versus temperature curve, and γ the psychrometric constant ($0.066 kPaC^{-1}$), and Rn_c the canopy component of the net radiation.

For the estimation of the soil heat flux the TSM assumes that

$$G = C_g \times Rn_s \tag{10}$$

where Rn_s is the soil component of the net radiation and C_g constant taken as 0.35 (Santanello and Friedl, 2003).

The net radiation can be estimated using the recently revised version of the two-source model as described by Li et al. (2005), which is based on the model developed by Campbell and Norman (1998) and can be described as

$$Rn = Rn_c + Rn_s \tag{11}$$

$$Rn_c = Ln_c + (1-\tau_s)(1-\alpha_c)S \tag{12}$$

$$Rn_s = Ln_s + \tau_s(1-\alpha_s)S \tag{13}$$

where Ln_c and Ln_s are the canopy and soil components of the long wave radiation estimated using Equations 14 and 15, respectively, α_s the soil albedo, α_c the canopy albedo, τ_s the solar transmittance , and S the solar radiation.

$$Ln_c = [1-\exp(-k_L \Omega LAI)][L_{sky} + L_c + L_s] \tag{14}$$

$$Ln_c = \exp(-k_L \Omega LAI)L_{sky} + [1-\exp(-k_L \Omega LAI)]L_c + L_s \tag{15}$$

where k_L is an extinction coefficient, L_{sky}, L_c, and L_s the long wave radiation from the sky, canopy, and soil, which can be calculated from air, canopy, and soil temperatures, respectively, and Ω is the clumping factor as function of the sun zenith angle.

To estimate the T_c and T_s, the TSM assumes that they are related to the radiometric surface temperature T_R through Equation 18.

$$T_R(\phi) = \left[f_c(\phi)T_c^4 + (1-f_c(\phi))T_s^4\right]^{1/4} \tag{16}$$

where $f_c(\phi)$ is the fraction of vegetation cover as function of the view zenith angle ϕ , estimated using Equations 17 and 18.

$$f_c(\phi) = 1-\exp\left(\frac{-0.5\Omega LAI}{\cos(\phi)}\right) \tag{17}$$

$$\Omega(\phi) = \frac{\Omega(0)\Omega(90)}{\Omega(0) + [\Omega(90)-\Omega(0)]\exp(k\phi^P)} \tag{18}$$

where Ω is the clumping factor at the view zenith angle, k and p empirical coefficients estimated using the procedure described by Li et al. (2005).

To have spatial estimate for the crop height h_c and the leaf area index LAI the formulation developed by Anderson et al. (2004) are used as described by Equations 19 and 20 and for Corn and Soybean, respectively, and Equation 21 for the leaf area index.

$$h_{c\_corn} = (1.2 \times NDWI + 0.6) \times (1 + 0.04 \times \exp(5.3 \times NDWI)) \quad (19)$$

$$h_{c\_soybean} = (0.5 \times NDWI + 0.26) \times (1 + 0.005 \times \exp(4.5 \times NDWI)) \quad (20)$$

$$LAI = (2.88 \times NDWI + 1.14) \times (1 + 0.104 \times \exp(4.1 \times NDWI)) \quad (21)$$

where NDWI is the normalized difference water index,

Both the estimated and measured instantaneous latent heat fluxes were converted to daily ET values in order to be compared against each other. The ratio between the instantaneous actual ET from the energy balance to instantaneous reference evapotranspiration ET_o is calculated and multiplied by the daily reference ET_o to extrapolate to daily actual ET values, assuming that the ratio is constant throughout the specific DOY. The ET_o values were obtained from a reference ET weather station within the project area.

Modeling Tool

In order to perform the spatial analysis, a Visual Basic code was developed and designed to run within ArcGIS platform. The code written to apply the TSM is part of a framework called Spatial EvapoTranspiration Modeling Interface or (SETMI) which consists of different user friendly windows that allows the user to select the required images for the analysis, their spectral band arrangement, to enter weather data, and to select the crop types. The output layer options allows for the selection of intermediate layers such as LAI and final output layers such as Rn, H, G, and LE. A snapshot of the SETMI main window is shown in Figure 2.

Model Verification

The comparison between surface energy balance flux measurements obtained using the eddy covariance systems and the TSM spatial estimates was conducted by integrating the spatial fluxes using the footprint model called Flux Source Area Model FSAM developed by Schmid (1995). In order to obtain the footprints for each field, the FSAM approach requires the friction velocity, roughness length for momentum, Monin-Obukhov stability length, height of zero plane displacements, and standard deviation of wind direction. The FSAM provides the weights of contribution to the upwind source area to the total area from which flux measurements are obtained. The FSAM provides 90 % of the total source area that contributes to the measured energy heat fluxes. With the assistance of the wind direction, the footprints for each satellite overpass date and time and were geo-referenced to the specified field and tower, to be using in the integration of the spatial fluxes.

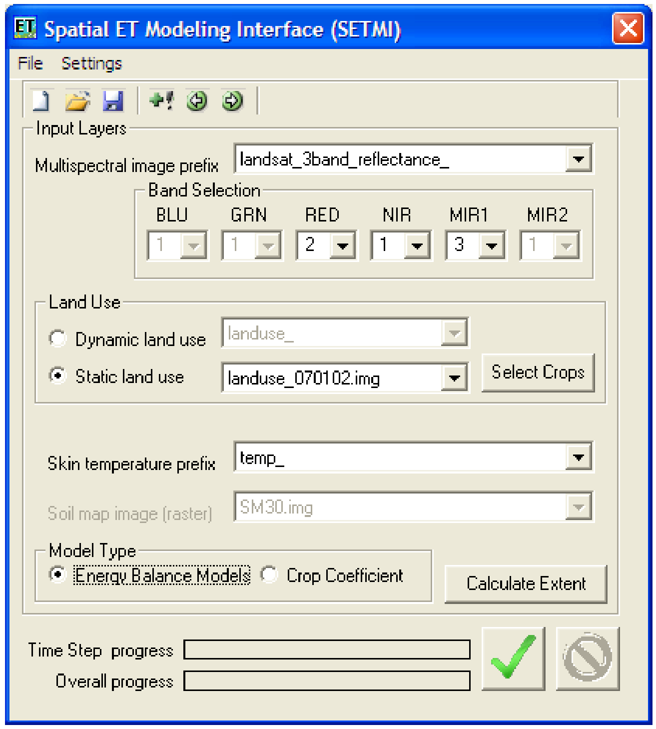

Figure 2. Snapshot for SETMI main window.

The statistical measurements used to compare the estimates with the measurements are the root mean square error RMSE, the mean absolute error MAE and the BIAS described in Equations 23, 24, and 25, respectively.

$$RMSE = \frac{1}{n}\sqrt{\sum_{i=1}^{n}(P_i - O_i)^2} \quad (23)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n} abs(P_i - O_i) \quad (24)$$

$$BIAS = \frac{1}{n}\sum_{i=1}^{n}(P_i - O_i) \quad (25)$$

where P_i and O_i are the estimated and measured values for each value i and total number of measurements n.

The estimated surface energy fluxes were compared to adjusted measured fluxes due to the problem of lack of closure of the energy balance in typical eddy covariance systems measurements. The first method used for estimating closure was the residual method which assumes that all the error in closure should be added to LE. The second method uses the Bowen ratio to proportionally distribute the error between LE and H. The error in closure is reported for each day and crop.

DATA

Study Site

The study site consisted of mostly rain fed corn and soybean fields covering an area of approximately 12× 22 kilometers located south of Ames, Iowa. The crop season starts in late April/early May and lasts until late September/early October. The average annual precipitation is 835 mm.

Remote Sensing Data

The remote sensing data used consisted of Landsat TM5 and TM7 images acquired during the summer of 2002 to match the period of SMACEX project intensive field campaign. The images used in this paper were taken on day of years DOY 174, 182, and 189. These images were atmospherically corrected using MODTRAN (Berk et al., 1989) to obtain at-surface reflectance for the short bands and the radiometric surface temperature with the longwave band. Only the four bands namely red (R), near infrared (NIR), mid infrared1 (MIDIR1), and the thermal infrared of the Landsat images were required for the analysis. Another data set necessary to complete the analysis was the land use image, which identifies the crop types and locations during the study period.

Ground Based Data

The ground based data consisted of air temperature, wind speed, height of measurements, vapor pressure, and incoming solar radiation. Also eddy covariance measurements of surface energy fluxes of Rn, H, LE, and G were acquired in order to be compared with the estimated fluxes. Addition measurements also necessary for model verification were friction velocity, wind direction, and standard deviation of wind direction.

The data from only 8 of the 12 available eddy covariance systems are processed for the purpose of the analysis. The selected corn fields were 6, 24, 33, 151, and 152, while the soybean fields were 3, 13, 23, 161, and 162. The locations of these systems are shown in Figure 3.

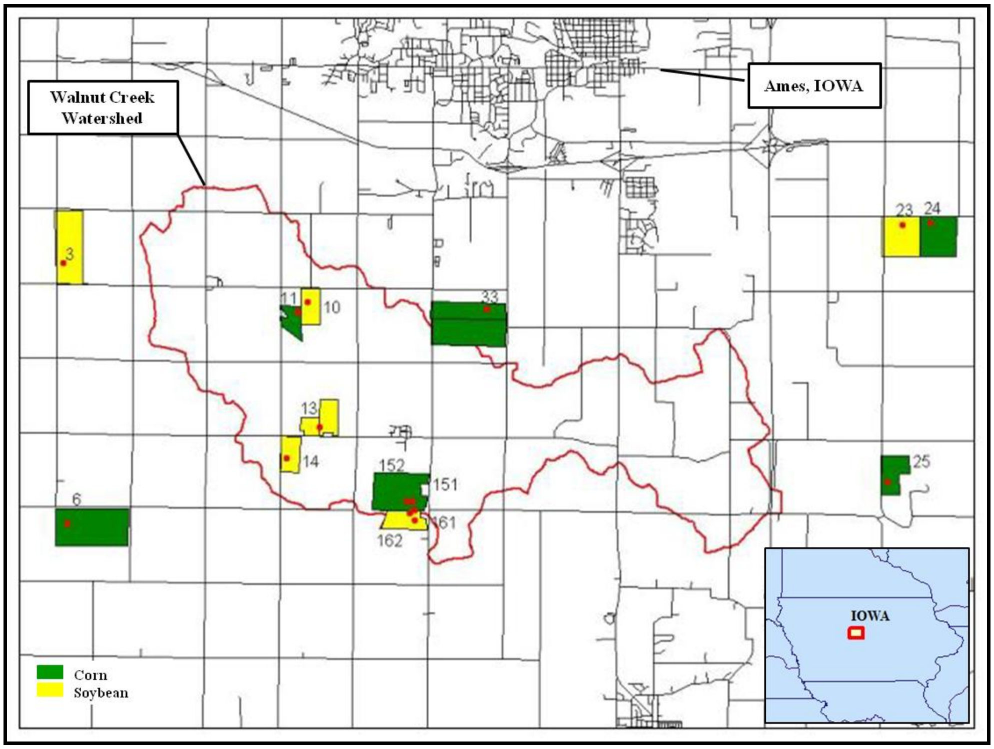

Figure 3. Schematic diagram for the study area, the locations of the eddy covariance systems, and the crop type in the fields.

RESULTS AND DISCUSSION

The latent heat flux LE for DOY 174 (June 23, 2002) clipped to the area around fields 151 and 152 (corn) and fields 161 and 162 (soybean) is shown in Figure 4. The result shows the spatial variability of LE over both corn and soybean fields. The LE for corn field is relatively higher than for soybean which should be the case because of the crop physiological differences.

The source area footprint for DOY 189 for tower 151 in corn field 15 is shown in Figure 5. It shows that the source area extends up to 257 meter from the eddy covariance system in the direction 210º from north based on the wind direction measurements and with a width of about 90 meters perpendicular to the wind direction.

The results obtained for the estimated and measured H_{Re} adjusted with the residual method are shown in Figure 6 and for those H_{BR} adjusted to the Bowen ratio are shown in Figure 7. Generally the results show that for both H_{Re} and H_{BR}, the model underestimates the sensible heat flux with relatively better estimates for H_{Re}. The corn fields show lower sensible heat flux values than the soybean fields as expected because it was at higher green cover, therefore most of the energy was used for LE as the results indicate later in the this section. Comparing measurements adjusted by the two closure methods with the estimated sensible heat flux the RMSE for H_{Re} is 30 (Wm^{-2}) lower than that for H_{BR} 49 (Wm^{-2}), the MAE for H_{Re} is 21 (Wm^{-2}) while it is 37 (Wm^{-2}) for H_{BR}, and the BIAS is -9 (Wm^{-2}) for H_{Re} while it is -31 (Wm^{-2}) for H_{BR}.

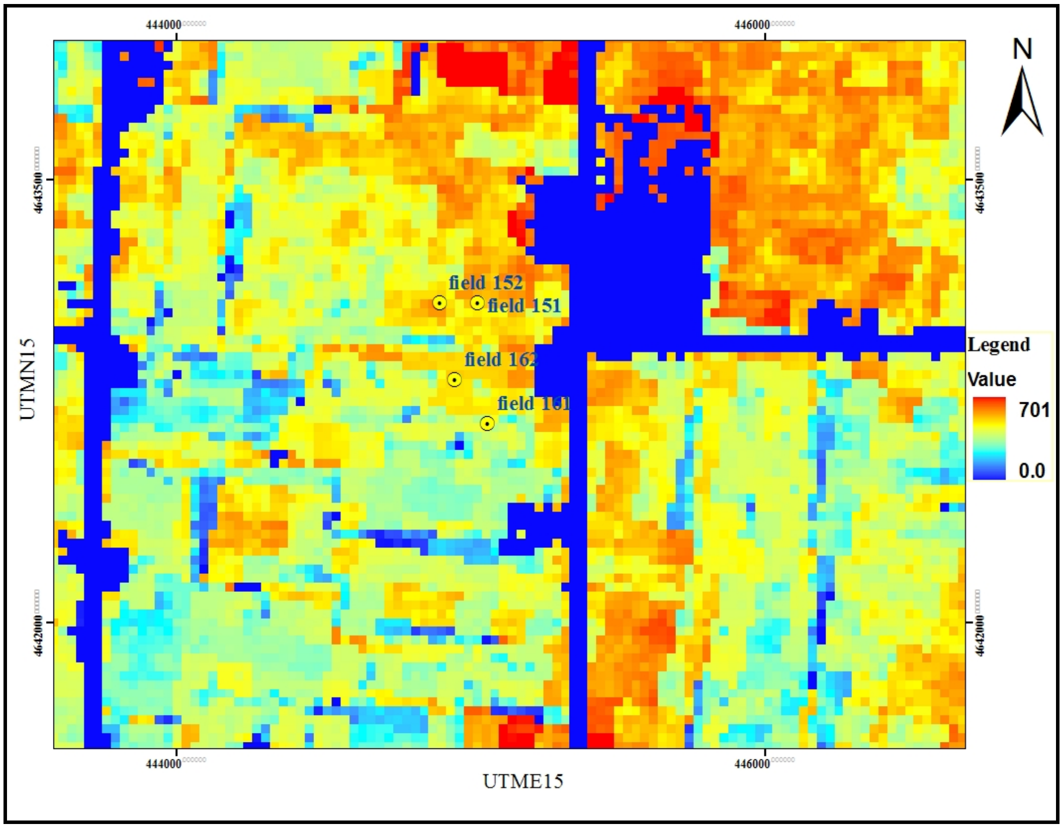

Figure 4. Snapshot of the latent heat flux LE on DOY 174 (June 23, 2002) clipped around the fields 151, 152, 161, and 162.

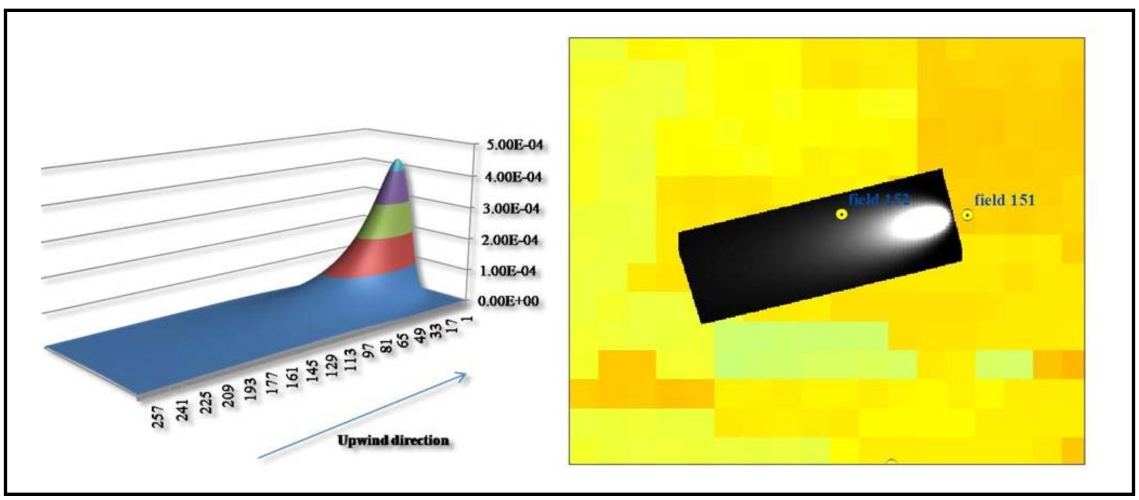

Figure 5. Source area footprint for tower 151 in corn for field on DOY 189.

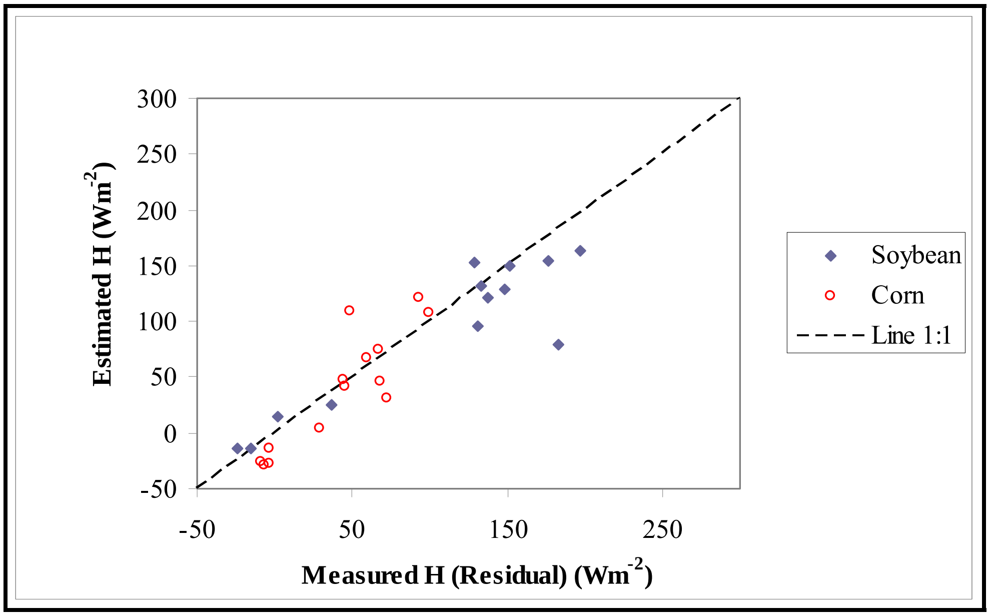

Figure 6. Plot of adjusted H_{Re} (Residual) versus estimated sensible heat flux H.

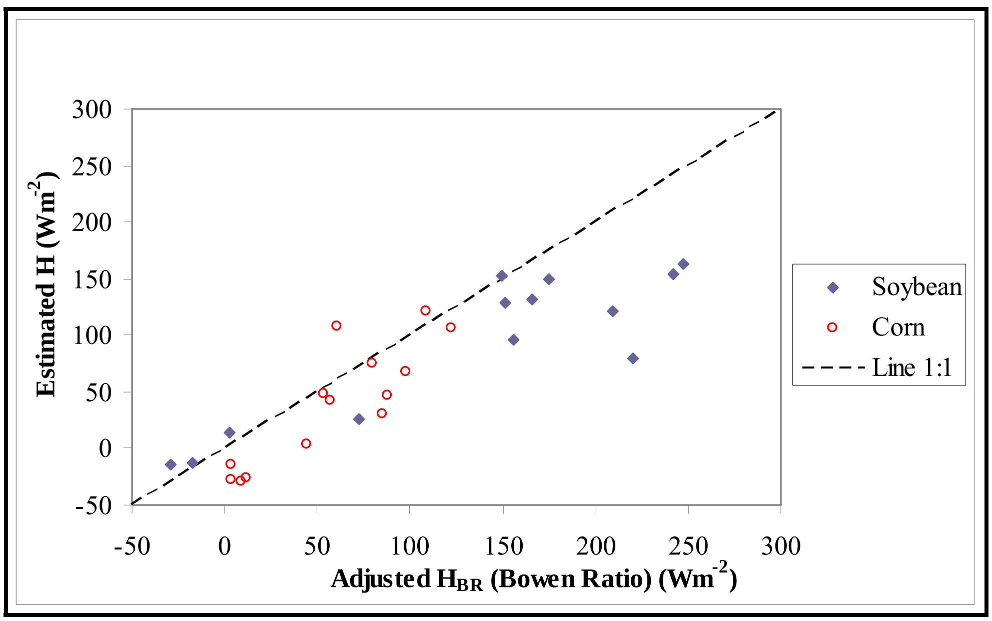

Figure 7. Plot of adjusted H_{BR} (Bowen Ratio) versus estimated sensible heat flux H.

The comparison between the estimated and measured LE_{Re} adjusted using the residual method are shown in Figure 8, and for those LE_{BR} adjusted with Bowen ratio are shown in Figure 9. Generally, both plots show good agreement between measured and estimated latent heat fluxes. However, when comparing the closure methods, LE_{Re} resulted in an underestimation of the LE fluxes compared with LE_{BR}. The LE fluxes in the corn fields were higher than those for soybean fields. From Table 1, the RMSE for LE_{Re} is 45 (Wm^{-2}) while it is 46 (Wm^{-2}) for LE_{BR}, the MAE is 34 (Wm^{-2}) for LE_{Re} and 38 (Wm^{-2}) for LE_{BR}, and the BIAS is -19 (Wm^{-2}) for LE_{Re} and 3 (Wm^{-2}) for LE_{BR}.

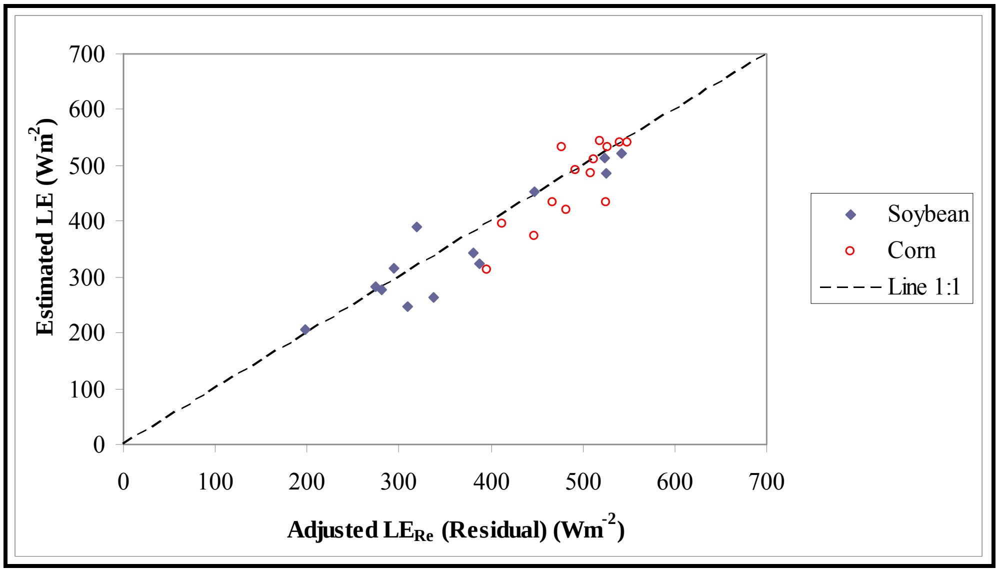

Figure 8. Plot of adjusted LE_{Re} (Residual) versus estimated latent heat flux LE.

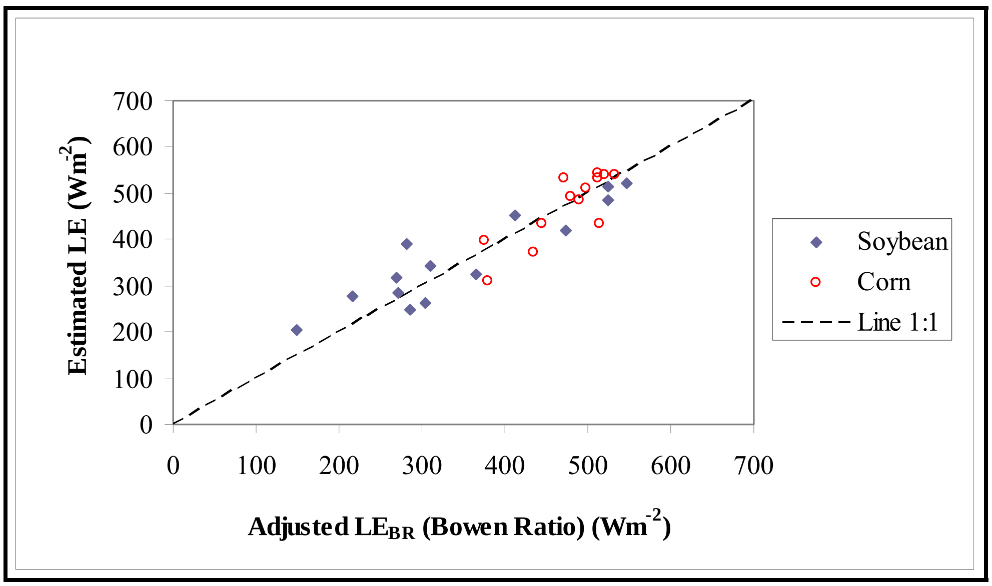

Figure 9. Plot of adjusted LE_{BR} (Bowen Ratio) versus estimated latent heat flux LE.

A comparison of the estimated and measured G is shown in Figure 10. The result shows an overestimation of G. The soil heat fluxes in the corn fields were relatively lower than those in the soybean fields since it had a higher green cover and LAI than the soybean fields. Table 1 shows that the RMSE is 29 (Wm^{-2}), the MAE 23 (Wm^{-2}), and the BIAS 22 (Wm^{-2}).

The net radiation results are shown in Figure 11. The corn fields showed relatively higher values of net radiation but with less agreement with measurements compared to the soybean fields. From Table 1 the RMSE is 17 (Wm^{-2}), and the MAE 13 (Wm^{-2}). The estimated model BIAS is -7 (Wm^{-2}) which indicates that the model underestimates the Rn.

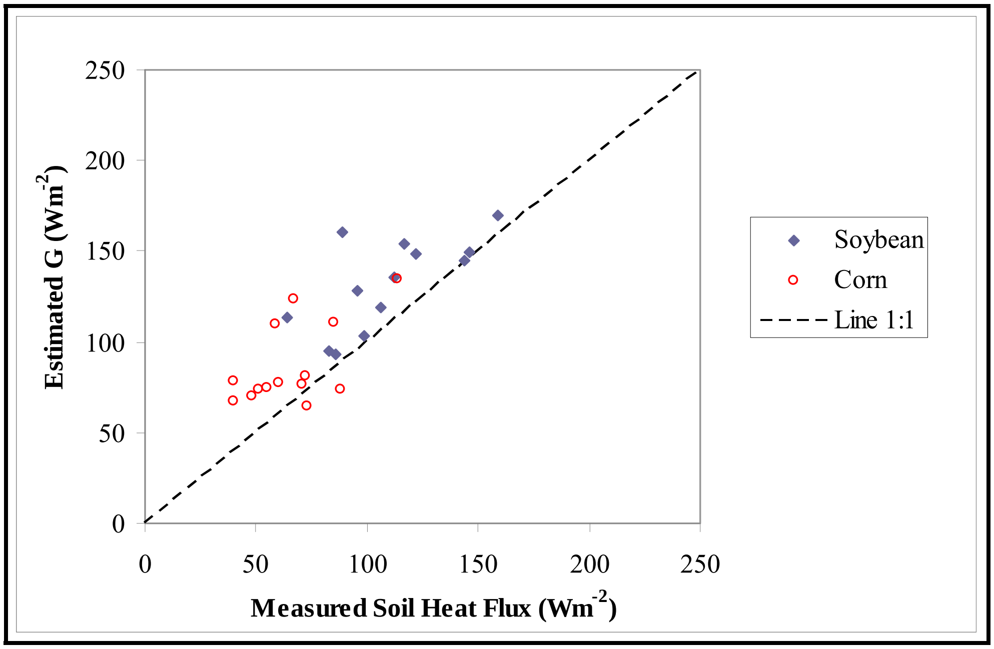

Figure 10. Plot of measured versus estimated soil heat fluxes.

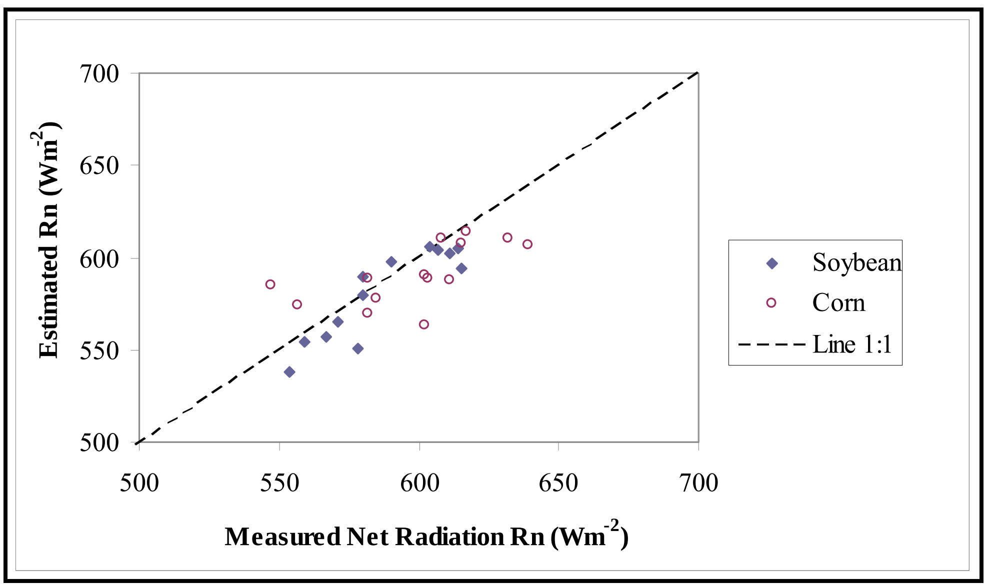

Figure 11. Plot of measured versus estimated net radiation.

Daily ET estimates are compared for the residual ET_{Re} (mm/day) and Bowen ratio ET_{BR} methods of closure in Figures 12 and 13, respectively, and a summary of the statistical results is shown in Table 1.The results show good agreement between measurements and estimates with slight underestimation in both cases.

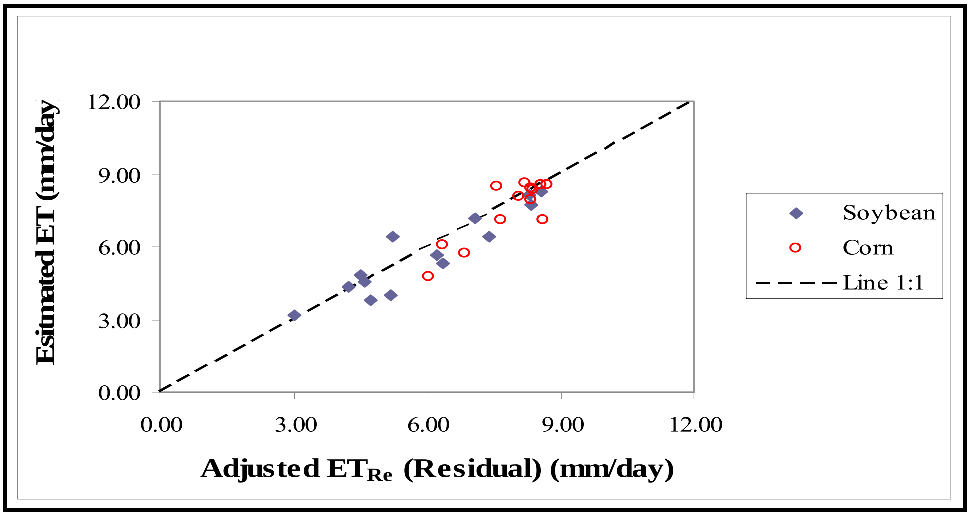

Figure 12. Plot of adjusted ET_{Re} (Residual) versus estimated ET.

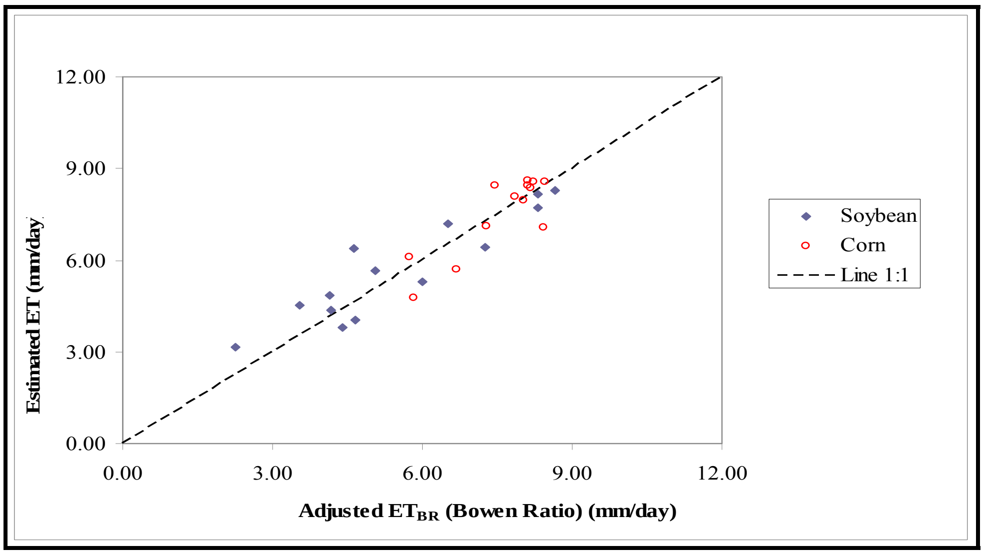

Figure 13. Plot of adjusted ET_{BR} (Bowen Ratio) versus estimated ET.

Table 1. Summary of statistical comparison between estimated and measured of the surface energy fluxes.

	RMSE	MAE	BIAS
H_{Re} (Wm^{-2})	30	21	-9
H_{BR} (Wm^{-2})	49	37	-31
LE_{Re} (Wm^{-2})	45	34	-19
LE_{BR} (Wm^{-2})	46	38	3
G (Wm^{-2})	29	23	22
R_n (Wm^{-2})	17	13	-7
ET_{Re} (mm/day)	0.71	0.53	-0.29
ET_{BR} (mm/day)	0.72	0.60	-0.05

CONCLUSIONS

The current study applied the two-source energy balance model to rain fed corn and soybean cropped fields located in Ames, Iowa. The version of the TSM used is the series resistance formulation for the estimation of the sensible heat flux. A visual basic interface was developed called SETMI that uses the ArcGIS as a platform to perform the analysis.

Landsat TM images were used as the remotely sensed inputs supported with ground based data acquired during the SMACEX project. Two different methods of forcing closure in the eddy covariance flux measurements were tested; the residual and the Bowen ratio methods. The footprint FSAM was used to integrate the source area spatially distributed fluxes in order to be compared with the measured fluxes.

The results indicate that this version of the TSM, when considering the overall performance, slightly underestimates H and LE with BIAS of -9 (Wm^{-2}) and -19 (Wm^{-2}) for H_{Re} and LE_{Re}, respectively. The error in the estimates described by the RMSE are 30 (Wm^{-2}) and 45 (Wm^{-2}) for H_{Re} and LE_{Re}, respectively. There might be a room to improve the model performance by exploring recent modifications for the TSM in decomposing Rn (Anderson et al., 2007). Also the accumulated uncertainty from estimating the different biophysical parameters (e.g. LAI and h_c) could have reduced the model performance and can be improved by exploring different methods. The daily ET_{Re} results showed an underestimation as indicated by the BIAS of -0.29 (mm/day).

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MODEL FOR CALCULATING CONSUMPTIVE USE (IDSCU)

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David Patterson [2]

ABSTRACT

The Integrated Decision Support Group at Colorado State University has been working with a group of water users from the South Platte in Colorado to develop different tools to meet their modeling and data needs. As part of this effort a consumptive use model called the Integrated Decision Support Consumptive Use Model (IDSCU) has been developed. The model calculates water use using multiple ET equations, can compare the results of different ET equations, and shows how water supplies and weather combine to form the depletions of ground and surface water for each modeling area. Users can enter water supplies from multiple sources such as wells or ditches. IDSCU can generate an irrigation schedule based on the user-supplied information such as crop characteristics, soil characteristics and crop rooting depth. IDSCU can also be used to determine the amount of groundwater irrigation that is required if the user has surface water that is augmented by well water. The model has the ability to access weather data on the internet from Coagmet (Colorado), Northern Colorado Water Conservancy District (Colorado), ET Toolbox (New Mexico), AZMET (Arizona) and CIMIS (California). The user can setup templates with weather and crop information for an area, which can be used as the basis for new datasets covered by the same area. Templates store crop characteristics, crop coefficients, water supplies from ditch diversion records and weather information. It can be downloaded from the web www.ids.colostate.edu/projects/idscu. The presentation will give an overview and provide examples of applications of the model.

INTRODUCTION

The Integrated Decision Support Group at Colorado State University has been working with a group of water users from the South Platte in Colorado to develop tools to meet their modeling and data needs. As part of this effort a consumptive use model called the Integrated Decision Support Consumptive Use Model (IDSCU) has been developed. The model has the capability of calculating the water use by means of multiple ET equations, comparing results if different ET equations are used, determine the water demand for multiple fields (the model allows the user to enter either individual fields, groups of fields (farms) or whole canal systems). The users can enter water supplies from multiple sources (wells or ditches) and the IDSCU will calculate a water budget for each field. In addition, the IDSCU can generate an irrigation schedule based on the user-supplied information regarding maximum allowable depletion for each crop, soil characteristics and rooting depth. The IDSCU can also be used to determine the amount of supplemental irrigation that is required if the user has surface water available (diversion records) that is

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being augmented by well water. Currently this model has the ability to automatically access weather data (assuming the user is connected to the internet) from Coagmet (Colorado), Northern Colorado Water Conservancy District (Colorado), ET Toolbox (New Mexico), AZMET (Arizona) and CIMIS (California).

The IDSCU Model can compute monthly CU using the SCS Blaney Criddle, Calibrated Blaney-Criddle, Hargreaves, and Pochop methods. Daily CU estimates can be computed by the model using the Penman-Monteith, Kimberly-Penman, Penman 1948 and the new ASCE standardized reference evapotranspiration equation. In addition the model allows the user to enter a user supplied ET which is currently being use to compare the results from ET calculated from remote sensing by importing the ET estimates from models such as the Remote Sensing of ET (ReSET) developed by Elhaddad and Garcia (2008).

The IDSCU Model has a Graphical User Interface (GUI), and the main window is shown in Figure 1. On the lower right hand side of the main screen are a number of buttons that allow the user to access pop-up screens for entering or modifying crop characteristics, crop coefficients, weather data, surface water supplies, modeling area information, well information, and the weather stations that apply to each modeling area.

The IDSCU Model allows users to generate data based on historical data. The user may generate pre- or post-historical data by averaging selected years, repeating a selected year, or repeating a sequence of years (Figure 2). The model is also capable of generating input and output displays for all year types (calendar, irrigation, and water).

Weather data is needed to calculate reference ET, so the user must input the latitude and longitude, elevation, and height of temperature and wind measurements of each weather station. Depending on the ET method, the model uses yearly frost dates, daily minimum and maximum temperature data, precipitation, solar radiation, and wind speed. The user then associates a group of weather stations to each modeling area by assigning a weight based on each station’s influence on the area.

The model can calculate CU or Irrigation Water Requirements (IWR) with or without using soil moisture. The model can use supplies from ditch allotments and apply them to the consumptive use computed for crops. If the crop is still short of water, the balance is assumed to come from ground water wells or be shown as a shortage depending on the options selected in the well information window. The GUI allows users to compare the CU computed with different methods and computes ratios between the different methods. This allows users to evaluate the difference between ET methods as well as provide some guidance for users if they are interested in calibrating a monthly method based on the differences between the monthly aggregated values of daily ET methods.

When pumping records are available, users may enter either monthly or total annual pumping. If the user enters total annual pumping the model will distribute the pumping into monthly values based on whether the well is agricultural or non-agricultural. The model also allows the user to enter a Presumptive Depletion Factor (PDF) for each well. The PDF is a calculated factor that estimates the amount of pumping that is used to meet CU. If the user provides values for pumping and a PDF, the model calculates the depletions of groundwater to meet crop CU as pumping multiplied by PDF. The amount of groundwater depletion can also be calculated based on the ET method(s) and a water budget. The depletions of groundwater based on both PDF and ET can be compared to check if the two values of depletion of groundwater are similar.

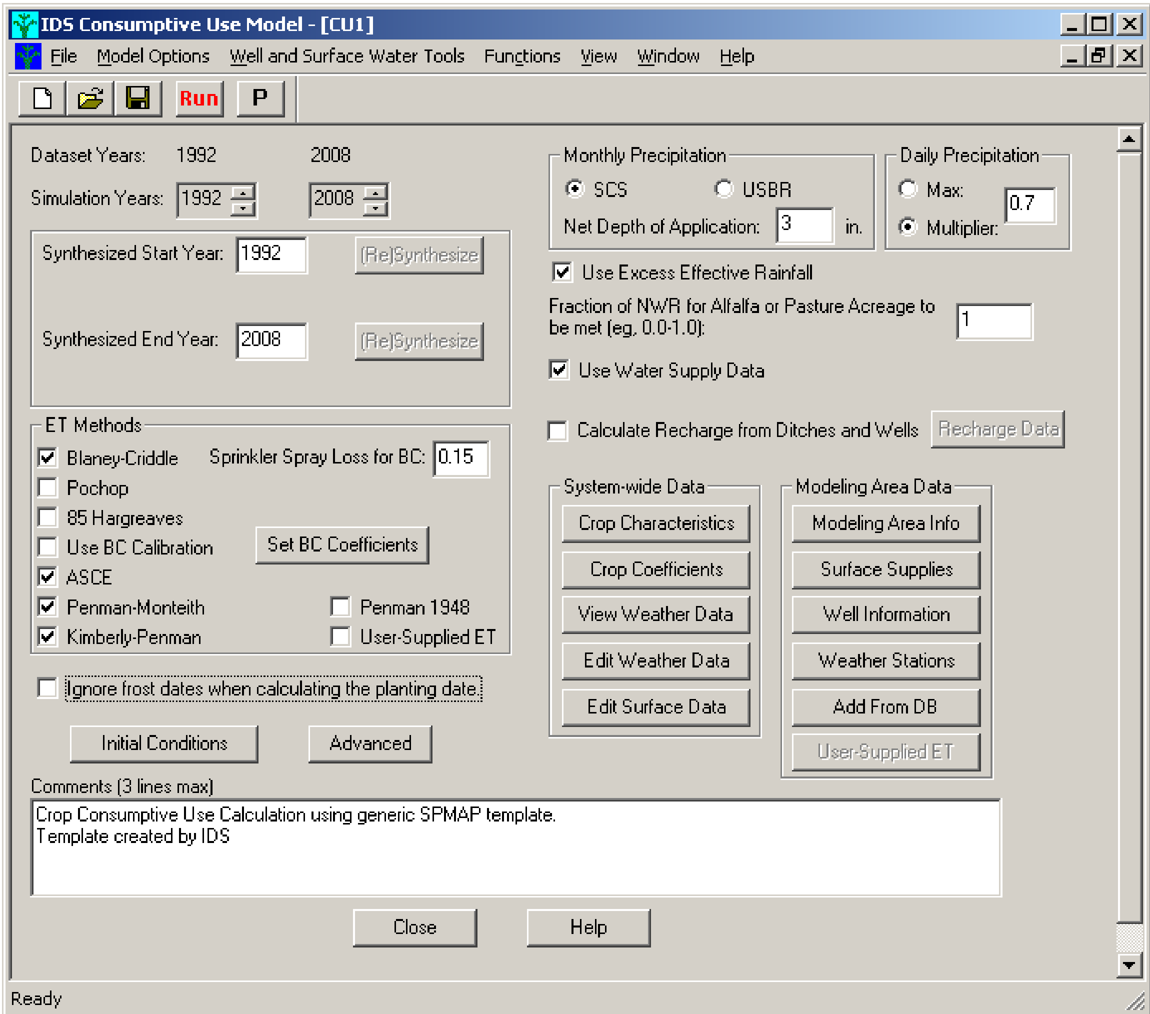

Figure 1. IDSCU Main Interface Window.

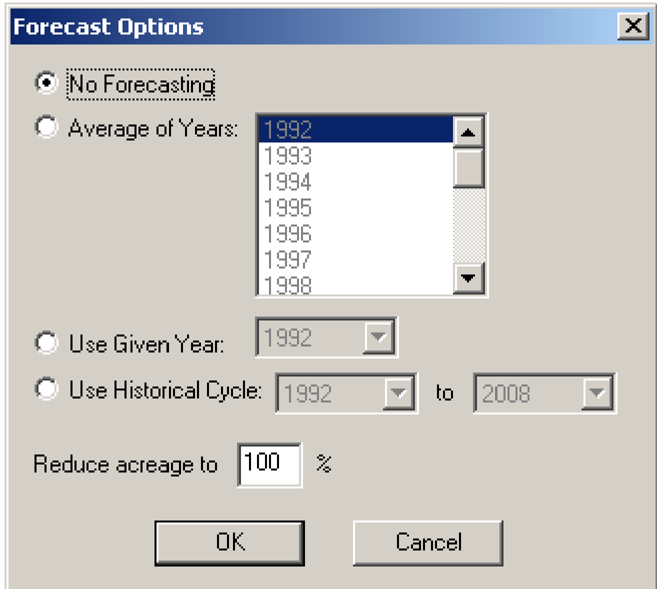

Figure 2. IDSCU Forecasting Options.

QUANTIFICATION OF WATER SUPPLIES

Water supplies are normally from two sources, surface water and groundwater pumping. The model allows users to query the State Engineers Office database for Colorado (Hydrobase) to generate a set of diversion records for different ditches or diversion structures. Users may also build a set of diversion records for different ditches or diversion structures by entering the diversion records manually. The surface supply for each modeling area is then calculated by assigning one or more surface supply ditches or structures to it. The IDSCU Model requires users to enter the shares for each ditch or structure that are owned by each modeling area (Figure 3). The amount of shares for a particular ditch that are assigned to a modeling area can vary from year to year enabling users to evaluate the impact of leasing water in certain years. In the event that the user has headgate diversion records, these can be entered for each modeling area.

For groundwater pumping, users may enter monthly groundwater pumping, or if the user only has total annual pumping, the model has the ability to distribute annual pumping into monthly values for agricultural and non-agricultural wells.

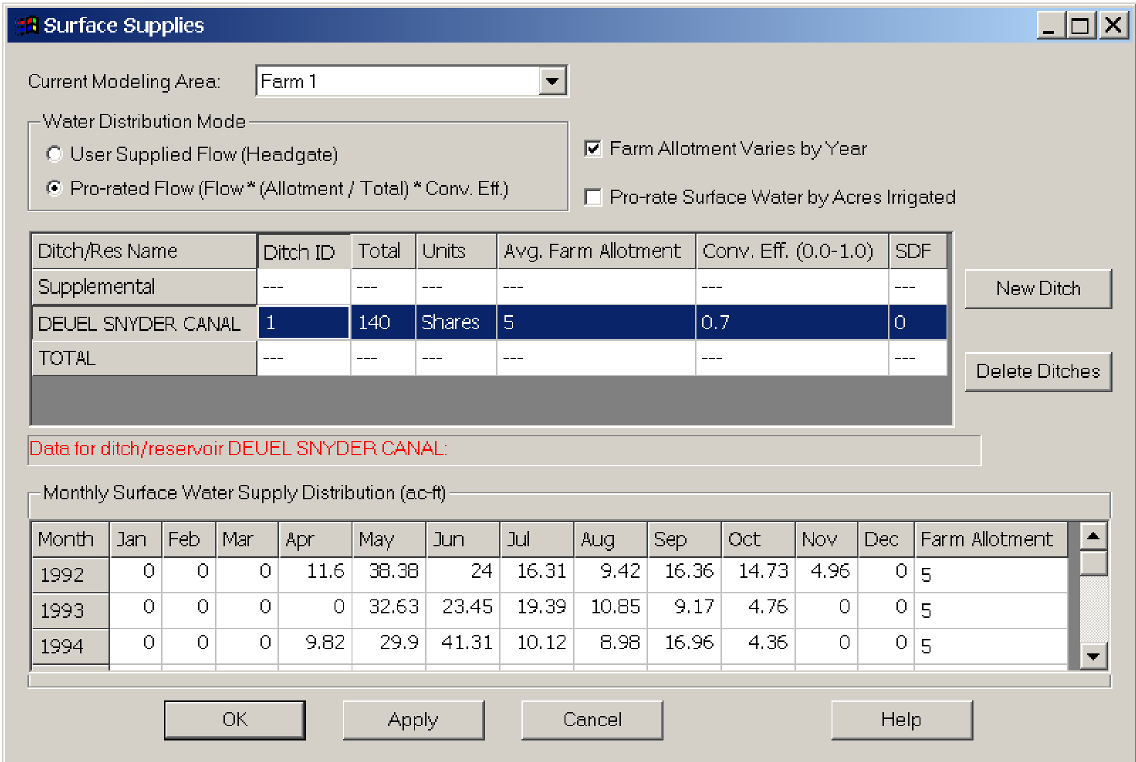

Figure 3. IDSCU GUI for Surface Supply Options

QUANTIFICATION OF DEPLETION OF GROUNDWATER

After obtaining an estimate of the water demand and supply, the IDSCU model can compute depletions of both surface and groundwater with or without a soil moisture budget (Figure 4). Users may evaluate the impacts of the groundwater depletions based on whether the groundwater is a primary or supplemental source of water and if the well's efficiency is based on a PDF. The model allows the user to display all components of the water budget. The user has the option of evaluating a water budget with or without soil moisture. Once the user selects either with or without soil moisture the model displays a window (Figure 5) with all components of the water budget. The user can then select to view different components of the water budget but selecting the different components from the upper right side of Figure 5. As the user select different components those components are shown on the bottom part of the screen. The user has multiple options of the time step to see the data (daily, monthly or yearly). The results may be plotted with the click of a button using the IDSCU Model's built-in graphics package (Figure 6). Users may compare the results of different ET methods (Figure 7) by selecting two methods and displaying the ET estimates for each method as well as the ratio of the two methods.

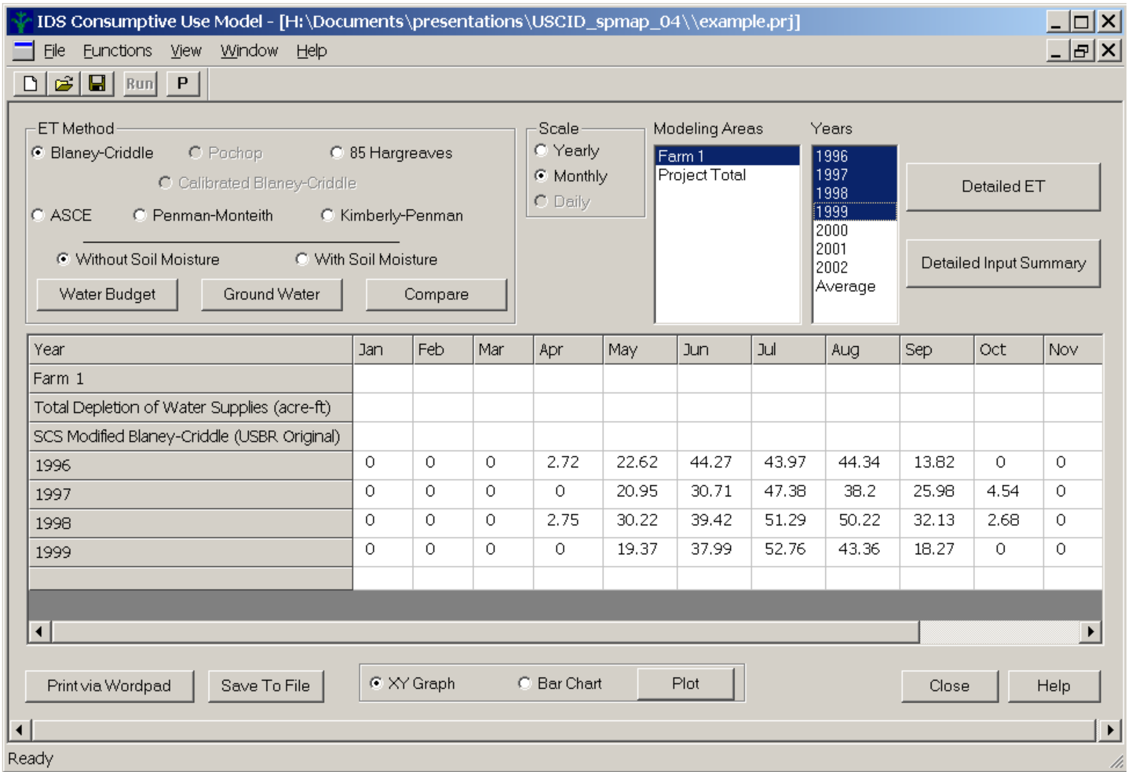

Figure 4. IDSCU GUI General Output Screen.

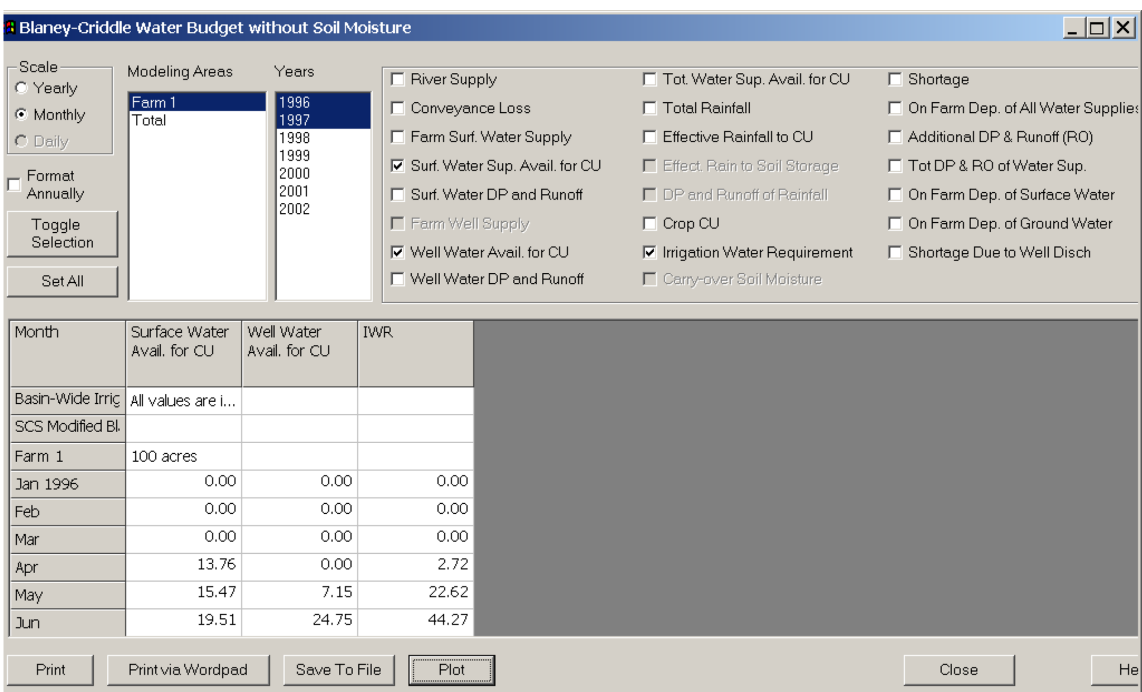

Figure 5. IDSCU GUI for Water Budget Output Screen.

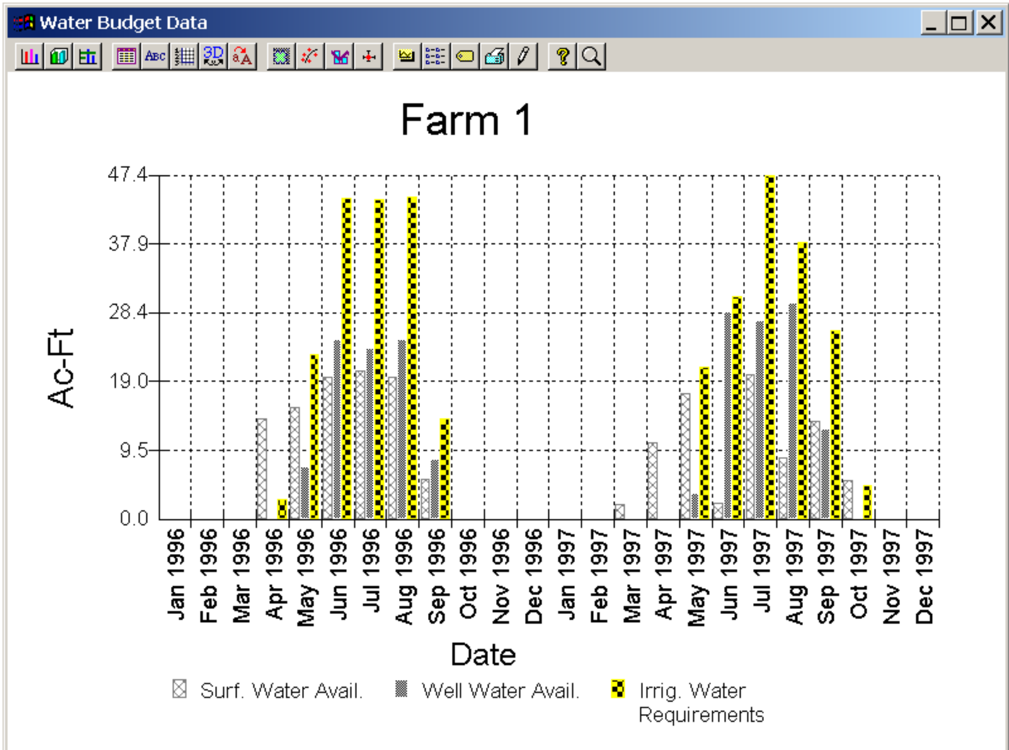

Figure 6. IDSCU GUI Water Budget Sample Plot.

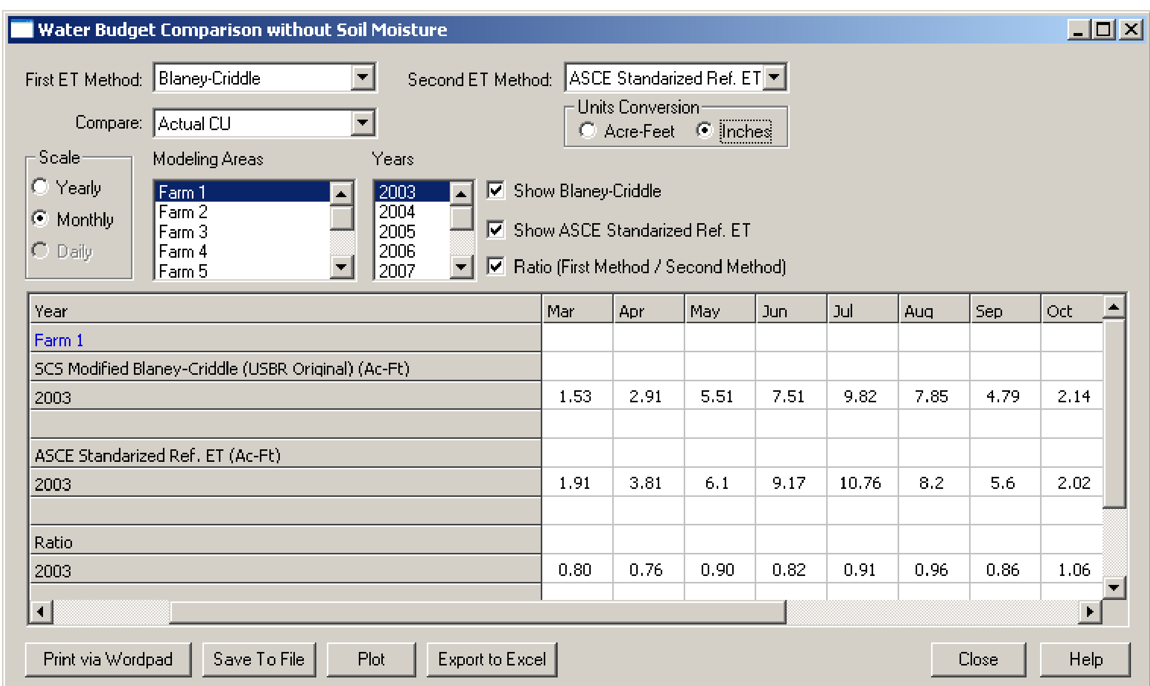

Figure 7. IDSCU GUI of Comparison of ET Method Results

The interface can also display the detailed output from each ET method such as the reference ET, the start and end of crop growth, the effective rain, and the crop CU on a daily or monthly time step (Figure 8).

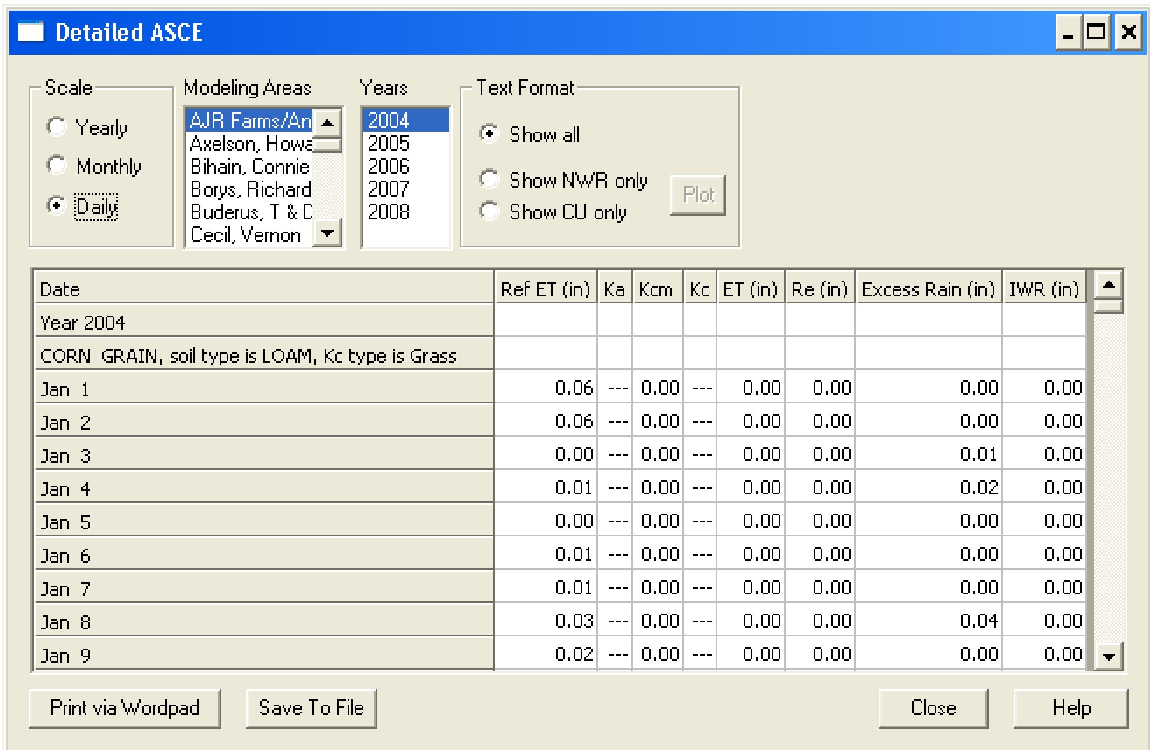

Figure 8. IDSCU GUI Detailed ET Output.

The IDSCU model was initially created as a response to the needs of water users in the South Platte of Colorado. The capabilities of the model have been expanded and the model has been applied in several states around the western US. The model has the ability to access weather data on the internet from Coagmet (Colorado), Northern Colorado Water Conservancy District (Colorado), ET Toolbox (New Mexico), AZMET (Arizona) and CIMIS (California) as well as the user can enter or import (by cutting and pasting or entering manually) their own weather data. The model is free and can be downloaded from the web at the following URL:www.ids.colostate.edu/projects/idscu At the webpage for downloading the model there is a changelog file that users can download which tracks any updates and bug fixes with the different versions of the model. In addition the model has an interactive help (Figure 9) that provides the user with information about the different options of the model.

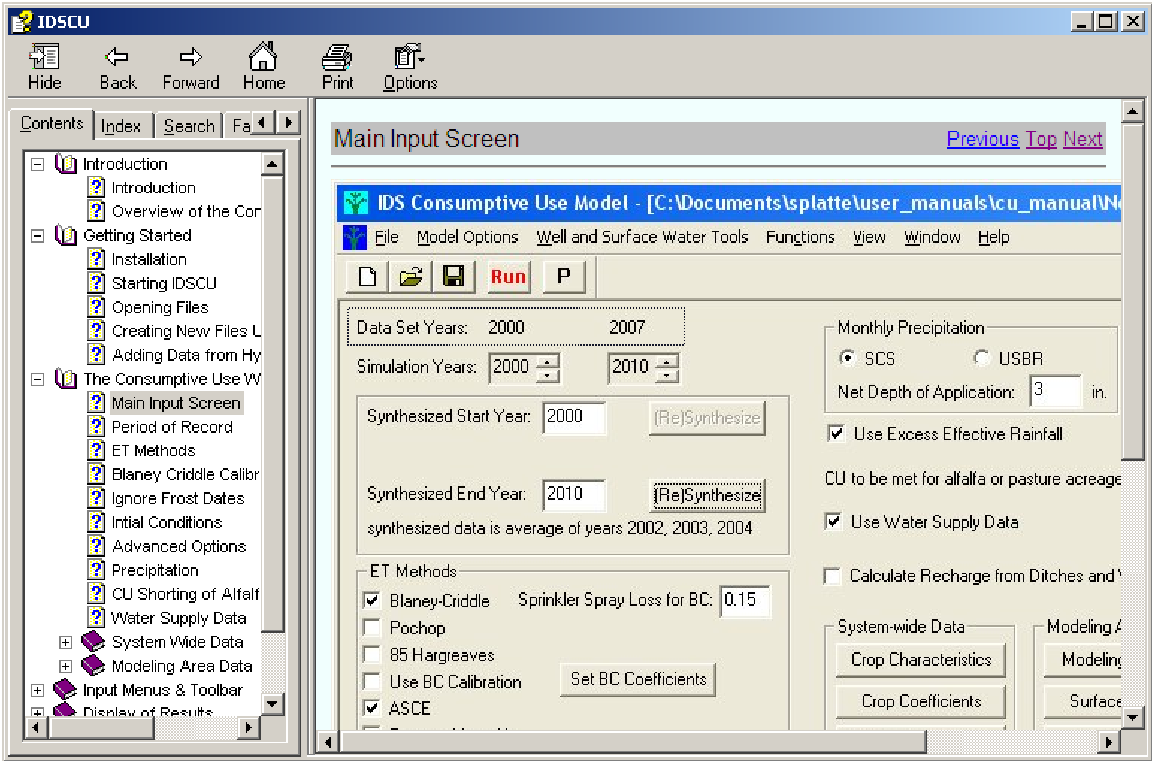

Figure 9. IDSCU Help Screen

ACKNOWLEDGMENT

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RECONCILING DISPARATE CONCEPTUAL AND SIMULATION MODELS FOR MULTI-MODEL PERENNIAL YIELD OPTIMIZATION

Bassel Timani[1]
Richard C. Peralta, P.E.[2]

ABSTRACT

Water policy makers often use Simulation/Optimization (S/O) models to aid water policy development. Stake-holder agreement on conceptual and numerical models, and posed optimization problems, makes policy development easier. Disagreement on conceptual models leads to the use of different simulators for the same area. For years, Cache Valley, Utah, decision makers have used results from a perennial yield pumping S/O model that included constraints preventing excessive pumping-induced surface water depletion. As a simulator, that S/O model used a USGS-calibrated MODFLOW implementation based upon a USGS conceptual flow model. However, some knowledgeable hydrogeologists disagreed with the USGS conceptual model. Cache County funded development of a different conceptual model and MODFLOW implementation (the MM model). To increase stake-holder support for policy decisions, we present a method for developing optimal perennial yield strategies that simultaneously considers both conceptual model implementations. This required modifying the MM model by replacing some drain cells with river cells, without disrupting computed flows (re-calibration yields 0.2' residual mean error for head, and 84 percent correlation coefficient). A table of correspondence relates the 6 USGS model layer to the 11 MM model layers. Using equivalent background well packages in the USGS and modified MM models creates analogous background conditions for each modeling realization (representation of reality). Applying equivalent constraints to both models during simultaneous optimization yields an optimal pumping strategy that is spatially the same in both models (in X-Y plane), but different responses per system. The preliminary optimization was not corrected for system nonlinearities. Such correction is the next step of this reconnaissance effort.

INTRODUCTION

Water policy decisions are more easily made when all stake-holders agree on the validity of the same conceptual and numerical models, and optimization problem to be solved. A groundwater conceptual model describes the characteristics and dynamics of a physical hydrogeologic system. A simulation model is the mathematical representation the conceptual model. Problems arise when governmental agencies and share- or stake-holders cannot agree on the same conceptual and numerical models.

Simulation/Optimization (S/O) models have long been used for maximizing perennial (safe) yield pumping strategies. S/O models couple simulation models with optimization

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models to solve a posed optimization problem. An optimization problem consists of an objective function, set of constraints and bounds. Maximizing total groundwater pumping is a common objective function in groundwater studies.

S/O models should incorporate simulator(s) that adequately represent the physical system. An S/O model is as accurate as the simulator(s) it employs. Generally, S/O models use a single simulator. To reconcile disagreements among stake-holder groups, here we present multi-conceptual model optimization (MCMO). The employed S/O model optimizes while employing more than one conceptual/numerical model simulator at the same time. Each simulator is a different realization (representation of reality).

Trial and error is one way to address multiple conceptual and numerical models at the same time. The modeler begins by optimizing for each model independently. Then, he modifies one or both of the strategies until a single resulting strategy satisfies the set of respective bounds and constraints in both models. MCMO combines both models and computes an optimal strategy that satisfies constraints in both models.

The proposed MCMO tool automatically creates a surrogate multi-conceptual model optimization problem and uses influence coefficients, the response matrix method and cycling (successive linear optimization) to compute an optimal strategy accurate for a nonlinear aquifer system. Cycling will cause state variables computed via RM approach acceptably close to those obtained from MODFLOW. To date, MCMO does not cycle to address aquifer system nonlinearities.

Cache Valley is an attractive case study because two technical groups proposed different conceptual and numerical models to describe its groundwater movement. The United States Geological Survey (USGS) calibrated MODFLOW for the area, (Kariya et al., 1994). That model is here termed USGS. For a different conceptual model, Myers (2003) and Lachmar et al. (2004) also calibrated MODFLOW (we term that model MM). The two models differ in employed units, model architecture, hydraulic properties, and boundary conditions. Another attractive Cache Valley characteristic is the possibility of increasing groundwater pumping without causing unacceptable environmental consequences or violating legal rights (Peralta et al., in revision).

This paper discusses preliminary application of MCMO to Cache Valley. Two simulators are used simultaneously during the optimization, the USGS model and a model (termed NDM) derived from the MM model. NDM was created to allow constraints and bounds comparable to those applied in the USGS model. This paper describes NDM preparation, preliminary computed reconnaissance strategies, and implications.

LITERATURE REVIEW

Simulation/Optimization Modeling

A simulation model is a mathematical representation of a physical system. The essential simulation model in groundwater studies is a flow simulation model. Optimization algorithms are used for computing an optimal strategy for a posed problem. Combining these two entities yields a flow Simulation/optimization (S/O) model. Optimal control (OC), embedding approach (EM) and response matrix (RM) approaches have been used for S/O modeling over the past three decades. The OC method implicitly solves the optimization problem within each iteration (Wanakule et al., 1986). In the EM approach, all simulation equations are included in the optimization problem. With the EM approach, successive linear optimization converges to optimal steady or transient solutions for nonlinear real-world situations (Peralta et al., 1985; Gharbi et al., 1994).

The RM approach utilizes the concept of superposition. Superposition states that for a linear system, the effect of multiple stimuli on a system is the summation of the effect of each stimulus on the system. To develop the response matrix, the RM approach requires running the simulation model once for the unmanaged situation and once for each "managed" stimulus. Using superposition for non-linear systems involves solving a series of linear optimization problems to gradually converge to a stable solution. Some researchers most simply refer to this process as "Cycling" (Peralta et al., 1993; Takahashi et al., 1995). Ahlfeld et al., (2008), and others term the process "Successive Linear Optimization.

GWM (Ahlfeld et al., 2005), a groundwater management tool, was recently added to MODFLOW-2000 (Harbaugh et al., 2000). Several other S/O models have been successfully applied within Utah (Belaineh et al., 1995; Peralta 2001). US/REMAX (Peralta et al., 1993) was used to compute preliminary optimal strategies for Cache Valley (Peralta et al., 1995; Johnson et al., 1997). Peralta et al. (2009) used SOMO1Cs (SSOL, 2009), a US/REMAX successor, to compute optimal strategies for Cache Valley with enhanced protection of environmental and legal rights.

Cache Valley

Peterson (1946) evaluated the availability of groundwater for irrigation and domestic uses. Beer (1967) presented a water budget for Southern Cache Valley. Clyde et al. (1984) presented a calibrated groundwater flow simulation model for the Utah portion of Cache Valley.

Kariya et al. (1994) calibrated MODFLOW for the Cache Valley aquifer system. The USGS model discretizes the area into 82 rows, 39 columns and 6 layers. It represents aquifer-surface water seepage using drain, river and GHB boundary conditions. It uses feet and seconds as units of length and time, respectively. The USGS model is the most widely accepted conceptual and numerical Cache Valley groundwater flow model.

The Utah Department of Natural Resources (UDNR, 1997) estimated that pumping an extra 35.22 cubic feet per second (cfs) above a baseline of 39.20 cfs for 30 years will cause a 27.62 cfs depletion in the aquifer and 13.70 cfs in surface water depletion. They predicted this would cause groundwater heads to decline from the 1990 levels by 5 feet in much of the valley and 10 feet in some locations.

Myers (2003) and Lachmar et al. (2004) evaluated the USGS conceptual and numerical models. They developed a different conceptual model and calibrated MODFLOW for that (the MM model). The MM model uses the same number of rows and columns as the USGS model but has 11 layers, two describing confining layers. MM uses drain and GHB boundary conditions to represent aquifer-surface water seepage. Units are feet and days.

MATERIALS AND METHODS

Introduction

The optimization problem being solved here is patterned after that of Peralta et al (in revision), who used the USGS simulator. To protect legal water rights and the environment, they constrained aquifer head, river-aquifer seepage (RAS), drain-aquifer seepage (DAS), and general head-aquifer seepage (GAS).

MCMO application requires that all physical system realizations be treated comparably--optimization sub-problems solved for each realization should be as physically similar as possible. This requires applying comparable constraints in each employed simulator. Here, MCMO must use two simulators, the USGS and one other, and comparable constraints and bounds in each, for maximizing groundwater extraction from Cache Valley, Utah. However, the two initially available simulators represented aquifer-surface water interaction differently. The USGS model uses river, drain and GHB cells to model aquifer-surface water seepage. The MM simulation model used drain and GHB cells to model aquifer-surface water seepage.

To enhance comparability between MCMO-employed realizations, we modified the MM into what we term the NDM model. Preparing the NDM MODFLOW implementation required re-performing the MM calibration, relating pumping locations between the two simulators, and creating comparable boundary conditions. Subsequent sections describe these actions, the optimization problem being solved, and optimal results.

NDM Simulation Model Creation and Calibration

The NDM model was created from the MM model to increase comparability between the two simulators to be used within the MMO process. Converting the MM model into the NDM model required: including a river package, and creating an equivalent well package and a layer correspondence table with the USGS model. Both well packages place pumping rates at the same MODFLOW rows and columns, but in different layers. Table 1 contrasts some features of the three Cache Valley simulation models.

Table 1. Pertinent Features of 3 Cache Valley Simulation Models

Model	Units		# of Layers	Cell correspondence[&]?	B.C. employed			Modflow		Flow files* available?
	L	T			D	R	G	verison	solver	
USGS	ft	sec	6	N/A	yes	yes	yes	1996	PCG2	Yes
MM	ft	day	11	yes	yes	No	yes	1988	N/A	No
NDM	ft	day	11	yes	yes	yes	yes	2000	PCG2	Yes

L: length; T: time; N/A: not applicable or not available; &: model cell (R,C) corresponds with USGS cell (R,C); D: Drain; R: River; G: GHB; *: flow files of the calibrated model

Incorporating River Cells To represent losing river reaches, the MM model used drain cells instead of the river cells used in the USGS model. To increase comparability between models, the NDM model employs river cells in many MM drain cell locations, and appropriately modified input drain and river cell data packages.

Figures 1 and 2 show the spatial distribution of NDM boundary conditions. Groundwater flow is simulated in white cells. GHB cells in layers 2-4 were defined along the eastern and western edges of the active study area starting at row 28 and ending at row 67. Layers 5-8 GHB cells were defined along the eastern edge of the active cells only.

Creating Equivalent Well Packages Both MCMO optimization subsimulators should employ comparable background conditions and constraints Well packages that model the same background pumping rates at the same depth are required. The USGS and MM models used different well packages. This difference was in the areal spread, screened layers and pumping rates. The way these well packages were created led to this variation. Well packages with the same pumping rates and locations will produce background conditions of different value in the USGS and MM or NDM models because of the difference in boundary conditions and hydraulic properties. The USGS model well package was created for the 1990 conditions (Das, 2002). The MM (Myers, 2003; Lachmar et al., 2004) or NDM well package was created for the 1999 conditions. The MM well package being more recent than the USGS one was the background well package of choice. Of course, the well package has to be adjusted for units and layer correspondence before the adjusted well package can be used in the USGS model.

Creating Layer Correspondence It is crucial that stimuli (such as pumping) and constraints of the MCMO S/O models to occur at the same horizontal and vertical locations. A table of correspondence related the USGS and NDM layers. It was impossible to use the background well package to deduce the correspondence between the USGS and NDM model layers because the background well package of each model did not use the same well locations or rates. The depth of each model layer below layer 1 of the USGS and NDM simulation models is assumed constant. Figure 3 shows the depth of each model bottom elevation

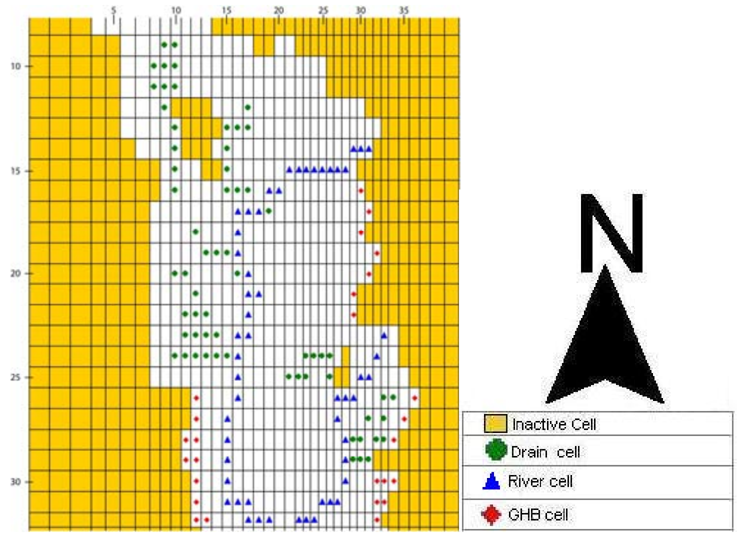

Figure 1. Northern Cache Valley NDM Layer 1 Boundary Conditions

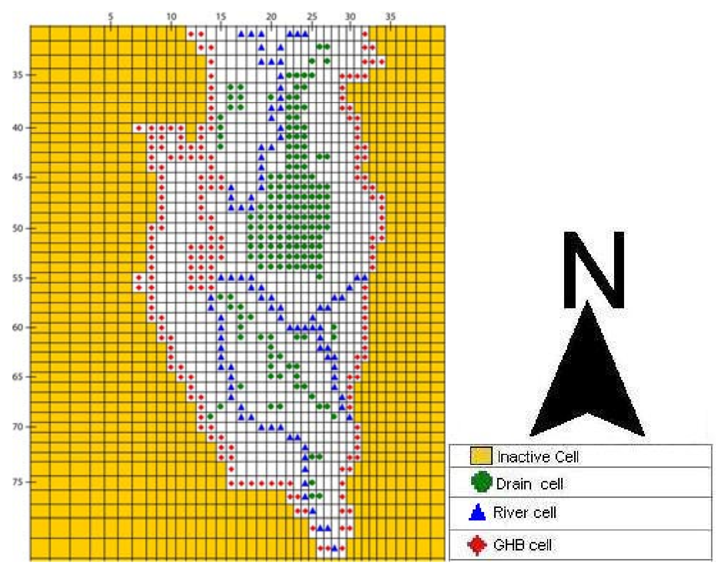

Figure 2. Southern Cache Valley NDM Layer 1 Boundary Conditions

below the model surface. Table 2 shows the assumed correspondence of the USGS and NDM layers based on Figure 3.

NDM Model Calibration Numerical models created to represent a physical system must be calibrated to adequate fidelity. Visual MODFLOW (version 4.3.0.154) and the accompanying WinPEST (Version 4.2.0 Build 152) (Waterloo, 2008) were used to calibrate to match the 1999-2002 measured heads at 55 observation locations by changing hydraulic conductivity, storage and recharge. For this, WHS generously granted us a fully functional Visual MODFLOW (VMF) trial version free of charge.

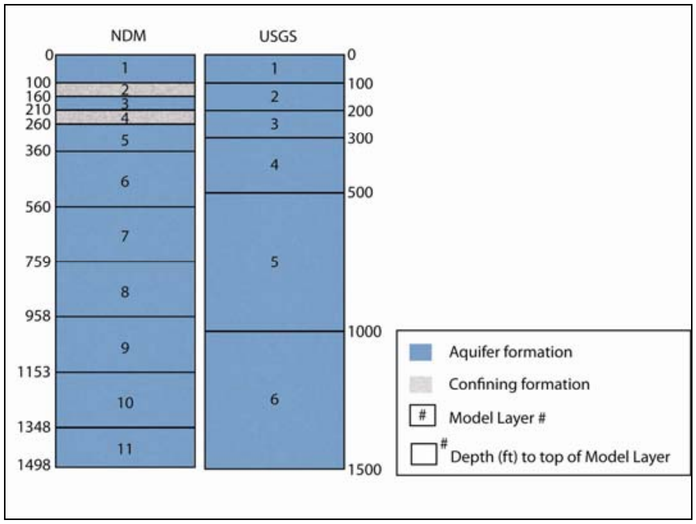

Figure 3. Schematic Showing Layer Discretizations of USGS and NDM Models

Table 2. Model Layer Correspondence between USGS and NDM Models

NDM Layer	Analogous USGS Layer
1	1
2, 3	2
4, 5	3
6	4
7, 8	5
9, 10, 11	6

For steady-state simulation, porosity or storativity do not affect results. Thus, VMF was allowed to only change hydraulic conductivity for calibrating the NDM model to match 55 measured head values. This run used WinPEST for calibration and MODFLOW 2000 as flow simulator. The selected calibration parameters yield a residual mean of 0.2’, a 0.5’standard error of the estimate and an 84% correlation coefficient (Figure 4).

ASTM Standard D 5981-96 (ASTM, 2007) suggests calibrating against head and flow measured values. In the absence of measured flow terms, lack of consistent estimates of flow values in previous studies (Kariya, 1994; Robinson, 1999; Myers, 2003; Lachmar et al., 2004) and as a least-cost alternative to obtaining these measurements, we analyzed the computed flow terms of the NDM model after its calibration was over. There was a 20% increase in GHB inflow and 29% increase in ET outflow of NDM compared to MM. These increases can be attributed to the change in head distribution resulting from the introduction of the river package. NDM inflows and outflows were between those of the USGS and MM model, with insignificant volume balance error.

NDM hydraulic conductivity maps (Timani et al., 2009) show no evidence of spot and abrupt changes in the value as indication of malpractice during the calibration process. Table 3 shows the minimum and maximum hydraulic conductivity (ft/day) for layer 1 and transmissivity (ft^2/day) values in the active region of each layer below layer 1 for USGS and NDM models. Calculated transmissivity values for NDM layers 2–11 assumed

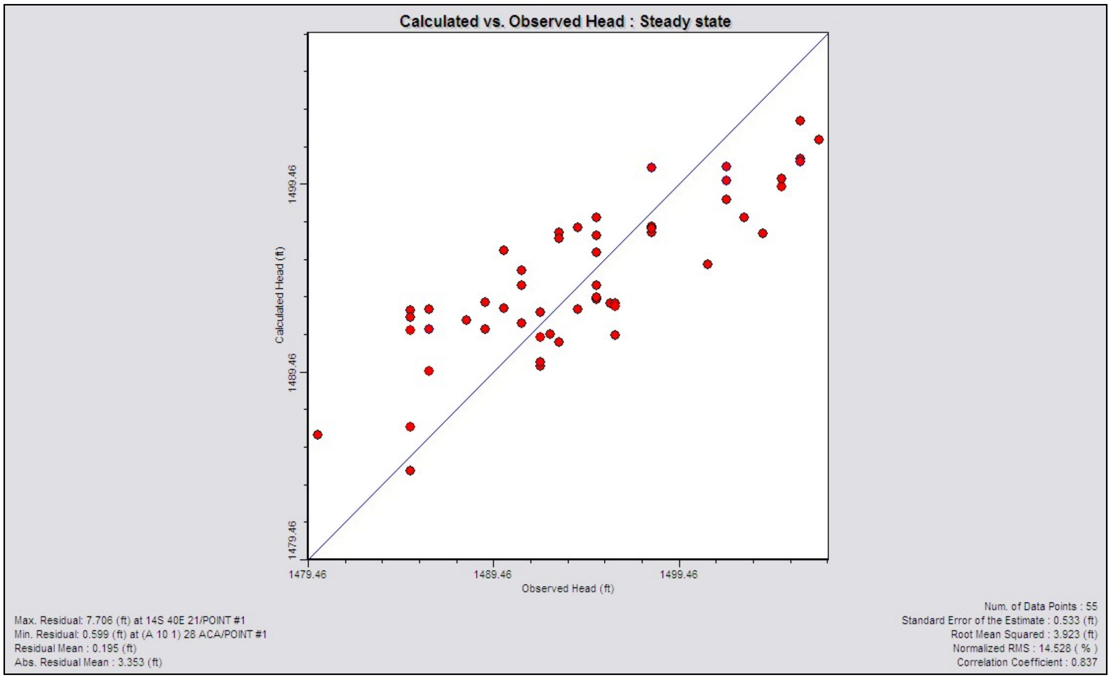

Figure 4. Statistical Inferences for NDM Calibration

Table 3. Min & Max Layer Hydraulic Conductivity (ft/day) or Transmissivity (ft^2/day)

Layer	USGS		NDM	
	Min	Max	Min	Max
1	1	100	62	1,341
2	100	10,022	140	1,530
3	100	10,022	117	32,358
4	200	20,013	117	1,275
5	200	20,013	105	134,110
6	200	20,013	210	268,220
7	N/A	N/A	209	266,879
8	N/A	N/A	209	266,879
9	N/A	N/A	205	261,514
10	N/A	N/A	205	261,514
11	N/A	N/A	158	201,165

the water table above the layer top. The transmissivity values for NDM layers were an order of magnitude greater than the corresponding transmissivity values of the USGS model layers. NDM layers 2 and 4 that described the model confining layers had no correspondence with the USGS model layers. To describe the effect of the confining layers on the flow of groundwater between layers, USGS used the vertical leakance term to specify the leakance between the layers irrespective of the head gradient.

Employed Simulation/Optimization Model

For this preliminary exercise, MCMO employed the RM approach without adaptation for non-linear systems. It employed MODFLOW (Harbaugh et al., 2000), to compute influence coefficients quantifying impact of each managed stimulus location on each state variable. GAMS Base Module build 4783/4799 version 22.7.2 (GAMS, 2008) computed optimal solutions for the posed optimization problem.

Not reported here, the next step will be automated MCMO RM application to thoroughly address aquifer system nonlinearities. That RM approach loops through a set of sequential steps: compute influence coefficients (ICs) using numerical simulator, populate convolution equations with the ICs, compute an optimal strategy, modify unit stimulus. This loop terminates at the "compute an optimal strategy" step when decision variables, such as pumping rates, don't change with optimization. At that point, state variables computed using the convolution equations are acceptably close to the state variable values computed using MODFLOW (Harbaugh et al., 2000). Within each cycle, the MINOS optimization algorithm (Murtagh and Saunders, 1998) solves that cycle's linear optimization problem. This method can ensure convergence to an optimal strategy even for non-linear aquifer conditions. SOMO1Cs (SSOL, 2009) is used to solve a posed optimization problem. Changing input values to an optimization problem creates a new problem. Each of these problems is referred to as a scenario.

This study reports results from three formulations. Formulations differ in the simulation (S) model(s) employed in the S/O model. One formulation uses the USGS implementation. Another uses NDM. The third formulation, uses both USGS and NDM simulators within MCMO.

For each formulation, we compute optimal strategies for three identical scenarios. All scenarios use an objective function that maximizes the total groundwater extracted from 18 candidate pumping blocks or locations while satisfying a set of constraints. Scenarios differ in imposed constraints. Constraints include bounds on heads of candidate pumping blocks, drain cells, river cells and seepage constraints on river-aquifer seepage (RAS), drain-aquifer seepage (DAS) and GHB-aquifer seepage (GAS). Flows and heads computed in this study are steady state. The MCMO formulation includes constraints forcing equivalent pumping within USGS and NDM simulators (i.e. same location and rate).

Simulation/Optimization Scenario Overview

A common practice in S/O modeling is to compare managed scenarios with a background scenario. S/O models that use single simulation model have one background scenario. S/O models that use multiple simulation models should report comparable background scenarios.

USGS and NDM are the two simulation models of Cache Valley that will be included in the S/O model of this study. Comparable well packages must be used in the USGS and

NDM models to create comparable background scenarios. The well distribution used by the MM model is the most recent, and is preferred. Table 2 is used to adjust the layers in which the NDM wells are screened to create the well package to use with the USGS model. Constraints employed in S/O model should be absent when computing the background conditions.

Employed Constraints Head and seepage constraints are posed on managed scenarios to allow water policy makers to choose the scenario that best fits their need. Here, lower bounds on head at candidate pumping locations are used to avoid excessive drawdowns. Constraints posed on heads at river and drain cells prevent cells from becoming hydraulically disconnected from the aquifer (if they were not in the initial or background case). Loose bounds are placed on head upper bounds because no manageable injection is allowed. In the MCMO formulation, constraints force both simulators to be stressed with equivalent pumping strategies.

Background Scenario Employing the pumping rates in the background well package results in a “Background” or “BG” scenario. Results from this scenario affect most of the bounds or constraints. All drain cells are grouped into one DAS group. River cells are all included into one RAS group. USGS uses GHB cells to model Hyrum and Cutler Reservoirs. Based on the flow direction of the GHB cells used to model these reservoirs, each GHB cell is included in one of two GAS Groups. All other USGS GHB cells are defined in GAS Group 3 (used for monitoring purposes only). On the other hand, NDM uses river, drain and GHB cells to model Hyrum and Cutler reservoirs. The NDM GHB cells used to model these reservoirs (in Layer 1) are assigned to one of two groups based on their flow direction. The NDM GHB cells not used to model the reservoirs are defined in a GAS group depending on their layer and flow direction. The USGS model has three GAS groups. The NDM model has 11 GAS groups.

Managed Scenarios Three scenarios are posed to illustrate system response and the impact of contention on allowable groundwater extraction. Background group seepage rates from each RAS, DAS and GAS group are not allowed to decrease by more than 10%. These constraints will protect down-gradient surface water senior rights. All scenarios report increase in pumping over the background or existing pumping. The first scenario shows the increase in total pumping for the posed optimization problem. The next scenario shows the effect of 1’ relaxation for each of the tight constraint of the previous scenario. The last scenario explores the use of the group seepage constraints on the same optimization problem as the other two scenarios.

Head at the (Layer, Row, Column) (L, R, C) cell of candidate pumping blocks (CPBs), in each of the two models is not allowed to drop by more than 20’ from the background level. At many other non-pumping cells in the same (R, C) location as CPBs, head is not allowed to drop by more than 10' from the background level (for the USGS model these bounded heads are in layers layer 1- 4; corresponding NDM heads are bounded). The head at flowing drain cells and hydraulically connected river cells is not allowed to drop below the drain or river bottom in managed scenarios.

RESULTS AND DISCUSSION

This study computed optimal strategies that simultaneously satisfy comparable constraints within two Cache Valley aquifer system realizations. The employed MCMO approach is intended to help avoid the need for stakeholders, water policy makers and government agencies to agree concerning which study area conceptual and numerical model is most valid. This paper discusses preliminary results, not corrected for system nonlinearities. After adaptation for nonlinearities, employed S/O model constraints will help assure computation of perennial (safe) yield pumping strategies. To date, all computed maximum pumping strategies exceed the background (historic) pumping.

Table 4 summarizes the increase in pumping beyond background levels resulting from using USGS and NDM independently and simultaneously, as S models within the S/O model. It identifies the wells that pump, the tight constraints and group seepage rates. When using the USGS S model, Scenario 3, the least restrictive, shows that the pumping rate would almost double if head constraints are absent. Analyzing the head levels for this scenario reveals that only two head control locations will violate the posed 20' and 10' head constraint on cells of CPB cells. Removing the head constraints from Scenario 3 of the second formulation (NDM) did not have a similar effect as it did with the USGS model. Most active CPBs and most of the managed pumping occur in NDM model layer 6. GAS Group 7 contains the GHB cells modeled in layer 6. Scenario 2 tight GAS Group 7 prevented much increase as a result of removing the head constraints. Lower bounds on six head control locations of CPBs would have been violated.

Table 4. Optimal Rates, Active Pumping Blocks and Tight Head Control Locations of Optimized Scenarios

Model	USGS (Formulation 1)				NDM (Formulation 2)				MCMO (Formulation 3)				
Variable / Scenario	Pumping (cfd)	Total Surface Water Seepage Rate (cfd)	Active CPBs	Tight HCLs	Pumping (cfd)	Active CPBs	Tight HCLs	Total Surface Water Seepage Rate (cfd)	Pumping (cfd)	Total Surface Water Seepage Rate (cfd) USGS	Total Surface Water Seepage Rate (cfd) NDM	Active CPBs	Tight HCLs
BG	0.00E+00	1.51E+07	-	-	0.00E+00	-	-	9.15E+06	0.00E+00	1.51E+07	9.15E+06	-	-
Scenario 1	2.88E+05	1.48E+07	13,15,16	59,254	1.06E+06	1-4,6,16	6,12,15,311	8.32E+06	2.83E+05	1.48E+07	8.89E+06	13,15,16	59,254
Scenario 2	3.08E+05	1.47E+07	2,4,15,16	59	1.09E+06	1-5,16	6,12,15	8.30E+06	2.99E+05	1.48E+07	8.87E+06	13,15,16	59
Scenario 3	6.12E+05	1.44E+07	2,16	-	1.30E+06	2-4,16	-	8.15E+06	3.17E+05	1.47E+07	8.87E+06	2,16	-

Figure 5 shows three sets of pareto-optimal curves of total pumping increase versus total surface water seepage. Each curve shows the least amount of total surface water seepage rate possible for a particular increase in pumping rate. Distinct curves represent scenarios performed while considering the NDM and USGS models independently (USGS and NDM lines) and simultaneously (MCMO USGS and MCMO NDM lines). Strategies (points) below each curve are suboptimal because more surface water can occur for a given increase in groundwater pumping. Strategies above the lines are unrealistic (infeasible) because no such surface water seepage rate can result from that increase in groundwater pumping rate.

CONCLUSIONS

As aquifers are studied, greater understanding of how they work is gained. This gained information is used to create updated and more reliable models (TWDB, 2009). A reported strategy is optimal for the posed optimization problem and as accurate as the simulator.

Here, we address a situation in which stake-holders disagree on which of two simulators is more valid for Cache Valley, Utah. We propose an MCMO optimization approach that simultaneously considers two simulators. Implementing that approach required that one simulator be modified to make it more directly comparable to the other simulator. Modification included conversion of some model drain cells to river cells.

After developing comparable background conditions for both simulators, optimization produced maximum pumping strategies for each simulator independently and together. These strategies are only preliminary because they have not been adjusted to address physical system nonlinearity. The next step, already underway, is to automate the computational process so it corrects for system nonlinearity.

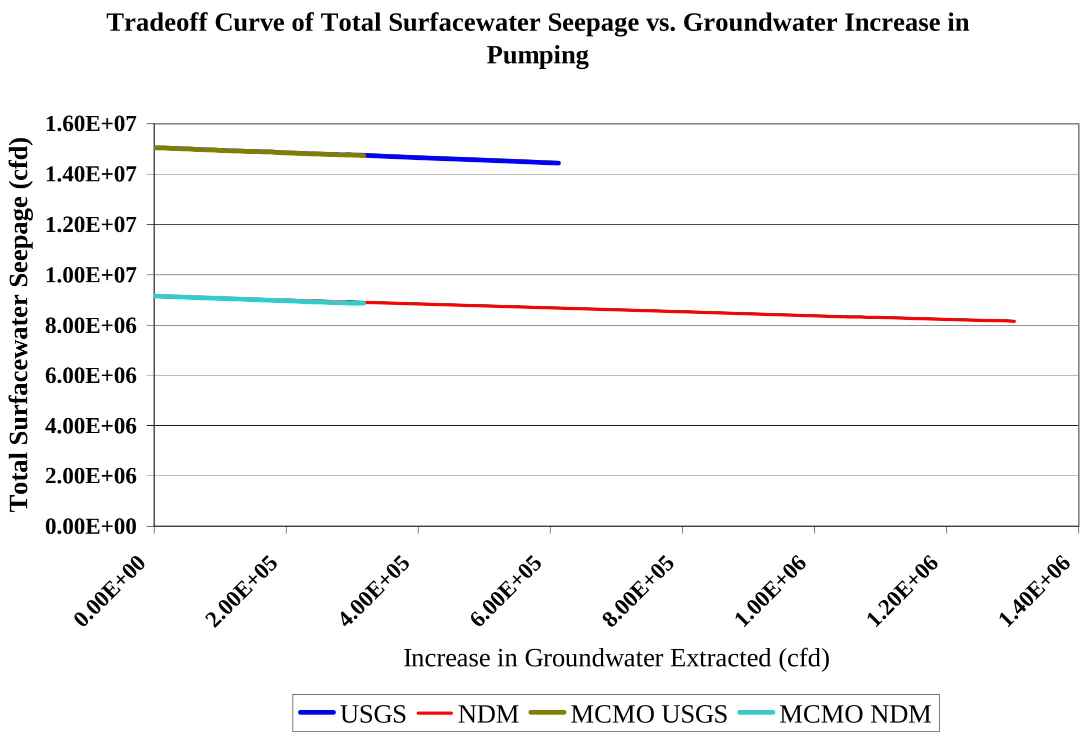

Figure 5. Total Surface Water Seepage Rate vs. Increase in Groundwater Pumping Tradeoff Curve

The proposed Multi-Conceptual Model Optimization (MCMO) approach is promising for areas where multiple conceptual and numerical models exist, and stake-holders cannot agree on which to adopt.

In this study, the importance of the group seepage constraints is masked by constraints forcing pumping to be equivalent in both models. This occurs because of differences boundary conditions. In other situations, one would expect that constraints limiting aquifer-surface water seepage would be more significant.

As water needs increase, so does the need to better use available water resources. This study indicates the possibility of developing perennial yield strategies for Cache Valley even in the absence of agreement on a single conceptual model for the valley. Reasonable agreement on a single model and use of transient simulation would help improve water use.

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AUTOMATING PIUTE DAM AND THE EIGHT CANALS THAT IT SERVES

Blake E. Durtschi[1]

ABSTRACT

Piute Dam and Reservoir are located on the upper Sevier River in south central Utah. The reservoir has a capacity of 60,000 AF and serves eight canal companies located around the city of Richfield. Because of lag times between the reservoir and the various canals and an unregulated inflow below the dam (Clear Creek), setting reservoir releases is an art (and not always successful). Too much or too little water at the lowest canal diversion is a problem.

Several years ago, a gate actuator was installed on Piute Dam outlet works. Telemetry to the dam was also established. This summer, the Piute Reservoir and Canal Company and Bureau of Reclamation will be fully automating the dam. The focus of this work has been to design a forecasting model for use in calculating a suggested reservoir release. This decision-support tool uses hourly measurements from a real-time monitoring system (www.sevierriver.org) to design a control algorithm for the reservoir release. The most efficient controller is then determined through simulation. This paper shows how the model and controller were implemented using the existing SCADA (supervisory control and data acquisition) system for the 2009 irrigation season. The benefits from using the controller will be estimated.

Demand forecasts for the individual canals will be provided using the existing website of the Sevier River Water Users Association (www.sevierriver.org). This Internet-based system will also be used to control the individual gates on the eight canals. Proper security is being installed to protect the integrity of the automation system.

INTRODUCTION

The Sevier River, in central Utah, serves primarily as irrigation water with a small amount used for municipal water in the local towns. The Sevier River Basin is completely enclosed so that any water flowing down the river empties into the desert. The Piute Dam and reservoir are located on the upper portion of this river. Water released from the reservoir may be diverted into one of several canals. Any water not diverted into the canals continues down the river and is lost for any other use. This makes the Sevier River a great location to practice water conservation using automated control. Water can be conserved by designing a control algorithm which releases just enough water from the reservoir that every canal gets the water it needs, but no more. Determining how much water to release is made difficult because of large delays in the time it takes the water to move down the river, uncontrolled inflows, and various environmental factors which affect the amount of water such as evaporation, seepage, or rainfall.

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Figure 1 shows the stretch of river below the Piute reservoir. The release from the dam determines how much water enters the system. There is also an uncontrolled, but measured inflow at Clear Creek, and eight diversion canals that take water out of the river**.** At the end of the river is the small Vermillion Dam. The goal is to have no water flowing past Vermillion Dam as it will be lost to our water users.

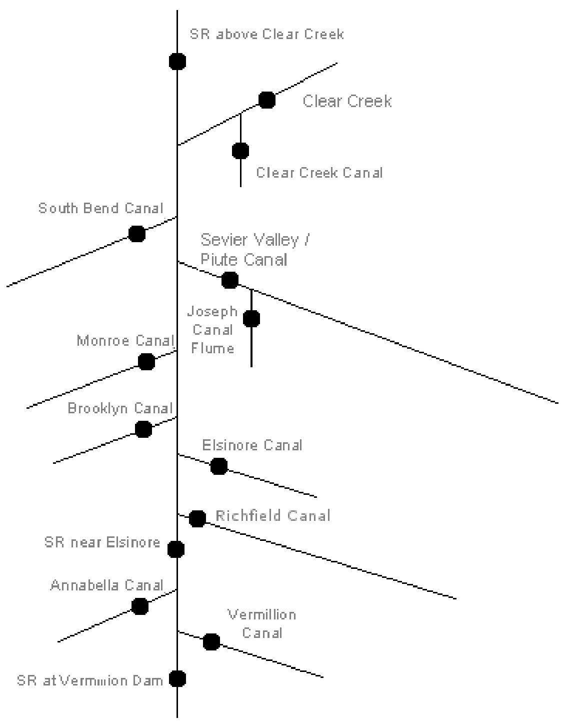

Figure 1. Stick figure showing the stretch of the Sevier River below the Piute Dam.

Table 1. Delays associated with each station along the Sevier River.

Station Name	Symbol	Delay (hours to bottom of river)
Piute Reservoir	srps	32
Sevier River above Clear Creek	srcc	18
Clear Creek	ccd	18
South Bend Canal	sbch	16
Sevier Valley Piute Canal	svpc	15
Joseph Canal	jch	15
Monroe Canal	mch	14
Brooklyn Canal	bch	13
Elsinore Canal	ech	12
Richfield Canal	rch	12
Sevier River near Elsinore	sre	12
Anabella Canal	ach	8
Vermillion Canal	vch	0
Sevier River at Vermillion	srv	0

Each black circle in figure 1 shows where there is a station measuring flow. Each of the stations on an out-flowing canal also have a locally controlled gate which regulates the flow to match a flow value set by the canal owner. There are also four measuring stations along the river, one at the reservoir release (not shown), another just above Clear Creek, one near Elsinore, and one measuring flow past Vermillion Dam. Flow data is collected at all of these stations every hour and stored into a central database. This remote monitoring and telemetry has been installed in the system since the summer of 2000.

Much of the previous work in canal/river automation has been focused on obtaining accurate measurements of the canal/river and manually controlling gates remotely. Few rivers or canal systems in the world have a computer determining how to control the gates releasing water from various reservoirs, this is groundbreaking work. Another reason few canal/river systems are controlled this way is because individuals can be skeptical about having their livelihood controlled by a computer. There are, however, two groups that have had success in controlling rivers and canals using computers: one in southern France, and one in Australia.

The group in southern France (Litrico, Malaterre, et. al.) has designed various algorithms, including robust control and proportional-integral (PI) algorithms, to control gates on different canal systems [1], [3]. They have also done some work with canal modeling using St. Venant equations for water flow [4]. The group in Australia, led by Erik Weyer, has modeled canals using a mass balance model and designed several different controllers including PI, and liner quadratic Gaussian control (LQG) to control canal gates [6], [7].

None of these approaches work very well with our system. First, the work has been done on canals that have a very small grade and accurate flow measurements. The flow measurements on our river are not very accurate and may be off by as much as 10%. Also our river has steep grade which causes the water to flow more quickly than in the canals which changes the system dynamics. Second, the amount of time the water takes to move down stream (delay) in our stretch of river is over a day and we only receive data once an hour. Previous work has been on canals with much less delay and data collection every second or minute. Because of these differences we will be using a different model than these groups.

The following sections describe the mathematical modeling of the Sevier River and the control algorithm design. Then it is shown how this controller is implemented into the existing SCADA system. Specifically, the system was expanded to include a control algorithm which could automatically set the flows of the reservoir and canals, and to include a system to allow canal owners to input their future water orders.

MODELING THE SEVIER RIVER

Determining the Delay

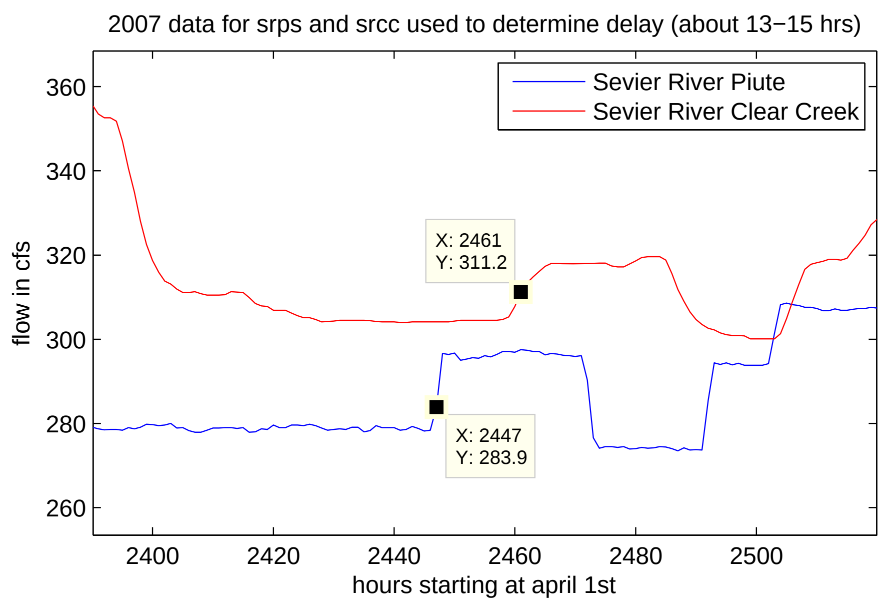

Figure 2. The delay for the stretch of river between the reservoir and Clear Creek is found by finding the corresponding changes and measuring the delay.

To determine the varying amounts of delay in the system we look at flows from two points along the river and look for corresponding changes. We took data from 2007 and found several places in the data where there were large fluctuations in the flow and averaged the delay time to find the different delays in the system. This technique is shown in figure 2. To find the delay of the canals we use the same technique, however we look for places where the upstream river flow stays constant, the canal has a large shift, and the downstream river flow shifts in the opposite direction of the canal flow. Table 1 shows the delays for each part of the system.

Selecting Data

Since water conservation is most important during the irrigation season the model needs to be effective in describing the river during the spring and summer months. River data during the months of April through September for six years (2000-2004, 2006) will be used to train the model, and data from those same months for 2007 and 2008 will be used to validate the model. Data from the year 2005 was not used because that year was a flood year and the flows are unlike any other year. When that year is used for training it causes the model to predict too much water for the other years. It is possible to use 2005 data to learn a model which can be used in flood years, though it has not been done here.

Model Selection

The first step in modeling the Sevier River is to select a model class that captures the dynamics of the river. Previously, Maxwell compared several different models of the Sevier River [5], and concluded that a parameterized mass balance model most correctly describes the river during summer months when river flows are high. We select a parameterized mass balance model as the basis of our model class and add that to a third order system in order to capture some of the smoothing effects of water flow.

We model the Sevier River as a multiple input single output (MISO) system with the flow past Vermillion Dam being the system output. We treat the river inflows and the outflows to the canals as inputs because each represents an external influence on the water in the river. The coefficients to the outflows will be fixed at negative one. This is reasonable since water is being taken out and it is measured as it leaves the system. We let the coefficients to the inputs be variables to be learned from the data, to allow the model to account for evaporation, seepage, or other inflows or outflows that may occur along the river before the water reaches the bottom.

$$y(k) = a_1 y(k-1) + a_2 y(k-2) + a_3 y(k-3) + b_1 u_1(k-d_1) + b_2 u_2(k-d_2) - \sum_{i=3}^{9} b_i (k-d_i) \quad (1)$$

Our model (1) states that the output at time k, $y(k)$, is determined by the previous three outputs as well as the positive and negative flows added by the inputs. We define inputs in the order that they affect the system, u_1 as the reservoir release, u_2 as the inflow at Clear Creek, and $u_3, \ldots, u_9$ as the other canals. We also define d_i, $(i = 1, \ldots, 9)$ to be the delay of the river from input i to the end of the river.

To select a model from our specified model class we use an iterative maximum likelihood minimization method to select model parameters for our model. The parameters of our model are:

$$\begin{bmatrix} a1 \\ a2 \\ a3 \\ b1 \\ b2 \end{bmatrix} = \begin{bmatrix} -.7949 \\ -.4595 \\ -.1705 \\ .839 \\ 1.973 \end{bmatrix}. \tag{2}$$

These parameters seem reasonable. Both of the inputs have positive coefficients. Also the larger coefficient from Clear Creek could be explained by it being an unregulated inflow and could represent all other unmeasured inflows along the river which would seem to be higher if the Creek is higher and lower otherwise. The coefficient less than one from the reservoir could be explained by the effects of evaporation and seepage of the released water all down the river.

In order to get a better fit for the model it was necessary to add a filter to the model to smooth out the output. A low pass filter was designed to minimize the mean squared error of the model when compared to the validation set. The filter gives a reduction in root mean squared error from 21.8 to 21.1 yielding the final model of:

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) \\ y(k) &= Cx(k) \end{aligned} \tag{3}$$

where

$$A = \begin{bmatrix} -0.7949 & -0.4595 & -0.1705 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0.0952 & 0 & 0 & 0.9048 \end{bmatrix}, \quad B = \begin{bmatrix} 0.839 & 1.973 & -1 & \cdots & -1 \\ 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \end{bmatrix},$$

$$C = [0 \quad 0 \quad 0 \quad 1].$$

<u>Model Validation</u>

Figure 3 shows the output predictions of our model for the validation set. The top graph is 2008 data and the bottom graph is 2007 data. Table 2 shows the absolute and root mean squared errors for both years and together.

The model definitely captures many of the trends and changes for both years, but also has periods where its predictions are off especially at the beginning and the end of the season. One limitation on performance is the reliability of the flow measuring devices. The measurements of flow are rated to be within 10% of actual flows. For the flows on this river that can easily be 5 to 10 cubic feet per second. Over several canals this can add up to a large variance. Also, when flows are at zero or close to zero the sensors may still report flows due to sediment build up in the sensor.

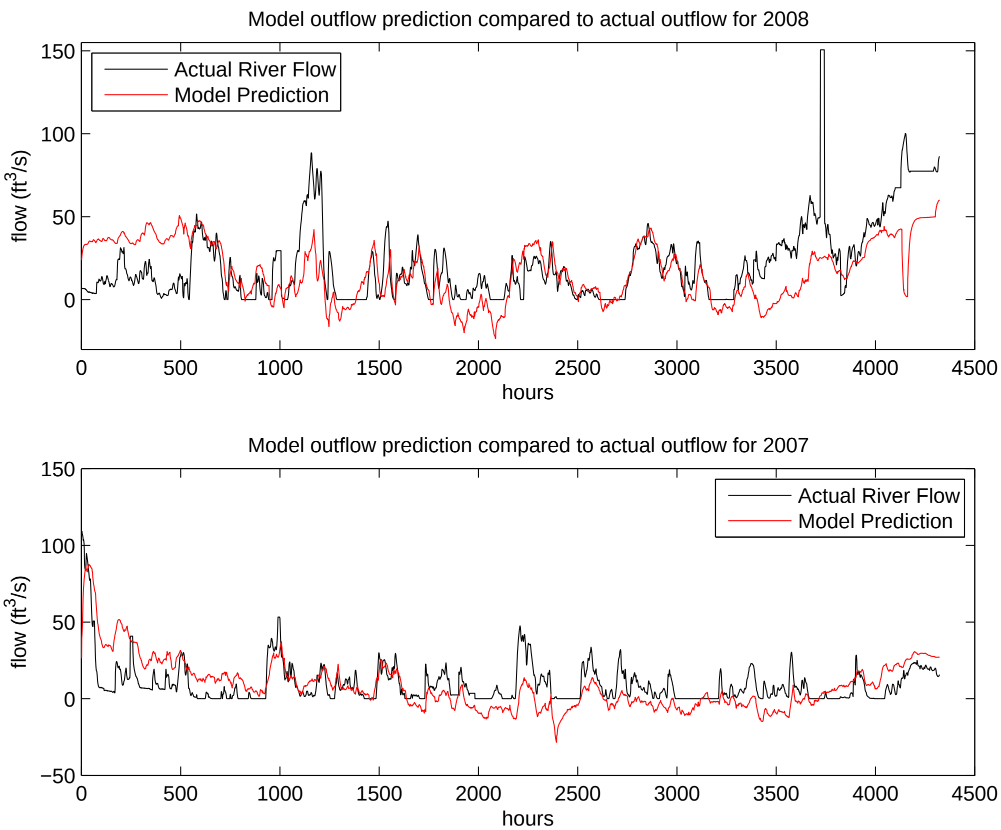

Figure 3. The model output compared with the actual river output. The top graph is 2008 data, while the bottom graph is 2007 data.

Table 2. Error of Model on Two Validation Sets

Year	Root Mean Squared Error	Absolute Error
2008	21.67	15.30
2007	13.37	10.62
2007-2008	17.80	12.96

Another reason for some of the error is that we allow the model to predict negative values. The river cannot have a negative flow, but a negative prediction is the same as predicting a shortage for the last canal. Thus a flow of -10 cfs means that the last canal has 10 less cfs than ordered. Because we did not keep track of how much water was ordered for each canal, it is difficult to determine how much shortage there was in the river when the flow was at zero. So, when the river is at zero and the model predicts some negative value, the negative prediction could be close to the actual state of the system.

There are a few possible explanations for the models poor performance at the beginning and end of the season. At the beginning of the season many of the canals are not being used and have a flow of zero but because of sediment the sensors may be recording one, this can cause unusually large errors. Also, some of the canals turn off before the end of the season which could contribute to large errors at that time as well. Typically more rainfall occurs at the beginning and end of the season, this would cause more water to be entering the system at those times. Another explanation for the error could be temperature which has a great impact on evaporation. During the beginning and end of the season the temperature is considerably lower than the middle of the season.

We feel that even with the error it is still a good model given its relative simplicity. Even when there is some error the model still captures the trends and seems to be off by a constant factor. This leads us to believe that we will be able to control this river and that feedback control can improve system performance

CONTROLLER DESIGN

The objective of the controller for the Sevier River is to select the reservoir release, u_1, in order to cause the output to match some desired reference signal. On the Sevier River the goal is to minimize water waste so the reference signal for the output of the system will generally be set at some small amount or zero, and stay constant the majority of the time. The controller will then have to decide how much water to let out so that water is delivered to all the canals and the outflow at the end remains low.

Control Architecture

For our controller design we are going to use the two part control architecture shown in figure 4. The first part of the controller is a feed forward controller (F in the figure). It uses any a priori information that we have available in order to determine a close estimate of what the control input should be. For the Sevier River this information includes the reference signal as well as future water orders for the canals. The second part of the controller is the feedback controller (K in the figure). This portion of the controller uses error from the system output in order to 'fine tune' the estimates from the feed forward controller.

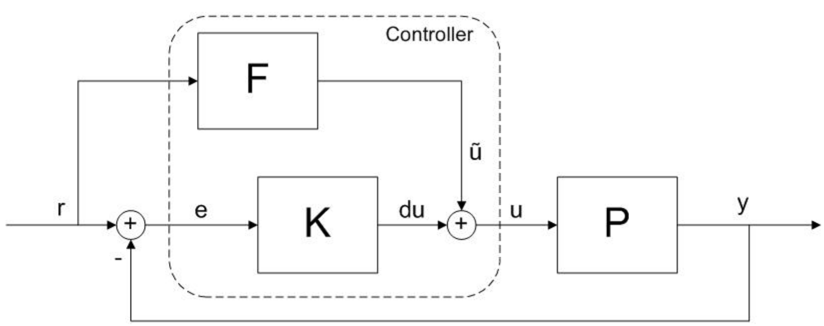

Figure 4. The control algorithm is split up into two pieces. The feed forward controller, F, uses all available information to get an approximate control choice, ũ. The feedback controller, K, uses the error, e, to adjust the approximation by du.

The control algorithm should be able to control for step changes in the output of the river or in the orders of any of the canals. Because of the large delays in the system it will be difficult to have the algorithm track these changes quickly, but it must eventually control the flow to the right value. The control algorithm should also be robust to disturbances in the flows of the river (such as rain or high evaporation), incorrect measurements, and unexpected changes in the canal flows. The control algorithm must still work if the model parameter choices are incorrect or if the delay in the river is different than we have modeled.

Control Design

First we design the feed forward, F, part of the control algorithm. In order to asymptotically track step changes in the output, the final value of output needs to be equal to the reference command. Using knowledge of the final value theorem[2], F is selected to be the inverse of the final value of the system, P. Thus $F = P(1)^{-1}$, where $P(1)$ is the discrete time transfer function of the system evaluated at $z = 1$, which is also the final value of the system.

Since the model developed in the previous section represents the river the best we can, that model is used to determine $P(1)^{-1}$. The transfer function for the model is

$$P = \frac{.0952z^2}{(z-.9048)(z+.533)(z^2+.2619z+.3199)} \tag{4}$$

Applying the final value theorem to the model yields a final value of .412. So F then becomes, $F = 1/.412 = 2.426$.

The feed forward controller also receives the future water orders from the different canals as estimates of the future canal flows. It uses these orders in order to predict what will happen to the canal inputs to the plant. From (3) notice that the inputs are each multiplied by a gain and added to the system. This controller takes each canal order, multiplies it by the inverse of the gain from the model, and subtracts it from the control input. This has the effect of changing the reservoir release early, by the same amount that the input will affect the flow in the river later on.

Next the feedback part of the control algorithm needs to be designed. One of the most common feedback controller designs is the proportional integral (PI) controller which has the property of tracking step changes in the output. The PI controller designed for this system is of the form,

$$K = k_p + \frac{k_i}{z-1}, \tag{5}$$

[2] See *Optimal control theory: a course in automatic control theory* by Robert Pallu de La Barrière for an in depth explanation of the final value theorem and its importance in controller design

where k_p is the proportional constant or proportional gain, k_i is the integral constant or the integral gain, and z is the discrete Laplace variable. These two gains must be carefully selected in order to achieve desired control results. If the gains are too high our controller may become unstable, too low and the controller will not achieve desired results.

Following a standard process for selecting these two gains results in $k_p = 1$ and $k_i = .05$. These parameters give the controller a gain margin of 2.69 and a phase margin of 139 degrees. These margins are sufficient for the closed loop system to be stable even with the large delays in our system. Figure 5 shows that the closed loop system with the controller is stable even with a delay of eight hours more or eight hours less than we have estimated. The performance improves with less delay and is worse with more delay.

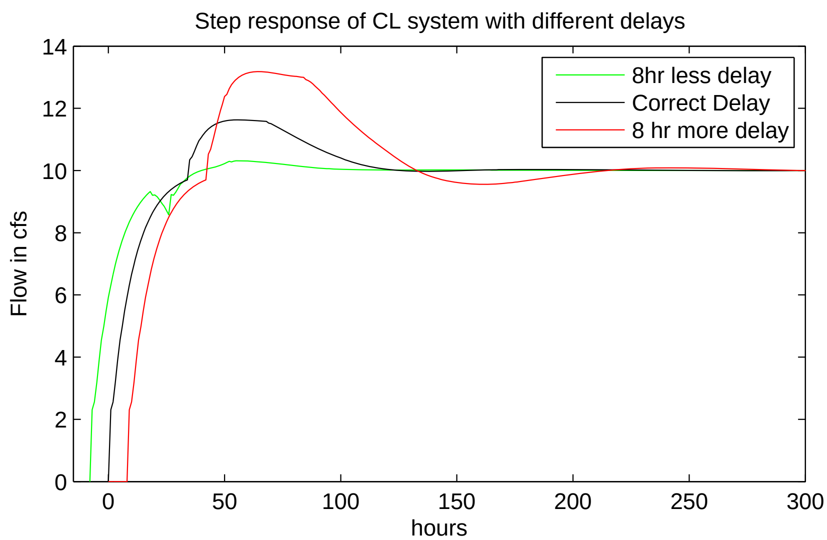

Figure 5. Closed loop system response for the scenario where the actual river delay is 8 hours less than estimated, the same as estimated, or 8 hours more than estimated.

CONTROLLER VALIDATION

In this section the controller is shown to remain stable even with outside disturbances and inaccuracies in the model. This is known as robust stability. The performance of the controller remains acceptable with disturbances and inaccurate model parameters as well.

Disturbance in Canal Input

The first type of disturbance to consider is if a canal takes more or less water than is ordered. This can happen when water users take more or less water than they requested or if the canal measurements are incorrect. It can also happen if the true impact of a canal input on the river flow is not -1 as in the model, but some other value. This would mean that the parameter for the canal input is incorrect. Figure 6 shows the controllers response to this disturbance. At 100 hours a 10 cfs step input to a canal occurs. This canal disturbance has no order attached to it and so there is no way for the feed forward controller to compensate for the disturbance. There is a delay of 20 hours before the disturbance affects the river output. At that point the controller begins to make changes but the river flow continues to drop for 32 hours since it takes that long for the changes to reach the end of the river. From the time the changes start to affect the river output it takes approximately 35 hours to correct back to within 10% error of the reference.

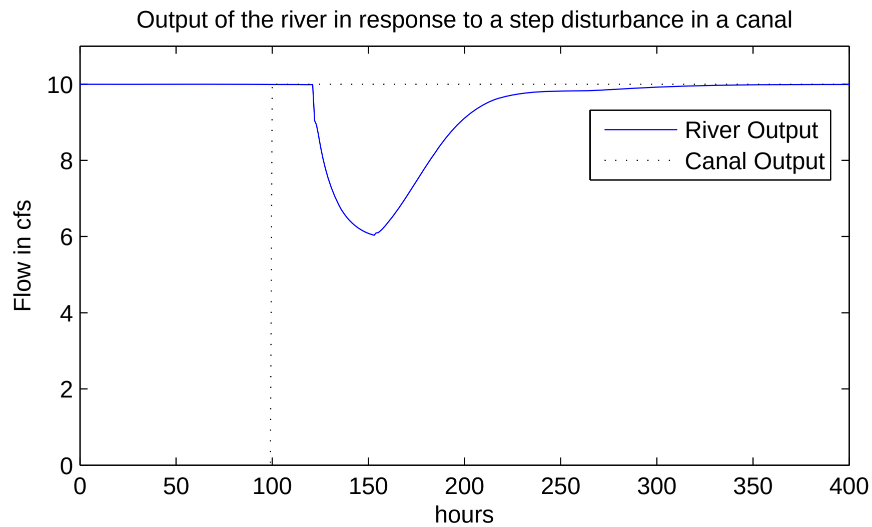

Figure 6. Output of the river with the controller implemented if at 100 hours a canal suddenly takes 10 more cfs without ordering it

The performance of this controller at rejecting disturbances in inputs seems disappointing, taking over 100 hours to correct from a step disturbance. While this is slow, the controller performed well for several reasons. First, stability is maintained in the controller. Second, the disturbance in the canal was 10 cfs, yet the error in the outflow was mitigated by 60%. Third, this is an extreme situation where the disturbance was held out indefinitely. Usually when users make errors in the order it is corrected within a day, which would help the performance of this controller.

Sensitivity to Input and Output Noise

High frequency white noise is not too damaging to the system. In fact we have assumed that many of our measurements are going to have noise in them. Figure 7 shows the output of the system when noise is added to the input and the output. Input noise is added to the reservoir release and is shown in the top graph. Output noise is added to the output measurement and is shown on the bottom graph. The noise is added to a simulation with a step input at time zero and a step disturbance on a canal at time 500. The system remains stable although the controller is unable to correct for the noise. General performance does not seem to be slowed down due to the noise. The rise time and the disturbance rejection do not take any longer.

Simulation on 2008 Data

As a final method of validating the controller it was tested on the true river data for the summer of 2008. The desire was to validate whether the controller remains stable and meets desirable control objectives with noisy data. Another goal was to say what the controller would have done if it had been running in 2008 and how much water would it have saved. Since there is not any order data for 2008, the actual amount of water that was flowing out of the canal is used as its order. Then that order is given to the feed forward controller with enough advance that it can make any changes it needs. Figure 8 shows the output of the controller with the model when using 1 cfs as the reference signal and when using 5 cfs as the reference signal.

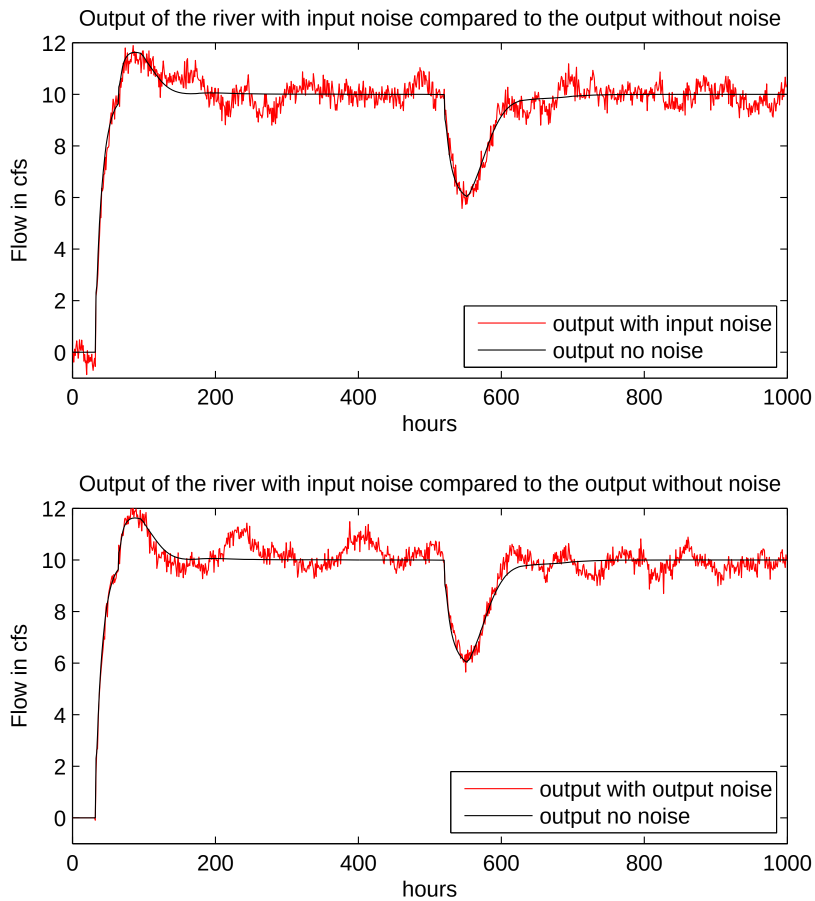

Figure 7. Response of the river to input noise (top) and output noise (bottom). Noise does not affect the overall controller response but does affect the final settling error.

From figure 8 it is easy to see that the controller would have conserved water compared to the actual flow in 2008. The figure also shows the flow of water going negative at times. This represents a shortage to the last canal. This is not very desirable. In fact, it may be more desirable to waste a little water in order to not have a water shortage. One way to do this is to increase the reference command until the controlled output goes below zero infrequently. Table 3 shows the water savings and water shorted by running our controller with varying reference points. As the controller tries to hold the river release closer to zero more water is saved, however more water is shorted as well.

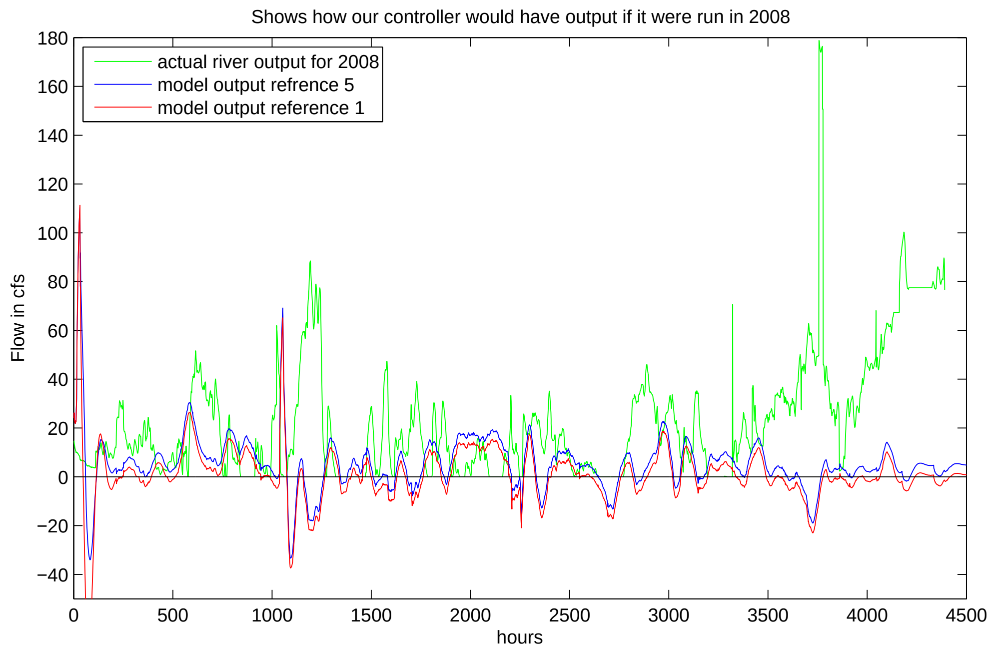

Figure 8. An estimate of how the river output would have been if the controller was running on the system in 2008 with a reference command of 1 cfs (red) and 5 cfs (blue). The green graph shows the actual river output.

Table 3. Water savings and shortages at different output targets (in acre feet)

Reference Command For Output	Water Saved	Water Shorted (Less than Zero)
r = 1 cfs	6514 AF	650 AF
r = 5 cfs	5508 AF	312 AF
r = 10 cfs	3985 AF	140 AF
r = 15 cfs	2375 AF	55 AF
r = 20 cfs	716 AF	20 AF

IMPLEMENTATION INTO EXISTING SCADA SYSTEM

In this section we describe how the control algorithm is implemented and added to the existing SCADA system. Until now the focus has been on creating a model of the river and designing a controller for the reservoir gate. First the existing SCADA system is described. Then, the three parts of the controller implementation are explained. Following the description of the system the two major problems of communication and security are discussed.

SCADA System

The preexisting system without the control algorithm consists of stations along the river, a server application called Loggernet to connect with the stations, a database for data storage, and a website for viewing the data. The data flow between these pieces is shown by the red arrows in figure 9. Each station consists of a data-logger with measurement sensors, a solar powered battery charger, and a communication radio. Most stations also contain automated gates and a local controller of these gates so that the flow can be set by canal owners and the gates will automatically adjust to let that flow through the gate. Gate automation is done by measuring the flow a little downstream of the gate and adjusting the gate until the flow matches the desired set point.

Campbell Scientific's application, Loggernet, is used to remotely connect to the data-loggers [2]. It is set to connect to each station and collect the flow and other sensor data every hour. It stores this data in a large database. Loggernet also has the capability to allow a user to manually connect to a station in order for a user to change the flow set point. An extensive website (www.sevierriver.org) allows anyone to access the data stored in the database for each station. After locating the station, historical data can be viewed and downloaded.

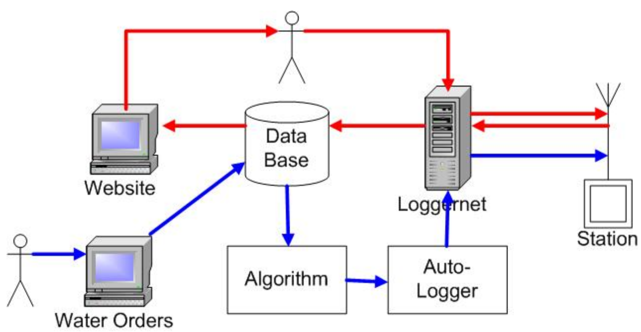

Figure 9. Data flow diagram of the original SCADA system (red), and with the addition of the controller (blue).

Control Algorithm Implementation

The architecture of the control algorithm contains three pieces which work together to control the reservoir and the gates on the canals. The data flow for the different pieces of the control implementation is shown by the blue arrows in figure 9. The first part is the online water order form. This form allows canal owners to go online and enter the future orders for their canals. These orders are stored in the database so they can be accessed by the controller.

The second part is the implementation of the controller itself. The controller has access to the database of water orders and current river flows. It calculates how much water to let out of the reservoir using the algorithm described in the previous section, and sends that value to the auto-logger. The controller also sends new set points for the canal to the auto-logger.

The third part of the implementation is the auto-logger which runs on top of Loggernet. This program receives gate set points from the control algorithm and uses Loggernet to communicate the set point to the data-logger. Just as in the original system Loggernet handles all of the radio communications. The reason for the auto-logger is to automate the sending of the set points to the station without a human initializing the change.

One major benefit of this three part implementation is its modularity. It allows the control algorithm to be completely redesigned or implemented in a new language without changing the rest of the implementation. Likewise, other parts may be redesigned or improved as well.

Communication with the Stations

Loggernet software handles the communication between the server and each of the stations on the river. This communication travels via ethernet to a data hut near Richfield, then from there travels by radio to the different stations. These radio communication channels present the single most challenging part of making the system functional. The radio channels can be very noisy and unreliable at times. It can take a long time to connect or transmit data and the signal can be dropped entirely. Also the entire system of stations is on just a couple of radio frequencies. If someone is using the frequency to change a stations flow or read its values then the platform will not be able to connect to any other station on the same frequency. This can become more serious when someone forgets to log off and keeps the line tied up for several hours.

The system has been designed to mitigate communications problems and increase the reliability of the system. The system connects to the stations once per hour to make needed changes, this reduces traffic on the radio frequencies. The system is also designed to make all the needed changes on the canals so there should not be a need for users to use the communication channels as often.

Before the system ties up the communication lines, it first checks to determine whether there has been a significant change in the order for the canal or reservoir release. A significant change is .25 cfs for a canal and 2 cfs for the reservoir. If there has not been a significant change, it will not call to make a change. The only communication initiated by the system is for those stations where there is a significant change. If communication fails, the system will quit all communications and wait for 30 seconds and then try again. After three separate tries it will give up until the next hour.

Security and Reliability

Because water is the livelihood of those who are served by the reservoir, great care must be taken to make the system secure and reliable. If the system fails, the failure must be recognized in time to minimize the damage. If a farmer looses water for a few days his crop for the year could be ruined. This danger causes many of the water users to be reluctant to allow the system to control the reservoir and the gates.

The online water order entry form uses SSL encryption and a password system to ensure the identity of those using the system. Those who use the system must have their account manually verified and be given access to each canal they are to control. Users are not allowed to see any canal that has not been assigned to them.

If at any time the system has trouble making a change on a canal or the reservoir, it will send an email notification that there is a problem. The email will then be forwarded via short message service (SMS) to the administrator's cell phone. That way, someone knows of the problem immediately, and can evaluate and fix the problem. Possible errors that are reported are communication errors, software errors, file read or syntax errors, or if the flow is outside of some pre-specified range.

As a last fail-safe, every station is equipped with a flag that must be turned on for the system to control the gate. The value, AUTOMODL, must be set to 1 otherwise the controller will not attempt to change the flow set point. If at any time the system must be discontinued for an emergency reason, one can simply change the flag to be zero. Having the fail-safe flag means that in the worst case scenario, the administrator can just turn off the controller and move the gate manually.

CONCLUSION

A fully automated system has been designed for the control of the Piute Dam and the eight canals downstream. The system takes water orders for anticipated demand from the canal operators and uses them to determine how much water should be released from the reservoir. A controller has been developed and validated to outperform previous control methods and has the potential to conserve water for years to come. The modular design of the system allows for the modification of the controller if needed. Several simulations have been run to validate the stability and potential water savings of the controller and it is planned to be run on the Sevier River system during the summer of 2010.

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MODERNISING IRRIGATION INFRASTRUCTURE, VICTORIA AUSTRALIA

Tony Oakes[1]

ABSTRACT

In response to more than a decade of sustained drought the Victorian State Government has embarked on a major infrastructure upgrade of the State's largest irrigation system. This two billion dollar investment program is being executed in two phases with the first phase, that represents A$1B focussing on improving the channel delivery systems and the second $1B focusing on farm system improvements. The primary focus of the investment is to improve the distribution efficiency and improve customer service with the first phase targeting annual water savings of 225,000 ML, which is the subject of this paper. These savings are to be equally shared between the environment, farmers via an increased allocation and an agriculture-to-urban transfer where 75,000 ML will be pumped into the Melbourne Urban system.

The paper will provide background on the project and then a high level overview of the technical challenges in implementing around 6,000 in-system regulating gates and 15,000 farm meters.

INTRODUCTION

The Goulburn-Murray Irrigation District, located in Northern Victoria is Australia's largest Irrigation district, as depicted in Figure 1. The district is partitioned into six local administrative areas and spans an area of more than 200 km in an east-west direction and 75 km in a north-south orientation. It is a large interconnected network with water supplied primarily from the Murray and Goulburn Rivers. The 6,300 km of channels are equipped with approximately 8,000 regulating bays at 6,000 regulating structures and 24,000 customer supply points. SKM[[i]] reported that the annual diversions for the decade from 1989/1990 were of the order of 3,200,000 ML with approximately 2,250,000 ML delivered to farms, which equates to a distribution efficiency of the order of 70%. SKM indicated that this annual loss of 950,000 ML was comprised of the following components

- Channel outfalls (spills)
- Leakage (point source)
- Seepage (diffuse)
- Evaporation
- Meter error
- System filling
- Unauthorised use

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More than a decade of drought has demonstrated that the volume of water available for diversion into the channel network is significantly less than the “wet” 1990s. For the 15-year period from 1993/1994 to 2007/2008 Goulburn-Murray Water (G-MW)[ii] documents the average annual diversion as 2,562,000 ML with deliveries to the farm gate of 1,816,000 ML which equates to a “System Operating Requirement” (losses) of 746,000 ML per annum for the period. For the 2007/2008 season the impact of the prolonged drought is stark with a diversion of 1,010,000 ML and deliveries of only 638,000 ML. The 372,000 ML operating requirement is attributed to the lower deliveries, the partial implementation of channel automation, reduced irrigation season and shutdown of parts of the channel network where there was no seasonal demand.

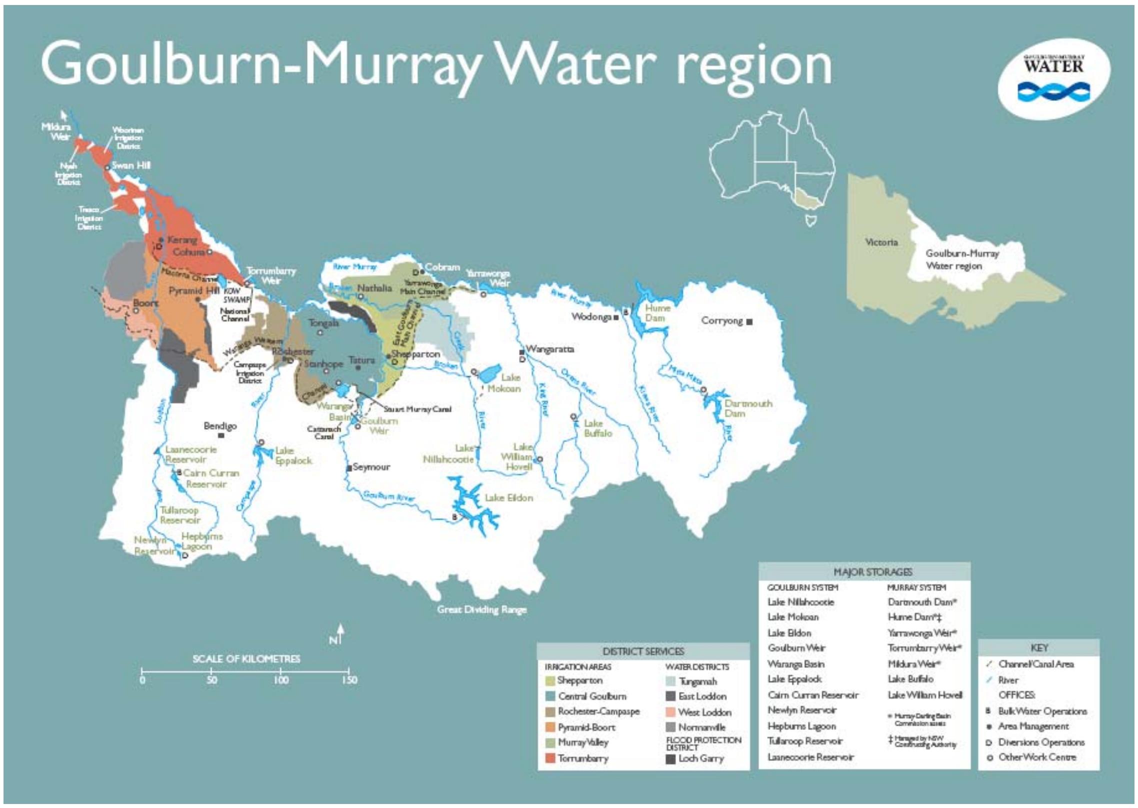

Figure 1. Goulburn-Murray Irrigation District

A key goal of the massive modernisation investment is to reduce system losses to mitigate the impact of reduced resource availability. Additional benefits accrue from improved customer service by providing near on demand supply with high reliability flow rates to farm justifying significant investment in on farm technologies to improve productivity and reduce water use.

BACKGROUND

Total Channel Control® (TCC®) was first introduced on a pilot basis to the Central Goulburn No 2 channel system in 2002. TCC® is an integrated system of intelligent automated gates, advanced communications technology and sophisticated modelling and control software. It transforms manually operated open channel systems from labour intensive, conservatively operated, high water loss irrigation supply systems into responsive, flexible and efficient systems that enable irrigators to get water at the flow rate and time they require.

In this pilot implementation manual drop board structures at 38 sites were replaced with automated FlumeGate™s and 136 Dethridge Outlets were also replaced with a further 136 FlumeGates. This pilot project demonstrated that automation of open channels was both technically and economically feasible at this scale and considerable insight was provided into the understanding of the losses – as detailed in [[iii]]

A significant expansion of this pilot was implemented in 2004 [[iv]] and after detailed consideration and evaluation of the success, the Victorian Government committed to implement the channel control and complimentary technology across the whole system. This paper provides a high level overview of key aspects of this massive project and details from the implementation during the 2008/2009 irrigation season. At the time of writing the 2009/2010 (1,100 regulator gates) works have just been installed.

GATES

The FlumeGate™, an advanced automated measurement and control device, is the cornerstone of the TCC® system. The gate is fully self-contained with a high degree of integration between the actuation, instrumentation and control components. The gate is designed to retrofit into existing regulating structures. Figure 2 shows nine gates installed at the heading of the CG No 8 channel in the Central Goulburn Irrigation District. Figure 5 shows the SCADA screen used to present the information transmitted from this site.

A total of 1,530 FlumeGates were manufactured during 2008 and they were installed during the winter of 2008 by FutureFlow Pty Ltd, an alliance of Transfield Services, Comdain, SKM and Goulburn-Murray Water. At most sites the gates were retrofitted into the existing structure, as in Figure 2, which shows the offtake to the CG No 8 channel system. Minor civil works were undertaken at some sites, but in general few new structures were required.

Figure 2. 9 FlumeGate™s at the CG No 8 Channel Offtake

COMMUNICATIONS

A critical element of the project was to design and install a communication network to support communication between equipment in the field and the office. A total of 50 communication nodes were deployed across the district as depicted in Figure 4. Key features of the design were to use FHSS (Frequency Hopping Spread Spectrum) radio systems from each node to cover a radius of approximately 15-20 km. In the initial implementation, the design objective was to "load" each node with 200 remote units, with provision for a further 200 units by collocating another master radio at each node. FHSS technology was chosen for the following reasons:

- No requirement for licensing, as they operate in the 915MHz – 928MHz ISM band
- High speed air interface running at 19,200bps
- Low maintenance requirements
- Excellent sensitivity -116 dbm
- Designed for robust communications in an unlicensed band
- Ease of deployment

Data distribution to each node site is via two independent communication links, to provide full backbone redundancy in the event of a single link failure. The primary link is provided by Motorola Canopy point to point broadband link equipment. The canopy TCP/IP links provide data at a rate of up to 30MBit per second to each of the nodes. These links have been arranged in a tree fashion to minimise propagation delays in the system. The alternative link is provided by a 3G GPRS modem connecting to the 3G mobile phone system. This system provides excellent bandwidth and maintains a true IP path as a secondary link to the node site. Routing across the primary and secondary links is provided by the Motorola MDLC protocol, as depicted in Figure 3.

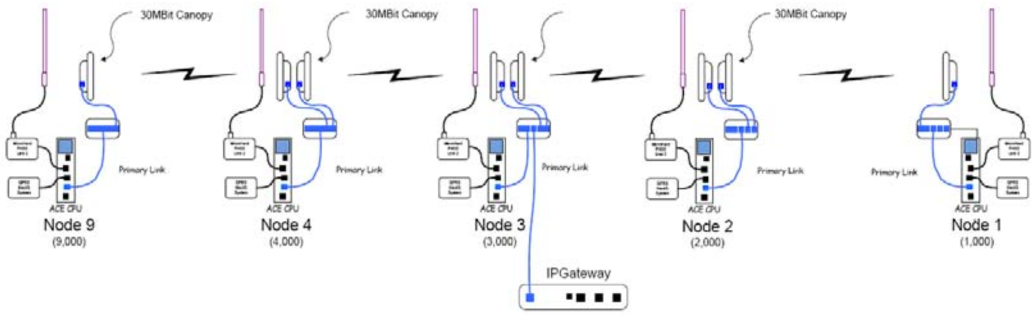

Figure 3. Communications Node Architecture

A key requirement was to use solar power for both the node and remote sites.

Figure 4. Communications Node Site

SCADA

The requirement to install 1,530 gates necessitates an efficient strategy for the rollout of the SCADA system. The address of each gate was assigned in the factory and the host system engineered using specialised "batch" style facilities, prior to the installation of the gate. Gate installation and dry commissioning was undertaken in a couple of hours and this includes the completion of the host system commissioning Inspection and Test Plan (ITP) to demonstrate and test remote operation and control. In addition to a full functional check of the gate, this dry commissioning process fine tunes the gate position to take account of any site specific geometry to ensure the gate tip can be reliably positioned with the required mm accuracy.

Figure 5. SCADA Screen Interface

The primary mechanism for operators to access the SCADA screen for each site is via the schematic representation of the water network- the tool operators use to plan and schedule orders prior to the introduction of channel automation. This arrangement provides a smooth transition for operators as the primary user interface remains unchanged, but in addition to planned information on water orders, operators now have seamless access to real time flow and water level information and plant status. The schematic interface for a small section of network is shown in Figure 6.

Operators can also access site specific screens through a more traditional menu system and summary screens. Access to all information contained in the SCADA database is available to the enterprise through a flexible WEB based interface, which also provides the delivery mechanism for customised reporting.

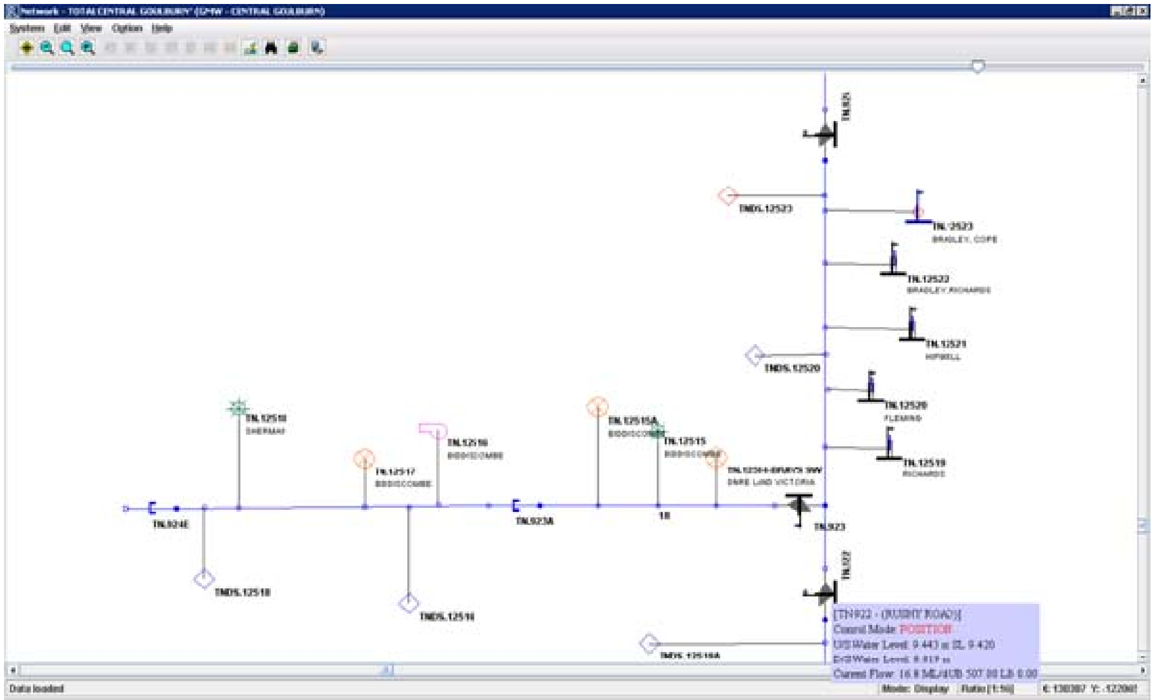

Figure 6. Schematic Interface

CONTROL ENGINEERING

Transforming a large manually planned and operated irrigation network to completely automated operation is a non trivial exercise. Customers in the district have been required to lodge their water orders directly into the system for more than 15 years, initially using Interactive Voice Response technology, but more recently with an alternative to use the WEB. After lodgement these order requests are scheduled by “planners” to meet the constraints of manual operation and the scheduled commencement times are “confirmed” by the customer the day before operation commences. In terms of the customer there two key changes; firstly the scheduling of the order is done on-line to meet the constraints of the automated control system and secondly the customer supply point operates automatically at the approved times and flow rate(s).

However, for the irrigation district staff, the transition from manual operation to automated control is done on a step wise basis with a prime focus on smoothly migrating to fully automated operation on the following basis.

1. The channel offtakes or headings are operated in automated flow control mode with the flows determined using the traditional planning process. Note that there is no tuning required for automated flow control.
2. The in-line gates are operated in position mode either from the field using the local keypad interface or from the office using the SCADA system. In both cases the operators have a flow “calculator” available to quickly determine the required gates position for the planned flow. Note that operations continue on the basis of the supply driven or upstream control paradigm associated with manual control

systems. The operators have the advantage of continuous water level and flow computation and can configure alarms to draw attention to specific conditions. This provides significantly more insight into the system than traditional manual operation.

3. The control system parameters are determined from either the physical parameter or observations of water levels associated with designed flow changes using specialised techniques as generally detailed in [v]
4. These control parameters are downloaded to the gates using the SCADA network and a group of one or more pools, starting from the top of the channel system, are migrated from manual to automated operation by remotely changing the Control Mode variable in the gate from Position to TCC mode. In practical terms this means shifting the boundary of the point where the flow is specified further down the channel until the entire channel is commissioned. At this point operation is considered to be demand driven or downstream control based.
5. The final step is to "turn on" the automatic scheduling that changes the scheduling process from a human to a machine – this is achieved by 'flicking" two software "switches". It is this final step that provides the customers with the near on demand service.

After the transformation the system is closely monitored for approximately one week, depending on demand. Any fine tuning required is generally undertaken during this period. It also provides an opportunity to identify any gross errors, usually as a result of an incorrect geometry measurement, that invariably occurs in such a large implementation.

The 1,530 gates created a total of 327 pools in the Shepparton Irrigation Area, 246 pools in the Central Goulburn Irrigation Area and 25 in the Murray Valley Irrigation area, a total of 598 pools.

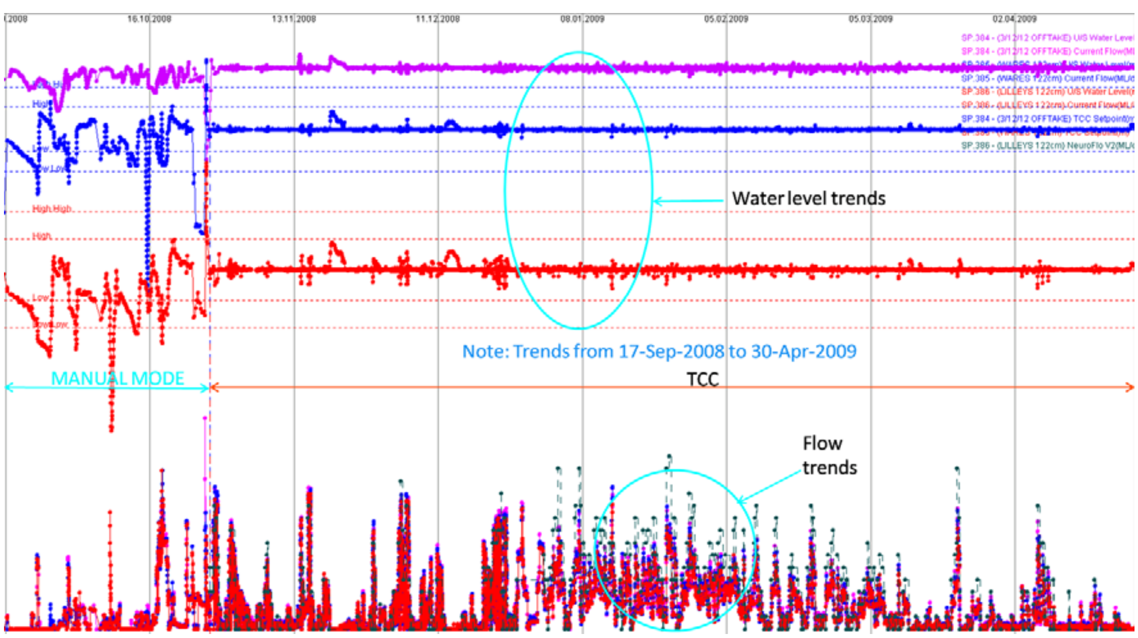

Figure 7. Transformation to Automated Control – Water Levels and Flows

There is no doubt that the installation of remotely controlled and real time monitored gates provides an opportunity to improve manual operation using the gates, particularly with the intelligent configuration of the alarm system. However, the overriding message from the transition experience is that it is exceedingly difficult for operators to make decisions on the settings required at more than 1,500 gates to minimise water level disturbances, maximise customer service and minimise wastage. Figure 7 illustrates the water levels and flows at three regulators on a channel and the water level variation before and after the commissioning of the automated control is quite stark. Note that under automated control near constant water levels are provided against a background of continually varying flows and hence customer demand.

Another key objective of the project is to eliminate spills from the channel system. Figure 8 shows the instantaneous flow and cumulative volume from the outfall of the Central Goulburn No 5 channel system before and after the implementation of TCC. This channel has a flow capacity of 250 ML/Day (approximately three cumecs) and a farmer allocation of 12,250 ML.

The system was operated manually from the beginning of the season until 13 November 2008 when automation was implemented. Up to that date cumulative outfalls totalled 286ML. After automation outfalls were dramatically reduced, with only 3ML passed during the remainder of the season.

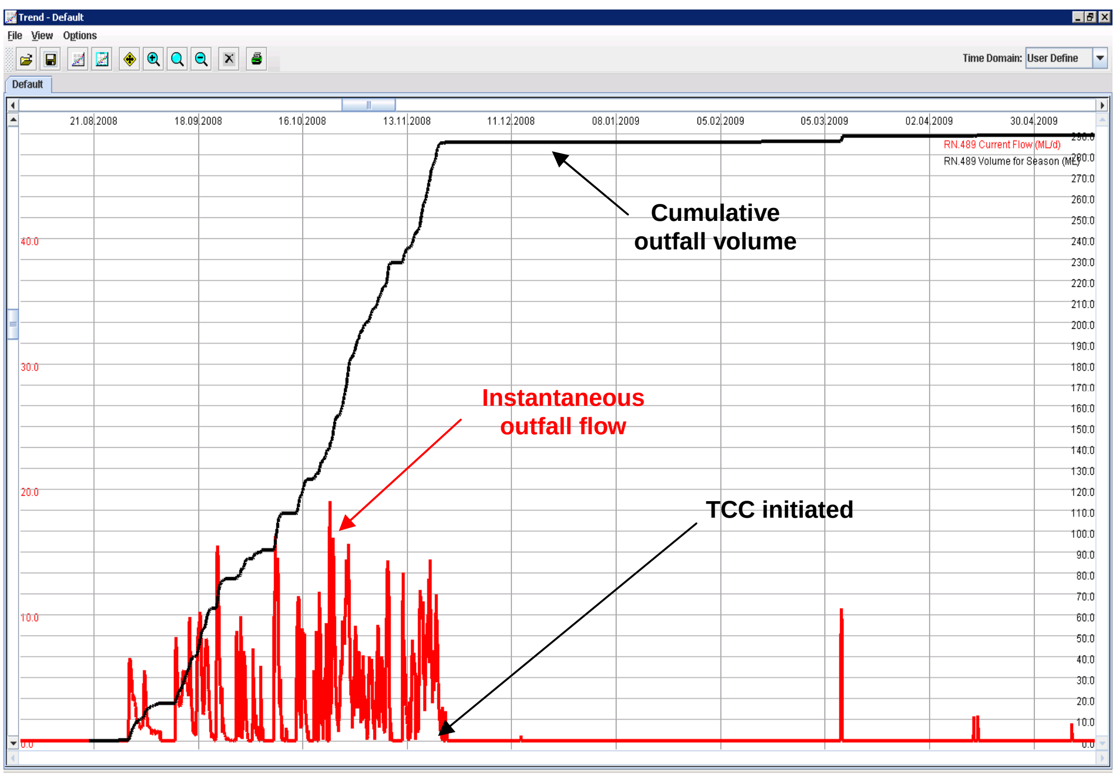

Figure 8. Outfall and Cumulative Volumes pre and post automation

This pattern is representative of the experience across the entire network.

CONCLUSIONS

The experience from the large scale implementation of open channel control technology in Northern Victoria, Australia is that significant quantities of water can be saved within the distribution system. There is clear evidence that outfalls can be effectively stopped on a large channel networks and this is a significant outcome as outfalls have traditionally been a dominant component of system loss. In addition the provision of near on demand customer service enables customers to improve the scheduling of irrigation applications with flow on water savings and productivity improvements. It is expected that this revolution in customer service will enable further improvements in on farm water use efficiency and productivity.

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FLOW CONDITIONER DESIGN FOR IMPROVING OPEN CHANNEL FLOW MEASUREMENT ACCURACY FROM A SONTEK ARGONAUT-SW

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ABSTRACT

Acoustic Doppler Velocity Meters (ADVMs) have become popular for open channel flow measurement. However, the methods used to calculate mean channel velocity from the ADVM sample (such as flow rate indexing procedure or theoretical computations such as depth-integrated power law) require significant investment in calibration time and channel improvements to provide reasonable calibration accuracy. This study utilized a Computational Fluid Dynamics model validated with the physical Cal Poly flume to design a device to condition the flow through the upward-looking ADVM sampling beams. It was found that a simple linear relationship exists between the mean sample velocity and the actual mean channel velocity when the conditioning device was used. A procedure has been developed to design a flow conditioner for applications in open channels where ADVM devices will be installed. The designed conditioner is shorter than expected and the ADVM requires minimal calibration, reducing the cost of construction and time required for calibration. Test results indicate that the flow rate measurement accuracy from the ADVM with the flow conditioner can be improved to within +/-2.2% under a range of typical flow rate and depth conditions.

INTRODUCTION

In the past decade there have been significant advances in new acoustic velocity measurement technologies. The Irrigation Training and Research Center (ITRC) has tested a variety of acoustic Doppler, magnetic, and transient-time devices in the laboratory and in irrigation districts for pipelines and canals.

Commercial Acoustic Doppler Velocity Meters (ADVMs) sometimes provide considerable advantages over traditional techniques such as current metering, stage-discharge relationships, flumes and weirs because they require no headloss, provide real-time data, are more accurate than stage rating, and are less expensive than the alternatives. However, for the canals and drainage ditches in irrigation districts, ADVMs still have significant problems including the time required for, and the uncertainties related to, accurate calibration of the device.

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In some cases, this problem is approached by integrating the one-sixth Power Law over the depth of the ADVM measurement region to relate the ADVM average sample velocity to the cross-sectional average velocity (Huhta and Ward 2003). However, this method shows poor accuracy in field applications and is not recommended (Styles et al. 2006). Likely reasons that the depth integrated Power Law does not perform adequately in field installations are that the method does not directly account for either channel geometry or roughness when relating sample velocities to the cross-sectional average velocity.

The alternative to the depth-integrated Power Law or other theoretical procedures is to calibrate the device for each installation. The recommended ADVM calibration procedure is termed the "Flow Rate Indexing Procedure" (QIP). The QIP relates the ADVM velocity to the cross-sectional average velocity measured using a "standard" device such as a current meter (Morlock et al. 2002; Styles et al. 2006) at numerous points in a cross section. At least 10 calibration points over the full range of flow rates and channel depths are recommended. In an agricultural installation it could take several months of calendar time to obtain readings over the full range of flows because low flow rates may only be available during the spring and fall. If sedimentation or vegetative growth is prevalent, this procedure may have to be completed every several years. The cost advantage of the ADVM installation degrades once the cost of labor for calibration is included.

In order to maintain accurate ADVM flow rate measurement post-calibration, a well-maintained cross section is necessary. Concrete lining of a flow measurement section 5 to 10 times the channel width typically provides the most stable cross section and is generally recommended for ADVM installations where accurate flow data is desired (Styles et al. 2006).

In recent years numerous ADVM designs have been developed for open channel and closed conduit flow measurement. Most common designs utilized in open channels are either horizontal profiling where the device is mounted on the side of a channel or bridge pier, or vertical profiling where the device is mounted on the channel bottom and velocities are sampled vertically. This paper will discuss an ADVM that is bottom-mounted in the center of the channel and uses two acoustic beams: one pointed in the upstream direction at an angle of 45˚ from vertical and the second pointed in the downstream direction at an angle of 45˚ from vertical (termed "upward-looking" ADVM). A third vertical transducer is used to provide flow depth measurements. A SonTek/YSI Argonaut-SW (SonTek-SW) with these characteristics was utilized for the physical measurements in this study.

As with most ADVM devices, the first velocity reading must be taken with a recommended "blanking distance" away from the device. The SonTek-SW is approximately 6 cm high and has a recommended blanking distance of 7-8 cm. Assuming a mounting bracket is used that adds 1-2 cm, the distance between the channel bottom and the first velocity measurement is typically 15-16 cm.

This paper will present a velocity conditioner design consisting of a relatively short contraction, which can be used in conjunction with the SonTek-SW to improve flow measurement accuracy with minimal calibration. The design parameters for the contraction were developed using a 3-D computation fluid dynamics software. The design was validated by taking physical measurements in the Cal Poly ITRC flume.

The conditioner is recommended to replace the concrete lined flow measurement section because it not only provides a constant cross section but also, as will be seen in the results presented in this paper, the required calibration can be minimized or eliminated completely while maintaining a high degree of accuracy. The conditioner presented here will likely be shorter than a concrete lined section that has a similar shape as the existing channel, which could result in a reduced installation cost.

CONDITIONER DESIGN

A computational fluid dynamics (CFD) software called Flow 3D™ was used to design a velocity profile conditioning device that could be used in open channels in conjunction with an upward-looking ADVM. Flow 3D™ was selected because it handles free surface flows well and has been field tested under a number of hydraulic conditions (Cook and Richmond 2001). Flow 3D solves the Reynolds-Averaged Navier-Stokes (RANS) equations by finite volume method, three-dimensionally using a Cartesian grid system and resolving free surface flow using a volume-of-fluid (VOF) model.

Prior to designing the conditioner, the CFD model accuracy was verified against physical measurements. A model was constructed with the same dimensions as the actual large rectangular flume at the Irrigation Training and Research Center, California Polytechnic State University, San Luis Obispo (Cal Poly flume). Velocity measurements were taken in the Cal Poly flume under a variety of flow rate and depth scenarios. CFD simulations were conducted under the same flow rate and depth scenarios and the velocities from the model were compared to the actual flume measurements.

Once model accuracy was verified, differing conditioner designs were simulated. It was found that subcritical side contractions with a smooth inlet transition provided a reliable velocity distribution in the measurement section. With the velocity measurements taken near the start of the contraction throat, the ADVM average sample velocity was shown to have a direct linear relationship with the channels cross-sectional average velocity. Figure 1 shows a plan view of the proposed contraction with the basic design parameters.

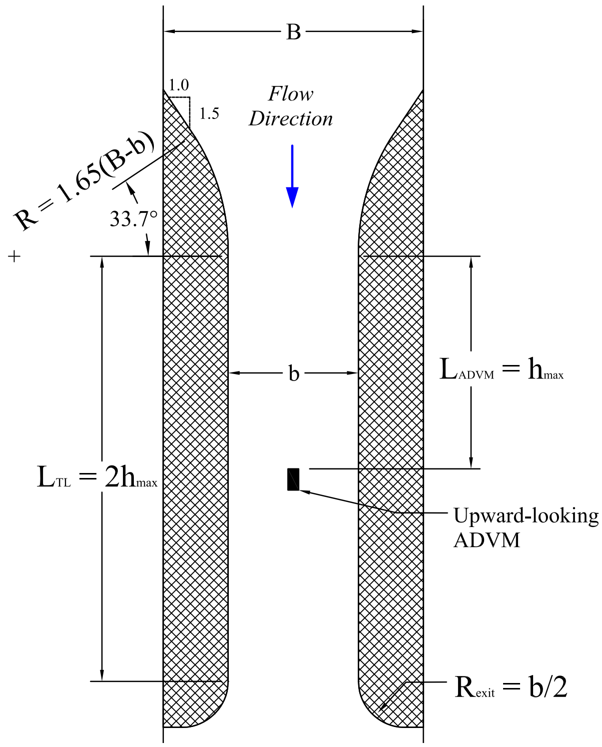

Figure 1. Plan view of the contraction used for velocity conditioning with a SonTek-SW.

The contraction ratio is commonly calculated as *b*/*B*, where *b* is the contraction opening width and *B* is the upstream channel width measured at 50% of the maximum flow depth. The contraction entrance is a combination of straight section at a ratio of 1:1.5 (perpendicular:parallel to channel side) and a rounded section with radius, *R*, which leads into the contraction throat. This entrance design was first published by Smith (1967) and was selected because it provides a smooth transition with minimal flow separation at the throat entrance. It was also felt that this entrance would be easier to construct, making it less costly than alternative designs with similar hydraulic characteristics.

The contraction throat length and location of the upward-looking ADVM are functions of the ADVM beam angle. SonTek-SW utilizes a 45˚ beam angle from vertical for the upstream and downstream beams for a total of 90˚ between the two velocity sampling beams. In order to maintain sampling within the contraction throat (straight section) the contraction throat length (L_{TL}) must be 2 times the maximum expected water level (h_{max}). The ADVM must be located (L_{ADVM}) at a distance equal to h_{max} from the start of the contraction throat. The exit transition is not as critical as the entrance since downstream conditions have not been shown to impact the velocity readings. Figure 1 shows a simple rounded exit with a radius (R_{exit}) equal to *b*/2.

Importantly, the flow within the contraction must remain subcritical. The contraction ratio (CR=*b*/*B*) selected for the design should not exceed a maximum (CR_{max}) of 0.75. The minimum CR should be selected so that the Froude number (F) within the contracted section does not significantly exceed 0.45 to minimize wave formation within the measurement section. The minimum CR (CR_{min}) and contraction opening (b_{min}) can be calculated as:

$$CR_{\min} = \frac{Q_{\max}}{0.45 B h_{\min*}^{3/2} g^{1/2}} \tag{1}$$

$$b_{\min} = \frac{Q_{\max}}{0.45 h_{\min*}^{3/2} g^{1/2}} \tag{2}$$

where Q_{max} = maximum expected flow rate in the channel, h_{min*} is the minimum flow depth expected in the channel at the maximum flow rate, B is the upstream channel width measured from bank to bank at 50% of the maximum depth, and g is gravitational acceleration. Actual h_{min*} will be lower in the contraction as velocity is accelerated in the contraction due to the change from potential energy to kinetic energy. This will cause the post-design Froude number to be slightly greater than 0.45 if b_{min} is selected as the contraction width design. Ideally, the design CR should be selected somewhere between CR_{max} and CR_{min} to maintain the maximum F between 0.2 and 0.3.

The height of the conditioner should provide sufficient freeboard so that water does not pass over the top of the contracted sides. The bottom of the contraction should be at the same elevation as the existing channel.

The conditioner shown in Figure 1 was modeled under the four flow rate scenarios and three depth scenarios shown in Table 1. Contraction ratios (CR) of 0.5 and 0.75 were simulated at most of the flow and depth scenarios. However, scenarios that resulted in critical or supercritical flow within the contraction were not analyzed.

Table 1. Contraction ratios (CR) simulated at each depth and flow rate scenario.

Flow Rate	Nominal Depth		
(cms)	1 m	0.65 m	0.35 m
0.283	0.5, 0.75	0.5, 0.75	0.75
0.425	0.5, 0.75	0.5, 0.75	none
0.566	0.5, 0.75	0.75	none
0.708	0.5, 0.75	0.75	none

Data was extracted from each simulation along the same beam paths as a SonTek-SW would sample (45˚ beam angles from vertical). Data was extracted at and above a buffer distance of 0.15 m from the channel floor (assuming a blanking distance of 0.08 m above the sensor and assuming the sensor and mounting bracket height is 0.07 m) at intervals of 0.034 m up to the water surface. This simulates the dynamic boundary setting of the SonTek-SW where the SonTek averages velocities from the buffer distance to the water surface. Velocity data from the upstream and downstream beams was averaged to develop the average ADVM velocity (V_{ADVM}). The cross-sectional average velocity (V) was computed using the known flow rate divided by cross-sectional wetted area calculated using the contraction opening (b) and water depth (h) at the simulated SonTek-SW location.

Figure 2 shows the simulated SonTek-SW average sample velocity (V_{ADVM}) compared to the cross-sectional average velocity (V) from the simulations. The linear regression on the data from Figure 2 generates the following equation with an $r^2 = 0.9995$:

$$V_{calc} = C_{sc} V_{ADVM} \tag{3}$$

where V_{calc} = calculated cross-sectional average velocity and C_{sc} is the subcritical contraction coefficient which is equal to 0.9498 for a buffer distance of approximately 0.15 m.

Equation 3 is only valid for SonTek-SW using 45˚ beam angles, within a conditioner designed using parameters from Figure 1, with a buffer distance of 0.15 m to 0.16 m, and where V_{ADVM} is obtained as the raw depth averaged velocity using the dynamic boundary condition.

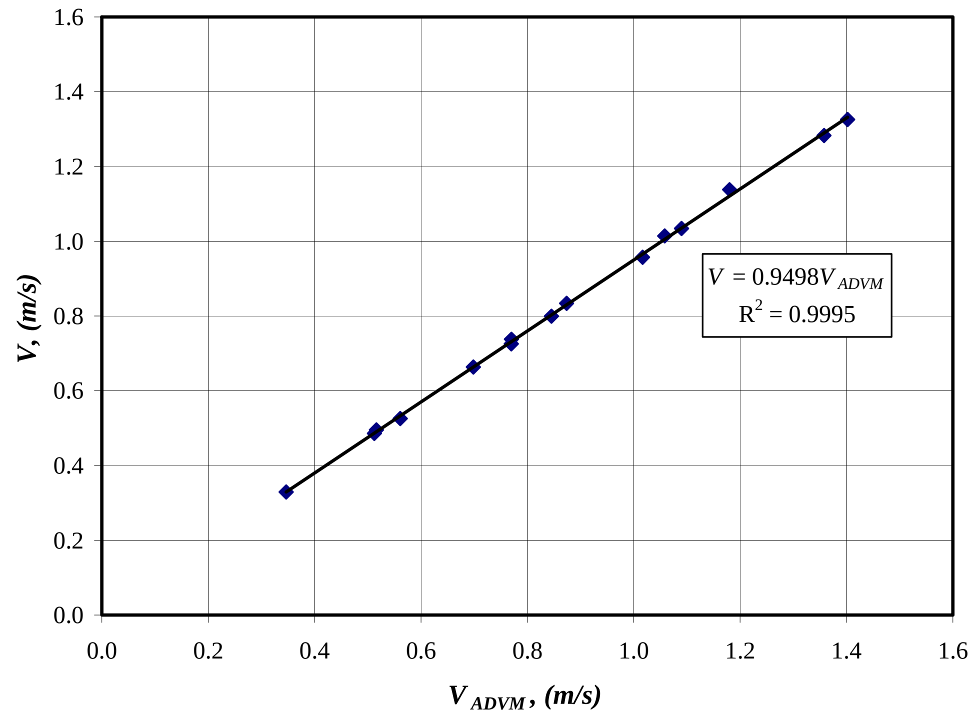

Figure 2. Comparison of ADVM sample velocity (V_{ADVM}) to cross-sectional average velocity (V) at the ADVM within the conditioner from CFD simulation results used to derive the linear relationship between the values

Evaluation of Accuracy of Equation 3 using CFD Results

The CFD data extracted from simulations in Table 1 were used to calculate the cross sectional average velocity (V_{calc}) using Equation 3. Table 2 shows the percent error between V_{calc} and the actual cross-sectional average velocity (V) from the simulations.

Table 2. Comparison of V_{calc} and V from the CFD simulations

Flow Rate (cms)	Nominal Depth (m)	Contraction Ratio (CR)	V_{ADVM} (m/s)	V_{calc} (m/s)	V (m/s)	Percent Error
0.283	1.00	0.50	0.516	0.490	0.495	-0.95%
0.283	1.00	0.75	0.347	0.329	0.329	0.06%
0.425	1.00	0.50	0.770	0.732	0.738	-0.84%
0.425	1.00	0.75	0.512	0.487	0.486	0.18%
0.566	1.00	0.50	1.059	1.005	1.014	-0.86%
0.566	1.00	0.75	0.698	0.663	0.663	0.02%
0.708	1.00	0.50	1.358	1.289	1.283	0.51%
0.708	1.00	0.75	0.874	0.830	0.834	-0.44%
0.283	0.35	0.75	1.017	0.966	0.957	0.89%
0.283	0.65	0.50	0.845	0.803	0.800	0.44%
0.283	0.65	0.75	0.561	0.533	0.526	1.33%
0.425	0.65	0.50	1.180	1.121	1.138	-1.48%
0.425	0.65	0.75	0.770	0.731	0.726	0.75%
0.566	0.65	0.75	1.090	1.035	1.034	0.10%
0.708	0.65	0.75	1.402	1.332	1.326	0.45%

The results in Table 2 show errors between -1.48% and 1.33% using Equation 3 to relate V_{ADVM} to V. The range of percent error is considered excellent and confirms the accuracy of Equation 3 for simulated flows.

PHYSICAL TESTING OF THE CONDITIONER

Experimental Setup

The contraction design parameters from Figure 1 were used to construct a contraction for testing in the Cal Poly flume. The Cal Poly flume is 1.215 m wide by 1.215 m deep by 86 m long (Figure 3). The bottom slope of the painted steel flume is 0.002. Flume components are capable of handling flow rates up to 0.85 cubic meters per second (cms). The testing region of the flume is approximately 54 meters long. The starting point of the testing region was just downstream of a flow conditioner consisting of a honeycomb of 3 inch diameter PVC pipes approximately 1 meter in length (Figure 3). The water level in the testing region is regulated by a vertical weir at the downstream end of the flume.


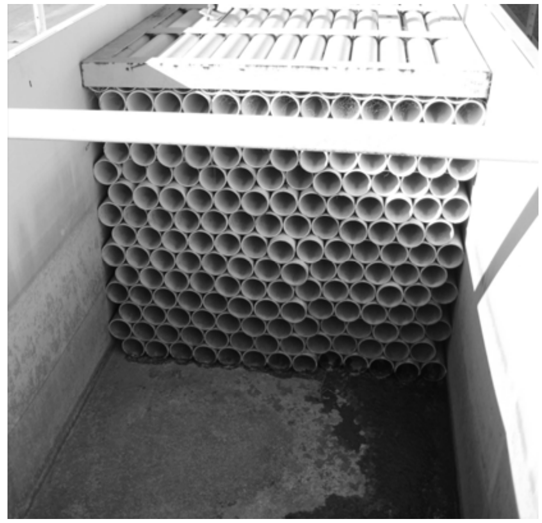

Figure 3. Cal Poly flume, looking downstream (left) and honeycomb flow conditioner (right)

The Cal Poly ITRC flume uses a recirculation facility to achieve high flow rates in the flume. The flow rate into the flume is regulated through a valve at the flume entrance and is measured in real-time by a calibrated 0.76 m diameter McCrometer Magmeter.

The conditioner design parameters for the CR of 0.5 included a L_{TL} of 2 m, an entrance radius (R) of 1 m, and an R_{exit} of 0.3 m. The subcritical contraction design was installed in the Cal Poly flume 30 m downstream of the flow measurement section entrance.

A SonTek-SW, an upward-looking ADVM with a beam angle of 45˚, was installed within the contraction at a distance of 1.0 m (L_{ADVM}) downstream of the start of the throat. The SonTek-SW's average velocity samples were developed using the SonTek's dynamic boundary setting whereby the SonTek takes a depth-averaged velocity above a buffer distance of 0.15 m from the channel bottom to just below the water surface. The SonTek automatically adjusts the top velocity boundary depending on the real-time water level. The V_{ADVM} sampling interval was 5 to 10 minutes and the number of samples for each scenario ranged from 20 to 50.


Figure 4. Subcritical contraction and SonTek-SW installed in the Cal Poly ITRC flume.

Physical tests analyzed nominal flow rates of 0.283, 0.425, and 0.566 cms at nominal depths of 0.7 and 1.0 m maintaining F below 0.45. The actual flow rates and depths varied somewhat from nominal because of hydraulic conditions related to the conditioner and the inability to match the nominal values exactly with the VFD and downstream weir.

Actual cross-sectional average velocity (V_{actual}) was developed using flow rate values from the Magmeter and a cross-sectional area calculated using the SonTek-SW measured water levels at the SonTek location and the contraction opening width.

Equation 3 was used to calculate V_{calc}, which is an estimate of V_{actual}. The C_{sc} used for Equation 3 was .9498 with V_{calc} calculated as:

$$V_{calc} = 0.9498 V_{ADVM} \tag{4}$$

The percent error between the calculated (V_{calc}) and V_{actual} was computed as:

$$Error = \frac{(V_{calc} - V_{actual})}{V_{actual}} * 100\% \tag{5}$$

Results and Discussion

The results of the physical tests are shown in Table 3. The percent error between calculated cross-sectional average velocity (V_{calc}) and actual cross-sectional velocity (V_{actual}) on average over all of the samples was less than +/-1%. The results indicate that using the conditioner with Equation 3 has a range of errors within +/-2.2% without any calibration.

Table 3. Results of the subcritical contraction with the SonTek-SW from physical measurements in the Cal Poly ITRC flume.

Actual Flow (cms)	Number of Samples	Average				Error of V_{calc}		
		Depth (m)	V_{ADVM} m/s	V_{calc} m/s	V_{actual} m/s	Average %	Minimum %	Maximum %
0.292	30	0.926	0.543	0.516	0.518	-0.35%	-2.15%	1.32%
0.440	50	1.000	0.767	0.728	0.722	0.86%	0.03%	1.74%
0.571	20	1.053	0.939	0.891	0.889	0.32%	-0.21%	1.22%
0.293	30	0.739	0.682	0.648	0.651	-0.39%	-2.09%	1.33%
0.440	50	0.731	1.046	0.993	0.987	0.69%	-0.73%	1.69%

The results show successful validation of the conditioner design. The ranges of errors from the physical test are considered excellent for open channel flow measurement.

SUMMARY

A concrete cross section with a special velocity profile conditioning design was presented that can be used in conjunction with a SonTek-SW or similar upward-looking ADVM to provide accurate out-of-the-box calibration. Initial CFD simulation results were validated using physical measurements taken at the Cal Poly ITRC flume. Results indicate that the conditioner used in conjunction with the SonTek-SW will provide accurate flow rate measurement within a +/-2.2% error without calibration.

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SEEPAGE EVALUATIONS IN CACHE VALLEY IRRIGATION CANALS

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ABSTRACT

The Logan and the Blacksmith Fork irrigation systems in the Cache Valley, Utah, convey water distribution through earthen canals. Previous researchers and local water masters reported the existence of seepage problems in these canals, but there is very little knowledge of the amount of seepage, and of the spatial locations and temporal variation of these losses. The present study provides a better understanding of the seepage behavior within and between these canals throughout the irrigation area, as these canals pass through a varying landscape, including agricultural fields, steep slopes, marshes, and residential areas.

Measurements of the canal seepage were performed from June to October, 2008. The inflow-outflow method was used to measure steady-state seepage loss rates in selected canal reaches, using an acoustic flow meter. As a result, seepage gaining streams, losing streams, and gaining-losing streams were identified. Spatial and temporal variation of the seepage was observed. In this regard, spatial variation was observed along the canals whereby a descending trend of the mean seepage loss was found in the downstream direction. Spatial variation was also found between canals because the reaches on canals located in the eastern part of Logan City presented higher seepage losses than those of the canal reaches in the western part of the city. Moreover, temporal variations were identified in that a monthly comparison of seepage losses within reaches indicated higher seepage losses in late July and August. Additionally, comments about the performance of the acoustic flow meter are presented in this paper.

INTRODUCTION

Effective management of water in an irrigation system requires knowledge of the quantity of water flowing in the canal in order to send the right quantity of water to every user at the right time, avoid unnecessary losses, and avoid physical and environmental damages. Seepage outflows affect the operation and maintenance of the canals in the sense that part of the water diverted for the users is lost from the conveyance system, and at the same time this water might produce piping, canal bank erosion (whether the canal is lined or not), produce excessive saturation, uplift pressure, which might produce failures of the canal and other structures (Rushton and Redshaw 1979). At the same time, canal seepage

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potentially constitutes a usable water resource even after it leaves the canals since it recharges the aquifers, though it requires energy to re-acquire this water.

In the Cache Valley, the Nibley Blacksmith Fork canal conveys water from the Blacksmith Fork River, and the Logan River irrigation system conveys water from the Logan River through ten open channels. The conveyance system operates only during the irrigation season (April-October) to distribute water to the users. Recently, efforts have been made to improve water management in many of the canals, including the installation of a data acquisition and telemetry system and data loggers on flumes. Nevertheless, there are very few measurements to quantify the amount of seepage affecting these canals, seepage that the managers must deal with in order to provide the right amount of water to the users. In fact, Tammali (2005) and local water masters indicated that these irrigation water delivery systems have seepage problems, but there is very little knowledge of the amount and, in some cases, of the spatial locations and temporal variation of the losses. Moreover the Cache Valley Regional Council (through the "Vision to 2020" commission), considered that the effective management of water resources in the Cache Valley will only be done through knowledge of the quantity and quality of this resource, and deemed it necessary to evaluate canal seepage (Cache Chamber of Commerce 2006).

Therefore, the aim of the present applied research project was to quantify and better understand canal seepage in the Logan and Fork Blacksmith River irrigation systems during most of the 2008 irrigation season. The acquired information is expected to contribute to improve water management in the Cache Valley, Utah, and to help determining the most important canal reaches in terms of canal lining requirements.

LITERATURE REVIEW

Seepage from an irrigation canal refers to the water that percolates into the soil strata through the wetted perimeter of a canal (Rushton and Redshaw 1979). Once the surface water from the canals seeps through the wetted perimeter, it enters into the groundwater reservoir. This flow through porous media is governed by Darcy's law expressed by Eq. 1 (Rushton and Redshaw 1979), and the amount of seepage through an area A is expressed by Eq. 2 (Cedergren 1988).

$$v = ki \tag{1}$$

$$Q = kiAt \tag{2}$$

where, v = seepage velocity; k = hydraulic conductivity, or permeability; i = hydraulic gradient; Q = volume of seepage; A = area of contact between water and soil; and, t = time. Additionally, according to Winter et al. (2002) surface and groundwater interactions occur in three different ways: gaining stream (groundwater enters through the streambed), losing stream (surface water enters to groundwater reservoir through the streambed), and gaining-losing stream (gaining and losing streams are present in different reaches of the stream).

According to the Unites States Geological Survey (1977), seepage from an irrigation canal is usually measured by inflow-outflow studies, ponding tests, or seepage-meter studies. Seepage-meters are rarely used because they can give variable, and sometimes inconsistent, values (USGS 1977). According to different authors (Alam and Butha 2004; Blackwell 1951; United States Geological Survey 1977) the ponding method is the most accurate method to measure canal seepage, but does not reflect the usual operating conditions of the irrigation system, also it has the disadvantage that the canal cannot be in operation while the test is performed (the test can take several days), and the construction of the dikes might be expensive and could damage the canal (United States Geological Survey 1977). In this regard, Alam and Butha (2004) concluded that the selection of the best method for a particular project depends on different factors such as the nature of the project, the time availability, the magnitude of the seepage loss, the availability of equipment, and others. For the execution of the present project the inflow-outflow method was used. This method is a water balance approach that consists in the direct measurement of the flow rate entering and exiting a reach of canal. Thus, from Eq. 3 it is possible to estimate the seepage losses (S). Figure 1 shows the scheme of this method.

$$S = Q_i + R - Q_o - D + I - E \tag{3}$$

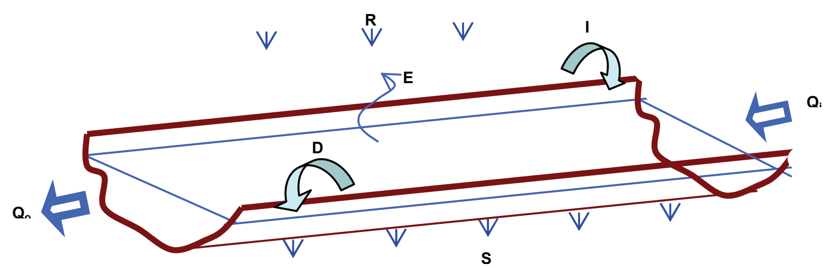


Figure 1. Mass balance for the inflow-outflow method

where *S* is the seepage rate; *Qi* is the upstream inflow; *R* is rainfall; Q_o is the downstream outflow; *D* is the flow diverted along the reach; *I* is the inflow along the reach; and, *E* is evaporation. To use this method it is necessary to have steady flow conditions (whereby the change in reach storage is zero), and sufficiently long canal reaches to obtain a measurable loss (Blackwell 1951).

Flow rate in a cross section, perpendicular to the main flow direction, is estimated by Eq. 4:

$$Q = V*A \tag{4}$$

where Q is the discharge (in volume per unit time); V is the mean velocity of the flow; and, A is the area of the cross section. For measuring flow in open channels the cross section is usually divided in sub-sections. The area is obtained by direct measurement of the sub-section width and water depth at the edges of every sub-section. The estimation of the mean velocity in a sub-section was done in this study using the Reduced Point Method. This method consists in measuring the velocity at fixed water depths (0.2, 0.6, 0.8 of the water depth in the cross section) and usually is done using current meters.

Some of the most common arithmetic methods to calculate the total discharge in a channel cross section are the mean-section and the mid-section methods. These methods differ in the location of the station in which the velocity measurement is done. According to Young (1950), quoted by Rantz (1982), the midsection-method is slightly more accurate than the mean-section method. Therefore, the mid-section method was used in the present project. For applying the mid-section method**,** the channel cross section is divided in subsections and the center of the subsection constitutes the station in which velocity measurements are done. Then, the total discharge is obtained by the sum of the discharge in each subsection into which the channel cross section was divided (Eq. 5).

$$Q = \Sigma V_i * d_i * (b_{i+1} - b_{i-1})/2 \quad (5)$$

where Q = flow rate; b = position of the station along the tag line; d = water depth in the station; $_i$ = position number; and, V = mean velocity in the station.

Finally, according to Skogerboe and Merkley (1996) one of the three common ways to express the seepage rate is in lps/100 m (Eq. 6):

$$Q_l = 10^5 * (Q_u - Q_d)/L \quad (6)$$

where Q_l = seepage loss; Q_u = inflow rate (m^3/s); Q_d = outflow rate (m^3/s); and, L = reach length (m).

The measurement of mean velocity at a fixed point in a stream cross section is commonly done using current meters. In the present research, the FlowTracker® ADV® manufactured by SonTek/YSI, Inc., was used to measure flow velocity at points in the canal cross section. It uses acoustic signals to determine the velocity of remote particles into the water, then it is assumed that the velocity of the particles represents the velocity of the water. In this device a beam transmits an acoustic signal with a known frequency, then this signal hits moving particles (small sediments or bubbles suspended in the water) in a remote sampling volume, and immediately the signal is rebound with a different frequency. Finally, the rebound signal is picked up by two receivers localized upstream and downstream to the position of the beam. The determination of the velocity of the particles is made using the Doppler acoustic law which states that the frequency of the sound is shifted when the source of sound is moving relative to the receiver (SonTek 2007).

METHODOLOGY AND SELECTED REACHES

<u>Canal reach selection</u>

Preliminary reach selection was done using a GIS map developed by Tammali (2005). Definitive selection was done during field inspection during the spring of 2008. For the present project some preferred characteristics were defined in order to select the most adequate reaches and cross sections to make the measurements.

<u>Preferred Characteristic for a Canal Reach Selection</u>:

Accessibility and safety: The safety and accessibility by car or walking through an access road was critical since it facilitates the inspection of inflows and outflows present along the reach, reduce the time to commute between upstream and downstream cross sections, and reduce the chance of having un-steady flow between cross sections. For this reason, locations covered with vegetation or surrounded by fences were avoided when possible; otherwise the inspection was done by walking inside the canal.
Few inflows and outflows: Less number of outflows means less time used to finish the measurements in one reach and less potential measurement error. For this reason, the reaches were first selected based on the number of existent inflows and outflows reported by Tammali (2005), and the definitive reaches were selected at the moment of field inspection, considering the number of inflow and outflow (gates, pipes, and pumps) locations with flowing water.
Measurable inflows and outflows: For more accurate seepage estimation the inflows and outflows had to be measurable, for this reason submerged pipes, pumps, gates diverting direct into houses and gates diverting into buried pipes were avoided.
Long reaches: When using the inflow-outflow method, sufficiently long reaches are required to have a measurable loss (Blackwell 1951), as stated above. In this study the longest possible reaches were selected in each case.
Spatially distributed reaches: The reaches were located as equally distributed as possible, given several practical considerations, along each channel.
Type of lining: The measurements were taken in reaches with the same type of lining. The types of linings found in the canals included plastic, concrete, and unlined earthen material (the most common, by far).

<u>Preferred Characteristics of a Channel Cross Section:</u> Safety and recommendations of the International Standard Organization (2007) ISO 748:2007(E) and the Unites States Geological Survey (2007) were evaluated to select proper cross sections:

- Restrict measurements to steady flow conditions
- Use a straight section of channel
- Avoid vortices, reverse flow or dead water
- There should not be any obstructions in the cross section
- Look for locations where the main flow is orthogonal to the cross section
- Regular distribution of the velocity

Finally, the reaches selected for the present study are shown in Fig. 2 where every reach was named SX, where X is a consecutive number that represents the position of the reach in the canal (from upstream to downstream starting with 1). The reaches were selected based on the criteria previously stated, and selection of representative reaches based on other canal characteristics (such us type of soil, soil hydraulic conductivity, slope, canal lining, groundwater table depth, geological faults, slope, and other factors affecting seepage) was not affordable under the used methodology.

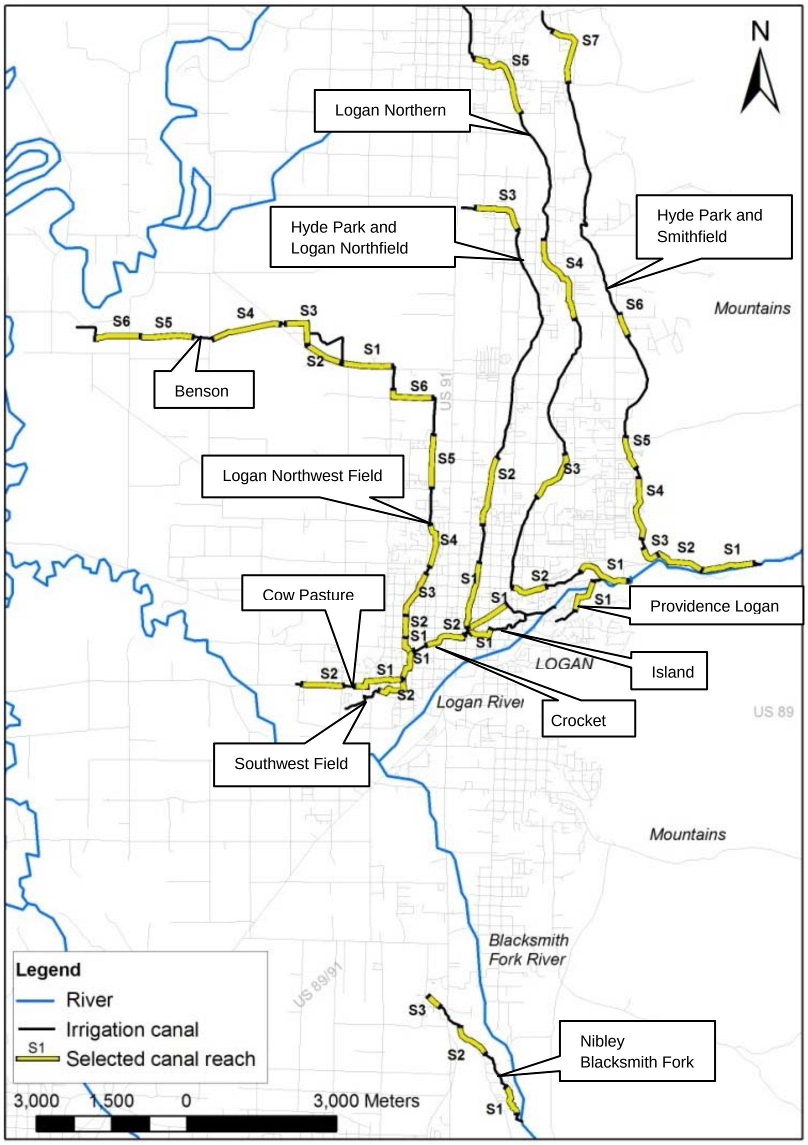


Figure 2. Selected reaches

Seepage Estimation

The seepage measurements were done using the inflow-outflow method in the selected canal reaches, and evaporation was assumed to be negligible. Discharge measurements were estimated using an acoustic current meter, and the measurement of velocities was done using the wading method. The estimation of the mean velocity in each station and in the cross section was obtained using the reduced-point method. The area was obtained from the measurement of water depth at every station along the cross section; for a more accurate estimation of the area at the edges, the velocities at the edges of the canal were measure in order to determine the boundary between the flowing water and dead water, vortices, and other factors. The computation of the discharge was done using the mid-section method, and the measurement of low-flow pipe discharges (lateral inflow and outflow) was done using the volumetric method.

FIELD WORK AND EQUIPMENT PERFORMANCE

Field Work

The field work was done from June to October 2008. Activities performed in the field were:

- Monitoring of water levels: water level marks were located in preliminary upstream and downstream cross sections and inflows and outflows along the reach, in order to observe if the water depth varies. Measurements were done while the water depth remained constant; otherwise the field work at the canal was stopped (because unsteady flow conditions were detected).

- Reach and cross section selection: Based on preliminary selection, the inflow and outflows (gates, pipes, pumps, etc) were located and evaluated to determine if measurement with the available equipments were possible, otherwise the reach length was reduced or abandoned. Nevertheless, repeated visits were done in reaches that presented high number of open outlets and inlets at the moment of the survey, until few operating inlets and outlets were found.

- Measurement of velocities: Upstream inflow, downstream outflow, flow diverted and inflows were measured. The number of verticals per section was determined in the field, taking into account the canal width, the uniformity of the canal bottom, eddies, the available time to develop the measurement, and the ISO 748.2007 (E) and United States Geological Survey recommendations. Also, some parameters were monitored during the velocity measurement, in order to observe if debris, eddies, lack of perpendicularity, or lack of particles in the water affected the velocity measurements. Those parameters are the standard error of velocity, flow angle, the Signal-to-Noise ratio (SNR) value (measure of the strength of the reflected acoustic signal), and spikes in velocity (velocities that exceed Eq. 7 or are lower than Eq. 8).

$$Q_3 + 2*IQR = UL \tag{7}$$

$$Q_1 + 2*IQR = LL \tag{8}$$

where Q_3 = Lower quartile of the velocity samples, Q_1 = Upper quartile of the velocity samples, $IQR = Q_3 - Q_1$, UL is the Upper limit and LL is the Lower limit.

Equipment Performance

The FlowTracker® ADV® was used in widely varying conditions, and its performance for the present project is briefly explained in this section.

Measurement in Low Water Depth with Low Velocities: The flow meter was useful to determine velocities at water depths as low as 8 cm and low velocity flows (such as 0.05 m/s).

Measure Under Low SNR: SNR stands for Signal-to-Noise Ratio and is expressed in logarithmic units (dB). It is a quality control parameter given by the FlowTracker. It indicates the strength of the acoustic signal reflected by particles in the water with respect to the ambient noise level. Thus, the more abundant the particles reflecting the sound are, the greater the SNR is. The recommendable SNR is 10dB; however, it can work accurately from 4 dB and higher (SonTek 2007).

During the velocity measurement in the S6 reach of the Benson canal a low SNR was detected. At the moment of the measurement the water had visible suspended particles. However, SNR values such as 10.6 dB and 0 dB were found at the beginning and at the end of this section, respectively. The SNR increased once a person walked upstream into the canal; also, there were no hydraulic jumps for at least 2.5 km in the upstream direction, and the mean velocity at the furthest downstream cross section was around 0.09 m/s. Therefore, this low SNR might be due to the lack of mixing, and low flow velocities, which contribute to the reduction of air bubbles and to the settlement of suspended solids that reflect the sound transmitted by the acoustic flow meter.

Measurement in Vegetated Canals or with Presence of Debris: Heavy bottom vegetation in channels disturbs the flow and produces spikes in velocity measurement, inappropriate velocity profiles, negative velocities behind the aquatic plants, etc. Also, aquatic plants and debris blocked the probe and fouled the equipment operation.

Flow Direction: The angle of the flow given by the flow meter was useful to determine if the tag line needed adjustments to be perpendicular to the flow, or otherwise if the cross section was not adequate.

Measurement in Irregular Cross Sections: In sections with irregular bed channel additional depth measurements were done using the “None” feature in the FlowTracker in order to obtain a better estimation of the cross-sectional area.

Inspection of Submerged Gates and Pipes: During the inspection of lateral inflows and outflows along a selected reach, it was difficult to determine if submerged pipes and gates were working. In order to figure out if laterals were diverting or picking water up from the canal, the FlowTracker® ADV® was used to estimate the velocity and direction of the water entering or exiting the lateral. For this purpose the flow meter was used in the “General” mode and the probe was located as close as possible to the pipe or gate entrance avoiding producing quality control boundary warnings. Then, the velocities in the X axis (Vx) and Y axis (Vy) corresponding to the probe coordinate system (X and Y axes are as shown in Fig. 3) were observed in order to determine the resultant direction of the flow at the entrance of the laterals. Figure 3 shows some of the velocity directions obtained during measurements. In cases 1 and 2 it was assumed the outflow laterals were not diverting water, and in case 3 it was assumed that water was entering the lateral.

RESULTS

The resultant average seepage in each reach is shown in Table 1, where positive values mean net seepage losses from the reach, and negative values mean a net seepage gain of water into the reach. Also, comparison of the canals in a particular period is desired to show the spatial seepage behavior in the irrigation system area. Due to time limitations and other factors, measurements could not be done in a single month for all of the eleven canals under evaluation, but most of the reaches were measured in August. Thus, 28 reaches corresponding to five canals had measurements taken in August, four reaches corresponding to three canals had measurements taken towards the end of July and beginning of August, and measurements could not be taken in three of the canals in August. Hence, the end of July and August was selected as the period for comparing the eight canals. This is done to illustrate the variation of the seepage over time during a particular period. Figure 4 shows the Logan irrigation canals, the measured sections and the estimated mean seepage (represented by bars) for the period of comparison.

As observed in Figure 4, the seepage manifests spatial variation along all the canals. Seepage losses in the east part of the city are higher than seepage on the west side, were losing and gaining streams exist. Also, reaches close to the Logan River presented higher seepage losses than reaches located further downstream in the canal.

Table 1. Estimated Average Seepage

Canal	**Reach**	**Estimated Seepage (lps/100 m)**				
		Jun	**Jul**	**Aug**	**Sep**	**Oct**
Black Smith Fork River						
Nibley-Blacksmith Fork Canal	S1		7.03			
	S2		8.65			
	S3		-5.02			
Logan River						
Hyde Park and Smithfield Irrigation Canal	S1	8.99	12.4	11.3		11.5
	S2		10.1	16.5		
	S3		6.14	11.8		
	S4	5.95		3.53		2.10
	S5			9.04		
	S6			10.0		
	S7			6.84		
Logan Northern Irrigation Canal	S1	2.52	9.37	12.7		3.55
	S2			11.29		
	S3			2.88		
	S4			2.64		
	S5			1.09		
Hyde Park and Logan Northfield	S1		2.44	7.10		0.86
	S2			5.96		
	S3			-0.01		
Logan Northwest Field canal	S1	21.6	20.2	16.5		3.63
	S2	1.51	1.79	1.94		5.97
	S3		2.50	5.46		
	S4		0.76	-2.65		
	S5		-3.51	1.20		
	S6		-1.30	3.23		
Benson Irrigation canal	S1	-2.30		5.01*		3.88
	S2					-2.13
	S3			0.01		-4.63
	S4	1.36		1.77*	0.87	
	S5			2.75		
	S6			0.41		
Crocket Canal	S1	7.53	-13.2	-3.79		-1.72
	S2		6.02	16.7		0.19
Cow Pasture Canal	S1	1.72		3.21		
	S2			0.49*		
Southwest Field Canal	S1	1.63		1.95		
	S2			1.66*		
Providence Logan	S1	1.76				
Logan Island Canal	S1				4.90	

**Measurements in these reaches were made at the end of July*

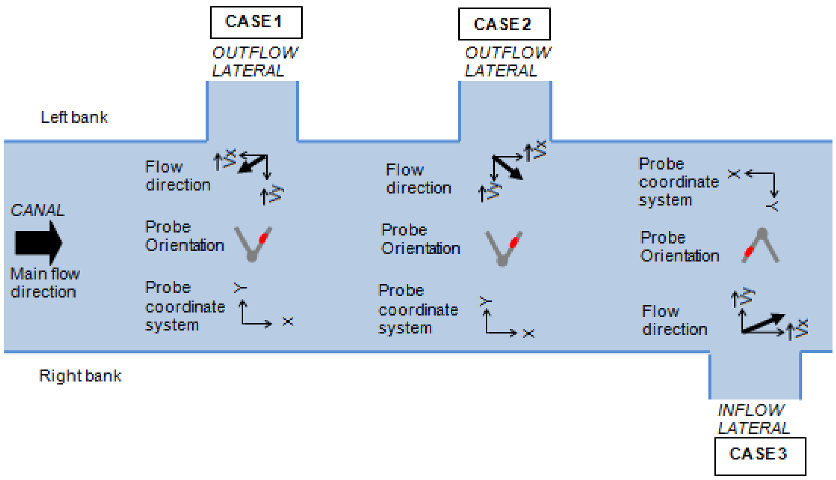


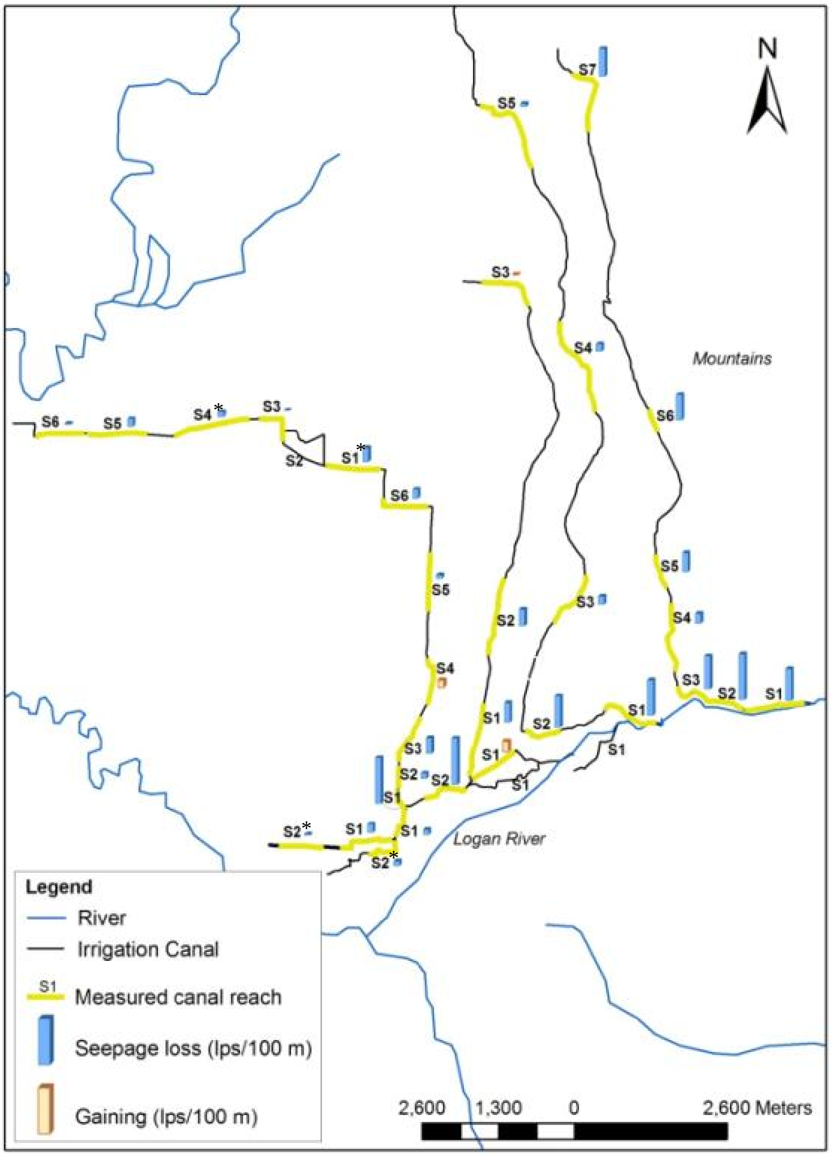
Figure 3. Flow directions at canal inflow/outflow locations

DISCUSSION

From the analysis of the results, it can be stated that in the evaluated reaches the seepage presented spatial and temporal variation. With respect to the temporal variation, 12 out of the 17 reaches show the highest seepage in late July and August. Also, six reaches (S1 in the Crocket canal; S4, S5, S6 in the Logan Northwest canal; and, S1and S3 in the Benson canal) switched from seepage gain to seepage looses and vice-versa. With respect to spatial variation, Fig. 4 compiles the seepage for the comparison month, and shows the spatial variation along every canal. It is observed in Fig. 4 that most of the canals showed a descending trend in the mean seepage losses in the downstream direction. Thus, the upstream reaches presented higher seepage losses than the downstream reaches. Also, losing-gaining streams can be observed.

Additionally, from Fig. 4, the reaches exhibited spatial seepage rate variations as canals move from the east to the west part of the city. In this sense the sections in the Hyde Park and Smithfield canal shows higher seepage losses than sections in the Logan Northern canal, and in turn the Logan Northern canal shows higher seepage rates than the Hyde Park and Logan Northfield canals. The Logan Northfield canal had slightly higher seepage losses than the Logan Northwest Field canal, which presented both losing and gaining streams. Highest seepage gains were measured in reach S1 of the Crocket canal.

The highest seepage losses were found in the Hyde Park and Smithfield canals in reaches S1, S2, and S3 (along Canyon Road), in the Logan Northern canal in reaches S1 and S2 (along Canyon Road), in the Crocket canal in reach S2, and in the Logan Northwest Field Canal in reach S1. It is important to mention that flowing water beside the canal was observed in the first six reaches mentioned above. Likewise, infiltration of water in basements close to the seventh mentioned reach was reported. Further studies are required to know if this water come as part of the seepage losses in these reaches and to know the precise location of the leakage if any.



**Measurements in these reaches were made towards the end of July.*

Figure 4. Estimated mean seepage in August 2008 for the Logan irrigation canals

Also, losses were expected in the Crocket canal because Tammali (2005) reported that this canal had seepage losses affecting Canyon Road; however, net seepage gains were observed in the present study. From careful inspection it was concluded that there were no pipes or springs along this reach, therefore the gain might come through the streambed. The possible reason for this conflicting observation could be the recent repair work performed after Tammali's study was undertaken. This implies that there were seepage gains at the time of the previous study, but were negligible in comparison to the seepage losses prior to the repair work, hence net seepage was accounted as seepage loss and not as a gain. Additionally, in order to confirm the calculated seepage value, repeated measurements were done on July 14 and 27 using different cross sections for reach S1, and in both measurements net seepage gains were again obtained.

Using GIS soil coverages from the Natural Resources Conservation Service (source SSURGO http://soils.usda.gov/ 2008), and the maps provided in the State of Utah - GIS division webpage (source http://gis.utah.gov/ 2008), some maps (such as contour level, geologic faults, shallow groundwater, wetlands, type of soil, and saturated hydraulic conductivity maps) were overlayed with the canals in order to contrast and observe patterns in the seepage behavior. . From the superposition it was observed that the Logan and Blacksmith Fork irrigation systems are surrounded by agricultural areas (recharge for the aquifer). The higher topographic level is located in the east part toward the mountains and the lower topographic level is located in the west part of the Logan and Nibley canals, in which shallow groundwater area is observed (this shallow groundwater zone might be variable due to recharges coming from spring runoff and irrigation water). High permeability soils are located close to the mountains and around the Logan and Blacksmith Fork rivers. Geological faults are observed crossing reach S3 at the Hyde Park and Smithfield canal; however, no extraordinary seepage was found in this reach. As a result of the superposition the following was observed:

- Two reaches (S1, S2 at Hyde Park and Smithfield canal) with the highest seepage losses located in the hillside of the mountains over natural rock. Most likely seepage is driven by the permeability of interstices (cracks and joints) in the rock. A seepage face was also observed in the hillside and this probably comes from the canal.

- Four reaches with the highest seepage (S3 at Hyde Park and Smithfield canal, S1 and S2 at Hyde Park and Logan Northern, S1 at Crocket canal) are located in gravelly loam soils, which also correspond to areas with the highest saturated hydraulic conductivity, steep slopes, far away from the shallow ground water and consequently far away from wetlands. In contrast reaches with the lowest seepage (S4, S5, S6 at Logan Northwest Field canal, S3 at Hyde Park and Logan Northfield canal, and S1, S2, S3, S4 at Benson canal) are located in silty clay and silty clay loam soils (clay content in these areas is around 32 – 52%), with low permeability, in shallow ground water area and with very mild slopes. The remaining reaches are located mainly on silt loam and loam soils with intermediate permeability.

- Exceptions to the previous observations are the S1 reach at Logan Northwest Field canal and the S2 reach at the Crocket canal. Both of these reaches presented high seepage loss although they are located in a shallow groundwater area. Dissimilarities observed in these reaches (in contrast with other reaches in shallow groundwater) are: high hydraulic conductivity, these two reaches are located on the top of steep slope terrains close to the Logan river, and the type of soil is gravelly loam (same type of soil as reaches with the highest seepage) while the others reaches are located over silty clay and silty clay loam soils. The high seepage observed might be a result of the interaction of the surface water with the shallow groundwater through a high permeable soil, in which the underground flow direction possibly is affected by the topographical position, and by the interaction with the Logan River, a natural drainage.

- In contrast, the Nibley Blacksmith Fork canal is located in gravelly loam soil (same type of soil of reaches with the highest seepage), surrounded by some wetland, the terrain in the area is not as steep as the area with reaches with the highest seepage. The reaches in this canal have lesser seepage losses than other reaches in the same type of soil, and the furthest downstream reach (S3) presented net seepage gains. The different behavior might be due to the topography, possible influence of the groundwater table, wetlands, and conveyance properties of this canal.

- In the Crocket canal it was observed that reach S1 presented the highest gaining-losing stream. This reach is located in the bottom part of a steep slope in the Logan Canyon, in gravelly loam soil (same type of soil of reaches with the highest seepage), with high hydraulic conductivity, with no visual presence of springs or pipes. This gaining may be a response of some interaction between groundwater coming from irrigated areas in the upper part of the canyon and the wetted perimeter of the canal.

- Also, it was observed that reaches at the Logan Northwest Field, Benson, Cow Pasture, Southwest Field and the S3 reach of the Logan and Northfield canals are all located in the shallow groundwater region and surrounded by wetlands. It is highly possible that gaining-losing streams might be present in this area. In fact, in the present study some reaches in this area were found to have gaining and gaining-losing behavior (e.g. S4, S5, S6 at the Logan Northwest Field canal, S1 and S3 in the Benson canal, S3 in the Hyde Park and Logan Northfield canals). Variations of seepage in these streams may be seasonal and highly dependent on the shallow groundwater table behavior and local underground water pathways.

Additionally, it was observed that the sealing of bottom and walls of the earthen canals changed along the canal and during the irrigation season. Thus, at the head of the canals the bottom was usually somewhat stony, while downstream accumulation of sediment and vegetative growth were observed. Also, in some sections the sediment in the streambed was removed (apparently due to higher flows in the canals). Thus, permeability of the streambed may be highly variable along the canal during the irrigation season, and might differ from the representative values given on the soils map.

Although a kind of pattern between the estimated canal seepage and the type of soil, shallow groundwater and topography was observed, the previous approach to understand seepage behavior in the reaches that were evaluated suffer from the lack of knowledge of the real conditions of the factors present in the canal (e.g. groundwater table, permeability, wetted perimeter, and others, are unknown). Thus, a simple extrapolation of the seepage observed in the reaches to the whole canals is inaccurate. In fact, according to the United States Geological Survey (1977) to extrapolate measured seepage to the influenced area is necessary to know the next information: soil types, conveyance properties (mean flow, wetted perimeter, and longitudinal bed slope), and geo-hydrologic settings, referred to the water table position in relation with the canal. Deeming the lack of knowledge of those factors, and considering that some observed factors (such as channel surface sealing, vegetation wetted perimeter, depth of water, and others) varied in the same reach in time and space, the losses should be understood as the seepage for the given reach under the given conditions during the time the measurements were performed. Consequently, further studies are required to understand canal seepage behavior in Cache Valley, and further information about the behavior of factors affecting canal seepage is required in order to extrapolate the measured seepage to others reaches in the canals.

CONCLUSIONS

Canal seepage in the canal systems that were studied manifests spatial and temporal variations. Monthly comparison of seepage losses within the reaches did indicate a higher seepage loss during the late July and August period. Spatial variation indicates that within canals most of the canals presented a descending trend of the mean seepage loss as the reaches go downstream. Between canals it was observed that reaches located in the east part of Logan City presented higher seepage losses than reaches in the canals on the west side. A superposition of the seepage and GIS maps showed a pattern between the estimated canal seepage and the surrounding type of soil, the saturated hydraulic conductivity, the presence of the shallow groundwater and the topography. However, further study and information is required in order to extrapolate the measured seepage to other canal sections. Also, reaches with the highest seepage losses were identified to be S1, S2 and S3 in the Hyde Park and Smithfield irrigation canals, S1 and S2 in the Logan Northern irrigation canal, S2 in the Crocket canal, and S1 in the Logan Northwest Field canal, where five of the seven reaches mentioned presented flowing water beside the canal, and one reach has been implicated with regard to flooding problems in a residential area. Also, seepage gaining and gaining-losing streams exist in these canals.

The current meter used in the project (FlowTracker® ADV®) was useful during the data collection since it facilitated: the determination of the approximate boundary between dead and flowing water, the verification of perpendicularity of tag line and flow, the verification of submerged laterals, and the measurement of low flow velocities. Additionally, a low SNR was detected at the end of the Benson canal, although the water had visible suspended particles. This reach had low flow velocity (0.09 m/s), and no evidence of hydraulic jumps for a distance of 2.5 km in the upstream direction.

RECOMMENDATIONS

- Reaches with significant losses should be evaluated in greater detail in order to determine precise locations of seepage. The ponding method can be used to determine a more precise location of the cracks (if any), and tracer studies can be use to verify if the water in the basements of residential areas and beside some canals come from the irrigation canals.
- Highly vegetated sections could not be measured with the proposed methodology. However it could be used after maintenance activities (weeding) have been performed.
- Further studies of the factors affecting seepage in the canals are required in order to improve the understanding of the seepage behavior found in the present study.

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PIVOT IRRIGATION: WIRELESS NETWORKING AND REMOTE SENSOR MONITORING

Dan Steele[1]

ABSTRACT

As the automation of both private and corporate farms is embraced, the use of sophisticated pivot irrigation systems and smart agriculture practices is readily being adopted. Many new telemetry technologies are available today. It is common to have 100 percent communication to all farm pivot locations and see data throughput from pivot sites of 19.2 kbps up to 115.2 kbps.

The latest telemetry trend is “wireless instrumentation” or the ability to control or monitor analog and digital signals without the constraints of wire. These signals may be used to communicate to and from the pivot to the farm to check moisture and temperature sensors, chemical soil samples, wind speed for the best time to water, the actual pivot location and pump power usage. This capability, together with Internet access, allows the entire pivot system to be viewed anytime via a smart telephone. The farm can remotely operate the pivot system, report and view status changes, and see the remote sensors’ status. Until recently, all these field devices had to be hard-wired or use expensive cellular or satellite hardware. Now they can be done wirelessly utilizing spread spectrum 900MHz or 2.4GHz radios that have input and output control functions built right in. Some licensed VHF or UHF radio systems also offer IO options.

This paper reviews the advantages of using non-fee-based wireless networking and remote monitoring to more affordably, effectively track and report on pivot irrigation farms. It offers examples with pros and cons between traditional and newer approaches.

INTRODUCTION AND BACKGROUND

Figure 1. AmWest, Inc. installing pivot control box.

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As the automation of both private and corporate farms is embraced, we see the use of sophisticated pivot irrigation systems and smart agriculture practices due to new technologies (see Figure 1). The human imagination continues to create new ways to use this technology and push those technology providers for more powerful tools. Ten to 15 years ago, even the most advanced automated pivot systems seldom used telemetry, and, if they did the data throughput was extremely slow and seldom provided coverage to all the pivot irrigation sites. Some of the wireless technology also was expensive. Therefore, the telemetry technology was difficult to use effectively because only some sites could be remotely monitored or where farms were paying by the data byte or monthly usage fees to the technology provider.

With many new telemetry technologies available today, it is common to have 100 percent communication to all farm pivot locations and see data throughput from pivot sites of 19.2 kbps up to 115.2 kbps. Additionally, high speed backbone telemetry is available with both serial and Ethernet connectivity with speeds close to a megabit per second range. With the use of IP wireless devices, MPEG4 IP Ethernet cameras can be added to the system for remote viewing of the pivot system and to check on the field crop or farm conditions. In addition, hybrid wireless systems can be utilized where needed to combine different wireless technologies over large geographic areas or remote locations. This can include both cellular, satellite and microwave products that can be deployed for remote areas, or if a higher speed backhaul of data is required.

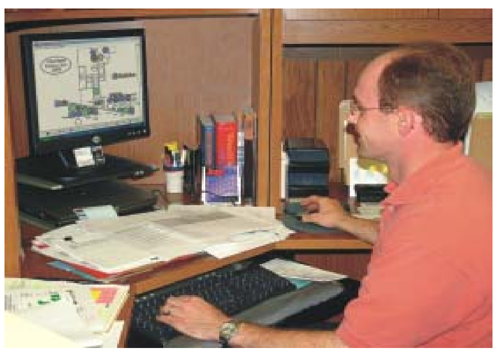

Figure 2. Automated pivot irrigation SCADA system software by Reinke Irrigation

New radio products keep shrinking in size - but are getting smarter and most have both serial and Ethernet data interface options. Hybrid systems that use a mix of technologies is common as well, and can help save costs by using one technology that has monthly costs or fees and piggy-backing on to that network with a license-free system that can collect all the data from the local pivot irrigation sites back to that location. The use of GPS tracking devices is quite common to help with the location of the trailing end sprinkler on the pivot line and this information can be displayed on a computer screen or a PDA phone.

<u>SCADA definition — Supervisory Control and Data Acquisition</u>

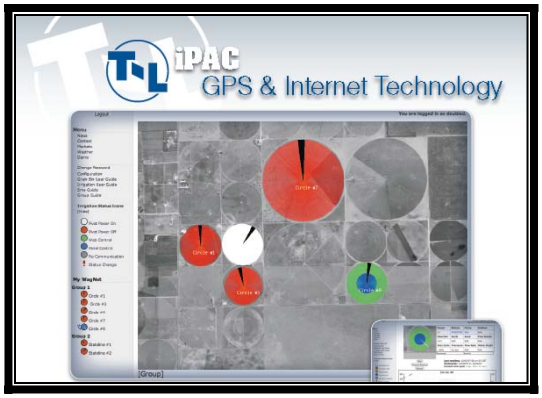

Figure 3. T-L Irrigation iPAC Control system

Figure 4. Lindsay Irrigation Field NET Software

The latest telemetry trend is “wireless instrumentation” or being able to control and/or monitor analog and digital signals without the constraints of wire. These signals may be used to communicate to and from the pivot to the farm to check moisture and temperature sensors, chemical soil samples, wind speed for the best time to water, the actual pivot location and pump power usage that can be viewed anytime. The capability with Web Internet access allows the entire pivot system to be viewed via a smart telephone or the user can look at a Website anywhere to have access to all the data and view the pivot irrigation system remotely. With this technology, the user of the farm can remotely operate the pivot system, report and view status changes, and see the remote sensors’ status. Until recently, all of these field devices that had to be hard-wired, or use expensive cellular or satellite communication hardware, now can be done wirelessly and without any cost to the user using unlicensed spectrum with “spread spectrum 900MHz radios.” These radio products also can have input and output control functions built right in or can integrate into a remote terminal unit (RTU) or some other type of control device. One way they can send this information from the sensors to the host is using standard Modbus protocol and assigning Modbus registers to the field input devices.

Several pivot irrigation companies offer some type of wireless communication service that might include cellular, satellite, unlicensed or licensed radios or a combination of two technologies, depending on the farm location. The use of these wireless devices allows farm managers to view the operating status of the irrigation system, how much water is being used, the power consumption, and weather and soil conditions. Web-based programs allow access to this information from anywhere in the world as long as users have Internet access and the information can be displayed on PDA type cellular phones.

Some of the management tools that have been in the market place for a while include OnTrac from Rienke Irrigation, iPAC from T-L Irrigation (see Figure 3), Remote Tracker from Valley Irrigation, Field Net from Lindsay Corporation (see Figure 4) and Control Master from Pierce Irrigation (see Figure 5), to name a few. Some use their own software packages or web interfaces and others use off-the-shelf SCADA software, like Wonderware, Citect or Intellusion that can be customized specifically for each user and is fairly inexpensive. The use of field sensors and weather monitors is another way to optimize and ensure that the correct amount of fertilizer, water and time of watering is applied.

The use of wireless has created an influx of technology that has impacted the speed, size and variety of devices that can be embedded into the controllers, sensors and remote devices that have very small power requirements and can run off small lithium batteries or small DC power sources. The new wireless products have become smarter and have the capability to work in several different field environments. Along with all the new wireless products, there are several new antenna options available today that can help with difficult antenna mounting locations, constrained space, and variety of gain and antenna patterns.

Wireless devices with IO (input and output) capability are common, and analog and discrete information can be sent back and forth from the radio to the host or SCADA software. The most common way of doing this is using Modbus protocol and assigning Modbus register values to the input and output required. (see Modbus definition) These devices include pressure, temperature, flow sensors or valves that can be remotely turned on or off. Pump status and GPS coordinates can be carried back to the host computer and displayed with the SCADA software.

Figure 5. Pierce Irrigation Control Master software and controller

History of the Modbus protocol

Some communication standards just emerge. Not because they are pushed by a large group of vendors or a special standards organization. These standards—like the *Modbus interface*—emerge because they are good, simple to implement and, therefore, are adapted by many manufacturers. Because of this, *Modbus* became the first widely accepted fieldbus standard.

Modbus established its roots in the late 1970's. In fact, it was 1979 when PLC manufacturer Modicon—now a brand of Schneider Electric's Telemecanique—published the Modbus communication interface for a multidrop network based on a master/client architecture. Communication between the Modbus nodes was achieved with messages. It was an open standard that described the messaging structure. The original Modbus interface ran on RS-232, but later Modbus implementations used RS-485 because it allowed longer distances, higher speeds and the possibility of a true multi-drop network. In a short time, hundreds of vendors implemented the Modbus messaging system in their devices and Modbus became the de facto standard for industrial communication networks.

The great thing about the Modbus standard is its flexibility, but, at the same time, it also is the ease of implementation and use of it. There are intelligent devices, like microcontrollers, PLCs, etc. that is able to communicate via Modbus, but many types of sensors that have standard analog or discrete outputs can send their data to host systems. While Modbus previously was used on wired serial communication lines, there also are extensions to the standard for wireless communications and TCP/IP networks.

Modbus Message Structure: The Modbus communication interface is built around messages. The format of these Modbus messages is independent of the type of physical interface used. The same messages used on *Modbus/TCP* are the same as on plain old **RS232** over Ethernet. . This gives the Modbus interface definition a very long lifetime. The same protocol can be used regardless of the connection type. Because of this, Modbus allows users to easily upgrade the hardware structure of an industrial network without the need for large changes in the software. A device also can communicate with several Modbus nodes at once, even if they are connected with different interface types, without the need to use a different protocol for every connection.

Figure 6. AmWest, Inc. installing the Pivot Controller with 900MHz Radio

CENTER PIVOT INNOVATORS

Even before the first patent on center pivot technology ran out, Valley Manufacturing (later named Valmont Industries) had competitors. Lawsuits often followed, but the competition pushed innovation forward. Valmont is headquartered in Valley, Neb..

The Raincat. By 1959, an Australian company had modified the basic Valley approach and produced a center pivot system called the Grasslands. It featured many innovations that would become the standards for the industry in the future. The machine had electric motors to drive it (rather than water drives) and a truss system under each pipe span to bow and support the pipe (rather than overhead cables). A California pump manufacturer, Layne and Bowler, brought the system to America, put rubber tires on it and renamed it the Raincat. But California farmers didn't need center pivots as badly as farmers on the Plains. So, the company went through several ownership changes, eventually landing in Greeley, Colo. Raincat went out of business in the early 1980s.

Reinke. Richard Reinke was a Nebraska farmer's son who taught himself to be an engineer and draftsman. In 1954, he started Reinke Manufacturing in Deshler, Neb., and introduced his first center pivot system in 1966. To avoid infringing on Valley's patents, Reinke had to come up with new ideas, and he did. He was the first to make his electric drive systems reversible, so that a farmer could back the system up. He was the first to put his electric motors in the middle of each tower base and connect drive shafts to the gearboxes on each wheel. He was the first to patent the "bow-string" truss system under the pipe spans that most pivots use now. He was the first to use a electrical "collector ring" to transfer power from the pivot point down the spans so that a wire wouldn't wrap up as the pivot went around and have to be unwrapped after each revolution. In all, he patented more than 30 innovations for center pivot designs. Richard Reinke died in 2003 at the age of 80, but his company is still operating in Deshler. They've diversified into building trailers and chassis equipment for over-the-road trucks.

Lindsay. Lindsay Manufacturing is based in the small Nebraska town of the same name where Paul Zimmerer and his two sons set up shop in 1958. First, they made tow-line irrigation systems. Ten years later, they came out with their first center pivot system under the name "Zimmatic." Because the terrain around Lindsay was hilly, they introduced a "uni-knuckle" joint at each tower instead of the ball-joint that other builders used. This allowed the Zimmatic to move over very rough hills and valleys. They also used an external collector ring – instead of Reinke's internal ring – to transfer electrical power down the system. The company grew fast, and in 1974 the Zimmerers sold out to DeKalb AgResearch. But the family continued to operate the firm. Finally, in 1988 the company again went independent through an over-the-counter stock offering.

T-L Irrigation. Leroy Thom was a Hastings, Neb., area farmer who had tried his hand at everything from custom combining to irrigation engineering. In 1969, he and his two sons, Dave and Jim, decided they could improve on the other center pivot designs by using hydraulic motors on each tower. Hydraulics would enable their systems to move around the field at a constant rate rather than starting and stopping at set intervals. The company claims that their systems are more reliable, can be fixed by farmers who are used to hydraulic systems and apply water more evenly. Today, T-L Irrigation employs more than 250 people in Hastings.

Lockwood Corporation actually started in 1935 in Gering, Neb., to produce potato-farming equipment. In 1969, it decided to get into the irrigation business and bought a small Texas firm that was making the "Hydro-Cycle" pivot system. It moved the operation to Gering and completely redesigned the system. It became one of the five largest manufacturers of center pivot systems. In the late 1990s, the company went through ownership changes and is now known as Universal Irrigation Company, although the systems are still marketed under the Lockwood brand name.

AmWest, Inc. is located in Ft. Lupton, Co. For more than 25 years, AmWest has delivered full-service water equipment strategies, technology, installation, maintenance and expertise to its customers primarily through out the Rocky Mountain region, but also on a global scale (see Figures 7 and 8). Its reputation for excellence is unparalleled in the industry as its customers rely on the company's superior equipment and round-the-clock service. AmWest's skilled technicians bring clients more than150 years of experience designing, constructing and servicing water systems principally for municipal and large commercial projects.

Other Innovators. Over the years, there have been more than 80 individuals or companies who have tried to make and sell center pivot systems. Some of the smaller companies were bought by the giants. For instance, when Valmont realized that farmers saw an advantage in the undertruss system to support the spans, they bought out a small company in Grant, Neb., that was building an undertruss system.

Other small companies started up, fought for market share for a while and migrated to other businesses.

Kroy. In York, Neb., a car dealer named Paul Geis had a small business making irrigation pipe and began making center pivot systems in 1968. He marketed the systems under the name of "Kroy" – York spelled backward. But his compressed air drive system didn't really catch on. Geis sold the center pivot business to a well driller in Sidney, Neb., who quit the business in the late 1970s. Geis continued to manufacture aluminum and PVC pipes and fittings for industry, construction and other irrigation methods.

Oasis. Just down the road from York in Henderson, well driller Gus Thieszen took his own chance in the center pivot business in the late 1960s. Thieszen brought out his "Oasis" model center pivot then, but the system never really caught on. He stopped manufacturing the system after only a few years. He was one of scores of Ag innovators who tested the market and had to fold up their enterprise.

Pivots Go Worldwide. Today, only six center pivot manufacturing companies remain, and the four largest — Valmont, Lindsay, Reinke, and T-L — are in Nebraska. Wade Rain and Pierce Irrigation are in Oregon. On this "Then & Now" page, today's center pivot market is outlined in www.livinghistoryfarm.org.

Also, Robert Daugherty remembers how the worldwide market for Valmont pivots just seemed to develop as news of the innovation spread around the agricultural community. The other manufacturers saw similar interest, but worldwide market challenged some of the smaller manufacturers.

Ref: http://www.livinghistoryfarm.org/farminginthe50s/water_05.html

Figure 7 and Figure 8. AmWest, Inc. installing a control box with a 900 MHz Spread Spectrum Radio

CONCLUSIONS

The use of wireless products will continue to grow. With commercial farms trying to conserve water resources, manage power use, have access to the health of the pivot system and handle the crops that grow at anytime and anywhere - they will need more wireless technology. The bandwidth requirements will increase too, and other IP devices will be added and be more common place. New embedded products will help save costs and be part of the system instead of being an after thought. The use of different radio frequencies, field sensors, faster connection speeds and other wireless products will continue - software and other services will help the farm and farmer have all the information they need at their fingertips (see Figure 9 and Figure 10).

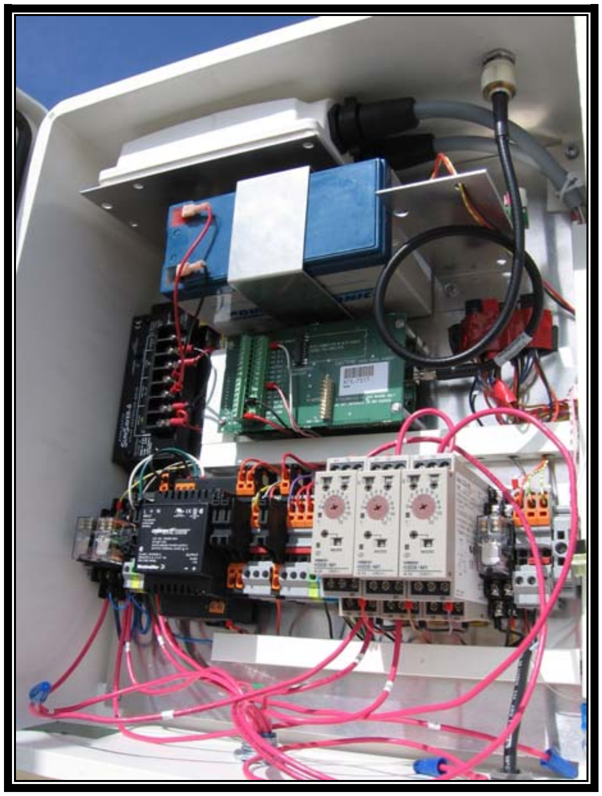

Figure 9. Master RTU/ Controller and 900MHz Radio that communicates to each pivot control box at the Farm.

Figure 10. New variable frequency drive for the pivot irrigation water pump that will save energy costs and help prolong the pump life.

ACKNOWLEDGEMENTS

I appreciated the opportunity I had to visit with all of the pivot manufacturers and for all the engineering, skills and hard work that it takes to manufacture pivot irrigation systems installed all over the world. We have many arid places on earth that irrigation is the only way farmers can grow crops and produce. I also want to express gratitude to AmWest Controls for the resources, pivot irrigation experience and actual field photos. Finally, for Wessel's Living Farm in York, Neb. I applaud their efforts, resources, farm information and the work they do for the preservation of rural farm life in America.

SOLAR-POWERED AUTOMATION ON IRRIGATION DELIVERY SYSTEMS

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ABSTRACT

For the last 20 years, the Bureau of Reclamation (Provo Area Office) has been working with irrigators throughout the Intermountain West to develop, install, and test solar-powered DIY (do-it-yourself) gate actuators and other water monitoring and control devices. To date, over 100 control devices have been installed in Utah, Wyoming, Idaho, Oregon, Colorado, and New Mexico. Demonstration units have also been sent to Kansas, Mexico, and China. Reclamation has also worked with several manufacturers and vendors in the development of 24-VDC commercial gate actuators. Additionally, manufacturers have started marketing a wide variety of complete automated solar-powered gate units.

VISION

In Utah and the surrounding areas, systems of weather, hydrologic, and other environmental sensors are being distributed basin-wide (Hansen et al, 2002). This trend will continue to expand as motes and nanotechnologies continue to evolve, and communication options become more sophisticated. Real-time data from ever-increasingly sophisticated environmental sensors combined with information from other sources (e.g. human, webcam, remote sensing) can then be linked by wireless and Internet communications to data collections and analyses centers outfitted with data-fusion, decision-support tools (including ever more realistic simulations).

From this developing "central nervous center," signals are sent back to water control structures. Future self-regulating river basins are created, which will be critical for 24/7 operations and for adapting to uncertain hydrologic variation created by global climate change. Tightly regulated rivers are susceptible to precise operations. For example, with automation it is possible to return diurnal fluctuation to stretches of a river. Real-time operating systems will also be the foundation for sustainable future development.

Comprehensive real-time monitoring and control facilities have been installed in several Intermountain river basins including the Sevier, San Rafael, Duchesne, Spanish Fork, and Bear (see Figure 1). A system on the upper Green River is currently in its nascent stage. The Sanpitch and Price Rivers currently have partial systems. All real-time information is currently being reported on the following river basin websites: www.sevierriver.org,

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www.ewcd.org, www.duchesneriver.org, www.spanishforkriver.org, and www.bearriverbasin.org.

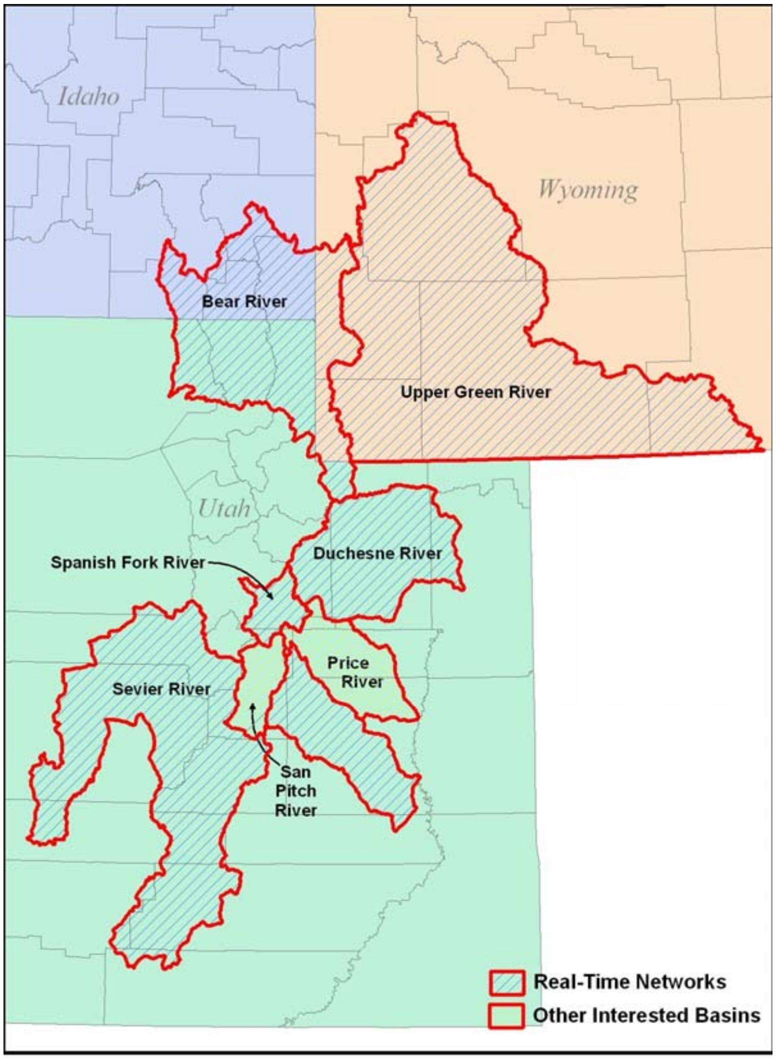


Figure 1. River Basin Real-Time Monitoring and Control Systems

BACKGROUND

Key ingredients in the river-basin mélange are control devices and structures, many of which are in very remote areas requiring alternative power sources (Pugh and Hansen, 1996). Over the last 20 years, Reclamation staff has experimented, tested, and installed a variety of solar-powered gate actuators. The examples below are not exhaustive, but do represent a cross-section of the technologies that are available and that the Provo Area Office has installed and evaluated.

Many modernization programs for the operation of canals and river basins involve the mechanization of water control gates. Gate actuators provide a method of raising and lowering canal gates using DC-powered electric motors instead of human power. A common response to studies recommending automation has been that the cost of purchasing and the problems and complexity of maintaining commercially available actuators are high, thereby jeopardizing implementation plans. However, recent advances with solar-powered gate actuators have made automation feasible for the majority of applications (Hansen and Pugh, 1997).

Reclamation has tried several permutations of solar-powered gate actuators (Hansen et al, 2001) including: (1) mechanical DIY units on slide gates; (2) hydraulic DIY units on slide gates; (3) commercial units on slide gates; (4) mechanical DIY units on radial gates; (5) commercial units on radial gates; (6) commercial drawbridge gates; (7) commercial pillow gates; and (8) commercial scissor gates. Solar energy has also been used to power real-time environmental monitoring systems. Other types of alternative power have also been tried including a micro-hydro unit on Joe's Valley Dam, a Federal facility in central Utah. This unit provides all the electricity needs for lights, monitoring and control equipment, webcams, and security systems. The Joe's Valley micro-hydro unit replaced an existing diesel generator.

DO-IT-YOURSELF ACTUATORS

Mechanical

The most popular automation model for a frame-model slide gate (undershot) is the DIY mechanical actuator which consists of a 1/16th horsepower gear motor, a bicycle-type lift apparatus (chain and sprocket), and a cover over the gate stem which contains a gate position sensor and limit switches. Utah State University staff demonstrated the feasibility of these in the 1980s and Reclamation staff made refinements in subsequent years.

A gate system is typically powered by 1 or 2 deep-cycle batteries which are charged by a 20-, 30-, or 40-watt solar panel. The latter also powers the remote terminal unit or RTU (which includes a communication system). The preexistent slide gate requires only minor modification for the installation of a large gear which is attached to the 12-VDC gear motor with an industrial chain. The gate actuator takes a day or two to install (see Photographs 1, 2 and 3). In the event of subsequent problems, troubleshooting and repairs are trivial and the parts are inexpensive. The total cost of parts for one gate is approximately $3,000.

Photograph 1. Huntington Canal Diversion Structure Prior to Gate Actuator Installation near Huntington, UT

Photograph 2. Gate Actuators Being Installed on Huntington Canal Diversion Structure

Photograph 3. Gate Actuator Installed on Scipio Canal near Scipio, UT

This DIY actuator can also be installed on a pedestal gate, but a frame needs to be constructed over the pedestal, and the larger sprocket is mounted to the top of the wheel (see Photograph 4). A similar system can also be used on radial gates. A permutation of the DIY gate was also developed to keep the gate stem open. This latter feature is valuable when using a webcam to monitor conditions at and around the structure (including gate position). Discussing this latter option, “ITRC (International Training and Research Center, 2000) feels the device (the one that leaves the gate stem open) is too complex for most (irrigation) districts to construct and any cost savings would be offset by the time required for construction.”

Photograph 4. Gate Actuator Being Installed on a Pedestal Gate on Scipio Dam Outlet Works near Scipio, UT

Hydraulic

To automate a hydraulic gate, two things are needed: (1) gate position and (2) gate control. The preferable gate position reading is taken by direct connection to the physical gate or gate stem. This reduces the chances of false readings due to gear slippage, slop, or mechanical failure. The gate position can be taken using a retractable cable sensor connected to the gate itself or the hydraulic ram if the gate is not accessible.

Hydraulic gate control can be added to several types of existing systems. For a gate controlled by a hand-operated hydraulic pump, the automation system must be added leaving the existing system functional. To automate a hand-control gate, an electric hydraulic pump (preferably 12 or 24 VDC), and electronic solenoid valves must be added. The solenoid valves and the motor must be placed in parallel with the hand valves and hand pump.

Hydraulic gate control can also be installed on an existing motorized hydraulic system. An electric switch must be added so either an automated or a manual mode can be selected but not run simultaneously. If the valves are manual, solenoid valves must also be added. If the pump on/off switch can not be controlled automatically, a relay must be added.

For a new system with an existing gate, hydraulic rams, an electric hydraulic pump, solenoid valves, and pump control relays must be added. For a simpler version, using a pressure switch and an accumulator tank (a tank which acts as a pressure reservoir) to maintain hydraulic pressure can replace the pump control solenoid.

COMMERCIAL PRODUCTS

Commercial Gate Actuators

A variety of commercial gate actuators and systems that can be solar powered are also available. When Reclamation initially started 20 years ago, none of the major actuator manufacturers had 12- or 24-VDC models. On one test site, an inverter was installed to power a 110-VDC gate actuator system. This test, while successful, was not a very efficient or elegant solution. Eventually a local vendor was willing to install a 24-VDC motor on a commercially available actuator. This proved to be a very acceptable solution. Eventually other manufacturers developed similar products. These systems work fine, but are frequently over-engineered for many irrigation applications. For example, maintenance is considerably more complicated than with the DIY model. According to the previously mentioned ITRC report: “Commercial actuators generally have additional electronic features built into them for control or safety purposes, and all of the components are placed into a tight bundle. ITRC has found that irrigation district personnel (especially in small irrigation districts) are unable to troubleshoot or repair the commercial actuators. Therefore, if one small component has a problem, the complete unit will often be abandoned. Irrigation district personnel appear to be willing to forego some of the extra capabilities in order to gain simplicity and ease of service and component replacement." Reclamation has had similar experiences.

Commercial Gates

There are several overshot gate models that include the gate and other parts of the structure in the total package. Three examples or these are the: (1) draw-bridge gate; (2) scissor gate; and (3) pneumatic crest gate. All can be powered by solar energy systems.

Drawbridge Gate: This overshot gate consists of a gate leaf, hinge, and hoist mechanism. This gate is likened to a drawbridge hinged across the bottom of a vertical-walled channel. When the gate is horizontal (fully open), water flows through the channel uninterrupted. As the cable hoist raises the downstream end of the gate, water flows over the lip while the channel sides restrict the water. The hoist can be operated by a 12- or 24-VDC motor.

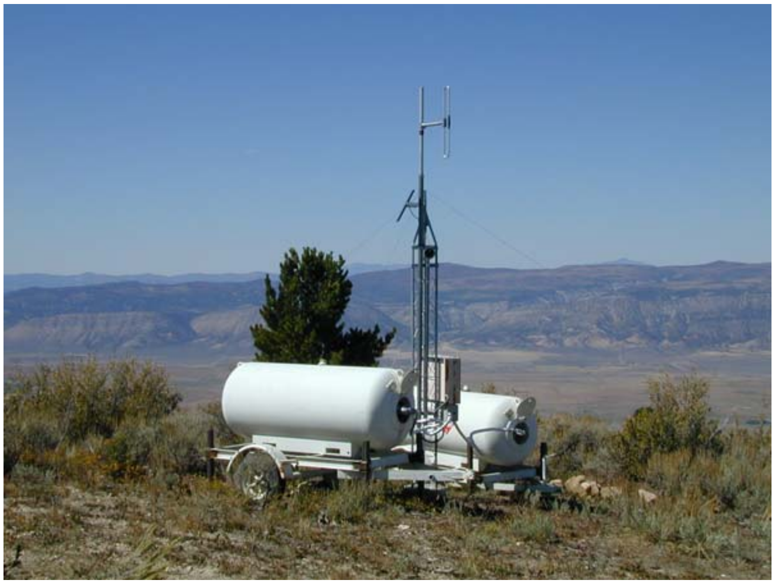
Scissor Gate: One version of the scissor gate, invented by Peter Langemann and manufactured by AquaSystems 2000 Inc. (a Canadian firm), is an arrangement of hinged leaves that function as an adjustable weir to provide either flow control or upstream level control. Each gate is fully self-contained and incorporates a 12-VDC motor and gear reducer, limit switches, and electrical control panel.

Pneumatic Crest (Pillow) Gate: Working with Obermeyer, Inc. (Ft. Collins, Colorado, USA), an overshot gate for use in check and similar structures has been tested. The Obermeyer gate is hinged across the bottom and is moved up and down by an air bladder. A small 12-VDC air compressor is used to inflate the bladder. During 1994, an Obermeyer gate was retrofitted into a check structure of a canal in north-central Utah.

OTHER SOLAR-POWERED ACTIVITIES

A variety of other water and water-related facilities have been solar powered, including: (1) real-time flow measurement and soil-moisture monitoring (see Photograph 5) units; (2) webcams for security and monitoring real-time water and weather conditions; (3) mountain-based cloud-seeding units (and potentially other geoengineering activities) (see Photograph 6); and (4) outdoor kiosks that dispense real-time and other information. It is anticipated that in the near future, solar-powered monitoring and control systems will be densely packed throughout river basins.

Photograph 5. Installing Soil-Moisture Monitoring Units near Delta, UT



Photograph 6. Solar Powered, High-Mountain Cloud-seeding Units in Sanpete County, UT

CONCLUSIONS

Solar power makes the installation of SCADA (real-time monitoring and control) systems on even small reservoirs and canals financially feasible. There are a variety of funding mechanisms that encourage water resource automation. For many irrigation systems, solar-powered automation systems are the "best bang they can get for their water – efficiency bucks."

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IMPROVING IRRIGATION SYSTEM PERFORMANCE IN THE MIDDLE RIO GRANDE THROUGH SCHEDULED WATER DELIVERY

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ABSTRACT

Scheduled water delivery (SWD) provides the opportunity to increase overall irrigation system performance and define legitimate water use in regions without adjudication. A well-managed program of scheduled water delivery is able to fulfill seasonal crop water requirements in a timely manner, but requires less water than on-demand water delivery. In order to successfully realize SWD in an irrigation district, several components need to be addressed and developed simultaneously.

This paper will present results of on-going research in the Middle Rio Grande Conservancy District (MRGCD) related to implementation of scheduled water delivery supported by a decision-support system (DSS) and modernization of irrigation infrastructure. A DSS developed over the last four years uses linear programming to find an optimum water delivery schedule for all canal service areas in the MRGCD irrigation system. The DSS has been developed for the entire MRGCD and a significant validation effort of input parameters and model logic has been completed.

The second component for implementing scheduled water delivery is a program of irrigation infrastructure modernization with Supervisory Control and Data Acquisition (SCADA) system. Over the past six years, the MRGCD has modernized canal infrastructure and developed a SCADA system with the focus being to improve water use efficiency.

The third component in implementing scheduled water delivery is its acceptance by all water users as a matter of district policy and practice. To gain acceptance and disseminate information regarding SWD, a public outreach program was formulated that includes providing water users information through newsletters, websites, and public meetings. It also included training related MRGCD staff in the concepts and practice of scheduled water delivery and the use of related decision-support systems.

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INTRODUCTION

Irrigated agriculture in the Western United States has traditionally been the backbone of the rural economy. The climate in the American West with low annual rainfall of 8-14 inches is not conducive to dry land farming. Topography in the West is characterized by the Rocky Mountains which accumulate significant snowfall, and the peaks of the snowmelt hydrograph are stored in reservoirs allowing for irrigation throughout the summer crop growing season. Of the total available surface water, irrigated agriculture uses roughly 80 to 90% (Oad et al. 2009; Oad and Kullman, 2006). The combined demands of agriculture, urban, and industrial sectors in the past have left little water for fish and wildlife. Since irrigated agriculture uses roughly 80 to 90% of surface water in the West, it is often targeted for decrease diversions. Due to fish and wildlife concerns and demands from a growing urban population, the pressure for flow reductions on irrigated agriculture increases every year. In order to sustain itself and deal with external pressure for reduced river diversions irrigated agriculture has to become more efficient in its water consumption. This paper focuses on research regarding improving water delivery operations, specifically scheduled water delivery, in the Middle Rio Grande irrigation system through the use of a decision support system and SCADA technology.

Middle Rio Grande Valley

The Middle Rio Grande (MRG) Valley runs north to south through central New Mexico from Cochiti Reservoir to the headwaters of Elephant Butte Reservoir, a distance of approximately 175 miles. The valley is narrow, with the majority of water use occurring within five miles on either side of the river. The bosque, or riverside forest of cottonwood and salt cedar, is supported by waters of the Rio Grande and is surrounded by widespread irrigated farming. The Cities of Albuquerque, Rio Rancho, Belen and several smaller communities are located in and adjacent to the MRG Valley. Although the valley receives less than 10 inches of rainfall annually, it supports a rich and diverse ecosystem of fish and wildlife and is a common outdoor resource for communities in the region. Water supply available for use in the MRG Valley includes: native flow of the Rio Grande and its tributaries, allocated according to the Rio Grande Compact of 1938; San Juan-Chama (SJC) project water, obtained via a trans-mountain diversion from the Colorado River system; and groundwater. Water is fully appropriated in the MRG Valley and its utilization is limited by the Rio Grande Compact, which sets forth a schedule of deliveries of native Rio Grande water from Colorado to New Mexico and from New Mexico to Texas (Rio Grande Compact Commission, 1997), and between the United States and the Republic of Mexico. Water demand in the MRG Valley includes irrigated agriculture in the Middle Rio Grande Conservancy District (MRGCD), Pueblo prior and paramount and other currently un-adjudicated rights, and municipal and industrial consumption. In addition to these demands, there are significant consumptive uses associated with the riparian vegetation, and reservoir evaporation. There are also river flow targets associated with two federally-listed endangered species, the Rio Grande silvery minnow (*Hybognathus amarus*), and the southwestern willow fly catcher (*Empidonax traillii extimus)* (USFWS, 2003**).**

Middle Rio Grande Conservancy District

The MRGCD was formed in 1925 in response to flooding and the deterioration of irrigation works (Shah, 2001). Water diverted by the MRGCD originates as native flow of the Rio Grande and its tributaries, including the Rio Chama. The MRGCD is able to store water in several upstream reservoirs including El Vado and Heron reservoirs. The MRGCD services irrigators from Cochiti Reservoir to the northern boundary of the Bosque del Apache National Wildlife Refuge. Irrigation facilities managed by the MRGCD divert water from the river to service agricultural lands, which include small urban parcels and large tracts that produce alfalfa, pasture, corn, and vegetable crops such as green chile, the later of which is famous throughout the Southwest. The MRGCD supplies water to its four divisions -- Cochiti, Albuquerque, Belen and Socorro -- through Cochiti Dam and Angostura, Isleta and San Acacia diversion weirs, respectively. Water is conveyed in the MRGCD by gravity flow through primarily earthen ditches. On-farm water management is entirely the responsibility of water users and application is typically surface (flood) irrigation, either basin or furrow. The MRGCD does not meter individual farm turnouts, and ditch-riders estimate water delivery on the basis of time required for irrigation. Therefore, the quantity of water applied to fields is not measured. The total irrigated land within the MRGCD is approximately 60,000 acres. Figure 1 displays the location of the MRGCD.

During the recent drought years, low flows combined with flow requirements for the endangered Rio Grande silvery minnow have drastically reduced available water supplies. In order to deal with reduced water availability, the MRGCD has taken a proactive approach to be a more efficient water user and service its irrigators with reduced river diversions. Towards this end, the division managers and ditch-riders are increasingly practicing scheduled water delivery, which is an effective way to fulfill demand with reduced available water.

Scheduled Water Delivery (SWD) is used in irrigation systems worldwide to improve water delivery and to support water conservation. In SWD, lateral canals receive water from the main canal by turns, allowing water use in some laterals while others are closed. In addition to this water scheduling among laterals, there can be scheduling within laterals whereby water use is distributed in turns among farm turnouts along a lateral. By distributing water among users in a systematic scheduled fashion, an irrigation district can decrease water diversions and still meet crop water use requirements.

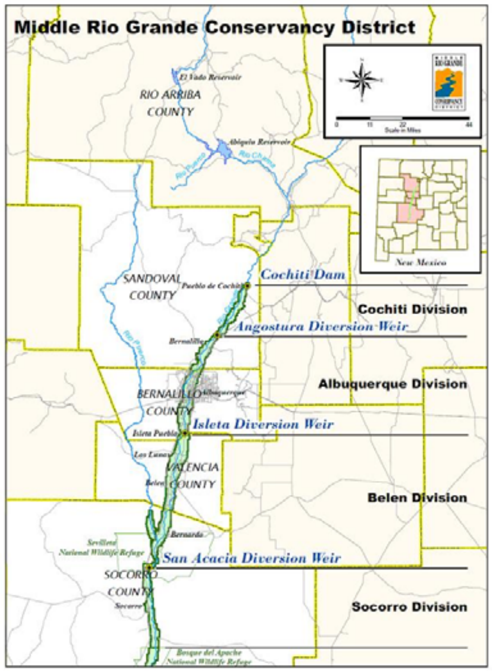

Figure 1. Middle Rio Grande Conservancy District (MRGCD)

<u>Decision Support Modelling of Irrigation Systems</u>

The New Mexico Interstate Stream Commission (NMISC) and the MRGCD have sponsored a research project with Colorado State University to develop a decision support system (DSS) to model and assist implementation of scheduled water delivery in the MRGCD's service area. A DSS is a logical arrangement of information including engineering models, field data, Geographic Information System (GIS) and graphical user interfaces, and is used by managers to make informed decisions. In irrigation systems, a DSS can organize information about water demand in the service area and then schedule available water supplies to efficiently fulfill the demand. Figure 2 displays a conceptual view of how a DSS can be used to develop scheduled water delivery.

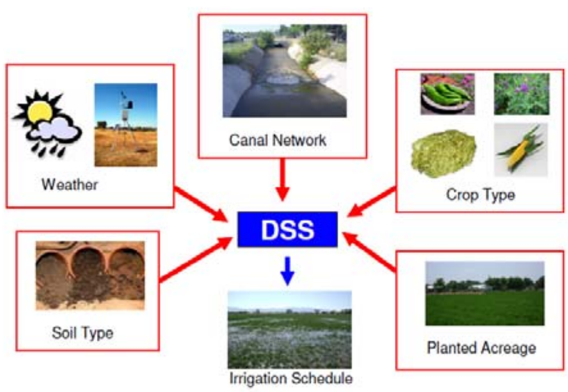

Figure 2. Conceptual View of a Generic SWD DSS

The conceptual problem addressed by a DSS for an irrigation system is how best to route water supply in a main canal to its laterals so that the required river water diversion is minimized. The desirable solution to this problem should be “demand-driven”, in the sense that it should be based on a realistic estimation of water demand. The water demand in a lateral canal service area, or for an irrigated parcel, can be predicted throughout the season through analysis of information on the irrigated area, crop type and soil characteristics. The important demand concepts are: 1) When is water supply needed to meet crop demand (Irrigation Timing), 2) How long is the water supply needed during an irrigation event (Irrigation Duration), and 3) How often must irrigation events occur for a given service area (Frequency of Irrigation).

Decision support systems have found implementation throughout the American West and are mostly used to regulate river flow. Decision support systems on the river level are linked to gauging stations and are used to administer water rights at diversions points. Although decision support systems have proved their worth in river management, few have been implemented for modeling irrigation canals and laterals (NMISC, 2006).

DECISION SUPPORT SYSTEM FOR THE MIDDLE RIO GRANDE

The first component in achieving scheduled water delivery in the MRGCD is the DSS. The DSS was formulated using linear programming with the use of an objective function. A detailed description of model programming can be found in (Oad et al. 2009). Overall model structure consists of three modules that function in concert to calculate the most efficient irrigation water delivery.

Model Structure

The DSS consists of three model elements or modules: a water demand module, a supply network module, and a scheduling module. A Graphical User Interface (GUI) provides a means for linking the three elements of the DSS. This GUI is an interactive means for the user to access data and output for the system. The project GIS and databases are used to develop input for both the water demand and the supply network modules. Some of the input is directly linked through the GUI and some is handled externally in the DSS. Figure 3 displays the structure of the MRGCD DSS.

Water Demand Module. The water demand module of the MRGCD DSS is implemented either through the ET TOOLBOX for the Middle Rio Grande or the Integrated Decision Support Consumptive Use, or IDSCU model, a model developed over a period of years at the Colorado State University. The ET Toolbox is a web application developed by the Bureau of Reclamation that estimates real-time evapotranspiration from distributed climate stations, NexRAD precipitation data, and remotely sensed cropping patterns. Crop consumptive use is calculated using the Penman-Montieth method. The reference ET (ET_o) is calculated using weather data from the MRGCD. Crop coefficients using growing degree days are applied to the Penman-based ET_o to obtain a consumptive use for each crop type throughout the growing season. The water demand module performs these calculations to obtain a spatially-averaged consumptive use at the lateral service area level, using the distribution of crop types within each service area.

The crop irrigation requirement (CIR) is calculated by accounting for the effective precipitation using the Soil Conservation Service Method. The crop irrigation requirement is calculated on a daily basis, corresponding to the water needed to directly satisfy crop needs for all acres in the service area. The crop irrigation requirement for the service area is subsequently passed to the supply network module, where it is divided by an efficiency factor to obtain a lateral service area delivery requirement (LDR).

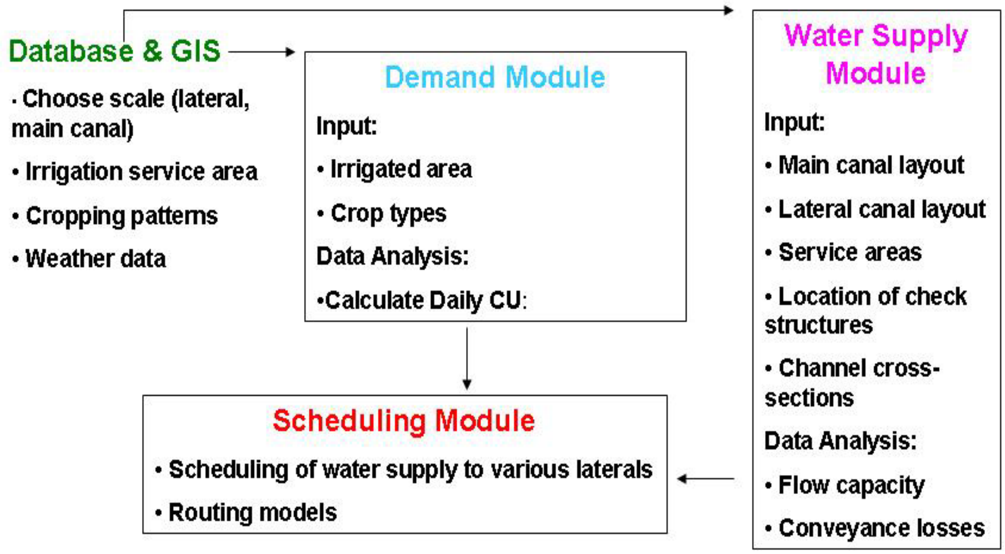

Figure 3. DSS Structure Displaying the Three Modules and Database

Based on acreages, crop types and soil types within each lateral service area, a Readily Available Moisture (RAM) is calculated. The RAM calculated in this context represents a storage capacity to be filled and depleted over several irrigation cycles during the course of the irrigation season. During each irrigation, it is expected that an amount of water equal to the RAM will be stored in soils, which is then depleted, due to crop water use.

Supply Network Module. The supply network module represents the layout of the conveyance system, its physical properties, supply to the conveyance network, and the relative location of diversions from the network to the lateral service area. The layout of the conveyance system is specified through a user-designed link-node network. Through the DSS GUI, a user can drag and drop different types of nodes such as inflows, demands and return flow nodes. The link-node network represents the connections between canals or laterals and demands for water at each service area. Figure 4 displays the supply network.

Irrigation Scheduling Module. The irrigation scheduling module can be used to plan water deliveries to meet crop demand at the lateral and at the main canal level. The module calculates and displays a schedule for the laterals on a given main canal. This schedule indicates how many laterals can be run at a time, how long each lateral should run and how often. The module is currently set up to run on a daily time step. This module calculates the daily irrigation schedule using mass balance equations and a linear programming solver. The approach is based on the consideration that the farm soil root-zone is a reservoir for water storage, for which irrigation applications are inflows and CIR is an outflow. Figure 5 displays a calendar developed by the irrigation scheduling module.

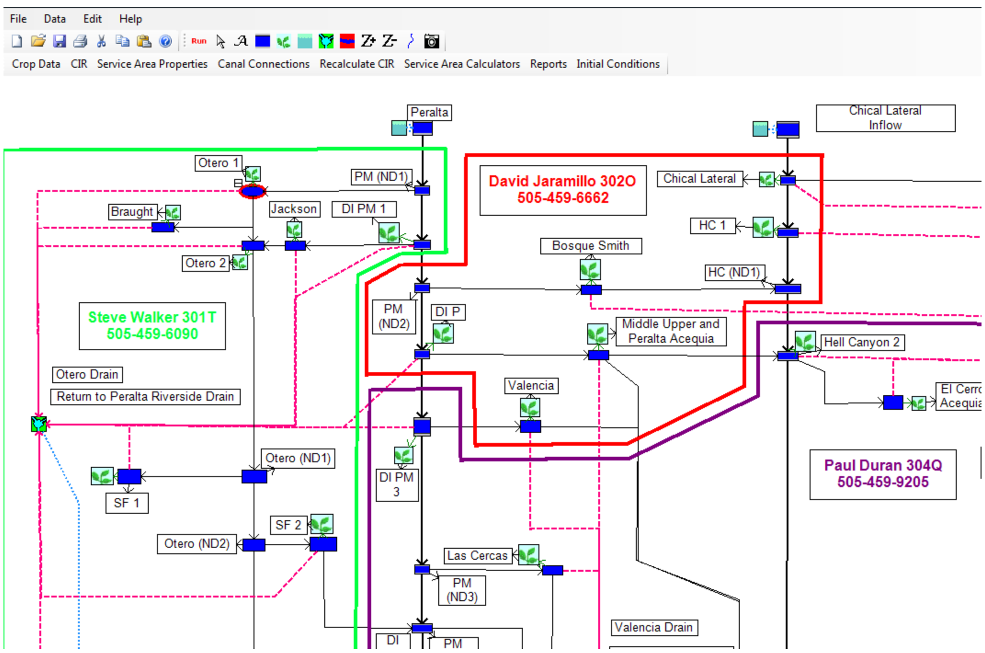

Figure 4. Representation of DSS Supply Network

May

Sun	Mon	Tues	Wed	Thur	Fri	Sat
					1 35 cfs	2 35 cfs
3 35 cfs	4 35 cfs	5 35 cfs	6 35 cfs	7 35 cfs	8 35 cfs	9 35 cfs
10 35 cfs	11 35 cfs	12 35 cfs	13 20 cfs	14 20 cfs	15 10 cfs	16 10 cfs
17 10 cfs	18 10 cfs	19 10 cfs	20 10 cfs	21	22	23
24	25	26 35 cfs	27 35 cfs	28 35 cfs	29 35 cfs	30 35 cfs
31 35 cfs						

Figure 5. Irrigation Calendar Developed Using the Scheduling Module

The DSS has undergone extensive calibration and validation and has proved to be reliable and able to create irrigation schedules based on crop demand (Oad et al. 2009).

SUPERVISORY CONTROL AND DATA ACQUISITION (SCADA) SYSTEM

Along with the development of the DSS to aid in scheduled water delivery the MGRCD has been proactive in updating aging infrastructure as well as incorporating advanced technology such as SCADA (Supervisory Control and Data Acquisition) for more precise and controlled water delivery. This updated technology will allow for the control that is necessary for implementing the irrigation schedules recommended by the DSS and represents the second component necessary for achieving scheduled water delivery.

Over the past few years, the MRGCD has developed a SCADA system with the focus being to improve water use efficiency throughout the Middle Rio Grande Valley (Gensler et al. 2009). The MRGCD program of measurement and automation was built entirely in-house using inexpensive components due to budget constraints. Using traditional SCADA components as well as adaptations of technology from other industries makes the MRGCD SCADA setup unique. The developed SCADA system consists of five main components:

- Water Measurement Structures
- Automated Control Structures
- Instrumentation
- Telemetry
- Control Software

<u>Water Measurement Structures</u>

Water measurement is the single most important component of the MRGCD's SCADA experience, since all operational decisions require sound knowledge of available water supplies and the demand throughout the system. When the MRGCD was initially constructed, considerable thought to water measurement was given. Over the years, gauging stations equipped with measurement instrumentation gradually deteriorated and quality of flow records declined.

In 1996, the MRGCD was operating only 15 gauges on 1,200 miles of canals. The following year, the MRGCD officially embarked upon its modernization program. The construction of new flow gauges was the first step in this program. New gauges were constructed at key points in the canal system, notably at diversion structures and at return flow points. Efforts were also made to improve the quality of measurements. Open channel gauging sites with no control structures gave way to site specific measuring structures. A variety of flow measurement structures were built in the MRGCD and include sharp crested weirs, broad crested weirs, adjustable weirs and Parshall flumes. Current MRGCD design standards specify that new gauges are constructed with broad-crested weirs using WINFLUME for design and calibration. Currently, MRGCD is operating 75 gauges.

Automated Control Structures

With the advent of better data collection, it became apparent to the MRGCD that automated control was necessary. Data from gauges revealed that many operational problems occurred because canal operators could not be physically present at all times. Automation began with an experimental effort at a wasteway that had been fitted with an automated Langemann gate (Figure 6) for water measurement. The MRGCD built the prototype electronic controller and created the control software for this first automated gate, borrowing heavily from Bureau of Reclamation experience in Utah. Success and invaluable experience from the first automated structure led to installation of over 40 additional automated structures using commercial control products.

Most of the MRGCD's recent automation efforts have involved the installation of Langemann overshot gates (Aqua Systems, 2006). The majority of these can be easily retrofitted to existing structures, though some involve the construction of new check or heading structures. The Langemann Gate has the capability to maintain a constant upstream water level as a check structure or it can provide a constant flow rate to downstream users (Figure 6). The Langemann gate is equipped with solar panels to power both gate operation and telemetry units. The gates employ integrated electronic controllers built around IC Tech Radio Terminal Units (RTU's) and Aqua Systems 2000 software. Langemann gates in the MRGCD are used as checks, turnouts, spillways, and diversion structures.

Figure 6. Langemann Gate

Some existing radial gates have also been automated. Conversion involves selection of a gearbox, motor, and controller. Some in-house fabrication is involved to adapt the drive unit to the existing gate hoist shaft. Early conversion attempts used an AMI controller supplied by Aqua Systems 2000, but recently the MRGCD has used the IC Tech RTU, which can be programmed to calculate flow through automated radial gates. Though not as accurate as overshot gates, this is useful for setting target bypass flows at diversion structures for endangered species flow requirements.

Instrumentation

Flow measurement and automated control must include some level of instrumentation. In the 1930's, a float in a stilling well driving a pen across a revolving strip of paper was adequate. In fact, at the beginning of modernization efforts, the MRGCD was still using 15 Stevens A-71 stage recorders. Diversions into the canal system were only known after the strip charts were collected and processed at the end of the irrigation season.

Modernization meant a device was needed to generate an electronic output that could be digitally stored or transmitted. Initially, shaft encoders were used for this purpose, providing input for electronic data loggers. Experimentation with submersible pressure sensors soon followed, and these have been adopted, although a number of shaft encoders are still in use. Recently, sonar sensors have been used satisfactorily at a number of sites. The MRGCD has learned that different situations call for specific sensor types and sensors are selected for applications where they are most appropriate.

Telemetry

Data from electronic data-loggers was initially downloaded manually and proved to be only a minimal improvement over strip chart recording, though processing was much faster. To address data downloading concerns, telemetry was adopted to bring the recorded data back to MRGCD headquarters at regular intervals. The MRGCD's initial exposure to telemetry was through the addition of GOES satellite transmitters to existing electronic data loggers. This method worked, but presented limitations. Data could only be transmitted periodically, and at regularly scheduled intervals. Of greater consequence was that the GOES system, at least as used by the MRGCD, was a one-way link. Data could be received from gauging stations, but not sent back to them.

To address the rising cost of telemetry using cell phone service, experiments with FM radio telemetry were conducted. These began as a way to bring multiple stream gage sites to a central data logger, which would then be relayed via GOES to MRGCD. First attempts with FM radio were not encouraging; however a successful system was eventually developed. As this use of FM radio telemetry (licensed 450 mHz) expanded, and knowledge of radio telemetry grew, it was soon realized that data could be directly transmitted to MRGCD headquarters without using the GOES system.

The shift to FM radio produced what is one of the more unique features of the MRGCD telemetry system. The data link proved so reliable, that there was no longer a need to store data on site, and the use of data loggers was mostly discontinued, the exception being weather stations. In effect, a single desktop computer at the MRGCD headquarters has become the data-logger for the entire stream gauge and gate system, being connected to sensors in the field through the FM radio link. Three repeater sites are used to relay data up and down the length of the valley, with transmission up to 75 miles. Also, this has the benefit of being a 2-way link, so various setup and control parameters can be transmitted to devices along the canals.

The MRGCD telemetry network consists exclusively of IC Tech RTU's. Several different types of these units are used, depending on the application. The simplest units contain only a modem and radio, and transmit collected and processed weather station data from Campbell Scientific CR10X dataloggers.

The majority of the RTU's contain a modem, radio, and an input/output (I/O) board packaged into a single unit. Sensors can be connected directly to these and read remotely over the radio link. A variety of analog (4-20ma, 0-20ma, 0-5v) and digital (SDI-12, RS-485) output devices can be accommodated this way. Another type includes a programmable (RP-52 BASIC) controller. This type is used for all automatic control sites and places where unusual processing of sensor outputs such as averaging values, combining values, or timed functions, are required. At the present time, the MRGCD telemetry network gathers data from 75 stream flow gages and 18 ag-met stations, and controls 50 automated gates (Figure 7).

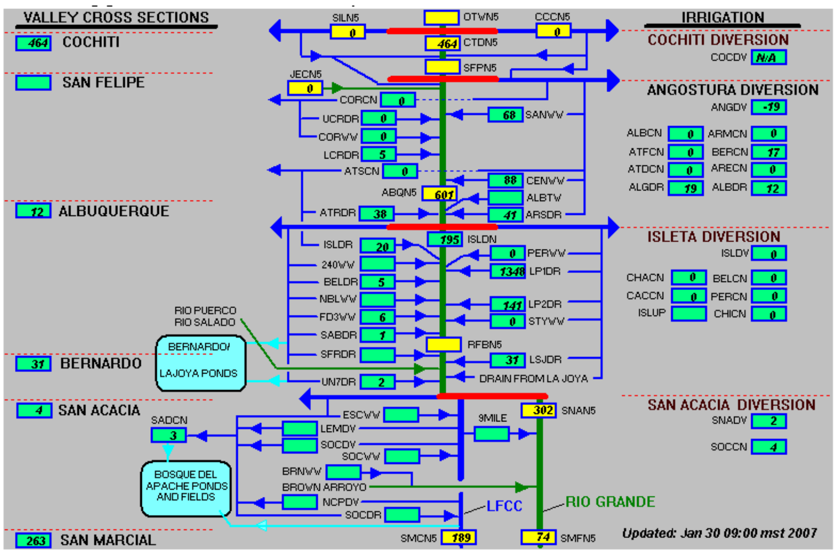

Figure 7. MRGCD Telemetry Network

Control Software

Measurement, automation, and telemetry components were developed simultaneously, but largely independent of one another. While each component functioned as expected, components did not exist as a harmonious whole, or what could truly be called a SCADA system. The missing component was software to tie all the processes together. There are a variety of commercially available software packages for such use and the MRGCD experimented with several. Ultimately, the MRGCD chose to purchase the commercial software package Vsystem and to employ the vendor Vista Controls to develop new features specific to the control of a canal network. Installation and setup was done by the MRGCD.

This system, known affectionately as the Supervisory Hydro-data Acquisition and Handling System (SHAHS, named after Mr. S.K. Shah), gathers data from RTU's on a regular basis. With the capability to define both timed and event driven poll routines, and specify a virtually unlimited number of RTU's and MODBUS registers to collect, virtually any piece of information can be collected at any desired time. The Vsystem software can process data through a myriad of mathematical functions, and combine outputs from multiple stations. Vsystem also incorporates the ability to permanently store data in its own internal database, Microsoft® Structured Query Language (SQL) databases, or export data in other formats. Data can be displayed in a user-created graphical user interface (GUI) which MRGCD water operations personnel use to monitor water movement. The screens can also execute scripts to generate data, control parameters, control gate set points, and monitor alarm conditions for automated control structures. Finally, the GUI's can be used to control automated structures by transmitting new parameters, setpoints, and flowrates. With the simultaneous development of the MRGCD DSS and SCADA system, the possibility to implement scheduled water delivery based on crop demand could be realized.

Linking DSS and SCADA

The first step was incorporating the DSS into the MRGCD SCADA System. This involved converting the DSS output into a data stream format that was compatible with the MRGCD Vsystem software. The DSS gives MRGCD operators a required irrigation delivery on a lateral level based on crop demand, as well as the timing of that irrigation. The required delivery and timing is imported into the graphical user interface (GUI) of the MRGCD SCADA system daily, so that actual deliveries along the canal system can be compared to the required deliveries. The GUI allows water managers to remotely change automated gate settings so that actual diversions closely represent water requirements. This provides better water management within the MRGCD and allows for a minimized river diversion as the required and actual diversion values converge. Figure 8 displays the MRGCD SCADA screen with actual deliveries and DSS recommendations.

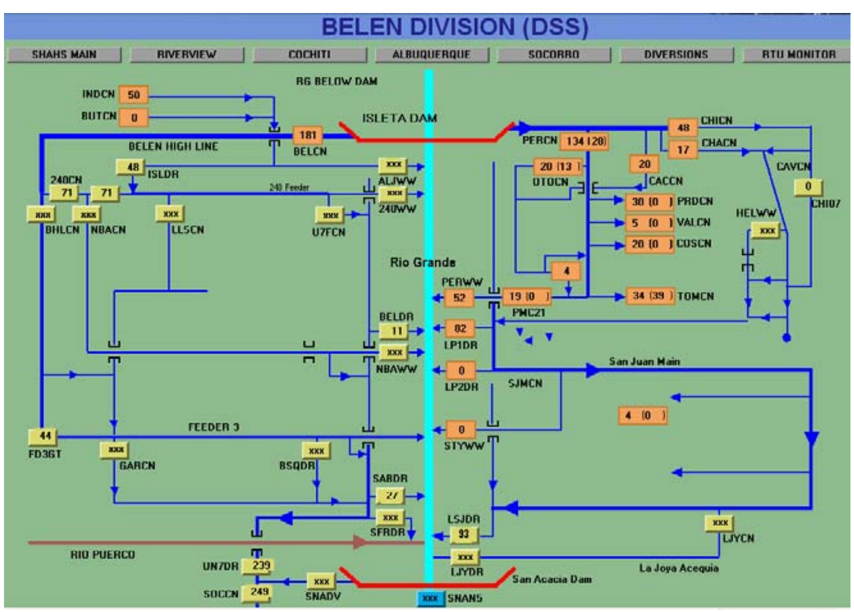

Figure 8. MRGCD SCADA Screen with Actual Deliveries and DSS Recommendations

IMPLEMENTATON OF DSS

The third and final component of achieving scheduled water delivery in the MRGCD was an in depth public outreach campaign. The adoption and acceptance of scheduled water delivery by the MRGCD and its water users is closely tied to understanding the principles and the benefits that this more intensive management provides. Public outreach is a timely and effective strategy for disseminating information and a necessity if water users are to accept the policy of scheduled water delivery. The program was designed to provide education and information to MRGCD water users. The information included the need to practice scheduled water delivery, that schedules are based on crop water requirements, how it will be implemented, and that it leads to fair and efficient water distribution for all concerned. Additionally, a major goal of the public outreach program was to get feedback and comments from water users and address concerns that they might have with scheduled water delivery.

There were two broad categories of information that needed to be conveyed and discussed with the MRGCD water users. The first was information related to the science, policy, and practice of scheduled water delivery as compared to the historic practice of continuous canal water delivery. The second category was the explanation of the tools, such as the DSS and SCADA, available to the MRGCD to effectively facilitate and implement scheduled water delivery.

The first step in public outreach was providing information on scheduled water delivery and the associated technology on the MRGCD website. The information provided explains the DSS and the practice of scheduled water delivery under a section of the MRGCD website that is devoted solely to the DSS and water scheduling. Figure 9 displays the links on the MRGCD homepage www.mrgcd.com and an article about the DSS.

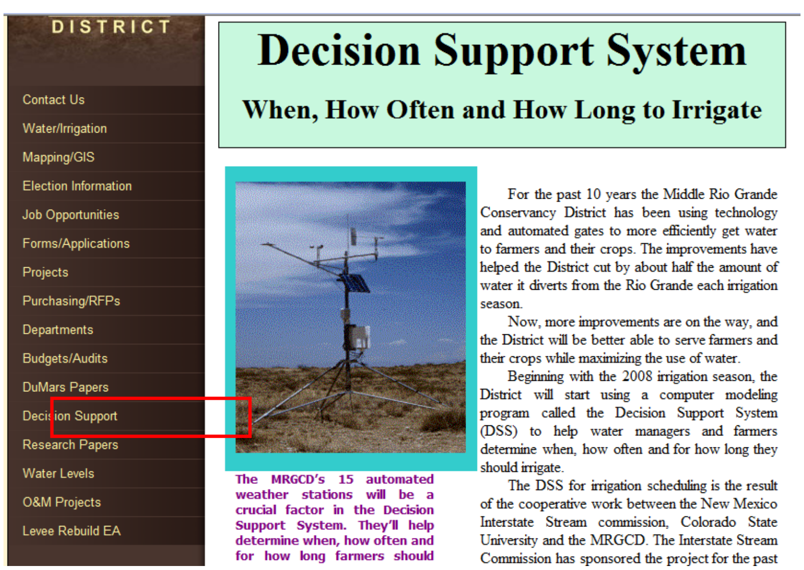

Figure 9. Article Explaining DSS on MRGCD Website

The second step of the public outreach program was including an article about scheduled water delivery in the MRGCD newsletter that gets delivered every two months. The article in the newsletter was entitled, "Computer Irrigation Scheduling Software to Remove Guesswork for Irrigators," and was delivered to over 50,000 water users, property owners, and other stakeholders in the Middle Rio Grande Valley. The article was also posted on the MRGCD website and linked to the Decision Support Section of the website. Developments regarding scheduled water delivery are periodically inserted into the newsletter to inform farmers about any changes or progress.

The third and key component of the public outreach program has been to conduct outreach meetings with water users throughout the MRGCD. Large scale public outreach meetings have been held in the Belen, Socorro, and Albuquerque Divisions. Small scale neighborhood meetings were held in the more urban sections of the Albuquerque North and South Valley to deal with the higher population density. These meetings were advertised in the MRGCD newsletter and personal invitations were sent to water users resulting in excellent turnout. Smaller meetings and presentations have also been held at the Los Poblanos Irrigation Workshop, and throughout the Belen Division. Meetings with over 100 individual farmers have also been held to clarify scheduled water delivery, the DSS, and to address concerns. These meetings provided a productive venue to educate farmers about scheduled water delivery, modernization efforts, and the DSS. The meetings also provided the opportunity to inform water users about future plans in the MRGCD. Additionally, water users were able to ask questions, voice concerns, offer valuable suggestions, and provide information critical to successfully implementing scheduled water delivery. One unexpected benefit of the outreach meetings has been that reporters have been present at several of the meetings which resulted in newspaper articles published in the Albuquerque Journal and the Valencia County News Bulletin. Three total articles have been published describing scheduled water delivery, its benefits, and the technology being used to implement scheduling.

The fourth aspect of the public outreach campaign has been to gain the support of the MRGCD Board of Directors and CEO. Presentations of scheduled water delivery and the DSS have been made to the MRGCD Board and CEO on four occasions and have been received well. The MRGCD Board understands the need for scheduled water delivery and supported the use of the DSS to develop water delivery schedules beginning in 2008. At a recent meeting the board re-emphasized their complete support of scheduled water delivery practice utilizing the DSS as an advisory tool. In tandem, the MRGCD water policy has been placed on the website in order to clarify any confusion. The policy states that water for irrigation must be scheduled with the ditch-rider and that rotational scheduling will be implemented during times of water shortage. Such political support has been invaluable in gaining water user acceptance of scheduled water delivery.

The fifth main aspect of implementing scheduled water delivery and the DSS has been the training of ditch-riders and water management personnel. For the DSS to be accepted by the MRGCD, it was necessary to have the water operations personnel running the DSS and creating water delivery schedules. The training of the ditch-riders consisted of education in regards to the scientific principles used in the DSS, a tutorial on how to develop schedules with the DSS, and training on the use of soil moisture sensors. For the 2009 irrigation season ditch-riders were given portable Aquaterr™ soil moisture meters to ensure that water delivery schedules were not adversely affecting crop growth in their service areas.

The five steps of the public outreach campaign have resulted in positive progress towards district wide scheduled water delivery. First, MRGCD water users can easily access information about relevant issues such as irrigation water delivery and scheduling of their water supply. The public outreach program also provided a much needed opportunity for water users and managers to meet and discuss issues related to an extremely precious resource – irrigation water. Before this program, there was no structured process whereby the water users could meet as a group and discuss their concerns and questions with their water provider.

Second, the public outreach program has resulted in the limited implementation of the DSS. The DSS is currently being used to develop irrigation schedules in the form of a calendar which determines when certain lateral canals need to be running to meet crop demand. The area over which the implementation is occurring represents roughly 14% of the total irrigated acreage in the MRGCD. The calendars are allowing irrigators to plan their water use and provide for a more reliable water delivery method. Without calendars or scheduling, water deliveries were often unreliable and unpredictable. Creating schedules that address water deliveries in advance allows managers to adjust deliveries upstream accordingly.

Overall, scheduling has been successful in several aspects. The schedules have resulted in increased head in the irrigation ditches, increased reliability in water delivery, and efficiency improvements. From a management standpoint, the DSS has resulted in a much more organized protocol for delivering water by determining water delivery targets in advance, which allows managers to adjust deliveries upstream accordingly. Over time, scheduled water delivery and the MRGCD DSS will be used throughout the entire district.

RESULTS

Using limited scheduled water delivery and infrastructural improvements, the MRGCD has been able to significantly reduce river diversions. Historically, the MRGCD diverted as much as 600,000 AF/year from the Rio Grande. Over the last 3 years, their diversions have averaged less than 350,000 AF/year. This is a significant accomplishment as the MRGCD has been able to reduce diversion to meet fish and wildlife concerns, while still providing the needed water to irrigators. Figure 10 displays the decreasing trend in total MRGCD river diversions. Currently scheduling is only practiced in a few limited areas, leaving much room for efficiency improvement.

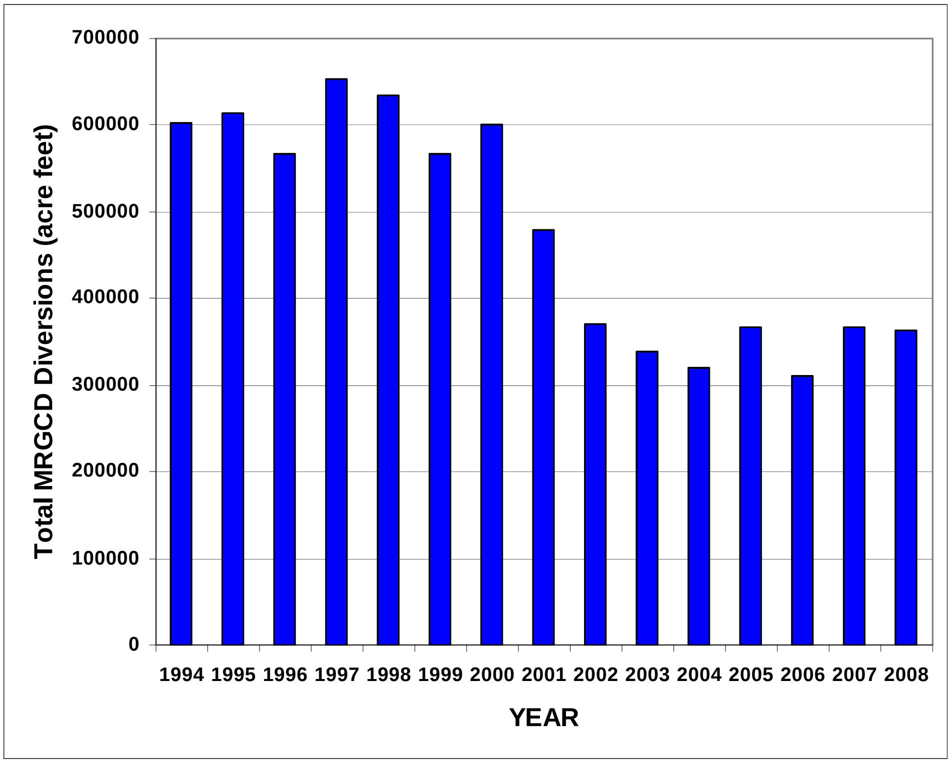

Figure 10. MRGCD River Diversions by Year

CONCLUSIONS AND FURTHER RESEARCH

An integrated decision support system and SCADA system for the Middle Rio Grande Conservancy District has been developed that models the canal network and can compute water delivery options for optimum water delivery scheduling. The system additionally allows for local and automated controls which can be actuated at a central office. The linking of the MRGCD SCADA and the DSS provides operators with a required irrigation delivery on a lateral level based on crop demand as well as the timing of that irrigation. This provides better water management within the MRGCD and allows for a minimized river diversion as the required and actual diversion values converge. The system has also resulted in increased head in the irrigation ditches, increased reliability in water delivery, efficiency improvements, and improved protocol for anticipating future water demands. The public outreach campaign has been successful in educating water users on the principles of scheduled water delivery as well as providing much needed opportunities for water users and water managers to discuss water delivery issues.

Future plans for scheduled water delivery in the MRGCD include expanding the use of the DSS and scheduled water delivery. Plans also include further modernization efforts and continued public outreach and training programs to facilitate scheduled water delivery. Through expanded implementation of scheduled water delivery and the DSS the MRCGD will further reduce river diversions, while continuing to sustain irrigated agriculture in the Middle Rio Grande Valley.

ACKNOWLEDGEMENTS

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ENVIRONMENTAL MITIGATION IN THE CENTRAL UTAH PROJECT: A UNIVERSE OF OPPORTUNITIES UNFOLDS

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ABSTRACT

The Central Utah Project (CUP), a major Federal water resources development in Utah, began as early as 1964, long before the major Federal environmental legislation we are familiar with today was enacted in the United States. Nevertheless, environmental mitigation, as required by laws at the time, was planned by the Federal resource agencies coincident with engineering studies. Environmental mitigation for the CUP is reviewed with special emphasis on the evolution of mitigation strategies over time. The project itself has changed substantially over the years, as have the commitments for environmental mitigation. In 1992 the United States Congress mandated a radically new approach to completion of the environmental commitments for the CUP. An independent Federal commission was created, wholly separate from the water project planning agencies, to coordinate, fund and implement all environmental mitigation for the CUP. The structure, function and advantages of this new commission are discussed as a possible model for mitigation success in other projects.

The present plan for mitigation, revised and adopted as recently as 2004, is presented with emphasis on the new approaches and accomplishments. Expenses for mitigation can only be estimated. The cost of environmental mitigation for the CUP has increased from initial estimates of $6.5 million (US$ 1964) to about $198 million (US$ 2009).

INTRODUCTION

A dictionary definition of the word "mitigation" is: 1) to lessen in force or intensity (wrath, grief, harshness, pain, etc); 2) to moderate the severity of (anything distressing) [18]. An expanded definition, developed as guidance by the U.S. Bureau of Reclamation (Reclamation) in 1972 for the environmental review of its projects, is more pertinent for this paper: "Measures that are proposed and/or required to be undertaken to enhance, protect, or mitigate impacts on the environment by the project actions, including any associated research or monitoring"[19].

The Central Utah Project (CUP) environmental impact mitigation program (limited to mitigation for impacts to fish, wildlife and recreation) has a long evolutionary history of planning and implementation. Over time, the CUP project design has changed markedly, our understanding of fish, wildlife and recreation needs has increased, the knowledge base of resources and opportunities has expanded, and legal imperatives related to conservation have evolved. Above all, the public now demands a greater voice, stricter agency accountability and a more enlightened approach to federal project impact mitigation. In any such atmosphere, political forces will inevitably respond.

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This paper outlines this evolution of mitigation thinking and planning from a virtually exclusive focus on sport fish and game species and angler/hunter use of resources, to recognition that a "universe of opportunities" [1] needs to be the starting point for the consideration of mitigation. This is particularly true for a project as complex, as controversial, and with as many and varied environmental impacts as the CUP.

For environmental impact mitigation, this concept of a "universe of opportunities" goes beyond simply moderating the severity of direct project impacts. A "universe of opportunities" seeks to identify the full range of actions that are reasonable and feasible to eliminate or minimize adverse aspects of a project, and even enhance environments that are adversely affected by the project. What is needed most is recognition that large and complex water resource development projects have an equally wide range of impacts extending far beyond the high water line of the reservoir or the edge of the canal. Development and diversion of Colorado River water from eastern Utah has fostered, in large measure, the urban expansions that have filled wetlands, converted grassland habitats, and pushed highways and housing into big game winter range on the populous Wasatch Front of Utah, where this water is actually used. A cramped definition of "mitigation" addressing only the immediate and direct project effects serves only those who would ignore or minimize the full range of project issues.[2] It also unfairly shifts a large portion of project costs onto the environment.

Substantially increased Federal funding for this expanded CUP mitigation program has allowed more freedom, flexibility and creativity within this new planning environment. Money solves many problems. However, enlightened attitudes by CUP project planners and local water user groups, the support of Federal and state resource agencies, and effective activism of non-governmental environmental groups are equally as responsible for the mitigation successes.

THE CENTRAL UTAH PROJECT

The Central Utah Project, its history [10], the engineering challenges of its water delivery systems [11] and other interesting aspects [12] have been thoroughly described at previous USCID conferences. Briefly, the CUP, authorized under the multi-project Colorado River Storage Project Act (43 USC 620) of 1956 (CRSP), is the largest Federal water resources project in the State of Utah, designed to utilize a portion of Utah's share

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[2] This does not mean that anything desirable (or feasible) is appropriate mitigation, regardless of costs. The Department of the Interior believes that a rule of reason must apply. Mitigation must address project impacts and otherwise be economically and technically feasible. As much as the water project itself, mitigation features are valuable public resources yielding valuable public benefits for which public funding is justified.

The extent to which indirect project impacts must be addressed can have substantial influence on mitigation planning unique to each project. With regard to the CUP, the U.S. Congress authorized a specific schedule of mitigation measures, thus imposing limitations. The same Congress endowed the Mitigation Commission with independent authority to consider any other aspect of mitigation it deems more appropriate to the mitigation objectives of the CUP. The Commission may undertake a benefit/cost analysis or any other means to inform its decision on mitigation.

of Colorado River water assigned to it under the Colorado River Compact of 1922. Two CUP units--Vernal Unit and Jensen Unit—develop and use water in Utah's eastern Uinta Basin, itself part of the Colorado River basin. The Bonneville Unit, by far the largest, is one of the most complex and expensive trans-mountain water diversion projects ever built by Reclamation. It diverts water from streams in the Uinta basin via dams, reservoirs, tunnels and pipelines, for delivery to the Wasatch Front for irrigation, municipal and industrial uses and for fish and wildlife and recreational purposes. See Figure1.

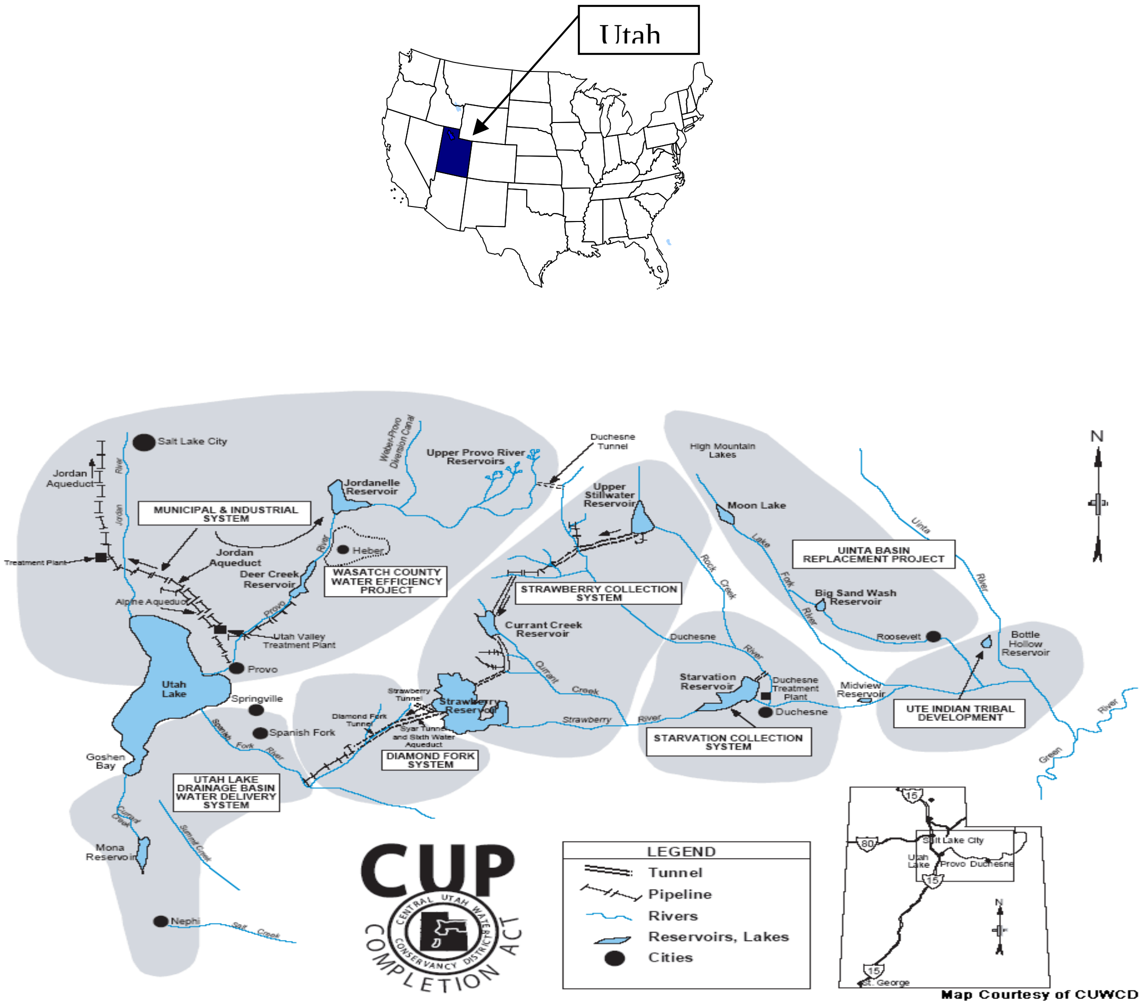

Figure 1. Central Utah Project Location and Features

Environmental Impacts of the CUP

Environmental impacts of the CUP have been evaluated, reported and revisited as project imperatives have changed over the years. Evolving from primarily an irrigation plan, the CUP now largely serves a municipal and industrial function. These changes have influenced the scope and magnitude of the project's environmental impacts and, appropriately, altered the direction and elements of mitigation.

For those wishing to immerse themselves in the minutia of CUP environmental impacts, the most comprehensive assessments are the original environmental impact statement, completed in 1973 [7], and the more recent evaluations of Bonneville Unit systems [15, 16, 17].[3] The major areas of environmental impact are summarized below.

Table 1. Summary of CUP Environmental Impacts[4]

Parameter	Negative Impacts	Positive Impacts
Aquatic Environmental Impacts	• Reservoirs inundate/alter/destroy stream ecosystems • Diversions reduce in stream flows altering/destroying streams • Imported water creates damaging high instream flows. • Aquatic species populations (typically cold water species) are altered, reduced or destroyed. • Flow alterations reduce, alter or destroy downstream aquatic ecosystems. • Sensitive in-stream habitats (spawning) are altered or destroyed • Riparian (streamside) habitats reduced or destroyed • Water quality degradation in reservoirs and downstream	• Lake fish populations created ◦ Warm-water species • Economic development • Water resources development for agriculture and cities • Flood control • Recreation (see below)

Terrestrial Environmental Impacts	• Reservoirs inundate wildlife range
	  ◦ Summer/winter game ranges
	  ◦ Sensitive species of concern (sage grouse)
	• Agricultural/residential development replaces wildlife range
	• Game migration interrupted
	• Increased game-auto collisions
		• Agricultural, industrial, urban development improvements

[3] Separate environmental impact statements were prepared for other CUP systems: the Vernal and Jensen Units, Wasatch County Water Efficiency Project, Uinta Basin Replacement Project.

[4] Other environmental impact parameters such as surface and groundwater hydrology, cultural resources, and a wide range of socio-economic issues (employment, income, public health and safety) are pertinent and typically included in the environmental impact statements. In practice, mitigation for these impacts is typically incorporated as part of project design and construction.

Parameter	Negative Impacts	Positive Impacts
	• Human socio-economic impacts (rural land uses/lifestyles)	
Wetlands Impacts	• Reservoirs inundate wetlands • Diversions reduce riparian (streamside) wetland water sources • Canal modifications reduce seepage wetlands • Wetland habitat and associated fish and wildlife and plant populations are altered or destroyed. • Groundwater recharge, pollution control services reduced	• Increased vector control • Land use conversions can yield economic benefits
Recreation	• Public stream access reduced • Stream fishing opportunities reduced • Game hunting opportunities reduced	• Flat water fishing/boating/other recreation created • Economic development
Endangered/Sensitive Species	• Terrestrial and aquatic species impacted by diversions, low instream flows, poor water quality	

Environmental Impact Mitigation for the CUP

A thorough presentation of the evolution of Federal environmental law pertaining to impact mitigation is available elsewhere [13]. Two early laws with particular relevance to CUP mitigation are summarized here for context. Both were (and remain) powerful mandates for mitigation of water project impacts, exerting substantial and lasting influence on CUP planning.

Fish and Wildlife Coordination Act – Among the earliest Congressional attempts to balance water resource development with the protection of fish and wildlife values is the Fish and Wildlife Coordination Act (16 USC 661 *et seq*) (FWCA). First enacted in 1934, with important amendments in 1946 and 1958 (largely contemporaneous with CUP planning) the FWCA requires consultations between the water planning agency and the U.S. Fish and Wildlife Service (FWS) "whenever the waters of any stream or other body of water are authorized to be impounded, diverted or otherwise controlled for any purpose whatever by any department or agency of the United States…" The purpose of such consultation was to ensure "adequate provision …for the conservation, maintenance, and management of wildlife". The FWS typically writes a report recommending "justifiable means and measures for wildlife purposes…" to be included as part of the project design "…to achieve maximum overall project benefits." The FWCA report is to receive "equal consideration" with other features of water resource development (i.e., irrigation, flood control, hydroelectric power, etc). The U.S. Fish and Wildlife Service completed its first FWCA report on the Bonneville Unit in 1965 [14] which contained a comprehensive plan for mitigation.[5]

However, Reclamation retained the final authority regarding which mitigation actions would be included in the project. More importantly, Reclamation requested and controlled all Federal funding for mitigation. Over the years these decisions were routinely influenced by the ability or willingness of Reclamation to seek mitigation funds, the impacts on project feasibility, and even the views of water user.

<u>Colorado River Storage Project Act, Section 8</u> – Congress has long recognized that water project construction on the upper Colorado River would impact fish and wildlife resources. Section 8 of the CRSPA authorizes planning and funding for "…facilities to mitigate losses of, and improve conditions for, the propagation of fish and wildlife." These authorities include the acquisition of lands, withdrawal of existing public lands, and disposal to other Federal, state and local governmental agencies on terms and conditions that will best promote their development and operations in the public interest.

<u>The Evolution of Mitigation Plans in the Central Utah Project</u>

Pursuant to the language in FWCA and CRSP Section 8, the impact assessment and subsequent mitigation recommendations focused on fish and wildlife. This mindset was characterized by certain limitations:

<u>Sport fish and wildlife species</u> – game species such as deer, trout, waterfowl, upland game birds, and furbearers are the focus of the 1965 FWCA report on the Bonneville Unit. There is no mention of non-game species or species of other special concern.

<u>Measure of value was sport use of the resources</u> – traditionally hunter and fisherman uses of a resource (i.e., consumptive uses) were the measure of the value recognized by the FWS in its assessment of impacts and also in any valuation of a mitigation feature. For example, wetlands were assessed as to their capability to support days of waterfowl hunting with no consideration of wetland values such as groundwater recharge, pollution control, or bird-watching. Impacts on streams were similarly evaluated in terms of sport fishing-days.

<u>Economic justification was the primary criterion</u> – mitigation features typically had to generate monetary benefits equal to or exceeding their costs. Thus, if the resource agencies recommended the acquisition of land for big game or a minimum conservation

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[5] The 1965 report refers to earlier reports on fish and wildlife aspects of the Central Utah Project prepared by the USFWS dated January and February, 1951. These reports are no longer available, but document the early and ongoing pattern of consultations among the agencies on these issues under FWCA.

pool in a project reservoir, their assessment of user-days and value[6] had to equal or exceed than that lost by the project in order to be considered.

Management considerations were an obstacle – even when all other factors aligned favorably, the issues of management remained. Utah State Division of Wildlife Resources, the U.S. Forest Service, or U.S. Fish and Wildlife Service typically had to accept these facilities and the perpetual burden of their management and funding.

By the 1980's the CUP was perceived by the public environmental groups as ill-considered and creating significant environmental impacts to streams, wetlands, and big game habitats that were not being properly addressed by the project [2].[7] While the resource agencies had secured important commitments for big game, cold water sport fisheries and wetlands mitigation [21, 22, 23], implementation was far behind schedule. There had been no consideration of non-game fish or wildlife species (let alone plants), issues of growing concern to the public.[8] There had been no compliance with the Federal Endangered Species Act of 1973 even though several endangered and threatened species had been designated in the CUP impact area.

A growing body of science was rapidly revising impact assessment methodologies for federal projects during the 1980's. New policy [24] refocused mitigation onto habitat value for a range of key evaluation species, not just sport fish and wildlife. Habitat Evaluation Procedures (HEP) [25], developed by the U.S. Fish and Wildlife Service, sought habitat-based standards for impact assessments of Federal projects using species models and rating systems to evaluate the quality of habitat impacted by a project. Resulting calculations are considered more relevant to modern mitigation planning than the value of hunter-day or fisherman-day uses.[9] Such assessment methodologies quickly identified the shortcomings of traditional mitigation thinking. Finally, the growing inability of the other resource agencies to fund management of mitigation properties quickly exposed the fundamental weakness of this aspect of mitigation planning.

THE DAWN OF A NEW UNIVERSE

By 1988 the convergence of a number of financial and political factors brought the realization that material changes were needed in order to achieve any further progress to complete the Central Utah Project. Authorized funding had been expended and the United States Congress was reluctant to increase CUP funding for a third time in 25 years [2]. National and local environmental groups had effectively lobbied Congress to

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[6] Hunter/fisherman/recreationist user-day values have been calculated by independent recreation economists for use by FWS.
[7] The Central Utah Project had been on the "hit list" of federal water projects to be cancelled by U.S. President Jimmy Carter in the late 1970's.
[8] A number of public laws, notably the Endangered Species had been enacted by this time. However, implementing regulations were as yet new, or unwritten, and public policy and interpretations of these requirements were not as they are perceived today.
[9] Inflationary economic pressures throughout the 1970's and 1980's had largely rendered any calculation of the dollar value of a hunter-day or fisherman-day meaningless. While the FWS attempted to measure the economic benefits of hunting and fishing, their data were frequently inaccurate when received.

recognize that the CUP, as then planned, was obsolete—a plan for irrigation in a state with little valuable agriculture and a society that was rapidly urbanizing. New directions and new partnerships were needed to augment the traditional water project power structure. Long-standing concerns of the environmental community regarding CUP project impacts and mitigation had to be addressed or the project would not likely be completed.

The planning and coordination on this new strategy was lead by the Central Utah Water Conservancy District, in Orem, Utah, the local project sponsor of the CUP. District leadership set a new tone of cooperation and openness to ideas and groups that had long been shut out of the planning process. Over four years of effort, they crafted a new coalition of national and local environmental groups who were prepared to accept the needs of water development in Utah in exchange for real reform of the CUP. This new cooperative effort was key to securing renewed Congressional support for the CUP.

Origin and Role of the Utah Reclamation Mitigation and Conservation Commission

In a radical departure from traditional water project planning, Congress redirected the responsibilities for completion of the project construction from Reclamation to the Central Utah Water Conservancy District. Fish, wildlife and recreation mitigation was assigned to a new and independent Federal Commission, the Utah Reclamation Mitigation and Conservation Commission (Commission) vested with the responsibility to plan, fund and implement the fish, wildlife and recreation mitigation for the CUP.[10] It was the intent of Congress to have a comprehensive and integrated program for the mitigation of project impacts focused within a single, independent entity, ending the old policy that spread responsibilities among different Federal and state resource agencies.

The Commission works independently, but within the existing framework of federal environmental laws and regulations.[11] While the Central Utah Project Completion Act (CUPCA) amended Section 8 of the CRSPA (at least for the CUP) it explicitly did not alter the authorities or responsibilities of other agencies respecting the project.[12] Thus, the U.S. Fish and Wildlife Service continues to fulfill its statutory obligations under the FWCA to determine necessary fish and wildlife mitigation and recommend measures to fulfill such mitigation.

Ultimately, the Secretary of the Interior is responsible for completion of the CUP including the environmental impact mitigation. The Department looks specifically to the FWS for documentation that Commission activities meet the requirements of the FWCA (and other Federal environmental law). The Department assists with the Commission budgets, but otherwise does not supervise the work of this independent presidential

[10] The Commission was modeled somewhat after the successful Northwest Power Planning Council created by the Northwest Power Act (16 USC 839-839h) which has achieved success in advancing mitigation and conservation work to conserve migratory salmon resources at Federal hydropower developments in the Pacific Northwest of the USA.
[11] CUPCA Section 301(c) (3) and Title VI.
[12] CUPCA Section 301(h) 7.

commission. Anytime independent entities must cooperate on a common mission, there needs to be coordination and communication among respective agency staffs, or difficulties will arise.

Details of the new Commission's policies and procedures are fully expounded elsewhere [5, 6]. Mitigation accomplishments are presented in the FWS "Greenbook" [20] and the 2004 Fish and Wildlife Appendix to the Bonneville Unit Definite Plan Report [3].

Key factors that render the Commission a successful model as a vehicle for mitigation are:

Independence – The dispersion of mitigation responsibilities among several Federal and state resource agencies had been a primary cause for delays in implementing CUP mitigation. Assigning mitigation responsibility to a single entity has increased the accountability for reclamation mitigation in Utah. This independence includes authority to alter a mitigation measure if, after public involvement and interagency consultation, the Commission determines benefits to fish, wildlife or recreation will be better served by allocating funds in a different manner.[13] The Commission must still work cooperatively with the CUP planning agencies and engineers to coordinate mitigation needs with water project plans.

Separate funding – Historically, mitigation funding was via CRSPA budget requests that competed with other Reclamation funding. With CUPCA, mitigation funding is divorced from construction. Mitigation funding is to be proportional and concurrent with construction funding. A new account in the U.S. Treasury[14] holds funds to cover mitigation costs that will continue to be incurred long after CUP is completed. Operating as a trust fund, this will allow the Commission to continue its work indefinitely without need for continuing appropriations. Funds to operate and maintain mitigation features in perpetuity are now available.

Public involvement – The Commission operates with public involvement which has strengthened the mitigation planning process by inviting formal participation by interest groups that never before had a role in CUP mitigation planning.

Mandate – The mandate of the Commission goes far beyond the narrow and traditional application of the term "mitigation." While the Commission is primarily to implement CUP mitigation, it also has broad authority to amend mitigation direction to reflect changes in priorities that may result from public involvement or due to natural conditions or newly emerging mitigation needs within the CUP.[15] The Commission is to develop a

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[13] CUPCA Sec 301(f)2. This authority is subject only to the condition that the U.S. Fish and Wildlife Service must approve any reallocation from fish and wildlife purposes to recreation. This minor condition has never caused a dispute or interrupted Commission work.

[14] The Utah Reclamation Mitigation and Conservation Account was created by Title IV of CUPCA with perpetual funding sources.

[15] Examples of emerging project impact issues not previously recognized in CUP are: 1) endangered and threatened species of plants and animals in the CUP area; 2) non-native invasive species that have been favored by irrigation developments and operations; 3) environmental contaminants such as selenium for

broad range of projects appropriate to its authorities[16] including other Reclamation mitigation in Utah [5].

Many new areas of environmental mitigation are now included under the umbrella of CUP completion. Table 2 builds from Table 1 to illustrate the expanded mitigation concepts that characterize the new mandates under CUPCA to improve the fish and wildlife mitigation component of the project. It is important to note that many mitigation concepts originally planned were retained in this new "universe of opportunities." In many cases the concepts were expanded in scope to improve their effectiveness or yield additional public benefits.

Among the most important of these new CUP mitigation reforms are:

Instream flows are mandated by statute and provided by project water – flow requirements established by statute will secure these mitigation commitments in a permanent and perpetual manner that is superior to project agreements that could change. Project water represents an assured supply to fulfill these commitments. Moreover, project impacts are mitigated by the project and not unrelated externalities (payment of funds, water owned by other entities).

Funding and authority to secure additional non-project water for mitigation – additional funding for aquatic mitigation in the form of instream flows had never been a part of CUP mitigation. (Conservation pools and reservoir releases that otherwise meet downstream water uses, traditionally been included as mitigation, are coincident with project itself.) The authority to acquire non-project water has created a "marketplace" for water that has benefitted water users and advanced mitigation goals.

Use of eminent domain to secure lands and waters needed for project mitigation – use of condemnation authorities was virtually unprecedented for environmental impact mitigation.

Land acquisition for public uses apart from sport hunting and fishing – traditional mitigation has long included land acquisitions for National Wildlife Refuges or State Wildlife Management Areas. The CUPCA authorized acquisitions for wetland preserves,

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which more scientific information has become available. Each of these issues requires funding for research, management and effective mitigation if we are to deal with the harmful effects of the CUP.

[16] It is not to be assumed the Commission has *carte blanc*, expending public funding on whatever it chooses. CUPCA (Section 301(g)(4) prescribes the standards the Commission is to use in determining the types of measures to be included in its plans and thus eligible for funding . In addition, mitigation concepts are presented and adopted pursuant to the Commission's planning rule (43 CFR 1000) which contains further project evaluation criteria the Commission must follow. Departures from its approved Mitigation and Conservation Plan must be by amendment approved subsequent to public involvement. Certain specific shifts in funds must be specifically approved by the U.S. Fish and Wildlife Service. Finally, the Department of the Interior is able to exercise oversight via the Federal appropriations process which it prosecutes on behalf of the Commission.

Table 2. Evolution of Mitigation under the Central Utah Project Completion Act

Parameter	Traditional Mitigation	Universe of Opportunity
Aquatic Environmental Impacts	• Conservation pool in reservoir • Project water for selected streams • Irrigation by-passes/spills to sustain most streams • Rehabilitate high mountain reservoirs for public fishing • Instream fish habitat improvements at selected locations	• Project water maintains statutory minimum instream flows for key trout streams • Funding to acquire additional non-project water • Water conservation program linked to incentives for additional water in project streams • Advanced flow studies support comprehensive year-round flow recommendations. • Modification of existing diversions to restore natural flows or provide fish passage. • Riparian (streamside) focus for restoration/monitoring • Rehabilitate state fish hatcheries to produce sport fish • Increased instream flows improve water quality • Post-project water quality studies and remediation funding • Additional high mountain lakes rehabilitation for fishing • Provo River Restoration – 10-mile fish habitat enhancement
Terrestrial Environmental Impacts	• Acquire private lands to benefit big game (target winter range); develop management plans • Willing seller basis of acquisition • Transfer lands to state/federal agency for management • Game crossings over canals; escapement ramps in canals	• Increased funding for lands acquisition • Eminent domain (if necessary) to acquire lands • Transfer to managing entity with support funding for perpetual maintenance • Open canals eliminated from project or placed in pipelines to avoid big game impacts

Wetlands Impacts	• Land acquisition and creation of wetlands
	• "Postage-stamp" wetlands in each basin support low wetland values
	• Willing seller basis of acquisition
	• Transfer to willing managing entity
		• Ecosystem focus beyond waterfowl habitat
		  ◦ Sensitive species of concern – Example Spotted frog
		• Large wetland preserves to maximize wetland values
		  ◦ Great Salt Lake Wetlands Preserve
		  ◦ Utah Lake Wetland Preserve

		◦ Jordan River wetland corridor • Rehabilitation of state and Federal refuges on Great Salt Lake • Perpetual maintenance funding for managing entity • Eminent domain (if necessary) to acquire lands
Recreation	• Angler access easements along selected streams • Campgrounds, trails, boat ramps at reservoirs	• Angler access easements along 51 miles of streams • Funding for perpetual maintenance/management of easements • Recreation needs revisited ◦ RV access and parking ◦ Large-group and day-use recreation ◦ Modern sanitation, drinking water, and fire safety
Endangered/Sensitive Species	• Impacts not recognized on entire suites of species, mainly plants, invertebrates and fish • No mitigation proposed	• Establish Recovery Implementation Program • Implement approved Recovery Plan with Federal and non-Federal funding • Population monitoring/field studies to identify impacts to sensitive species • Commitments for future mitigation if necessary

public trail systems and general recreation, reflecting public demands for non-consumptive (i.e., beyond hunting and fishing) mitigation concepts.

Funding for perpetual maintenance of mitigation – a secure source of funds to maintain mitigation features is deemed equally important as maintaining the water project.

THE UNIVERSE CAN BE EXPENSIVE

The earliest documented estimate of mitigation expenses, reflecting the plan of action presented in 1964 Definite Plan Report for the CUP was $6.5 million ($US) in capital costs and $72,000 ($US) per year in operations costs [8]. In 1982, Reclamation estimated total Section 8 (CRSP) costs at $133.3 million [26]. By 1992 and enactment of CUPCA, that estimate had grown to $145 million ($US) to complete all currently planned mitigation. By October 2009 the total authorization for mitigation expenditures had grown to $198.3 million[17] [27]. In addition, the Mitigation Commission estimates it will need to generate about $1 million ($US) per year (2009 $US) from its trust fund to cover perpetual operations and maintenance expenses for CUP mitigation. While these costs are not always comparable because the scope and magnitude of mitigation has changed markedly over the years, they do indicate the elevated priority of environmental impact mitigation in the CUP.

SUMMARY

More than three years of hard work finally succeeded in convincing key parties, including the U.S. Congress, that the CUP could be "reinvented." With the efforts of leaders in the water user community, environmental groups and Congress, environmental mitigation planning broke from the traditional interpretations of the FWCA and Section 8 of the CRSP. Planners did not abandon all previous ideas and commitments for fish and wildlife mitigation. Much good work had been accomplished prior to CUPCA in the manner of land acquisition, instream flows, and wetlands enhancement pursuant to the FWCA and Section 8 of CRSP. However, with the recognition that the mitigation priorities and accomplishments were still inadequate, all agreed that fundamental reform was needed. The CUPCA, and its creation, the Mitigation Commission, provide the necessary authority and responsibility to develop new mitigation approaches and to build on past achievements.

The CUP demonstrates that it is never too late in project planning to improve environmental impact mitigation. If planners can get a glimpse of the universe of opportunities available, they will be surprised by the creative forces unleashed.

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[17] 2009 $US. CUPCA provides that authorized funds are increased each year by a factor for monetary inflation in order to preserve the purchasing power of Commission funds.

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HABITAT REPLACEMENT STRATEGIES FOR IRRIGATION SYSTEM IMPROVEMENTS ASSOCIATED WITH SALINITY CONTROL IMPLEMENTATION

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ABSTRACT

Implementation of irrigation system improvements such as canal lining or replacement with pipelines frequently results in the incidental loss of wetland habitat previously supported by seepage or spills from the inefficient system. Although the affected wetlands are typically non-jurisdictional in nature, the salinity control program authorizing legislation requires the replacement of lost wildlife habitat value. This paper discusses various strategies and approaches to address this issue, with particular emphasis on low cost, cooperative resolution. Examples of successful project implementation are provided, together with discussion of the potential ramifications of various long-term management approaches.

INTRODUCTION AND BACKGROUND

Brief Overview: Colorado River Salinity Control Program

The Colorado River and its tributaries provide municipal and industrial water to about 27 million people and irrigation water to nearly four million acres of land in the United States. The river also serves about 2.3 million people and 500,000 acres in Mexico. The threat of salinity is a major concern in both the United States and Mexico. Salinity (the presence of dissolved salts in fresh water) affects agricultural, municipal, and industrial water users. Although salinity control measures installed to date with US Department of Agriculture assistance control over 300,000 tons of salt annually, and control measures installed with Bureau of Reclamation assistance control nearly 500,000 tons each year, salinity in the Colorado River causes $300 million per year in damages[3].

In June 1974, Congress enacted the Colorado River Basin Salinity Control Act, Public Law 93-320, which directed the Secretary of the Interior to proceed with a program to enhance and protect the quality of water available in the Colorado River for use in the United States and the Republic of Mexico. In October 1984, Congress amended the original act by passing Public Law 98-569. Public Law 104-20 of July 28, 1995, authorizes the Secretary of the Interior, acting through the Bureau of Reclamation, to implement a basinwide salinity control program, working collaboratively with the seven Colorado River Basin states and the USDA Natural Resource Conservation Service as

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well as with local entities. The Secretary may carry out the purposes of this legislation directly, or make grants, enter into contracts, memoranda of agreement, commitments for grants, cooperative agreements, or advances of funds to non-federal entities under such terms and conditions as the Secretary may require.

This paper is focused on strategies for fulfilling the wildlife habitat replacement requirements associated with the salinity control program, drawing on the experiences of program implementation and management within the state of Utah by the Bureau of Reclamation, Provo Area Office (Reclamation).

Habitat Replacement Requirements

The Salinity Control Program's authorizing legislation, codified at 43 U.S.C. 1571-1599, contains a unique requirement to replace wildlife values foregone as a result of irrigation system improvements to reduce salt loading. In implementing the program, this means that habitat predicted to be lost as the result of a project must be replaced, even if environmental analysis pursuant to the National Environmental Policy Act does not predict significant effects to wildlife or habitat.

Irrigation systems in Utah and the rest of the arid western United States have been essential to human survival and agriculture since the 19th century settlement by European descendants. The irrigation canal could be considered the first and most important public utility in Utah. There are roughly 1,500 irrigation companies located in Utah, and many earthen, open ditch systems are still in use. Because these systems are the main source of the salinity problem in need of control, they are the focus of salinity program funding to facilitate replacement with pipelines and sprinkler irrigation systems. However, the authorizing legislation recognized that over the decades, the seepage from these canals has created linear wetland and riparian corridors which in turn have come to be relied on by wildlife; hence the statutory requirement that wildlife habitat is to be accounted for as the agricultural landscape changes.

Early salinity program implementation calculated habitat replacement requirements on an acre-for-acre basis, assuming that 100% of viable habitat along a canal or lateral would disappear after the canal was replaced with a pipeline. As the program has evolved, it has been recognized that qualitative rather than quantitative measurements are preferable. Habitat to be lost is surveyed and values assigned that can equate to the values of potential replacement property. The habitat value of a proposed replacement property must equal or exceed values of the wildlife habitat predicted to be lost as a result of a salinity control project. Qualitative analyses of proposed replacement habitat include location of the prospective replacement property (riparian corridors are preferred locations), its current condition, the potential for improvement of the property to benefit wildlife, and its viability as a long term habitat. The acquired property must be improved in a manner that equates to the values lost as a result of the salinity control project.
The following are minimum requirements for habitat replacement for salinity control projects, as determined by Reclamation in coordination with state and federal wildlife agencies:

- There shall be no net loss of habitat function. This is to say that acreage amounts need not be the same, but that there is no net loss in total value to wildlife.
- A guarantee or reasonable assurance must be provided that the replacement habitat features will survive and function (e.g., with an assured water supply) for the life of the project, assumed to be 50 years. The replacement land must be protected through acquisition or easement, and long-term management and monitoring is necessary to assure that the needed wildlife values are maintained.
- Long-term management must assure that changing conditions over time (e.g. introduction or spread of exotic plant species) will not reduce the function of the site as wildlife habitat.
- Habitat replacement should be implemented in advance of project (pipeline) construction or otherwise, must occur concurrently.

Figure 1. The Huntington-Cleveland Irrigation Company's Cleveland Canal provides an example of wildlife habitat expected to be lost when the canal is replaced with a pipeline.

REPLACEMENT STRATEGIES

The approach to identifying the specific method for habitat replacement for each salinity control project follows the same guidelines generally used for wildlife management and environmental compliance. The ideal situation for any project is avoidance of impacts. Avoidance of impacts means not allowing impacts to occur in the first place. Although difficult to achieve for most salinity control projects, this is the preferred approach to project implementation—designing a project so that it doesn't cause impacts, and a resource remains unaffected and viable during and after project implementation. If avoidance of impacts to habitat can be achieved for a salinity control project, then there is no need to undertake habitat replacement for that project.

When impacts to habitat are unavoidable, then habitat replacement is required. Post-construction preservation of pre-construction existing habitat can be an acceptable means of fulfilling the habitat replacement requirements of the salinity control program. Preservation of existing pre-project habitat means designing and implementing a management plan that assures that the habitat will remain viable for the life of the project. For example, habitat along a canal which is also located near natural seeps or a natural watershed might be designated for preservation, with monitoring and management intervention (water supply, invasive species control, etc.) as needed.

Where avoidance and preservation are not feasible, then acquisition and improvement of replacement property is the required approach.

All of these strategies for fulfilling the salinity program wildlife habitat replacement requirements have been tried over the years, with varying degrees of success. The following section provides specific examples of habitat replacement efforts.

Leaving Canal Prisms Open to Capture Stormwater Runoff

Leaving canal prisms open, if successful, can provide the preferred 'in kind in place' replacement of wildlife values foregone. An abandoned canal prism, left open, might have the potential to capture sufficient snowmelt, residual water from adjacent areas, or storm and natural seepage water that could continue to support existing vegetation and wildlife habitat along the prism. Analysis is necessary to determine whether there are reliably sufficient water sources to support the vegetation types in place. Two examples of this approach are listed below.

Burns Bench Irrigation Company Salinity Control Project: The Burns Bench project, completed in 2004, replaced the Burns Bench Canal, Murray Ditch and Burton Ditch near Jensen, Utah. The total length of the canals replaced with pipeline was 11.5 miles. Canal seepage-induced wetlands were predicted to be impacted due to the elimination of the water source. The excavation and installation of the pipeline along the canal right of way removed grassy, herbaceous vegetation and shrubs serving as habitat to a number of endemic wildlife species. To replace habitat values foregone for wetland and riparian impacts, the canals were left open to collect runoff and spring seepage in order to maintain and where possible expand the existing habitat in comparison to pre-project conditions. Most of the canal prism changed from bare soil to a vegetated community within one year (Lopez, 2009). Five years after project completion, annual monitoring by Reclamation continues to verify that the required habitat values are being maintained. This is consistent with general observations of abandoned canals-- when annual maintenance including clearing of vegetation no longer occurs, vegetation is established in the prisms within a year or two. In this particular project, common cattail (*Typha latifolia),* Fremont cottonwood (*Populus fremontii*) and coyote willow (*Salix exigua*) are abundant. Other abundant species include common reed (*Phragmites australis),* and Reed canarygrass (*Phalaris arundinacea*). The presence of these invasive species could be considered a double-edged sword- they do provide habitat value and for older projects, the management approach typically allowed invasives to remain in place, being controlled as necessary to prevent their spreading further. More recently, the management strategies for habitat replacement properties have included plans to replace invasive species with native species over time.

<u>South Lateral Salinity Control Project:</u> The South Lateral project, completed in 2002, replaced with pipeline approximately 2.9 miles of the Duchesne Feeder Canal South Lateral near Bridgeland, Utah. The habitat replacement plan for this project identified 1.27 acres of riparian habitat along the ditch prism of South Lateral and 3.44 acres of side slope habitat along the hillside traversed by the lateral. The plan further stated that habitat replacement would not be required since these habitat acres would remain viable following piping of the lateral due to the seep water from a near hillside area. This habitat replacement plan was consistent with the stated preference of the U.S. Fish and Wildlife Service to avoid impacts where possible. Seven-plus years after project completion, replacement of wildlife values foregone has been achieved consistent with the management plan. Lower areas of the canal that are close to irrigation fields continue to support coyote willow (*Salix exigua)* and Fremont cottonwood (*Populus fremontii)*. Other areas along the canal support some upland vegetation species.

It is worth noting that when dealing with small acreage amounts as with this project, it would be difficult to come up with a stand-alone replacement property that meets all the desired criteria, except by combining with a number of other small-acreage needs to establish a larger replacement property that fulfills the requirements for several projects.

It should also be noted, in using abandoned canal prisms for habitat replacement over the 50-year life of a salinity control project, that as urban development around canals occur, canal companies may fear liability issues leading to a need to fill in old prisms and/or abandon easements. In such cases, they would have to reinitiate coordination with Reclamation and the wildlife agencies to plan and implement an alternate habitat replacement plan.

Managing Abandoned Canal Prisms (Stormwater Supplemented as Needed by Irrigation Water) to Maintain Habitat

Simply leaving canal prisms in place does not guarantee that viable wildlife habitat will survive over the long term. Often, there is insufficient natural water to support mature cottonwoods and riparian vegetation that were created by canal seepage. Managing abandoned canal systems can be an acceptable means of preventing habitat loss resulting from salinity project implementation. This is the approach that was used for the Ferron salinity control project habitat management plan.

The Ferron Project watershed area covers 191,000 acres. It is located in Emery County, Utah. The salinity control project area included 8,747 acres of irrigated land. The entire canal system was replaced with pipelines and all laterals and sub laterals within the project area were eliminated. Sprinkler irrigation replaced flood irrigation on over 97% of the farms within the project area.

Predicted habitat loss due to the salinity control project totaled 60.5 acres. The Ferron Canal and Reservoir Company designed a habitat replacement project to maintain 131 acres of habitat (64.4 acres of that total to directly offset project impacts, and an additional 66.6 acres as assurance that project impacts would be offset for the life of the project, with the possibility that some of this acreage might be determined to be bankable for use by future salinity control projects) along or near abandoned canals as part of its salinity control irrigation project. Maintenance of these acres is accomplished by guaranteeing appropriate water supply so as to maintain existing habitat along the canal Right of Way. This water supply is anticipated to be met through natural means, or through inadvertent operational overflow of regulation ponds. If this is not the case, the canal company has committed to provide irrigation water consistent with existing water rights to ensure maintenance of this habitat. Where a proposed habitat replacement plan includes providing water from the irrigation company sources, the water must be diverted and used consistent with the company's existing water rights, or a change to water rights (such as a change in point of diversion and nature of use) must be sought from the state engineer. Alternatively, a new non-irrigation company water supply would need to be obtained and changed to make it viable for the habitat management plan.

Information acquired late in 2008 from monitoring and conversations with landowners along the habitat management area indicate a potential problem not foreseen when the habitat replacement project was approved. In the 5 years since the project was approved, vegetation within the canal prism has survived, and thrived, since the canals are no longer cleaned annually for water transportation use. As a result, vegetation at the ends of the canals is receiving less water, which could become problematic for some of the vegetation, especially mature cottonwoods. Follow-up with the canal company is needed to see what adjustments might be made to ensure long term viability of the habitat.

Figure 2. The Ferron Project's habitat replacement plan includes supplemented water in the abandoned canals when natural stormwater runoff is not sufficient to maintain vegetation, especially mature cottonwoods.

<u>Acquire and Improve Property in Partnership with State or Local Agency, Turning Over Long Term Management to that Agency</u>

Any property acquired for habitat replacement for a salinity control project must be managed to ensure that wildlife values are maintained for the life of the project. An ideal means of achieving the desired management is to partner with a state or local agency that desires oversight of and access to such a property. Reclamation has routinely coordinated on all wildlife replacement needs with the Utah Division of Wildlife Resources (DWR). Where both agencies' needs can be accommodated by a particular project's wildlife replacement requirement, meeting these joint needs becomes a high priority and a 'win-win' situation.

One example of a project's habitat replacement needs resulting in a good fit with DWR's wildlife management goals is the Mallard Springs property. As noted above, small projects with small habitat replacement acreage requirements are not conducive to management by state wildlife agencies; such scattered, small parcels would be difficult to staff and fund. However, when a project (or combination of projects) has a large enough acreage requirement, an ideal situation exists for partnership. Such was the case with Mallard Springs in Duchesne County, Utah, about 1.5 miles southeast of the town of Myton.

Mallard Springs Property: The Mallard Springs Wildlife Management Area (WMA), now managed by the DWR, fulfills a 163-acre wildlife replacement requirement for the Duchesne County Water Conservancy District (DCWCD) Salinity Control Project (Phase I). This pipeline project replaced five existing open channel canals, totaling about 31 miles. The 160-acre property acquired for habitat replacement is part of the 247-acre WMA and was built in 1993 by Reclamation, with design input and coordination from DWR and the U.S. Fish and Wildlife Service. The property consists of emergent wetland vegetation in a series of depressions with an open water stream flowing through them. Each depression is connected by a 40–foot-long underground rock filled channel. Wet meadow areas are present at this property. The DCWCD is responsible for maintaining the irrigation system. DWR manages the property for waterfowl habitat and hunting, and it also supports a wide variety of birds and mammals.

Figure 3. The Mallard Springs Wildlife Management Area, which fulfills the habitat replacement requirement for DCWCD Salinity Control Project Phase 1, was a cooperative effort in which the applicant acquired the property, Reclamation worked with the State DWR and U.S. Fish and Wildlife Service to design and construct habitat improvements, and the State DWR manages the property.

Acquire and Improve Property in Partnership with a Non-Governmental Entity

In addition to partnering with state or local agencies, Reclamation has successfully partnered with non-governmental entities to fulfill habitat replacement needs. There is a variety of mechanisms that can be used to assure management for wildlife for the life of the relevant salinity control project. One tool is execution of a conservation easement, filed with the county, which assures continued use of the property for wildlife habitat. An example provided below is the Wall Property in Uintah County, Utah. Another tool is partnership with a corporation, as was achieved with the Cottonwood Property in Emery County, Utah.

Wall Property: The Wall property south of Jensen, Utah totals 127 acres and serves as wildlife replacement for the DCWCD Salinity Control Project (Phase II) as well as the Union Canal Salinity Control Project. The DCWCD Phase II project replaced three canal systems totaling slightly less than 52 miles with pipeline, and required 53.78 acres of wildlife habitat replacement. The Union Canal project replaced 4.75 miles of canal and had a wildlife replacement requirement of 3.18 acres. In 2002, the U.S. Fish and Wildlife Service Utah Field Office recommended this property for the purposes of fish and wildlife habitat replacement for the Salinity Control Program (USFWS 2002.). The property was acquired by the DCWCD and was placed in a perpetual conservation easement filed with Uintah County in July 2003. DCWCD coordinates with Reclamation in implementing the management plan on this property, which includes selective grazing for whitetop control as well as other invasive species control. The habitat value of this property has dramatically improved over the past 5 years, and large numbers of migratory birds (including Sandhill cranes) and large and small mammals are commonly observed there. The location of this property within the designated critical habitat of four endangered Colorado River fish species adds to its value.

Figure 4. The Wall Property's wildlife habitat values have dramatically increased since implementation of the habitat management plan. Management includes strategic fencing, grazing to target control of whitetop, and longer range plans to control tamarisk and Russian olive.

Cottonwood Property: This 100-acre property is owned by PacifiCorp, and is located in Emery County, Utah. This property serves as wildlife replacement for the Castle Valley winter water and anticipated Cottonwood salinity projects. The winter water project consisted of replacing the winter stock water function of the irrigation canal with a piped, pressurized winter stock water distribution system. This allowed utilization of the canal to be terminated during the non-agricultural season, thus eliminating all winter seepage loss. This, in turn, eliminated all winter saline return flows associated with the canal.

The Cottonwood Creek Restoration and Mitigation Project involved the protection and restoration of wetland and riparian habitat on land along Cottonwood Creek. The project was jointly designed and implemented by PacifiCorp, Reclamation, DWR, and the Emery Water Conservation District, and this cooperative group meets annually to review the overall status of the property and plan any needed management or maintenance activities. This property consists of natural wetland, riparian, and upland areas along the Cottonwood Creek floodplain which were enhanced by the addition of rock sills in the creek. Based on the success of this project, PacifiCorp is continuing to coordinate with Reclamation, DWR, and water users in the Price-San Rafael Salinity Control Project Area to explore prospective future habitat replacement projects.

Figure 5. The Cottonwood Property habitat replacement plan provided a combination of enhancement of natural riparian features, a man-made pond, and vegetation management to create a thriving wildlife habitat.

Figure 6. A Great Blue Herron using Cottonwood Creek within habitat property, May 2009

Partnership with Private Landowners to Dedicate Lands and Water to Wildlife Habitat

Exploring all possibilities to establish successful wildlife replacement for salinity control projects, one proposal approved by Reclamation involved a set of agreements between the irrigation district and private landowners whereby the landowners agreed to manage portions of their privately owned properties for the benefit of wildlife. The risk of landowners not fulfilling their agreed upon responsibilities for the life of the project was foreseen by the proposing irrigation company, and they signed agreements with 'backup' landowners who would be willing to participate in the future, should the need arise, to maintain the required acreage and habitat quality. In approving the Wellington Project habitat replacement plan, Reclamation observed its potential value of enhancing local appreciation for wildlife and wildlife habitat, and so far, this has proved to be the case. Landowners who had not previously paid particular attention to the flora and fauna on their farm began to take the time to observe the wildlife and gain some appreciation for the value of preserving habitat.

Wellington Properties: The properties managed for habitat replacement for the Wellington salinity control project are located in and around Wellington, Utah. Unlike all other habitat replacement activities overseen by Reclamation, which only served to fulfill requirements for 'off farm' salinity control improvements, these properties include sufficient acreage to also serve as habitat replacement for the 'on farm' portions of the Wellington salinity control project. The Wellington project replaced approximately 28.1 miles of canals with pipeline and used a combined on/off farm system (sprinklers) to improve irrigation efficiency. The project also involved the installation of a winter water delivery system for livestock.

The Wellington properties managed for wildlife total 199.4 acres. After initial design of the project was completed by DWR, the Wellington Canal Company (WCC) contracted with Price River Soil Conservation District (PRSCD) to plan and supervise the implementation of those wildlife enhancement acres. The goal was to achieve a surplus bank of wildlife enhancement acres up to and beyond the 50-year commitment. Monitoring of the properties thus far has shown that while there were isolated failures in terms of planting of specific vegetation, overall the properties are maintaining the necessary values and function to replace the wildlife values lost as a result of the salinity control project.

Figure 7. A portion of the Wellington Project habitat replacement plan located on private property.

Figure 8. View of habitat along Wellington Canal, maintained as part of the Wellington Project's habitat replacement plan.

As noted in the discussion of the Ferron Project, the dedication of water to a habitat replacement project must be consistent with existing irrigation company water rights or an approved change would need to be made to these water rights, or a new water right must be obtained and moved to the project. There are a variety of possible approaches, depending on the size of the property being managed for the benefit of wildlife. For example, small parcels on private land could benefit from the irrigation of a pasture which could occur under existing unmodified water rights. Where crops are irrigated, adjacent habitat has been observed to receive enough return water to not only survive, but thrive. Although return flows might have benefits to wildlife in some circumstances, the issue of salinity loading need to be carefully considered. Larger projects of several hundred acres would likely not be viable without dedicated water rights.

CONCLUSION

In over 15 years of overseeing salinity control projects, Reclamation's Provo Area Office has worked with the applicants and state and Federal wildlife officials to assure appropriate wildlife habitat replacement for each project. A variety of different strategies has been pursued, and while there have been isolated cases where habitat did not achieve and sustain predicted values, overall, all of the different strategies have shown at least 'average' success. On the whole, we conclude based on our experience to date that the most successful projects are those with large acreage, fulfilling requirements for more than one salinity control project, undertaken in partnership with another agency or entity that has an interest and the ability to assure long term viability of habitat values.

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MODELING SPATIAL AND TEMPORAL VARIABILITY IN IRRIGATION AND DRAINAGE SYSTEMS: IMPROVEMENTS TO THE COLORADO STATE IRRIGATION AND DRAINAGE MODEL (CSUID)

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ABSTRACT

The Colorado State University irrigation and drainage model (CSUID) is a three dimensional variable saturated-unsaturated numerical model that simulates the subsurface flow and transport processes. A wide range of enhancements have been done to CSUID to fully simulate the response of agricultural fields to external stresses such as subsurface drainage systems, root extractions and irrigation activities. The model is also capable of simulating salinity transport process through the vadose zone and in the saturated zone. The partition of salinity between the soil solid phase and the water phase is included in the model to simulate the accumulation of salts in the root zone.

The strength of CSUID is in its ability to simulate irrigation-drainage activities taking into account spatially and temporal variably in water quality and quantity and under spatial heterogeneous soil properties. Soil properties such as hydraulic conductivity, porosity, Van Genutchen retention curve parameters, storativity, dispersivity, partition coefficients are all modeled as spatially variables. Having a model with these capabilities is an important step toward understanding the uncertainty in the design and management of irrigation-drainage systems. The model contains a Graphical User Interface that allows the user to visualize the input and output.

INTRODUCTION

Numerical models are essential tools in the management of water resources. The role of irrigation and drainage model models is to improve our understanding of the hydrogeological processes for the entire subsurface zone and also as predictive tools to help in making decisions. Simulating the entire subsurface zone, saturated and unsaturated zones, is of valuable significance for better management of irrigation and drainage activities. Rubin (1968) was a pioneer in the modeling of unsaturated and saturated zones as one process. Freeze (1972) used one flow continuity equation to numerically simulate the entire subsurface zones. The nonlinearity of the flow equation was the main challenge for robust and computational effective models. Small time steps and fine grid schemes are usually used to obtain acceptable numerical results from the nonlinear equations. This, in turn, normally hampers the use of such models at the field

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scale due to the expensive computational effort. Two numerical methods are usually used to solve nonlinear equation systems, there are: (1) Picard method, and (2) Newton Raphson method. The Newton Raphson method shows that it is more robust and computationally efficient but its stability depends on the initial conditions and the spatial and temporal discretization of the problem at hand. The Picard method is widely used due to its unconditional stability.

The Colorado State University Irrigation and Drainage model (CSUID) is a decision support tool that is used in the design and management of irrigation and drainage systems. It facilitates the calculation of root growth calculations, flow and transport in the unsaturated and saturated zones, drain discharge, and crop yield estimates (Garcia et al 2002). CSUID was originally designed to numerically apply the quasi-three-dimensional finite-difference scheme to solve the flow equations in the unsaturated zone using a one dimensional Richard's equation and the three dimensional equations to solve the flow in the saturated zone (Manguerra and Garcia 1995). The model was enhanced later to solve the fully three dimensional case.

The objectives of this paper are to introduce the enhancements to CSUID which include (1) the use of the modified Richard's equation to solve the entire subsurface as a single flow process, (2) enhancements to the numerical solver efficiency for flow by using the mixed form of the Richard's equation (Celia 1992) to reduce the mass balance error, (3) the use of the dispersion-advection equation with the full dispersion tensor matrix and adsorption–desorption of ions in the water soil system, (4) new solvers were added for flow and transport processes using the preconditioned conjugate gradient method, (5) the ability of the model to simulate drainage system outflow and salinity hydrographs were enhanced, (6) the model capabilities were expanded to accept three dimensional soil properties for all model inputs which include hydraulic conductivity, dispersivities, porosity, specific storativity and Van Genutchen parameters (α, n, θ_r).

Flow Equation

The modified Richard's equation (equation 1) that accounts for the unsaturated-saturated flow is used. The modified Richard's equation differs from the classical Richard's equation (1931) in that it accounts for two different storage mechanisms. In the saturated zone the specific capacity models the storage mechanism in the unsaturated zone, the specific capacity equal zero in the saturated zone and the specific storativity term will be dominant.

$$\frac{\partial}{\partial x}\left(k_{xx}(\psi)\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{yy}(\psi)\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_{zz}(\psi)\frac{\partial h}{\partial z}\right)+Q=C(\psi)\frac{\partial h}{\partial t}+S_s\frac{\theta}{n_e}\frac{\partial h}{\partial t} \qquad (1)$$

Where:

h is the hydraulic head [L] ,

$k_{xx}(\psi), k_{yy}(\psi), k_{zz}(\Psi)$ are the hydraulic conductivity in the principle direction x,y,z respectively [L/T],

ψ is the capillary pressure [L],

Q is the volumetric source or the sink per unit volume of the aquifer [T^{-1}],
$C(\psi) = \dfrac{\partial \theta}{\partial \psi}$ is the specific capacity [L^{-1}],
S_s is the specific storativity [L^{-1}],
θ is the volumetric water content [L^3/L^3],
n_e is the effective porosity [L^3/L^3].

The saturation pressure relationship is simulated by using the Van Genutchen relationship (Van Genutchen 1980). This model is usually preferred by modelers due to the continuity of the equation. The Van Genutchen equation is

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + (\alpha h)^n\right)^m} \qquad (2)$$

Where:
θ_s is the saturated water content,
θ_r is the residual water content,
α, n, m are Van Genutchen model fitting parameters.
The α, n, θ_r, porosity, storativity, hydraulic conductivity and mechanical dispersion are assigned to the model as three dimensional variables to account for the spatial variability and uncertainty in soil parameters.

Transport Equation

The transport process is modeled mathematically by the advection dispersion equation (equation 3). The transport equation simulates the partitioning of salinity between the solid phase and the water phase. The solution supports also the full dispersion tensor matrix.

$$\frac{\partial(\theta C)}{\partial t} = \frac{\partial}{\partial x_i}\left(\theta D_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{\partial}{\partial x_i}(\theta v_i C) + q_s C_s + R \qquad (3)$$

Where:
C is the concentration [M/L^3],
i, j represent the x,y,z direction,
D is the hydrodynamic dispersion coefficient [L^2/T],
v is the seepage velocity [L/T] ,
q_s is the sink-source term and defined as the volumetric flux of per unit volume of aquifer [T^{-1}],
C_s is the source or the sink concentration [M/L^3],
R is the sorption term [ML^3/T].

The salinity sources could be the irrigation water salinity and boundary condition salinities. The sink sources could be outflow salinity from the drain.

Boundary Conditions

The model allows different types of boundary conditions. First type boundary conditions can be used such as constant head or constant concentrations. Second type boundary conditions include a specified flux with specified boundary conditions. These boundaries allow the modeler to simulate a wide range of problems. Currently, the CSUID model is modified to account for the third type boundary condition or general boundary condition as is called in MODFLOW documentation (McDonaldand Harbaugh 1988). This boundary condition imposes a linear relationship between an external constant head and the lateral flow into the model domain. The general boundary condition allows the change in lateral flow into the model as the difference between an external head and an internal head change.

Irrigation

The modeler can divide the simulated area into several basins. Each basin can be assigned a different irrigation schedule. The model allows the user to assign different irrigation application depths with different salinity concentration for each irrigation. This capability will enhance the flexibility and applicability of the model. CSUID can be used as a design tool for irrigation schedules based on the response of a water soil system to the evapotranspiration stress. The importance of CSUID is that it takes into account the impact of soil properties and the contribution of shallow water to the root uptake.

Root Extraction and Crop Yield Functions

The general equation to model root extraction can be described in equation (4). Where $\alpha(h, h_\phi, x)$ is the root zone response function, and b(x) represents the root growth function. CSUID gives the user the option to choose different combinations of these two functions. Another family of crop yield functions are used in CSUID to approximate the response of the crop to stress resulted from water content shortage and osmotic pressures induced by saline water. The reference evapotranspiration is an input parameter which could be obtained from other sources such as ET estimation models, remote sensing, etc. Other parameters modelers need to obtain are the crop coefficients that represent the impact of crop conditions on water uptake.

$$S(h, h_\phi, x) = \alpha(h, h_\phi, x) b(x) T_p \tag{4}$$

Where

$S(h, h_\phi, x)$ is the volumetric root water uptake per unit volume of the aquifer [1/T],

$\alpha(h, h_\phi, x)$ is the water stress and osmotic stress response function[-],

h is water head [L] ,

h_ϕ is the osmotic head [L],

$b(x)$ is the root growth function [L^{-1}],

T_p is the potential transpiration [L/T],

Subsurface Drainage

The drain flow can be simulated using the conductance equation such as equation 5 where the flow into the drain is a function of the elevation of water table above the drain and the conductance of the drain. The conductance of the drain represents the ease of water movement from the soil to the drain.

$$Q_d = C_d (h - D) \tag{5}$$

Where
Q_d [L^3/T],
C_d is the drain conductance [L^2/T],
h is the water table above the drain [L],
And D is the elevation of the drainage [L].

Numerical Solution

Richard's equation (equation 1) is a nonlinear equation that has a limited number of analytical solutions for simplified cases. This explains the popularity of the numerical solutions that are based on finite difference or finite element approximations of the Richard's equation. Head based Richard's equation usually produce large mass balance errors (Celia 1990), while water content based equations usually produce acceptable mass balance errors. However, the water content based equation will not be able to solve the flow equation in the saturated zone since the change in the water pressure does not produce a change in the water content. Celia suggested using the mixed Richard's equation 6. This equation is used in SWAP (van Dam et al., 1997) and HYDRUS (Simunek et al., 1998, 1999a). The precondition conjugate gradient method is used to solve the system of nonlinear equations in an iterative way.

$$C\frac{\partial h}{\partial t} + \frac{\theta}{n_e} S_s \frac{\partial h}{\partial t} \cong \frac{\theta^{n,m-1} + C^{n,m-1}\left(h^{n,m} - h^{n,m-1}\right)}{\Delta t} + \left(\frac{\theta}{n_e}\right)^{n-1/2} S_s \frac{h^{n,m} - h^{n-1}}{\Delta t} \tag{6}$$

Where

n represents the time level,
m iteration level,
Δt time step.

The advection dispersion transport equation (equation 2) can be linear or nonlinear depending on the adsorption term. If the linear isotherm is used to calculate the sorped phase then the transport equation will be linear and nonlinear if the Freundlich or Langmuir isotherms are used.

The Eulerian approach is used to solve the transport equation so the concentration will be approximated at fix grid nodes as opposed to Lagrangian method where the grid is moving or deforming with the flow. The use of Eulerian approach is impacted by the problem of artificial oscillation and numerical dispersion. This problem can be overcome by using small time steps and small spatial grid size. A Courant number (vt/x) of less than 2 will eliminate the oscillation, where v is the seepage velocity, t is the time step and x is grid size.

Sorption Desorption Process

The partitioning of chemical ions between the water phase and soil phase are approximated by a linear relationship. The nonlinear Freundlich and Langmuir sorption isotherms are avoided in this model in order to reduce the nonlinearity of the simulation that already exists in the flow equation. The adopted approximation of the absorption-desorption process is a linear relation with a maximum salinity capacity that the water can hold, after which the ions will be concentrated on the soil grains or as separate salt solid phase.

Model Limitations

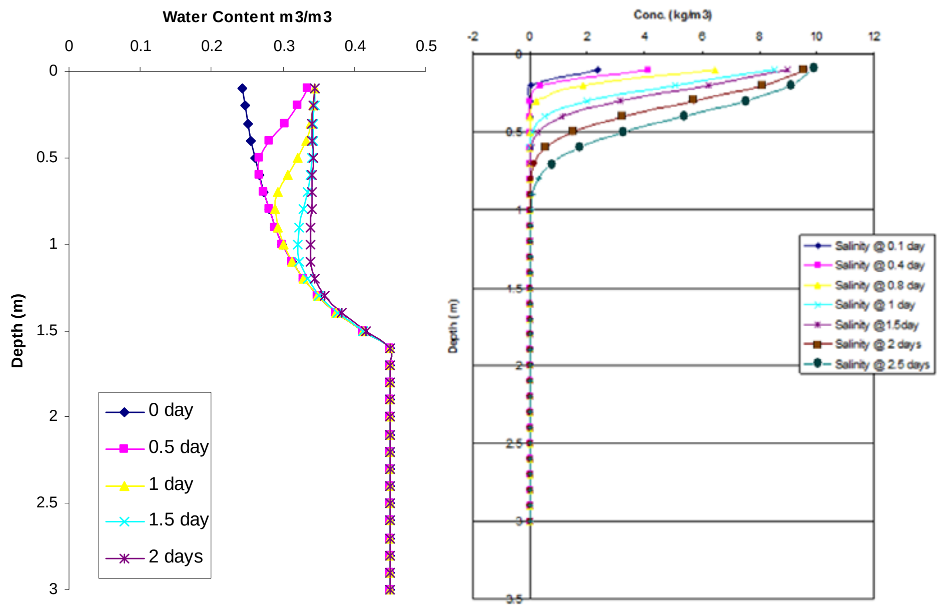
CSUID only simulates the liquid phase of water. The impact of the entrapped air on infiltration and swelling of the soil are not simulated in the model. Near dry conditions where water transmits to the atmosphere as vapor phase are not simulated. In order to simulate the evaporation process at the soil surface the liquid phase flow, the vapor phase flow and heat transfer equations should be solve simultaneously.

The model does not simulate the hysteretic phenomena in water flow and also ignores the potential gradients resulting from the different chemical concentrations, temperature and osmosis pressures. These limitations are not restrictive to the numerical simulation of the saturated-unsaturated flow.

ONE-DIMENSIONAL ILLUSTRATIVE EXAMPLES

Infiltration Example

The model was run to simulate the infiltration in a column of soil with a hydraulic conductivity of 5 m/day. An irrigation event of 8 cm/day and of salinity concentration of 10 g/L is applied for two days. The changes in water content and salinity profiles were plotted in Figures 1a, 1b.



(a) (b)

Figure 1. (a) Water Content profile with time, (b) Salinity profile with time after saline irrigation event.

Leaching Example

In this example the initial salinity of the soil water profile was assumed to be zero and it was irrigated using saline water (5 g/L) for one day, then a fresh water (rainfall event) was assumed. The output results (Figure 2) show the salination and desalination of root zone following each of the events. This example is for homogenous soils and explains the leaching of salinity from the root zone. If heterogeneous soils are used, then more flow will occur in the high conductivities zones and salinity will remain in low conductivity zones.

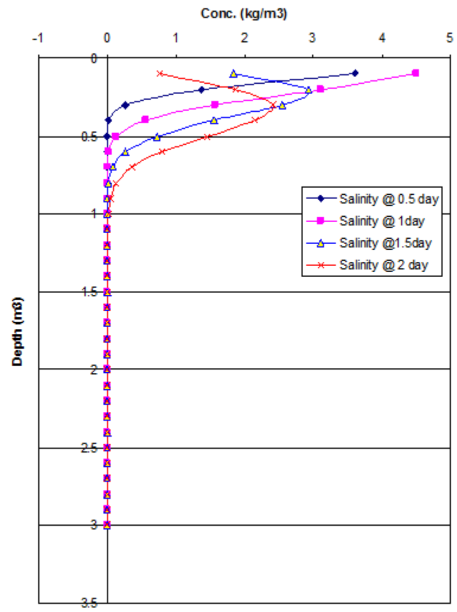


Figure 2. Salinization of the root zone due to saline water irrigation event followed by a rainfall event with zero salinity

Three Dimensional Water Table Control Problem

In this example, an irrigation event is applied on part of the field to simulate the impact of irrigation on a shallow water table. Waterlogging problem can be flagged if the water table reaches the root zone or if the water content of the root zone reaches saturation. Figures 3 and 4 show a cross section of the field with the change of water content distribution and salinity concentrations with time.

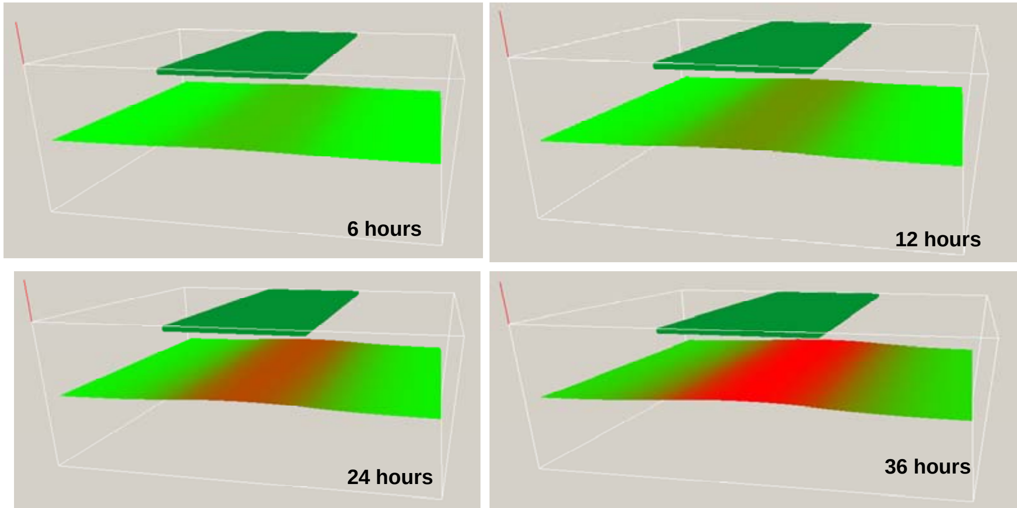


Figure 3. Response of water table to irrigation event on part of the field.

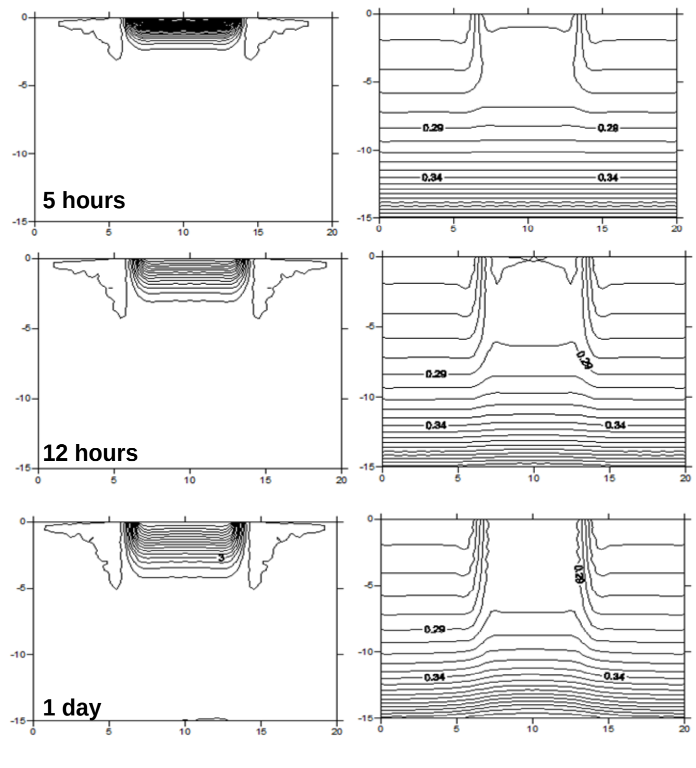


Figure 4. Cross sections of a field under irrigation using saline water. (a) is the salinity distribution with time, (b) water content distribution with time.

Drainage Example

In this example, drainage is used in the input to simulate the response of the water table to a subsurface drainage pipe. Figure 5 shows the change in water table with time. CSUID will also generate a flow and salinity hydrograph for each drain. The drain hydrograph shown in Figure 6a and 6b shows that the outflow rate is higher at the start of the simulation and it decreases until it reaches a steady state flow rate. This is because at the start of the simulation the water table is high above the drain and the hydraulic gradient is at its maximum. As the water table decreases, the hydraulic gradient decrease and the flow rate, in turn, will decrease.

Figure 6a shows the hydrographs for two cases, the first case is a hydrograph without irrigation and the second case is a hydrograph with irrigation. Figure 6b shows the hydrograph for a field that was irrigated for 5 days. The response of the hydrograph to irrigation can be clearly noticed. The hydrograph in Figure 6c shows the salinity of the drain for a case when a saline pulse of irrigation is applied followed by irrigation with water of very low salinity.

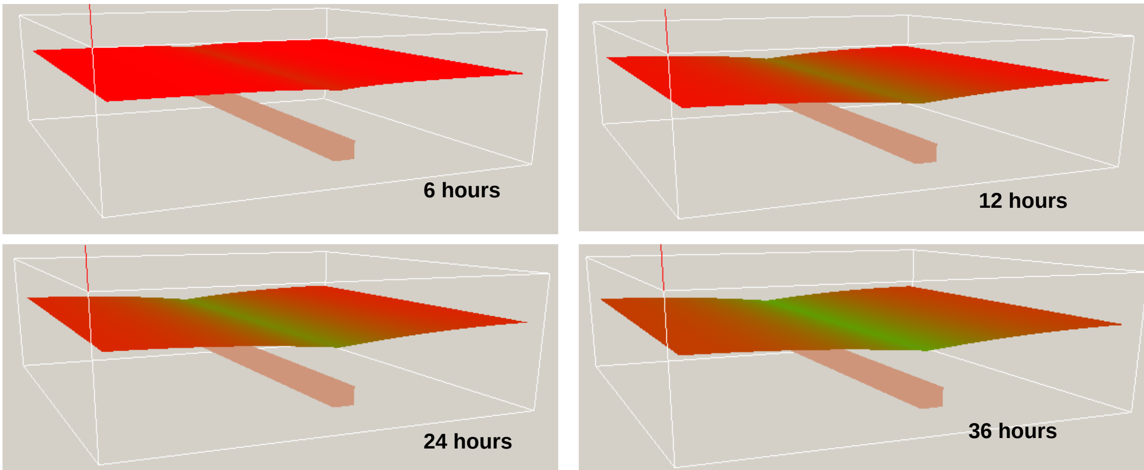
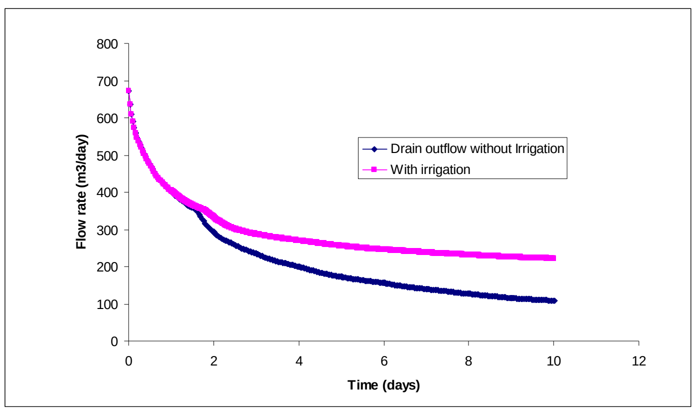
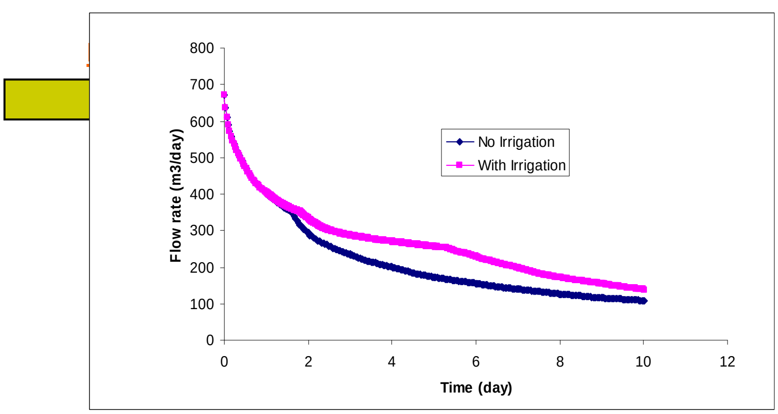


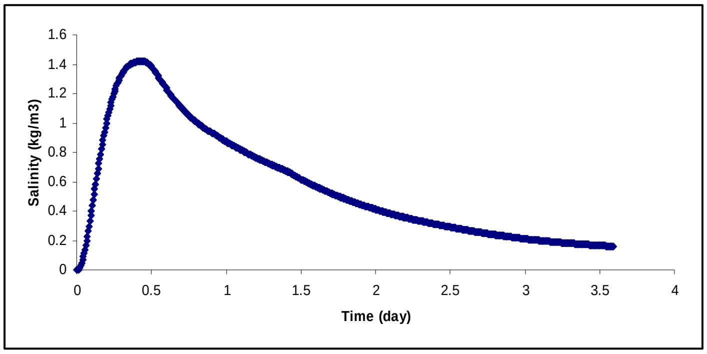
Figure 5. Water table response with time to drainage system.



(a)



(b)



(c)

Figure 6. Drain hydrographs for different cases, (a) Drain outflow hydrograph for the field with irrigation and without irrigation, (b) Outflow hydrograph for irrigation of 5 days then the irrigation stopped, (c) Salinity hydrograph of irrigation using a pulse of saline water then continue the irrigation using water with no salinity.

CONCLUSION

This paper describes the enhancements to the Colorado State University Irrigation and Drainage (CSUID) model. CSUID is an effective tool that can be used to simulate the shallow groundwater systems and simulate irrigation and drainage activities. The ability of the model to consider the variability in the soil properties in all three dimensions is a unique feature that provides a unique modeling capability. The numerical solvers were modified to minimize the mass balance error by using the mixed head and water content based Richard's equation introduced by Celia (1990). The preconditioned conjugate gradient method is used to solve the flow equation and the transport equation. CSUID has a graphical user interface that helps the modeler to build the dataset and assign input parameters and visualize the output. Illustrative examples show that the model is able to response as predicted under certain stresses.

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INNOVATIVE DRAINAGE MANGEMENT IN THE PANOCHE AREA, SAN JOAQUIN VALLEY, CALIFORNIA

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ABSTRACT

The drainage reuse portion of the Grassland Bypass Project has been very successful in reducing the amount of drainage water discharged to the San Joaquin River while maintaining the productivity of approximately 100,000 acres of highly productive agricultural lands in the Central Valley near Merced and Los Banos.

The Grassland Bypass Project is an innovative program that was designed to improve water quality in the channels used to deliver water to wetland areas. Prior to the Project, subsurface drainage water was conveyed through those channels in route to the San Joaquin River and limited their availability to deliver high-quality habitat supplies. The Project consolidates subsurface drainage flows on a regional basis and utilizes a portion of the federal San Luis Drain to convey the flows around the habitat areas.

The Grassland Bypass Project began in Water Year 1997 (October 1996 though September 1997). The volume of drainage has been reduced significantly since this time including a selenium load reduction of 85% in Water Year 2008 compared to pre-project discharges in Water Year 1996. Additionally the volume of drainage discharge has been reduced by 73%, the salt load by 72%, and the boron load by 69%. These reductions are possible through; 1) Conservation, which includes improved irrigation application and canal lining; and 2) Reuse and treatment, which includes recycling, use of subsurface drainage water on salt tolerant crops such as Jose Tall Wheatgrass and pistachios.

INTRODUCTION AND BACKGROUND

The Grassland Drainage Area is a highly productive agricultural region on the Westside of the San Joaquin Valley (see Figure 1). The region is approximately 100,000 acres lying generally south of Los Banos, between the San Joaquin River and Interstate 5. The Grassland Drainage Area includes Broadview Water District, Camp 13 Drainage District, Charleston Drainage District, Firebaugh Canal Water District, Pacheco Water District, and Panoche Drainage District, along with some areas that are not incorporated into any district. The region is overlain by coastal range sediments that are generally heavy clays and contain a variety of dissolved minerals including boron and selenium. These soil conditions have contributed to a healthy and productive agricultural environment but

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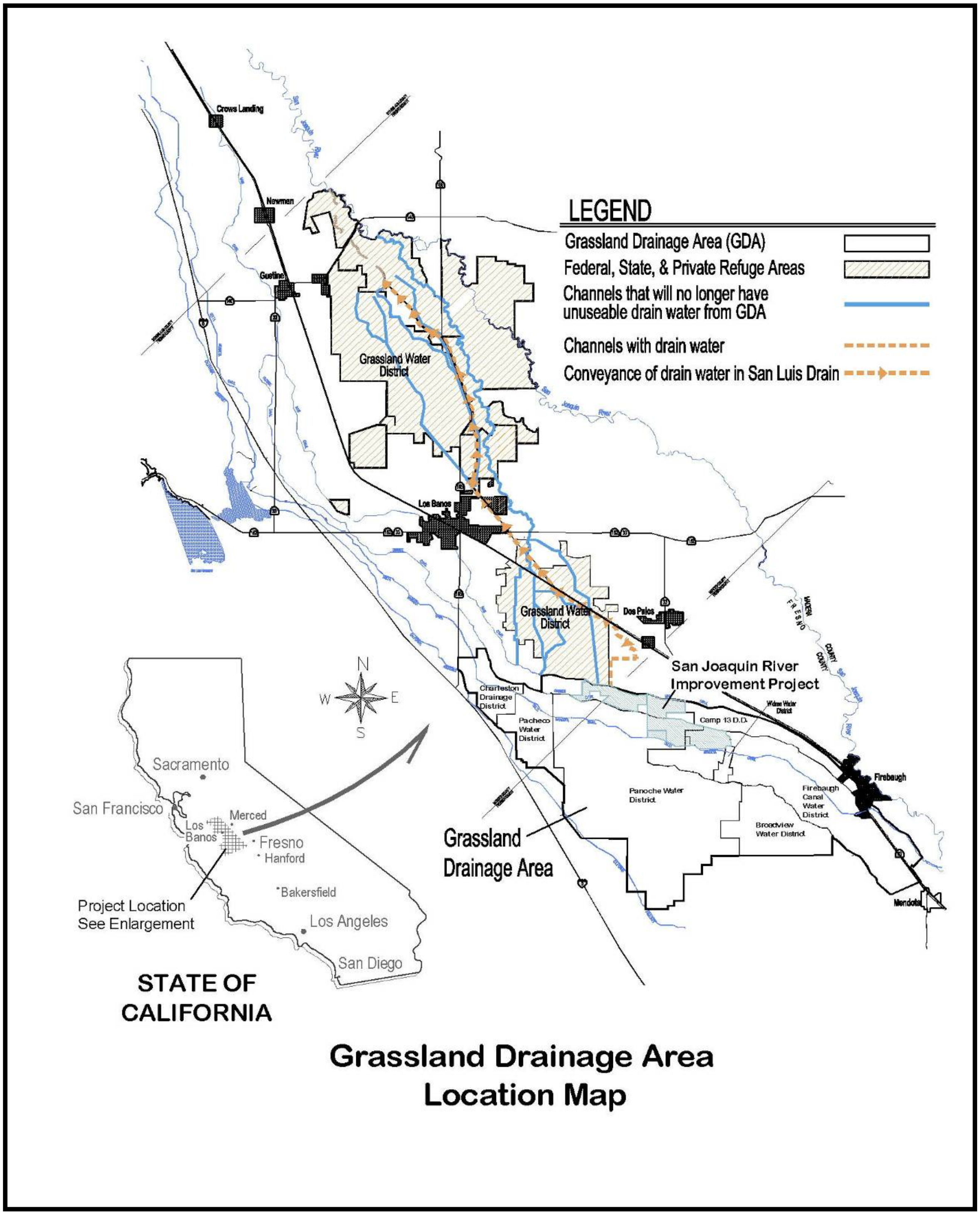

Figure 1. Grassland Drainage Area

their heavy clay nature has also created a perched water table that threatens this productivity. The perched water table is managed with subsurface (tile) drain systems and deep earthen channels which provide an outlet for the shallow groundwater. However, the subsurface drain water is high in dissolved minerals including selenium, which pose an environmental risk to wildlife. In the past, this drain water was discharged through channels that also supplied fresh water to the Grasslands[4]. Because of the risk to wildlife, these wetland supply channels could not deliver water to Grasslands while carrying tile drainage and a “flip-flop” management system was developed – where the channels alternated between conveying drain water and delivering fresh water to Grasslands.

Although this system allowed for fresh water deliveries to the wetlands, it was inefficient and still exposed wildlife to selenium in the drainage water. It also failed to meet selenium and other water quality objectives. The Grassland Bypass Project was developed to address these issues.

The Grassland Bypass Project is an innovative project designed to improve water quality in drainage channels used to deliver water to wetland areas. The Grassland Bypass Project consolidated regional subsurface flows into a single channel, removing drain water from nearly 100 miles of wetland supply canals. Selenium load allocations (total maximum monthly loads or TMMLs) were also incorporated into the project, which reduce annually (see Figure 2). Although the project has been successful in meeting the selenium TMMLs, the water quality objectives for selenium have not always been met. Because of this, along with future requirements to meet salt and boron water quality standards, the Grassland Area Farmers have developed a plan to eliminate agricultural drainage discharge from the region. This plan has evolved into the Westside Regional Drainage Plan (Westside Plan or Plan).

The Westside Plan is intended to 1) identify scientifically sound projects proven to be effective in reducing drainage; 2) develop an aggressive implementation plan initially utilizing existing projects documented to be environmentally sound; and 3) curtail discharges to the San Joaquin River in accordance with impending regulatory constraints while maintaining the ability to farm.

The Plan focuses on regional drainage projects that can be implemented on a short timeline. Drainage must be addressed on a regional basis but must allow for each sub-area’s specific needs and resources. The Plan’s key management components for the Grassland Drainage Area are: 1) Source Control, 2) Groundwater Management, 3) Drainage Reuse Projects, and 4) Drain Water Treatment and/or Salt Disposal. As drainage projects are implemented, they will be evaluated for long-term sustainability of the complete solution.

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[4] A wetland area generally north of the Grassland Drainage Area.

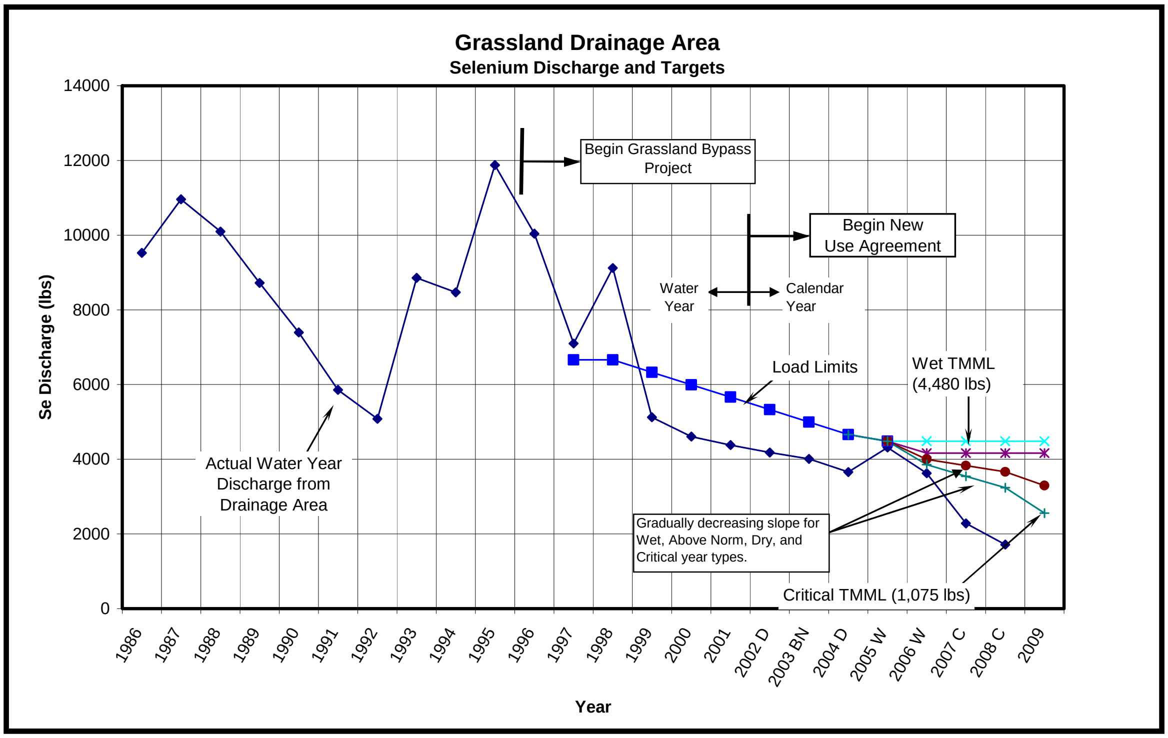

Figure 2. Selenium Load Discharge and Targets

PROJECT HISTORY

The Grassland Bypass Channel construction was completed in the summer of 1996 and drainage flows from the Grassland Drainage Area were first diverted into the channel and the San Luis Drain in October of 1996 under a Use Agreement with the U.S. Bureau of Reclamation and Waste Discharge Requirements (WDR) issued by the Central Valley Regional Water Quality Control Board. The WDR set monthly and annual selenium load allocations for discharge through the San Luis Drain, which reduced annually. Drainage discharge and water quality were monitored at several locations beginning at the point of discharge into the San Luis Drain (Site A), and including the point of discharge from the San Luis Drain to Mud Slough (Site B, the selenium load compliance point), a number of locations along Mud Slough and the San Joaquin River. In addition to selenium, water quality was monitored for salinity (measured as electrical conductivity) and boron, as well as chronic toxicity to algae, fathead minnow, and zooplankton (*daphnia magna*). Figure 2 shows the annual selenium load discharge and load allocation since the beginning of the Grassland Bypass Project.

<u>Water Year 1997 (October 96 through September 97)</u>

Water Year 1997 was the first operational year of the Grassland Bypass Project. The Grassland Area Farmers successfully connected the regional drainage system to the Bypass Channel and were able to eliminate drainage discharges through the wetland channels. However, significant rainfall occurred in December and January and the resulting runoff exceeded the capacity of the San Luis Drain. Some drainage flows were diverted into the wetland channels for a short period during January. The selenium load allocation was exceeded in January, February, March, April, May and June and it became apparent that, since the Grassland Area Farmers were being held responsible for storm event flows, more effective drainage management tools were needed in order to meet the load allocations. Several of the Districts began construction of local and regional recirculation systems to divert drainage flows back into the irrigation system and reduce discharge.

Water Year 1998 (October 97 through September 98)

Water Year 98 was the wettest year in the history of the Grassland Bypass Project. Rain fell in eight of the twelve months and total more than 17 inches (averaged over five stations). Significant portions of the Grassland Drainage Area were flooded. Once again, the runoff created by the rainfall exceeded the capacity of the San Luis Drain, and flows were diverted into wetland channels. The selenium load allocation was exceeded in February, March, April, May, June, and July. The recent completion of drainage recirculation systems provided some relief, however because the majority of the runoff occurred outside of the irrigation season there was little demand for the recycled drainage. In order to provide some additional relief, Panoche Drainage District obtained a lease on some acreage of pasture and irrigated it with drain water – the first attempt of drainage reuse. During the 1998 irrigation season, more than 1,200 acre feet of drain water was diverted to the pasture, removing about 330 pounds of selenium from the drainage system. This innovative drainage management tool would eventually evolve into the San Joaquin River Improvement Project (SJRIP).

Water Year 1999 (October 1998 through September 1999)

Water Year 99 was the first year with relatively normal rainfall since the start of the project (classified as an “above normal” year type after four consecutive “wet” year types). The Grassland Area Farmers were able to take advantage of the tools and experience developed over the previous two years and selenium load discharged through the Grassland Bypass Project did not exceed the allocation in any month.

Water Year 2000 (October 1999 through September 2000)

Water Year 2000 was an “above normal” year type and, as in Water Year 99, the selenium load allocations were not exceeded in any month. The effectiveness of the drainage reuse project as a drainage management tool had become apparent, and Panoche Drainage District began negotiations with landowners to purchase 4,000 acres of marginal land that would become the SJRIP.

Water Year 2001 (October 2000 through September 2001)

Water Year 01 was the last year of the original use agreement and WDR, and the Grassland Area Farmers completed negotiations with stakeholders and government agencies to develop a new use agreement and WDR. The new WDR included selenium load allocations that were dependant on water year type. Also in 2001, Panoche Drainage District completed the purchase of the SJRIP, with funding assistance from California Proposition 13. The selenium load allocation was not exceeded in any month.

Water Year 2002 (October 2001 through September 2002)

Water Year 02 was the first year of the new use agreement and WDR. It was a “dry” water year type and the selenium load allocations were not exceeded in any month. After five years of operation, the Grassland Bypass Project had reduced selenium load discharge by 60% (compared to Water Year 1996, pre-project).

Water Year 2003 (October 2002 through September 2003)

Water Year 03 was a “below normal” water year type. The selenium load allocation was exceeded in March, although by less than 3%. The allocation was met in all of the remaining months.

Water Year 2004 (October 2003 through September 2004)

Water Year 04 was a “dry” water year type and the selenium load allocation was met in all months except for March, where it was exceeded by 1.5%. Grassland Area Farmers were aggressively implementing drainage management tools including canal lining, development of the SJRIP, and irrigation improvements (with State and district funding assistance as well as private funding).

Water Year 2005 (October 2004 through September 2005)

Water Year 05 was the first “wet” year type since 1998, with more than 12 inches of rain falling between October and May. The rainfall generated significant runoff contributing to the drainage volumes and in February, flows in the San Luis Drain threatened to exceed it’s capacity under the use agreement, and drainage was diverted into the wetland channels for a period of six days. The persistent wet conditions precluded operation of the SJRIP, the recirculation systems, and most of the other drainage management tools available, and the selenium load allocations were exceeded in January, February, and March. The selenium load allocation was not exceeded in any other month.

Water Year 2006 (October 2005 through September 2006)

Water Year 06 was a “wet” year type, with more than 10 inches of rainfall occurring between October and May. The selenium load allocation was exceeded in January due to rain runoff, but was met in all other months.

Water Year 2007 (October 2006 through September 2007)

Water Year 07 was a "critical" year type, with less than 4 inches of rainfall. Several of the water districts within the Grassland Drainage Area experienced significant water supply reductions. The annual selenium load discharge was reduced by 78% (compared to Water Year 95) and the load allocation was not exceeded in any month. In January of 2007, the San Luis & Delta-Mendota Water Authority was awarded a $25 million state grant through Proposition 50 for implementation of drainage management projects. This grant provided funding for a variety of projects including the purchase of an additional 2,000 acres to expand the SJRIP, planting of salt tolerant crops for reuse, groundwater management, and drainage treatment studies.

Water Year 2008 (October 2007 through September 2008)

Water Year 2008 was a "critical" water year type. The selenium load discharge was reduced by 85% compared to Water Year 95, and the load allocation was met in all months. The Proposition 50 funding was used to purchase an additional 2,000 acres for the SJRIP, plant more than 300 acres of salt tolerant crops, well installations for groundwater management, and selection of a drainage treatment process. However, state budget issues have suspended the Proposition 50 funding and the associated projects have been on hold.

DRAINAGE MANGEMENT COMPONENTS

The Westside Plan identified four effective projects to manage and reduce drainage discharge through the Grassland Bypass Project. These include source control projects such as irrigation and infrastructure improvements to reduce the overall subsurface drainage production, groundwater management to lower the perched water level, drainage reuse to reduce the volume of drain water through the irrigation of salt tolerant crops, and drainage treatment to remove the salt and dissolved minerals. The ultimate goal of this plan will be to eliminate agricultural drainage discharge[5] from the Grassland Drainage Area. Figure 3 shows an estimate of the impact of each of the drainage management components.

[5] Excluding excessive rainfall runoff.

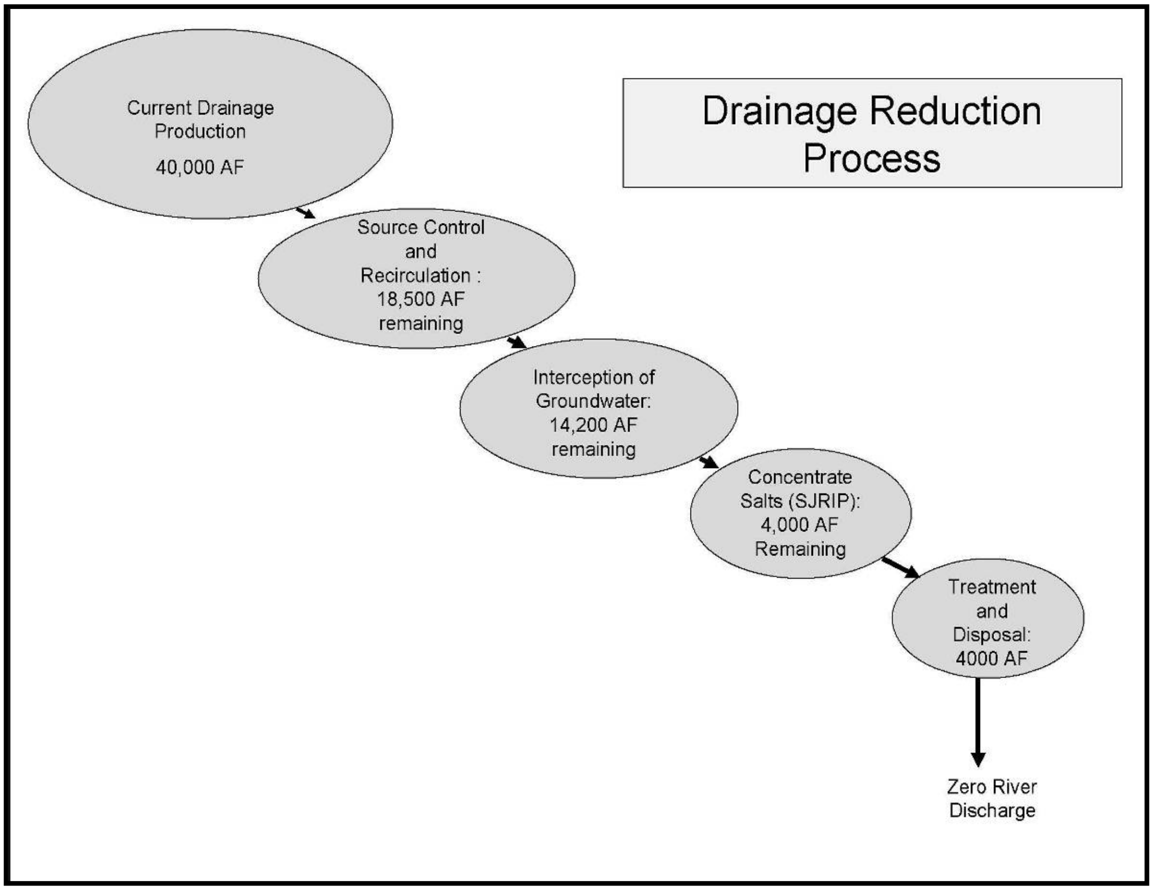

Figure 3. Drainage Management Components

Source Control Projects

Microsprinklers

Source control projects are projects that can reduce the volume of water contributing to subsurface drainage production usually by reducing deep percolation. Source control projects can usually be divided into two categories: irrigation improvements and distribution infrastructure improvements.

Irrigation improvement projects include converting from a low efficiency irrigation system (such as furrow irrigation) to a high efficiency system (such as drip or micro sprinklers). The State of California and the local districts have made financial assistance (in the form of low interest loans) available to growers as an incentive to convert from conventional irrigation practices to high efficiency drip irrigation (and similar systems). Since the beginning of the Grassland Bypass Project, more than 45,000 acres within the Grassland Drainage Area have converted to high efficiency irrigation systems.

Distribution infrastructure improvement projects typically include the replacement of an unlined irrigation canal with a concrete lined channel or pipeline. Unlined channels within the Grassland Drainage Area can contribute more than 200 acre feet of seepage per year for each unlined mile. More than 10 miles of unlined canals have been lined or converted to pipelines since the beginning of the Grassland Bypass Project.

Canal Lining

Drainage Recirculation

Drainage recirculation is the process of redirecting drain water back into the irrigation system and it is one of the first drainage management tools implemented by the Grassland Area Farmers. Virtually all of the districts within the Grassland Drainage Area have some capacity for recirculation. Drainage recirculation is carefully monitored to maintain a blended water quality sufficient for agricultural use.

Recirculation Plant

Groundwater Management

A study performed in 2002, by the San Joaquin River Exchange Contractor's Water Authority (Exchange Contractor's) and the U.S. Bureau of Reclamation indicated that the pumping of strategically placed wells (pumping above the Corcoran Clay) could lower the perched water table and reduce the discharge of nearby subsurface drainage systems. A portion of the funding provided through the Proposition 50 grant has been allocated to the installation of these wells, with about five wells completed in 2008.

Drainage Reuse

Drainage reuse is the practice of using subsurface drain water as an irrigation source for salt tolerant crops. Drainage reuse began in the Grassland Drainage Area in 1998, when Panoche Drainage District began applying drain water to pasture fields. Since then, the San Joaquin River Improvement Project (SJRIP) has evolved into a 6,000 acre area with six crop varieties ranging from alfalfa (moderately salt tolerant) to paspalum grass (a halophyte). Currently, about 4,300 acres of the SJRIP are developed to receive drain water.

Jose Tall Wheatgrass on the SJRIP

Pistachios on the SJRIP

Drainage reuse has been an extremely effective tool in reducing drainage volume discharged from the Grassland Drainage Area but it is not without challenges. Because of the saline nature of the water applied, soil salinity needs to be carefully managed to prevent salt buildup in the root zone. Subsurface drainage systems have been installed on about 1700 acres, with plans to tile most of the SJRIP, however soil salinity is also managed through rotation where fields are fallowed or irrigated with fresh water for a season. Once the SJRIP is fully developed, the estimated drainage capacity of the project will be between 20,000 and 30,000 acre feet annually, provided the drain water is available for reuse when it is needed. Table 1 shows the annual drainage reuse for the SJRIP since the beginning of the project.

Table 1. The Panoche Drainage District Reuse Project and SJRIP Annual Drainage Reuse Volume and Loads.

Water Year	Reused Drain Water	Displaced Selenium	Displaced Boron	Displaced Salt
	(acre feet)	(pounds)	(pounds)	(tons)
1998[¥]	1,211	329	NA	4,608
1999[¥]	2,612	321	NA	10,230
2000[¥]	2,020	423	NA	7,699
2001	2,850	1,025	61,847	14,491
2002	3,711	1,119	77,134	17,715
2003	5,376	1,626	141,299	27,728
2004	7,890	2,417	193,956	41,444
2005	8,143	2,150	210,627	40,492
2006	9,139	2,825	184,289	51,882
2007	11,233	3,441	210,582	61,412
2008	14,955	3,844	238,435	80,900

NA = Not Available

[¥] Panoche Drainage District reuse project prior to SJRIP

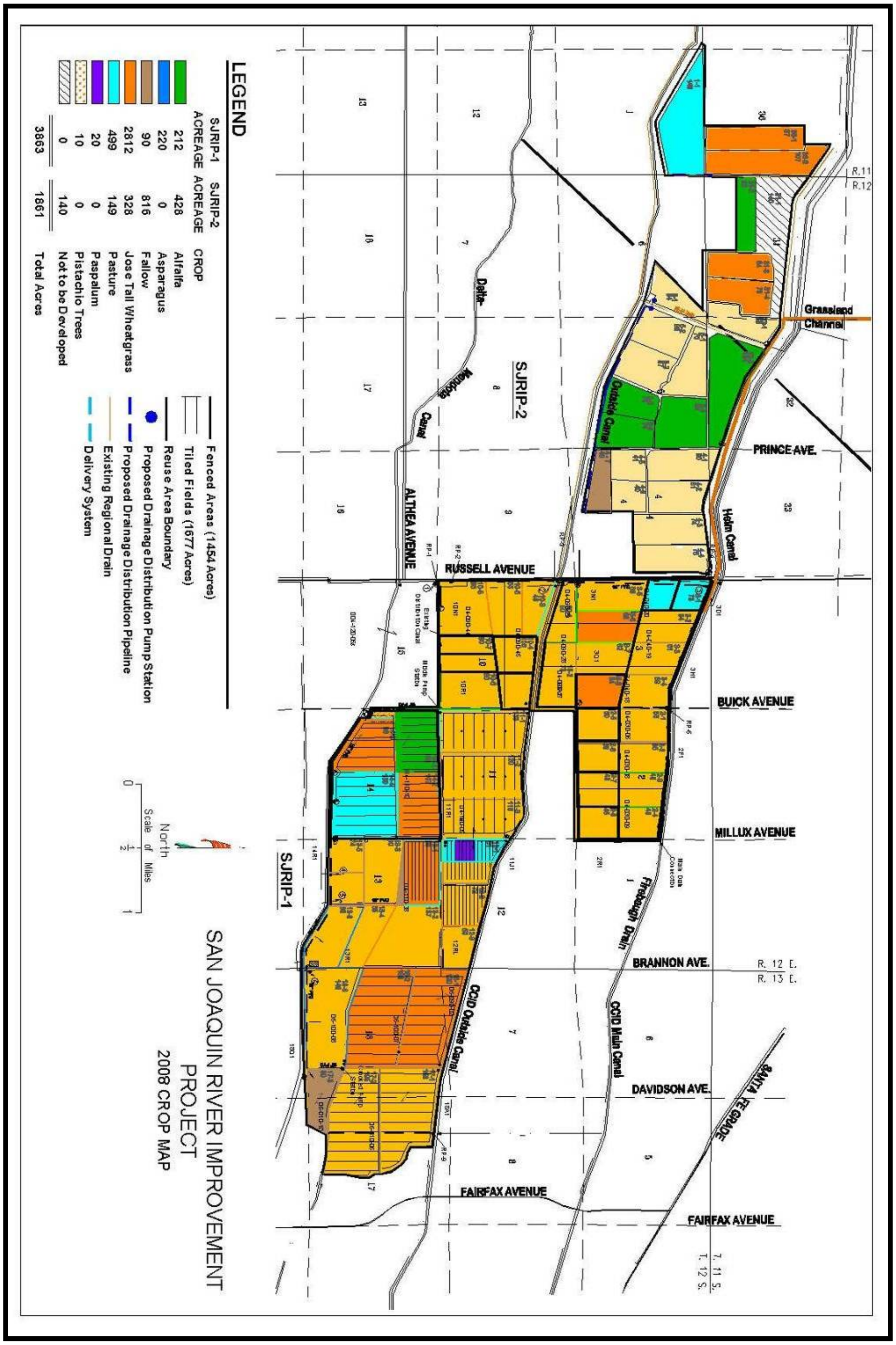

Figure 4. SJRIP cropping map as of 2008, including the newly acquired 2000 acres.

Drainage Treatment/Disposal

Membrane treatment could be part of the drainage treatment process

The application of saline drain water for irrigation on the SJRIP will result in some subsurface drain water generated by the drainage systems. Careful design of the drainage systems and irrigation management will minimize the volume of water generated; however it will be too saline for reuse and will need to be managed in some form. Currently, the Grassland Area Farmers are researching methods to treat this water, generating a usable treated product and a dry waste that can be easily managed. A pilot test is expected to start in 2009 and will result in parameters for a full-scale treatment plant design and estimate of cost. If it turns out that drainage treatment is not affordable, other methods of managing the reuse area soil salinity will need to be pursued. These would likely include field rotation and periodic fallowing and may require further expansion of the SJRIP.

PROJECT IMPACTS

The Grassland Bypass Project has been successful in reducing the volume of subsurface drain water discharged from the 100,000 acre Grassland Drainage Area which maintaining viable farming within the region. In 1995, prior to the Grassland Bypass Project, more than 57,000 acre feet of drain water was discharged through the wetland channels. This not only impacted the water quality of the San Joaquin River system but exposed waterfowl attracted to the Grassland area wetlands to elevated levels of selenium and other constituents. The Grassland Bypass Project eliminated drainage discharge into the wetland channels[6] and consolidated all of the drainage within the Grassland Drainage Area into one channel. By 2008, the volume of discharged drain water was reduced from more than 57,500 acre feet to about 15,700 (a 73% reduction in discharge). Similar reductions occur in the discharged load of selenium, salt, and boron. Table 2 shows the annual reduction in drainage discharge and associated constituent load.

[6] Except for during extreme storm events.

Table 2. Grassland Bypass project Annual Discharge and Loads

Discharge Comparison from Grassland Drainage Area
Values October thru September

	WY 95	WY 96	WY 97	WY 98	WY 99	WY 00	WY 01
Volume (AF)	57,574	52,978	39,856	49,289	32,317	31,342	28,235
Se (lbs)	11,875	10,034	7,096	9,118	5,124	4,603	4,377
Salt (tons)	237,530	197,526	172,602	213,533	149,081	139,303	142,415
B (1,000 lbs)	868	723	753	983	630	619	423
Se (ppm)	0.076	0.070	0.066	0.068	0.058	0.054	0.057
Salt (µmhos/cm)	4,102	3,707	4,306	4,308	4,587	4,420	5,016
Boron (ppm)	5.5	5.0	7.0	7.3	7.2	7.3	5.5

	WY 02	WY 03	WY 04	WY 05	WY 06	WY 07	WY 08	Reduction from WY 95 to WY 08
Volume (AF)	28,358	27,345	27,640	29,957	25,995	18,531	15,665	73%
Se (lbs)	3,939	4,032	3,860	4,305	3,563	2,554	1,736	85%
Salt (tons)	128,411	126,500	121,138	138,908	119,646	79,094	66,254	72%
B (1,000 lbs)	544	554	530	585	539	278	269	69%
Se (ppm)	0.051	0.054	0.051	0.053	0.050	0.051	0.041	
Salt (µmhos/cm)	4,503	4,600	4,358	4,611	4,577	4,244	4,206	
Boron (ppm)	7.1	7.5	7.1	7.2	7.6	5.5	6.3	

FUTURE ACTIVITIES

Although the success of the Grassland Bypass Project in reducing drainage discharge is evident, future water quality objectives will require near zero discharge from the Grassland Drainage Area. Full implementation of the solution components developed by the Grassland Area Farmers will be necessary to achieve this. Significant progress towards that end has been made:

- Drainage recirculation systems have been installed in nearly all of the Grassland Drainage Area districts.
- 4,300 acres of reuse area has been planted to salt tolerant crops – capable of reusing some 15,000 acre feet of drainage annually.
- About 50% of the farmed acreage has been converted to high efficiency irrigation with many growers planning on installing new systems in coming years.
- Five wells have been installed in strategic locations to help lower the local perched water table.
- A treatment system is planned to be piloted in the near future. This system will run near 20 gpm and treat subsurface rain water generated by the SJRIP. It is expected that this pilot test will provide sufficient information to develop a full-scale treatment process and estimate the capital and operational costs of such a plant.

However, in order to eliminate discharge completely, all of these solution components need to be fully developed. In particular, the full 6,000 acres of the SJRIP need to be developed and necessary infrastructure to deliver drain water to the project needs to be constructed. In addition to that, a successful treatment process (or some other method to manage soil salinity) needs to be developed to full-scale to sustain long-term use of the SJRIP.

In addition to the local resources applied to this project, significant funding assistance from the U.S. Bureau of Reclamation and the State of California has been necessary to move the project forward. Table 3 shows a breakdown of the funding applied to the project and their source since the beginning of the Grassland Bypass Project. Table 3 does not include funding provided by the U.S. Bureau of Reclamation and the Central Valley Regional Water Quality Control Board for compliance monitoring, which has been on-going since Water Year 1996.

Table 3. Funding Sources

Source	Amount
Grant Funding	$ 66,000,000
Loan Funding (Farmer repays)	$ 15,000,000
District Funding (Farmer funded)	$ 23,000,000
Total	$ 104,000,000

EFFECT OF SUSTAINED DEFICIT IRRIGATION ON HAY AND OIL YIELD OF NATIVE SPEARMINT (*Mentha spicata*)

Romulus O. Okwany[1]
Troy R. Peters, PhD, P.E.[2]
Kerry L. Ringer, PhD[3]

ABSTRACT

An experiment was conducted to quantify the local yield and crop water requirement responses of spearmint to different levels of water deficit in a Pacific Northwest arid environment. A line source sprinkler system was used to apply water to the test plots where the applied water varied nearly linearly with distance from the sprinkler line. This resulted in the application of varying irrigation amounts from full irrigation to 100% water deficit. The 100% irrigation amounts were controlled by neutron probe soil moisture measurements and irrigation scheduled to refill the soil water deficit to field capacity on a weekly basis. The varying irrigation amounts were confirmed with catch cans at each of five different irrigation levels and were read after all the irrigations to verify the amounts of applied water. The hay and oil yields at different water deficit levels were thereafter evaluated. The total oil content that was distilled from the mint hay samples stayed fairly constant despite significantly decreased mint hay yields with increased water deficit. The mint oil quality indicators improved with deficit irrigation. This study indicates that spearmint is a suitable crop for a sustained deficit irrigation management strategy that would reduce farm operation technicalities of regulated deficit irrigation while considerably conserving irrigation water and power.

INTRODUCTION

Water shortage is the most important factor restricting crop production in the world (Umar, 2006) as it constrains plant growth and production (Yadav et al., 1999). Full irrigation to increase yields to meet increasing food and fiber demands is not an option in water scarce regions (Geerts, et al. 2008a). Deficit irrigation is providing a possible solution to the dilemma of sustaining and/or increasing production Geets, et al 2008b).

With diminishing water and land resources the primary purpose of the world's irrigation is to sustain agricultural production and then strive for increased output, thereby providing a more stable supply of agricultural production (FAO, 2002). Water shortage challenge has thus shifted crop production function from the land productivity concept to water productivity (Sarwar and Perry, 2002; Zwart and Bastiaanssen, 2004; and Fereres and Soriano, 2007).

Crop response to deficit irrigation is becoming an important consideration for establishing irrigation management strategies under limited water supply conditions.

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Deficit irrigation is the practice of applying less than crop evapotranspiration demand with intent of imposing a managed level of water stress to the crop (Grant, 2008). The strategy is to maintain plants under certain water deficit for a prescribed duration of the growth season with the aim of controlling reproductive and vegetative growth to improve water use efficiency and/or crop quality. Deficit irrigation has been practiced in many areas of the world (English and Raja 1996). It requires precision irrigation and thus at its core it requires the understanding of the crop's evapotranspiration (Imtiyaz et al., 2000), crop response to water deficit and use of highly efficient irrigation systems.

The importance of quantification of local response to irrigation is of noted importance to establishing area-specific irrigation management strategies (Payero et al., 2008). For different crops, deficit irrigation has been shown to save irrigation water (Girona et al., 2005), increase WUE (yield/total irrigation water) improve crop quality (dos Santos et al., 2007), speed maturation (Gelly, et al., 2004) and may not seriously affect yields (Goldhamer, 1999). Water deficiency primarily affects crops by reducing the dry matter accumulation (Karam et al., 2003) due to reduced dry matter development (Lopez et al. 1996 a, b). These results have been explained on the basis of the plants compensatory mechanisms after experiencing moderate water deficit. The plants suppress biomass production and activate oil and/seed as a survival technique and in the process irrigation water may be saved to a certain degree without much reduction in crop yield (Cui et al., 2008).

The effects of deficit irrigation on different crops have been studied quite extensively for several decades (English and Raja, 1996). Deficit irrigation has been shown to have varying effects on quality attributes of various crops but its specific effect on spearmint oil yield and oil quality is not well understood. Mint is an important essential oil-producing crop grown for use in the pharmaceutical, cosmetic, food and flavor industries (Ram et al., 2006)

This study evaluated the response of spearmint crop to overhead-sprinkler-applied deficit irrigation. The viability of deficit irrigation for spearmint was assessed based on oil yield, oil quality, water use efficiency and dry matter production of a native spearmint crop in the semi arid climate of mid central Washington.

MATERIALS AND METHODS

Site Description

Field experiments were carried out during the 2008 growing season. The experimental fields were located at the Washington State University, Irrigated Agriculture Research and Extension Center (IAREC), Prosser, WA (46.29N 119.75W; 350 m.a.s.l.). The climate at Prosser is semi arid, with annual average precipitation of approximately 195 mm (7.7 inches) and an average annual alfalfa reference ET of 895 mm (35.3 inches). The soil at the experimental site is a Warden Silt Loam with a root zone field capacity of 22.5%, permanent wilting point was 7% and a bulk density of 1.37 g/cm^3.

Experimental Design

The experiment was conducted between early April and mid October 2008. The experiment was a split-block design with five irrigation treatments and 6 pest control treatments in three blocked replications. All plots were 20 ft x 10 ft. The line source sprinkler system had risers spaced 20 ft apart along the length of the field. The irrigation treatments were applied through an overhead line-source sprinkler system running in the middle of the minor blocks. This applied irrigation water at gradually decreasing amounts towards the outer experimental plots. The aim was to develop a well-defined crop response functions to irrigation levels ranging from dry-land to normal irrigation. The pest control treatments were randomized within each block across irrigation treatments. Finally, each irrigation and pest control block was replicated in three randomized units (pest study reported on a different document). In this paper we present results of analysis of the control plots in which standard cultivation practices were adopted for fertilization, weed and pest management during the growing season.

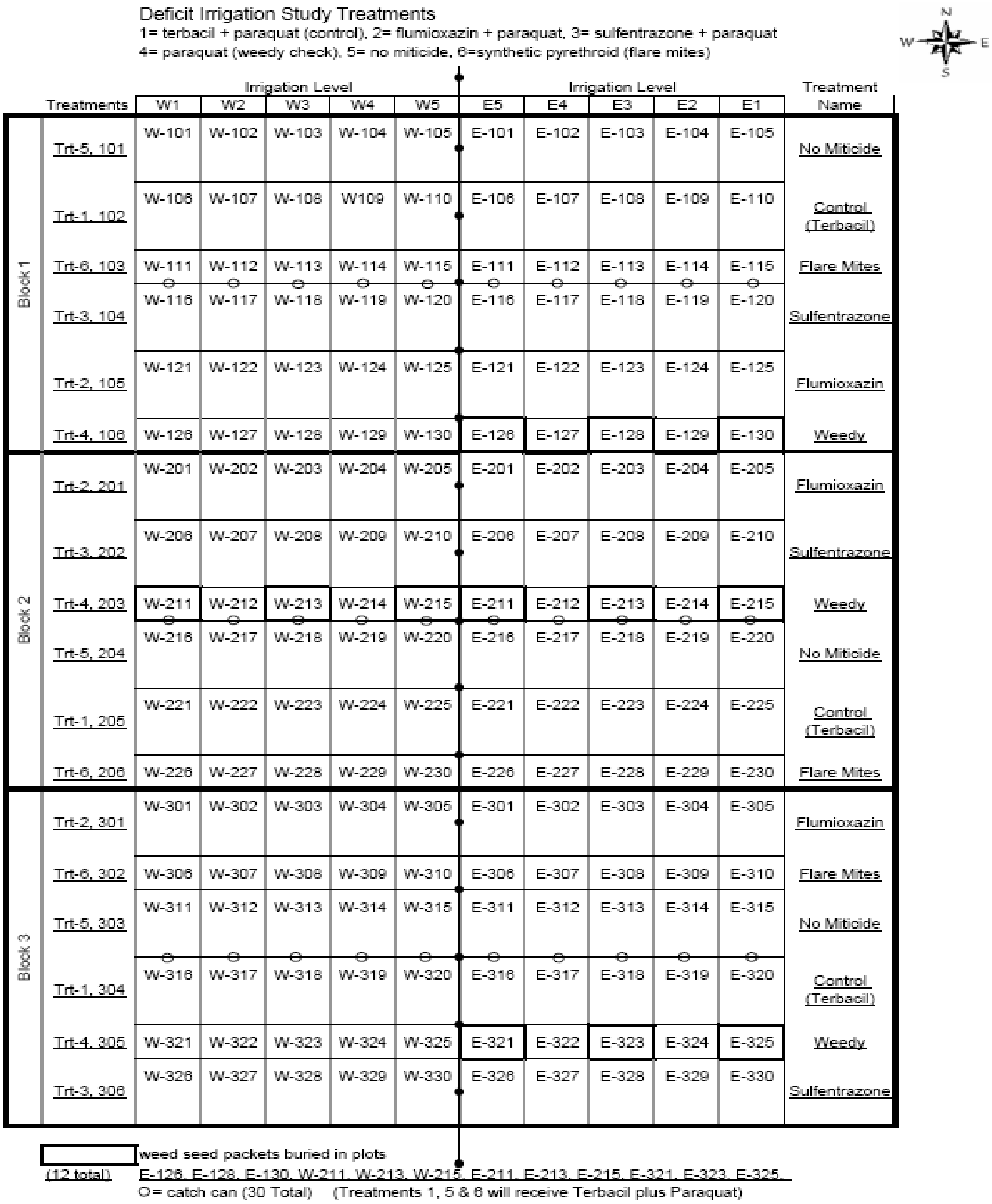

Figure 1. Experimental Plot Plan

Dry Matter and Oil Measurements

During each of two harvests, a representative swath from each plot was harvested using a plot combine harvester and weighed for total yield measurements. The green hay yield for each plot was determined from the weighed swath yield. A 9.5 kg (21 lb) sample of green hay was put in burlap sacks for transport to the lab for drying and analysis. At the second harvest, a smaller sample of the green hay was also taken for mint hay moisture content determination. The 9.5 kg (21 lb) samples were air dried and oil extracted by hydrodistillation and oil quality parameters determined by GC/MS. with Flame Ionization Detector analysis for oil component quantification.

Irrigation Requirement

A neutron scattering moisture gauge (503 DR Hydroprobe; CPN International Inc., Martinez, CA, USA) was used to make weekly soil moisture measurements. Irrigation was then scheduled to replenish the soil water deficit in the center-most (100% irrigation) plots to ensure that these plots didn't suffer any water shortages. The water applied decreased with distance from the central line irrigation line in the field (line-source experiment). Neutron probe readings were made through access tubes that were placed in the center of each plot across the center of the control blocks. The soil water balance was determined to provide scheduling information for each irrigation schedule. Computation and management of the irrigation management was carried out using a simple Excel datasheet. Irrigations were applied two to three times a week depending on level of soil water depletion within the limits of soil water infiltration rate. This was to manage the soil moisture depletion to a narrow margin to maintain the moisture content at a fairly stable range with minimal surface runoff and the 100% ET level maintained at near field capacity. Water deficit across the plots was created by applying lesser volume of water for the same irrigation interval on each irrigation level as dictated by the decreasing application from the line-source sprinkler line.

Harvest Index and Irrigation Water Use Efficiency

Harvest Index (HI) is the proportion of the marketable product to the harvestable product that is used in crop modeling (Stockle and Campbell, 1985; Bryant et al., 1992) to estimate water stress coefficient (Stockle and Campbell, 1985). Harvest index is an indicator of the production efficiency of the crop.

Irrigation Water Use Efficiency (IWUE) is a term used to promote irrigation water efficiency by relating level of crop production (marketable product) to irrigation level (Bos 1980). A high IWUE is an indicator of the increased value of the irrigation water with respect to the marketable product of the crop.

Harvest Index (HI, lbs of oil per acre-in of applied water) and irrigation water use efficiency (*IWUE*, ml oil/in water) were calculated as:

$$HI = \frac{OY}{GHY_{ac}}$$

(Equation 1)

and,

$$IWUE = \frac{OC \times GHY_p}{I_p}$$

(Equation 2)

where:

OY = oil yield (lbs/acre),
GHY_{ac} = green hay yield (ton/acre),
OC = oil yield (ml/lb per plot),
GHY_p = green hay yield (lb/plot) and
I_p = seasonal irrigation (in)

Statistical Analysis

To evaluate the effect of irrigation treatments on the oil and hay yield of the spearmint analysis-of-variance (ANOVA) was performed using Statistical Analysis Software (SAS 9.1.2, SAS Institute Ltd., USA) for each harvest of the crop. Regression analyses were also performed to evaluate yield factors and relationships.

RESULTS

Soil Moisture Content

For the 2008 growing season all treatments started with the same soil water content in the soil profile from the winter moisture recharge. Neutron probe readings at the start of the growing season in early April verified uniform soil moisture content in the top 48 inches of the soil profile. There was a cumulative precipitation of only 1.37 inches throughout the growing season. The growing season precipitation was minimal at the experimental location so that the evapotranspiration was mainly from ground water storage and/or irrigation water applied. Applied water ranged from 0.0 – 9.1 inches for the first cutting and 0.0 – 25.3 inches for the second cutting. The difference in irrigation water demands between first and second harvests are due to the profile water storage that was used in the first harvest relative to the second harvest thus a lower application.

The soil water balance scheduling system based on neutron probe measurements provided an accurate scheduling method as noted from the fairly stable profile water contents through the season. Except for the top 12 inches of the soil profile where moisture depletion was also very dependent on the evaporative effects of the weather conditions, the soil moisture depletion was entirely attributable to the crop withdrawal.

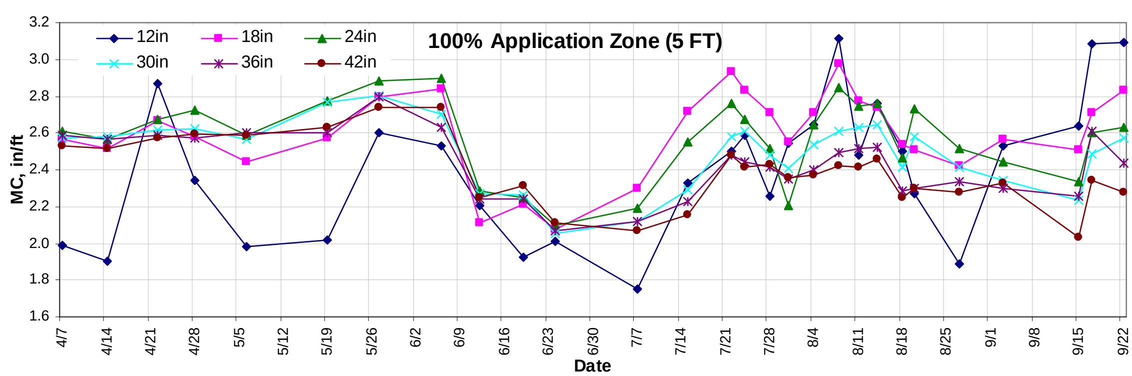

Figure 2. Seasonal Profile Moisture Content on the Scheduling Plots

There was a substantial increase in total irrigation water applied to the second cutting compared to the first cutting. This is attributable to higher evapotranspirative demand due to hotter weather and longer days. The water-stressed plots were able to utilize existing soil moisture, and only saw significant water stress toward the end of the first cutting growth period.

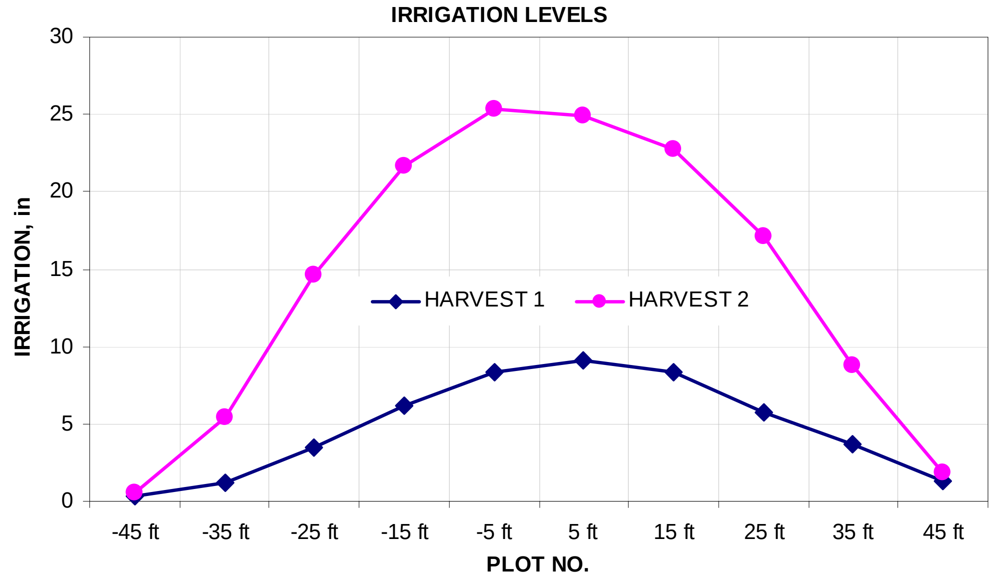

Figure 3. First and Second Harvest Applied Irrigation Water for Each Irrigation Level

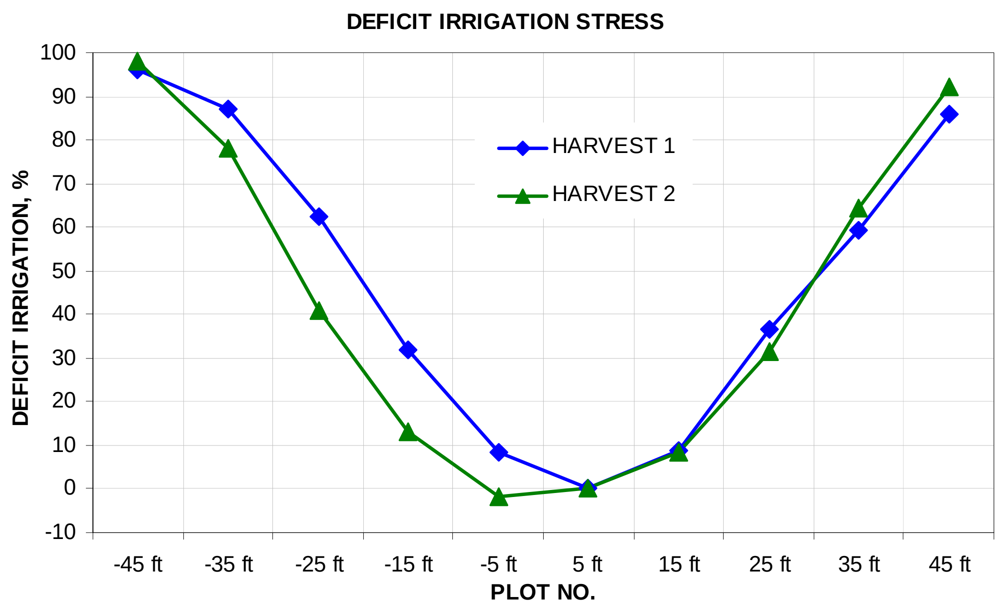

Figure 4. Deficit Irrigation Level (%) in the First and Second Harvests

Oil Quantity Yield

The spearmint oil yield was found to be fairly constant at about 60 lbs/acre for the first harvest (H1) but with a yield decrease from about 38 lbs/acre at full irrigation down to about 20 lbs/acre at 95% deficit irrigation on the second harvest (H2). These show that despite the substantial reduction in water supply to the crop we still obtain good oil yields. This loss of oil yield is estimated to be a fair foregone cost with respect to the extra water requirements to achieve the maximum yields.

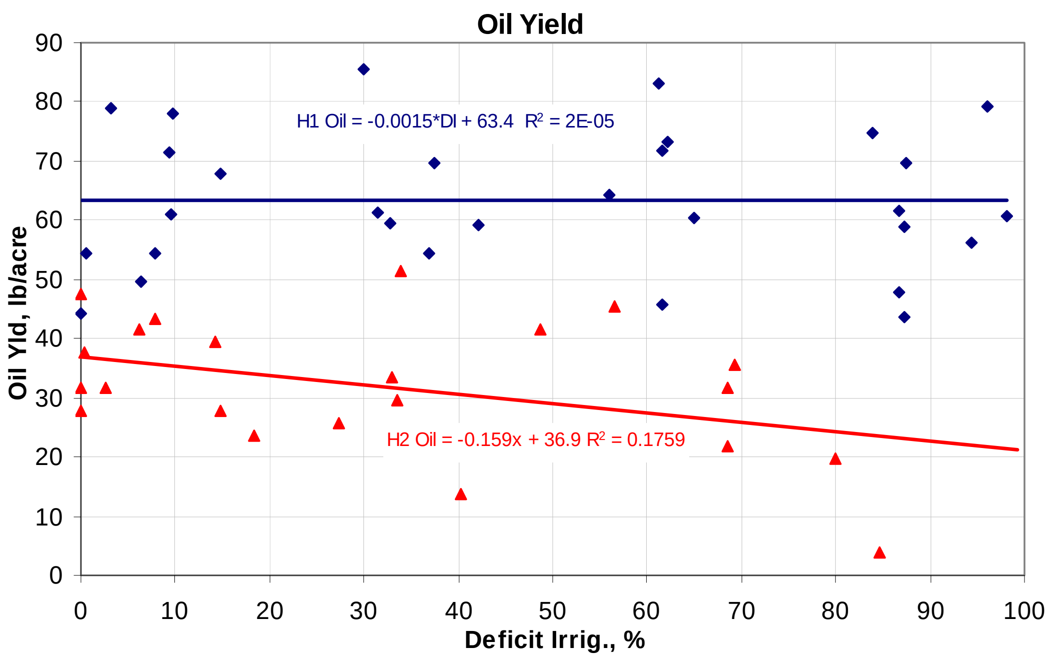

Figure 5. Oil Yields at the Various Deficit Irrigation Levels for H1 and H2

Harvest Index

The harvest index is a measure of the marketable oil yield per ton of harvested mint hay. This “oil concentration” was shown to increase substantially with increasing deficit irrigation. This indicates a possibility for cutting costs in the harvest, transportation and stilling processes if the oil yields per acre and overall oil quality can be maintained with deficit irrigation.

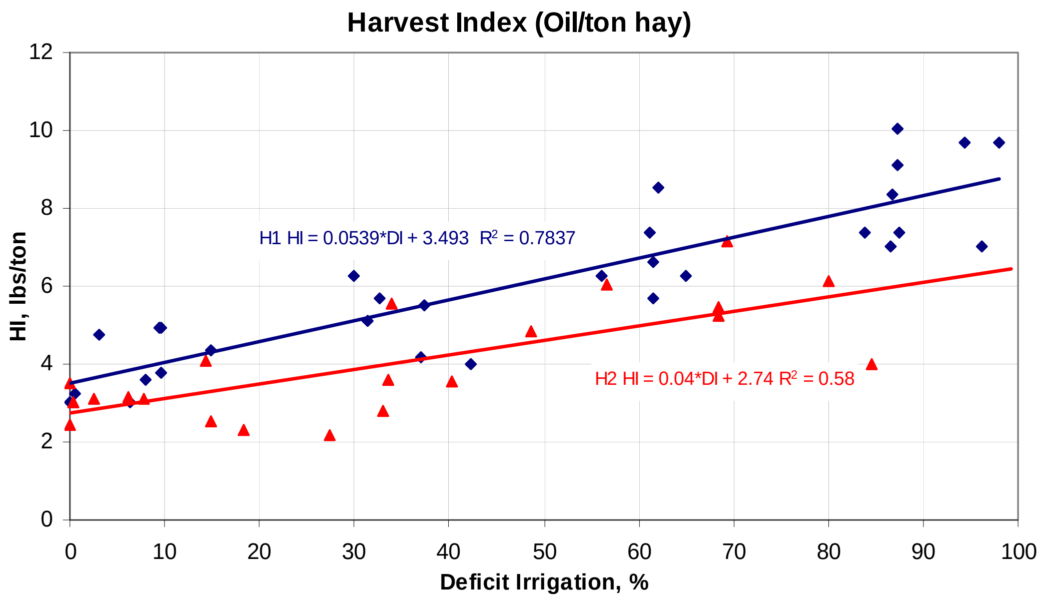

Figure 6. Harvest Indices at the Various Deficit Irrigation Levels for Both Harvests

<u>Hay Yield</u>

Another measure of the spearmint yield is the hay material produced. The mean wet hay yields at the different water stress levels indicate a decreasing biomass production with increasing deficit irrigation. A simple linear regression shows a reduction of between 9 and 11 ton/acre with a decrease in irrigation water of 95% from full irrigation. There were no significant yields at the most stressed plots for the second harvest.

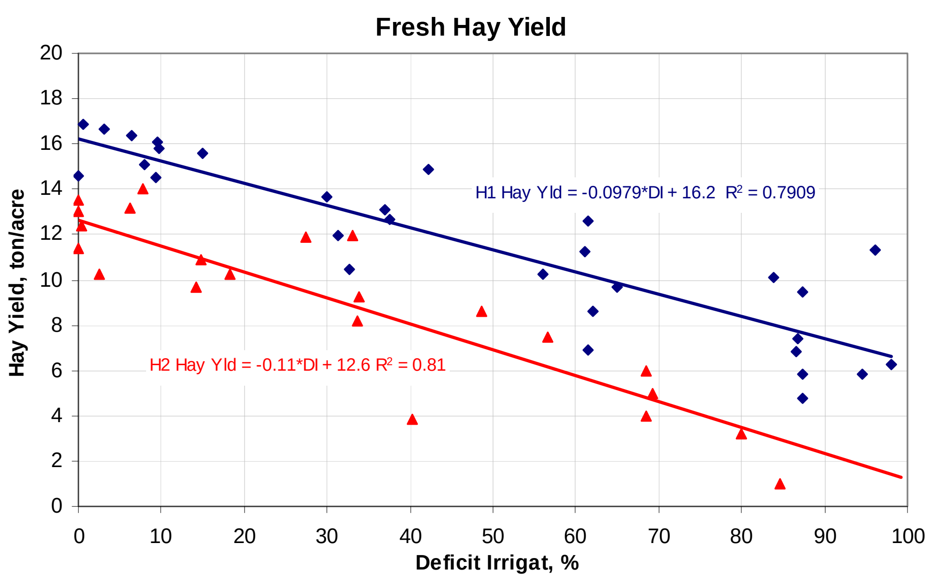

Figure 7. Fresh Hay Yield at the Various Deficit Irrigation Levels for Both Harvests

Irrigation Water Use Efficiency

The irrigation water use efficiency, which indicates the marginal increase in marketable yield from a unit increase in irrigation water, shows an exponential increase during the first harvest (H1) but only a slight increase up to 35% deficit irrigation in the second harvest (H2). This indicates that up to 35% stress level the deficit irrigation has positive effect on the total oil yield but beyond this level we start experiencing a general loss of marketable yield. A linear regression of the average seasonal yield shows a 0.04 ml/in increase in IWUE with increasing stress levels. The irrigation water use efficiency was attributable to the reduced ET and increased oil yields under water stress conditions. These results agree with the general conclusions by Ram Et al. (2006) that the irrigation water use efficiency is higher in the drier regimes and lower in wetter regimes.

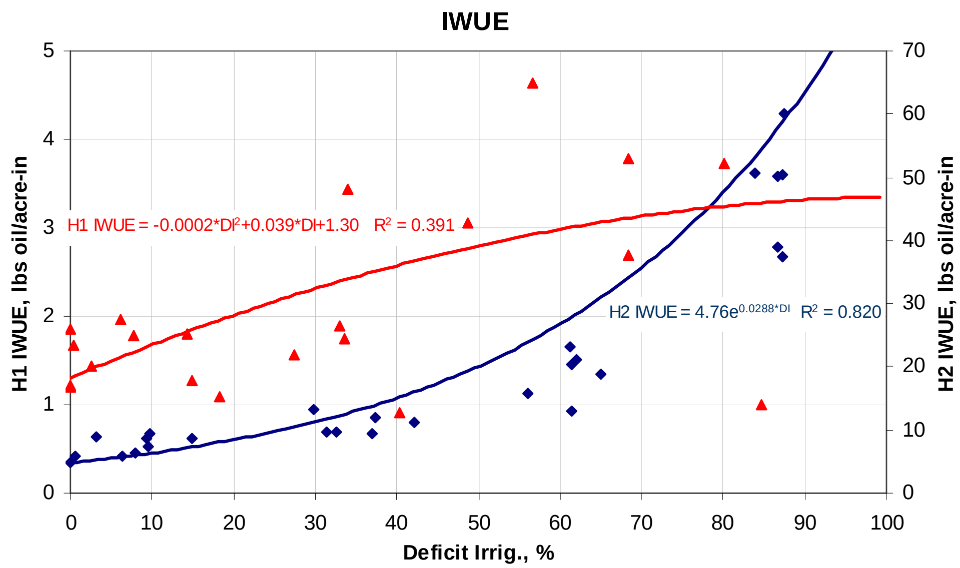

Figure 8. Irrigation Water Use Efficiency (IWUE) at the Various Deficit Irrigation Levels For Both Harvests

Oil Components

The percent composition of the various oil components was measured using gas chromatography with flame ionization detection (FID) standards. The results indicated that the Carvone oil content decreased with increased irrigation whereas the Limonene oil content increased. The increasing Carvone content and decreasing limonene contentsuggest an early/faster maturity of the spearmint with higher water stress. These results concur with those of Gershenzon et al. (2000), Singh and Saini (2008), and Delfine, et al. (2005). The compositions of Myrcene, Cineole, Terpineol, Bourbonene, Caryophylene, Farnesene, and Cubebene were also measured but there were no significant differences across water stress treatments.

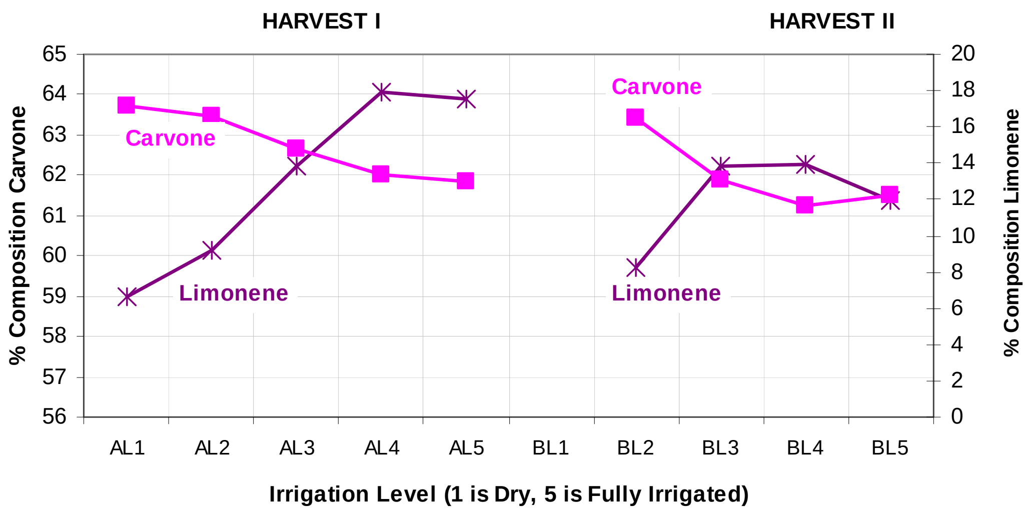

Figure 9. Percent Composition of Carvone and Limonene in the Mint Oil from Both Harvests

DISCUSSION AND CONCLUSIONS

Sustained deficit irrigation clearly decreased hay yields. Oil yields per acre were similar in the first harvest despite the lower hay yields. Oil yields decreased during the second harvest due to severe crop stand loss on the most water stressed plots (over 80% water deficit). The oil content (harvest index) per ton of harvested hay clearly increased with increasing water stress for both harvests. Similar results were found by Crowe (1994) in which he suggested that the more vigorous plants (less water stressed) have higher stem-to-leaf ratios with lower oil concentration and yield. Oil component analysis was also done and it was found that the Carvone content increased and Limonene content decreased while carvone content increased with increasing water stress demonstrating an earlier maturity for water stressed mint. Over time severe deficit irrigation caused a clear decrease in the plant population and stands health and therefore lower total oil yields per acre. It is likely that there is a potential to use deficit irrigation for increased profit mint grower's profits. Lower mint hay yields could mean faster harvesting, lower transportation costs, less time in the still, and lower stilling energy costs. The lower water use would also mean less wear and tear on pumps and irrigation machinery and subsequent lower pumping energy costs. If this can be done while maintaining or improving the overall oil yield and oil quality this should result in improved grower profits. This study thus shows that spearmint oil production harvest index is higher than for the hay yield confirming that oil production can be sustained at a higher level despite a reduction in vegetative growth, as suggested by Girona et al., (2002) and Lavee, et al. (2007). As noted earlier by Scavroni, et al. (2005), though a high dry matter content of spearmint does indicate a higher essential oil yield the relationship is not fully proportional and should not be used as a market measure of oil production. Due to the severe loss of crop stand at higher water deficits post harvest full irrigation on the stressed plots can be implemented to sustain leaf activity and promote nutrient storage and help rejuvenate the crop stand.

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DEFICIT IRRIGATED CORN EVAPOTRANSPIRATION ESTIMATES USING CANOPY TEMPERATURE DATA

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ABSTRACT

Sustainability of irrigated agriculture with declining water supplies is a primary agricultural issue in the U.S. Great Plains. Consequently, the paradigm of maximizing production through full irrigation must be abandoned. Imposing water deficits on crops during non-critical growth periods must be implemented to maximize net economic output per unit of water consumed by the plant. An irrigation timing and amount determination for such a scenario is not a simple, straight-forward procedure. Methods that monitor plant parameters would appear to be most promising. Several canopy temperature based irrigation timing techniques exist that determine when to irrigate but do not indicate how much to irrigate. The reference ET-crop coefficient procedure for determining crop ET which is used in fully irrigated crop conditions would be easiest to implement; however, the water stress coefficient used in that procedure may not be applicable for prolonged periods of water stress. Thus, the objective of this paper was to investigate use of a ratio of canopy temperature (T_c) measured over fully irrigated and water stressed corn as a substitute for the water stress coefficient presently used in the reference ET-crop coefficient concept. Preliminary results indicated that the T_c ratio (T_c of fully irrigated corn divided by the T_c of water stressed corn) may be a reasonable quantitative water stress coefficient for calculating crop ET under water stress conditions. Furthermore, it lends itself to hourly incorporation of plant stress effects on crop ET if canopy temperature is continuously measured throughout the day.

INTRODUCTION

Evapotranspiration (ET) is the combined processes of water lost from the soil surface by evaporation and from the plant by transpiration. There is no easy way of distinguishing between the two processes; consequently, ET is commonly computed using measured weather data, crop characteristics and soil factors. The Food and Agriculture Organization Irrigation and Drainage Paper No. 56, i.e., FAO 56 (Allen et al., 1998) distinguishes between reference crop evapotranspiration (ET_o), crop evapotranspiration under standard conditions (ET_c) and crop evapotranspiration under non-standard conditions ($ET_{c\ adj}$). The only factors affecting ET_o are climatic parameters at a given location and time of year. ET_c is crop evapotranspiration from well fertilized, disease-

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free crops grown in large areas with optimum soil water conditions to achieve full production under the prevailing climatic conditions. $ET_{c\ adj}$ is crop evapotranspiration resulting from non-optimal conditions such as soil water shortage, low soil fertility, soil salinity and/or the presence of pests and diseases. The ET from crops grown under standard conditions can be determined by adjusting ET_o with crop coefficients (K_c) that relate ET_c to ET_o. Estimated ET from crops grown under non-standard conditions is typically adjusted through use of a water stress coefficient (K_s) dependent on available soil water and/or by adjusting the crop coefficient to account for anomalies that affect crop growth.

Numerous methods for scheduling irrigations have been developed that are based on different types of information for making irrigation decisions. The easiest to implement is the reference ET-crop coefficient concept to estimate daily soil water depletions to determine when to irrigate and how much water to apply. This method was designed for water management of fully irrigated crops with limited water stress allowed. The paradigm of maximizing production through full irrigation must be abandoned in order to sustain irrigated agriculture with declining water supplies. Water deficits must be imposed on crops during non-critical growth periods to maximize net economic output per unit of water consumed by the plant. An irrigation timing and amount determination for such a scenario is not a simple, straight-forward procedure. When water deficits are imposed on crops due to limited water availability, a method that directly monitors a plant parameter to infer plant water status provides the most accurate assessment of crop water status.

Crop water status can be quantified using infrared thermometers (IRTs) to measure canopy temperature in canopy temperature based irrigation timing techniques. Some of these techniques have been available for more than 25 years. The crop water stress index (CWSI) developed by Idso et al. (1981) and Jackson et al. (1981) has been used to determine when to irrigate and has been shown to reduce applied water compared to other scheduling techniques (Wanjura et al., 1992). Unfortunately, the amount of water used by the crop to estimate irrigation amount is not determined by this index.

Efforts have been made to determine irrigation requirements (how much to irrigate) by various techniques to compliment CWSI measurements (when to irrigate). Kjelgaard et al. (1996) used a canopy temperature energy balance (CTEB) model to determine daily ET. They found that CTEB ET estimates were within 10% of Bowen ratio energy balance ET values for substantial portions of two corn growing seasons. They determined that these ET estimates were within an acceptable uncertainty for ET estimates for use in most irrigation practices. However, the CTEB method is instrumentation intensive for practical use. Therefore, Kjelgaard et al. (1996) estimated net radiation from total incoming solar radiation and soil heat flux from net radiation and leaf area index to replace measured values. Based on these estimated values, CTEB ET estimates were similar to those obtained using measured values which indicated that a reasonable chance existed for reducing instrumentation requirements. However, soil heat flux estimates were also based on leaf area index values which are not readily available for specific crop conditions.

Colaizzi et al. (2003) investigated the relationship between the CWSI and K_s to estimate the fraction of soil moisture depletion (fDEP). The FAO 56 K_s (Allen et al., 1998) and Jensen K_s (Jensen et al., 1970) algorithms were evaluated. The Jensen K_s algorithm produced a better correlation between the CWSI and soil moisture than the FAO 56 K_s algorithm. Disagreement was greatest for fDEP < 0.6 because the K_s models are less sensitive to changes in fDEP in this range. Based on the estimate of K_s from CWSI, fDEP and the root zone soil moisture depletion (how much to irrigate) were calculated. A potential problem with this approach is inadequate knowledge of soil properties (field capacity and permanent wilting points) due to spatially variable soils within a field and crop rooting depths, hence, total available water within the crop root zone is unknown.

A simple, robust method is needed to estimate K_s for use in the reference ET-crop coefficient approach for estimating crop ET ($ET_{c\ adj}$) for canopy temperature-based irrigation timing techniques. Thus, the objective of this paper was to investigate use of measured canopy temperature of corn grown under standard conditions (fully irrigated) and non-standard conditions (water stressed) to calculate a ratio of canopy temperatures (standard condition divided by non-standard condition) as a substitute for K_s. This approach was inspired by techniques used for in-season assessment of plant N status whereby the target area was compared to a reference area that was supplied with sufficient N to alleviate N deficiency (Schepers et al., 1992; Bausch and Duke, 1996).

METHODS AND MATERIALS

Data for this study were collected during the 2008 growing season at the Limited Irrigation Research Farm (LIRF) northeast of Greeley, CO. LIRF is a 16 ha field research facility to conduct research on crop response related to full and deficit irrigation in four crop blocks. Each crop block contains 24 plots that are 12 rows wide (0.76 m row spacing) by 40 m long. Crop rows have a north/south orientation. Six water treatments replicated four times are imposed on the particular crop grown within each block. The four crops rotated through the four crop blocks are winter wheat, field corn, sunflower (oil), and dry beans (pinto). The six water treatments applied to each of these crops are:

- #1 – 100% (fully meet predicted water requirements)
- #2 – 85% (receive 85% of treatment #1)
- #3 – 70% (receive 70% of treatment #1)
- #4 – 70% (receive 70% of treatment #1)
- #5 – 55% (receive 55% of treatment #1)
- #6 – 40% (receive 40% of treatment #1).

Treatment 3 is applied proportional to treatment 1 at each irrigation. Treatments 2, 4, 5, and 6 are targeted to be seasonally proportional to treatment 1 but the water applications are distributed in response to critical growth periods (Stewart et al., 1975). This results in water applications below the treatment amount between establishment and reproductive growth stages and during maturation growth stages, and water applications above the treatment amount during the critical reproductive growth stage. All treatments are irrigated equally during the germination and plant establishment period.

Irrigation water is delivered to the corner of each plot and applied through polyethylene header pipes to drip irrigation tubing (16mm thick walled tubing with 1.1 L/h conventional inline emitters on 30 cm spacing) laid on the surface near each plant row. Flow rates and volumes to each treatment are measured with turbine flow meters. Irrigation applications to each treatment are controlled and recorded with Campbell Scientific CR 1000 data loggers. Water is supplied from groundwater, stored in a 22,000 L storage tank, and pressurized with a pressure-controlled variable frequency drive booster pump.

An automated weather station is located near the plots in a 0.5 ha grass plot. Hourly data from the station is used to calculate ASCE Standardized Penman-Monteith (ASCE-EWRI, 2005) alfalfa reference evapotranspiration (ET_r). Basal crop coefficients (Allen et al., 2007) and the FAO 56 (Allen et al., 1989) K_s procedure are used to calculate ET_c from calculated ET_r.

Soil water content is measured in each plot between 30 and 200 cm depth with neutron attenuation (503 DR Hydroprobe moisture gauge, Campbell Pacific Nuclear) at an access tube near the center of each plot. Surface soil moisture content (0-15 cm) is measured with a MiniTrase portable TDR system (SoilMoisture). Irrigations are scheduled using measured soil water depletion and predicted soil water depletions based on ET_c calculations.

Plant measurements are taken periodically to determine plant response to the various water treatments. Plant growth stage is assessed visually. Plant height measurements represent a visual mean across the top of the crop canopy, i.e., not individual plants. Canopy cover is assessed with a photosynthetically active radiation sensor (AccuPAR LP80, Decagon Devices, Inc.) from above and below canopy measurements and from images acquired with a digital camera (ADC, TetraCam, Inc.). Multi-spectral radiometers and infrared thermometers (IRTs) mounted on a mobile platform measure canopy reflectance and temperature, respectively. In addition to the IRTs mounted on the mobile platform, stationary IRTs (IRR-PN, Apogee Instruments, Inc.) are located in selected plots to continuously measure canopy temperature. These IRTs have a 36° field-of-view; they are positioned at a 60° view angle (30° below the horizontal), look 45° from North (northeast), and are 0.76 m above the crop canopy. They view an elliptical area with a theoretical major and minor axis of 2.9 m and 1.2 m, respectively. The IRTs are adjusted for crop height three times per week during vegetative growth.

Two adjacent 2 ha fields are each planted to one of the four crops so that each crop is grown in alternate years. Bowen ratio energy balance (BREB) instrumentation is installed near the center of each field to estimate ET_c. The crop in each of these fields is irrigated to meet full water requirements and measured ET_c is compared to calculated water use in the 100% water treatment. The fields adjacent to these fields and the plot area (four blocks) are used as buffer areas and are planted to the same crops planted in the BREB fields.

Results presented in this paper are for corn grown during the 2008 growing season in one replication of the small plots with irrigation treatments 1 and 5. DeKalb brand 52-59 (VT3) corn seed was planted May 12 (DOY 133) at 80,000 seeds/ha. Nitrogen fertilizer applications were based on soil samples and applied preplant broadcast (50 kg/ha), at planting (33 kg/ha), and through the irrigation system (34 kg/ha).

RESULTS AND DISCUSSION

The corn block was sprinkle irrigated (May 21) to achieve emergence which occurred about June 1 (DOY 153). A 30 mm precipitation event occurred on June 6 (DOY 158); the next measurable event (42 mm) was on August 6 (DOY 219). Stationary IRTs were installed on July 17 (DOY 199) for continuous canopy temperature measurements in irrigation treatments 1 and 5. Corn in treatment 1 at that time had 13 mature leaves [V13 growth stage (Ritchie et al., 1986)] whereas treatment 5 was at V10. Canopy cover was 77% and 50% for treatments 1 and 5, respectively; plant height was 1.3 m and 0.85 m, respectively. Thus, plant canopies were sufficiently dense to insure that the IRTs were viewing mostly plant material and very little, if any, soil.

Figure 1 shows the basal crop coefficient (K_{cb}) curves for irrigation treatments 1 and 5 adjusted for plant growth conditions and occurrence of effective cover as determined from canopy cover measurements averaged for the four replications within the corn

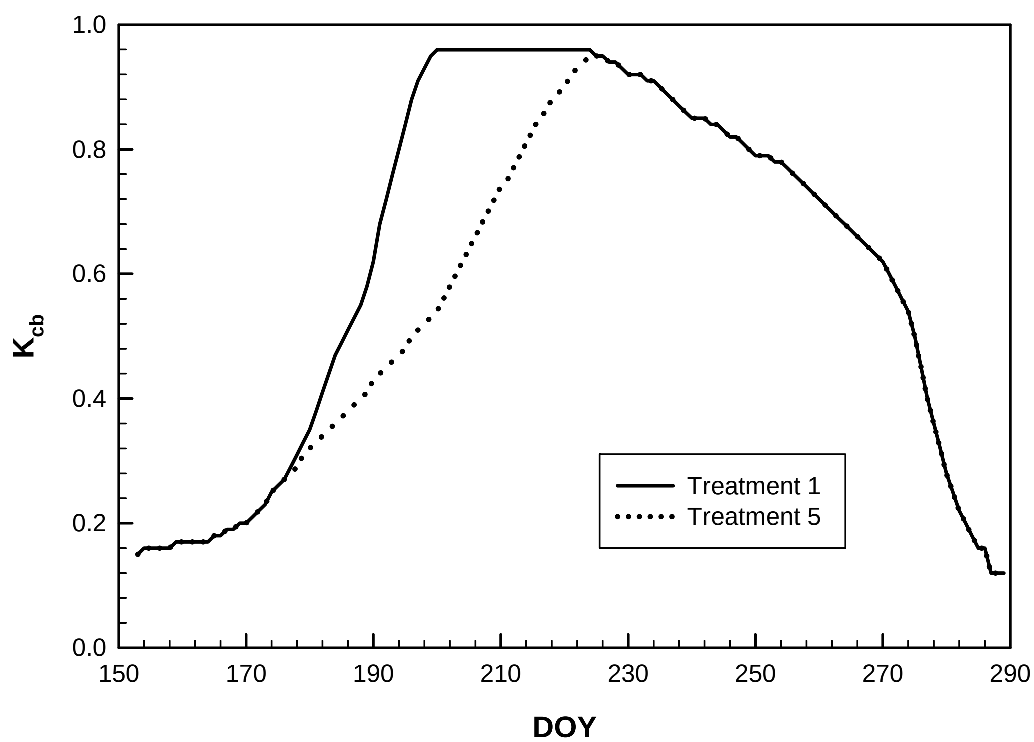

Figure 1. Corn Basal Crop Coefficient Curves for the Two Irrigation Treatments

block. Effective cover was assumed to occur when canopy cover reached 80%; however Stegman et al. (1980) considered effective cover for ET of agricultural crops to occur around a leaf area index of 3 and/or 75% ground cover. Treatment 1 reached effective cover on July 18 (DOY 200) whereas effective cover for treatment 5 occurred on August 12 (DOY 225). Figure 2a shows the difference in corn growth and condition on July 31 (DOY 213) for the two treatments; treatment 1 (right side of the image) was at the V18 growth stage and had a plant height of 2.1 m while treatment 5 (left side of the image) was at V15 with a plant height of 1.1 m. Figures 2b (treatment 5) and 2c (treatment 1) were taken with a nadir view camera on the mobile platform on the same day; canopy cover determined from these images was 63% and 91%, respectively.

Figure 2. Images Showing Differences between the Two Corn Irrigation Treatments on July 31 (DOY 213)

The 25 day period between occurrences of effective cover for the two irrigation treatments was selected for comparing canopy temperature of the water stressed treatment to the well irrigated treatment. At the end of this 25-day period, irrigation treatment 1 was 2.6 m in height and in the R2 (blister) growth stage while treatment 5 was 1.6 m tall and at the R1 (silk) growth stage. Figure 3 shows the canopy temperature

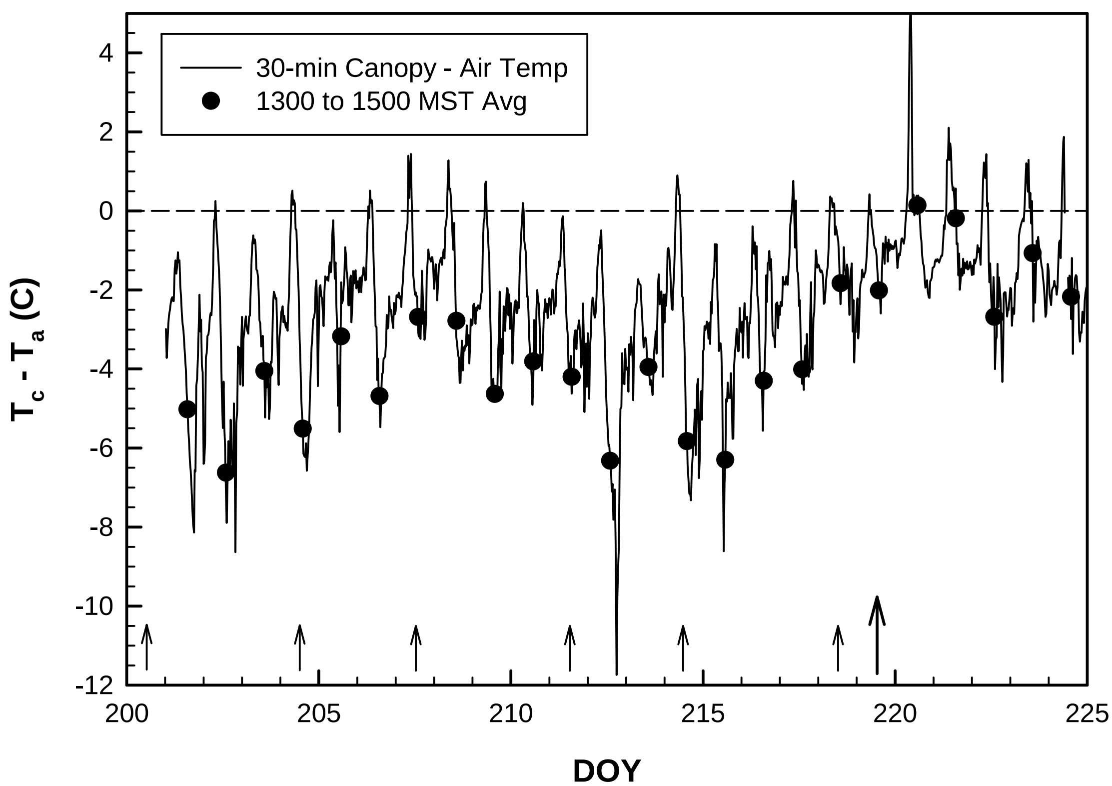

Figure 3. Canopy Temperature minus Air Temperature for Treatment 1 (Well-Watered Corn). Short Arrows are Irrigation Dates; Long Arrows are Precipitation Events.

minus air temperature for treatment 1 to indicate that corn in that treatment was not under water stress. Irrigations occurred on DOY 200 (24.1 mm), 204 (32.5 mm), 207 (28.5 mm), 211 (26.4 mm), 214 (28.6 mm), and 218 (22.4 mm). As mentioned earlier, a rainfall event occurred on DOY 219 (42.0 mm). The solid line is a trace of the temperature difference averaged over 30-min intervals throughout each day. Air temperature measurements used were those measured at the upper air sensor (1.2 m above the canopy) on the Bowen ratio mast in the Bowen ratio corn block. Canopy minus air temperature differences were mostly negative, i.e., the canopy was cooler than the air indicating freely transpiring corn. A positive temperature difference occurred sometimes around 0730 to 0930 MST which may be related to dew on the corn leaves. The filled circles represent the 1300 to 1500 MST temperature difference average which is typically the warmest time period during the day. A temperature difference greater than or slightly less than zero occurred on DOY 221 and DOY 222 following the rain event on DOY 219.

The solid line in Figure 4 represents the 30-min time trace throughout the day of canopy temperature in the well irrigated treatment (treatment 1) divided by the canopy temperature in the water stressed treatment (treatment 5). The filled circles represent the

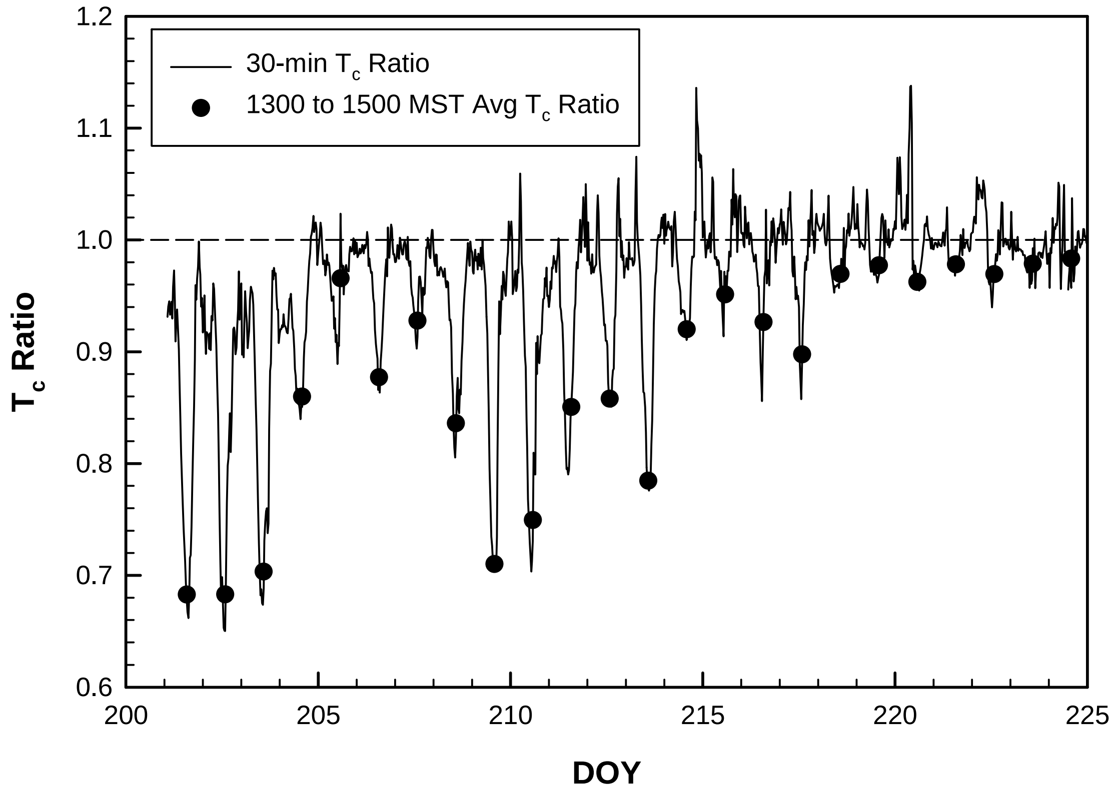

Figure 4. Canopy Temperature (T_c) Ratio Calculated from T_c (well irrigated) Divided by T_c (water stressed) for Corn Irrigation Treatment 5

1300 to 1500 MST average canopy temperature (T_c) ratio for each day. If treatment 5 was not water stressed and the canopy temperature measured by the IRT in treatment 5 produced the same canopy temperature measured by the IRT in treatment 1, the T_c ratio would equal one. As canopy temperature in the water stressed treatment increased due to less available soil water and reduced transpiration, the T_c ratio became less than one similar to K_s calculated from total available soil water within the crop root zone and measured root zone depletion. This is shown in Figure 5. However, the swings in magnitude of the T_c ratio are not as dramatic as the K_s values. A time offset exists between the K_s and T_c ratio values since the T_c ratio represents the 1300 to 1500 MST time period. Use of canopy temperature may be a more realistic parameter than soil water content to represent a stress coefficient due to the complicated physiological processes that plants undergo as they encounter water stress and compensate for this stress. Treatment 5 irrigations occurred on DOY 204 (22.3 mm), 211 (15.7 mm), 214(19.9 mm), and 218 (17.8 mm) during the 25-day evaluation period. Notice that the T_c ratio values following the irrigation event on DOY 218 and the precipitation event on DOY 219 are around 0.96 to 0.98 instead of 1. One would think after 60 mm of

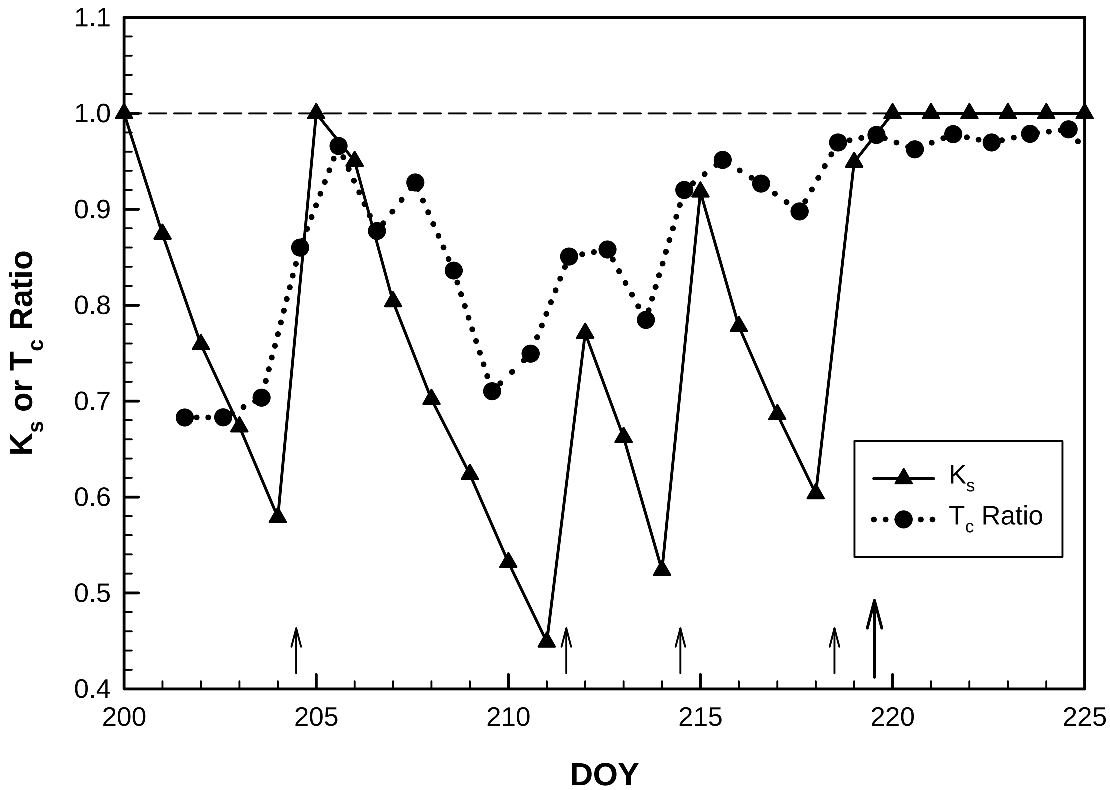

Figure 5. Comparison of the T_c Ratio with the K_s Stress Coefficient for Irrigation Treatment 5. Irrigation Dates are Short Arrows; Long Arrows are Precipitation Events.

combined irrigation and rainfall that the T_c ratio should equal 1; this may be due to canopy temperature being measured by two separate but well calibrated IRTs. Ideally, canopy temperature measurements should be measured with a common sensor to minimize sensor bias. However, this may not be practical. This difference may be real because the plant may not be capable of transpiring at its assumed potential rate due to earlier water stress. Figure 6 shows that $ET_{c\ adj}$ determined from the T_c ratio technique was greater than what was determined by the K_s technique for most of the comparison period. Cumulative $ET_{c\ adj}$ was 13 mm greater for the T_c ratio technique over the 25-day investigative period. However, for DOY 221 to 224 (a well watered time period) $ET_{c\ adj}$ was essentially the same for the K_s and T_c ratio techniques for treatment 5 ignoring the time offset associated with the T_c ratio and not much different from ET_c for treatment 1.

CONCLUSION

A ratio of canopy temperature (T_c) measured over corn in a well irrigated plot and a water stressed plot (T_c well divided by T_c stressed, i.e., T_c ratio) was investigated for comparison to the water stress coefficient (K_s) traditionally used in the reference ET-crop coefficient procedure to estimate crop ET. Based on the time period selected to compare the two techniques, this preliminary investigation indicated that the T_c ratio technique has potential as a quantitative water stress coefficient for water stressed crops and merits

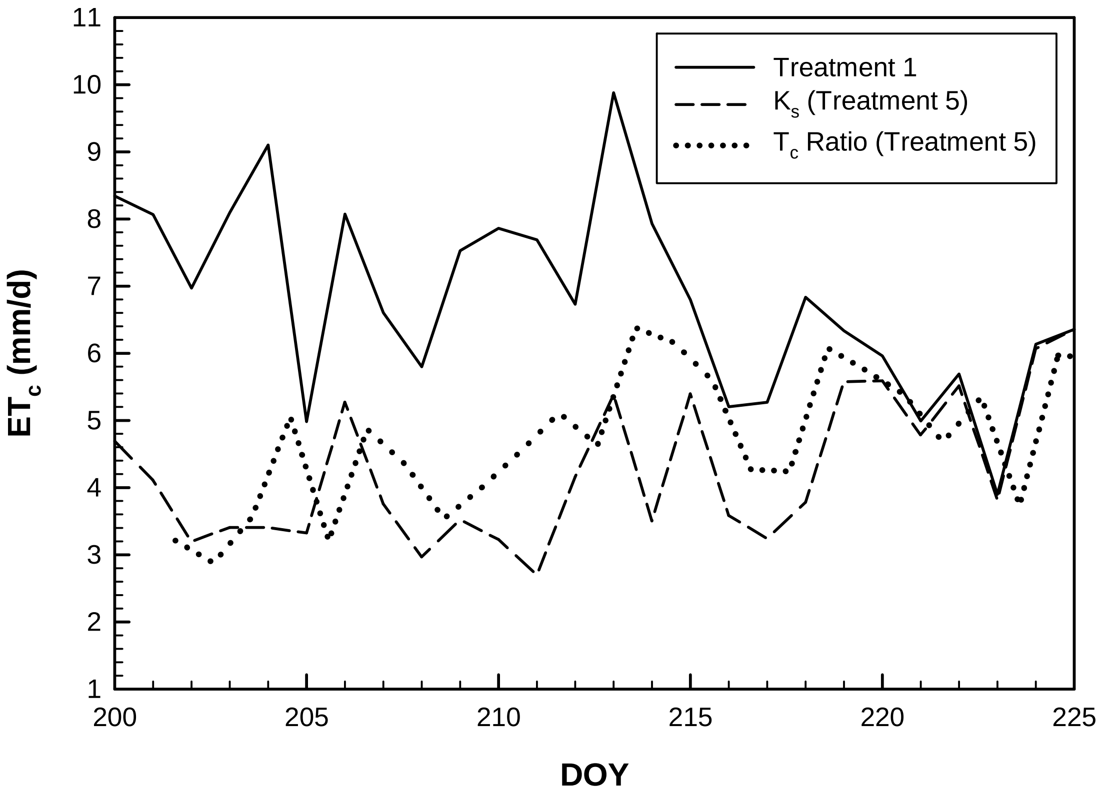

Figure 6. Comparison of $ET_{c\ adj}$ for the T_c Ratio and K_s Techniques for Irrigation Treatment 5 with ET_c for Irrigation Treatment 1

additional study. Furthermore, the T_c ratio lends itself to hourly incorporation of plant stress effects on crop ET when using hourly calculated reference ET. To determine which technique is more correct would require continuous soil water content measurements throughout the potential root zone in several locations in both irrigation treatments as well as daily plant water status (leaf water potential and stomatal conductance) measurements in both treatments.

DISCLAIMER

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

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CROP WATER PRODUCTIVITY TOWARDS FUTURE SUSTAINABLE AGRICULTURE IN EGYPT

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ABSTRACT

Water is characterized such as no alternative source can substitute it and it is not a commercial resource or commodity. The great challenge for the coming decades will be the task of increasing food production with less water particularly in basins with limited water resources. Molden et al. (2003) estimated that, by year 2020, approximately 75% of the world's population will live in areas experiencing physical or economic water scarcity. Most of these areas happen to be where most of the poor and food insecure people live. Meeting their food needs with locally produced food presents enormous challenge. Hence, the need is to increase water productivity of agricultural production systems in water scarce areas where the poor population is dependent on local production.

Increasing the productivity in agriculture will play a vital role in easing competition for scarce resources, prevention of environmental degradation, and provision of food security. Crop water productivity depends on several factors including crop genetic material, water management practices, economic and policy incentives, and people's acceptance. In a broad sense, productivity of water refers to the benefits derived from the use of water and is most often given in terms of mass of product, or its monetary value, per unit of water.

Therefore, the main goal of the current practical study is to assess water productivity for different crops, assist decision makers in developing sustainable agricultural policies for Egypt and maximize national water resources' productivity in different agricultural activities considering the supply and demand aspects and based on the efficient utilization of the water resource.

STUDY SPECIFIC ACTIVITIES

To successfully achieve the main study's goal, several major activities will be carried out as follows:

- Describe the current cropping pattern.
- Evaluate the crop water requirement pattern.
- Evaluate the gross margin of main crops in both new and old lands.
- Evaluate the water productivity of agricultural crops under different irrigation methods.

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- Evaluate the net water return of agricultural crops under different irrigation methods.
- Evaluate the net water return of crop rotations under different irrigation methods.

STUDY PROBLEM

The last year witnessed sharply changes in agricultural prices of all crops, particularly as a result of utilizing some crops such as corn, sugarcane, and sugar beet in producing ethanol as an alternative source of energy. The competition between using crops for food and energy changed the cropping pattern and farmer's attitudes in the world. The world agricultural crop prices affected the Egyptian local prices. The increase in producing energy from agriculture commodities has also affected the price of agricultural inputs, particularly machinery and fertilizer. Therefore, crop water productivity is considered an important factor that needs to be evaluated accurately towards future sustainable water and agriculture policies.

COLLECTED DATA UTILIZED

Data and information were collected to meet the current research objectives. The collected data were classified according to the following two categories:

Secondary Data

- Total cropped areas at the national level in both new and old lands. (Data source: Agriculture Economic Affairs Sector)
- Water Requirements at field levels in old lands (CAPMAS, Central agency for Public Mobilization and Statistics, Bulletin of irrigation and water requirement).
- Water requirements at field levels in new lands under the applied irrigation system. (Agricultural Research Center, Soil, Water and Environment Research Institute)

Cross-Sectional Data (Field Survey Data)

This type of data was collected through a specific questionnaire that was designed to collect certain data regarding the crop income in both new and old lands. This questionnaire is mainly concerned with the cost items and returns of the main crops.

METHODOLOGY OF STUDY

To assess the crops' water productivity, the current research reviewed the previously applied methodologies for crop water productivity assessment and implements the model that could be adopted to achieve the study's objectives.

Approach 1: Production Function Utilization

Agricultural production involves the combination of all inputs that are essential to produce agricultural outputs. For each agricultural production system, a generic production function (input-output relationship) can be derived as follows

$$Y = f(x1, x2, x3, \ldots xn) \quad (1)$$

Where Y is the output and x1, x2, x3, and xn are the production factors (land, labor, water, capital, energy and other inputs used in the production).

As production resources become scarce, producers seek ways to enhance the productivity of the resources and of the entire production system. Understanding the production function is a pre-condition for identifying opportunities for improving the performance of a production system. Increases in productivity can be achieved by two approaches: (a) increasing technical efficiency through more efficient utilization of production inputs; and (b) increasing allocation efficiency by producing outputs with the highest returns. An analysis of a single factor production function enables us to assess opportunities for maximizing returns from the use of this factor. Towards achieving the current research's goal, it is assumed that the only way to increase crop yield is by increasing the productivity of the water input. To optimize the production system, you must understand how output increases with increase in water input. The contribution of water to the production process can be described on both average and marginal basis at different levels of water input as follows:

Average Product of Water = Output / Water Input
Marginal Product of Water = Change in Output / Change in Water Input

The water output per feddan, Feddan = 4200 m^2, is defined as a function of effective water used by the plant. This is equivalent to the term resulting from the multiplication of the water use efficiency parameter and applied water. Three models could be used for the production function approach as follows:

Model 1: Some of the early work on water productivity was performed by Hexem and Heady (1978), who used field experiments in the United States to estimate yield as a function of inputs including water and fertilizer. One commonly used production function in the economic literature is a Cobb-Douglas production function of the form:

$$Y = Ax^{\delta}, \text{ with a requirement that } \delta < 1. \quad (2)$$

Where:
Y = Yield output per feddan
A = Equation parameter
δ = Equation parameter < 1
x = Water use input

Model 2: While some researchers have shown that Model 1 representation is reasonably accurate at the aggregate level, econometric evidence has shown that it is a poor representation of the yield response to water at a more micro-level. On the other hand, the literature showed evidence that a quadratic function is a better representation of water productivity as follows:

$$Y = a + bx - cx^2 \tag{3}$$

Where:
Y = Yield output per feddan
a = Equation parameter > 0
b = Equation parameter > 0
c = Equation parameter > 0
x = Water use input > 0

This functional form has the property that above some level of input use, yields begin to decline. With an extreme weather shock, such as a flood, one can easily see how a field of crops is washed away, and the benefits of that additional flood water are negative.

Model 3**:** Another commonly used function is the Von Liebig, which assumes water exhibits constant returns below some threshold level, and a zero return above that threshold. This takes a form such as:

$Y = Ax \text{ if } x \leq x^*$
and
$Y = Ax^* \text{ if } x > x^*$

Existing literature work finds it is unclear which of these three functional forms is the most accurate, and further work needs to be done on this subject.

Approach 2: Crop Budget Approach

Crop budget is considered one of the economic tools to estimate the net return or profit. The estimated profit can be compared against the estimated per feddan profit for other crops and used to select the more profitable crops and crop combinations to be grown each year. It is worth noting that the profit in this budget may not be the maximum profit possible from one feddan of a specific crop. Any crop budget represents only one point on a production function. Therefore, there is a crop budget for every point on a production function; so a budget does not automatically determine the profit maximizing input levels. However, the profit must be properly interpreted, as it is the return or profit above all costs including opportunity costs on owned inputs, (Kay, 1981).

The first approach (the three models described above) requires the observations of the actual experiments that represent the quantity of water consumed and the associated crop's yield, with all other production factors held constant. For this reason, the current study adopted the second approach to assess the crop water productivity in terms of physical unit of production and monetary units. As mentioned above, the crop budget represents only one point on the production function and the net return does not represent the profit maximization. Therefore, the current study considered this fact and collected data from different farmers, carried out their crop budgets for each crop and calculated the average of these budgets to represent the reality of the crop budget situation.

THE FIELD SURVEY DATA

As mentioned above, specific field survey data is collected within the current study through questionnaire interviews. These data were analyzed and utilized to measure five indicators; break even yield, break even price, crop water productivity unit, crop water net return and crop rotation water net return.

Questionnaire Design

The questionnaire was designed and prepared for the farmers to collect certain types of data and information to support achieving the current research goal and objectives. The collection of data and information was carried out through direct interviews with farmers. Specifically, the questionnaire includes the following data and information items:

- Land tenure and size.
- Current cropping rotations.
- Variable costs of farm inputs; quantities and their associated prices.
- Total production and their associated prices.
- Labor requirements and their associated wages for different operations.
- Machinery requirements and their associated wages for different operations.
- Interest on variable costs.
- Fixed costs; machinery depreciation, interest, taxes, insurance and land charge.

Description of the Study Sample

The current research selected a stratified two-stage sampling of the farmers of Menoufia and Nubaria’s villages, i.e. Menoufia represent the case of old lands with traditional irrigation and Nubaria for the new lands, it means reclaimed areas, with modern irrigation. The village represented the primary sample unit and the farmer was the secondary sample unit. From each selected village, 25 farmers were selected according to their proportional land holding sizes in order to make sure that the target farmers are homogenous in the sample and to capture all characteristics from different perspectives.

Sample Size and Selection

The first target population consisted of all farmers who are planting field crops, vegetables and fruits. The research team visited 10 farmers in each governorate and tested the questionnaire with them. From the pre test of surveyed data to be collected, the research team computed the variations of certain indication variables. Based on these variations, the proper sample size was determined to be 50 from each governorate. The sampled farmers were distributed as shown in table (1). It is worth noting that Nubaria, as the case of new land, has small farmer beneficiaries, graduates and investors. The sample has only contained small farmers and graduates because of some difficulties of meeting investors and the variations of the cropping pattern and crop production between investors and the other two classes.

Table 1. Distribution of sampled farmers according to holding size and location in sample governorates, 2008.

Holding Size Category	Menoufia	Nubaria
Less than 1 Feddan	10	0
1 - 3	20	0
3 - 5	15	0
Greater than 5 Feddans	5	50
Total	50	50

Source: Collected and calculated from the field survey, 2008.

0's in Nubaria are due to the minimum farms' size that equal to 5 feddan.

CURRENT CROPPING PATTERN IN EGYPT

The cropping pattern refers to the total area cultivated by different crops and their relative importance in the winter, summer, and nili, nili is an agricultural season lied between winter and summer seasons. It begins from June to September, seasons. Some cropping patterns were prepared as specific groups of crops, i.e. cereals, legumes, fodder, oil crops …etc, based on the target objectives. However, in all cases, the cropping pattern reflects the relative importance of the specific crop or group of crops to the total cultivated areas. Table (2) and figure (1) represented the winter cropping pattern structure. It could be noted that clover and wheat occupied about 76% of the total cropped area in winter season; distributed as 80% in old lands and 60% in new land because of planting barely(barley is a cereal crop) in new land which represented about 18.6% from total area cultivated in new land winter season.

In the summer season, the main crops are maize, rice, cotton, sugarcane and sorghum. The relative importance of them is 24.7%, 25.7%, 8.8%, 5.1% and 5.3% of total summer area distributed by different values between old and new lands as shown in table 3 and figure 2 below. The structure of the main activity in new land is different from old land area in summer season. Tomato and other vegetables represented about 43% while maize (white and yellow) and peanut represented about 17.2% and 12.7% of total summer crops respectively.

Table 2. Winter Cropping Pattern in Egypt, 2007.

Crop	Old Lands		New Lands		Total	
	Area (Feddan)	%	Area (Feddan)	%	Area (Feddan)	%
Clover	2102137	38.8	219884	18.5	2322021	35.2
Wheat	2220710	41.0	494819	41.6	2715529	41.1
Barely	23243	0.4	221862	18.6	245105	3.7
Faba bean	166192	3.1	69210	5.8	235402	3.6
Lentil	1841	0.0	34	0.0	1875	0.0
Fenugreek	11628	0.2	2380	0.2	14008	0.2
Check Peas	10787	0.2	72	0.0	10859	0.2
Lupine	2050	0.0	1695	0.1	3745	0.1
Flax	20378	0.4	442	0.0	20820	0.3
Winter Onion	69869	1.3	16772	1.4	86641	1.3
Garlic	21296	0.4	3557	0.3	24853	0.4
Sugar beat	225773	4.2	22535	1.9	248308	3.8
Potato	89650	1.7	19538	1.6	109188	1.7
Tomato	162074	3.0	38219	3.2	200293	3.0
Other Vegetables	236381	4.4	73467	6.2	309848	4.7
Other Field Crop	48830	0.9	5669	0.5	54499	0.8
Total	5412839	100	1190155	100	6602994	100

Source: Ministry of Agriculture and Land Reclamation, Economic Affairs sector, Agricultural Economics Bulletin, 2007.

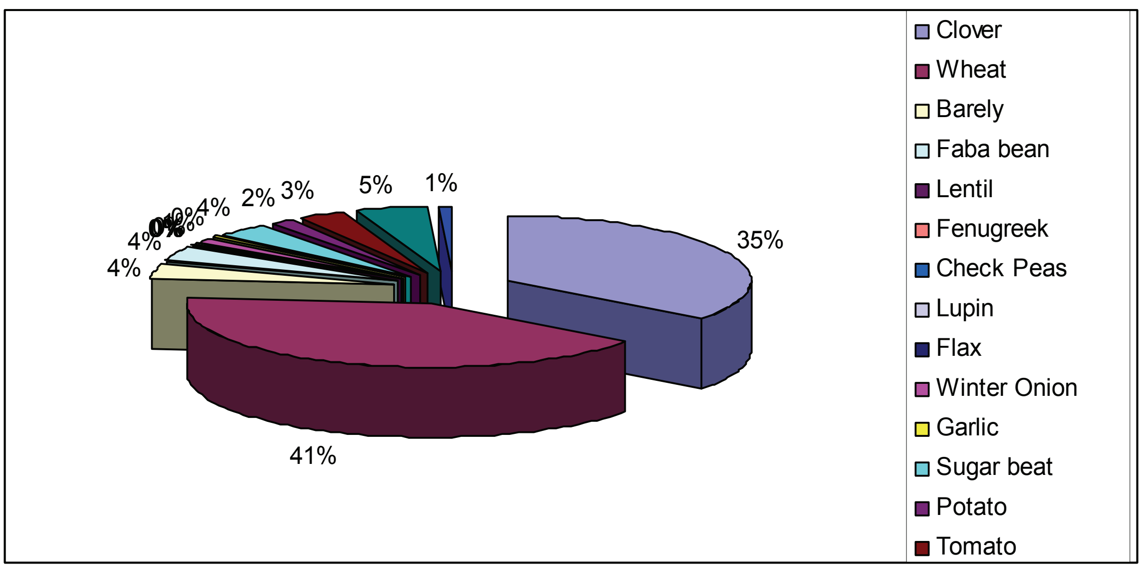

Figure 1. Winter Cropping Pattern Structure in Egypt, 2007.

Table 3. Summer Cropping Pattern in Egypt, 2007.

Crop	**Old Lands**		**New Lands**		**Total**	
	Area	**%**	**Area**	**%**	**Area**	**%**
Maize	1487697	26.4	120671	13.5	1608368	24.7
Sorghum	331984	5.9	15251	1.7	347235	5.3
Rice	1611804	28.7	60908	6.8	1672712	25.7
Yellow maize	143731	2.6	33455	3.7	177186	2.7
Pea nut	42240	0.8	113065	12.7	155305	2.4
Sesame	30412	0.5	44454	5.0	74866	1.1
Soya bean	18259	0.3	276	0.0	18535	0.3
Sun flower	22704	0.4	4472	0.5	27176	0.4
Summer Onion	12813	0.2	2505	0.3	15318	0.2
Potato	74926	1.3	10926	1.2	85852	1.3
Tomato	161090	2.9	105868	11.8	266958	4.1
Other Vegetables	549037	9.8	276096	30.9	825133	12.7
Other Field crops	275914	4.9	58375	6.5	334289	5.1
Sugarcane	295919	5.3	39144	4.4	335063	5.1
Cotton	566416	10.1	8150	0.9	574566	8.8
Total	5624946	100	893616	100	6518562	100

Source: Ministry of Agriculture and Land Reclamation, Economic Affairs sector, Agricultural Economics Bulletin, 2007.

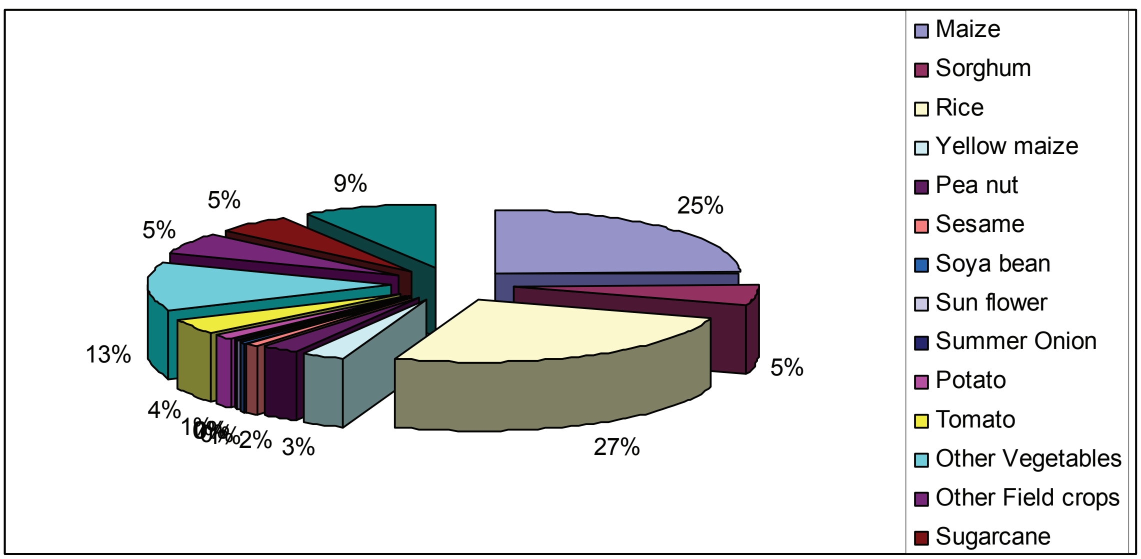

Figure 2. Summer Cropping Pattern Structure in Egypt, 2007.

In the nili season, the structure of cropping pattern also differed in the old and new lands and could be similar to the case of summer season. Tomato and other vegetables recorded about 37% versus 29% of total nili cropped area in both new and old lands respectively. The main constraint of this crop season is mainly the time of crops' planting and harvesting in addition to weather. For this reason, the crops cultivated in the nili season mainly appeared in Upper Egypt, (See table 4 and figure 3 bellow).

Table 4. Nili Cropping Pattern in Egypt, 2007.

Crop	Old Lands		New Lands		Total	
	Area (Feddan)	%	Area (Feddan)	%	Area (Feddan)	%
Maize	220761	38.9	22385	28.6	243146	37.6
Sorghum	6329	1.1	382	0.5	6711	1.0
Rice	403	0.1	2534	3.2	2937	0.5
Yellow maize	29130	5.1	15882	20.3	45012	7.0
Nili onion	14723	2.6	623	0.8	15346	2.4
Potato	61993	10.9	0	0.0	61993	9.6
Tomato	55183	9.7	14774	18.9	69957	10.8
Other Vegetables	111996	19.7	13858	17.7	125854	19.5
Other Field crops	67356	11.9	7752	9.9	75108	11.6
Total	567874	100.0	78190	100.0	646064	100.0

Source: Ministry of Agriculture and Land Reclamation, Economic Affairs sector, Agricultural Economics Bulletin, 2007.

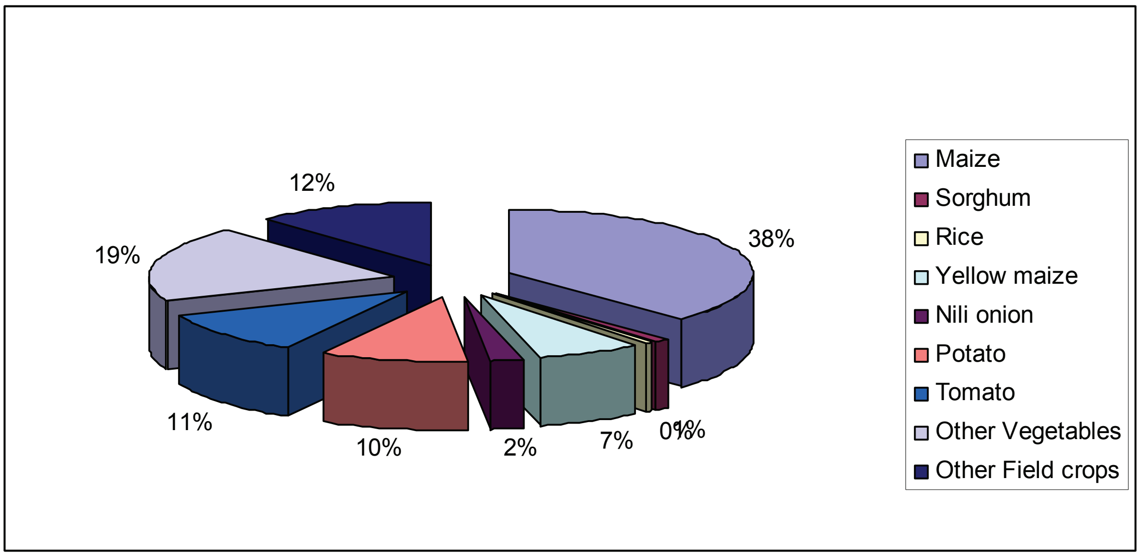

Figure 3. Nili Cropping Pattern Structure in Egypt, 2007.

WATER REQUIREMENT PATTERN

The water requirement pattern depends mainly on the cropping pattern. It is calculated from the cropping pattern based on multiplying the specific crop cultivated area by its per feddan water requirement and summed them up to estimate the total water requirement in winter, summer and nili seasons. Of course, the structure of water requirement pattern depends on per feddan crop water requirement as seen in tables 5, 6 and 7 and figures 4, 5 and 6 below. In the winter season, clover and wheat consumed about 81% of total water in the winter season. In the summer season, in spite of the relative importance of area cultivated by maize and rice that occupied 24.7% and 25.7% respectively, the rice crop consumed about 38% versus 24% by maize from total water consumption because of highly water requirement of rice. Therefore, more attention was introduced to decrease the area planted to rice and re-allocating it among other crops in the original areas or reclaimed additional areas. However, the decision here will depend on the objectives of agricultural strategy sector.

Table 5. Total Winter Water requirement Pattern in Egypt, 2007.

Crop	Old Lands			New Lands			Total million CM
	Area Feddan	Water Req. CM/Feddan	Total Water Req. million CM	Area Feddan	Water Req. CM/Feddan	Total Water Req. million CM	
Clover	2102137	2773.0	5829.2	219884	2608.0	573.5	6402.7
Wheat	2220710	1677.0	3724.1	494819	1751.0	866.4	4590.6
Barely	23243	1354.0	31.5	221862	1751.0	388.5	420.0
Faba bean	166192	1371.0	227.8	69210	1008.0	69.8	297.6
Lentil	1841	1837.0	3.4	34	1930.0	0.1	3.4
Fenu Greack	11628	1356.0	15.8	2380	n.a		15.8
Check Peas	10787	1704.0	18.4	72	n.a		18.4
Lupin	2050	1441.0	3.0	1695	n.a		3.0
Flax	20378	1234.0	25.1	442	1660.0	0.7	25.9
Winter Onion	69869	1862.0	130.1	16772	1610.0	27.0	157.1
Garlic	21296	1478.0	31.5	3557	1220.0	4.3	35.8
Sugar beat	225773	2007.0	453.1	22535	1415.0	31.9	485.0
Potato	89650	2003.0	179.6	19538	760.0	14.8	194.4
Tomato	162074	2003.0	324.6	38219	1066.0	40.7	365.4
Other Vegetables	236381	2003.0	473.5	73467	877.0	64.4	537.9
Other Field Crop	48830	2003.0	97.8	5669	n.a		97.8
Total	5412839			1190155			13650.7

Source: - Ministry of Agriculture and Land Reclamation, Economic Affairs sector, Agricultural Economics Bulletin, 2007.
- CAPMAS, Central agency for Public Mobilization and Statistics, Water Resources and Irrigation Bulletin, 2004.

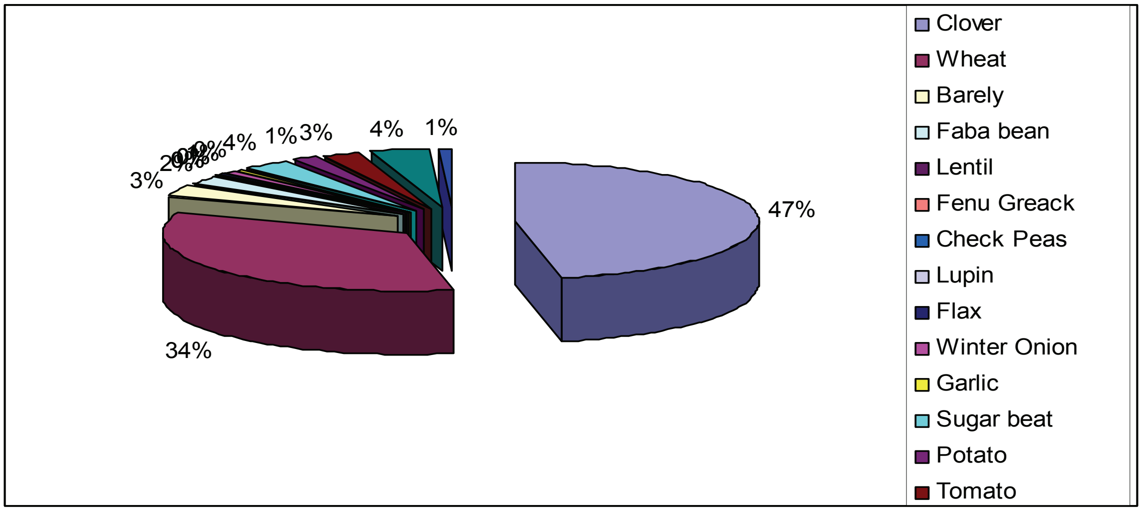

Figure 4. Total Winter Water requirements Pattern Structure in Egypt, 2007.

Table 6. Total Summer Water requirement Pattern in Egypt, 2007.

Crop	Old Lands			New Lands			Total million CM
	Area Feddan	Water Req. CM/Feddan	Water Req. Total million CM	Area Feddan	Water Req. CM/Feddan	Water Req. Total million CM	
Maize	1487697	3914.0	5822.8	120671	2171.0	262.0	6084.8
Sorghum	331984	2980.0	989.3	15251	1583.0	24.1	1013.5
Rice	1611804	5821.0	9382.3	60908	n.a		9382.3
Yellow maize	143731	3914.0	562.6	33455	n.a		562.6
Pea nut	42240	3895.0	164.5	113065	2686.0	303.7	468.2
Sesame	30412	2740.0	83.3	44454	n.a		83.3
Soya bean	18259	2955.0	54.0	276	2272.0	0.6	54.6
Sun flower	22704	2322.0	52.7	4472	2070.0	9.3	62.0
Summer Onion	12813	3658.0	46.9	2505	n.a		46.9
Potato	74926	2861.0	214.4	10926	1562.0	17.1	231.4
Tomato	161090	2861.0	460.9	105868	2146.0	227.2	688.1
Other Vegetables	549037	2861.0	1570.8	276096	n.a		1570.8
Other Field crops	275914	2861.0	789.4	58375	n.a		789.4
Sugarcane	295919	8854.0	2620.1	39144	n.a		2620.1
Cotton	566416	3102.0	1757.0	8150	n.a		1757.0
Total							25414.9

Source: - Ministry of Agriculture and Land Reclamation, Economic Affairs sector, Agricultural Economics Bulletin, 2007.
- CAPMAS, Central agency for Public Mobilization and Statistics, Water Resources and Irrigation Bulletin, 2004.

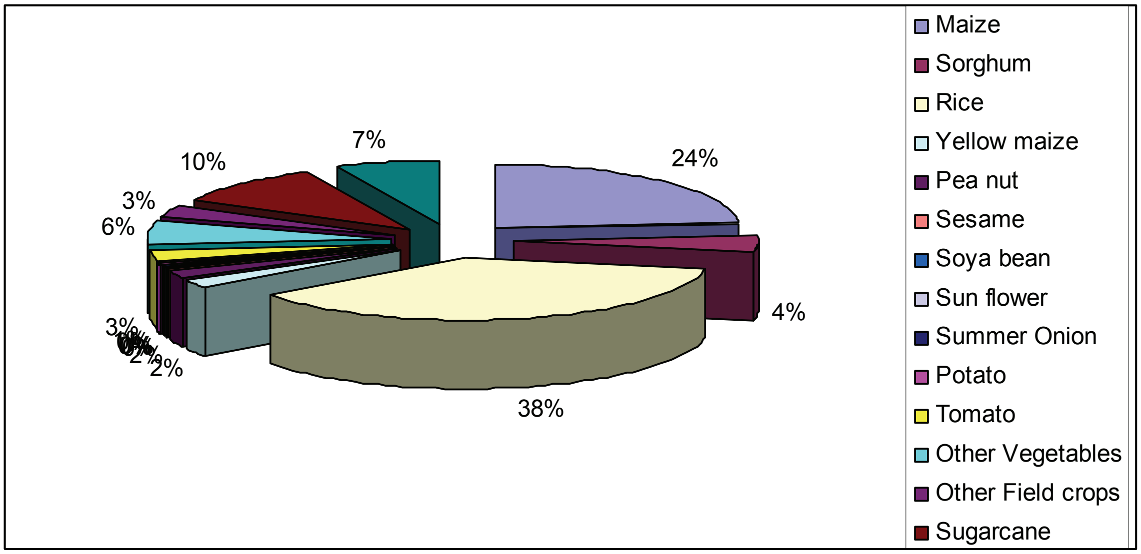

Figure 5. Total Summer Water requirement Pattern Structure in Egypt, 2007.

Table 7. Total Nili Water requirement Pattern in Egypt, 2007.

Crop	Old Lands			New Lands			Total Water Req. (CM)
	Area Feddan	Water Req. per Feddan	Water Req. Sub-total (CM)	Area Feddan	Water Req. per Feddan CM	Water Req. Sub-total (CM)	
Maize	220761	2436	537773796	22385	2436	54529860	592303656
Sorghum	6329	1947	12322563	382	1947	743754	13066317
Rice	403	6187	2493361	2534	6187	15677858	18171219
Yellow maize	29130	2436	70960680	15882	2436	38688552	109649232
Nili onion	14723	3161	46539403	623	3161	1969303	48508706
Potato	61993	2532	156966276	0	2532	0	156966276
Tomato	55183	2532	139723356	14774	2532	37407768	177131124
Other Vegetables	111996	2532	283573872	13858	2532	35088456	318662328
Other Field crops	67356	2532	170545392	7752	2532	19628064	190173456
Total	567874		1420898699	78190		203733615	1624632314

Source: - Ministry of Agriculture and Land Reclamation, Economic Affairs sector, Agricultural Economics Bulletin, 2007.

- CAPMAS, Central agency for Public Mobilization and Statistics, Water Resources and Irrigation Bulletin, 2004.

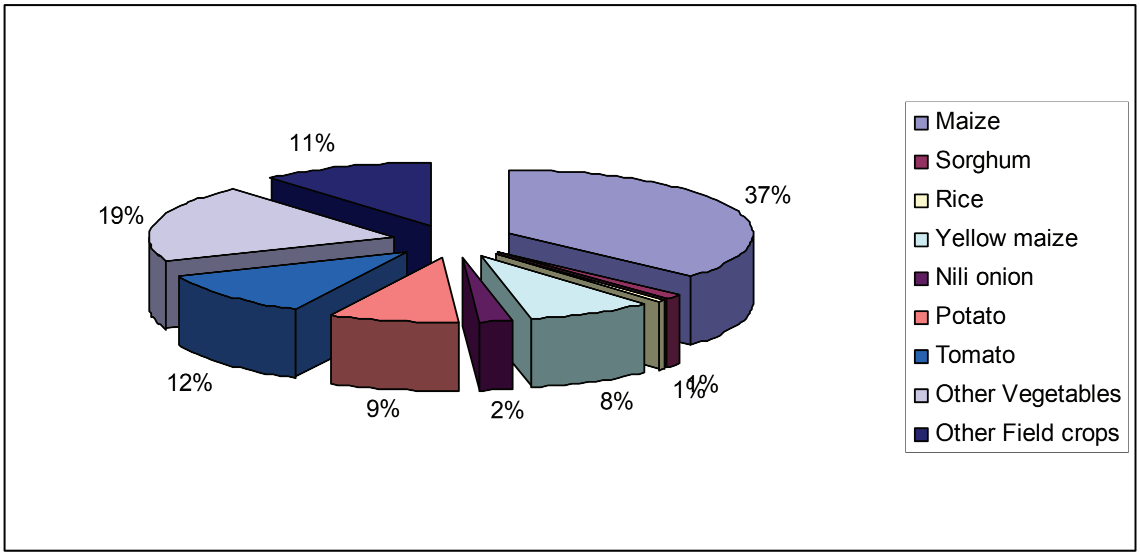

Figure 6. Total Nili Water requirement Pattern in Egypt, 2007.

CROP BUDGET

Crop budget can be organized and presented in several different formats, but they typically contain three different sections: income, variable costs and fixed costs. Following are the steps to estimate these sections in details:

Income

The first step to estimate income is to estimate the total production. Total production includes main and by product yield and the associated prices of these outputs for the studied crops. Of course, these variables are the average at the sampling level and could be considered a good estimate for the actual case in the previous agricultural year.

Variable Costs

The variable costs include seed, fertilizer, machinery, labor, machinery repairs, fuel and other items of variable cost. The variable costs are calculated by multiplying the quantities of each input by the associated price. The study also estimated the charge for the opportunity cost on capital invested in the variable costs. This charge covers the time period between expenditure of the capital and harvest when the income is received. Within the current research, an average time period of 6 months is assumed and a 10% opportunity cost is charged on the value of variable costs.

Fixed Costs

Fixed costs in the crop budget include machinery fixed costs and land charge. In the Egyptian circumstances, most of machinery work is hired and could be calculated as variable costs. Therefore, the fixed costs here are the charge of land. Land charge is the opportunity cost of land and represents the return for its use in crop production. Three methods could be adopted to determine the land charge: (1) an interest opportunity cost based on the current value of the land, (2) the owner's rental income from a typical crop share lease, or (3) a typical cash rent charge. The current research adopted the third method because of available knowledge for the cash rent of each crop in advance as can be obtained in the Egyptian rural societies.

Net Return

Net return calculated as the difference between the total return; total production multiplied by their farm gate prices, and the total costs calculated from the three items above. The net return here is not similar as its value published in agricultural economic bulletin because of the sharp increase in the price of fertilizer, energy, labor wages and land rent in addition to the high increase of the output prices. On the other hand, each crop budget estimated the shadow prices of all owned inputs and estimated all the other items of irrigation cost that included fuel and oil, custom application, equipment rent, depreciation, taxes and insurances. The price of water as a resource was considered as a cost recovery of water resource. Therefore, the net return here is expressing the economic profit.

Water Input

The water input can be specified as volume (m^3) or as the value of water expressed as the highest opportunity cost in alternative uses of the water. To estimate the water requirement of different crops, the current study utilized the data published by CAPMAS-Irrigation and Water Resource Bulletin at the field level and specifically the water requirement data for each crop at the field level.

Water Productivity Definition

Different indicators for water productivity could be used. In the current study, crop water productivity focuses on the field level. Water productivity at the field level refers to the amount of crop output in physical terms (crop yield in kilogram) or monetary terms (crop yield times its price in financial or economic terms) divided by the amount of water consumed (evaporated from the soil and transpired by the plant, the evapo - transpiration) - in other words, the crop per drop. However, productivity is a measure of performance expressed as the ratio of output to input. Productivity may be assessed for the whole system or parts of it. It could account for all or one of the inputs of the production system giving rise to two productivity indicators:

- **Total productivity :** the ratio of total tangible outputs divided by total tangible inputs; and
- **Partial or single factor productivity:** the ratio of total tangible output to input of one factor within a system. In farming systems the factors could be water, land, capital, labor and nutrients.

Water productivity (WP) is a partial-factor productivity that measures how the systems convert water into goods and services. Its generic definition can be recognized as:

Water Productivity (WP) = Output Derived from Water Use/ Water Input

Indicators of Crop Water Productivity

Water productivity is a very robust measure that can be applied at different scales to suit the needs of different stakeholders, (Shetty, 2006; Sharma, 2006). This is achieved by defining the inputs of water and outputs in units appropriate to the users' needs.
The numerator (output derived from water use) can be defined in the following ways:

- Physical output, which can be total biomass or harvestable product;
- Economic output (the cash value of output) either gross benefit or net benefit.

RESULTS OF WINTER FIELD CROPS

Following the previously mentioned methodology and equations, results of crop water productivity within winter season are presented in table (8) and figure (7). These results indicated that total productivity in old land is higher than in new land and consequently the net return because of higher production and lower costs in old land, except for the faba bean crop. However, the situation will be different if the water were not free. In new lands, the irrigation method is either sprinkler or dripper that consumed less water than the flood method. Water productivity in physical units can be used only to compare the productivity of water in old and new lands for the same crop. From this indicator, crop water productivity is higher in old land, i.e. flood irrigation method, than new one in both wheat and long clover while the opposite occurred in the case of faba bean and sugar beat which used the drip irrigation method because of the less water lost in drip irrigation compared with sprinkler and flood and less water is consequently consumed. The indicator of net return of water illustrated the same results of the physical one in addition to the variability of water return in old and new lands for long clover crop.

Table 8. Crop Water Productivity for Main Winter Field Crops in Old and New Lands under Different Irrigation Methods.

Crop	Wheat		Long Clover		Faba bean		Sugar beat	
	Old Land	New Land	Old Land	New Land	Old Land	New Land	Old Land	New Land
Irrigation Method	**Flood**	Sprinkler	**Flood**	Sprinkler	**Flood**	Drip	**Flood**	Drip
Water Requirement (m^3/Feddan)	1677	1751	2773	2608	1371	1008	2007	1415
Total Production (Ton Feddan)	3.41	2.48	30	26	1.4	1.55	25	19
Net Return (L.E/Feddan)	5,850	3,054	1,056	950	1000	1,732	779	779
Water Productivity Indicators:								
Water Unit Productivity (Kg/CM)	1.97	1.37	10.82	9.97	1.02	1.54	12.46	13.43
Water Unit Net Return (L.E/CM)	3.49	1.74	0.38	0.36	0.73	1.72	0.39	0.55

- Ton = 1000 kg, L.E Egyptian Pound and it is a currency of Egypt.

Source: - Calculated from the survey data of agricultural year 2007/2008.
Central agency for Public Mobilization and Statistics, Bulletin of irrigation and water requirement, 2004.

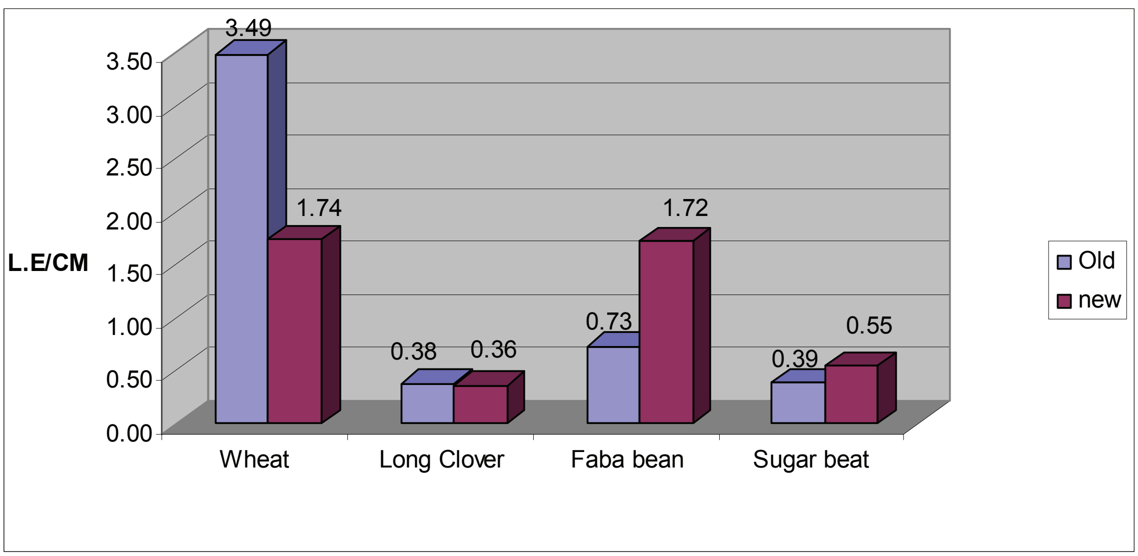

Figure 7. Crop Water Productivity for Main Winter Field Crops in Old and New Lands under Different Irrigation Methods.

RESULTS OF SUMMER FIELD CROPS

In the case of summer field crops, there is a high variation of production among the different crops. This variation is mainly due to the high response of these crops to water in summer because of the high temperature compared to the winter season. However, there is no area planted to cotton and rice in new lands for technical reasons. The variation in the water productivity in physical unit is low for maize and sugarcane while it is higher in onion crop (5.88 against 4.1 Kg/CM) and consequently the net return of water is 2.23 versus 1.61 L.E/CM for the same comparison. Table 9 and Figure 8 show the crop water productivity in both terms for the main summer crops.

Table 9. Crop Water Productivity for Main Summer Field Crops in Old and New Lands under Different Irrigation Methods.

	Maize		Rice		Cotton		Sugarcane		Onion	
Crop	Old Land	New Land	Old Land	New Land	Old Land	New Land	Old Land	New Land	Old Land	New Land
Irrigation Method	**Flood**	Drip	**Flood**	0	**Flood**	0	**Flood**	Drip	**Flood**	Drip
Water Requirement (CM/Feddan)	3914	2171	5821	0	3102	0	8854	0	3658	0
Total Production (Ton/Feddan)	4.37	2.85	4	0	1.26	0	51	46	15	10
Net Return (L.E/Feddan)	734	500	1,783	0	2,523	0	3998	2700	5898	3,796
Water Productivity Indicators:										
Water Unit Productivity (Kg/CM)	1.58	1.31	0.69	0	0.41	0	5.8	5.11	4.10	5.88
Water Unit Net Return (L.E/CM)	0.25	0.23	0.31	0	0.81	0	0.45	0.3	1.61	2.23

Source: - Calculated from the survey data of agricultural year 2007/2008.
CAPMAS, Central Agency for Public Mobilization and Statistics, Water Resources and Irrigation Bulletin, 2004.

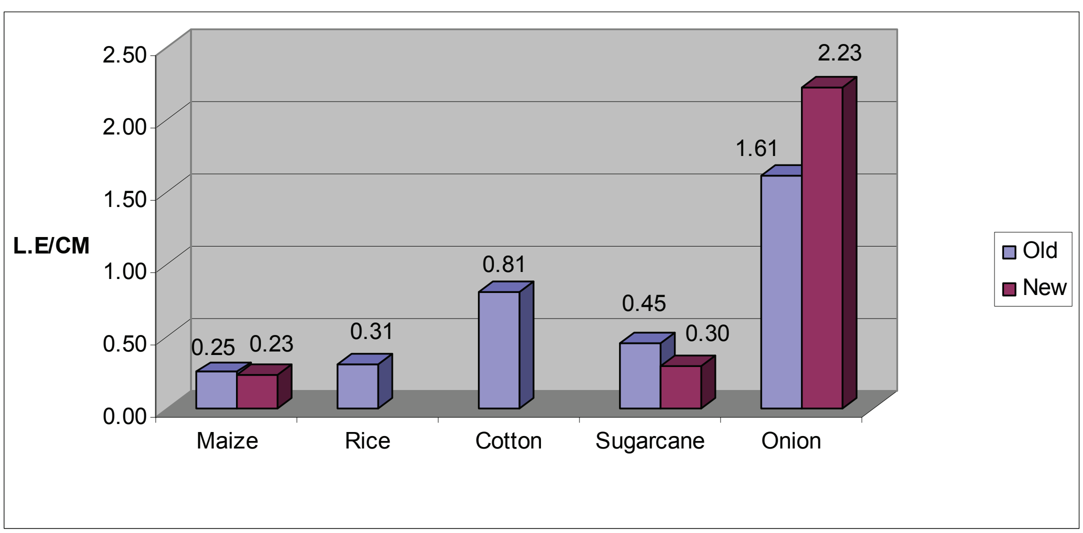

Figure 8. Crop Water Productivity for Main Summer Field Crops in Old and New Lands under Different Irrigation Methods.

RESULTS OF VEGETABLE CROPS

Vegetables are considered the promising agriculture crops in new lands. The vegetable production mainly depends on the technology applied from land preparation until the post harvest of these vegetable crops. There are technical logistics for the different vegetable crops - each one has a specific package of technology. The productivity of any input, i.e. land, labor, capital and water depend on the level of the technology applied. Total production here is recorded for small farmers and graduates categories, i.e. not including investors as mentioned previously in the sample design section. Actually, the production for investors' category is very high but it cannot be used for comparison within the current study. Results, presented in table (10) and figure (9), indicate that there is a high variation in the physical water productivity among the three crops. It was higher in new land compared with old. On the other hand, the net return of water in new land is less than in old land in the case of green peas and tomato because of their lower of net return. The low aspect of this net return is due to the low price of production as a result of the plentiful supply at the time of sale.

Table 1. Crop Water Productivity for Main Vegetable Crops in Old and New Lands under Different Irrigation Methods.

	Tomato		Pepper		Green Peas	
Crop	Old Land	New Land	Old Land	New Land	Old Land	New Land
Irrigation Method	**Flood**	Drip	**Flood**	Drip	**Flood**	Drip
Water Requirement (CM/Feddan)*	2532	2532	2532	2532	2532	2532
Total Production (Ton/Feddan)	15	32	6	6.7	2.8	1.86
Net Return (L.E/Feddan)	6,383	4,615	5,433	6000	3500	3,291
Water Productivity Indicators:						
Water Unit Productivity (Kg/CM)	5.24	14.91	2.10	2.72	0.14	0.85
Water Unit Net Return (L.E/CM)	2.23	2.15	1.90	2.44	1.75	1.50

Source: - Calculated from the survey data of agricultural year 2007/2008.
CAPMAS, Central agency for Public Mobilization and Statistics, Water Resources and Irrigation Bulletin, 2004.
* Water requirements for vegetables are considered 2532 cubic meters because of the absence of accurate data for each crop.

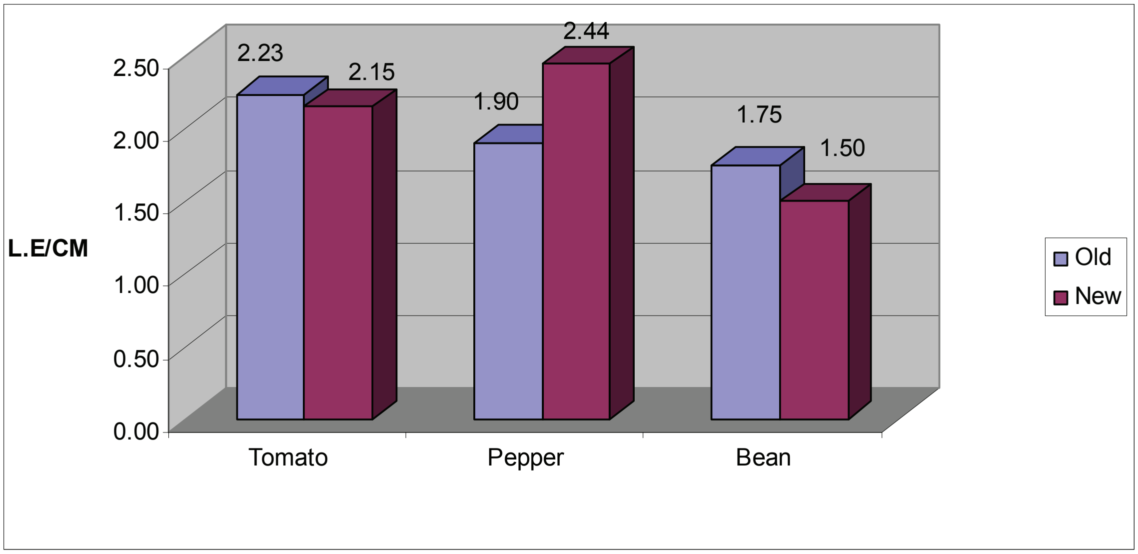

Figure 9. Crop Water Productivity for Main vegetable Crops in Old and New Lands under Different Irrigation Methods.

RESULTS OF FRUIT CROPS

Fruit production activities need a huge investment through establishing the nursery and preparing farms till the final phase of production and marketing. As mentioned above, the current study dealt with the graduates and small farmers in new lands. Table (11) and figure (10) show that water productivity in physical and net return units are lower in the case of new land compared with old for the three crops because of the age of trees, the experience of farmers and the ability to finance.

Table 11. Crop Water Productivity for Main Fruit Crops in Old and New Lands under Different Irrigation Methods

Crop	Orange		Grapes		Peach	
	Old Land	New Land	Old Land	New Land	Old Land	New Land
	Flood	Drip	**Flood**	Drip	**Flood**	Drip
Water Requirement (CM/Feddan)	5280	3500	4400	2800	4000	2800
Total Production (Ton/Feddan)	10	8	10	9	4	3
Net Return (L.E/Feddan)	3,128	3,599	10,371	3,922	3000	2,634
Water Productivity Indicators:						
Water Unit Productivity (Kg/CM)	1.74	1.29	2.15	1.82	0.86	0.65
Water Unit Net Return (L.E/CM)	***0.54***	0.62	2.22	0.79	0.64	0.66

Source: Calculated from the survey data of agricultural year 2007/2008. CAPMAS, Central agency for Public Mobilization and Statistics, Water Resources and Irrigation Bulletin, 2004.

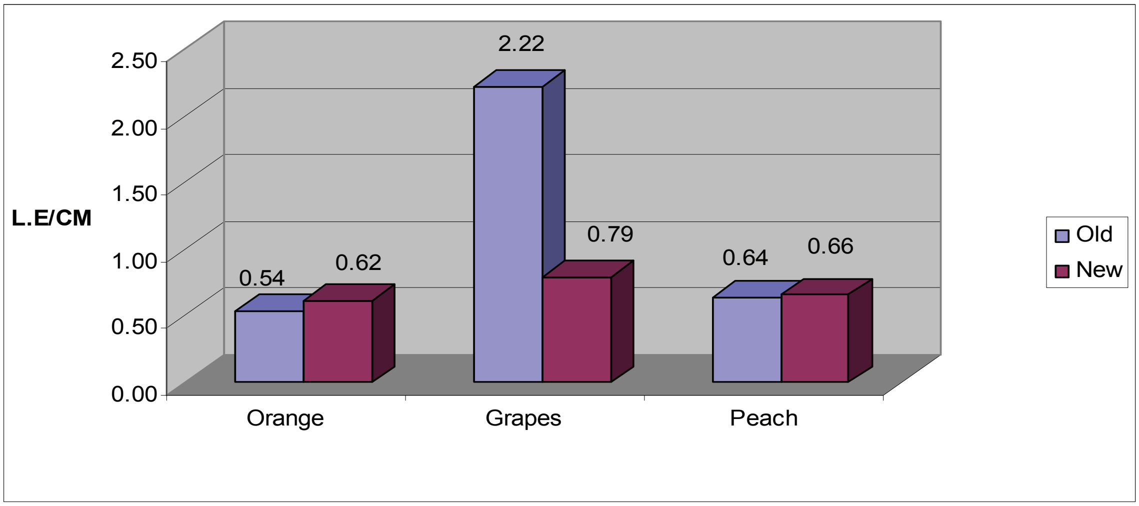

Figure 10. Crop Water Productivity for Main fruit Crops in Old and New Lands under Different Irrigation Methods.

RESULTS OF NET RETURN OF WATER TO CROP ROTATIONS

Crop rotation refers to the sequence of crops among the three seasons; winter, summer and nili. The current study focused on the dominant rotations for winter and summer crops because nili season's area for crop rotation is limited and was found only in Upper Egypt. To evaluate the net return of water, the study estimated the total net return of different crop rotations and their water requirements, ie. divided the total net return of crop rotations by their water requirements. However, the estimation of net water return allowed for the comparison of the different rotations and to determine which of them is more profitable in addition to comparing these crop rotations with sugarcane as a perennial crop.

As could be seen from table (12) and figure (11), the wheat + maize rotation is the highest one according to its profitability in both old and new lands. Wheat + rice rotation is the second one and cultivated only in old land. The main reason for high wheat rotation is mainly due to the high prices of wheat during the last year. The procured price of wheat was sharply increased from L.E/Ton 1200 to 2500; (i.e. L.E / Ardab, Ardab = 155 kg, 175 to 380). In general, the wheat and long clover rotations are the main ones in all Egypt; particularly after the Egyptian reform policy program and decreasing the area planted by cotton. As it is known, sugarcane is mainly planted in Upper Egypt and this affects its net return due to its limited cultivated area. From table (12), it is clear that short clover + cotton and wheat + maize rotations are higher in their net return of water than sugarcane while long clover + maize is less than sugarcane.

Table 12. Net return of water for different crop rotations.

Crop Rotation	Net Return (L.E)		Water Requirement (Cubic meters per feddan)		Net Return of water per crop rotation (L.E/CM)	
	Old land	New land	Old land	New land	Old land	New land
Short Clover + Cotton	2839.8	0	3933.9	0	0.72	
Long clover + Maize	1790	1450	6687.0	4779.0	0.27	0.30
Long clover + Rice	2838.8	0	8594.0	0	0.33	
Wheat + Maize	6584	3554	5591.0	3922.0	1.18	0.91
Wheat + Rice	7632.8		7498.0		1.02	
Sugar beat + Maize	1512.5	1279	5921.0	3586.0	0.26	0.36
Sugar beat + Rice	2561.3		7828.0		0.33	
Sugarcane	3998		8854.0		0.45	

Source: - Calculated from the survey data of agricultural year 2007/2008.
CAPMAS, Central agency for Public Mobilization and Statistics, Water Resources and Irrigation Bulletin, 2004.

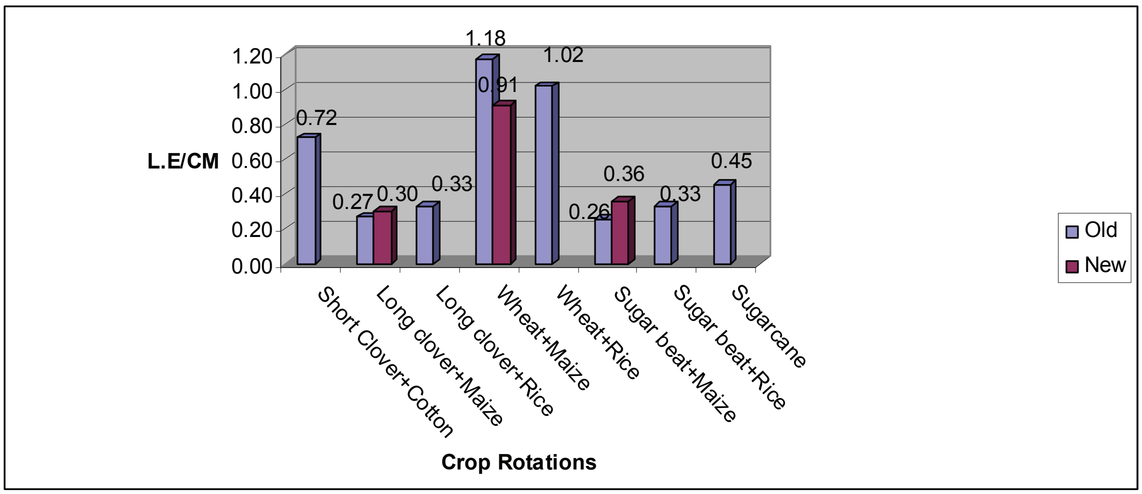

Figure 11. Net return of water for different crop rotations

SUMMARY AND CONCLUSION

With scarce water conditions, crop water productivity and its net return play a vital role in developing sustainable agricultural and water policies. Crop water productivity and its net return depend on many factors, both local and international. Therefore, their accurate determination has to be carried out through various field agriculture and water requirement investigations as well as their economic aspects. The authors of the current study designed a questionnaire for collecting the required data for crop budget and other field conditions in addition to the other collected data and information from various agricultural and water organizations. After several analyses were performed for the collected data and information to accurately determine the crop water productivity and its net return for the various cultivated crops in Egypt within the three seasons (winter, summer, and nili) and for old and new lands. All results of the investigated items were tabulated and graphed in a certain specific format that can assist decision makers in drawing future sustainable agricultural and water policy for Egypt and maximizing national water resource productivity in different agricultural activities considering the resource supply and demand and based on the efficient utilization of the water resources.

According to the results of individual crops' net return from water, presented in the current manuscript, it can be concluded that onion and cotton crops have the highest net return from one cubic meter of water compared with rice. On the other hand, maize net return is currently less than rice. This fact is due to the low local price of maize. It is expected that maize prices will increase with the Bio-fuel initiative that will force the international prices for maize to increase.

According to the results of crop rotations, presented in the current manuscript, it can be concluded that wheat + maize rotation has the highest water productivity according to its profitability in both old and new lands. Wheat + rice rotation is the second one and cultivated only in old land. The main reason for high wheat rotation is mainly due to the high price of wheat during the last year. The procured price of wheat was sharply increased from L.E/Ton 1200 to 2500; (i.e. L.E / Ardab 175 to 380). In general, wheat and long clover rotations are dominant in all Egypt; particularly after the Egyptian reform policy program and decreasing the area planted to cotton. As it is known, sugarcane is mainly planted in Upper Egypt and this affects its net return due to its limited cultivated area. To compare the sugarcane water productivity, it has to be compared with other rotation productivity since it is considered a perennial crop. In addition, short clover + cotton and wheat + maize rotations are higher in their net return for water than sugarcane while long clover + maize rotation is less than sugarcane regarding its water net return.

Based on the study's conclusions, it is very important to activate the role of agricultural extension as well as water users' associations in providing the various farmers with the necessary information about the most financially rewarding crops' rotations and individual crops; and educate farmers how to cultivate the maximum profitable crops and in which season and area.

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REGULATED DEFICIT IRRIGATION AND COTTON PRODUCTION RESPONSES IN SOUTHWEST TEXAS

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ABSTRACT

The urban water demand in Southwest Texas has grown rapidly in recent years due to large population increase. Regulated deficit irrigation (RDI) is one important measure for saving water while maintaining crop yield/ net benefit. An RDI field experiment was conducted at the Texas AgriLIFE Research and Extension Center at Uvalde in the summer of 2008 to examine the water saving potential. Seven irrigation schemes and four varieties were assigned to the experimental field to test their effects on lint yield.

The results showed that: 1) The threshold of the replacement ratio is between 0.7 and 0.8 in fixed ratio irrigation schemes. Dynamic irrigation schemes showed a higher potential to save irrigation water. 2) The fiber quality was affected more by varieties than by irrigation schemes. A 50X (fixed 50% ratio) scheme has the potential risk to produce relatively lower quality cotton fiber by affecting fiber length and fiber yellowness. Considering its negative effect on lint yield as well, the 50X scheme is definitely not recommended. The two dynamic irrigation schemes, 50D and 70D, showed no negative effect on fiber quality. The 70D scheme has some potential to increase the fiber quality in fiber length, uniformity, fiber strength and reflectance; however, this scheme uses more irrigation water that the 50D scheme. Although further research is needed before making definitive conclusions, both dynamic schemes could be applied to maintain lint yield and fiber quality while saving more water, compared to the fixed ratio irrigation schemes.

INTRODUCTION

The urban water demand in Southwest Texas has grown rapidly in recent years due to the fast population increase. Since the water resources in this area are limited, making a good plan for the available water supply is crucial. One possible way to assist in solving this problem is to reduce the agricultural water use through irrigation scheduling. However, the economic crop yield, or growers' profit, should at least be maintained.

Regulated deficit irrigation (RDI) is one important measure for saving water and maintaining crop yield and growers' net benefit (Goodwin, 2000; Jones, 2004; Fereres et al.,2007). Another advantage of deficit irrigation, according to Cull et al. (1981), is to permit utilization of precipitation. Some RDI studies were done over the last decades in North China (Zhang et al., 1998b; Zhang et al., 1999; Kang et al., 2000), Australia

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(French and Schultz, 1984), West Germany (Ehlers, 1989), North Syria (Zhang et al., 1998a), Turkey (Mert,2005; Basal et al., 2009; Dagdelen et al., 2009) and North Texas, USA (Howell et al., 2004). Several different irrigation regimes were tested, and the water use efficiency and transpiration efficiency of both dry matter of shoot and grain yield were discussed in details. However, these results cannot be applied directly to South Texas, as the climatic and hydrologic conditions are not the same, and the different crops may have different responses. Most of the irrigation regimes mentioned in the literature are relatively simple - the irrigation frequency was controlled without considering much about the irrigated water amount - which weakens the ability of the results to recommend irrigation improvement and predict crop responses.

The objectives of this study are: 1) to find the maximum water saving potential for cotton production in Southwest Texas; and 2) provide suggested irrigation schedules based on the lint yield and fiber quality.

MATERIALS AND METHODS

The Cotton RDI Experiment in 2008

A field experiment was conducted at the Texas AgriLIFE Research and Extension Center at Uvalde in the summer of 2008. A split-split-plot design experiment was assigned in a 90^{o} wedge (approximately 16.2 ha) of a 250m long center pivot field. The wedge was divided into four spans (48.8 m width each) and two "buffer zones" (filler spans). Each span had 48 rows, which were sub-divided into four 12-row plots to which a cotton variety (DP555, DP164, FM9063, and 989B2R) was randomly assigned. The cotton was planted on April 15, 2008, and harvested on September 25 (162 days after planting /162 DAP)).

Irrigation was applied by a center pivot with a low energy precision application (LEPA) system with 95% efficiency. Seven irrigation regimes were selected, including the fully irrigated (100X) as reference; four fixed deficit irrigation regimes: 80X, 70X, 60X and 50X; and two dynamic irrigation regimes: 70D and 50D. The treatments refer to the percentage of the net evapotranspiration of the well-watered crop (ΔET), which equals to the difference between evapotranspiration (ET) and rainfall (P) in a certain period that is replaced:

$$\Delta ET = ET - P$$

For instance, the number 50 in 50X stands for 50% replacement; that is, for each 1 mm water loss in the net evapotranspiration, we provide 0.5 mm water back to the field through irrigation. In practice, we recorded the daily ET and P to calculate the daily net water loss (ΔET), and then accumulated the net water loss day by day until it reached a certain limit (we used 38 mm in 2008), at which time irrigation was applied. In the fixed scheme (marked as X), the replacement rate (as percentage of ΔET) was kept constant regardless of the growth stages; e.g., 50X means that in each irrigation application we compensated the field with 50% of the water loss. In the dynamic scheme (marked as D), the irrigation was applied in different replacement ratios at each growth stages.In the beginning of growing season, deficit irrigation is applied to make better root establishment; at blooming and fruit-set stages, the field is fully irrigated (Meng et al., 2007); from 25-50% open boll to harvest, again, deficit irrigation is applied due to less water use by plant (Cohen et al., 1995). In our case, the ratios in each stage of the 50D scheme were: starting with 50% till first bloom, then changing to 100% till 50%-open boll, and then 10% thereafter until harvest. The ratios of 70D scheme in each stage were: starting with 70% till first bloom, then increasing to 100% until 50%-open boll, and reducing to 15% from then on. Our intent was to maintain the actual water use at 45-55% for 50D, and 65-75% for 70D, assuming little effect from precipitation. However, if intensive rainfall was received, especially at the end of the growing season, the total ratio may reach a higher than expected number.

The Data Collection and Analysis

On September 25, 2008, 12 m^2 areas were randomly selected in each experimental unit and all seed cotton was harvested in these sample areas with a cotton picker. Then small sub-samples were selected from each harvested sample, and ginned in the Cotton Improvement Lab (Texas A&M Univ., College Station, TX). According to the weight ratio of lint to seed cotton of the small samples, the lint yield in each experimental unit was estimated (in kg/ ha).

The small samples then were sent to the Fiber & Biopolymer Research Institute (Texas Tech Univ., Lubbock, TX) for USDA standard HVI test. The micronaire, fiber length, fiber uniformity index, fiber strength, elongation, fiber reflectance and fiber yellowness were tested as fiber quality parameters.

The lint yield and fiber quality data were analysed with PROC GLM (for MANOVA test) and PROC MIXED in SAS 9.2 (SAS Inc., NC), against two factors: irrigation schemes (7 levels) and varieties (4 levels). Both equal and unequal variance situations were considered and the best fit was selected based on AIC values as final results.

RESULTS AND DISCUSSIONS

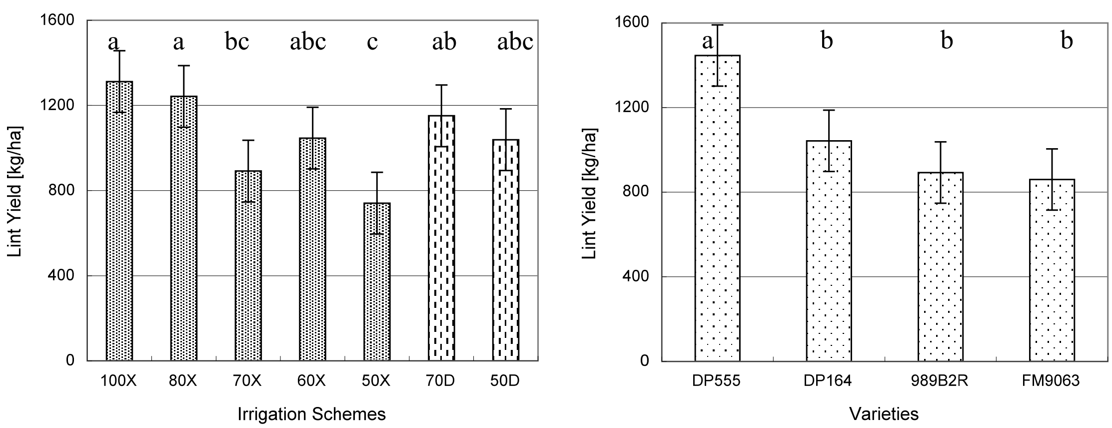
Lint Yield

The effects of irrigation scheme and variety on lint yield were first tested in the full statistical model to determine the significance of the interaction between the two factors. The interaction term was not significant, and thus was removed from the model. The main effect model indicated that both main effects were significant. The pairwised comparison results of irrigation scheme effect and variety effect are shown in Figure 1.

For fixed irrigation schemes, the lint yield of 80X and 100X were not different, but were significantly higher than that of 70X and 50X (Fig. 1(a)). Due to some technical failure the 60X treatment was over-irrigated twice in mid-July, which may have caused the abnormally high yield relative to 70X. It appears that the threshold of maintaining lint yield is between 70% and 80%. As the previous year research in Uvalde center showed that 75% replacement did not decrease lint yield significantly (result has not been published yet), and in some articles such as Basal et al. (2009) and Dagdelen et al. (2009) similar results were also reported, we conclude that the threshold was somewhere between 70% and 75%. It is not clear whether the threshold value is sensitive to the annual precipitation, which needs to be further studied.

The lint yield of the two dynamic schemes were not significantly lower than that of the 100% replacement. Thus, it appeared to be possible to save up to 50% of the irrigation water. However, our data were affected by two heavy rainfalls that occurred in mid-August, 2008, which brought 68.6 mm (Aug. 17, 2008) and 55.9 mm (Aug. 22-23, 2008) of precipitation, respectively. In this case there was no need to apply irrigation during the late growing season, but total ratios of 50D and 70D were raised to 80% and 85%, respectively. It is not possible to assume the possibility of 50% saving at this moment, but the 70% dynamic scheme could be applicable, which could potentially save up to 30% irrigation water, especially in late growing season.

The varietal response demonstrated in Fig. 1(b) showed that the lint yield of DP555 was approximately 50% higher than those of other varieties. No yield difference was found among the other three varieties.



(a) Irrigation Schemes (b) Varieties

Figure 1. Lint yield comparison among different irrigation schemes and varieties. The fixed schemes (100X, 80X, 70X, 60X, and 50X) are illustrated in dot-shaded bars, and dynamic schemes (70D and 50D) are shown in vertical-dashed bars in (a). The ranking results of the Tukey pairwised comparison are shown on the top of each bar. The bars with common letters are not significantly different. The line mark above/ below each bar is the confidence interval of each mean value.

Fiber Quality

Balkcom et al. (2006) reported that irrigation regimes affected several fiber quality parameters, such as fiber length, fiber uniformity and micronaire. The similar results were expected in our study. Before analyzing each fiber quality parameter individually, we ran MANOVA (through PROC GLM) to test the significance of the main effects (irrigation schemes, varieties) and their interaction (irrigation scheme by variety). The result (Table 1) showed that the irrigation-variety interaction was not significant, and both main effects were significant. Thus, the initial statistical model of each parameter analysis was set as two main effects only. As mentioned in the previous section, both equal and unequal variance models were considered while fitting the data, and the better fit was selected as the final model. Table 2 gives a summary of the final model selection for each parameter. We concluded that based on Table 2, the irrigation scheme had effects on all parameters except micronaire (fiber fineness) and elongation; variety effects were present in all parameters. The elongation and yellowness (Hunter's +b) showed unequal variance, while the variances of the other parameters could be assumed equal. These parameters were discussed below in details.

Table 1. MANOVA test result of fiber quality parameters

	Irrigation Scheme	Variety	Irrig * Var
Wilk's Lambda	0.3154	0.02613	0.2308
F-value	2.11	23.45	0.89
Degree of Freedom	48 / 382.93	24 / 223.92	144 / 580.13
Pr > F	< 0.0001	< 0.0001	0.8054

Table 2. Summary of the final model selection for each fiber quality parameter

Parameter	Irrigation Scheme	Variety	Equal Variance
Micronaire	NS	*	Yes
Fiber Length	*	*	Yes
Fiber Uniformity Index	*	*	Yes
Fiber Strength	*	*	Yes
Elongation	NS	*	No
Reflectance	*	*	Yes
Yellowness	*	*	No

*: significant at 0.05 level.   NS: not significant

Micronaire/ Fiber Fineness. There was no micronaire difference among the seven irrigation schemes (Table 2). DP555 had the highest micronaire value, and FM9063 had the lowest (Fig. 2). According to the fiber quality classification criteria provided by the National Cotton Council (www.cotton.org), FM9063's fibers were desirable (4.7 falls into 3.5-4.9), and the other three varieties' fibers were coarse (5.0 or higher).

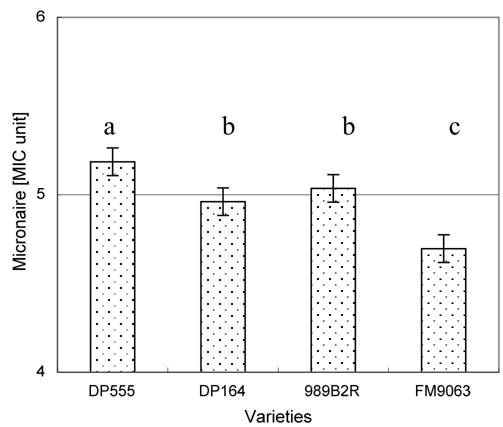
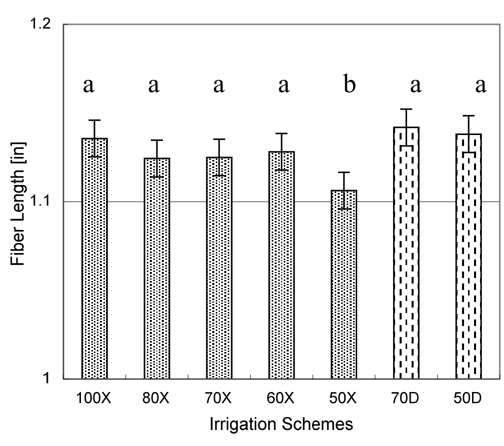


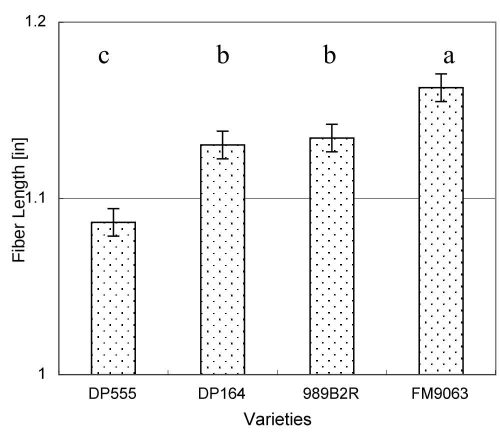
Figure 2. Micronaire comparison among four varieties. The line mark above/ below each bar is the confidence interval of each mean value.

Fiber Length. The 50X irrigation scheme significantly reduced the fiber length (Fig. 3(a)). Other fixed ratio schemes were not different. The two dynamic ratio schemes, especially the 50D, did not reduce fiber length. Although not significant, the mean fiber length of 70D is slightly higher than that of 100% irrigation, indicating that there might be potential to increase fiber length by the dynamic irrigation treatment. In general, all fiber length of each irrigation scheme showed long fiber (1.11 - 1.28). However, the mean fiber length of 50X is very close to the lower boundary, which may bring the risk of reducing fiber quality in length. In other words, 50X irrigation scheme may reduce fiber length, thus affecting the fiber quality.

The shortest fiber length was produced by DP555 and the longest by FM9063 (Fig. 3(b)). Besides DP555, the fiber length of the other three varieties exhibited long fibers. The mean fiber length of DP555 is 1.09, which is slightly lower than the lower boundary of the long fiber category, thus being classified into the medium group.



(a) Irrigation Schemes



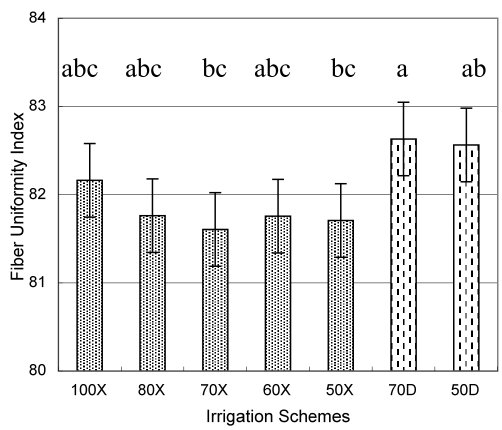
(b) Varieties

Figure 3. Fiber length comparison among different irrigation schemes and varieties. The two vertical-dash shaded bars in (a) are the two dynamic irrigation schemes. The ranking results of the Tukey pairwised comparison are shown on the top of each bar. The bars

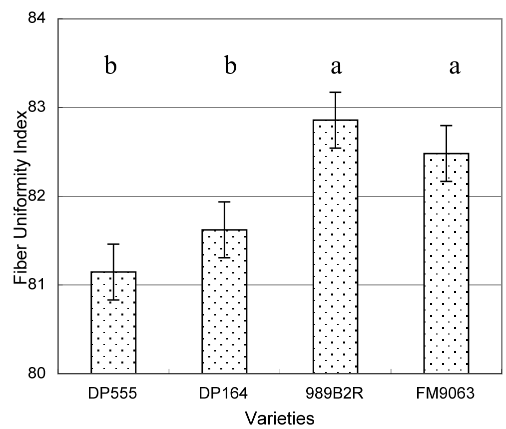
with common letters are not significantly different. The line mark above/ below each bar is the confidence interval of each mean value.

Fiber Uniformity Index (FUI). The fiber uniformity among five fixed ratio irrigation schemes were not different (Fig. 4(a)). Although not all significant, the two dynamic irrigation schemes illustrated higher uniformity than the fixed ratio ones, especially 50X and 70X. Both FUI means of the dynamic schemes were around 82.5, which is close to the lower boundary of the *high uniformity* classification (83 - 85). Other FUIs were between 80 and 82, which is classified as average uniformity. It seems that potentially, the dynamic irrigation schemes could improve the fiber uniformity.

Among four varieties, 989B2R showed the highest uniformity (classified as high according to NCC criteria), followed by FM9063; the uniformities of DP555 and DP164 were average, which were significantly lower than 989B2R and FM9063 (Fig. 4(b)).



(a) Irrigation Schemes

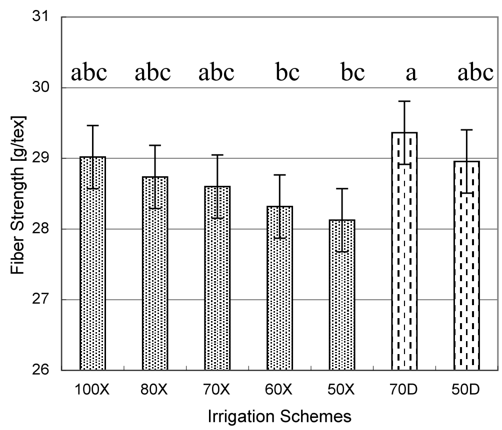


(b) Varieties

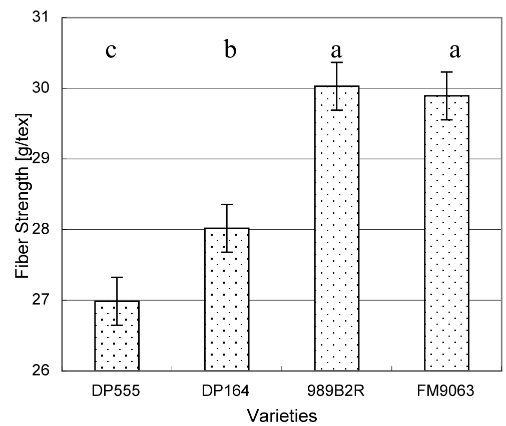
Figure 4. Fiber uniformity index (FUI) comparison among different irrigation schemes and varieties. The two vertical-dash shaded bars in (a) are the two dynamic irrigation schemes. The ranking results of the Tukey pairwised comparison are shown on the top of each bar. The bars with common letters are not significantly different. The line mark above/ below each bar is the confidence interval of each mean value.

Fiber Strength. The fiber strength of 70D was significantly higher than that of 60X and 50X, while other treatments showed no difference (Fig. 5(a)). The fiber strength of all seven irrigation schemes were classified as "high" (27-29 for long fiber). It seems that 70D has the potential to increase fiber strength.

The fiber strength of 989B2R and FM9063 were classified as "very high" (30-32 for long fiber). DP555 and DP164 had lower fiber strength values, which were still classified as "high" (27-29 for long fiber).



(a) Irrigation Schemes



(b) Varieties

Figure 5. Fiber strength comparison among different irrigation schemes and varieties. The two vertical-dash shaded bars in (a) are the two dynamic irrigation schemes. The ranking results of the Tukey pairwised comparison are shown on the top of each bar. The bars with common letters are not significantly different. The line mark above/ below each bar is the confidence interval of each mean value.

Elongation. No effect on elongation was found among the seven irrigation treatments. DP164 showed the highest elongation and DP555 the lowest (Fig. 6). The fiber elongation of all four varieties was classified as "average" (5.9-6.7).

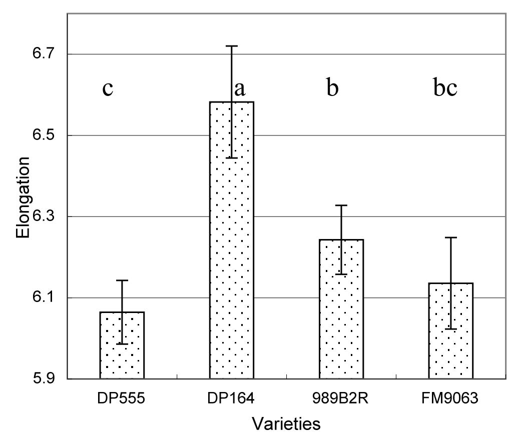
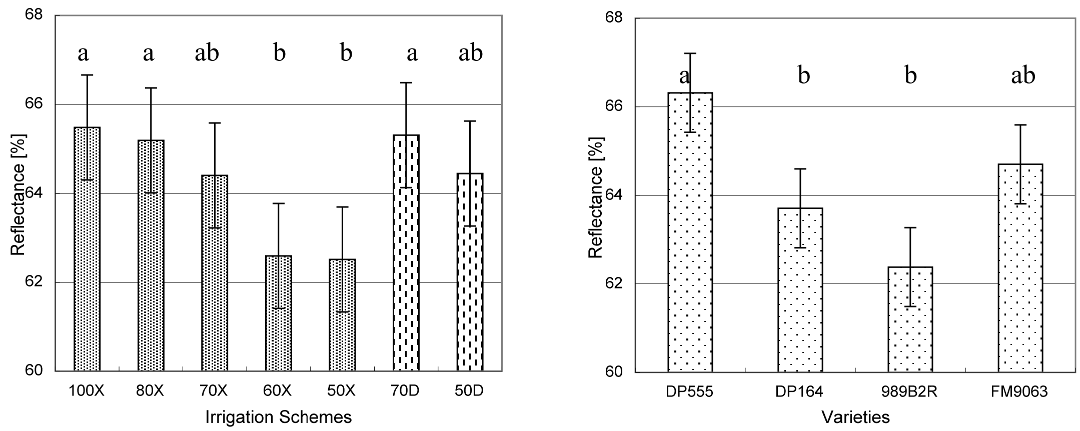


Figure 6. The fiber elognation comparison among four varieties. The ranking results of the Tukey pairwise comparison are shown on the top of each bar. The bars with common letters are not significantly different. The line mark above/ below each bar is the confidence interval of each mean value.

Fiber Greyness/ Percent Reflectance. The fibers of 60X and 50X had lower reflectance than 100X, 80X and 70D. In general, dynamic irrigation schemes did not reduce the fiber quality by affecting reflectance. The two dynamic schemes were not different than 100X

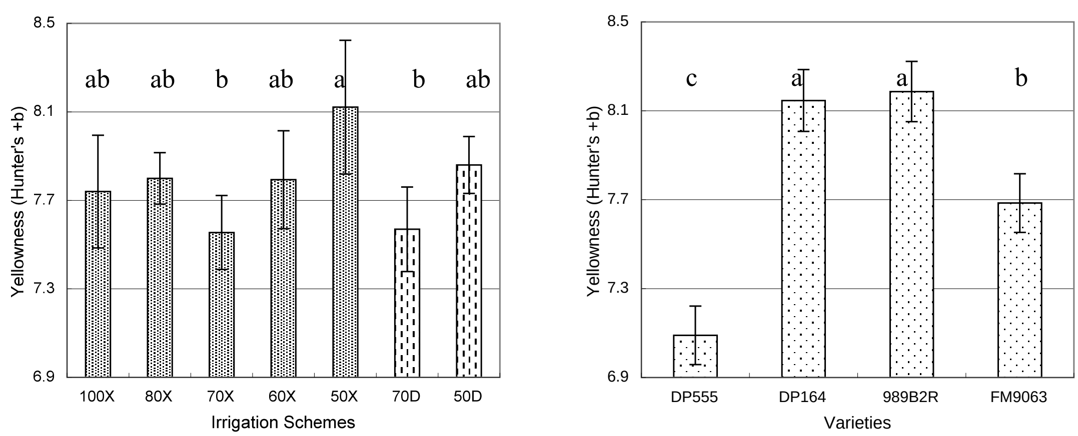
(Fig. 7(a)). DP555 and FM9063 showed higher reflectance than DP164 and 989B2R (Fig. 7(b)).



(a) Irrigation Schemes (b) Varieties

Figure 7. Fiber greyness/ reflectance [%] comparison among different irrigation schemes and varieties. The two vertical-dash shaded bars in (a) are the two dynamic irrigation schemes. The ranking results of the Tukey pairwised comparison are shown on the top of each bar. The bars with common letters are not significantly different. The line mark above/ below each bar is the confidence interval of each mean value.

<u>Fiber Yellowness (+b)</u>. 70X and 70D had lower yellowness indices compared to other irrigation schemes. 50X showed the highest yellowness with a larger variation than other treatments, indicating a potential risk of fiber quality reduction by increasing the yellowness (Fig. 8(a)). The fiber of DP555 was the least yellow fiber among all four varieties. DP164 and 989B2R produced the most yellow fiber (Fig. 8(b)).



(a) Irrigation Schemes (b) Varieties

Figure 8. Fiber yellowness (+b) comparison among different irrigation schemes and varieties. The two vertical-dash shaded bars in (a) are the two dynamic irrigation schemes.

The ranking results of the Tukey pairwised comparison are shown on the top of each bar. The bars with common letters are not significantly different. The line mark above/ below each bar is the confidence interval of each mean value.

CONCLUSIONS

In summary, the following conclusions can be drawn:

1) The threshold of the replacement ratio is between 0.7 and 0.8 in fixed ratio irrigation schemes. Dynamic irrigation schemes showed a higher potential to save irrigation water and still maintain yield and quality.

2) The fiber quality is affected more by variety than by irrigation scheme. The 50X scheme has the potential risk to produce relatively lower quality cotton fiber by affecting fiber length and fiber yellowness. Considering its negative effect on lint yield as well, the 50X scheme is not recommended. The two dynamic irrigation schemes, 50D and 70D, showed no negative effect on fiber quality. The 70D scheme may have some potential to increase the fiber quality in fiber length, uniformity, fiber strength and reflectance. Further research is needed before making conclusive recommendations, but it appears both dynamic schemes could be used to maintain lint yield and fiber quality while saving water.

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ADAPTIVE SCHEDULING ALGORITHM FOR A PV-POWERED IRRIGATION SYSTEM

Moustafa A. Fadel[1]

ABSTRACT

Optimal management of irrigation systems and their efficient use of energy is a major global concern where energy resources are jeopardized. Effective solar irradiance in the United Arab Emirates is available most of the year which makes it easy to project PV (Photo Voltaic) system output and the produced flow and pressure produced by a PV-powered DC pump. A PV- irrigation system was developed in the experimental farm of the College of Food and Agriculture, United Arab Emirates University.

In this paper an adaptive scheduling scheme is developed to provide an adaptive control of a photovoltaic powered irrigation system according to the availability of solar energy as well as the field conditions of the irrigated zones.

Simulation of the PV irrigation system including PV module, pump and irrigation network is carried out using Matlab ™ to predict power output using historical data, and water application rates accordingly. An executive irrigation schedule is also developed utilizing direct weather data from weather station to implement unexpected variation in weather conditions and field water requirements as well.

INTRODUCTION AND BACKGROUND

According to UN World Water Development Report in 2008, it is estimated that two out of every three people will live in water-stressed areas by the year 2025. In Africa alone, it is estimated that 25 countries will be experiencing water stress (below 1,700 m3 per capita per year) by 2025. Today, 450 million people in 29 countries suffer from water shortages.

Oi (2005) reported that water resources are essential for satisfying human needs, protecting health, and ensuring food and energy production, and the restoration of ecosystems, as well as for social and economic development and for sustainable development . There is a great and urgent need to supply environmentally sound technology for the provision of drinking water. Remote water pumping systems are a key component in meeting this need. It will also be the first stage of the purification and desalination plants to produce potable water.

Designing a PV- irrigation system capable of irrigating all zones of a field at the same time according to the maximum energy output would increase PV module, pumping and pipeline costs significantly. There are usually restrictions on available energy, so more PV modules would be dedicated to produce enough energy. In this research a control

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algorithm will be developed in order to sequence irrigation according to energy availability.

Hamrouni et al (2008) quoted Kim (2007) that the efficiency of the PV pumping system depends on several climatic factors such as solar radiation , ambient temperature and the state of the solar panel (ageing, cleanliness, etc..) .

Ghoneim (2006) reported that the use of photovoltaic power for water pumping is appropriate, as there is often a natural relationship between the availability of solar power and the water requirement. Water requirement increases during hot weather periods when the solar radiation intensity is high and the output of the solar array is at its maximum. On the other hand, the water requirement decreases when the weather is cool and the sunlight is less intense

Hamrouni et al (2008) modeled a PV pumping system, and concluded that these performances are maximal in the midday, but are reduced when the meteorological parameters are not optimum. In the last part of the paper, we have present several results of an experimental PV pumping system for a normal day. For normal functioning mode, all figures show a good agreement between the experimental and the simulated system.

Sheriff et al (2003) developed and validated a PV toolbox for the Matlab®/Simulink® environment.

Atlas and Sharaf (2007) developed a simple on-line fuzzy logic-based dynamic search, detection and tracking controller to ensure maximum power point (MPP) operation under variations in solar insulation, ambient temperature and electric load variations. They reported that PV arrays are built up with series/parallel-connected combinations of solar cells. A solar cell is usually represented as

$$V_c = \frac{AkT_c}{e} \ln\left(\frac{I_{ph} + I_0 - I_c}{I_p}\right) - R_s Ic \quad (1)$$

where e is electron charge ($1.602X10^{19}$ C), k the Boltzmann constant ($1.38X10^{23}$ J/K), IC the cell output current (A), I_{Ph} the photocurrent which is a function of irradiation level and junction temperature I_0 the reverse saturation current of diode (0.0002 A), R_S the series resistance of cell (0.001Ω), TC the reference cell operating temperature (20 ^oC), V_C the cell output voltage (V).

Faranda and Leva (2008) stated that a Maximum Power Point Tracking (MPPT) technique is needed to draw peak power from the solar array to maximize the produced energy. And Bouzidi et al (2009) presented a methodology to analyze the performance of photovoltaic system of pumping. Based on information from Arab et al (2004) ; Arab et al (1999); Arab et al (2005) and Hamidat (1999) , the sizing of PV array in terms of hydraulic power and solar irradiation is given by:

$$P = \frac{\rho \times g \times h \times Q \times \eta_r}{G_T \times \eta_{pv} \times \eta_s} \quad (2)$$

Where P is the electric power of the PV array (*Wc*), G_T the global irradiation on the PV array plane (kWh/m^2), η_r the array efficiency at reference temperature, η_{pv} the PV array efficiency under operations conditions, η_s the sub system efficiency, Q the flow rate (m^3/h), h the total pumping head (m), ρ the water density and g is the acceleration due to gravity, where

$$\eta_{pv} = f_m[1 - \alpha(T_c - T_r)] \times \eta_r \quad (3)$$

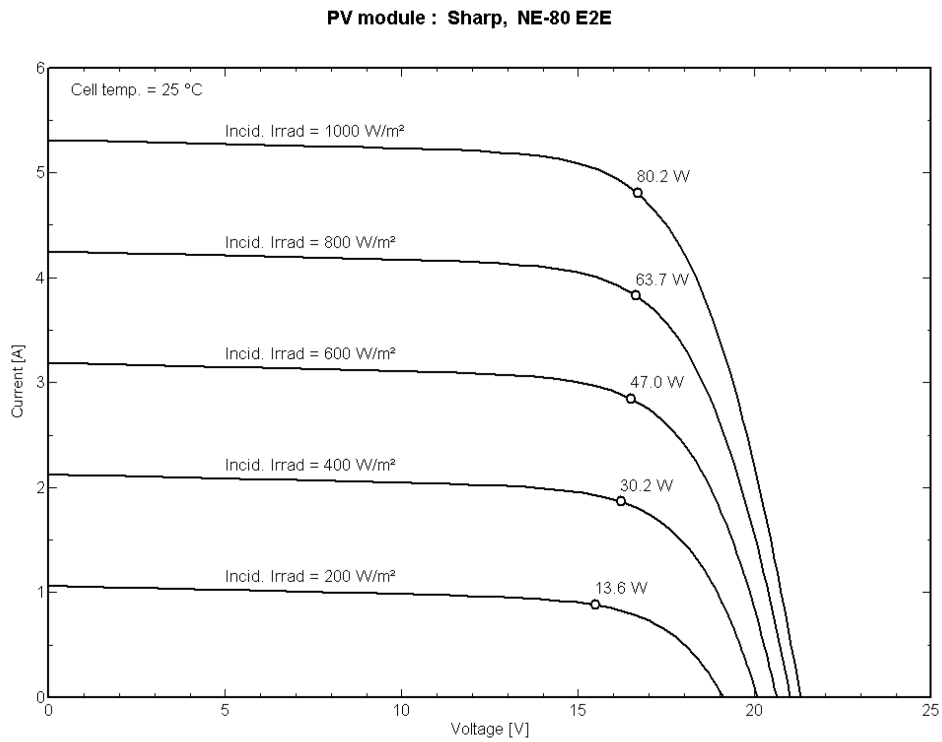
$$T_c = T_a + \frac{G_T}{800}(NOCT - 20) \quad (4)$$

Where f_m is the matching factor (==+0.90) , α the cell temperature coefficient 0.2 to 0.6%/^{o}C (0.004 to 0.005% / ^{o}C for Si), T_r the reference temperature, Tc the daily average cell temperature and Ta is the hourly ambient temperature ^{o}C.

MATERIALS AND METHODS

Solar Pumping System

The PV system consists of ten multi-crystalline silicon photovoltaic NE-80E2E Sharp modules with maximum power voltage (Vpm) 17.1V and 80W maximum power at a module temperature of 25^{o}C. Since the number of sunny days in the United Arab Emirates exceeds 350 days per year and for environmental reasons, the system was not equipped with batteries. The system is used to irrigate a shade house in the College of Food and Agriculture, UAE University. PV unite is located 24.356967 Latitude and 55.80842 Longitude.



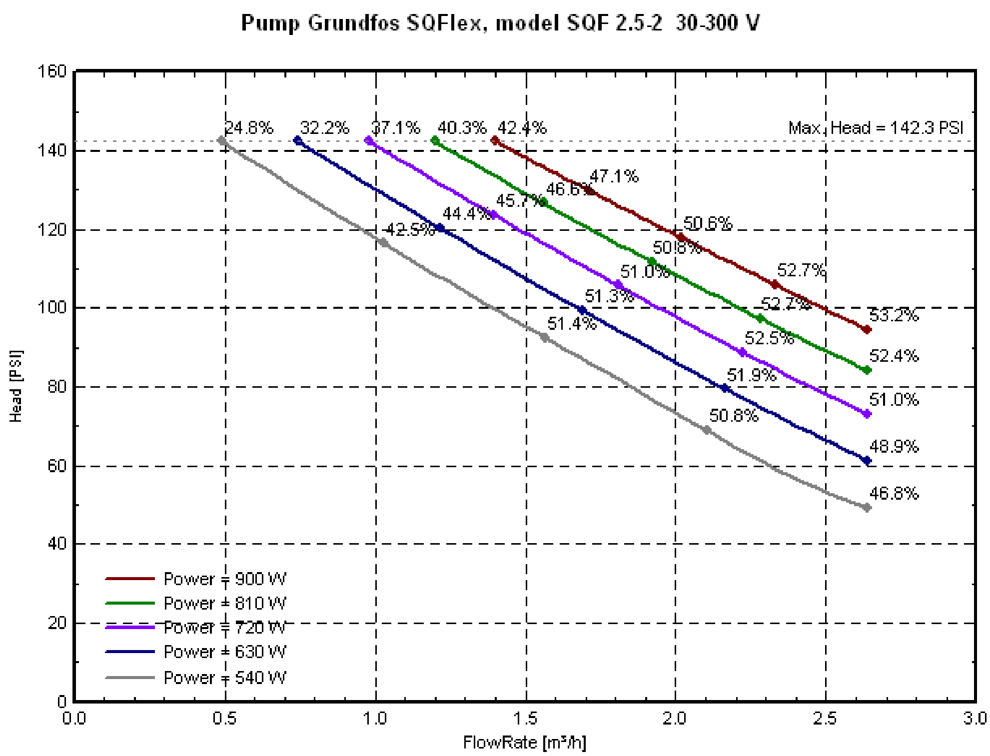


Figure 1. Solar-Pump Performance Charts

The Grundfos SQF 2.5-2 pump is designed especially for renewable energy sources, such as the sun and the wind energy. It is a submersible pump driven by a MFS3 motor with maximum power input of 900W. The speed range for the motor is 500-3000 rpm depending on the power input and the load and motor maximum current is 7 A. The pump delivers its maximum performance when one of the mentioned limitations is reached.

The pump is protected against over and under voltage overload and over-temperature and equipped with Maximum Power Point Tracking (MPPT). The built in electronic circuit enables the pump to keep its duty point continuously optimized according to the input power available.

Irrigation System

The expandable irrigation system is designed to irrigate two 24 x 13.5 m shade houses with 32 Hunter A10' rain shower sprinklers. The required pressure ranges between 15-70 PSI, with a precipitation rate approximately 1.5" (38 mm) per hour.
The pump is submersed in a 2000 gallon water tank and 8 solenoid valves divide the each shade-house area into 8 zones. (Fig. 2)

Water requirements of each zone is about 126 liters per day and the total water requirements of the whole shade house is 528 liters per day. On the other hand the head needed to operate the rain shower sprinkler should not be less than 20PSI (including the head losses through pipeline from pump to the f sprinkler) and optimum performance at 25 PSI and 1.56 GPM. The plan is to extend the shade house by adding more similar units and manipulate management to reach to the maximum solar-irrigation system.

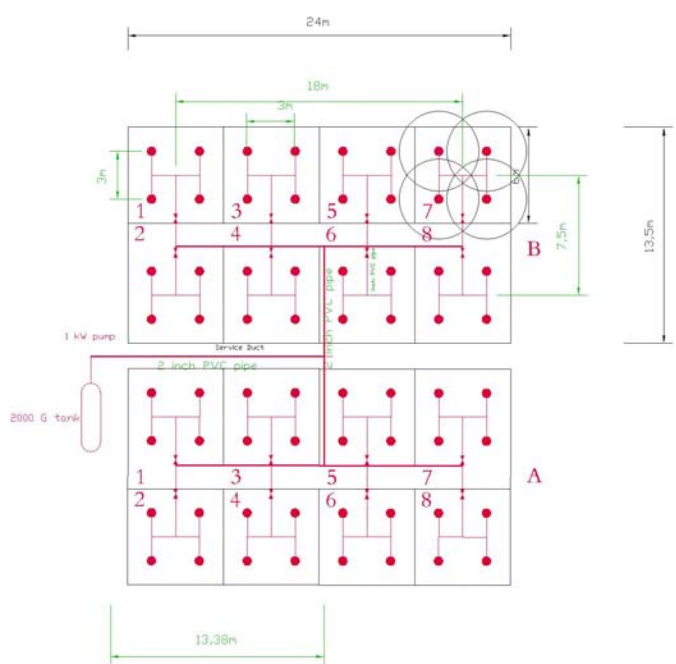


Figure 2. Schematic of the Irrigation System

Adaptive Scheduling Algorithm

Each 36 m^2 zone water requirement was calculated as 126 liter/day/zone where four sprayers are spraying with the variable rate according to the solar pump performance which depends on photovoltaic output. According to the theoretical sprinkler performance chart, sprinkler discharge is 5.15 LPM to 11.05 LPM when water pressure ranged ranges from 20 to 40 Psi.

Using this relation, the controller calculates operating time according to the expected pump output and then adjusts time according to the actual output.

Historical information

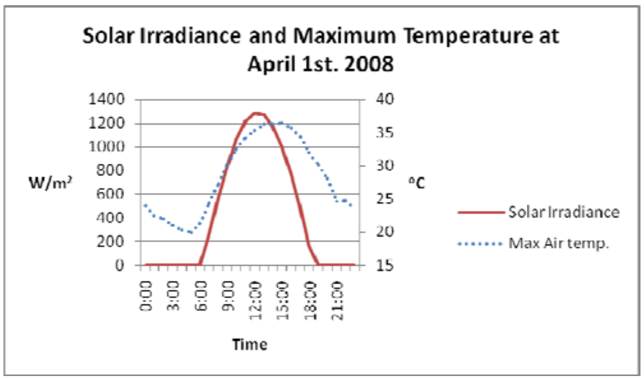


Figure 3. Hourly Maximum Temperature and Solar Irradiance, Al-Ain, April1st 2008

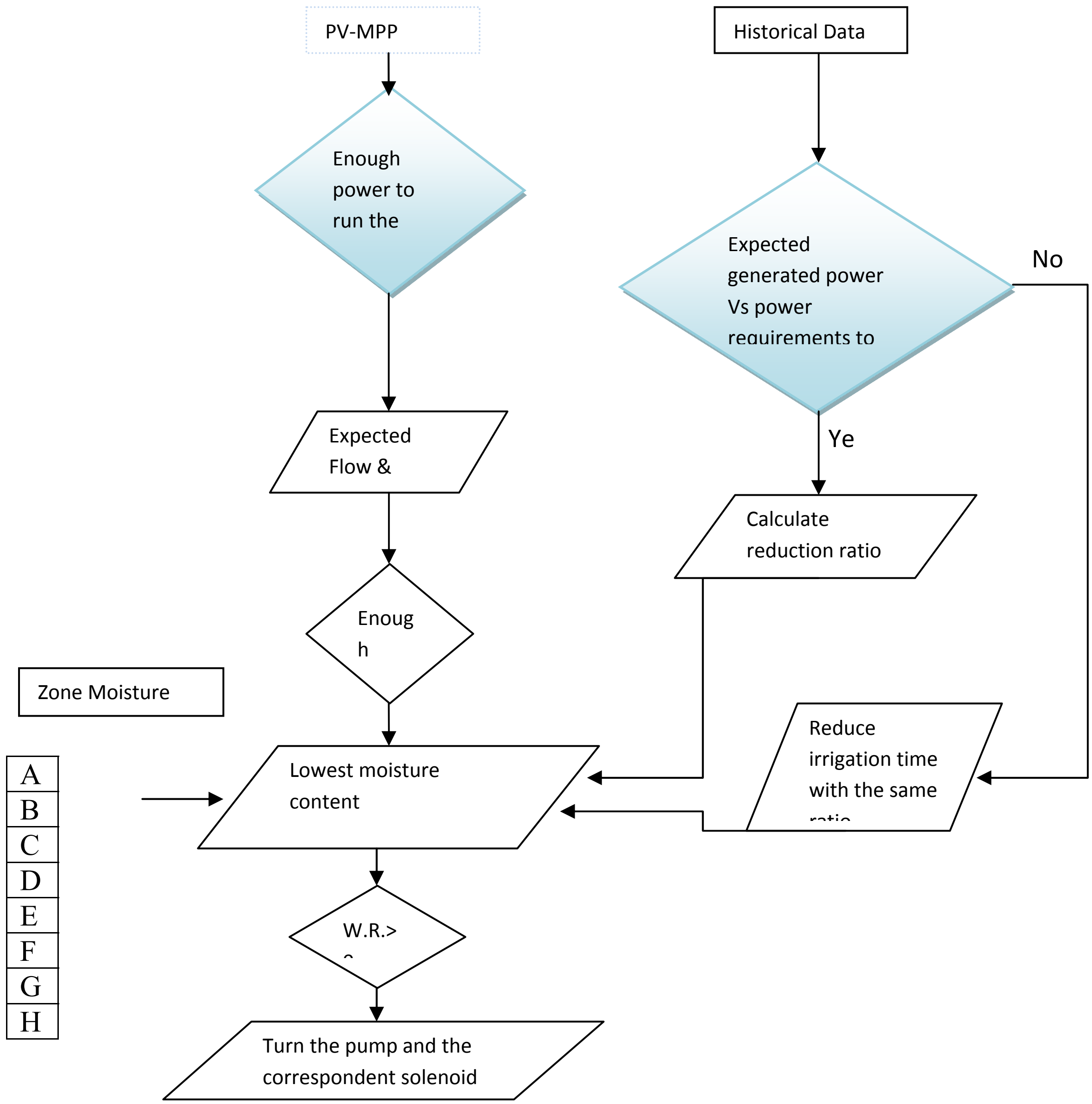
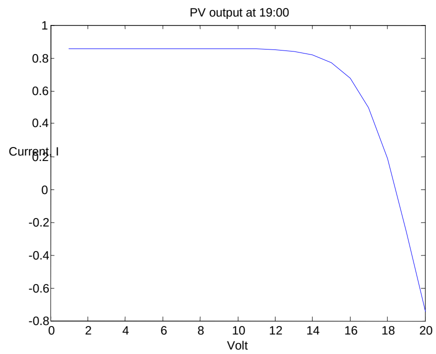
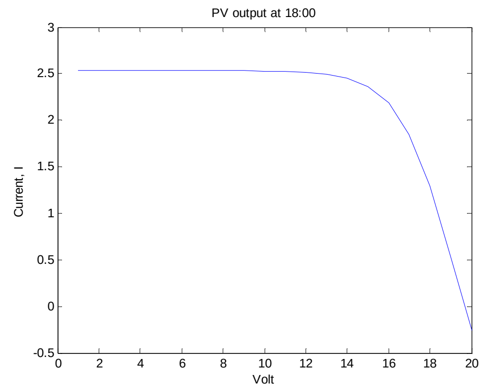


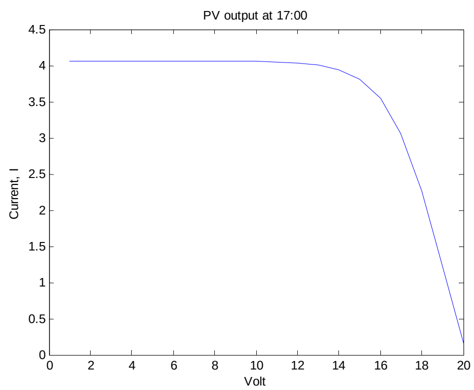
Figure 4. Control flow chart

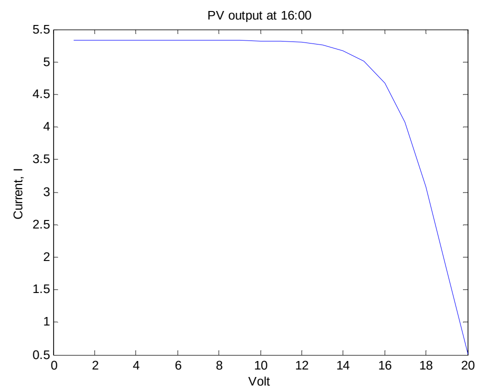
RESULTS AND DISCUSSIONS

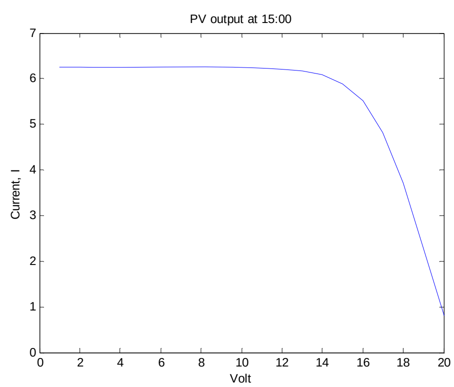
Simulation Results

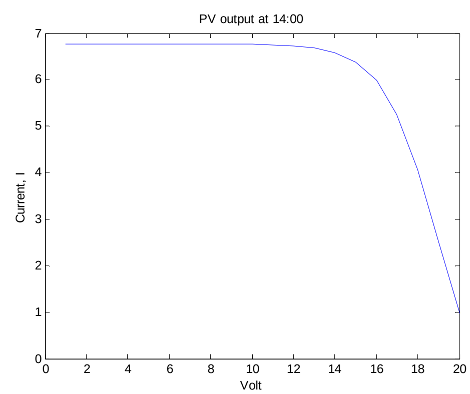












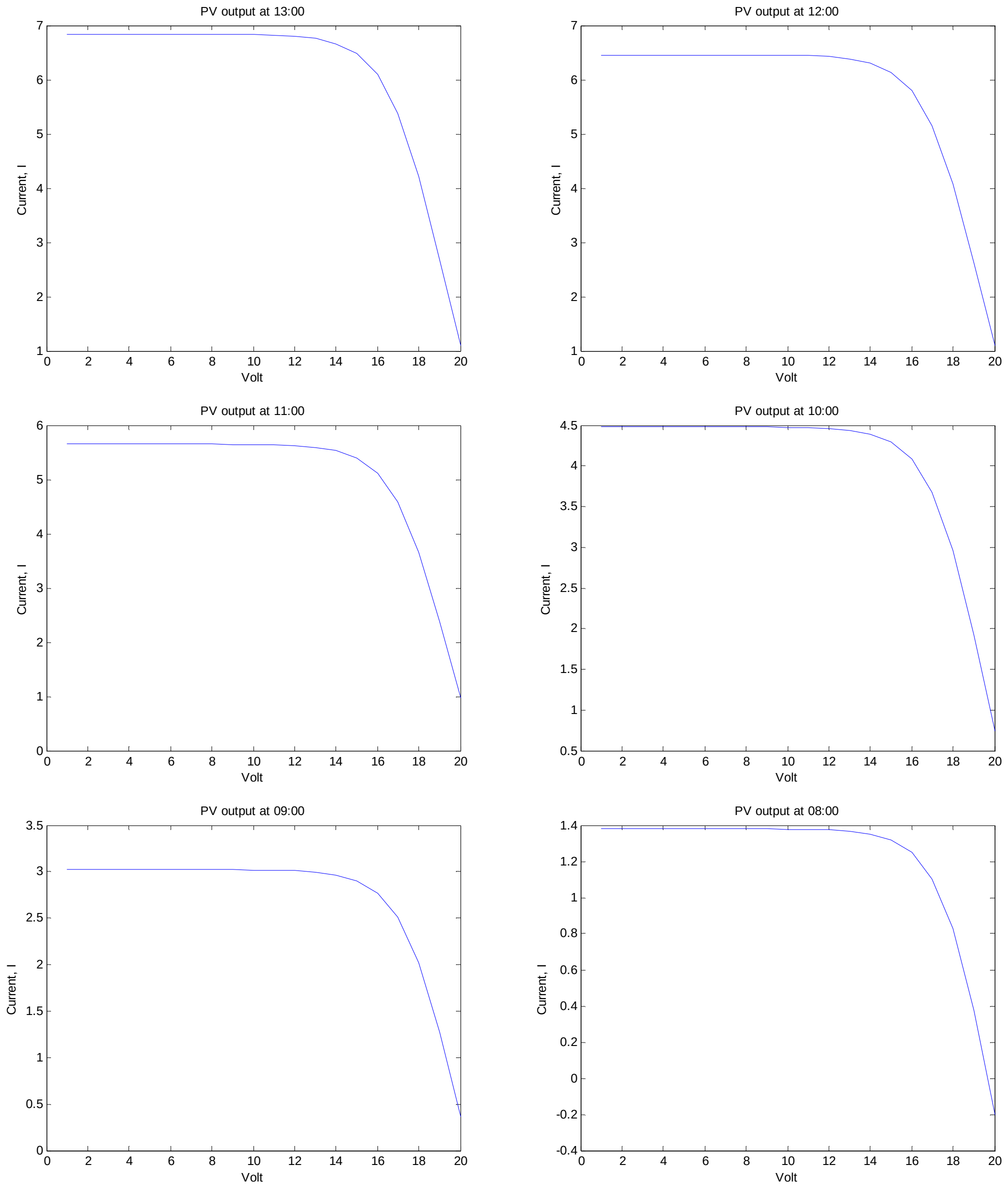


Figure 5. Simulation results of a PV module

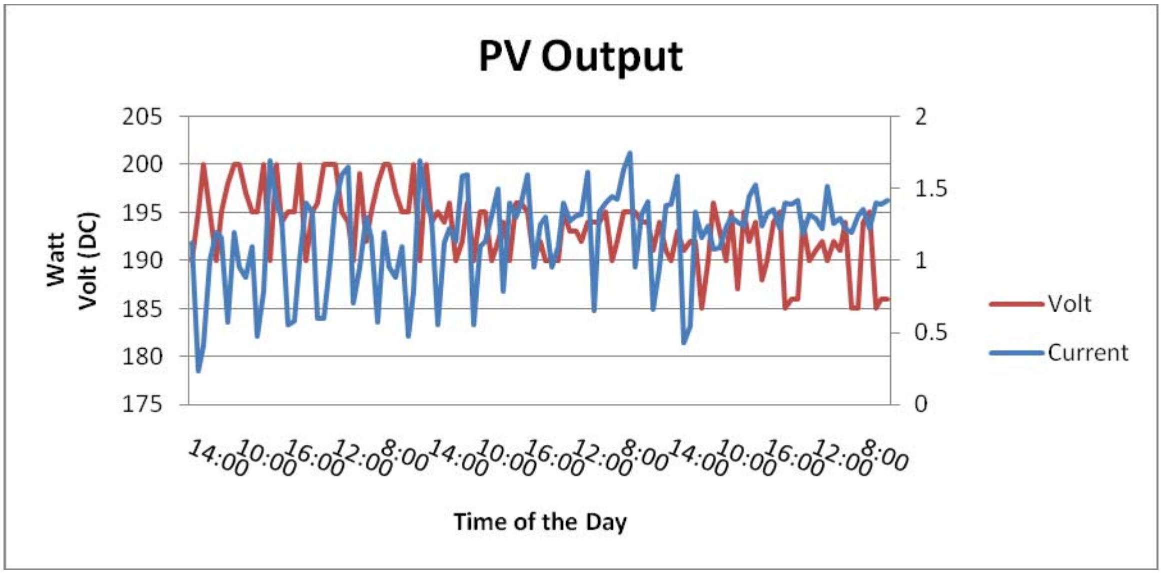


Figure 6. PV output in May 2009

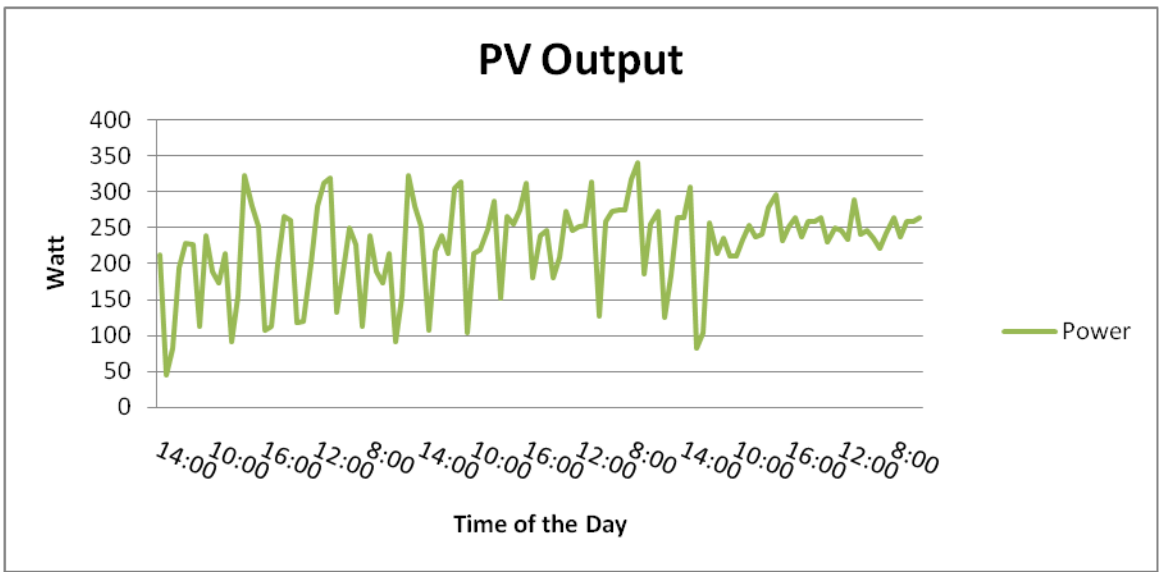


Figure 7. PV Power output, May 2009

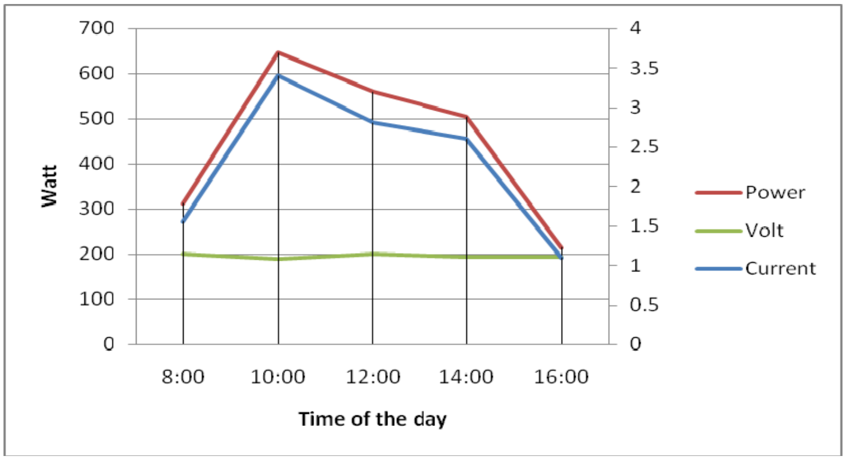


Figure 8. Hourly distribution of PV output

According to Figure 5&6, PV output reaches its maximum value around 10:00 am while the temperature is not high enough to reduce its efficiency. It seems that PV output should have been recorded before 8:00 am which exceeded the power generated at 16:00 and makes it helpful to start irrigating as early as 6:00 am using the available Wattage output.

Trying to keep pump performance efficiency more than 50%, the performance curve was used to generate a lookup table for each range of PV power output as shown in table 1 and 2. Table 1 shows the water requirements of each zone as a result of the difference between the daily water requirements and soil moisture content at specific time. The first three columns contain the available power from the simulation, expected water flow rate and the corresponding pressure from pump performance curve. This table is used to generate Table 2 where irrigated zone are sequenced according to its needed amount and the available water flow and pressure.

CONCLUSION

Photovoltaic utilization in agriculture should be studied to help farmers around the world to run agricultural businesses sustainably and effectively. Design of the irrigation system is a major factor to minimize the required pumping power and to improve its controllability. The developed control algorithm can help designers to minimize photovoltaic system sizing and hence maximize the feasibility of employing solar systems in irrigation networks.

Maximum actual power output did not exceed 45% of the nominal power output which may be a result of high ambient temperature increase. The developed algorithm scheduled the irrigation of the eight zones of each section (A & B), which minimized the total energy required for irrigation where it was 906 W theoretically and 1037 W practically.

Table 1. Flow Vs Pressure lookup table

Time	Power, W*	Flow rate, m^3/hr	Head , PSI	Zone							
				A1	A2	A3	A4	A5	A6	A7	A8
				WR	WR	WR	WR	WR	WR	WR	WR
8:00	224	-	-	126.0	124.0	109.0	118.0	105.0	124.0	110.0	118.0
9:00	480	1.6	92	128.5	126.5	111.2	125.4	107.1	126.5	112.2	120.4
10:00	720	1.8	103	131.1	129.0	113.4	132.8	109.2	129.0	114.4	122.8
11:00	754	1.8	105	133.7	138.6	115.7	135.2	111.4	131.6	116.7	125.2
12:00	812	1.8	112	136.4	144.2	118.0	137.7	113.7	134.2	119.1	127.7
13:00	863	1.9	118	139.1	146.9	120.3	140.3	115.9	136.9	121.4	130.3
14:00	852	1.9	118	141.9	149.6	122.8	145.9	118.2	139.6	123.9	132.9
15:00	795	1.85	115	144.7	152.4	125.2	155.5	120.6	142.4	126.4	135.5
16:00	790	1.85	115	147.6	155.3	127.7	158.3	123.0	145.3	128.9	138.3
17:00	656	1.7	100	150.6	168.2	130.3	161.0	125.5	148.2	131.5	141.0
18:00	400	-	-	153.6	171.2	132.9	163.8	128.0	151.2	134.1	143.8
19:00	136	-	-	156.7	184.2	135.5	166.7	130.6	154.2	136.8	146.7

*According to May 2008 data
WR: water requirement in Liters

Table 2. Theoretical irrigation schedule

Time	Power, W	Flow rate, m^3/hr	Head, PSI	Irrigated Zone
8:00	224	-	-	
9:00	480	1.6	92	A2(5min) ↔ A6(5.5min) ↔ B3(7min) ↔ B6(10min) ↔ B1(5min)
10:00	720	1.8	103	A4(5min) ↔ A8(4.5min ↔ B2(3min) ↔ B4(11min)
11:00	754	1.8	105	A7(4min) ↔ A3(5.5min) ↔ A5(4.5mi ↔ B5(6min) ↔ B7(4min) ↔ B8(5min)

Table 3. Practical irrigation schedule

Time	Power, W	Flow rate, m^3/hr	Head, PSI	Irrigated Zone
8:00	164	-	-	
10:00	390	1.0	71	A1(8.7min) ↔ A2(8.5min) ↔ A6(8.5min) ↔ B3(9.5min) ↔ B6(12min) ↔ B1(19min)
12:00	456	1.6	131	A4(5.6min) ↔ A7(5.5min) ↔ A8(5.5min) ↔ B5(8.5min) ↔ B2(10min) ↔ A5(6.5min)
14:00	425.6	1.2	57	B4(15.5min ↔ A3(6.5min) ↔ A8(7.5min) ↔ B8(11.5min)
16:00	89.7	-	-	

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JORDANELLE DAM HYDROELECTRIC PROJECT INCIDENTAL POWER GENERATION

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Reed R. Murray, P.E.[2]

ABSTRACT

The Jordanelle Dam Hydroelectric Project is new hydropower plant constructed at a federal dam by a non-federal public entity, after being selected by the U.S. Department of Interior, to develop the new low-impact hydropower at the existing federal dam. The Project, which began operations in July 2008, is an excellent example of a federal/non-federal arrangement of developing new hydropower that is incidental to other project purposes. It is the result of good resource planning and cooperation between federal and local public interests.

In July 2005, the U.S. Department of the Interior (Interior) approved the construction of a hydroelectric power generating facility at the federally owned Jordanelle Dam. The potential to produce hydroelectric power was incorporated into the original construction of the dam facilities, but by the late 1980s the United States decided to delay power development until a non-federal entity could privately finance the power facility. Central Utah Water Conservancy District (CUWCD) and Heber Light & Power (HLP) jointly competed against other proposing entities to develop power at the site under an arrangement with Interior called a "Lease of Power Privilege." The issues and coordination relating to the project to develop the new power are discussed and summarized in this paper.

BACKGROUND

Since early in Utah's history, hydropower has represented an important source of power for Utah cities, the early mining industry, and rural communities. The cities of Heber, Midway, and Charleston in Heber Valley joined together to form an joint public energy services company, Heber Light & Power (HLP), in 1909 to serve its communities with electric power. It immediately commenced construction of a hydroelectric plant. This plant received water from an irrigation canal, which diverted water from the Provo River approximately 2 miles above the hydropower plant. The water diverted into the irrigation canal, fell through two 140-foot penstocks and turned turbines and generators each with a capacity of 350 kW. The plant was upgraded in the 1950s to 450 kW and served the valley communities well until it was decommissioned in 1976.

Construction of the present-day Jordanelle Dam Hydroelectric Project is related to a large complex water supply project in Utah. The Colorado River is one of the most important

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rivers in America and critical to the western states. The 1,400-mile-long river provides water to seven Colorado River Basin states. In 1956, the Bureau of Reclamation (Reclamation) began developing the federally-owned Colorado River Storage Project (CRSP). The CRSP is a series of reservoirs on the Colorado River, developed to divert water for irrigation, municipal, and industrial use. CRSP consists of four mainstem projects and 11 additional participating projects, which are not located on the Colorado River, but are within the Colorado River Basin. The Central Utah Project (CUP), which includes Jordanelle Dam, is one of those participating projects.

Located in central Utah, the CUP is the largest water resource development ever undertaken in the state. The project provides Utah with the opportunity to use a portion of its allotment from the Colorado River, by means of a transbasin water diversion.
In October 1992, final construction of the CUP was reauthorized through Public Law 102-575, of which Titles II through VI comprise the Central Utah Project Completion Act (CUPCA). Under CUPCA, Congress provided direction for completing the CUP with certain modifications to the Reclamation plan of development. Section 208 of the CUPCA provides that CUP power facilities be developed and operated in accordance with the CRSP Act and states: “Use of Central Utah Project water diverted out of the Colorado River Basin for power purposes shall only be incidental to the delivery of water for other authorized project purposes.”

CUWCD was organized in 1964 under the laws of the state of Utah to represent the people within the CUP project area as the project sponsor and operator of the CUP facilities. As is the case with Reclamation projects, the CUP reimbursable costs are repaid by the project sponsor. In addition, with the enactment of CUPCA, CUWCD also pays 35 percent of the project’s development as a local cost share and then repays the remaining reimbursable portion of the 65 percent federal share.

Jordanelle Dam

Construction of the dam began in June 1987 and concluded in April 1993. The initial filling was made in 1996. The dam is 300 feet high with an active reservoir capacity of 314,000 acre-feet. It provides annual water supply of 15,000 acre-feet for irrigation and 92,400 acre-feet for municipal and industrial purposes. See Figure 1.

When the CUP was authorized in 1956 as part of the CRSP Act, the authorization included federal hydropower development. As a result, the outlet works of Jordanelle dam were designed and constructed in anticipation of hydropower being added at a future date.

Figure 1. Jordanelle Dam and Reservoir, located in Central Utah on the Provo River.

Power Jurisdiction

By the late 1980s, the U.S. government had decided to allow non-federal development of hydropower at Reclamation facilities. During this period, a disagreement arose between the Department of Energy and Department of the Interior about the licensing process for hydropower development at Reclamation facilities. The Federal Energy Regulatory Commission's (FERC) position was that the FERC process for licensing hydropower facilities was applicable to Reclamation facilities. The Interior, however, held the position that when Congress specifically authorizes power development on a Reclamation project, FERC jurisdiction is withdrawn. The issue was eventually resolved through a memorandum of understanding.

This understanding between the Department of Energy and Reclamation allows that the Secretary of the Interior is authorized to grant Lease of Power Privilege to non-Federal entities for the development of hydroelectric power plants. The Secretary may develop hydropower at Reclamation projects using Federal appropriations, or non-Federally under a Lease of Power Privilege, or through a partnership or other contractual arrangement using contributed funds.

Since no Federal appropriations were made available for hydropower development at Jordanelle, the decision was made to develop power under a "Lease of Power Privilege."

LEASE OF POWER PRIVILEGE

A Lease of Power Privilege (Lease) is a contractual right given to a non-Federal entity to use a Reclamation facility for electric power generation, as long as the development of the power generation is consistent with Reclamation's initial project purposes. A Lease is an alternative to Federal power development and is used where Reclamation has authority to develop power on any or all features of a Federal project. The Town Sites and Power Development Act of 1906 authorizes the Secretary of the Interior to lease surplus power or power privileges. The Reclamation Project Act of 1939 extended the contract term to a maximum of 40 years for the sale of power or Lease of Power Privileges, giving preference to municipalities and other public corporations or agencies, and also to cooperatives and other nonprofit organizations financed in whole or in part by loans made pursuant to the Rural Electrification Act of 1936 and any amendments thereof.

In October 1998, the CUWCD approached the Department of the Interior with a request to develop hydropower at Jordanelle Dam, under a Lease of Power Privilege. Even though the CUWCD operated the Jordanelle Dam, Interior determined that competitive proposals were required as a public process and in July 1999, Interior issued a request for proposals (RFP) for power development at Jordanelle. The RFP required that all responding developers design the hydropower plant to be incidental to other CUP project purposes and operations.

Many interested parties communicated with Interior and requested copies of documents, plans, and specifications relating the Jordanelle Dam. Due to the interest displayed by so many entities, Interior hosted a formal site visit at the potential hydropower site in late September. In October FERC concurred that it was within Interior's authority to issue a Lease of Power Privilege at Jordanelle Dam.

Proposal Evaluation

The CUWCD contracted with CH2M HILL in 1999 for engineering services, including preliminary evaluation and design services, so they could complete their proposal to develop the Jordanelle project. In January 2000, a joint partnership of CUWCD and HLP submitted their proposal to develop a hydropower project at Jordanelle Dam. Interior received a second proposal from the Utah Associated Municipal Power Systems (UAMPS).

Interior's selection process included a review and evaluation by an independent, multi-agency Technical Evaluation Team. Having the proposals reviewed and evaluated by individuals from the power community not associated with the CUP provided credibility to the selection process. The Technical Evaluation Team included power industry experts from the Western Power Administration (Western), Army Corps of Engineers, Bonneville Power Administration, and Reclamation. The team developed a ranking and prioritization system, based on the guidelines and criteria outlined in the original request for proposals. Interior's Solicitors Office was also involved in the early stages of the review and evaluation process, to ensure Federal law and policy was being followed.

On August 16, 2000, Interior announced that CUWCD and HLP had been selected as the Potential Lessee and established a five-year period for a Lease of Power to be negotiated and executed.

Negotiations

Once Interior had made the selection, the CUWCD and HLP began preparations for formal negotiations. Public negotiations began on November 17, 2000, and were attended by interested parties including local power developers, Western, Colorado River Energy Distributors, and Reclamation.

Under an agreement between the Department of Energy and Interior, whenever power generation is developed at any Reclamation facility, Western has the first right to market that power, if they choose to. Several meetings were held with the CUWCD/HLP, Interior, and Western discussing the potential for marketing Jordanelle power. The question on who would market the power was integral in the development of the project, in that it affected how CUWCD/HLP would finance the project, and whether or not CUWCD could rely on non-taxable bonds for project costs.

Western subsequently declined the offer to market the power from the Jordanelle project. With this critical decision made, CUWCD/HLP developed a marketing strategy and clarified their partnership arrangement: CUWCD would be the owner/operator of the hydropower generating plant, and HLP would be responsible for transmission and marketing of the power.

The 40-year lease established lease payments to Interior at a fixed rate with an annual increase of 3 percent on the gross power generated at the site. The lease agreement also covered the distribution of revenues from the project, including lease payments to Interior; the annual operation and maintenance of the facility; recovery of costs and debt payments associated with the facility; reserve accounts; any additional power revenues received by the lessee.

Even after the final negotiations between CUWCD/HLP and Interior, the groups continued to work on remaining issues such as water rights verification, insurance, lease rate, O&M, engineering feasibility, and financial feasibility.

Environmental Considerations and Agreements

The stream and area below the dam are critical to the success of the CUP. Losses of wetlands caused by the construction of Jordanelle dam were partially mitigated through the development of wetlands below the dam. Also, as a result of previous Reclamation projects, the Provo River below the dam had been turned into a lifeless channel with dikes to avoid flooding. As part of CUPCA, the Provo River has been restored by dike removal, stream restoration, and allowing the River to flow though its natural watercourse. Minimum stream flows below the dam were agreed to as part of the National Environmental Policy Act (NEPA) compliance for the dam and biological opinion on the Provo River. Also an endangered species of fish, the June sucker, lives in Utah Lake and spawns in the Provo River. These issues created a great amount of focus on environmental stewardship in relationship to the development of the hydropower project. In March 2004 the process for developing an environmental assessment began. The environmental assessment included the generation of power at Jordanelle and its transmission facilities into the Heber Valley. Interior issued a Finding of No Significant Impact (FONSI) on July 6, 2005.

With the terms of the lease of power negotiations substantially complete, CUWCD and HLP reached a final agreement regarding their respective responsibilities and financial arrangements in the power sales agreement. Since the power plant would be a run-of-the-river plant, the revenue from the power sales was variable. A detailed annual financial model, using the estimated water supply, was effective in helping show the financial feasibility of the project and estimating the relative financial obligations and revenue sharing between CUWCD and HLP, throughout the term of the Lease of Power. The generation facilities would be financed, constructed, owned, operated and maintained by CUWCD and all power generated would be purchased by HLP. The agreement allows each of the partners to best use their abilities, and to cooperate with each other to use the generating capacity of the dam and electric system of HLP for the benefit of the residents of CUWCD and HLP. The sales agreement between CUWCD and HLP was entered into on June 29, 2005.

With the environmental studies completed and the sales agreement in place, the partnership of CUWCD and HLP entered the Lease of Power contract with Interior in July 2005.

DESIGN AND PROJECT FINANCING

The preliminary design provided by CH2M HILL was refined and generation equipment firms were pre-qualified by CUWCD prior to 2005. The final design of the hydraulic turbine-generator equipment and appurtenant equipment began immediately after the agreements were signed. In October 2005, the project developers issued bidding documents seeking two identical horizontal-shaft, Francis-type turbines, two hydraulic power and control units, two synchronous generators, two butterfly-type turbine inlet valves, a plant control system, and spare parts and special installation services. The CUWCD awarded the contract to VA TECH HYDRO Canada Inc. for $4.9 million. After approval by the Interior, the CUWCD authorized VA TECH HYDRO to proceed with manufacture of the equipment in December 2005.

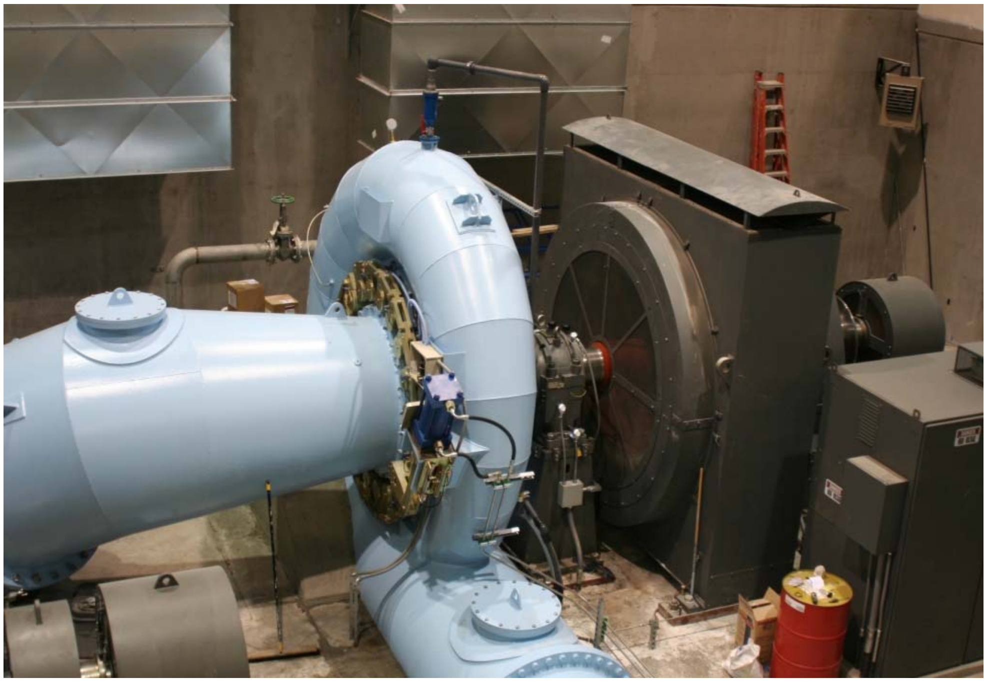

Figure 2. Turbine and Generator Equipment

The outlet works for the dam has a release capacity of more than 2,000 cfs and the hydraulic capacity of the horizontal Francis-type turbines are 300 cfs each under a net head of 270 feet. They are rated at 360 rpm and 8651 horsepower with an efficiency of 94.1 percent. The installed generating capacity is 12.6 MW, which makes the project the third largest hydroelectric power plant in Utah. The estimated annual energy production from the equipment is 39,000 MW.

The turbines and runner were manufactured by VA TECH Bouvier Hydro in Fontaine, France. The turbine inlet valves were manufactured by D2FC Energy Valves in France. The twin generators each generate at 12.47kV, are rated for 7,222 kVA, with an efficiency of 96.4 percent and were manufactured by Ideal Electric in Mansfield, Ohio. The hydraulic control system was manufactured by North American Hydro and the state-of-the-art plant control system was manufactured by Phoenix Power Control, Inc., Monroe, Washington.

The sizes and arrangement of the equipment were confirmed through the equipment submittal process and the final design of the power plant proceeded through the first six months of 2006. A design team consisting of engineering and operation staff of CUWCD, design review staff from Reclamation and Interior, and staff of HLP worked closely with CH2M HILL to prepare final details of the power plant facility. Additional geotechnical investigations confirmed the depth of bedrock for the final design of the foundation and the cutoff wall from the adjacent Provo River. The final design and bidding documents included the following elements:

- Construction of a secant pile wall dewatering cutoff
- Construction of a cast-in-place reinforced concrete power house building,

approximately 105 feet by 55 feet

- Construction of a welded steel penstock consisting of approximately 150 feet of 84-inch pipe
- Installation of owner-furnished main power transformer and turbine-generator equipment
- Testing and startup of the completed facility.

CONSTRUCTION

The CUWCD prequalified six contractors and in August 2006, received bids from four contractors, ranging from $10 million to $11.8 million, in contrast to the engineer's estimate of $8 million. The CUWCD staff evaluated the increased cost of construction against the estimated revenue of the project and recommended to its board of trustees that the bids were responsive and responsible and that the project would still be financially successful. After Interior gave approval to award the construction contract, CUWCD awarded the construction contract to W.W. Clyde & Company of Springville, Utah for $10 million with a project completion date of April 30, 2008.

Figure 3. Secant Pile Wall and Excavation

A key to CUWCD's success with its construction program has been its emphasis on partnering. CUWCD hosted a partnering workshop shortly after the contract was awarded, with representatives of CUWCD, HLP, W.W. Clyde and its subcontractors, and the Interior. This workshop allowed the participants to meet the project partners and discuss the project and schedule.

A groundbreaking ceremony was held Sept. 15, 2006 at the future site of the hydropower plant. The ceremony included many community leaders from the Heber Valley, as well as the project participants.

The first difficult construction activity was to construct the concrete secant pile water cutoff wall immediately adjacent to the Provo River. This wall was installed through cobble alluvial material into the underlying bedrock and was very effective in limiting seepage from the Provo River. Dewatering wells were also installed and operated to maintain the groundwater level below the area excavated for the powerhouse. These were maintained through construction of the lower levels of the powerhouse.

Figure 4. Winter Construction of Powerhouse

The construction project encountered difficult winter weather construction issues, especially during the critical installation the pre-purchased equipment. The concrete walls of the powerhouse were being constructed while the generation equipment was installed so a temporary enclosure was built around the generation equipment.

Constant care of the enclosure, with snow removal and reliable heating, required very close coordination to install the pre-purchased equipment in a precise manner in the midst of difficult weather conditions. Releases from the outlet works of the dam could not be interrupted during the project and being immediately adjacent to the work area, required construction of a 35-foot tall form wall to shield the project area from overspray in the summer and buildup of ice in the winter. Constructing the concrete powerhouse and installing the generation equipment during a winter season with above normal snowfall contributed to the project falling behind by about 3 months near the end of the project. This project delay and construction changes – which were very minimal – were successfully negotiated among the project's partners and the project schedule was successfully altered, to a completion date of July 1, 2008. The month of June 2008 required all of the project partners' dedicated efforts for the successful start up and commissioning of the operation of the facilities. The equipment and facilities commenced commercial operations on July 1, 2008. The project was formally dedicated August 26, 2008, which was attended by Utah's Governor, Congressional, State, and Federal representatives.

Figure 5. Jordanelle Dam Hydroelectric Project

The project has successfully produced clean, reliable energy since commencement of commercial operations, which is again satisfying to the cities and residents of Heber Valley.

WATER USE IN THE WESTERN U.S.: HOUSEHOLD KNOWLEDGE, PRIORITIES, AND WILLINGNESS-TO-PAY

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ABSTRACT

As the population in the Western U.S. continues to grow and urbanize, water continues to be reallocated from agricultural to urban uses, despite very little public input. Urban households are particularly important in the water policy process yet there is little empirical evidence of urban residents' preferences for coping with water scarcity. An Internet survey uncovers Western households' perceptions and preferences regarding water use, conservation, and reallocation, and their willingness to pay a fee in support of various water conservation and reallocation programs.

Eighty percent of survey respondents believe that water will be scarce in the next 25 years. The top-ranked strategies for increasing *short-term* water supplies were to restrict the amount of water on private and public landscapes. The top-ranked strategies for increasing *long-term* water supplies were to build reservoirs and re-use waste water on lawns and landscapes. The top-ranked funding options include increasing water rates based on water use and increasing fees on new housing developments. Just over half of all respondents expressed a willingness to pay the water fee.

INTRODUCTION

Water demands in the Western U.S. are increasing as a result of rapid population growth and urbanization, yet most rivers in the West are already fully-appropriated and large-scale infrastructural projects have become monetarily and environmentally costly. Thus, there is increasing interest in the reallocation of water among existing users.

Water continues to be transferred from agricultural to urban uses despite very little public input. There is anecdotal evidence of urban residents' growing resistance to permanent rural-to-urban water transfers (HDR Engineering, Inc., 2007) but there is little empirical evidence of the preferences that households have for long term water acquisition, how

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they would prefer meet the challenges of short term water scarcity, or how they value water in its many uses. Urban households are particularly important in the water policy process because they are a primary driver behind increased Western water demands; they will be asked to fund reallocations and other programs for meeting increasing demands; and their values and beliefs form the basis for the Western water political process and agenda.

Water transfers are the subject of intense policy debate in the Western U.S. (Knapp, et al., 2003). When policy debates arise over the desirability of water conservation or reallocation, it is important for policymakers to understand the forces underlying water demand in its various uses. And when considering various water acquisition strategies and planning for such strategies, it is important for water providers to know which programs are likely to garner the most financial and political support from their constituencies. On one hand, households may not wish to pay for a program when the perceived benefits are not immediate or are diffused among a wider population. On the other hand, there is evidence that consumers take into account more than a simple benefit-cost analysis when contemplating their support for a particular program. For instance, in their survey of urban households in California, Berk et al. (1995) found evidence that consumers place a substantial value on public and environmental goods and "doing the right thing" so long as the costs are within reasonable bounds.

The objective of this study is to examine the perceptions and preferences that western households have for water use and acquisition. Particular attention is focused on the relative ranking of options for meeting short term water shortages, the relative ranking of long-term water acquisition strategies, and households' willingness to pay for particular programs designed to address long-term water scarcity. This approach will improve the ability of states and other agencies to effectively meet the growing municipal water needs while remaining sensitive to public attitudes about water use, re-use, conservation, reallocation, and pricing.

METHODOLOGY AND DATA

This study focuses on the 17 westernmost states of the continental U.S.[6], where water is a particularly important topic due to rapid population growth and generally less abundant water supplies. Data were collected in two stages: Focus groups were conducted in selected regions of the study area to identify water issues of high priority and assist in the design of the survey that would follow. An Internet survey was then used to uncover Western households' perceptions and preferences regarding water use and management, and their willingness to pay a fee in support of a number of water conservation and reallocation programs.

Focus Groups

There were two technical focus groups—in Denver, CO and Reno, NV—and one non-technical focus group—also held in Denver. Participants in the technical focus groups

[6] These states are AZ, CA, CO, ID, KS, MT, NE, NV, NM, ND, OK, OR, SD, TX, UT, WA, and WY.

were water stakeholders in agricultural water issues (e.g., representatives of the agricultural industry and policymakers related to agriculture and water). Participants of the non-technical focus groups were members of the general public.

Internet Survey

The second stage of the study involved an Internet questionnaire of western households. The questionnaire was developed by an interdisciplinary group of researchers at Colorado State University and drew from the Colorado Institute of Public Policy report entitled, "Water in 2025: Beliefs and Values as a Means for Cooperation" (2006), which used a Q-survey methodology to uncover the full range of beliefs and values for Colorado water stakeholders.

The survey was administered by Survey Sampling Inc., a private firm specializing in sampling and administering surveys. E-mail invitations containing a link to the survey were sent to a random sample of households throughout the study area from May 2008 to June 2008. A total of 203,750 e-mail invitations were sent; of the 6,883 who opened the e-mail, 6,250 completed the survey, for a response rate of 90.8 percent. To test for non-response bias, an e-mail containing a small sub-set of the original survey questions was sent to non-respondents. The results did not reveal any significant differences between members of sample who completed the questionnaire and those who did not; thus, weighting for non-response bias was not warranted.

The survey contained a map of the United States, with the 17-state study area highlighted and defined as "the West" for the purpose of the survey. In addition to collecting demographic information about respondents, the survey measured Western households' familiarity with a number of water terms; perceptions regarding water use, scarcity, and policy; preferences regarding water use, conservation, and leasing, attitudes toward rural communities; and willingness to pay a fee in support of a number of water conservation and reallocation programs outlined in the survey. The next section describes the question categories and formats. The full survey can be obtained from the authors upon request.

In a number of questions, respondents were asked how they might prioritize among a list of options. For example, one question asked respondents to rank the 3 most important water uses during times of short-term scarcity from a list of 8 potential uses. This ranking question provides insights into the relative tradeoffs that survey respondents are willing to make among water uses in times of scarcity. In cases where respondents are asked to rank only a subset of all possible options, the mean rank can yield conflicting results (Leuschner et al., 1988). Thus, Leuschner et al.'s (1988) Relative Importance statistic is adapted to the survey responses as the appropriate measure of the relative rank of each item. This Relative Preference (RP) statistic is defined as:

$$RP_j = \frac{\sum_i \sum_k w_{ijk}}{\sum_i \sum_j \sum_k w_{ij..}} \times 100 \qquad (1)$$

where w_{ijk} = weight for rank i assigned to item j by respondent k
= 0 if item j is unranked

= I – *i* + 1 if item *j* has rank *i*.

RP_j is the proportion of total weights that the category received. The range of RP_j lies between zero and 100, and the sum of all RP_j's for a given question will equal 100. In the present case, I = 3, so a respondent's first choice was given a weight of 3, while the second choice was given a weight of 2 and the third a weight of 1. The remaining unranked categories received a weight of 0. The weights given by all respondents to a *particular* category were then summed and divided by the sum of the weights from *all* categories. The resulting percentage is the RP statistic for that category; it represents the proportion of total weights that the category received. The sum of all RP_j's for a given question will equal 100 but, as with mean rank values, statements cannot be made about the statistical significance of differences between RP_j values.

Other questions asked respondents for their level of agreement with a number of statements. These attitudinal questions were scored using a Likert scale which measured the extent of agreement with a statement as indicated by selection of one of five responses: *strongly disagree, disagree, neither agree nor disagree, agree,* or *strongly agree*. If a respondent strongly agreed with the statement, the response was given a value of 5, whereas *agreed, neutral, disagreed,* and *strongly disagreed* responses were given values of 4, 3, 2, and 1, respectively. For ease of interpretation, responses of 4 and 5 were grouped together into one "agree" category; responses of 1 and 2 were similarly grouped into one "disagree" category. Then, for each attitudinal question, the percentage of those who agreed with the statement was calculated along with the percentage that disagreed with the statement and the percentage of those who were neutral. The average level of agreement among survey respondents was also tabulated for each question.

The dichotomous choice (DC) question format was used to assess households' willingness-to-pay (WTP) a fee on their summer water bill to fund one or more of eight water programs. Compared open-ended questions, DC questions generate a scenario that is more similar to that encountered in day-to-day market transactions: respondents are simply asked whether they would pay a given dollar amount. This technique is also less stressful for the respondent than requiring a specific value to be named, thus lowering item non-response. Extensive evaluation of DC surveys in experimental settings suggests that their implications can be quite reliable, despite a variety of early concerns about the potential for biased responses (Cameron, 1988).

Respondents were given a list of eight programs related to water conservation and reallocation and then were asked whether or not they would be willing to pay a fee on their water bill during the summer months to support the programs. The proposed fee amount ranged from $5 to $25 in five-dollar increments. The WTP question was worded as follows:

> "Water providers might consider increasing water rates in order to find new sources of water, to pay for water conservation programs, or to help with problems that may arise as water is shifted to cities from other areas. Would you pay an additional <u>$X</u> per month on your water bill during the summer months if the fee was divided among the following programs?"

The eight programs were listed as:

1. To implement programs and technology to reduce household water consumption.
2. To construct a reservoir for water storage.
3. To create a system to reuse household waste water for watering public landscapes.
4. To set aside water for wildlife habitat in and around nearby streams.
5. To help keep irrigated farms in production.
6. To make infrastructure improvements in rural communities as compensation for water being transferred to cities.
7. To set aside water for public water-based recreation.
8. To provide subsidies on water-efficient appliances.

Respondents were then asked, regardless of whether they were willing to pay the fee, what proportion of the fee, should such a fee be instated, they would like to be allocated to each of the listed programs.

Deriving Individual WTP Amounts

The DC format does not reveal an individual's true WTP—only whether it falls above or below the offered amount. Nonetheless, the true WTP can be estimated parametrically (Loomis et al., 1997). This is because referendum data contain more information than conventional DC data—whereas ordinary logit models have a constant zero threshold, the referendum technique offers threshold amounts that vary across respondents. This added variability in the data makes it possible to identify the location and the scale of the underlying continuous valuation variable (Cameron, 1988). The approach begins with a binary logit equation of the general form:

$$P(Yes) = 1 - 1/[1 + \exp(\beta_0 - \beta_1 * \$X + \beta_2 * V_2 + \ldots + \beta_N * V_N] + \varepsilon \qquad (2)$$

where P(Yes) is the probability of a "Yes" response to the WTP question, \$X is the amount the respondent is asked to pay, the Vs represent all other explanatory variables, and the βs are coefficients to be estimated. Following Hanemann (1988), the underlying WTP function can be derived by re-parameterization of Equation (36) using β_1:

$$WTP = [\beta_0 + \beta_2 * (V_2) + \ldots + \beta_N * (V_N)] / |\beta_1| \qquad (3)$$

Median WTP can be estimated by inserting the average value of each explanatory variable into Equation (3). .

The binary WTP decision serves as the dependent variable in the logit model. One important explanatory variable is the size of the proposed fee. The Law of Demand suggests that this variable should have a negative effect on WTP—as a good becomes pricier, ceteris paribus, consumers demand less of it. The other explanatory variables fall into two general categories: demographics and attitudes of respondents. In addition to standard demographic variables like age, gender, race, education, and income, the following demographic variables were included:

Own: This dummy variable indicates a respondent who owns his or her place of residence. It is useful to distinguish between respondents who make decisions about water allocation and those who do not. For instance, those who own their place of residence may have more control over landscape watering policies. Additionally, some-owners may also face a higher per capita water bill to begin with due to the presence of a yard, and thus may be more sensitive to a rise in their water bill. Some apartment-dwellers do not even pay a separate water bill, instead paying a flat fee that is included as a part of their overall rent payment. These renters may not have to bear the burden of a water fee, at least in the short term, and thus may be more supportive of such a fee.

College: This dummy variable indicates that a respondent has attended some college. It is included to control for any influence that higher education may have on WTP.

Years in the West: Individuals who have lived in the West for longer may have a heightened awareness of the water issues facing the West and may be more sensitive to the recent population influx. Their opinions may thus differ from those of more recent migrants to the West.

Community Size: Individuals who grew up in large municipalities may have different levels of concern for irrigated agriculture and rural communities than individuals who grew up in smaller communities. This dummy variable indicates that a respondent grew up in a city with a population of 100,000 or more.

Water restriction: This variable indicates that a respondent's city implemented a mandatory water restriction within the past year. Such a restriction would likely increase awareness of water scarcity and may influence opinions regarding water policy. Respondents' general attitudes toward water policy and management will also influence their willingness to pay a water fee.

An individual's values and beliefs impact his or her behavior (Bright and Burtz, 2006). Thus, the following attitudinal variables were also included in the model:

Concerned about water conservation: This variable indicates the level of agreement with the statement: "Water conservation is an issue I am personally concerned about." Individuals who agree with this statement may be more willing to pay a fee that could go towards water conservation programs. Individuals who are more concerned about an issue can be expected to have greater motivation to do something—pay a fee in this case—to affect it.

Public money: This variable indicates the level of agreement with the statement "Public money should be used to develop or acquire new water resources." Because respondents *are* the public, agreement with this statement is essentially agreement that their money should be used for acquiring water supplies—paying the proposed fee is one way for them to do so. Also, most respondents' water providers are public entities[7], so individuals who agree with this statement may be more likely to pay a fee to their water provider.

Water Knowledge: Respondents were asked to state their level of familiarity, on a 3-point scale, with fourteen water terms. Responses of 'very familiar' were assigned a value of 3, while responses of 'somewhat familiar' and 'not at all familiar' were assigned values of 2 and 1, respectively. Respondents were then given a composite water knowledge score by summing their scores for each water term, yielding an ordered

[7] Eighty percent of respondents stated that they receive their water from a water district or city.

discrete variable. Familiarity with water terms and uses likely indicates interest in water use and policy and awareness of water issues facing the West, which may in turn translate into greater concern and thus greater WTP.

Voluntary Restrictions: This variable indicates level of agreement with the statement "Household water restrictions should be voluntary rather than mandated by the government." Individuals who believe strongly in independent choice and self-responsibility may be less likely to pay a fee in support of any program that is administered by a government entity.

Enough water in the West: This variable indicates the level of agreement with the statement "There is enough water in the Western U.S. to meet the future needs of all the people and businesses in the West for the next 25 years." Individuals who agree with this statement can be expected to have a lower willingness to pay for water programs.

Policy makers understand: This variable indicates the level of agreement with the statement, "Water policy makers understand my priorities for water use." Individuals who agree with this statement may have greater trust in public officials to allocate any fee revenues wisely, and thus may be more willing to entrust those officials with their money in the form of a water fee.

Satisfied with current management: This variable indicates the level of agreement with the statement, "I am satisfied with the current system of water management." Those who are satisfied with current water management may be less likely to pay money for a new program.

Limit growth: This variable indicates the level of agreement with the statement, "Growth of cities should be limited to manage water scarcity." Agreement with this statement may indicate a feeling that new residents are to blame for current water woes and that they alone should pay for any new water resources.

Regional planning: This variable indicates the level of agreement with the statement, "Regional land use and water planning is needed to manage water scarcity." Respondents who believe that regional land and water planning is needed may be less satisfied with the status quo and thus more willing to pay money to change it.

Government Subsidies: Respondents were asked to rank seven strategies for addressing long-term water needs. This dummy variable indicates that a respondent chose the strategy "Obtain subsidies from the Federal government" as their top choice. Such a choice implies a belief that the government should bear the responsibility of paying for water programs, and thus is expected to be negatively correlated with WTP.

Do nothing: This variable indicates the level of agreement with the notion that if water is taken from rural areas and given to cities, then those cities should not be required to do anything to compensate those rural communities. Respondents who agree with this notion lack a feeling of personal responsibility regarding this issue, and are thus expected to be less willing to pay the fee.

Economy over Environment: This variable indicates the level of agreement with the statement, "In water planning, the health of the economy is more important than protecting the environment." It is indicative of a relative preference for economic development over environmental conservation, and may influence the decision to pay the fee, given the various programs the fee aims to support.

To limit the complexity of a model, some researchers remove variables that are not individually statistically significant. The F-statistic and log-likelihood ratio (LR) were used to test the validity of removing the state dummy variables and four other explanatory variables that were not individually statistically significant in the original model specification. Neither statistic exceeded its critical value at the five percent level of significance (Table 1). Thus, the null hypothesis that these 20 variables are jointly zero cannot be rejected; accordingly, the variables were omitted from the regression.

Table 1. A Test for Redundant Variables

Redundant Variables: Male, Years in West, Water Restriction, College, AZ, CA, CO, ID, KS, MT, NE, NM, NV, ND, OK, OR, SD, TX, UT, WY	
F-statistic: 1.22	Probability (20, 4121): 0.2237
Log-likelihood ratio: 23.24	Probability (20): 0.2771

The log-likelihood ratio (LR) is the counterpart of the F-statistic in linear regression models and can be used to assess the overall fit of the logit model. The LR tests the joint null hypothesis that all slope coefficients are zero; thus, rejection of the null hypothesis indicates that the explanatory variables as a group help to explain WTP.

RESULTS AND DISCUSSION

The majority of respondents were female (74 %) and Caucasian (89 %), with most falling within the age range of 45 to 64 years (Table 2). Due to divergence from U.S. Census Bureau data, responses were weighted by age, gender, and state population. These weights were then normalized following Vaske (2008).

Table 2. Respondents' Ages

Age Group	**18 to 24**	**25 to 44**	**45 to 64**	**65 and over**
Proportion of Respondents	6.3 %	28.0 %	51.8 %	13.9 %

The size of respondents' current community and the community in which they grew up might influence their perceptions of water use and their preferences regarding water resource management. The largest shares of respondents grew up in large cities[8] and currently live in large cities. The type of home in which an individual resides might influence perceptions and preferences. Most respondents (74%) own their place of residence, and most (72%) live in single family homes. Most respondents receive their water from the city (Table 3).

Table 3. Respondents' Source of Household Water

Water Source	**City**	**Water District**	**Private Well**	**Unsure**
Proportions of Respondents	61.5%	20.6%	10.5%	7.5%

A respondent's tenure in the West may influence their experiences with, and concern regarding, water scarcity. A surprising majority of respondents (73%) reported having

[8] For the purposes of this study, a large city is defined as one with more than 250,000 residents.

lived in the West more than twenty years. Education and income are often important characteristics when describing the policy positions and choices of individuals. Most respondents (81%) had some educational training beyond high school, and their annual household income tended to be less than $75,000 (Figure 1).

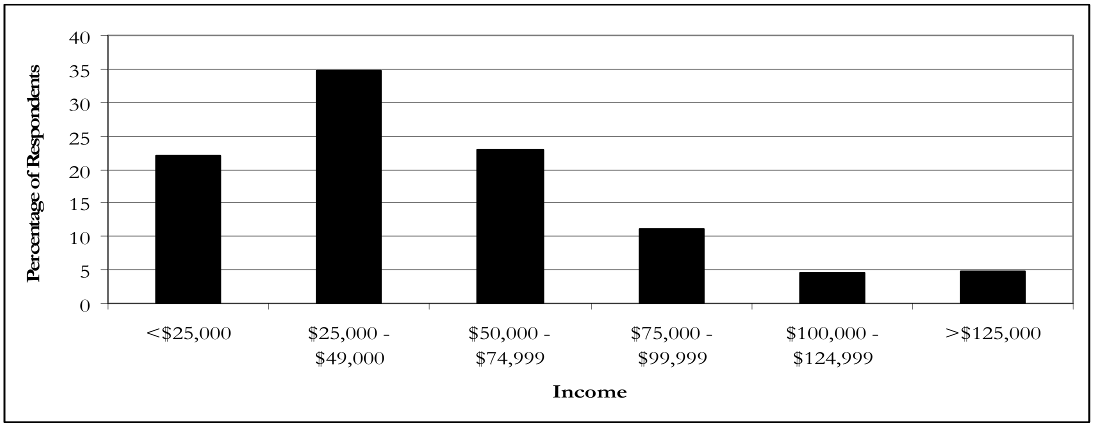

Figure 1. Respondents' Annual Income before Taxes

An individual's perception of water scarcity will likely influence his or her attitudes toward water conservation and their willingness to pay for various programs for addressing scarcity. In order to gauge their perceptions of current and future water scarcity in their state and the West, respondents were asked to indicate the extent to which they believed the following statements to be true or false:

1. There is enough water in my state to meet the current needs of all the people and businesses in my state.
2. There is enough water in my state to meet the future needs of all the people and businesses in my state for the next 25 years.
3. There is enough water in the Western United States to meet the current needs of all the people and businesses in the West.
4. There is enough water in the Western United States to meet the future needs of all the people and businesses in the West for the next 25 years.

Respondents generally believe that sufficient water supplies exist to meet the current needs in their state; however, future scarcity is a concern (Figure 2).

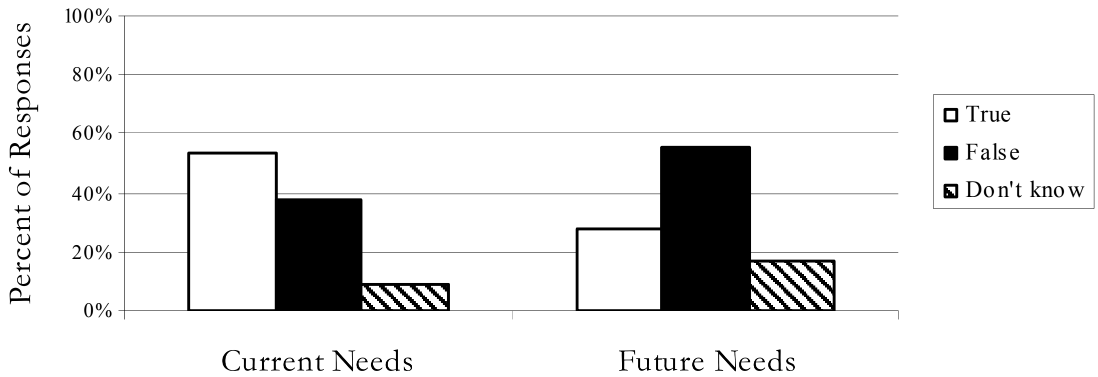

Figure 2. Respondents' Perceptions of Water Scarcity in their State

Respondents are less optimistic about water supplies across the West (Figure 3). Respondents believe that Western water resources are scarce and that the scarcity will persist.

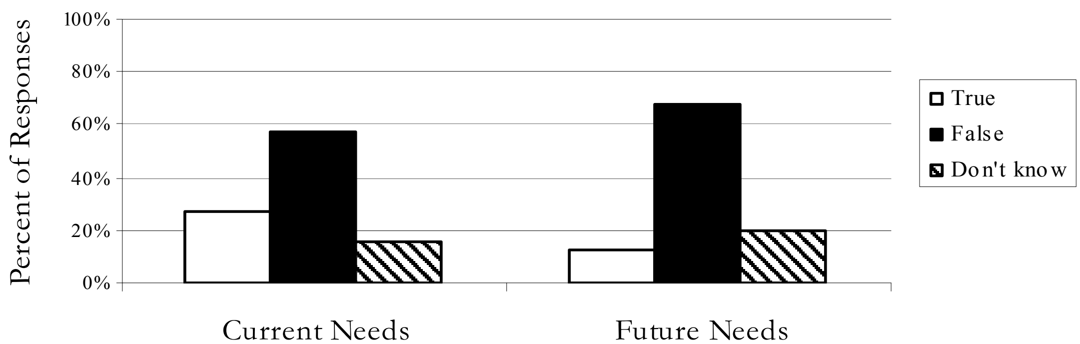

Figure 3. Respondents' Perceptions of Water Scarcity across the Western U.S.

The next section discusses the responses to a series of questions in which respondents were asked to rank their top-three choices out of a larger set of options. Their relative preferences (RPs) were then calculated and weighted according to gender, age, and state population as described in the Data and Methodology section.

Western states at times experience temporary water shortages[9] for a variety of reasons such as drought or over-allocation to certain uses. During these times, there may not be enough water to adequately provide for all water uses, and some prioritization must take place. The uses for which water might be allocated during times when water is limited were grouped into eight general categories. Respondents were asked to indicate which of these eight water uses should receive the first-, second-, and third-highest priorities for allocation when water is limited.

[9] Respondents were informed that, in this context, "temporary" refers to a shortage lasting less than 2 years.

Household water use garnered the highest priority among all water uses, while landscaping and recreation received the lowest levels of priority (Figure 4). Thus, while households do not want to reduce their indoor water use, they are willing to cut back on landscaping and recreational use of water. Irrigated farmland received the second-highest level of priority, providing one indication of the relatively high value that these households place on irrigated agriculture.

However, in the present context, water for the natural environment refers to such things as the provision of fish and wildlife habitat, while water for natural resource management refers to fire suppression and maintenance of stream banks, examples which were provided in the survey. Given the relative similarity between these two categories of water use, it may make sense to also consider the two categories together, in which case they overtake irrigated agriculture as the second-highest ranked water use category.

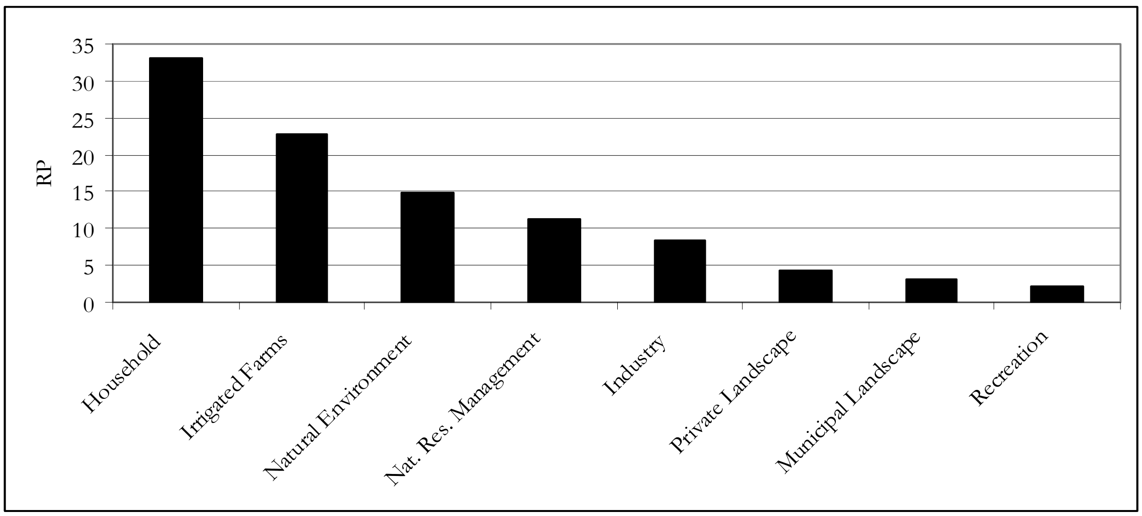

Figure 4. Respondents' Relative Preferences in Times of Short-Term Water Scarcity

Municipal water providers have several options for acquiring or stretching water supplies in times of *short-term* scarcity. Respondents were given a list of 8 such options and asked to list the 3 best options. Restricting private and public outdoor watering were by far the most preferred short-term strategies (Figure 5). Permanent water transfers from farms to cities were the lowest ranked strategy. In fact, respondents indicated they would rather pay higher water rates than dry up agriculture. This suggests that households may be aware of the negative effects of permanent water transfers and may take such effects into consideration when forming their preferences for water supply options. While higher rates were not preferred, it will be shown later that households are quite willing to pay a temporary water fee if the funds go toward a program they support.

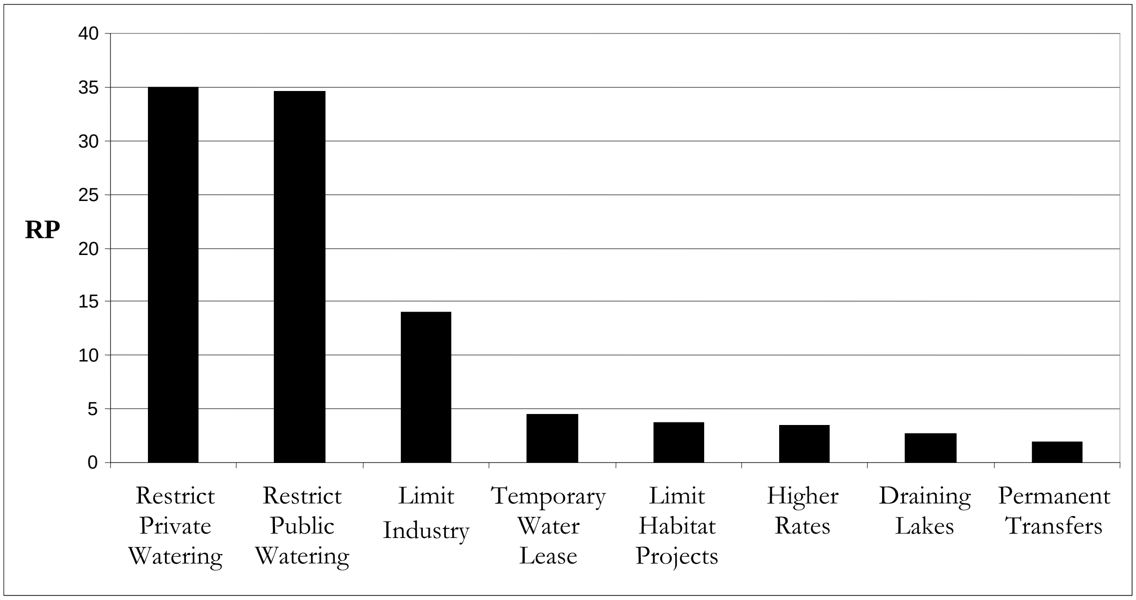

Figure 5. Respondents' Preferred Strategies for Meeting Short-Term Water Scarcity

Long-term water development strategies are more capital and construction intensive, and require longer-term planning. Respondents were given a list of 8 such strategies and were again asked to list the 3 best options. The most popular strategies for meeting long term needs were to build reservoirs and to re-use water on private lawns and public landscapes (Figure 6). The least popular alternative was buying water from farmers. Even when facing long-term drought conditions, households are reluctant to purchase water from farmers—this option is once again last in the rankings. The lack of support for permanent water transfers reiterates the call to find alternatives. One alternative is leasing water from farmers, and is discussed later in the paper.

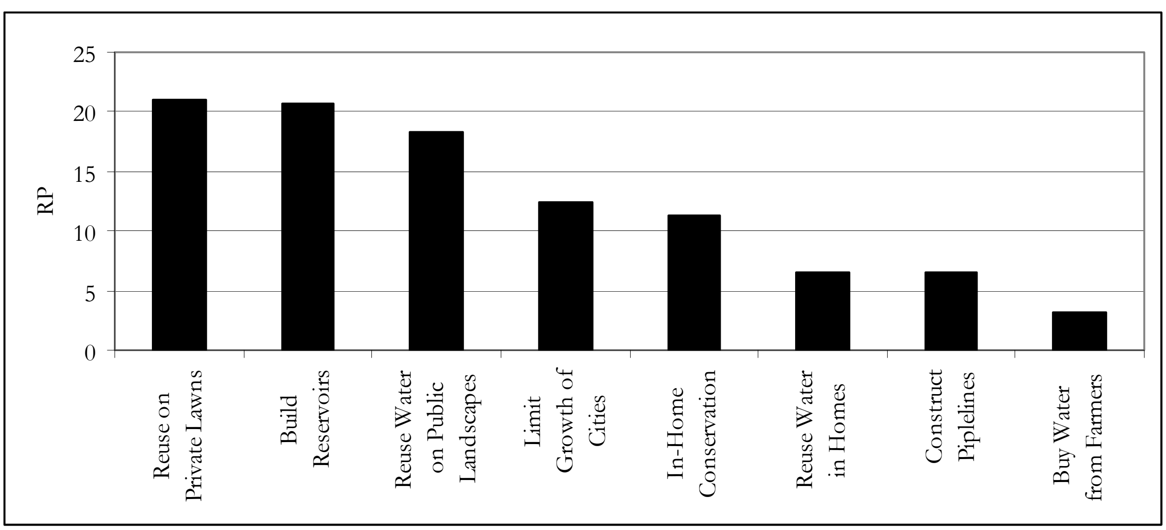

Figure 6. Respondents' Preferred Strategies for Meeting Long-Term Water Scarcity

All strategies for meeting long-term needs will require capital expenditures, and municipal water providers will be charged with acquiring funds. Respondents were given a list of seven opportunities for funding, and were again asked to rank their top 3 choices. Respondents find it more appealing to place the responsibility of funding additional water supplies on those who are creating the excess demand than to spread the cost equally across all households, preferring to fund new water supplies by increasing water rates for households that use more water and by charging higher fees on new housing (Figure 7). It is no surprise that increasing all water rates was the least popular option—because the majority of increased water demand is a result of population growth, those who already live in the region may feel that they should not have to pay for meeting those new demands. Similarly, those who use less water do not feel they should pay as high a rate as those who use more water.

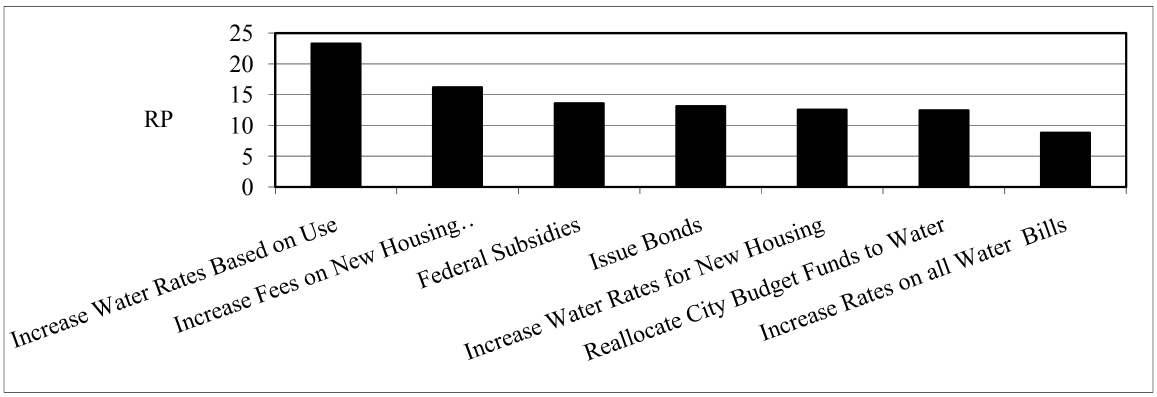

Figure 7. Respondents' Preferred Funding Options for Water Supplies

Diverting water from farms to cities can spur contentious debates. In this context, respondents were asked their level of agreement with the statement, "Cities should be able to divert water from rural areas if the cities need more water." Nearly a third of all respondents believe cities should be able to divert (Table 4). While only 36% of respondents believe that water leases are more beneficial to rural economies than permanent water transfers, this is 3 times the proportion of respondents who disagree with the notion. Indeed, the majority of responses are neutral, which likely stems from uncertainty about the effects of leases due to the limited number of lease programs currently in practice. While public opinions about water leases may be somewhat ambiguous, the opinions about permanent water transfers are not: fully 84% of respondents think the number of permanent water transfers from farms to cities should be limited, while only 4% do not think they should be limited.

The preceding results show that urban households do not prefer to permanently transfer water from farmers. However, it is not clear whether this is out of self-concern for food security, a local food supply, and lower food prices, or whether it is out of concern for farmers and rural communities. In this context, respondents were asked whether cities should be required to take certain actions after transferring water from rural areas. There appears to be a wide range of actions that cities could pursue that would be acceptable to the general public (Table 4).

Table 4. Respondents' Preferences for the Compensation of Rural Communities

Activity	% Agree (West)	% Agree (Colorado)
Conserve water on farms	84.8 %	84.6 %
Financially compensate rural communities	84.3 %	87.5 %
Provide job training	64.1 %	63.5 %
Restore irrigated farmland to native grasses	58.9 %	59.8 %
Create loan programs for start-up businesses	53.3 %	55.1 %
Invest in rural roads and schools	52.7 %	54.1 %
Do nothing	3.1 %	2.7 %

The action generating the greatest agreement was buying and installing equipment to conserve water on farms. Another highly ranked option is for cities to provide job training for rural residents. Training and business assistance programs can help entrepreneurs improve their business communication skills and build networks of small businesses. However, rural development strategies based on boosting human capital will only be successful if integrated with local economic development activities that boost demand for skilled workers in the region (Fitzgerald, 1995). Also, while entrepreneurship programs can provide opportunities for growth, the small businesses created are extremely vulnerable. As such, self-employment cannot serve as a substitute for other types of employment (Bates and Nucci, 1989). The least-preferred option, by far, is for cities to do nothing, again showcasing the negative stigma surrounding permanent water transfers.

Household conservation may be one strategy to reduce the demand for water resources. With this topic in mind, respondents were asked to provide their level of agreement with a number of statements about water conservation. Water conservation is a personal concern of 72% of respondents, and 75% of respondents report participating in water conservation strategies in their daily lives. 45% of respondents think that household water conservation should be voluntary. The effectiveness of conservation efforts may be limited as a result of demand hardening, whereby long-term conservation may reduce the water savings potential for short-term demand management strategies during water shortages (Flory and Panella, 1994). However, as pointed out by Mayer (2006), demand hardening is only a consideration during a water shortage and if conserved water is used to serve new customers (Mayer, 2006). Even under these conditions, demand hardening may not be a significant problem because most long-term water conservation programs focus on technological changes; customers can still achieve *behavioral* reductions during short-term water shortage (Mayer, 2006).

Several policy alternatives exist for managing water resources and water scarcity. Using the Likert scale, respondents were asked to rank their level of agreement with a number of statements regarding the role of government in water policy: There is strong agreement with the notions that public funds should be used to acquire and develop water resources (average Likert ranking of 4.2) and that the growth of cities should be limited to manage water scarcity (4.0). There is also general agreement with the notion that the number of permanent water transfers from farms to cities should be limited (3.8).

Respondents have varying perceptions about the institutions that govern water resource allocation and the role that individuals play when influencing these institutions. Respondents think regional land use and water resource planning is needed to manage water scarcity (average ranking of 4.3), but are not satisfied with current water management (2.5). They do not believe they have enough of a voice in water policy (2.4), that policymakers understand their priorities (2.4), or that all stakeholder groups are equally represented in water policy decisions (2.3). They also tend to agree that current water laws need to be changed (4.0).

A number of people and groups are in a position to make decisions about the best way to conserve water in communities. Respondents were asked to rank which of five groups should have the first-, second-, and third-most responsibility for making decisions about how water should be conserved in our communities. As Figure 8 shows, respondents prefer that that responsibility for conservation decisions fall to households and/or local government.

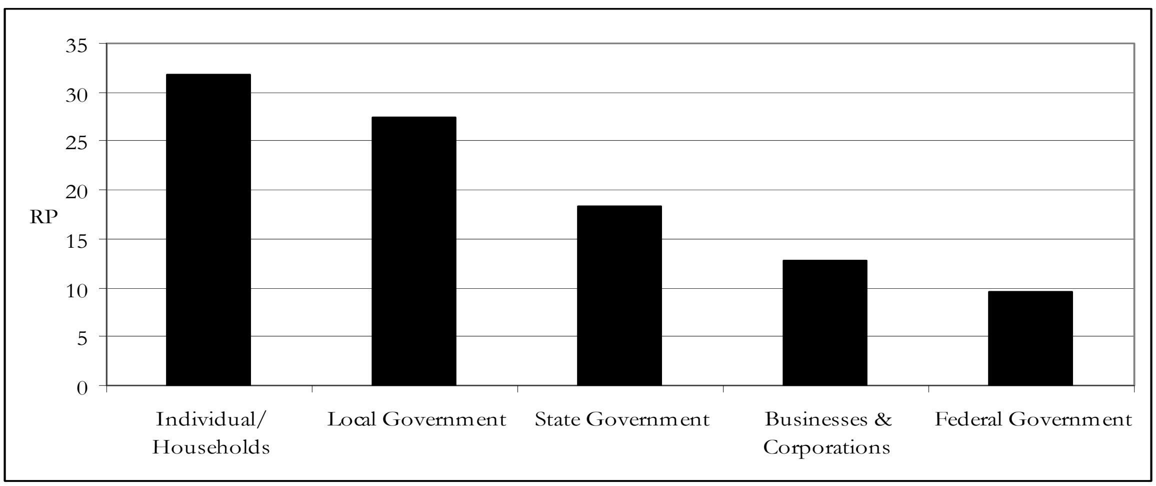

Figure 8. Respondents' Preferences about who should make Water Conservation Decisions

Water providers might consider increasing water rates to finance new sources of water. Using the dichotomous choice format, respondents were asked if they would be willing to pay an additional fee on their water bill during the summer months if the revenue went to the respondents' choice of eight listed programs.

Just over half of all respondents were willing to pay the fee. In line with economic theory, the proportion of respondents willing to pay the fee fell as the fee amount rose (Table 5). A slightly greater proportion of Colorado respondents were willing to pay the fee, perhaps reflecting Coloradans' heightened perceptions of current and future water scarcity.

Table 5. Willingness to Pay a Water Fee during the Summer Months

Fee Amount	**$5**	**$10**	**$15**	**$20**	**$25**	**Overall**
YES Responses (West)	63.6 %	55.5 %	47.3 %	43.5 %	37.3 %	52.1 %
YES Responses (Colorado)	70.6 %	65.9 %	57.9 %	40.2 %	44.9 %	55.3 %

Respondents were then asked to allocate the fee across the eight programs in any way they wished, *even if they did not support the fee*. The mean proportions are displayed in Table 6.

Table 6: Average Fee Allocations

Program	**Proportion of Fee**
Construct a reservoir for storage.	19.8 %
Keep irrigated farms in production	19.7 %
Create a system to reuse water for public landscapes.	19.2 %
Implement programs to reduce household water consumption.	16.1 %
Set aside water for wildlife habitat in nearby streams.	13.8 %
Provide subsidies for water efficient appliances.	12.3 %
Make infrastructure improvements in rural communities	7.2 %
Set aside water for public based recreation.	6.5 %

What drives the decision to pay the water fee? Insight is provided by a logit model regressing the binary WTP decision variable on a number of demographic and attitudinal variables (Table 7). The LR-statistic exceeds the critical value of 33.9 at the five percent level of significance; thus, we can conclude that the explanatory variables as a group help to explain WTP.

Table 7. Binary Logit Analysis of Western Households' Willingness to Pay a Water Fee

Dependent Variable: A WTP Response of "Yes"			
Explanatory Variable	**Coefficient**	**Standard Error**†	**Probability**
C	0.2639	0.5060	0.9444
Own**	-0.5336	0.0806	0.0000
Caucasian**	0.5042	0.1158	0.0000
Income**	0.2206	0.0282	0.0000
Fee Amount**	-0.0729	0.0053	0.0000
Grew Up in a City**	0.1609	0.0696	0.0333
Enough Water in West**	-0.0984	0.0364	0.0045
Personally Concerned about	0.1915	0.0421	0.0000
Voluntary Restrictions**	-0.2036	0.0311	0.0000
Water Knowledge**	0.0132	0.0061	0.0324
Regional Planning Needed**	0.2997	0.0538	0.0000
Limit City Growth**	-0.0909	0.0360	0.0099
Public Money**	0.3130	0.0400	0.0000
Satisfied with Current Management*	-0.0815	0.0450	0.0830
Policy makers Understand**	0.1273	0.0443	0.0037
Do Nothing**	-0.2110	0.0446	0.0000
Government Subsidies**	-0.5284	0.1000	0.0000
Age**	-0.0679	0.0148	0.0000
Age^2**	0.0007	0.0002	0.0000
New Housing**	-0.2265	0.0844	0.0043
Economy over Environment**	-0.0874	0.0322	0.0000
LR statistic: 784.82 (Probability = 0.0000)		Restricted Log-likelihood: -2,910	
Sum of squared residuals: 865.85		McFadden R-squared: 0.1483	

†QML (Huber/White) standard errors & covariance
**Statistically significant, $\rho<0.05$
*Statistically significant, $\rho<0.10$

In line with economic theory income was found to increase willingness to pay the fee. As expected, those who believe that public money should be used for water acquisition were more likely to pay the fee, as were those who feel that policymakers understand their priorities, those who feel that regional planning is needed, and those who are personally concerned about water conservation. Also as expected, water knowledge appears to increase willingness to pay a water fee. Caucasians and those who grew up in a city were also more willing to pay the fee.

In accordance with the Law of Demand, the size of the proposed fee had a negative effect on the WTP decision. As anticipated, home-owners were less likely to pay fee, as were those who feel that the growth of cities should be limited, those who believe there is enough water in the West, those who believe that water restrictions should be voluntary, those who feel that water acquisition should be paid through fees on new housing and/or government subsidies, and those who think the economy should be given precedence over the environment. Age was also found to reduce willingness to pay, which is intuitive—older individuals may gain little from a program that may take years to implement.

Using these logit coefficient estimates as inputs into Hanemann's (1984) method, the median WTP amount was determined to be $17.47. The preferred fee allocation can be used to estimate the median WTP for each of the eight programs.

CONCLUSIONS

There is a desire to change the current management of water resources in the West and to give more responsibility to individual households and local governments. Households prefer to secure additional water supplies through reservoir construction. However, households are also willing to pay for a number of water conservation and reallocation programs, particularly those that go towards keeping irrigated farms in production, reusing household water, and reducing household water consumption. There is some evidence that a water education program would increase the willingness to pay a water fee.

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COORDINATING WATER MANAGEMENT THROUGH AN INTEGRATED REGIONAL WATER MANAGEMENT PLAN (IRWMP)

David Cone[1]

ABSTRACT

Management of water resources has historically been limited to independent operations by overlying local water agencies, cities, and counties and individual water users. California legislature recognizes the benefits of integrating water resources management on a regional basis and has been encouraging the development of Integrated Regional Water Management Plans (IRWMP). The IRWMP process seeks to build upon the planning efforts of local agencies with the understanding that potential projects must approach water use and management from a regional perspective rather than an individual perspective. The regional integration is not intended to diminish the individual agency's decision-making power or its power to exercise its rights. Its goal is to enhance the collective power of the local agency and their ability to manage local resources. Participants are able to address water management issues on a much larger scale through an integrated planning framework. Some local problems cannot be solved without developing a regional approach.

This paper will describe how 6 water agencies, 10 cities, 3 counties, various local communities and other non-governmental parties worked together to develop and implement the Upper Kings Basin Integrated Regional Water Management Plan. The Plan covers an area of 610,000 acres with an irrigated land area of 480,000 acres. The main source of surface water and groundwater for the area is the Kings River. While the water rights on the river are held by the 28 members of the Kings River Water Association, three primary water right holders are participants in the Plan. The primary source of water for all of the parties is groundwater which is in an overdraft condition. None of the parties are able to solve or manage the problem of overdraft for the groundwater basin. Only through collaborative management can the problem of overdraft be managed.

INTRODUCTION AND WATER RESOURCE SETTING

The Kings River is located in central California. It provides on average 1,780,000 acre-feet of supplemental surface water (WRIME, 2007b) for the 28 members (water right holders) of the Kings River Water Association (KRWA). A Watermaster is employed by KRWA to oversee the water allocations and deliveries for the various members. The annual surface water supply is highly variable from a low of 385,000 acre-feet in 1977 to a high of 4,207,000 acre-feet in 1969 for the 1896 to 2008 period of record (USAOCE, 1979). The water right entitlement for each of the members is determined by the mean daily natural river flow based on their flow and storage rights. As a result of variable water supply and water rights differences, the farmers in the Kings River service area

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must depend on groundwater to make up for the deficiencies in surface water supply (Figure 1).

GROUNDWATER OVERDRAFT PROBLEM

The 28 member of the KRWA are local public water agencies (water districts, irrigation districts, and water storage districts) and private mutual water companies (canal companies, ditch companies, and irrigation companies). Each member is solely responsible for its share of the surface water supply and manages it accordingly. (Kings et al, 2003)

The three primary water right holders along with eight other KRWA members are located within the Kings Groundwater Basin (Figure 2). All of the farmers in the Basin depend upon the groundwater to supplement or meet their irrigation requirements. In addition, 26 cities and communities are solely dependent on groundwater in the Basin for their drinking water supplies (Figure 3). The City of Fresno is the second largest city in the United States reliant solely on groundwater (California, 2003). It appears as if Jacksonville, Florida is the largest with Miami, Florida as third largest. Also a significant amount of farmland in the Basin does not have any surface water allocation and groundwater is its only source of irrigation water.

All of the local water agencies, cities, counties, and individual water users have historically acted independently in the management of their water resources. In addition, groundwater in the Kings Basin is a private property right of the landowner and managed by the individual landowners.

As land in the Kings Basin was developed into farmland and as the cities and communities grew, it became apparent that the groundwater was in serious overdraft condition and would continue to get worse unless something was done. Water agency managers realized that they individually could not solve the overdraft problem on their own. Figure 4 illustrates the changes in groundwater storage in the Basin from 1964 to 2004.

EARLY ACTIVITIES

In 2001, Fresno Irrigation District, Consolidated Irrigation District, and Alta Irrigation District (the three primary water right holders on the upper portion of the Kings River) along with the Kings River Conservation District formed the Basin Advisory Panel (BAP) to begin addressing the groundwater overdraft problem and seeking ways to improve water management within the Basin. In addition, they invited the California Department of Water Resources, Division of Local Assistance, (DWR) to participate in the BAP. It became increasingly clear to the BAP that it would not be possible to solve the problem without having all of the stakeholders at the table.

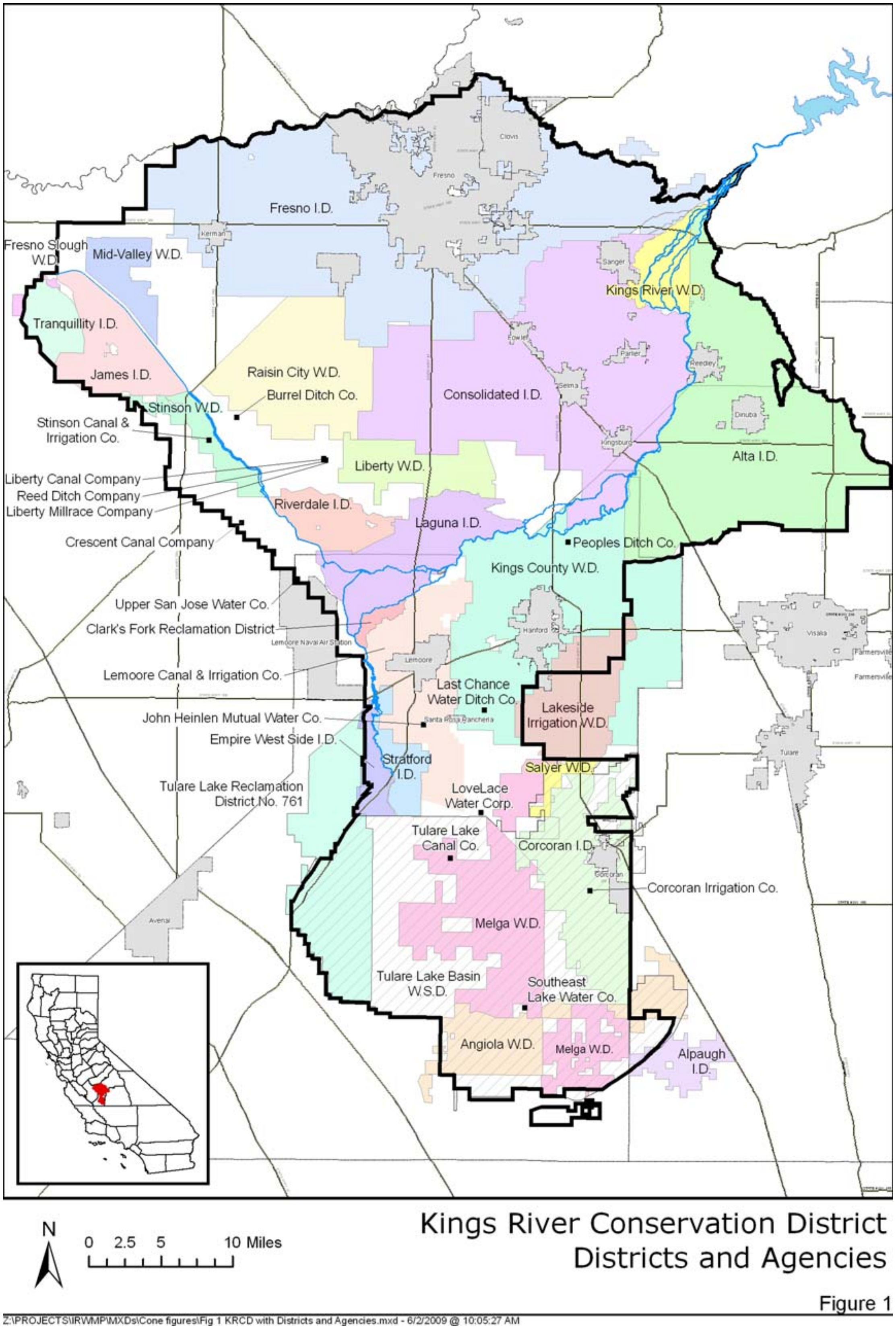
Fresno I.D.
Fresno Slough W.D.
Mid-Valley W.D.
Tranquillity I.D.
James I.D.
Raisin City W.D.
Burrel Ditch Co.
Consolidated I.D.
Kings River W.D.
Stinson W.D.
Stinson Canal & Irrigation Co.
Liberty Canal Company
Reed Ditch Company
Liberty Millrace Company
Liberty W.D.
Alta I.D.
Riverdale I.D.
Laguna I.D.
Peoples Ditch Co.
Crescent Canal Company
Kings County W.D.
Upper San Jose Water Co.
Clark's Fork Reclamation District
Lemoore Canal & Irrigation Co.
Last Chance Water Ditch Co.
Lakeside Irrigation W.D.
John Heinlen Mutual Water Co.
Empire West Side I.D.
Stratford I.D.
Salyer W.D.
Tulare Lake Reclamation District No. 761
LoveLace Water Corp.
Tulare Lake Canal Co.
Corcoran I.D.
Corcoran Irrigation Co.
Melga W.D.
Tulare Lake Basin W.S.D.
Southeast Lake Water Co.
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Figure 1.

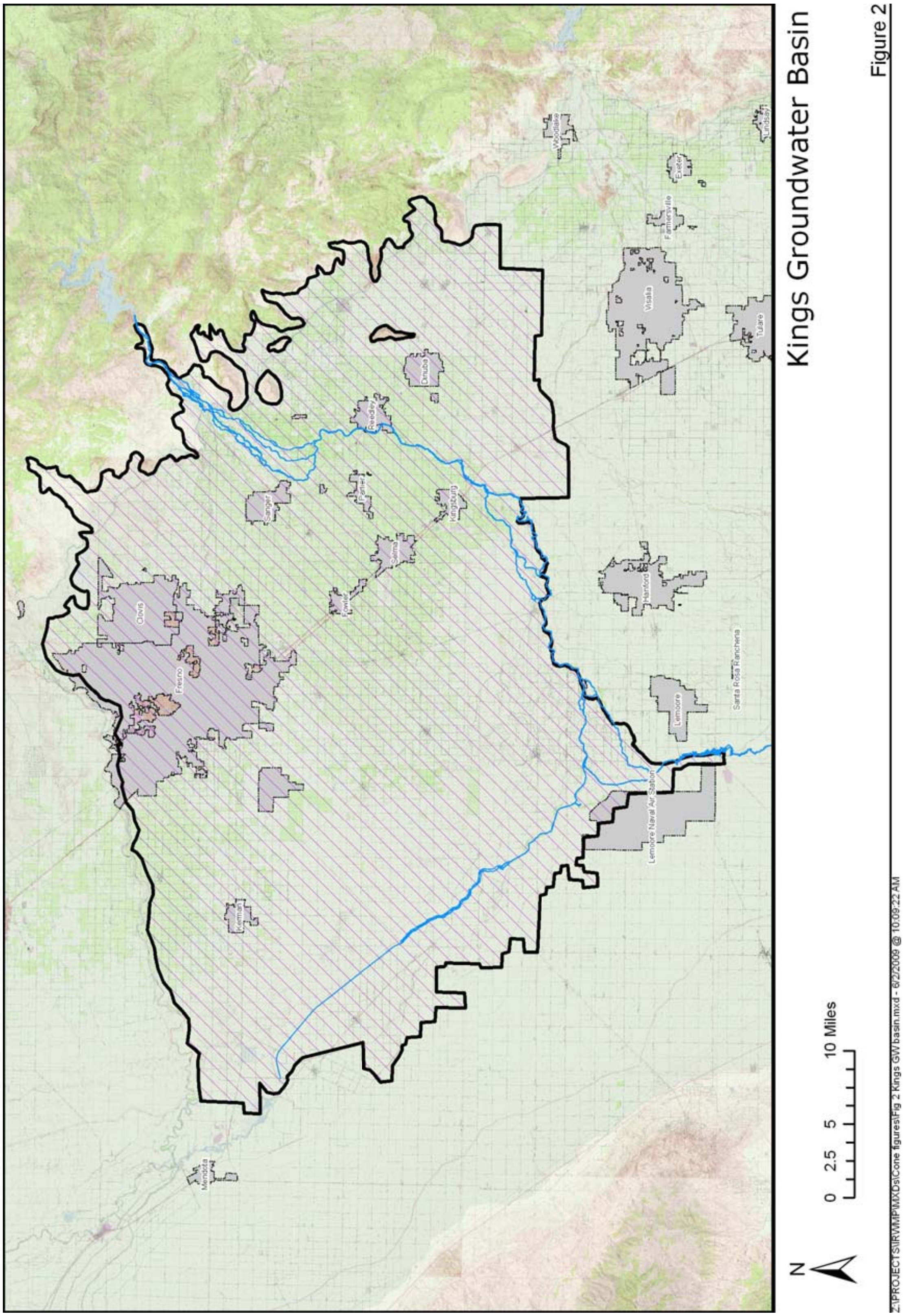
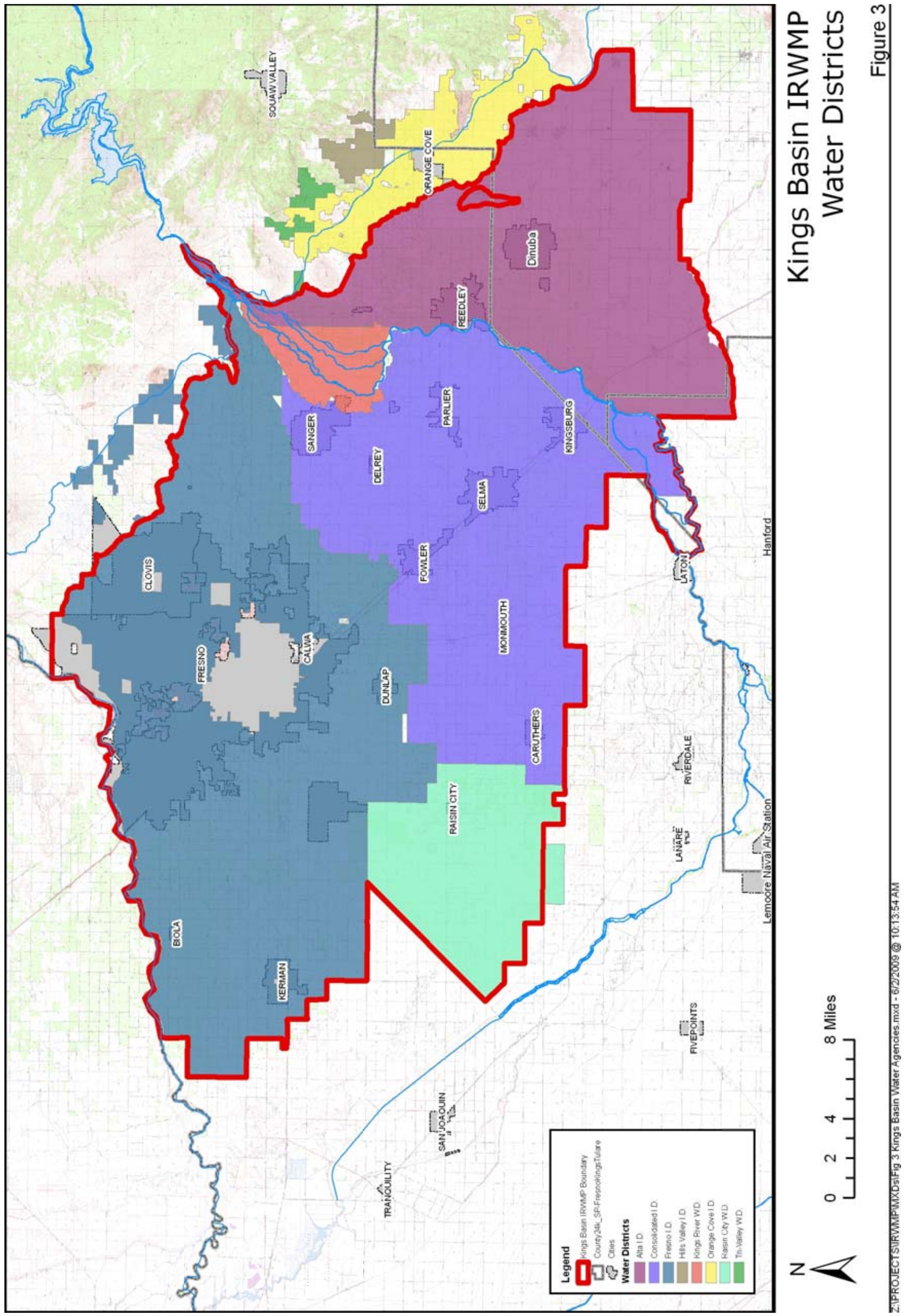

Kings Groundwater Basin
Figure 2
N
0 2.5 5 10 Miles
Woodlake
Exeter
Lindsay
Farmersville
Visalia
Tulare
Dinuba
Reedley
Sanger
Parlier
Kingsburg
Selma
Fowler
Clovis
Fresno
Hanford
Lemoore
Santa Rosa Rancheria
Lemoore Naval Air Station
Kerman
Mendota

Figure 2.


Kings Basin IRWMP
Water Districts
Figure 3
Legend
Kings Basin IRWMP Boundary
Cities
Water Districts
Alta I.D.
Consolidated I.D.
Fresno I.D.
Hills Valley I.D.
Kings River W.D.
Orange Cove I.D.
Raisin City W.D.
Tri-Valley W.D.
0 2 4 8 Miles
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SQUAW VALLEY
ORANGE COVE
Dinuba
REEDLEY
PARLIER
SANGER
DELREY
KINGSBURG
SELMA
FOWLER
CLOVIS
FRESNO
CALWA
DUNLAP
MONMOUTH
CARUTHERS
RAISIN CITY
RIVERDALE
LANARE
LATON
Hanford
Lemoore Naval Air Station
BIOLA
KERMAN
FIVEPOINTS
SAN JOAQUIN
TRANQUILITY

Figure 3.

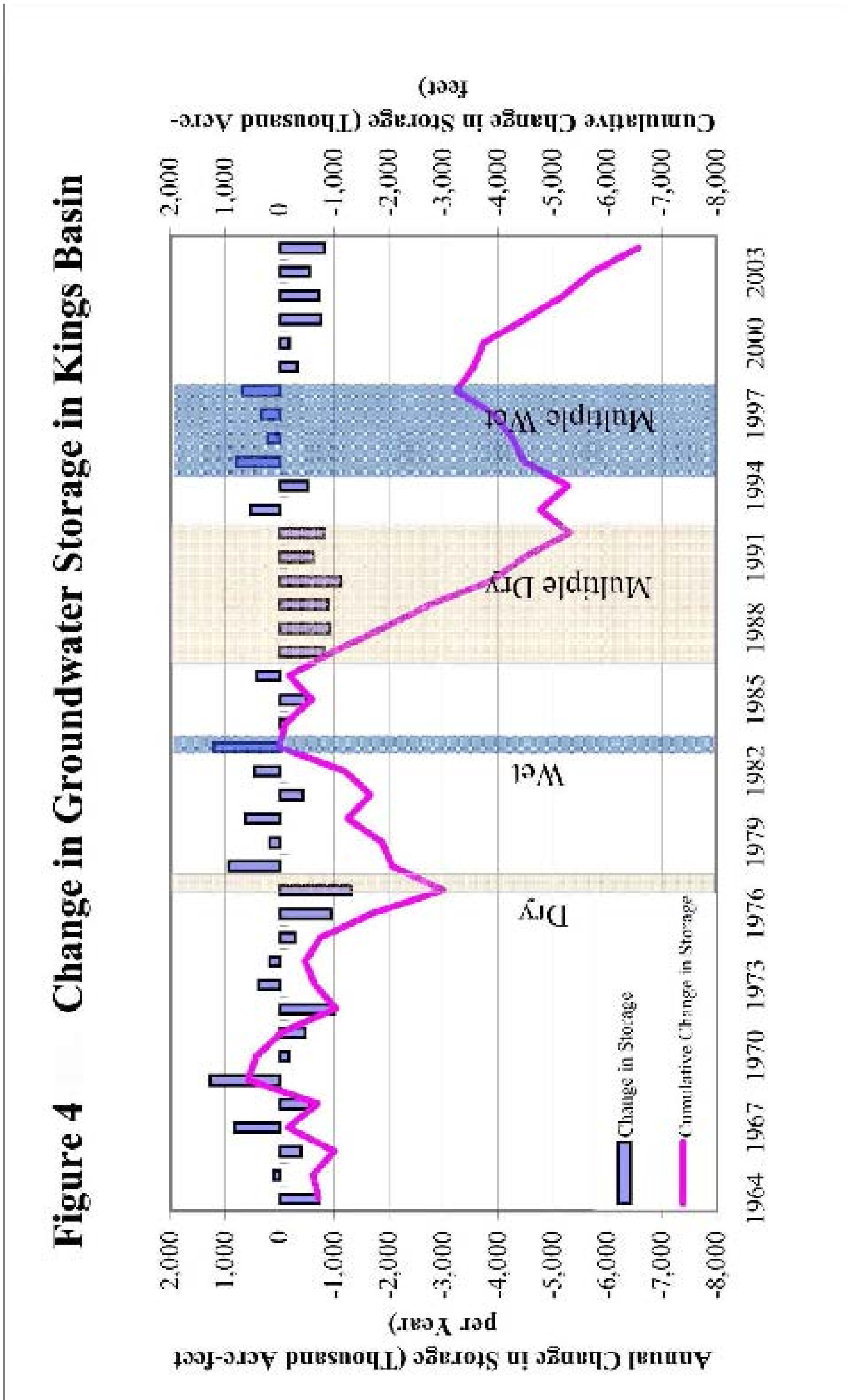

Figure 4. Changes in Groundwater Storage in the Kings Groundwater Basin

THE INTEGRATED REGIONAL WATER MANAGEMENT PROCESS

In 2002 California voters approved Proposition 50, a $4.6 billion (USD) bond measure, which encouraged the development of Integrated Regional Water Management Plans (Macaulay, 2007). Guidelines for the development and implementation of an IRWMP are delineated in California Water Code Section 10530 and Section 79560 (California, 2002a & 2002b). An IRWMP must “include a public process that provides outreach and an opportunity to participate in the plan development and implementation to appropriate local agencies and stakeholders” (California, 2002a). Figure 5 illustrates the water management strategies and elements required under the guidelines and requirements (WRIME, 2007b).

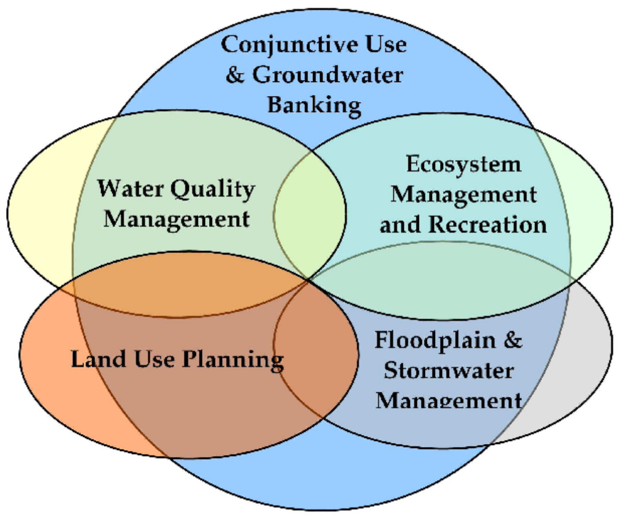

Figure 5. Upper Kings Basin IRWMP Project Categories and Integration Strategy

In 2004 the BAP transitioned into what is now called the Upper Kings Basin Water Forum (Water Forum). As part of the transition, all of the water entities, cities, communities, counties, and other interested parties (governmental and non-governmental parties) in the Basin were invited to participate. Some of the water entities in the western portion of the Basin declined to participate at that time. The group then formed into the Water Forum covering the upper portion of the Basin. It was clear to the participants that continued overdraft was not sustainable and an IRWMP was needed to address the problem.

DEVELOPMENT OF THE GROUNDWATER AND SURFACE WATER MODEL

The Water Forum with assistance from DWR began the process to develop an IRWMP. In order develop an IRWMP it was important to understand current groundwater conditions, historical conditions, and projected future conditions. A consultant was engaged to develop the Kings Basin Integrated Groundwater and Surface water Model (IGSM) to support the IRWMP planning analysis (WRIME, 2002, 2003, and 2007a). Figure 4 represent one of the outputs from the model. The model was developed to analyze the entire Basin as well as the IRWMP area (Figures 2 & 6). The Water Forum applied for and was awarded a $500,000 grant from DWR to develop the IGSM (KRCD, 2007).

UPPER KINGS BASIN INTEGRATED REGIONAL WATER MANAGEMENT PLAN

Prior to the development of the IRWMP, the Water Forum adopted the following vision statement: “The vision of the Upper Kings Basin Water Forum is a sustainable supply of the Kings River Basin’s finite surface water and groundwater resources through regional planning that is balanced and beneficial for environmental stewardship, overall quality of life, a sustainable economy, and adequate resources for future generations.” (WRIME, 2007b)

The Water Forum received another $500,000 grant from DWR to assist with the preparation of the IRWMP (KRCD, 2007) and the local stakeholders added another $375,000. The Upper Kings Basin Integrated Regional Water Management Plan was completed in June 2007 and approved and adopted in July 2007 by Kings River Conservation District representing the Water Forum (WRIME, 2007b).

The IRWMP defines problems and issues; regional objectives and goals; strategies for water management; and management actions and proposed projects to enhance the beneficial uses of water in the Basin. The IRWMP documents the overdraft and the Kings Basin water budget, including historical and potential future overdraft conditions, along with projects and programs to manage and develop the surface and groundwater supplies in a sustainable manner. Priorities for immediate, near-term, mid-term, and long-term investments in engineering solutions, programs, and institutional approaches are also documented.

The regional integration will not diminish the individual water management entity’s decision-making power or a local government’s power to exercise its rights. It enhances the collective power of the local entities and their abilities to manage local water resources. Participating entities will be able to address water management issues on a much larger scale through the integrated planning framework.

SUCCESSFUL RESULTS

In the fall of 2007, the Water Forum submitted the IRWMP to the DWR to determine if the IRWMP met the standards in the California Water Code Section 10530. It was determined that the IRWMP did meet the standards; therefore, the Water Forum was allowed to submit a grant proposal under Proposition 50. In late January of 2008, a grant application was submitted for 2 recharge/water banking projects. The Water Forum was awarded a grant in the amount of $6,063,375 to construct the projects: Alta Irrigation District’s Traver Pond Project covering 47 acres, $2,863,682 grant and Fresno Irrigation District’s Apex Ranch Project covering 220 acres, $4,000,000 grant plus $6,607,030 of local funds. The water supply benefits for these two projects under the IRWMP are estimated to be 16,000 acre-feet per year.

FUTURE DIRECTION

Kings River Conservation District has directly represented the Water Forum and has underwritten operational costs. Possible future governmental structure of the Water Forum was discussed in the IRWMP (WRIME, 2007b). It was determined by the participants that a Joint Powers Authority should be formed under California law to operate and manage Water Forum activities. The Joint Powers Agreement for the Upper Kings Basin IRWM Authority has been approved and is currently being adopted by the public agency participants. Provisions have been made in the Agreement for the involvement of the other stakeholders as Interested Parties to assure their involvement. The Interested Parties will serve on the Advisory Committee along with Authority Board Members.

The State of California is in the process of making grant funds available for IRWMP projects under Proposition 84 approved by the California voters in 2006. The first step in the process is labeled as the "Regional Acceptance Process" (RAP). KRCD has submitted a RAP application for the Water Forum (KRCD, 2009). The IRWMP and the Water Forum will be reviewed by DWR to determine if they truly represent a regional area as defined in the Water Code. Those RAP applications that are approved will be eligible to submit a grant application under Proposition 84. It is fully expected that the Water Forum RAP will be approved, qualifying the Water Forum to apply for additional grants for projects.

The western portion of the Basin is identified on Figure 6. The water entities in this area have now come to realize that they need to be involved in the process. Most of them have already joined the Water Forum as Interested Parties. The IRWMP will be revised within the next 2 years to include this area into the Joint Power Authority. The IGSM already covers this area so no modification of the model will be required.

CONCLUSIONS

Since its formation, the Upper Kings Basin Water Forum has met more than 27 times, sometimes with up to 50 people in attendance. It has been a very effective process with all of the stakeholders acting cooperatively and actively involved. The process has resulted in a work product that all of the parties have agreed to and will assist in the management of surface water and groundwater to work towards sustainability for the Basin. Integrated Regional Water Management Plans can be effective and beneficial in coordinating water resource management involving many stakeholders.

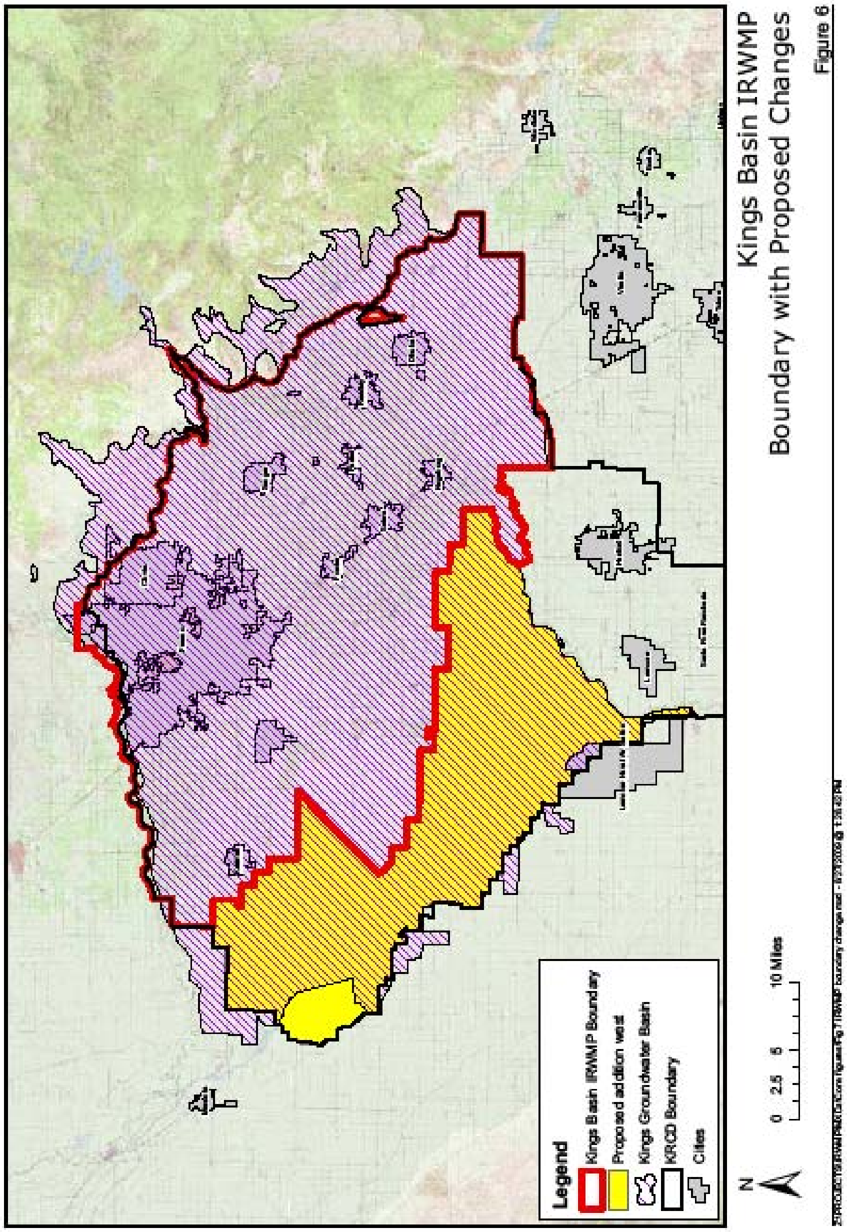
Kings Basin IRWMP
Boundary with Proposed Changes
Figure 6
Legend
Kings Basin IRWMP Boundary
Proposed addition west
Kings Groundwater Basin
KRCD Boundary
Cities
N
0 2.5 5 10 Miles

Figure 6.

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OPTIMIZING INTEGRATED WATER ALLOCATION TO PRIORITIZED WATER USERS

Richard C. Peralta, PhD, P.E.[1]

ABSTRACT

The Kingdom of Jordan will be unable to satisfy projected water need without dramatic management changes. Agriculture consumes most water. A national policy goal is for municipalities to have first use of water, although currently that is not always the case. Subsequent priorities for clean water use are to industry, tourism, and then agriculture. Available resources include treated wastewater (only for agriculture), renewable and fossil groundwater, surface water, desalinized ocean or brackish water, and hoped-for ‘peace treaty’ water.

A new mathematical computer optimization model (OM) develops water distribution strategies that minimize unsatisfied water need of each user type per allocation priority, or using weights. An optimal strategy specifies how much water (from each Source Center), should go to users via the clearly defined national water transfer (TF) system, versus via amorphous Local Distribution (LD) systems.

The OM: provides simultaneous mathematical optimization of all flows during all periods, thru TF and LD systems from Source Centers (SCs) to Demand Centers (DCs), with or without prioritized allocation. OM satisfies inputs limiting: flow capacities and directions; water takings from SCs, water Resource Types and governorates; and water delivered to DCs. It allows multiple periods of arbitrary duration for an entire system or sub-systems.

OM use has significant advantages over manually iterative strategy development. It can minimize unsatisfied national need based upon weights assigned to each DC. It can minimize unsatisfied demand of each user type sequentially per national priority policy. It is applicable or readily adaptable to a wide range of water-resource settings.

BACKGROUND

The Hashemite Kingdom of Jordan is among the five most arid countries in the world. Water scarcity is the most serious environmental challenge Jordan faces today. Per capita, Jordan is one of the poorest nations in the world in terms of water resources. Jordan shares surface water resources with adjacent countries, who exercise more control over the water than Jordan can.

At current per capita consumption rates, existing and projected populations require more utilizable water than is sustainably available. Mining renewable and nonrenewable aquifers is widespread. The Government of Jordan (GOJ) intends to address the situation

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by improving management and using additional resources (MWI/NWMPD and GTZ, 2004).

GOJ National Water Master Plan (NWMP) software includes an MS Office ACCESS data base, hydrologic simulators, water availability estimators, and water need projectors (MWI and GTZ, 2008). Figure 1 displays data extracted from the NWMP. Figure 1a illustrates GOJ administrative units (governorates), also referred to as balancing units (BUs). The NWMP assembles and aggregates data per BU per five-year time period, for a specified multi-period planning horizon.

Figure 1b shows water Source Centers (SCs). Each SC provides water of a specific Resource Type (ResTy). Considered ResTys are:
- renewable Ground Water (GW),
- Reservoir Safe yield (RS),
- surface water Base Flow (BF),
- Treated Waste-Water (TW),
- Additional resources (AD), including desalinized water, peace-treaty water, non-renewable groundwater, and any other special cases.

According to the NWMP, water is conveyed from SCs to water users only thru either the Local Distribution (LD) system or the more formally defined Transfer (TF) system. Figure 1c shows the TF system, consisting of TF segments and TF nodes (segment ends and junctions).

Conveyed water nomenclature is as follows. An Internal Transfer is water that enters and exits the TF within the same BU. An External Transfer is water that exits the TF in a different BU than the one in which it entered. Water conveyance via amorphous LD system occurs only within a BU that contains both the providing SC and the receiving DC. LD water never enters the TF system.

NWMP software uses the locations of water demands shown in Figure 1d. Each was historically termed a Demand Center (or DC). A single DC could have up to four user types—Municipal (MUN), industrial (IND), touristic (TOU), and agricultural irrigation (IRR). The NWMP historically partitioned the total flow to a DC into pre-specified proportions for the DC's respective user types. Through an input table, the NWMP would/would not allow a DCs different user types to receive water of different Resource Types thru different conveyance systems. That allowance table reflected combined physical and management reasons.

The NWMP includes projected water supply and demand data for multiple future situations. The situations differ in climatic and population assumptions. For each situation, the NWMP identifies the maximum amount of each Resource Type that should be taken per year within each BU. For renewable water resources, the maxima are based upon sustainability. For non-renewable resources, the upper limit is assumed, usually based on policy. The NWMP also contains conveyance system capacity information.

The NWMP software required much iterative manual simulation to develop water transfer strategies. Such a strategy consists of the routing of water from sources (Source Centers, or SCs) through conveyance systems to water users. It was not easy to assure satisfaction of all above maxima and system capacities when developing a strategy.

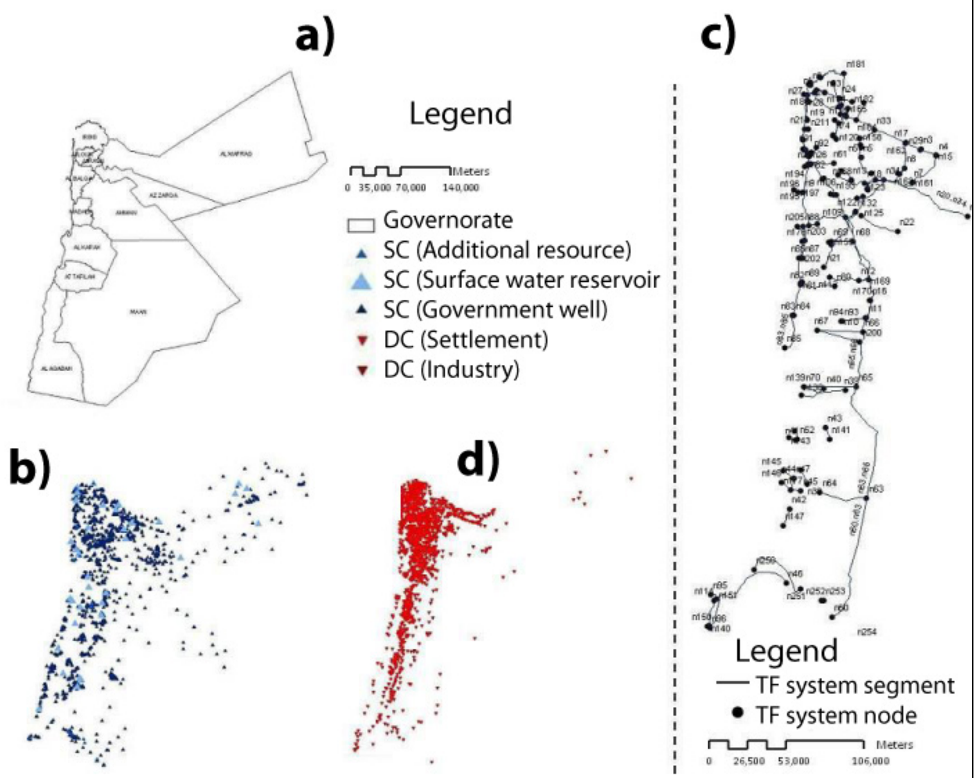

Figure 1. Jordanian: a) Governorates; b) Source Centers (SCs); c) Transfer (TF) system; and d) Demand Centers (DCs). Modified from MWI and GTZ (2008).

OM OVERVIEW

The Optimization Module (OM) presented here is designed to calculate mathematically optimal water management strategies for user-specified situations (Peralta, 2008a,b). Situations differ in climatic, population, infrastructural, and management assumptions and preferences.

The OM implements the following concepts to aid systematic processing and future development.

- Demand Centers and Quad-Demand Centers. Each historic DCs is termed a Quad-DC, to indicate that a Quad-DC can have up to four DCs, one for each of the four considered user types. OM explicitly optimizes water delivery to DCs, rather than to Quad-DCs. Total flow delivered to a Quad-DC is computed and can be constrained, but is not a defined decision variable.
- Water Resource Type and Conveyance Method. A ResTy-Con is a particular combination of water Resource Type and Conveyance Method. For example, LD-GW is renewable groundwater conveyed by Local Distribution. TF-GW is renewable groundwater conveyed by Transfer System.
- Bounds on Flows of Water Resource Types Delivered via Particular Conveyance Method. OM input clearly distinguishes between infra-structurally-related and management-related reasons for restricting flow of a particular ResTy-Con to a particular DC. Restrictions due to both kinds of reasons are input in separate tables.
- General Bounds on Flows Taken, Conveyed, and Delivered. Lower and Upper Bounds are default values or are input for all flows to be optimized by OM. Sample data includes upper limits on how much water can be taken from each SC, and current and projected water need of the different users (DCs) within each Quad-DC.

During a single optimization run, the OM develops optimal strategies in one of the following two ways:
- minimize weighted unsatisfied water need without considering allocation priorities. Input weights on unsatisfied need can differ by Demand Center, causing OM to try to satisfy some water needs more than others.
- minimize un-weighted unsatisfied water need, while performing priority-based allocation. OM will first try to satisfy water needs of the highest priority user, followed by needs of lower priority users, in order.

In all optimization runs, the OM optimally:
- assigns water from SCs to either Local Distribution (LD) or Transfer (TF) system conveyance. Water that cannot be routed all the way to a DC will not be assigned.
- routes all assigned water to DCs. Figure 2 simplistically illustrates water routing.
--Water flows conveyed via TF system are:
▪TFflow1 flows from an SC to a TF system entry point (TFin node).
▪TFflow2 flows from TFin node (or other TF node) thru a TF segment to a receiving TF node.
▪TFflow3 exits TF system via a TFout node, flows toward a DC, and reaches and is used within the DC.

--Water flows conveyed via LD system are:

- ▪LDflow1 departs an SC,
- ▪LDflow2 enters a Source Group (SG), consisting of similar SCs within a Balancing Unit (BU)
- ▪LDflow3 leaves an SG, flows toward a DC, and reaches and is used within the DC.

OM is applicable for any comparable situation. With minimal effort, it is adaptable to more complex situations. Other water Resource Types, SCs, DCs, and BUs, are easily incorporated. OM is applicable to parts of a study area.

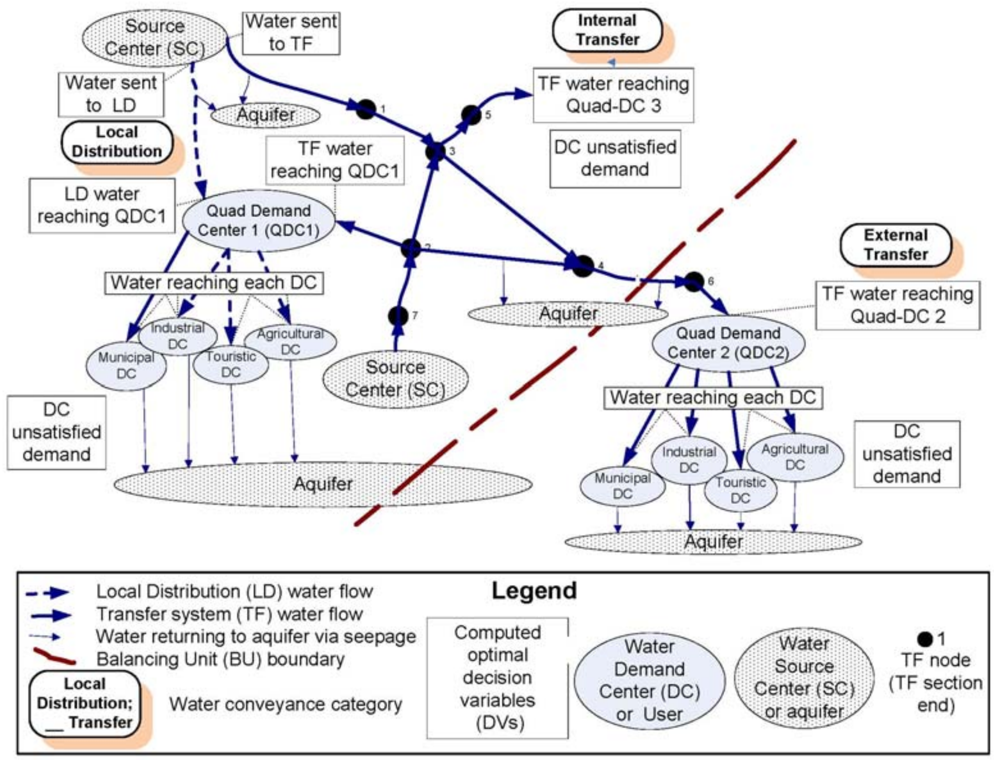

Figure 2. Selected OM optimized flows and decision variables (from Peralta, 2008a).

OM APPLICATION TO QUASI-HYPOTHETICAL JORDANIAN SYSTEM

The_Jordanian Ministry of Water and Irrigation (MWI) provided data for a pseudo-hypothetical study area for developing and testing OM features. Figure 3 shows that DCs, SCs, and conveyed flows of this system (HJ61H), extend almost from the northern to the southern ends of Jordan. A single DC or SC symbol in Figure 3 can represent multiple DCs or SCs, as shown in Figures 4 and 5. Figure 5 illustrates three new DCs (for Municipal, Touristic, and Irrigation users) used in lieu of the historic Quad-DC 0013. DC 0013MUN provides water to the Aqaba Treatment Plant, which provided treated wastewater to DC 0013IRR (Peralta, 2008b).

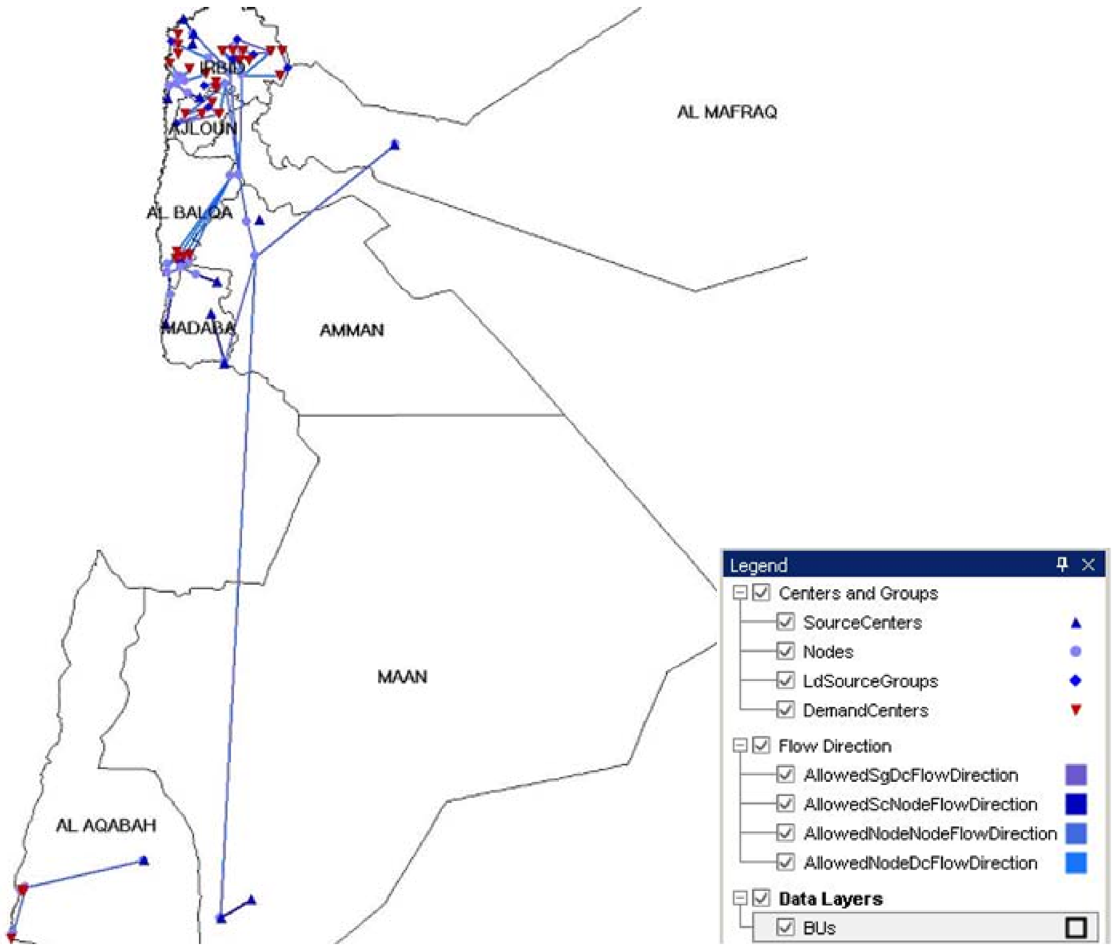

Figure 3. Hypothetical area HJ61H (from Peralta, 2008a)

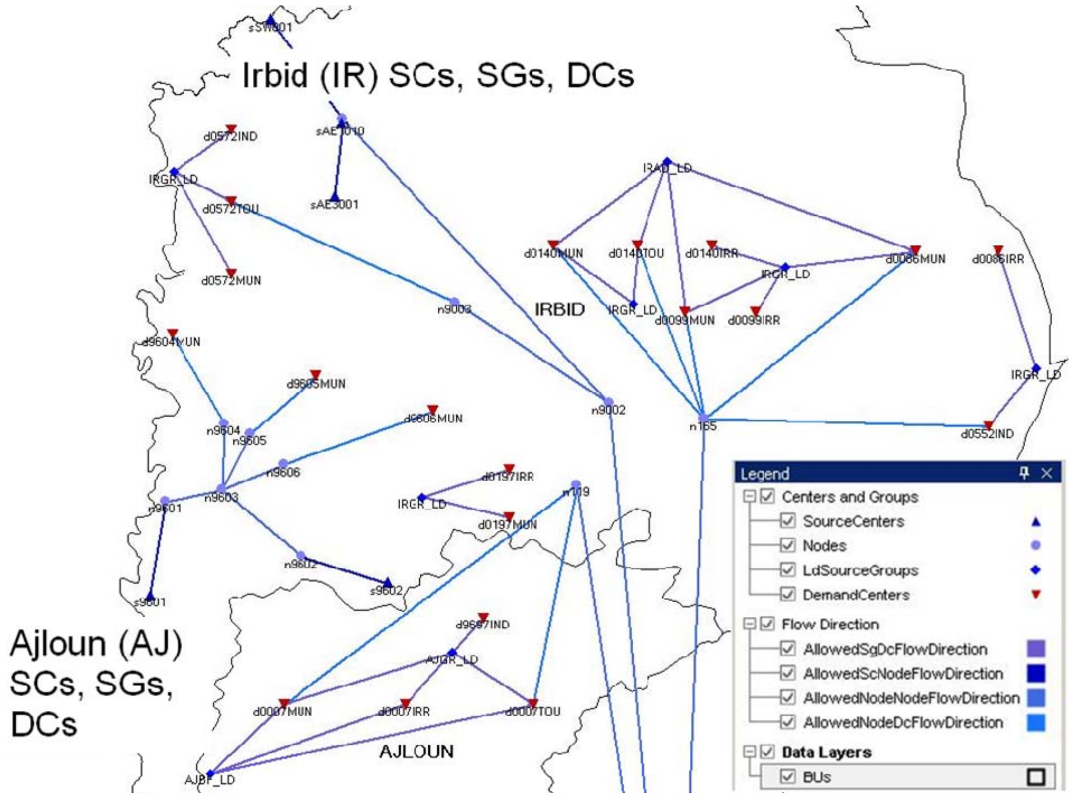

Figure 4. Northern quarter of Hypothetical area HJ61H (from Peralta, 2008a)

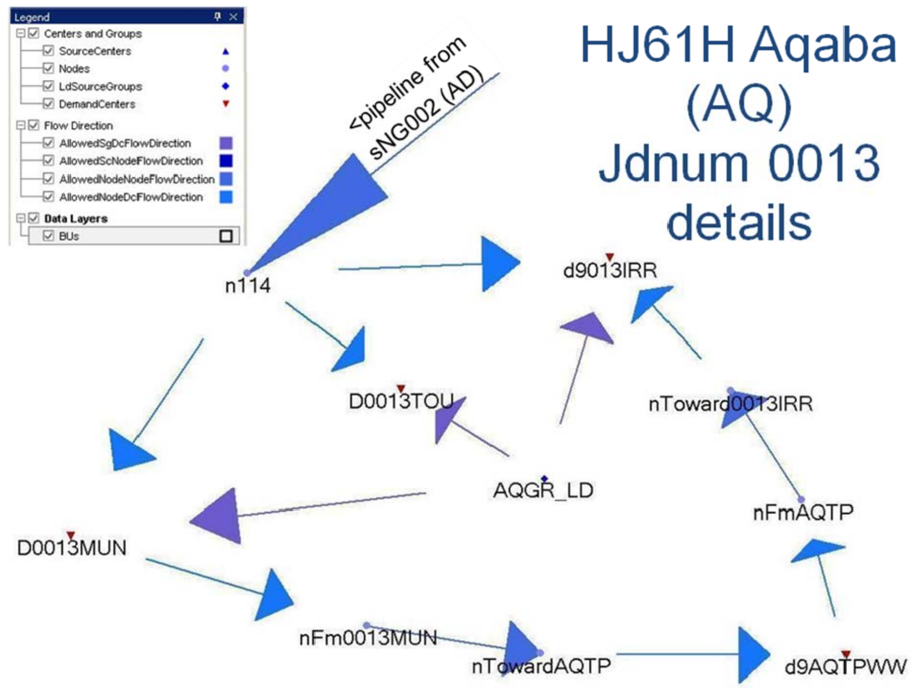

Figure 5. Details of Aqaba Quad-DC 0013 flows within Hypothetical area HJ61H (from Peralta, 2008a)

Per Peralta (2008b), HJ61H addresses 8 governorates (parts), three Resource Types, 21 SCs, and 29 DCs of all four user types. For two periods, OM simultaneously optimizes all flows in thru LD and TF conveyance. For convenience, input water availability, need, and conveyance capacity values are simple, and often multiples of 10.

Table 1 contrasts the results of optimizing using unsatisfied need Weights equaling 1.0 (i.e. without prioritized allocation), versus those from optimizing in order of priority. Both approaches provide the same objective function value of 145.395 units of unsatisfied demand, and both have 50 units of unassigned water because of conveyance capacity limits. However, the prioritized allocation approach has much less unsatisfied MUN need, and less IND need. It has slightly more TOU and much more IRR unsatisfied need.

Table 1. Total units of unsatisfied water need for a two-period optimizations with and without prioritized allocation, [L^3].

User type	Without prioritization	Prioritized allocation
MUN	80.00	20.0
IND	35.394	20.0
TOU	10.00	14.4
IRR	20.00	90.995
Total	145.395	145.395

In the scenario without prioritization, all weights equal 1.0. Thus both scenarios are linear optimization problems. Because the prioritized allocation scenario yields the same objective function value, we see that there are multiple optimal solutions having the same objective function value. That might not always be the case.

Input data changes (such as bounds on ResTyConvey, flow thru a pipeline, or others) could cause the Prioritized Allocation scenario to have more total unsatisfied need than a uniformly unity-weighted Without Prioritization scenario. Using weights different from unity in the Without Prioritization scenario could cause it to have less true unsatisfied need than the Prioritized Allocation scenario.

CONCLUSION

The Optimization Module (OM) computes optimal transient flow strategies to support National Water Master Planning (NWMP) software. OM minimizes total multi-period unsatisfied water need while: (1) employing a weighting coefficient for the unsatisfied need of each demand center (DC) and without prioritizing delivery to specific user types; or, (2) without using weighting coefficients, but prioritizing water deliver to municipal, industrial, touristic, and irrigation users, in order, (i.e. allocation optimization).

OM routes water from water sources to water demands thru either a precisely defined TransFer (TF) system, or a more amorphous (LD) system. The TF system allows water movement within and between model Balancing Units (BUs). The LD only moves water within its BU of origin.

OM:
- computes accurate volume balances;
- Satisfies all input limits on flow capacities and directions;
- Satisfies all input limits on water takings from SCs, Resource Types (ResTys), and Balancing Unit (BU) water resources.
- Satisfies all input limits on water delivered to DCs;
- Allows individual optimization periods of one year, or other duration;
- Allows multiplying objective function unsatisfied demand values by linear coefficients to provide simple economic optimization ability
- Provides shadow prices identifying tight constraints and quantifying expected objective function improvement resulting from relaxing a tight constraint
- Is applicable to all or part of Jordan, if all needed data is input.

The OM is a powerful optimization model that has been vigorously tested for quasi-hypothetical situations representing Jordanian conditions. The OM uses much data already available within the NWMP. To provide additional flow management ability, the OM requires some data currently not within the NWMP.

ACKNOWLEDGEMENTS

I am very grateful for the financial and other support provided by USAID (project officer Ross Hagan) and GTZ (project officer Andreas Lueck), and MWI. I very much appreciate the expression of GoJ needs provided by Suzan Taha of MWI/NWMPD. The detailing of NWMP processing and users instructions provided by Klaus Jacobi (AHT consulting firm), were invaluable. I appreciate the data-related or graphic help provided by Belal al Hanbali of MWI and Bassel Timani of Utah State University.

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IMPROVING THE OPERATIONAL EFFICIENCIES OF 19TH CENTURY IRRIGATION CANALS IN THE 21ST CENTURY — EXAMPLES IN IDAHO

Brian W. Sauer[1]
Lloyd Hicks[2]

ABSTRACT

The Great Feeder Canal is a 26-mile long natural channel developed in the late 1800's by Mormon settlers in Eastern Idaho to deliver Snake River water to 120,000 acres of farm land near the town of Rigby. The Great Feeder, with a capacity of over 5,000 cfs, delivers water to 14 major canals and 26 smaller canals. Several of the canal companies embarked on an effort to rehabilitate and modernize their 100-year old irrigation distribution systems with current technologies. Updates have included the rehabilitating and automating of water control structures, improved water measurement, and the installation of a shared radio telemetry system.

Overall water management in this large tract has been greatly improved. System improvements have resulted in significant conveyance efficiency improvements, reducing losses from spills and seepage and provided more constant and reliable deliveries to farms. Improved conveyance efficiencies have enabled irrigators to extend limited water supplies later into the irrigation season. With more reliable late-season supplies, even during recent drought periods, farmers have been able to reduce the risk of crop loss. This enabled growers to plant a wider variety of crops. The improvements have also helped improve the ability of water users to carry reservoir storage into the next year and provide a measure of future reliability.

The Burgess Canal and Irrigating Company (BCIC), the largest canal supplied by the Feeder, was established in 1886 and provides irrigation water to 22,000 acres of farmland. The Burgess Canal shareholders are finishing a 10-year program to improve system operations through improved water control and measurement. Major control structures are being rehabilitated and automated using durable, low-cost components and radio telemetry. Ramp flumes and other measurement devices were installed at the head of the main canal and other laterals. Steel trash diverters have been installed to protect automated gates from accumulation of debris and pass it though the distribution system.

The initial success of the BCIC prompted 10 other canal companies on the Great Feeder to start similar enhancements of their older systems. Currently there are approximately 40 automated control sites along the Feeder. BCIC and other canals have pooled resources to construct a network of 11 spread spectrum radio towers to connect most of the automated structures.

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BACKGROUND

History

Few European settlers inhabited the lands along the Snake River in what is now Eastern Idaho until the late 1860's when the U.S. military defeated the Shoshone and Bannock Indians and forced them onto reservations through the Fort Bridger Treaty in 1868. Beginning in 1871, the Utah and Northern Railroad was built north from the Union Pacific transcontinental line from Utah through the Idaho to connect the Salt Lake Valley with the copper mines near Butte in the Montana Territory. Settlers began homesteading in the Upper Snake River Valley as soon at the railroad came. Most of the new settlers were from Utah, encouraged by the Mormon Church to homestead in the region and large scale settlement ensued. By 1890, the Mormon settlers had built roads, bridges, dams, and irrigation canals that turned tens of thousands of acres of desert the Upper Snake River Valley into productive agricultural lands. Farms in the region grew sugar beets, potatoes, peas, grains and alfalfa.

Settlers in an area northeast of Idaho Falls, the largest city in the area, tapped into a side channel of the Snake River, known as the Dry Bed. This channel flows westward, through a broad alluvial plain know as the Rigby Fan, parallel to the south bank of the river for approximately 30 miles. Numerous distribution canals were constructed from the Dry Bed to new farms in the area, eventually supplying water to 120,000 acres. During the summer of 1894, low flows in the Snake caused the Dry Bed to run dry. In January, 1895, the Dry Bed canal companies pooled their resources to form the Great Feeder Canal Company to construct a large canal half a mile upstream to divert water from the river into the Dry Bed and improve the original Dry Bed channel. The canal, know as the Great Feeder Canal was opened with a gala celebration in June, 1895[3].

The finished headgates, 116 ft in total length, with a capacity of 5,000 cfs, were touted as the largest in the world. The company replaced the headgates in 1906 and again in 1915. The headgates were renovated in 1967 and are still in use today. Periodic work to the gates and the concrete structure maintain the integrity of the Great Feeder headworks. Small temporary dams, at first made of pole cribs and later replaced by cement overflows, have been built and rebuilt to direct the flow of the river into the head of the Great Feeder at various times.

With the construction of dams on the Snake River at Jackson Lake, Wyoming, in 1911 and American Falls and Palisades in Idaho in 1927 and 1957, respectively, many of the Great Feeder companies signed contracts with the U.S. Bureau of Reclamation for stored water to supplement their natural river flows. There are currently 40 irrigation diversions from the Great Feeder, with capacities ranging from less than 1 cfs to over 1,100 cfs.

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[3] Bonneville County Historical Society, "Idaho Falls, City of Destiny," 1991, Fritzen, Mary Jane, editor.

Canal Systems

Most of the distribution canal systems share a similar history with the Great Feeder. Originally, most of the water control structures were constructed from wood. As structures deteriorated over the years, wooden structures were gradually replaced with concrete and steel, although many still use wooden check boards to regulate canal levels at bifurcations and deliveries. Each canal has its own board of directors and a water master who manage and operate the facilities. The directors determine the canal's maintenance needs and set the assessments to charge users for these needs. None of the companies have their own maintenance crew so they contract out maintenance work to local contractors. Generally, the water master is only hired for the irrigation season which runs from May through October.

The water master's job is to operate the canal to assure that all of the canal's patrons receive their share of the water. The water master's responsibilities include taking daily water orders from his irrigators and placing a water order with the Great Feeder water master 24 hours in advance. He also adjusts control structures in his own canal to assure that individual irrigators on his canal receive the water they order.

Daily water orders from each canal's water master are sent to Water District 01 who compiles these orders and, in turn, places orders with the Bureau of Reclamation for releases from the several storage reservoirs in the Upper Snake River Basin. The Water District is the entity sanctioned by the Idaho Department of Water Resources to oversee water distribution within the Upper Snake Basin. The District encompasses over 1 million irrigated acres and more than 120 measured diversions. District 01 is headed by a watermaster who is considered a state employee but is elected and compensated directly by district water users. Proper water distribution under Idaho's prior appropriation system is the primary goal and responsibility of the District. Daily monitoring of natural stream flows, reservoir storage, and irrigation diversions are the primary duties of the watermaster and staff. All of these elements must be taken into account to assure proper water use accounting under the complex system of priority dates and decreed water rights for natural flow and reservoir storage.

Canal System Challenges

Canal companies along the Great Feeder face several operational challenges. By virtue of the Feeder's location just 30 miles downstream of Palisades Dam, flows in the Snake River at the Great Feeder headworks can vary substantially with changes in water releases. These flow adjustments at the dam and diversion changes at any of several large canals upstream of the Feeder can cause significant fluctuation in the river level and subsequent changes in the rate of diversion into the Feeder. Additionally, flow changes at any of the larger diversions along the 30-mile Great Feeder can impact downstream diversions.

The headgates on the Great Feeder are also subject to large accumulations of woody debris, particularly when the Snake River flows run high. These accumulations can partially block portions of the headworks and impact diversions. High flows, often greater than 20,000 cfs, occur during flood control releases from Palisades Dam and generally occur during the irrigation season in May and June. During high flow periods, Feeder operators occasionally station an excavator at the headworks to remove debris. High conveyance losses are another challenge faced by most Great Feeder canals. Because most of the area served by the Feeder is made of alluvial material, seepage losses are high. Some high-value crops, such as corn and potatoes are difficult to grow in this area because of the porous, rocky soils. Due to high conveyance losses, large flows are necessary at the head of the canal systems to assure adequate flow at the end. Historic annual diversions of many canals in the area are as high as 12 acre-ft per acre, with less than half of the diverted water reaching the farms. Seepage accounts for 30-40% of the conveyance losses. Seepage from area canals supports local shallow aquifers as well as the 10,800 square-mile Eastern Snake Plain aquifer that covers much of south-east Idaho.

Due to age of the canals, severe winter weather, and partially due to the local farm economy, many canal structures in the area have deteriorated and are in need of rehabilitation. This problem has been exacerbated by recent low commodity prices and a number of drought years, starting in the early 1990’s. It is difficult to adequately manage canal flows with the existing aging infrastructure. Additionally, few of the canals were constructed with accurate water measurement. The original measurement stations tend to “shift” or lose accuracy as vegetation increases in and along canals as the irrigation season progresses. The lack of accurate water measurement limits how precisely canal operators can regulate their distribution systems.

The Burgess Canal is the largest canal diverting from the Great Feeder, with a capacity of 1100 cfs at its head. The 22-mile long Burgess distributes water to 22,000 acres of farmland through a system of 15 large lateral canals and 12 smaller laterals. Because of the Burgess Canal’s large capacity and its location near the upper end of the Feeder, diversions from the Feeder were difficult to regulate. The Burgess typically took the brunt of planned or unplanned flow changes on the Feeder. Additionally, the Burgess headgates, located on an outside bend of the Feeder were subject to accumulations of debris which would partially block one or more of the 4 radial gates.

CANAL SYSTEM IMPROVEMENTS

In 2000, the board of the Burgess Canal & Irrigating Company (BCIC) started what became a 9-year program to improve the operations of the company’s distribution system by improving water control and measurement. The board hoped to address problems with variable canal flows, water shortages at the tail end of the system, and aging control structures. This process began at the head of the canal and worked downstream.

Prior to the 2001 irrigation season, the BCIC made significant concrete repairs and upgrades to the existing headgate structure, originally constructed in 1929. The four radial control gates at the structure were replaced by new steel slide gates. Two of the new gates were operated by AC-powered actuators, the other two with manual operators.

To help eliminate the problem with accumulation of floating debris on the upstream side of the gates, BCIC installed a 48-ft trash diverter across the entrance of the headworks structure.

The trash diverter has a reinforced steel plate that extends approximately 2 ft down from the upstream water surface. The diverter is angled slightly toward the center of the Feeder to deflect debris away from the Burgess headworks. This serves to reduce debris accumulation and to protect the automated gates from being damaged. The Great Feeder Canal carries water most of the year, so much of the construction was planned for the 2-week period when the Feeder is shut off for maintenance every March.

During the 2001 season, a Sutron 8200 programmable logic controller (PLC) was connected to the 240VAC Limitorque motorized actuators. The PLC was programmed to automatically adjust the gates to maintain a preset water level at the rated measurement section in the canal just downstream of the headgates. After some initial calibration problems, the automated gates did an excellent job of maintaining the desired diversion rates and the trash diverter kept most of the debris away from the headgates. Unfortunately, 2001 was an extremely dry year and the Burgess Canal irrigators used up their entire allotment of reservoir storage by September 8 and were forced to end the irrigation season.

Following the 2001 irrigation season, the Island Irrigation Company, with technical assistance from the Bureau of Reclamation, automated one of three existing gates on the Company's diversion structure downstream from the Burgess Canal on the Feeder. This project utilized a12-volt solar-powered gear motor and a Campbell Scientific CR10 data logger for a gate controller. The system was designed to adjust diversions to compensate for water level fluctuations in the Feeder as well as flow changes in the smaller Dilts Canal that splits from the Island Canal just below the headgate structure. This structure was operated without telemetry during the 2002 irrigation season. A laptop PC was used to make adjustments on-site. Prior to the 2003 season, the irrigation company added analog cell phone communications to incorporate remote operations and monitoring.

Diversions into the Burgess Canal were automatically regulated throughout the 2003 irrigation season. Diversions were maintained within 5 cfs or less of the desired level, despite normal fluctuations of flows in the Great Feeder. Prior to automating the gates, flows at the head of the Burgess Canal could vary as much as +/- 40-50 cfs with Feeder flow variations. While this improved the Burgess operations, this also caused greater water level fluctuations in canals diverting from the Great Feeder Canal downstream of the Burgess. By virtue of its large size and position near the head of the Great Feeder, the Burgess Canal dampened many of the impacts of flow changes in the Feeder for downstream diverters. With continuously regulated Burgess diversions, downstream diverters experienced greater impacts.

In 2003, the Burgess Canal began automation water control sites further down the canal system. The first canal site automated was the Midway structure, where four delivery canals, ranging from 20 to 160 cfs capacity, bifurcate from the main Burgess Canal, located approximately 16 miles from the head of the canal. The original concrete structure included manually operated wooden slide gates to regulate flows into each of the distribution canals. Water levels upstream of the structure were regulated with wooden check boards and a 15-ft steel slide gate. Because of the relatively shallow canal depths at the site, small water level fluctuations upstream of the check tended to cause significant fluctuations in delivery canal flows. As with the Burgess headworks, the Midway structure tended to accumulate woody debris, impacting canal operations.

The Midway structure was rehabilitated prior to the 2003 irrigation season. Damaged concrete piers were repaired and wooden slide gates were replaced with new steel slide gates. A steel overshot gate replaced the wooden stoplogs in the main check. All of the gates were motorized using 12V DC actuators made by the C.I. Automation Company. These actuators, which include integral limit switches and position indicators, are similar to devices originally used to move early satellite dishes and slide outs in recreational vehicles. The structure is controlled by a Campbell Scientific CR10X data logger. Pressure transducers measure water levels upstream of the structure. This water level data and data from position sensors on the delivery canal headgates are used in an orifice formula to estimate flows below the gates.

The Burgess Canal Company has continued to rehabilitate and automate all of the major control structures along the canal and is planning on completing the project in early 2010. When completed, the BCC will have automated 31 gates at 17 sites on their distribution system. Beginning in 2004**,** the BCIC began the installing spread-spectrum radio (SSR) communications at all of their automated structures, enabling the company's water master to monitor the sites and make any adjustments remotely. The radio link also provides the operator with instant notification of any unusual circumstances at any of the sites. Additionally, the BCC constructed a broad-crested weir or ramp flume at the head of the main canal to obtain more accurate water accounting.

Other canal companies along the Great Feeder have also upgraded their distribution systems in the past 10 years by automating control gates, installing telemetry and building new ramp flumes. Much of this work has utilized financial assistance from the Bureau of Reclamation's Water Conservation Field Services Program. The recipients of the federal assistance matched at least 50% of the total project costs with their own cash and in-kind services. Table 1 lists the entity and their related projects.

Table 1. Summary of Irrigation System Improvements Along the Great Feeder From 2000-2009

Entity	**Acreage served**	**System improvements**
Burgess Canal & Irrigation Company	22,000 ac	17 automated control sites, ramp flume, radio telemetry, debris diverter at canal headworks
Harrison Canal Company	13,000 ac	Automated canal headworks with diverter, radio telemetry, ramp flume
Island Canal Company & Dilts Irrigation Company	4,400 ac	Automated headworks, debris diverter telemetry, ramp flume
Lowder Slough Canal Co.	1,200 ac	Automated canal headworks, ramp flume
Parks & Lewisville Irrigation Company	11,500 ac	Automated canal headworks with diverter, ramp flume
North Rigby Canal Company	1,200 ac	Automated canal headworks with diverter, ramp flume
Clark & Edwards Canal Co.	1,700 ac	Automated canal headworks with diverter
Labelle Irrigation Company	2,900 ac	Ramp flume
Long Island Irrigation Co. & West Labelle Irrigation Co.	12,000 ac	Automated canal headworks with diverter
Great Feeder Canal Company	81,000 ac	Two automated diversion gates, telephone/radio telemetry, floating debris diverter on Snake River

As indicated in the table above, many of the canal companies have improved their water measurement capabilities by constructing ramp flumes, in most cases at the head of their canals. Most of the flumes were designed by Water District 01 staff as part of the District's efforts to improve water use accounting. Flow information from most of these flumes is transmitted to the District via satellite through the Bureau of Reclamation's Pacific Northwest Hydromet system.

Initially, many automated sites used telephone telemetry, either via land lines or analog cell phone. As the Burgess Canal expanded their automated system, they moved to spread-spectrum radio communications. Due to the local terrain and many trees, several 20-30 ft towers were needed to provide adequate radio coverage. As analog cell service was eliminated, other companies converted their communications to SSR as well. Since all of the canal companies in the area were using Campbell Scientific controllers and radio equipment, other companies' sites could be used as repeaters to relay radio transmissions. To date there are 21 SSR sites along the length of the Great Feeder.

BENEFITS OF SYSTEM IMPROVEMENTS

All of the Great Feeder irrigation companies have benefited from their recent system improvements, individually and collectively. Automated gates have given the canal operators the tools to better control their distribution systems. Eight of the major canals that divert from the Feeder have automated their headworks, eliminating much of the problems associated with flow variations in the Feeder. This alone has provided much more stable farm deliveries to their irrigators. Since 2006, when two of the Feeder's eight gates were automated, diversions into the Great Feeder have been much steadier as well, reducing the impacts of fluctuating flows in the Snake River below Palisades Dam. Benefits have included:

Reduced Diversions: Better water control has significantly reduced the conveyance losses in the individual distribution systems. Traditionally, the canal companies diverted extra water into their canals to avoid delivery shortages at the end of the system. Regulated diversions have eliminated the need for most of this extra water, much of which spilled into drains and wasteways. More efficient water distribution has helped to improve the available water supply. By lowering diversion rates early in the season, more reservoir storage is available for use later in the season. In drought years, many canals in the area ran out of water in August.

Prior to the system rehabilitation, operators estimate that daily operational spills from various points within the Burgess Canal distribution system totaled 25,000-30,000 acre-ft of water over the course of the irrigation season. This can be attributed to diverting as much as 100 cfs more than was actually delivered to farms. This extra water was diverted to assure adequate deliveries and to help compensate for the inevitable flow fluctuations caused to the lack of adequate water control at the head of the canal and within the distribution system. Currently, spills from the Burgess system have been reduced to minimal amounts while still providing adequate farm deliveries. This has enabled the company to utilize much of the "saved" water late in the irrigation season to extend the irrigation period and to assure full, late-season deliveries.

Other canals along the Great Feeder have been able to reduce operational losses through improved measurement and control of their distribution systems. While improvements on other canals have not been as extensive as on the Burgess, all have improved the efficiency of their operations and experienced similar benefits. Operational spills have been reduced, diversions into the distribution systems are accurately regulated, and irrigators receive more uniform deliveries at their headgates.

Improved Water Supply: Additionally, unused reservoir storage can be carried over into the following year, increasing the next year's water supply reliability. Unused reservoir storage can also be leased to others water users in the basin through the Water District 01 water bank. This allows the water to be leased to other irrigators, but for other uses including hydropower generation and augmenting Snake and Columbia River flows for downstream migration of endangered runs of salmon and steelhead smolts. Revenues from water bank leases can also provide a cash stream for lessors to help fund additional distribution system improvements.

Improved Facility Operations: The trash diverters installed at many of the sites have done an excellent job of preventing accumulations of debris at control structures. This has not only eliminated debris-caused flow restrictions, but has also protected the automated gates from damage. Additionally, telemetry at the structures can notify operators of unusual conditions, such as high water levels or non-functioning gates as soon as the problem occurs.

The automated gates have also reduced the time and travel required to operate the canal systems. In the past, canal operators made several trips a day to the headworks to make manual adjustments and then follow the flow change down the system, making adjustments at downstream control structures. With automated gates, the flows are regulated around the clock and can be kept much more constant. With telemetry, operators can check canal conditions at the site and make adjustments remotely.

The Burgess Canal Experience

The Burgess Canal & Irrigating Company began to see efficiency improvements in 2001, the first year of the company's multi-year improvement program. The trash diverter kept most of the large woody debris away from the canal headgates all season. In past years, it occasionally was necessary to bring in a hydraulic excavator to clear large debris from the canal headgates. One of the two motorized headgates was automated mid-season and was able to greatly reduce the swings in canal flows caused by flow changes in the Feeder. Prior to automation, the BCIC estimates that spills from these Feeder fluctuations resulted in cumulative losses of 6000 to 8000 acre-ft over a typical irrigation season,

As the BCIC began automating other control structures in the distribution system, the company's water master was able to better regulate flows in the main canal and in smaller distribution laterals. The system was able to automatically respond to flow variations caused by daily irrigation demand changes. Flows could be more closely matched with on-farm demands, virtually eliminating the long-standing practice of supplying (and spilling) extra water to avoid shortages at delivery points. The Company estimates that this added water resulted in nearly 100 cfs being lost to spills and additional seepage, or 25,000 to 30,000 acre-ft per year.

The Burgess water users have received other benefits from the system improvements that are more difficult to quantify, but are nonetheless important. The construction of the ramp flume at the head of the canal significantly improved the accuracy of the Burgess diversion measurement, yielding more accurate water accounting and better regulation of the diversion by the automated gates. Reducing flow fluctuations in the canal system has reduced erosion in the canal banks. The telemetry system enables the canal operators to monitor and adjust control structures remotely, saving time, fuel and mileage. The remote monitoring and control capabilities, coupled with better handling of floating debris, enabled the company to reduce its Watermaster position to part-time in 2009.

The cumulative effect of all of the BCIC's efficiency improvement efforts has been to improve the water supply reliability for the company's irrigators. This could be best illustrated during the 5-year drought period from 2001-2005. During these years, the company was able to stretch reduced water supplies through the whole growing season. This is unlike earlier drought years when the company ran out of water as early as July.

For the past four years, water supplies have been better and the BCIC has not used its full allotment of reservoir storage. This has enabled the company to carry this water into the next year. This not only improves the reliability of supplies for Burgess shareholders, but also enables the company to lease water, through the Water District 01 water bank, to other canal companies for irrigation or to utilities and government agencies for hydropower and environmental purposes. Improved water supply reliability has also increased cropping options for irrigators, enabling them to consider longer season crops, such as potatoes and corn, with less risk of water shortages.

While none of the other canal companies on the Great Feeder have rehabilitated and enhanced their distribution systems from top to bottom like the Burgess, all of the companies have experienced the same types of benefits from improved water measurement, improved water control, automation and telemetry. Additional work is still underway by several companies. With multiple canal companies involved with similar and related projects, another unintended benefit has been increased cooperation and interaction between the various irrigation entities along the Feeder.

SUMMARY

The Great Feeder Canal and the smaller irrigation canal systems that it serves were developed in the late 1800's in Eastern Idaho near the town of Rigby. The Great Feeder, with a capacity of over 5000 cfs, delivers water to 14 major canals and 26 smaller canals. Due to age of the canals, severe winter weather, and partially due to the local farm economy, many canal structures in the area deteriorated and were in need of rehabilitation. Canal system operators struggled to deliver water efficiently and meet the needs of their share holders, particularly in drought years.

In the past 9 years, the Burgess Canal and 12 other canals in the area have improved system operations through improved water control and measurement. Major control structures were rehabilitated and automated using durable, low-cost components and radio telemetry. Ramp flumes and other measurement devices were installed at the head of the main canals and other laterals to better manage flows. Steel trash diverters were installed to protect automated gates from accumulation of debris.

These efforts have resulted in improved operational efficiency and better service to their water users. Benefits have included:

1. Increased water use efficiency – Prior to these improvement projects, excessive operational losses reduced available water supplies and frequently caused late-season water shortages and reduced crop yields. These recent improvements have provided system operators with effective tools for managing their distribution systems and reducing losses. Also, accurate measurement helps canal operators better match canal flows with on-farm demand.

2. Improved supply reliability – Improved efficiency has helped to increase available water, effectively extending the length of the irrigation season in poor water years.

Better late-season water supplies have given farmers more crop choices. This has reduced the risk of planting more long-season crops such as potatoes, corn and alfalfa. Additionally, improved efficiency has increase the likelihood of carryover reservoir storage available for use in the next water year.

3. <u>Reduced operational costs</u> – The staff time and travel expenses of distribution system operators have been reduced substantially. Automated control structures have eliminated frequent trips to control structures to make manual adjustments. Telemetry permits operators to see the entire system at a glance, saving travel and spotting potential problems before they become serious.

4. <u>Improved cooperation between local entities</u> – The combined effort of the various independent irrigation entities has had the unplanned benefit of instilling more cooperation within the canal companies along the Great Feeder. Many of the canal companies are now working more closely on water operations and maintenance issues. There is a good deal of communication between the companies as they learn how to best use their new technologies.

DISCLAIMER

The information contained in this report regarding commercial products or firms may not be used for advertising or promotional purposes and is not to be construed as an endorsement of any product or firm by the U.S. Bureau of Reclamation or the Burgess Canal and Irrigating Company .

Figure 1. Headworks of the Great Feeder Canal along the Snake River, near Ririe, Idaho. Two gates at left were automated prior to 2007 irrigation season.

Figure 2. Upstream side of Burgess Canal headworks, July, 2000. Note deteriorated concrete and accumulation of woody debris. Windlass-style hoist operated four radial gates under concrete deck.

Figure 3. Rigby Canal headworks prior to rehabilitation and automation.

Figure 4. Rehabilitated Rigby Canal headworks. Project also included upstream trash diverter and downstream ramp flume.

Figure 5. Two automated gates controlling flow at Burgess Canal Midway structure. Overshot gate at right regulates pool height and passes debris. Slide gate at left regulates main canal flows. Smaller gates at left control flow into delivery laterals.

Figure 6. Steel trash diverter to deflect debris in the Great Feeder away from Clark & Edwards Canal headworks. Debris continues downstream over check structure at right.

Figure 7. Automated overshot gate at last control structure on the Burgess Canal. Spills can be measured as flows pass over gate. Debris is diverted over the gate and can be collected in normally dry wasteway below.

Figure 8. Automated headgate for small delivery lateral on the Burgess Canal. Gate position transducer and water level sensors in both upstream pool and on downstream side of the slide gate permit flow calculations.

Figure 9. Ramp flume at the head of the Burgess Canal. Flow data is used for controlling automated headgates. Fifteen-minute average flow measurements are transmitted via satellite to Water District 01 for water accounting every four hours.

SUSTAINABLE IRRIGATION WATER MANAGEMENT: A CASE STUDY ON SECONDARY CANAL OF SINDH PROVINCE OF PAKISTAN

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ABSTRACT

Sustainable irrigation water management requires a strong relationship among water users. The established Watercourse Associations (WCAs) at the tertiary level canal and Farmer Organization (FO) at the secondary level canal need to develop strong institute. The potential conflicts in water distribution equity among the water users and improvement in reliability of water delivery can be mitigated through appropriate technical and socio economic interventions such as water measuring mechanisms, proper maintenance, and investment on irrigation infrastructure improvements.

The Farmer Organization (FO) in the Daulatpur Minor was established in 2000, but the process of social mobilization for forming a Farmer Organization was started in 1999. The present study was carried out for the period from October 2006 to April 2007 (one crop season) for the purpose to assess water delivery to farmers, water use efficiency and farmer's role for sustainable irrigation water management.

The results on system performance demonstrate that the Daulatpur Minor received irrigation water for only 69 days out of 168 days allocated for winter crop season, thus the Minor remained closed for 99 days at various time and interval. However, the amount of water delivered to farmers was in excess as deliveries were estimated to be 8307 ac-ft (6.97 mm/day) including losses of the watercourse compared to the required 5056 ac-ft (4.24 mm/day) for the crop and water delivery to farmers along the distributary length was varying up to 95 percent. Consequently, water productivity achieved only Rupees (Rs) 1.10 /m^3 which, is equivalent to US$ 0.018 /m^3.

In order to manage irrigation water in a sustainable fashion, the Farmer Organizations played a role in maintaining the channels jointly. In all, they contributed labor and equipment while removing over 43,000 cubic meter of sediment. The imputed cost of these contributions was almost Rs. 12 per acre (US$ 0.2 per acre), which is much less when compared to government expenditures on operation and maintenance of channels. Due to removing the sediment, the head-tail water delivery ratio improved from 1.68 to 1.14 (Lashari B and Murry-Rust H.D (2002).

Further, the paper suggests that a water committee may be established at a district management level where various stakeholders are involved to further strengthen the newly established organizations for a better and more sustainable management of irrigation water.

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INTRODUCTION

Pakistan has a long history of irrigation. The country also has considerable experience in planning and implementing large irrigation development projects. The successful completion of these projects has made irrigated agriculture the country's engine of economic growth. Pakistan is arid to semi-arid country, located between the longitudes 61° east to 76° east and between latitude 23° north to 37° north. Total area of Pakistan is 196.7 million acres (79.61 million hectares). Population of the country is about 160 million and nearly 67.5 percent of it lives in the rural areas. Agriculture is the main stay of Pakistan's economy, contributing 35 percent to the gross domestic product and providing 60 percent of the labor force. Total annual cropped area is about 48.73 million acres (19.72 million hectares). Major crops grown are wheat, rice, cotton, maize and sugarcane which together make about 63 percent of the total cropped area.

The water delivery of the irrigation system of Pakistan has deteriorated due to neglected maintenance, inefficient operation, lack of coordination among water users, effective policies and their implementation and non functioning of many tertiary (watercourse) level irrigation system. Water distribution and deliveries to most of the farmers are erratic and unreliable. Typically, farmers have failed to make proper investment at the farm level such as laser leveling and farm layout that help a lot to improve the irrigation efficiency. Farmers at the tail ends of distribution system usually suffer from water shortage during critical growing periods that reduce yields and greatly increase the risks of spending for fertilizers and other input. In Sindh province of Pakistan, change in cropping pattern, influence of big farmers, political interference and rent seeking are the major problems of irrigation water mismanagement. In order to increase reliability, equity and efficiency, the accountability and discipline of system management needs to be developed.

The goals of sustainable irrigation water management should be to produce enough food for future generations within at least the limits of existing water resources to deliver water in equitable and reliable way to the users. To follow the rules and procedures defining rights and responsibilities, and penalties for breach of rules and when irrigation water is insufficient to meet crop demand limited irrigation management strategies should be considered to achieve the highest possible economic return [Perry C.J. (2001), Schneekloth J.P, etal (2001), Wahaj R Linden and Prathapar S. A (2000), Kupper M and Zaigham H (1998), Keith O and Raymond P (1999)].

In Pakistan, there are differences in water deliveries to different sub systems. Head-end areas receive significantly more water than their share, while tail-end areas receive comparatively less. The actual water distribution pattern failed to meet the targets agreed upon at the start of each season [(Kijne J.W, Murray-Rust D.H and Snellen W.B (2002), Vander Valde E.J (1991) and Bhutta N and Vander (1992)].

In order to improve the management of irrigation system a water budget for a tertiary (Watercourse) level is essential which provides much more reliable estimates of the time distribution of water supply required at the main subsystem outlet throughout the irrigation season. When this task is completed for many of the tertiary level in an irrigation project, then a more equitable water distribution will occur and crop yield can be expected to increase. The low rate for water charges (Rs 50/acre to Rs 125/acre) can be one of the main cause for irrigation mismanagement which results in the denial of water to the tail-end communities of the system (Skogerboe and Merkley (1996).

STUDY AREA

The Study was carried out in the command area of Daulatpur Minor which is off taking at RD 115 (23 mile) of West Branch System of Jamrao Canal (Fig 1). The salient features of the Minor are given in Table 1.

Table 1. Salient Features of the Daulatpur Minor

Description	Details
Name of Minor	Daulatpur
Off taking from West Branch at RD	115.0
Design Discharge (cusecs)	49.0
Length of Minor (RD)	31.9
Number of Watercourses	28
Number of Lined Watercourses	14
Gross Commanded Area (Acres)	11603
Cultural Commanded Area (acres)	10765

RD is reduced distance which is equal to 1000 feet.

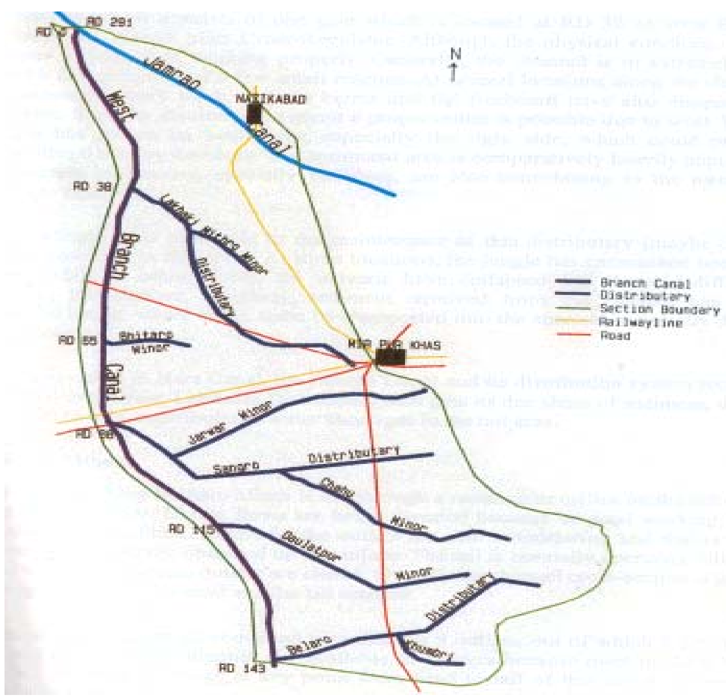

Figure 1. Location Map of the Minor off taking from West Branch Jamrao Canal.

DATA COLLECTION

To obtain a reliable data for flow of water in the Minor, all control structures (head regulator and all outlets) of the Minor were calibrated and rating tables were developed for all control structures. Daily water levels at head regulator and at outlets were recorded. Using the rating tables, the water levels were converted in discharges. The collected data was for the period from October 2006-March 2007 (winter crop season 2006-07).

To collect crop data the crop survey for three sample watercourses each from head, middle and tail sections were carried out. For crop survey watercourse command area maps were obtained from Irrigation and Power Department, Government of Sindh, Pakistan which describes the boundary, blocks and survey numbers. Each block consists of 16 acres of land.

To determine crop water requirement, the manual 1995 developed by Irrigation and Power Department (IPD) Government of Sindh was used which describes the crop water requirement of each crop based on climatic conditions and soil class.

To learn farmer's perception regarding their role in managing irrigation system, reforms in irrigation sector, economic benefits from the system and water related problems faced by the farmers, a semi-structured questionnaire was developed and used for data collection. The respondents were selected representing the whole system (Minor command area)

RESULTS AND DISCUSSION

Figure 2 shows that the delivery performance ratio (DPR- defined as ratio of actual discharge to design discharge) at the Minor head was above 1.0. which indicates that the Minor has been getting water from 110 percent to 140 percent of design discharge in one hand and another hand it has been closed 99 days out of 168 days allocated for winter crop season. During "on period" of 69 days the minor has received about 24.08 percent more flow than designed discharge whereas for the whole base period of 168 days (excluding annual closure during January) the average discharge is 30.46 ft^3/sec (or cusecs) which is 37.8 percent short against the design discharge. However, the amount of water delivered to farmers was estimated 8307 ac-ft (6.97 mm/day) against required 5056 ac-ft (4.24 mm/day) for the crop cultivated.

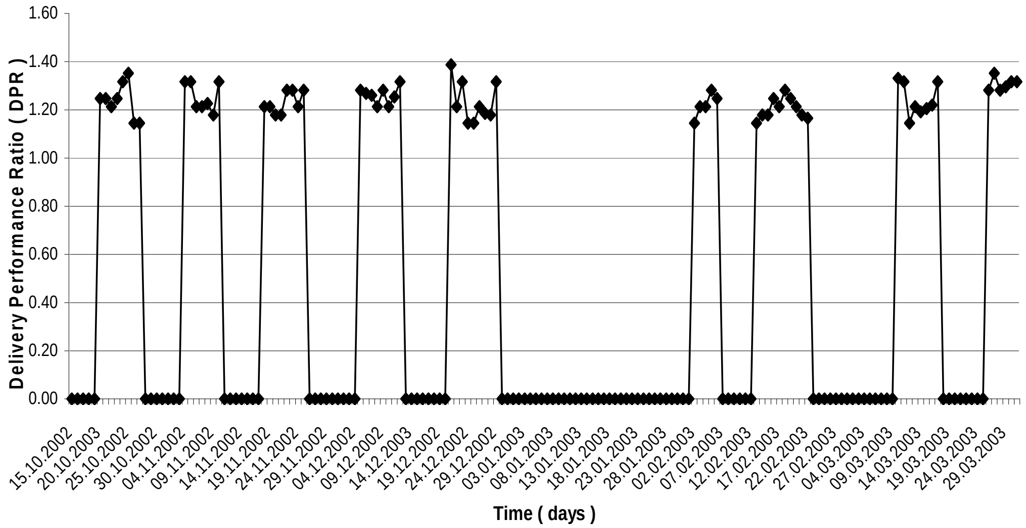

Figure 2. Water Delivery Performance Ratio at the Minor.

Results shown in Table 2 show that there is almost temporal consistency of water delivery on all three sample watercourses during whole crop season, however, the spatial variation is visible. It is unusual that middle reach watercourse is getting more water than head reach watercourse. Normally head reach gets more water, but some times when influential farmers are at middle reach then middle reach get more water.

Table 2. Water Delivery Performance Ratio for Sample Watercourses

Observation Month	Sample watercourses		
	385/1AL	377/2R	384/3L
October	1.37	2.22	1.47
November	1.57	2.19	1.46
December	1.56	2.02	1.35
January	0	(Canal closure period)	
February	1.58	1.95	1.30
March	1.47	1.96	1.30
Average	1.51	2.07	1.38

Results shown in Table 3 show that watercourse No. 385/1AL (head reach) was getting 51% more than designed discharge but the cropping intensity is 56% against the designed cropping intensity of 53%; similarly, middle reach watercourse No. 377/2R was getting 100 percent more water but the cropping intensity is very low i.e., 29 percent against 53 percent and at tail reach watercourse No. 384/3L was getting 38 percent more water than designed flow and cropping intensity is again very low. This all is due to cultivation of high delta crops like garden and sugarcane, unreliable supply of water and mismanagement of water.

Table 3. Cropping pattern and intensities of a sample water course on the Minor

WC NO.	Avg. DPR	CCA	Cropping Pattern (%)						Cropping Intensity
		(Acres)	Wheat	Garden	Fodder	Sugar-cane	Banana	Onion	%
385/1AL	1.51	130	27	41	14	12	3	3	56
377/2R	2.07	358	14	26	4	52	2	1	29
384/3L	1.38	455	31	39	6	17	6	1	25

Table 4. Volume Indices for Sample Watercourses

Water course number	Design Discharge (Cusecs)	Average Actual Discharge (Cusecs)	Average Discharge (168 Days) (Cusecs)	Volume (Acre- feet)
385/ 1AL	1.22	1.86	0.76	254.5
377/ 2R	0.95	2.02	0.83	276.39
384/3L	1.43	1.95	0.8	266.81

Table 5. Efficiency and Sufficiency of Sample Watercourses and Minor

Water course Number	Measured Volume (Acre- Feet)	Water Requirement (Acre- Feet)	Efficiency (%)	Sufficiency (%)
385/1AL	254.50	183.48	51.01	139.18
377/ 2R	276.39	260.03	66.80	106.29
384/3L	266.81	271.85	72.34	98.15
Minor	8307	5056.30	43.21	164.29

Tables 4 and 5 describe that average water deliveries (discharges) in three sample watercourses of head, middle and tail reaches are much higher than the designed discharge. Especially middle reach watercourse was getting more than 100 percent. While comparing the efficiency and sufficiency: the head reach watercourse has efficiency 51% against sufficiency of 139%, middle reach watercourse has efficiency 67% against sufficiency of 106% and tail reach watercourse has efficiency 72% against sufficiency of 98 and overall command area of the minor has efficiency 43.2% against 164.3% sufficiency.

Table 6. Water Productivity in the Minor Command Area during winter crop season 2006-07.

Crop	Cropped area	Total income of each crop	Gross Total income	Water delivered		Water productivity	
	(Acres)	(Rs)	(Rs)	(acre-ft)	m^3	Rs/m^3	US$/$m^3$
Wheat	725	1436950	11281296	8307	10250875	1.10	0.018
Garden	729	3280500					
Banana	56	3334688					
Fodder	170	968320					
Sugarcane	384	1958016					
Oilseed	26	302822					
onion	37	110704					

Results shown in Table 6 indicate that the water productivity resulted in a rate of return of Rs. 1.1/m^3 (US$ 0.018/m^3). This income is much less then compared to study conducted by Bastiaanssen (2002) for Pakistan which was Rs. 36/m^3. This is true because water availability in the Minor command area was only 69 days out of 168 days of the crop season. Thus the crop water requirement was not available at different crop growth stages which resulted in loss of crop yield.

The survey conducted in command area of the Minor which focuses on the role of various stakeholders of irrigated agriculture where most of the inputs and other relevant factors were investigated. The outcome of survey is depicted in the Table 7, which describes that major role for sustainable irrigated agriculture lies on Government of Sindh (GoS), Government of Pakistan (GoP), farmers and politicians then donors and then other organizations such as non-government organizations (NGOs), Sindh Irrigation and Drainage Authority (SIDA), FOs and insurance companies. Based on survey information a farmer advisory committee (Figure 3) was proposed to improve the system performance and also to improve crop yield by ensuring the inputs other than water.

Table 7. Stakeholder’s Role in Sustainable Management of Irrigated- Agriculture

Indicators	Roles of Different Stakeholders							
Irrigation Water	SIDA	FO’s	GoS	GoP	Farmers	Donor	Insurance	Politician	NGO’s
fertilizer	√	√	√	√	√	√	x	√	√
Seed	X	X	√	√	√	√	X	√	√
Pesticides	x	x	√	√	√	x	x	√	√
Agriculture Machinery	x	x	√	√	√	x	x	√	√
Risk management	x	x	√	√	√	√	X	√	x
Loans & Credit	x	x	√	√	√	√	√	√	x
Market	√	√	√	√	√	x	x	√	√
Taxes	√	√	√	√	√	√	x	√	x
Training	√	√	√	√	√	√	x	√	x
Awareness	√	√	√	√	√	√	x	√	√
Coordination	√	√	√	√	√	√	√	√	√

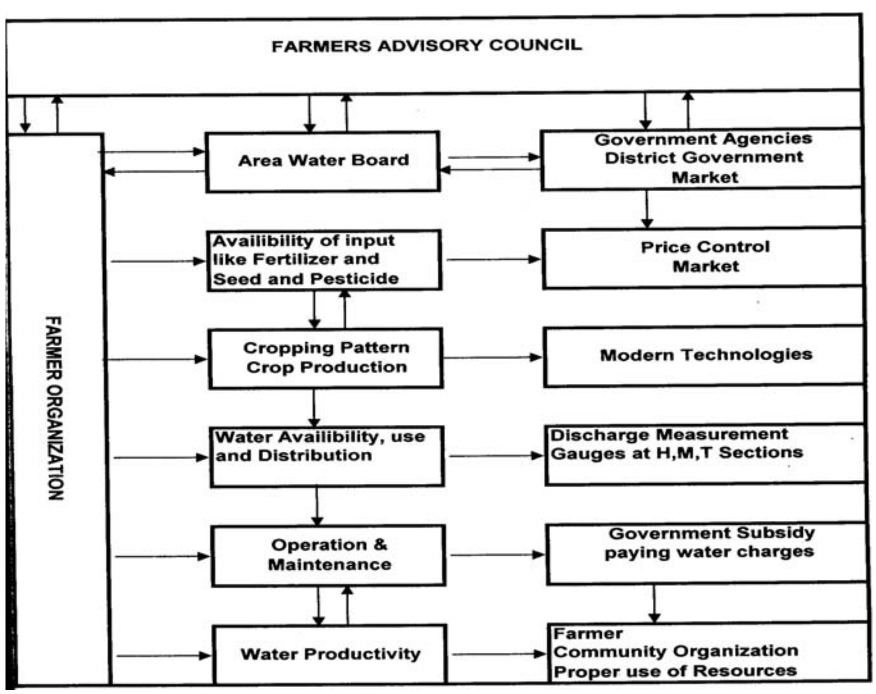

Figure 3. Composition of Farmers’ Advisory Committee.

CONCLUSIONS AND SUGGESTIONS

The water delivery to the command area of the Minor has been only 69 days out of 168 days of total cropping period. However, water delivery during the irrigation period of the Minor has always been more than the designed discharge and was between 115% and 140% of designed discharge. But this flow did not bring good yield of the crop because of continuous interruption in the flow of water which was not meeting the crop water requirement at different crop growth stages.

The water use efficiency for the command area of the Minor was found to be 43.2 percent while the sufficiency may have been as high as 164 percent. In fact, this inefficiency was occurred due to cultivation of high delta crops, rotational closure of the Minor (Unreliable supply) and mismanagement of water.

The unreliable supply and untimely availability of irrigation water to the farmers have seriously affected on crop yield and consequently, the crop production in the command area of the Minor has come to Rs. 1.10/m^3 (US$ 0.018/m^3). While the previous studies conducted by Bastiaanssen etal (2002) for Pakistan which was estimated Rs. 36/m^3.

The joint efforts of farmer organizations (FOs) contributed in terms of labor and equipment while removing over 43,000 cubic meter of sediment. The imputed cost of these contributions was almost Rs.12 per acre (US$ 0.2 per acre), which is much less when compared to government expenditures on operation and maintenance of channels. Due to FOs' physical intervention in many channels (Distributaries/Minors) the head-tail water delivery ratio improved from 1.68 to 1.14 (Lashari B and Murry-Rust D.H 2002). Therefore, the joint efforts of FO, GoS, GoP and politicians along with other support from the other stakeholders can improve crop productivity and yield significantly.

It is therefore, suggested that the farmer's advisory committee should be established at every district level where stakeholders of irrigated agriculture are members of the committee (Fig 3) which will help to ensure the reliable supply of all irrigated agriculture inputs to improve the productivity of crops. This committee also plays a main role in the sustainable water management and strength of the FOs.

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EGYPTIAN DRAINAGE WATER REUSE PRACTICES AND MEASURES TO ALLEVIATE RISK OF FAILURE

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ABSTRACT

The Egyptian total water requirements of all socio-economic sectors are estimated at 73 BCM/yr. The agriculture sector alone requires about 82% of this amount. A gap between fresh water resources and the country's requirement already exists. The possibility of increasing the fresh water resources from conventional sources is doubtful. In the meantime, non-conventional sources such as desalination or cloud seeding are also infeasible and expensive. In addition, water requirements of different sectors increase rapidly with time due to rapid population increase; ambitious agricultural expansion, and elevated living standards. Therefore, the fast and economic way to bridge such gap is to reuse the available and possible water resources more than one time. Reuse of agricultural drainage water became a national policy during the 1980s. Currently, 6.58 BCM of drainage water with an average salinity of 1.65 ds/m is reused each year. Another 1.9 BCM of drainage water is committed for reuse in the new reclamation areas in the near future.

Several types of reuse are being practiced in Egypt as gravity reuse, national reuse, intermediate reuse, unofficial reuse and reuse of wastewater treated effluents. The objective of this paper is to assess the status of drainage water reuse practices and challenges in the country and recommend measures to alleviate risk of failure. The reuse practice subject to several potential risks such as uncertainty of water availability for reuse due to unaccounted of other usage, introducing measure for water save or change in water allocation, water quality deterioration, introducing drinking water supply downstream reuse mixing site, changing cropping pattern within drainage catchment.

Measures to alleviate risk of failure for drainage water reuse practices would include six elements. First is to develop national atlas for objective uses for the water ways including irrigation and drainage system. Second is to redefine water availability for reuse practice at hydrological drainage catchment considering unofficial reuse and avoid double counting. Third is to locate the new drinking water supply intakes and wastewater treated effluents in coordination with Ministry of Water Resources and Irrigation. Fourth is to define the priorities for water quality improvement considering Ministry of Water Resources and Irrigation vision. Fifth is to review the reuse practices at hydrological drainage catchment to avoid any contrast. Sixth is to conduct feasibility study including water quality assessment, matching with present and future usages of the receiving water body and environmental impact assessment for any future reuse scheme.

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INTRODUCTION

Since the completion of the High Aswan Dam in 1970, irrigation has become possible throughout the year (perennial). All agricultural lands are more than double cropped (more than 200% cropping intensity). Among the main constraints to agriculture production in Egypt is the rise of the water table causing water logging and salinization. Therefore, drainage becomes obvious to control water table level and soil salinity. A system of open main and branch drains has been constructed since the start of the 20th century. This network of open drains solved the problem of water logging and salinity partially.

Currently, the total water requirements of all socio-economic sectors are estimated at 73 BCM/yr. The agriculture sector alone requires about 82% of this amount. A gap between fresh water resources and the country's requirement already exists. Reuse of drainage water holds great potential for saving valuable freshwater resources for competing prime uses that require more stringent water quality standards. It provides a reliable supply of irrigation water and rich nutrients to cropped fields. The Egyptian case in the field of water reuse is unique for the following reasons:

- all surplus water is returning to the system.
- in Upper Egypt, seepage, agriculture drainage water, sewerage water are returning back to the Nile and reused in the Delta area.
- downstream Delta Barrage drainage water, sewerage water and groundwater in the Delta is reused directly or by mixing;
- all sewerage water is drained to the agricultural drains;
- there is no special end systems for sewerage or industrial wastewater;
- the flexibility in water distribution is very limited since there is no intermediate reservoirs between Aswan and the sea; and
- a lot of activities requires marginal or low quality water where drains should end to the areas where such activities take place.

There are many systems of reuse practices which would contribute to the overall resilience of the Nile Delta agricultural and livelihoods system. The objective of this paper is to assess the status of drainage water reuse management and challenges in the country and recommend measures to alleviate risk of failure.

NEEDS FOR REUSE

Egypt is mostly a rainless country that leads to limited water resources. The yearly total run-off that could be harvested is limited 1.3 BCM/yr. The Egyptian water quota from the Nile is 55.5 BCM annually as specified in the 1959 agreement between Egypt and Sudan. Groundwater in the desert is very limited. The maximum possible amount expected from the groundwater fossil reservoirs is 3.5 BCM/yr. Currently, the total requirements of all socio-economic sectors are estimated at 76 BCM/yr. The agriculture sector alone requires about 82% of this amount. A gap between fresh water resources and the country's requirement already exists.

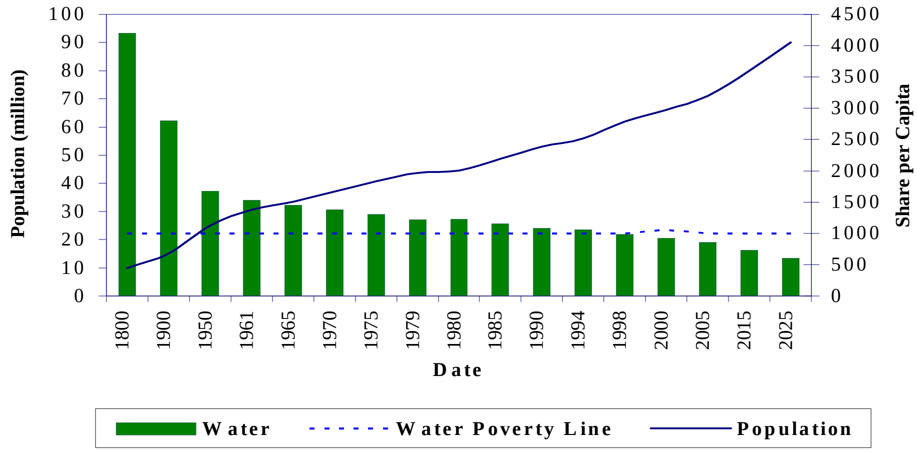

Figure 1. Population Growth and Water Availability

This gap is expected to widen in the future and the possibility of increasing the fresh water resources from conventional sources is doubtful. In the meantime, non-conventional sources such as desalination or cloud seeding are also infeasible and expensive. Therefore, the fast and economic way to bridge such gap is to reuse the available and possible water resources more than one time. Without reuse of drainage water, the national water budget will suffer a serious deficiency. Reuse of drainage water holds great potential for saving valuable freshwater resources for competing prime uses that require more stringent water quality standards. It provides a reliable supply of irrigation water and rich nutrients to cropped fields.

REUSE PRACTICES IN EGYPT

Several types of reuse practices can be distinguished in Egypt as:

- **Gravity reuse** of drainage water, which takes place in canals or river branches receive drainage water by gravity. This takes place for instance in the Nile Valley, where nearly all drainage water returns to the Nile River.
- **National reuse project** is the practice of pumping part of the drainage water flow into the irrigation water system.
- **Intermediate reuse project** is the mixing of drainage water and fresh irrigation supplies take place at lower level- with a drainage catchment coinciding with a number of secondary canals.
- **Unofficial reuse** is practiced by individual farmers who decide, when and how drainage water will be used for supplementing their irrigation water. Unofficial reuse of drainage water normally takes place near the tail ends of the irrigation canals.
- **Reuse of wastewater treated effluent** is reuse of treated effluents for restricted crops, landscape, green belt and forests.

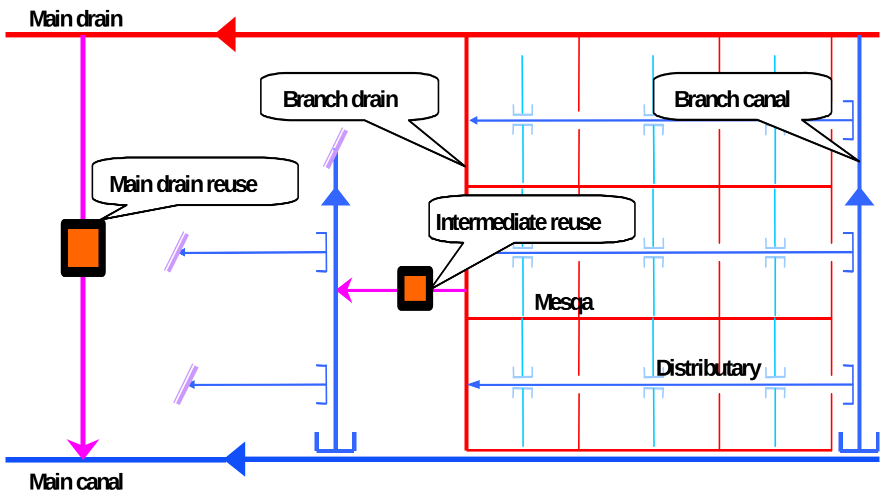

Figure 2. Typical Reuse scheme in the Nile Delta

FACTORS AFFECTING DRAINAGE REUSE PRACTICES

There are many factors that may adversely affect the drainage reuse in the Delta region, including pollution, Water save and improvement project, rice area reduction, and the Toshka project (S.T Abdel Gawad and A. El Sayed 2008).

Pollution

The quality of drainage water is threatened by the uncontrolled disposal of polluted effluents (domestic and industrial) and the improper disposal of solid and toxic wastes from agricultural and human activities. Figure (2) shows the drainage catchments in the Delta with health risk due to pollution. The high population densities and industrial activities in combination with insufficient sewerage facilities cause different levels of pollution load on drainage water to the extent that there is a health hazard.

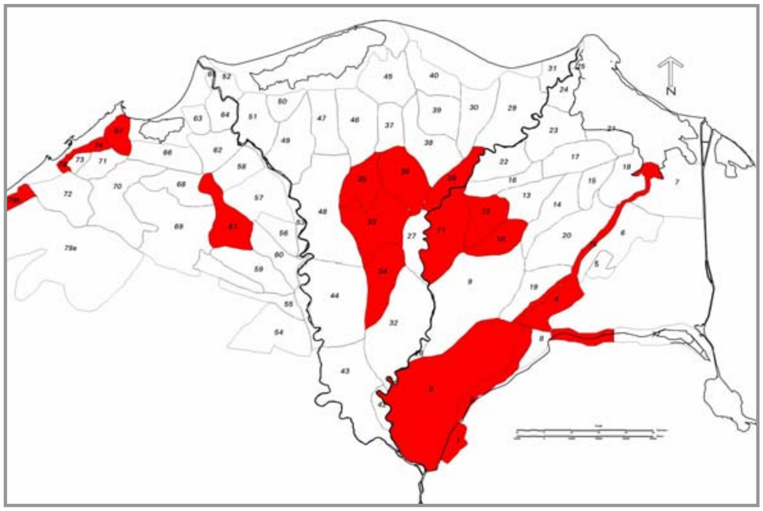

Figure 3. Drainage Catchments with Health Risk Due to Pollution

A number of reuse mixing stations in the Nile Delta have been entirely or periodically closed owing to the increasing degradation of drainage water quality such as:

1) Mahsama Pump Station in the Eastern Nile Delta was pumping approximately 200 million m3 of drainage water annually.
2) Upper Pump Station No 1 in the Middle Delta was constructed to pump approximately 100 million m3 annually.
3) In the Western Delta, the Umoum Reuse Project construction was finished during 1995. The project anticipated 1000 million m3 reuse annually of the drainage water.

Irrigation Improvement Project (IIP&IIIMP)

Egypt has launched an ambitious Irrigation Improvement Program (IIP) "later called Integrated Irrigation Improvement Management Project (IIIMP)", which includes the improvement of water delivery system, on farm-water management, irrigation methods and associated agronomic practices. The extension of these programs in the Delta will affect the generation and distribution of drainage water in the region. During 1989-97, Egypt has implemented these programs on over 350.000 feddans. According to the GOE plan, these programs will be extended to an area of 3.5 million feddans in the Delta by the year 2017.

Pilot areas indicated that irrigation efficiency could be improved by 10%. Therefore, it is expected that the expansion of IIP and IIIMP over the 3.5 million feddans in the Delta will eventually result in a reduction of 2.6 BCM drainage generation from the 1995-96 level of 19.5 BCM (12.4 BCM outflow, 4.3 BCM official reuse, and a Ministry's estimate of 2.8 BCM unofficial reuse). This 2.6 BCM drainage reduction will affect the volumes of drainage outflow as well as official reuse and unofficial reuse (DRI, 2003). The picture is illustrative only, but it indicates that if the ambitious IIIP extension plan will really be implemented, then the currently scheduled drainage reuse expansion will become partially unnecessary, since there would not be so much drain water available for reuse. It should also be noted that with increased irrigation efficiency, the decreased drain water will be accompanied by deteriorated water quality and at the same time increased availability of freshwater.

Rice Reduction

Rice is one of the most controversial crops in Egypt. Farmers favor the crop because of its high production yields and economic returns. Water engineers are more inclined to reduce the area under rice so that the large amount of rice irrigation water can be used for other demands such as expanding irrigation lands. There is a difference between rice planted in the south of the Delta and that in the north of the Delta. In the South, rice irrigation water is consumed only by crop evapotranspiration (ET) and drainage outflow from rice ponding is available for downstream reuse. While in the North, a large portion of the irrigation water is lost to a salt sink such as saline groundwater becomes valueless for reuse. Rice is a land reclamation crop in the North to prevent the seawater intrusion, and rice area reduction mainly applies to the south Delta region. Therefore, only the effect of South Delta rice reduction on drainage generation needs to be evaluated. The drainage reduction by rice area reduction would be about 2,000 m3/fed. With a possible 500,000 feddans rice area reduction in the southern Delta, the expected decrease of drainage would be about 1.0 BCM.

Toshka Project

Toshka is the largest irrigation project in Egypt after the AHD construction. It is designed to develop half million feddans of arable land in the next 10 to 20 years (Shalaby, A. 1997). At a designed annual irrigation requirement of 8,000 m3/fed under the local climatic conditions, the project will withdraw 4 BCM of water from Nasser Lake. For simplicity, the Toshka effect on Nile downstream water allocation is expressed as a 2-4 BCM reduction in current AHD release. To evaluate the Toshka effect on drainage reuse in the Delta, scenarios of 2-4 BCM reductions of HAD release were simulated in a Nile water balance calculation.

There is a compromise between the water allocated to the Valley and to the Delta. Reuse in the Delta region will have to be increased, but it will be bounded by the maximum reuse potential. With a 2 BCM withdrawal for Toshka, if maintaining Valley's 1996 water allocation, the Nile flow passing Cairo would be reduced from 35.3 BCM of 1996 to 33.3 BCM and the official drainage reuse in the region would have to be raised from the 4.3 BCM of 1996 to 6.3 BCM. The drainage outflow would be reduced from 12.4 BCM of 1996 to 10.4 BCM. Except for the intensified drain water reuse in the Delta, no extra effort would be required, and only the Delta region takes the pressure of the reduced AHD release.

With the Toshka project, the reuse of drain water in the Delta will have to be maximized. Whether this will be realistically possible remains questionable. Fortunately, Toshka may take 10 years for full development, and the required drainage reuse expansion can be conducted in a series of steps, or may be partially replaced by other water management measures, in the course of the next decades.

VARIABLES DOMAIN REUSE DECISION

Drainage water reuse is becoming an integral part of many national water programs particularly in water- short areas, as scarcity makes it necessary to use all available water. Drainage water is often available in large volumes, and therefore could cover a significant part of total irrigation demand, if adequately managed. Furthermore, reuse may help alleviate drainage disposal problems by reducing the volume of drainage water involved. Egypt made already leading steps towards integrated management of drainage water as part of the available annual water budget to meet the increasing water demands.

The employment of drainage water reuse on increasingly large levels constitutes a major environmental challenge if not properly managed. Thus, any reuse project should target at investigating the effect of reuse of drainage water in irrigation on soil, water, crops and the environment.

There are numerous variables that need attention in the reuse decision process (Abdel-Gawad, S. 2005):

- How much salinity can be tolerated in the irrigation water and soil before the overall agricultural productivity is negatively affected. Therefore, any planned reuse programs and drainage disposal need to give due weight to maintaining a favorable salt regime in the region.
- Use and development of well designed monitoring programs, reuse guidelines and modeling techniques are necessary tools to assess how the proposed reuse programs will change the natural conditions and how environmental values may be affected.
- The quality of drainage water is often threatened by the uncontrolled disposal of domestic and industrial effluents and the improper disposal of solid and toxic wastes from agricultural and human activated. Thus, laws and regulations on water quality and pollution control should be enforced. This might require reform to meet water quality and environmental needs.
- Reuse of drainage water at the lower level reduces the risks of pollution from domestic and industrial sources. This scale of intermediate reuse is important and offers potential for reuse projects.
- Environmental issues, which are frequently neglected, vary widely from one country to the other as well as from one project to the next. Therefore, a standardized approach in examining these would be unsuitable. It might be appropriate to assess what the main issues are and how serious each issue is in a country.
- As water reuse can affect health and environment, further research is needed to explore its full implications on water quality, public health and the environment.
- Costs and economics of reuse practice are not well known and special studies need to be carried out on a case by case basis.
- Planning and management of drainage reuse obviously involve other disciplines than engineering which necessitate the employment of a multidisciplinary approach.

MEASURES TO ALLEVIATE RISK OF FAILURE

Measures to alleviate risk of failure for drainage water reuse practices would include several elements which will presented in the following sections.

Develop National Water Atlas

First measure is to develop national water atlas for objective uses for the water ways including irrigation and drainage system. There are no agreed clear objective uses of water courses in Egypt. There are several Ministries and entities involved in water resources operation and interventions (Table 1). So, there is a need to clarify the objective uses and function of water ways in Egypt including irrigation and drainage.

Table 1. Water Usages and Responsible Ministries

Water Usage	Ministry / Authority
Drinking water	Ministry of Housing, Utilities and Urban Communities Ministry of Water Resources and Irrigation Ministry of Health and Population
Fishery	Ministry of Agriculture and Land Reclamation
Agriculture	Ministry of Water Resources and Irrigation Ministry of Agriculture and Land Reclamation
Recreations	Egyptian Environmental Affairs Agency
Livestock	Ministry of Agriculture and Land Reclamation
Industries	Ministry of Industry Ministry of Water Resources and Irrigation
Reuse of drainage water	Ministry of Water Resources and Irrigation Ministry of Agriculture and Land Reclamation
Navigation and water transport	Ministry of Transport Ministry of Water Resources and Irrigation

Redefine Water Availability for Reuse Scheme

Second measure is to redefine water availability for reuse scheme for each hydrological drainage catchment considering unofficial reuse and avoid double counting.

In many reuse scheme cases such as El Salam Canal Project, the drainage water to be mixed with the fresh water is over estimated. The lag time between the reuse study and implementation would take over 10 years. The assumed available drainage water for reuse mostly reduced due to unofficial reuse and other small scale reuse within the drainage catchment that did not count. Two options would be considered in such cases; first, is not to allow for any intervention could reduce water availability within the drainage catchment and second to have better estimate for water availability considering implementation schedule.

Locate Influents and Effluents in Coordination with MWRI

Third measure is to locate the new drinking water supply intakes and wastewater treated effluents in coordination with Ministry of Water Resources and Irrigation.

In the past, many drinking water supply intakes constructed downstream mixing point with drainage water such as Ismalia canal feeding Suez Canal Cities that lead to shutdown one of the reuse pumping station (Mahsama Pumping Station). Other reuse scheme located upstream drinking water supply intakes are in operation such as Alexandria city along El Mhamoudia canal. This situation would lead to overload of water treatment plants or health risk for water consumers.

In other cases, the treated wastewater effluents discharge into drains that flow into canals or River Nile (El Rahawi, Sabal and Tala drains into Damitta branch). The disposal of wastewater has significant negative impact on such reuse scheme that can be avoided if Ministry of Housing, Utilities and Urban Communities consult Ministry of Water Resources and Irrigation to come up with better alternative.

Define the Priorities for Water Quality Improvement Interventions

Pollution control actions are measures to reduce the load of wastewater in areas that are already polluted. Protection measures are measures to prevent vulnerable areas from being polluted in the future .

Pollution control actions in these areas should be aimed at the provision of adequate treatment facilities to those communities connected to sewerage systems and the provision of collection stations for the vacuum trucks. The collection stations could be connected to the existing treatment plants by forced mains or could be equipped with small treatment units. The budget for such intervention allocated through Ministry of Housing, Utilities and Urban Communities where they have their own priority areas.

Fourth measure is to define the priorities for water quality improvement interventions considering Ministry of Water Resources and Irrigation vision. The areas with health risks of low drainage water quality is limiting factor for sustainable reuse project. One of the criteria to define priority area is the catchment of current and planned reuse schemes. The following Figure illustrates one of attempt to define priority area by National Water Research Center, Ministry of Water Resources and Irrigation.

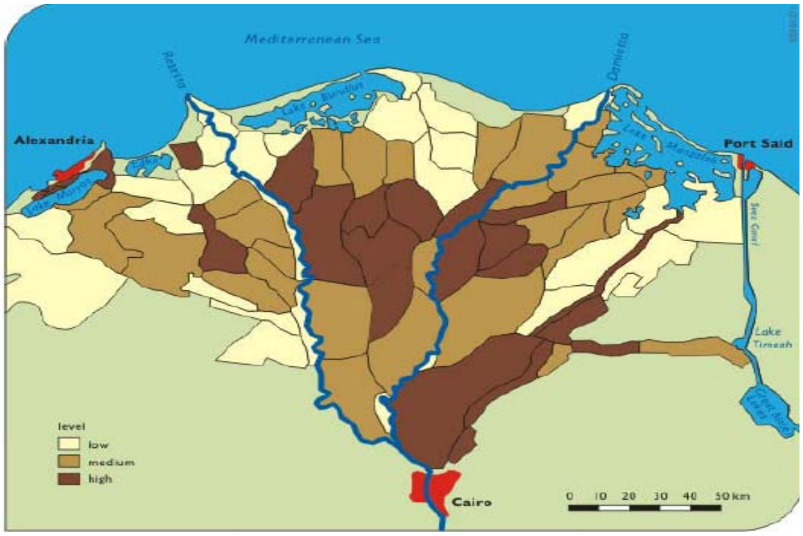

Figure 4. Drainage catchments with a priority action based on health risk criteria

Review the Reuse Practices at Hydrological Drainage Catchment

Fifth measure is to review the reuse practices at hydrological drainage catchment to avoid any contrast. In some cases, several reuse types are practiced that may impact each other; national reuse Project, intermediate reuse project and unofficial reuse through different sector within MWRI and farmers. Intermediate reuse projects match with short term plan and fill gabs between supply and demand as rapid intervention while national reuse projects match with long term plan. The following figure is an attempt illustrating reuse practice at hydrological drainage catchment with official and unofficial reuse. This figure would be updated to include the current and future practice and other practice such as intermediate reuse. The following step is to insure harmonization among the different reuse practice and drainage water availability.

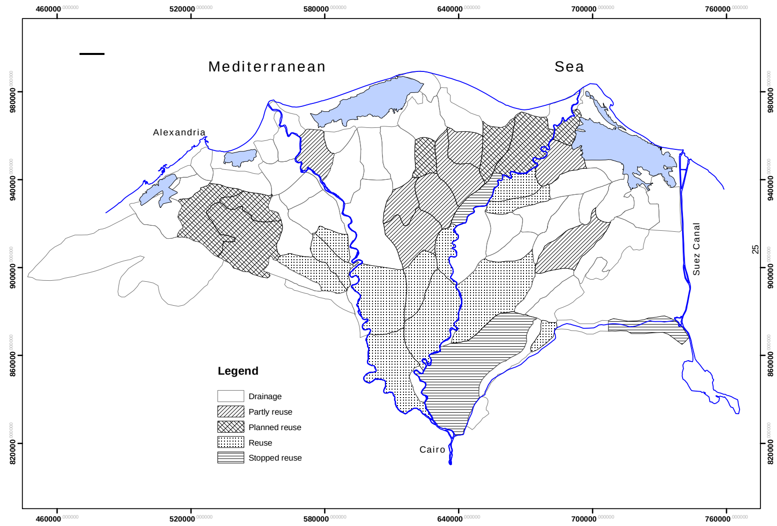

Figure 5. Drainage Catchments with official and unofficial reuse

Conduct Appropriate Feasibility Study

The reuse schemes cost GOE millions and in some cases are shutdown with no possibility to get any benefits from the project. So, there is a need to conduct feasibility study including water quality assessment, matching with present and future usages of the receiving water body and environmental impact assessment for any future reuse scheme.

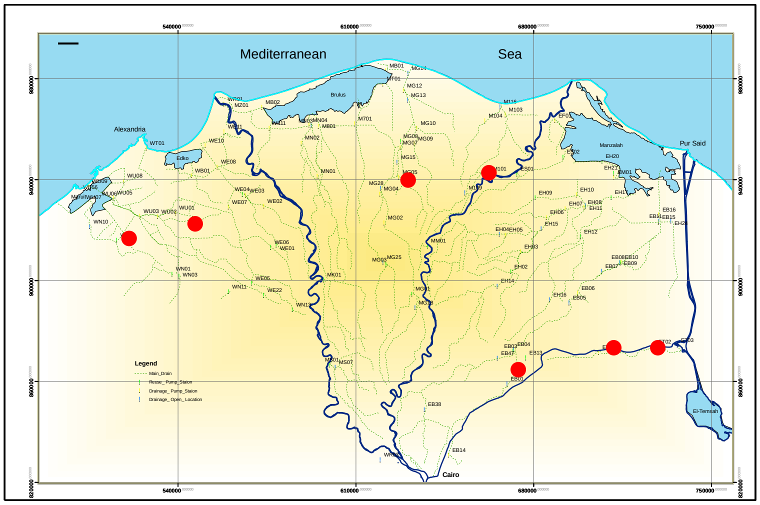

Figure 6. Closed drainage water reuse projects

STRATEGIES TO SUSTAIN DRAINAGE WATER REUSE PRACTICES

Strategies to sustain drainage water reuse practices are developed including:

- Shift to drainage water quality management;
- Define priority actions to enhance reuse potential
- Apply pesticides: policies, controls, subsidies and extension advice
- Increase municipal sewerage and wastewater treatment
- Initiate cost recovery for urban sanitary services
- Local action plans on domestic sanitation in rural areas
- Treatment of industrial wastewater package
- Introduce low cost effective technologies

Mitigation measures are implemented to ensure second and third recycling of drainage water such as introducing intermediate reuse; introduce low cost treatment technology - in-stream wetland; off-stream wetland treatment system; drainage water reuse guidelines; reuse of treated municipal wastewater and national legislation of wastewater reuse.

The catchments subject to second recycling are located upstream and midstream of Delta regions. Most of the recycling of drainage water is for agriculture use and livestock watering. The catchments subject to third recycling are located further downstream in Delta regions and Delta fringes. Most of the recycling is for "salt tolerance crops," livestock watering and aquaculture production; mainly fishing production.

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ECONOMIC EFFICIENCY OF DIFFERENT IRRIGATION TECHNIQUES IN ARMENIA

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ABSTRACT

The economic efficiency and rate of return of different irrigation techniques were demonstrated in Armenia under On-Farm Water Management Component of the Water-to-Market Project. The Project goal was to reduce rural poverty from 32% to 26% and boost annual incomes through sustainable increases in the economic performance of the agricultural sector after 5 years. The objective of the Water Management Component was to set up demonstration farms with irrigation improvements for farmers to adopt.

For calculating the economic efficiency, three major impact elements were taken into account: yield increase, water savings and labor savings. Necessary input data were collected from records of demonstration site farmers and questionnaires filled at the beginning and end of vegetation period. The indirect positive impacts of farmers adopting irrigation improvements were appraised as: 1) possibility to irrigate abandoned lands; 2) obtain higher yields; 3) provide opportunity to expand on agricultural activities (double cropping, etc.); and 3) enlarge irrigation system capacity to allow more farmers to share water and regulate its distribution in the peak growing season, and eliminate potential conflicts. In addition, the density of demonstration sites was assessed based on the number of the peasant farms and rural communities, density of farms, and average size of cultivated land, to assure high adoption rate among nearby farmers.

The adoption rate was assessed based on specified categories and density of farms in the third year of the five year project and provided a clear direction for future work.

INTRODUCTION

Background

The Water to Market project is the part of the five-year Compact between Millennium Challenge Corporation and the Government of Armenia. Its main goal is to reduce rural poverty from 32% to 26% and boost the annual incomes through sustainable increases in the economic performance of the agricultural sector. The targeted crops were primarily vegetables, grapes and variety of fruits (yield increase by 15.9, 22.5, and 13% respectively).

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Geography and topography

Armenia is a small landlocked country with a total area of 29,800 km^2. It is located south of the Caucasus Mountains. It is divided into ten marzes (regions). The altitude ranges from 380 to 4,090 m above sea level. More than 90% of the country lies above 1,000 m and 72% above 1,500 m. The landform generally comprises rocky high mountain ranges separated by narrow, irregular-shaped fertile valleys. The broad, flat, and fertile Ararat valley is located on the left bank of the Araks River. Most of the population and cultivated lands are here. The total population is about 3.23 million, of which 36% is rural. The average rural population density is 101 inhabitants / km^2. The average annual precipitation varies from 1,000 mm in the high mountains to 300 mm in the Ararat Valley. About 60 % of the territory receives less than 600 mm of rainfall per year. The total water resources of Armenia amount to 8.2 BCM/year, comprised of renewable surface water resources (7.2 BCM/year) and renewable groundwater resources (1 BCM/year). Armenia's only multi-year water storage is Lake Sevan (33 BCM). Considering these water resources, Armenia has an average of over 3,000 m^3/year water resources per capita. There are spatial and temporal imbalances of Armenia's water resource base. There is a wide fluctuation in the seasonal volume of river flow. About 55% of run-off occurs in the spring months.

Goal and objectives

To achieve the goal of poverty reduction in rural areas, the major activities of the On-Farm Water Management Component consist of introducing new on-farm water management technologies in situ and conducting trainings. The objective of establishing demonstration sites to improve farmers' skills in water management techniques will enhance the efficiency of water and labor use on the farms as well as introduce new more efficient irrigation technology, which would positively affect the yields of highly valuable crops.

By the end of the five year project it would be expected that approximately 38,000 farmers from the approximately 60,000 trained farmers would adopt the innovations demonstrated. As a result, there would be an increase of the net benefit from their farming operations.

METHODOLOGY AND IMPROVEMENTS

To enhance chances for success with the adoption of new and more modern on-farm water management technologies and techniques, it was decided to demonstrate them in a real farm condition, and set them up as much as possible in proximity to each other. This would allow multiple visits during field days of the trainees, so that they would be exposed to several technologies or improvements in one day. The demonstration of the on-farm water management technologies under real farm conditions definitely increases the adoption rate because the trainees receive feedback on the improvement from the demonstration directly from the 'host demo-farmer'.

The demonstrated irrigation improvements were grouped in 4 categories: 1) simple improvements, affordable mainly by small farmers, including siphons and spiles; 2) medium improvements, readily affordable by all farmers, including PVC or metal hydrants, gated pipes, lay-flat pipe, PE ditch; 3) advanced technologies, affordable mainly by big farmers, including drip and micro sprinkler irrigation systems; and, 4) equipment to help in irrigation scheduling: soil moisture meters/sensors, tensiometers and ET gauges. In demonstration sites with simple improvements, siphons or spiles were demonstrated with or without plastic or metal dams, plastic lining for farm ditch, sluice gate and V-notch. All demonstration sites have a minimum of two improvements in irrigation technology, one from first three groups and one from fourth group.

For calculating the economic efficiency, three major elements of impact were taken into account: yield increase, water savings and labor savings. The necessary input data were collected from records of demonstration site farmers (initial investment of the demonstrated improvement, maintenance, water and labor usage, weed control etc.) and filled in questionnaires at the beginning and end of the vegetation periods (for comparison of data before improvement and after the improvement). The questionnaires contain information on basic farmer's data – such as water source, irrigation method, irrigation practice, irrigation scheduling, yield, market prices for fruits and vegetables, labor cost and cost of irrigation, and water and labor usage.

Analysis of 60 demonstration sites on cost return of the improvement

From the existing 60 demonstration sites established in the course of the third year, the records were analyzed. All calculations were done for 1 ha of land. Because the impacts vary, depending on a crop type and variety, farmer's capacity, agricultural zone, water quality, soil texture, field topography, fertilizer quality, etc., summary was prepared for a range of possible impact for each improvement without taking into consideration the crop variety, agronomical practice, etc. Table 1 provides the summary.

Table 1. Cost Return of the Improvement

Irrigation Improvement	Initial expenditure divided by operation years (20), $	Annual maintenance estimated per ha , $	Increase of yield, %	Water savings, %	Labor savings, %	Fertilizer savings, $	Average savings for one season estimated per ha, $	Investment return year
Simple improvement	5-16	0-11	1-10	1-15	10-50	n/a	476	<1-2
Medium improvement	12-150	11-20	1-10	10-30	20-60	n/a	519	2-3.5
Advanced technology	200-250	45	20-50	30-60	90-95	33-50	3,295	1-3
Irrigation scheduling method	34-68 (for 5 yrs)	11	10-20	5-15	5-15	n/a	1,125	<1

<u>Indirect impacts of improvements</u>

The indirect impacts of implemented on-farm water management improvements were also estimated, and these are: 1) possibility to irrigate abandoned lands; 2) obtaining higher yield; 3) opportunity for farmers to expand their agricultural activities, such as double or triple cropping; and 4) enlargement of irrigation system capacity to allow more farmers to share the water source and regulate water distribution in the peak of the growing season, as well as eliminate conflicts (farmers waiting for irrigation, quarrels for water, etc.).

<u>Importance of density of demonstration sites</u>

For the effectiveness of the project demonstration sites, the important consideration was an assessment of the density of demonstration sites. In the Ararat Valley 10 (ten) demonstration sites with new technology - drip irrigation - was taken for recording direct adoptees, who adopted it after visiting at least one of the demonstration sites. The number of adoptees was 80. There were 5(five) adoptees who visited two demonstration sites; one of those sites was giving an opportunity to observe directly proper installation of the drip irrigation system.

The influence area of a demonstration site was studied. As illustrated in the figure below, the adoption rate is high when distance between a demonstration site and a place of an adoption is less than 10 km (66 adoptions), especially when the density of farms and communities is high.

To analyze the density of demonstration sites, three categories of demonstration sites according to distances between them were designated: 1) demonstration sites with distances less than 10 km, 2) demonstration sites with distances amongst them from 15 to 20 km, 3) demonstration sites with distances over 25 km. In case of possible inclusion of the same demonstration site into two groups, it was considered to divide the adoptees from that site into two halves.

The results show that adoption rate for first group is 20% higher than in second group and adoption rate of the second group is 50% higher than in third group.

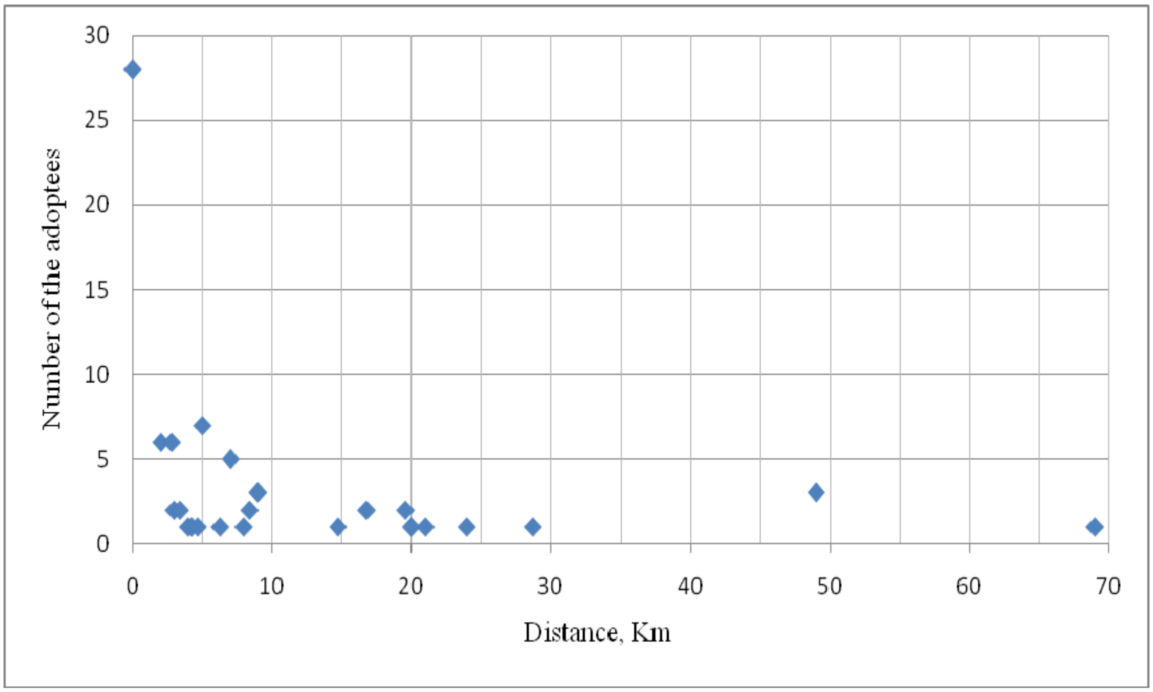

Figure 1. Relationship between Adoption Rate and Distance

CONCLUSION

Based on the assessment of the density of the existing demonstration sites, the number of the peasant farms, number of the rural communities, density of farms, and average size of cultivated land, it is recommended to establish demonstration sites for improvement of farmers' skills in the on-farm water management techniques and technologies in Armenia within a radius of less than 25km from each other.

Statistical data related to number of farms and communities in Armenia are in Table 2:

Table 2. Statistical Data Related to Number of Farms and Communities in Armenia

Marz /Region/	Number of peasant farms	Rural Communities	Calculated Density of farms	Land per farm(ha)
Aragatsotn	37119	111	334	1.5
Ararat	52902	93	569	0.63
Armavir	50332	94	535	0.99
Gegharkunik	48220	87	554	1.97
Lori	32542	105	310	1.42
Kotayk	37611	60	627	1.18
Shirak	28251	116	244	2.83
Syunik	12945	102	127	3.58
Vayots dzor	12828	41	313	1.74
Tavush	21938	57	385	1.45
Total in Armenia	334688	866	-	-

Resulting from the assessment of the economic efficiency and the rate of return of investing into different irrigation techniques and technologies, the number of demonstration sites for every marz was determined. This is basically supported by the data and survey information from the National Statistical Service of the Republic of Armenia. Within the Water-to-Market Project, it relates to the density of the demonstration sites, respectively the number of sites for every marz with representative irrigation improvements and their location – in the most suitable communities to insure high adoption rate among nearby farmers. The numbers of demonstration sites by marzes are shown in Table 3 below.

Table 3. Established and Planned Demonstration Sites by Marzes

Demo sites / Marzes	Established		Planned	
	Simple & medium improvements	Trickle irrigation	Simple & medium improvements	Trickle irrigation
Armavir	11	13	0	1
Ararat	7	13	0	2
Vayots Dzor	2	4	0	2
Aragatsotn	2	1	1	6
Gegharqunik	2	1	1	6
Kotayk	2	2	0	5
Tavush	3	3	0	3
Syunik	2	0	2	4
Shirak	1	1	2	5
Lori	1	1	3	5
Total	33	39	9	39
	72		48	

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CHANNEL-TO-PIPE CONVERSIONS IMPROVE WATER USE EFFICIENCY, DECREASE ENERGY AND MINIMIZE CAPITAL COSTS

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ABSTRACT

Irrigators in Australia have suffered severe drought conditions for a number of years which has focused their attention on water efficiency measures. Many irrigation systems are moving away from the use of inefficient open channel irrigation systems in favor of pressure pipe networks to reduce losses due to seepage and evaporation. Murrumbidgee Irrigation in New South Wales utilized an innovative optimization approach that enabled significant improvements in the economic viability and environmental sustainability of its channels-to-pipe conversion.

In designing a large-scale irrigation or stock and domestic pipe networks, there are many decisions that need to be made to satisfactorily achieve the design criteria—to satisfy customer and environmental demands, minimum allowable pressure, maximum allowable velocity, etc. It is also desirable that the design decisions are made so these criteria are achieved at the least possible cost to society and the environment.

Once the objectives and criteria have been defined, the basic decisions that are made when designing a hydraulic network include the location of pipes, pump stations, valves and delivery points; the size, material and class of each pipe segment in the network; and the capacity and pumping regime of each pump station in the network.

In contrast to a traditional trial-and-error simulation analysis to design its pipe network, Murrumbidgee Irrigation elected to utilize an optimization approach that investigated hundreds of thousands of trial solutions to determine a least-cost network that satisfied the stated objectives. The resulting design exhibited better hydraulic performance and significantly reduced capital, operating and environmental costs.

BACKGROUND AND SETTING

Climate change, rising energy costs and limited water resources are issues gaining increased attention globally as they affect much of the world's population. Over the past decade, Australia has been particularly impacted by severe drought conditions in many parts of the country. This has forced the federal and local governments, urban and rural

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water providers, irrigators and individuals to become acutely attuned to the need for conservation and water efficiency.

The role of irrigators in Australia is recognized in the Blueprint for a Living Continent released by the Wentworth Group of Concerned Scientists in November 2002 (www.wentworthgroup.org/about, May 2009). It sets out a five-point plan for securing a sustainable future for the continent and its people:

1. Clarify water property rights and the obligations associated with those rights to give farmers some certainty and to enable water to be recovered for the environment.
2. Restore environmental flows to stressed rivers, such as the River Murray and its tributaries.
3. Immediately end broad-scale land clearing of remnant native vegetation and assist rural communities with adjustment. This provides fundamental benefits to water quality, prevention of salinity, prevention of soil loss and conservation of biodiversity.
4. Pay farmers for environmental services (clean water, fresh air, healthy soils). Where we expect farmers to maintain land in a certain way that is above their duty of care, we should pay them to provide those services on behalf of the rest of Australia.
5. Incorporate into the cost of food, fiber and water the hidden subsidies currently borne by the environment, to assist farmers to farm sustainably and profitably in this country.

In 2004, the Wentworth Group released its Blueprint for a National Water Plan. The document outlines solutions for the protection and restoration of fresh water ecosystems, water conservation, and the restoration of environmental flows to catchments such as the Murray Darling Basin. The Blueprint contributed to the National Water Initiative; a historic agreement by the Prime Minister, Premiers and Chief Ministers, resulting in the establishment of the National Water Commission and a $2 billion commitment from the Australian Government (www.wentworthgroup.org/about, May 2009).

BENEFITS OF CHANNEL TO PIPE IRRIGATION OPTIMIZATION

As billions of dollars are being committed in Australia to water supply, water conservation and water efficiency, the high proportion of water used for irrigated agriculture has become subject to more and more scrutiny. The situation is certainly similar in other countries including the U.S. western states. The increased focus on water efficiency measures in Australia has sparked interest in alternatives to inefficient open channel irrigation systems. One measure that is gaining favor in spite of its high initial capital cost is the use of pressure pipe networks in order to reduce losses from seepage and evaporation. Pressure pipe networks not only conserve water and increase water efficiency but they also provide far greater control and flexibility in irrigation applications.

The design of irrigation systems or stock and domestic pipe networks requires that specific design and performance criteria be satisfied. The criteria include meeting customer and environmental demands, and meeting minimum allowable pressures and maximum allowable velocities. The design should achieve these and other specified criteria at the least possible cost to society and the environment. It turns out that developing least-cost network designs is difficult especially when using the modern industry-standard approach that relies on a network hydraulic simulation model.

The steps involved in a network design are first to define the design objectives and criteria. Next the basic design decisions for the pipe network are identified, including:

1. the network layout including location of pipes, pump stations, and valves,
2. the size, material and class of each pipe segment in the network, and
3. the capacity and pumping regime of each pump station in the network.

Even when dealing with small-scale pipe networks, it is impossible for an engineer or modeler to explore all combinations of the decisions in trying to determine a least-cost network that satisfies the specified design and performance criteria. Usually a small number of different pipe network layouts are trialed until a satisfactory design is achieved, but such designs developed through trial-and-error and engineering judgment alone are often far from the best that could be achieved.

More powerful tools are available that can be applied to readily solve the least-cost irrigation network design problem. For example, Optimatics' genetic algorithm optimization technology is being used in Australia to help rural water authorities and irrigation districts develop superior solutions. The optimized network designs have resulted in water systems that both perform better hydraulically while significantly reducing capital, operating and environmental costs. The innovative optimization approach described in this paper has enabled significant improvements in the economic viability and environmental sustainability of channels-to-pipe projects worth over a billion dollars in total.

The benefits in converting from open channel to pipe irrigation and in applying a formal optimization technique to prepare the network design include more than just water conservation, reduced water losses and more efficient water delivery. Benefits have also included decreased energy use for pumping, a lower carbon footprint, and near-optimal designs that can save tens of millions of dollars in new infrastructure costs. With network designs that significantly reduce the required pumping effort, energy savings also contribute to cost reduction. As an added benefit CO2 emission levels over the life of the project have been significantly reduced. Several of these key benefits are illustrated in the case study presented below for Murrumbidgee Irrigation in New South Wales, Australia.

CASE STUDY — MURRUMBIDGEE IRRIGATION, AUSTRALIA

The Murrumbidgee Irrigation Area is located in the state of New South Wales within the Murray-Darling River Basin in southeast Australia (see Figure 1). The basin covers over 1 million square kilometers, which is equivalent to 14% of Australia's total area. The Murray-Darling Basin drains into the Darling (2740 km), Murray (2530 km) and Murrumbidgee (1690 km) Rivers, which are Australia's three longest rivers. The total area of crops and pastures irrigated in the Basin is almost 1.5 million hectares, which is 71% of the total area of irrigated crops and pastures in Australia (www.mdbc.gov.au/about/ basin_ statistics).

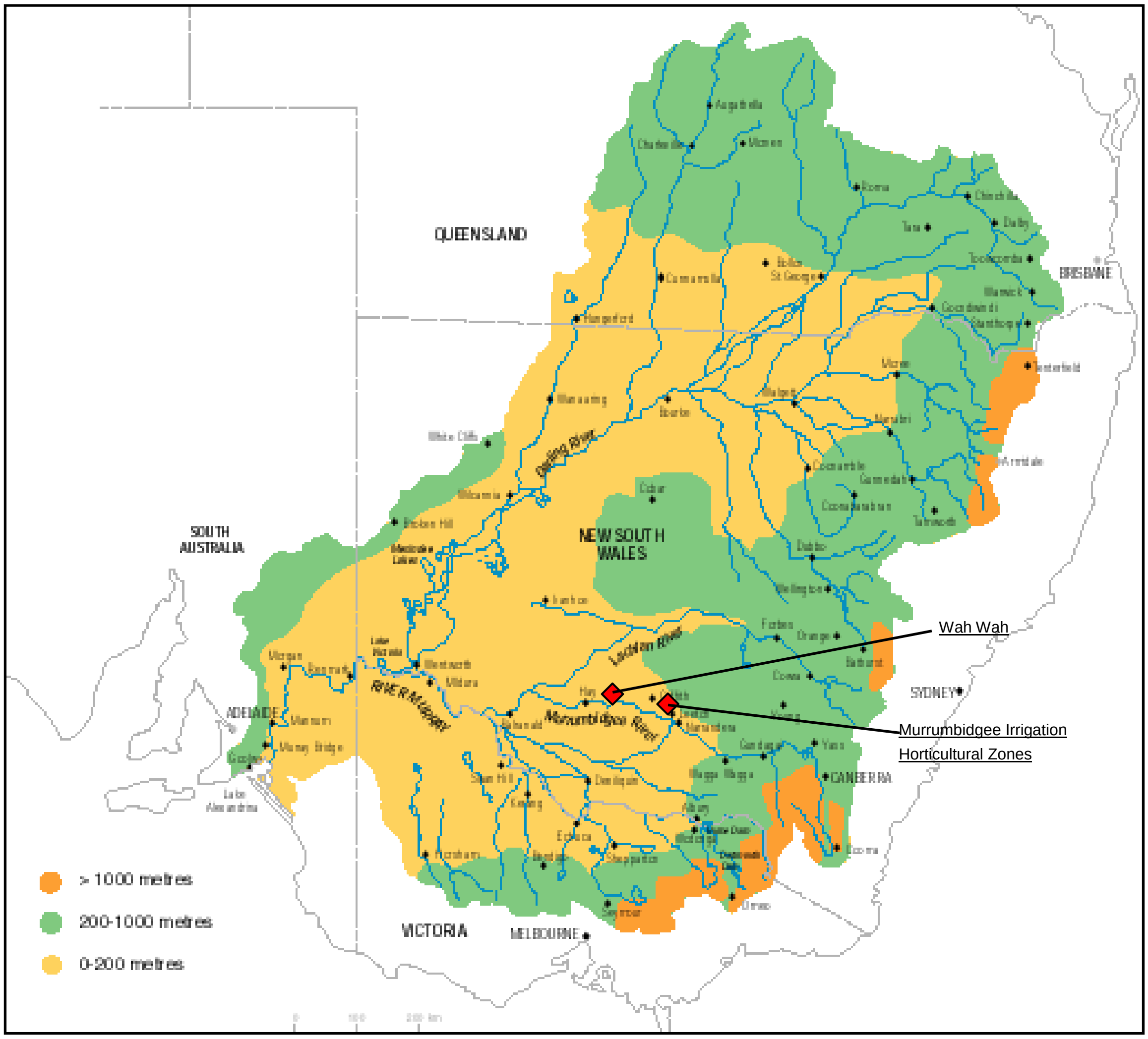

Figure 1. Murray-Darling Basin and Irrigation Study Locations

The Murrumbidgee Irrigation Area (MIA) was created under government ownership in the early 1900's to control and divert the flow of local river and creek systems for the purpose of food production. Irrigation water started flowing in 1912. MIA covers an area of 3,624 square kilometers with a local population of about 35,000. The topography is mostly flat open plains with Mirrool Creek draining the area. Two major storage dams with a combined storage of 2,654,000 ML supplies the irrigation flows. In 1999, MIA devolved from government ownership and is now owned and controlled by those who use the water (www.mirrigation.com.au/AboutUs/Water_for_Life.htm).

Figure 2 shows the Murrumbidgee Irrigation Area with the Mirrool and Yanco Irrigation Areas to the east and the Wah Wah Irrigation District to the west. Large area farms ranging from 200 to 320 hectares grow rice, corn, wheat and vegetables, prime lamb, wool and beef. The horticultural districts are scattered throughout the MIA and are characterized by good soils, concrete lined channels and high water security to suit high value crops like wine grapes, oranges, lemons, peaches, apricots, grapefruit, cherries, prunes and plums. Their average farm size is 16 to 20 hectares. Until recently furrow irrigation was the irrigation application method of choice.

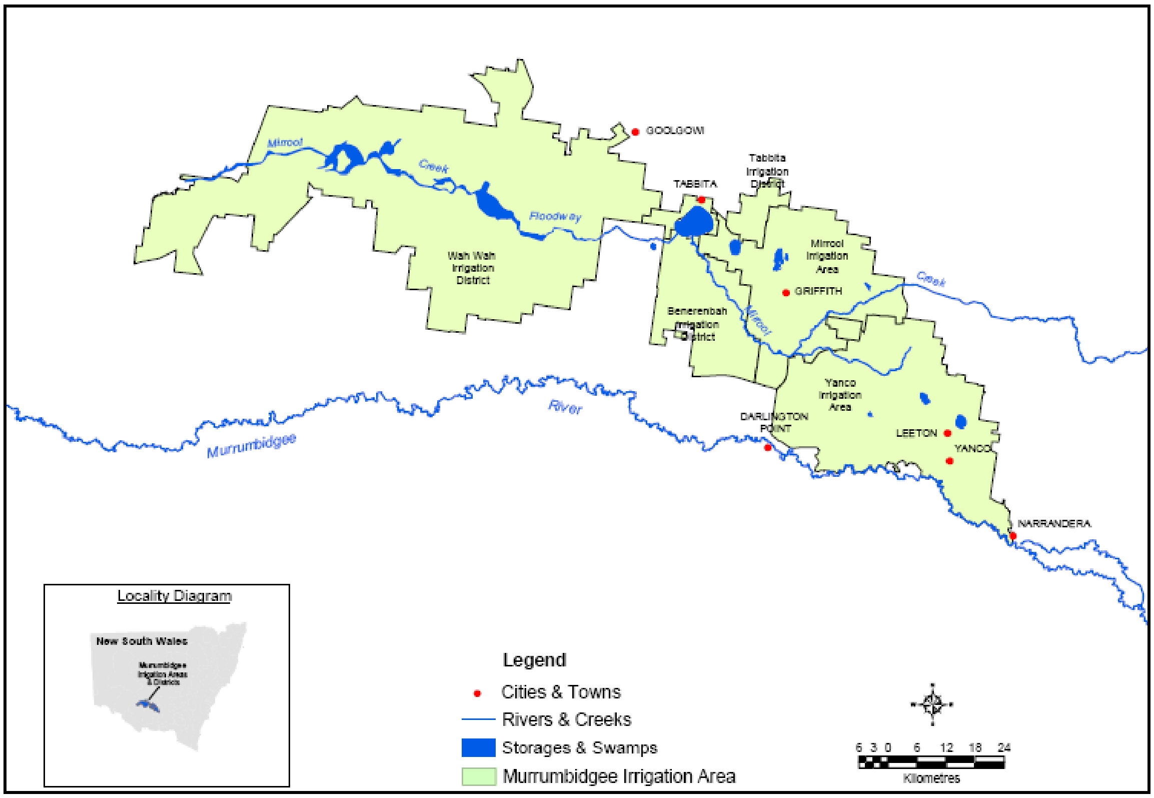

Figure 2. Murrumbidgee Irrigation Area

The recent extensive and severe drought has significantly impacted New South Wales and the farming communities of Murrumbidgee Irrigation Area. Water supplies have been drastically reduced and irrigation flows have been cut back. Murrumbidgee Irrigation has responded with a number of off-farm and on-farm initiatives to optimize available capital and water.

For example a community-wide plan called MIA EnviroWise is aimed at improving the integrated management of land, water and biodiversity. The program is concerned with ensuring the environmental and economic sustainability of the region.

MIA EnviroWise promotes water use efficiency programs designed to more accurately measure water supplied to crops and decrease the amount of water entering the underground system. Using water more efficiently means irrigators have water available for more cropping, and the environment benefits through decreased impacts from higher water tables. MIA EnviroWise programs also target water quality with initiatives that will improve the quality of water returned to the Murrumbidgee and Murray Rivers.

MIA EnviroWise Incentive Programs give farmers an opportunity to access a range of financial and other incentives for implementing improvements to their on-farm works. Efficiencies that have been implemented in the MIA include conversion to drip irrigation systems, soil moisture monitoring systems and soil suitability tests.

MI's Optimized Pipe Irrigation System Design Problem

A key component of Murrumbidgee Irrigation's (MI) capital works program targets the replacement of open channels in the horticultural districts. Conversion of these delivery systems to pipe systems reduces "off-farm" water losses, but also forms an important catalyst for "on-farm" water savings because centralized pumping and a high pressure delivery system enables cost-effective uptake of efficient drip and micro sprinkler irrigation.

A key part of the strategy for maximizing water savings and beneficial use of capital is the optimized design of the pipe systems. MI engaged Optimatics to plan, design and optimize the replacement of channel irrigation networks with more than 450 km of a new pipe system covering 30,000 hectares. The pipe network system was optimized to the minimize resources required (considering pipe diameter sizes and pumping energy needs) and the project capital costs and lifetime operating expenditures. Initially the optimization was formulated to determine optimal boundaries between the new distribution systems which unlike the channels, would no longer be constrained by contour. The number and location of pump stations was optimized and the relationship between cost and service level (peak flow rate per area, and minimum pressure) was also investigated. This required concurrent optimization of the locations of farm outlets which were not constrained to the existing outlet location from the supply channel.

With thousands of hectares of farm land to supply, MI required pipe network designs which covered thousands of square kilometers at a potential cost of hundreds of millions of dollars. MI's aim in choosing to apply a proven formal optimization approach was to identify least-cost, hydraulically robust designs. This could only be accomplished by considering a wide range of design options (pipeline diameters, pump stations, outlet locations) and optimizing each element in the designs.

The steps involved in the irrigation system optimization involved first creating hydraulic simulation models for each of the pressurized pipe networks to be designed. The models represented Murrumbidgee Irrigation's customers in 22 of its total 28 horticultural zones. To represent these customers, MI's GIS data was used to automatically determine the coordinates of each farm, and also calculate each of the farm areas so that demands could be developed. Through discussions with MI, three irrigation water demand loading cases were developed to represent peak loading, spur loading and average loading.

Once the models were created, potential pipeline and pump station options were identified for each area taking into account information provided by MI on existing open channel routes, roadways and farm boundaries. Preferred delivery points for each farm were also noted, and not constrained to the existing delivery points which were on the high side of the farm to suit gravity flow to on-farm furrow irrigation. MI requested consideration of a number of outlet locations for each farm based on the midpoints of the individual farm boundaries.

The optimized designs had to satisfy the design criteria specified by MI:

- Minimum allowable pressure criteria of 40 m
- Maximum flow rate criteria on some supply channels
- MI's spur loading rules (3 tail end outlets)
- Least present value of capital and future (discounted) energy costs

Two additional criteria were included but they did constrain the solutions:

- Maximum allowable pipe flow velocity criteria of 3 m/s
- Maximum allowable pressure criteria based on pipe class (72 m for Class 9)

Making Use of a Powerful Optimization Technique

Each of the 22 horticultural zones and additional stock and domestic areas to be designed represented a significant design problem. There were many variables (pipe locations and sizes, pump stations, pumping heads, outlet locations, etc.) and many potential viable solutions. Genetic algorithm (GA) optimization is a proven search technique that can handle such large problems to enable designers to find least-cost viable solutions.

Genetic algorithm (GA) optimization was first developed in the 1970's by Professor John Holland at the University of Michigan. It has since been applied to many industries to identify near-optimal solutions to complex engineering problems. GA optimization was first applied to water distribution system by researchers at the University of Adelaide in 1990. Optimatics has been applying GA technology to the optimization of water systems since 1996.

Genetic algorithm optimization is an evolutionary technique based upon the mechanisms of natural selection and genetics. "Survival of the fittest" relentlessly drives the genetic algorithm towards improved solutions. The GA process involves the selection, combination and manipulation of possible solution options represented by strings of numbers analogous to chromosomes.

GA optimization is a tremendously powerful and efficient optimization technique. Starting from an initial population of trial solutions (at generation 0), the GA uses certain operators to derive a subsequent population of off-spring solutions (at generation 1, 2, etc.). The three operators of selection, crossover and mutation act on successive generations to drive a process akin to natural selection. The fittest solutions in each generation have the greatest probability of surviving and then breeding to "evolve" better and better solutions. Fitness is a measure of each solution's cost and hydraulic performance.

With thousands of hectares of farm land to supply, thousands of potential pipeline routes and dozens of pump station sites to consider, the industry-standard trial-and-error simulation approach for the Murrumbidgee Irrigation Area is unlikely to identify least-cost solutions. A simulation-only approach cannot easily be applied to minimize capital and operating costs, while also satisfying the many hydraulic criteria (peak demands, minimum allowable pressures, maximum allowable pipe flow velocities). By applying GA optimization to the problem, Murrumbidgee Irrigation was assured that hundreds of millions of potential solutions were evaluated in the search for the best designs that suited their needs.

MI Horticultural Zones Optimized Design

One focus of the project was on supplying water to MI's Horticultural Farms in the Mirrool and Yanco areas, which mainly cultivate stone fruit, citrus and vines. By converting from open channels to pressure pipe delivery systems, the estimated water savings for MI Horticultural Zones are in the order of 50,000 ML/yr in off-farm and on-farm irrigation.

As described above, the optimization of horticultural zones involved large-scale hydraulic simulation model building covering many hectares of farm land, development of farm demands, and improved application of MI's spur loading demand rules. As the project proceeded, it also included optimization of additional farm irrigation water outlet delivery locations, and a greater number of decision variables (pipeline diameters, pump station sizes and locations, outlet locations) per optimization run.

Figure 3 illustrates the hydraulic model construction for Zone 18 (Tharbogang). The irrigation pipe location options for the most part follow existing open channels and farm boundaries. Six options to locate one or more new pump stations were considered as shown. Alternative outlet locations along each farm boundary are represented by the nodes in the model. Each optimization model run was carried out taking into account several demand loadings to ensure the selected pipelines and pumps could deliver the full range of anticipated irrigation flows and pressures. Each optimization run was formulated to evaluate and minimize project life-cycle costs considering both capital costs and lifetime operating costs.

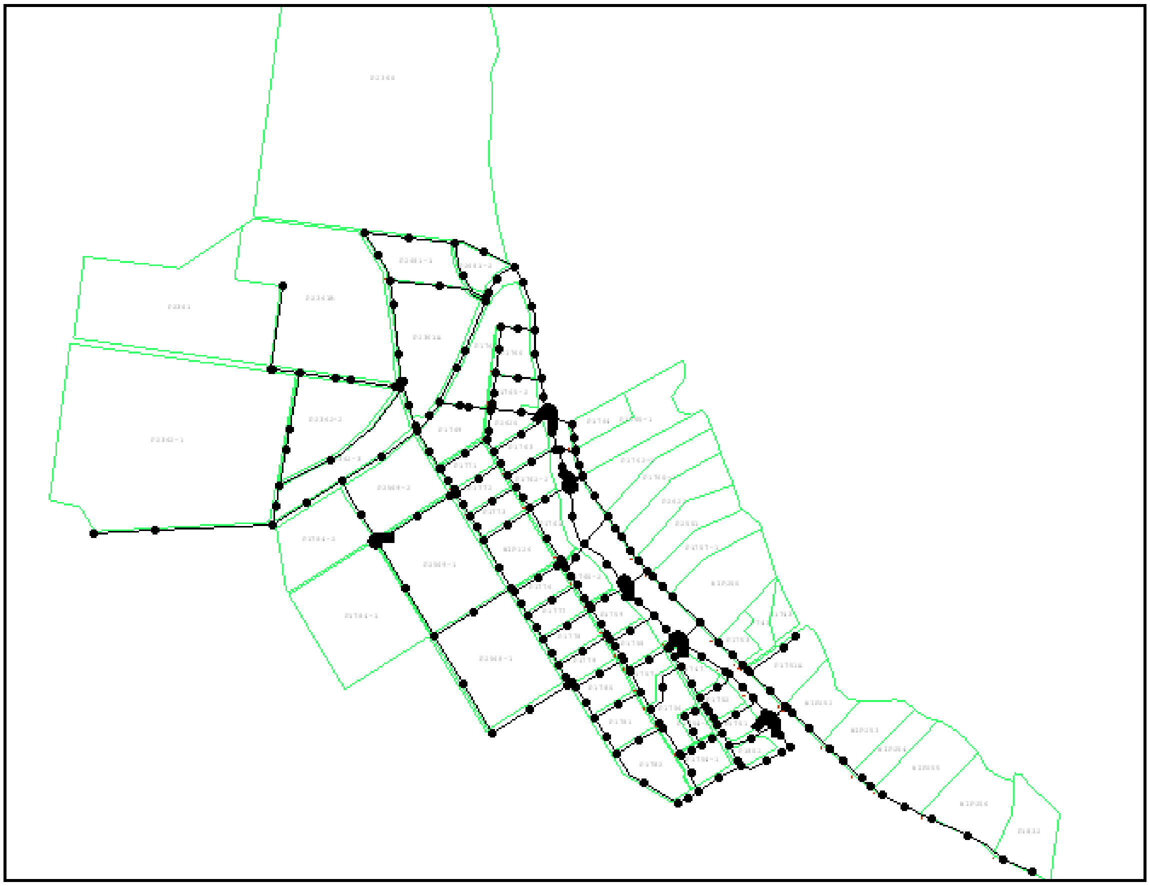

Figure 3. Zone 18 Hydraulic Model with Pipe and Pump Options

From the mix of allowable decision variable choices, the optimization created and evaluated in the hydraulic model millions of trial solutions as it searched for the best combination of options to satisfy the design criteria at the lowest cost. The final solution costs for each optimized area were critically important as the cost of the pipe schemes are being passed onto the growers through water purchase costs.

After optimization, Murrumbidgee Irrigation continued consultation with growers in Tharbogang and awarded a public tender for detailed design to HydroPlan. Following survey and site investigations, Optimatics revisited the analysis to ensure the latest pipe material and cost information was considered and to pin-point optimal pumping pressures. The final station is effectively two in one to respond to demand at farms which are higher and lower than the pump station. One delivers from 0 L/s at 45 m to 584 L/s at 78 m, and the other delivers from 0 L/s at 86 m to 460 L/s at 117 m.

Figure 4. The pump station at Tharbogang has 11 pumps to respond to demand

The overall MI channels to pipe optimization has the potential to pass on lower costs to hundreds of growers, as well as providing a more efficient scheme to water their crops and reduce water losses through evaporation and seepage that are systemic in open channel flow delivery systems.

Table 1 summarizes the final results of the optimized pipe network designs for 22 of Murrumbidgee Irrigation’s 28 Horticultural Zones.

Table 1. Solution Cost Breakdown for 22 MI Horticultural Zones

Zone	Total pipe length (m)	Total pipe capital cost ($ million)	Total pump capital cost ($ million)	Total pump operating cost ($ million)	Total solution cost ($ million)
Zone 4,5,6	49,646	$2.78	$2.08	$4.39	$9.25
Zone 7&8	12,981	$1.00	$1.01	$2.02	$4.03
Zone 9	71,945	$9.02	$6.56	$11.07	$26.65
Zone 10	10,205	$0.93	$0.87	$1.59	$3.39
Zone 11	47,670	$3.88	$2.41	$4.31	$10.59
Zone 16	35,336	$3.90	$1.72	$3.35	$8.97
Zone 17	26,330	$3.49	$2.00	$3.34	$8.84
Zone 18	13,980	$1.18	$0.97	$1.62	$3.77
Zone 19&20	25,706	$1.26	$0.96	$1.77	$3.99
Zone 21&22	76,840	$7.20	$6.36	$11.33	$24.88
Zone 24	13,435	$0.65	$0.51	$1.21	$2.37
Zone 25&26	53,660	$4.05	$2.54	$5.08	$11.67
Zone 27	17,268	$0.94	$0.69	$1.31	$2.94
Total	455,000	$40.28	$28.69	$52.38	$121.35

Note: Total pump operating cost is the estimated present value over the project life.

MI Wah Wah Stock and Domestic Optimized Design

Optimatics also assisted Murrumbidgee Irrigation with the design of a large stock and domestic system for the Wah Wah area. The Wah Wah stock and domestic system is currently supplied through open channels which again are to be replaced with a pressure pipe system. The estimated water savings are in the order of 10,000 ML/yr during dry years.

Whereas many of the larger Horticultural Zones had demands exceeding 5,000 L/s and required multiple large capacity pump stations and large diameter pipelines, total demand for the Wah Wah stock and domestic system is just 65 L/s. However, the Wah Wah system covers a much larger area than the entire Horticultural zones of Mirrool and Yanco—resulting in 1,600 km of pipelines compared to 455 km of pipe network for the Horticultural Zones.

The optimization of the Wah Wah stock and domestic system was complicated by the large area the system covers (long sections of pipeline to be sized and optimized), the flexibility of outlet locations, potential booster pump station locations and a number of different source and storage options. Over a dozen different solutions were developed and optimized for the Wah Wah system. These solutions considered different sources, storage, booster pump stations, consideration of on-farm costs, plus sensitivity to demand peaking factors. Total solution costs for the Wah Wah system ranged from A$32 million to A$84 million. Figure 5 shows the range of solution costs. The ease with which the optimization analysis was able to develop near-optimal solutions for a large number of alternative scenarios illustrates a further significant benefit to utilizing optimization to design pipe irrigation systems.

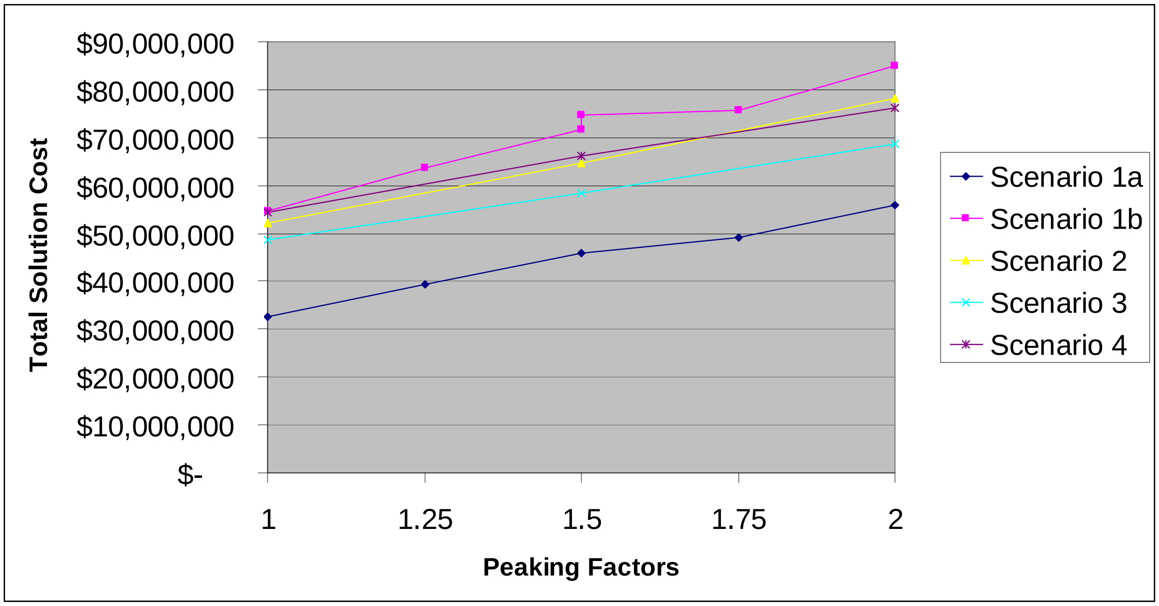

Figure 5. Wah Wah Optimized Solution Costs for Different Scenarios and Demands

SUMMARY AND CONCLUSIONS

The Murrumbidgee Irrigation case study presented in this paper describes how a powerful formal optimization technique was applied to develop optimized pipe irrigation project designs for both horticultural and stock and domestic irrigation systems. Other irrigation authorities in the area, such as Lower Murray Water, Coliban Water and Goulburn Murray Water, have also carried out irrigation optimization projects. In each case the optimization objective was to design a pressurized pipeline system to replace inefficient open channel irrigation systems.

Water losses in open channels through seepage and evaporation are the cause of major inefficiencies in irrigation systems. Replacing open channels with efficient pressure pipe systems is essential to the on-going sustainability of water resources, particularly under changed climate conditions as New South Wales, Australia feels that it has experienced. The savings in water are certainly significant for the case studies cited above:

- Murrumbidgee Irrigation Horticulture Zones - 450 km of new pipe for 50,000 ML/yr in estimated water savings
- Wah Wah Stock and Domestic – 1,600 km of new pipe for 10,000 ML/yr in estimated water savings

The power of the optimization used in designing the pressure pipe networks allows various objectives and options to be optimized. For example, these systems require hundreds of miles of pipelines to be routed and sized, exhibit complex spur loading rules, require trade-offs between pumping capacity and pipeline capacity, and require pipe class considerations to be taken into account.

By optimizing the pipe network designs for these irrigation system, irrigation authorities can implement more efficient systems that can better respond to a range of demand conditions. The optimization is able to evaluate the system sensitivity to various assumptions including high pressure system versus low pressure system, different source options, different demand rates, different outlet locations, different pump options, etc). Finally the irrigation authorities and the growers benefit from lower cost designs.

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WATER MANAGEMENT FOR SUSTAINABLE AGRICULTURAL DEVELOPMENT OF NORTH SINAI, EGYPT

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ABSTRACT

Optimum management of the currently available limited water resources in Egypt is important for making water savings for land expansion necessary for increased food security. One of the ways for more efficient use of this water is to recycle the agricultural drainage water through either direct use or after blending it with freshwater. The study reported here is based on an assessment of the water resources and cropping patterns in the North Sinai Development Project (NSDP) area. It reassessed the availability of drainage water from the Nile Delta and freshwater resources required to meet the demand of the quantity and the quality of the of irrigation water for the entire project area. The study re-examines the crop rotations originally planned by the project planners, and, considering the recent cropping interests of local farmers and expected changes in availability and quality of the drainage water, it suggests new cropping patterns and, accordingly, the readjusted water demand for the whole NSDP area. The crop intensity in the recommended cropping pattern will be 178% as compared to 167% in the original plan. The study also examines the current policy of allocation of the newly reclaimed land to various stakeholders (big investors, small investors, and small farmers) and it concludes that as the small-holder farmers tend to manage best the newly reclaimed lands allocated to them, their share in the allocation should increase. Irrigation with Nile water and drainage water mixtures in a 2:1 proportion, instead of 1:1 as originally planned, would be desirable to support sustainable agriculture in the area.

INTRODUCTION AND BACKGROUND

In an attempt to improve the productivity and sustainability of water use and increase water supply to bring 0.26 million ha additional land under cultivation, Egypt initiated the North Sinai Development Project (NSDP) in 1997. The irrigation canal of NSDP has been designed with the objective to discharge 4.45 billion m^3 of water, which is a 1:1 blend of agricultural drainage water with freshwater from River Nile.

The objective of the Project was to improve income distribution, to generate employment through the settlement of small holders, and to create new communities within the project

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area. To increase the amount of available irrigation water for the increased land, the Project focused on the reuse of agricultural drainage water by mixing it with fresh water from the river Nile. The salinity of drainage water is a function of the salinity of the applied water, soil salinity, and the salinity of the shallow groundwater (Ayers and Westcot, 1985, Pescod, 1992). Appropriate water management can reduce the volume of drainage water and make water available for other beneficial uses. Land management needs special consideration where competition for water is intense and where disposal of drainage water threatens ecologically sensitive areas.

In the next few years the amount of drainage water from the Nile Delta is predicted to be reduced due to the adoption of better water management practices. In this scenario, the use of drainage and fresh water in a 1:1 proportion will not be a pragmatic approach due to an increase in the salinity level of the drainage water.

In the early years of the NSDP, a small portion of the area had been reclaimed and handed over to the farmers settling there with a prescribed crop rotation plan. But after some time, when more migrant farmers got established there, they, based on economic considerations and traditional habits, started adopting new crops and rotations that were not prescribed by the Project in the original plan. Therefore, there is an urgent need to re-evaluate the planned cropping patterns considering the interest and values of local farmers and the changing situation regarding the volume and quality of drainage water for the scheme. The information would be of value to the NSDP planners because the Project was originally designed to meet the water requirements of the target area based on the planned cropping patterns. Therefore, it is necessary to reassess the available water resources and their use and develop appropriate recommendations to meet the objectives of NSDP. The study reported here was designed with two main objectives: a) to reassess the drainage water from Nile Delta and available fresh water resources and the proportion of their mixing to meet the quality irrigation water demand of the NSDP target area, and b) to re-assess the crop rotation plan considering the interest of local farmers.

WATER RESOURCES OF THE DELTA AND SINAI

Of the 55.5 billion m^3 water reaching Egypt via Nile River, most is used for irrigation purposes along the Nile Valley and the Delta generating approximately 14.0 billion m^3 of drainage water flowing out to the Mediterranean Sea. Rapidly increasing food demand in the face of limited water resources available is threatening development in Egypt. Therefore, full exploitation of the limited water resources is very important, especially through the improvement of irrigation system. Recognizing this fact early, the Egyptian Ministry of Water Resources and Irrigation (MWRI) initiated mitigation measures and a number of development projects were started to increase irrigation efficiency and agricultural productivity, as well as to improve drainage and groundwater management. For example, the objective of designing and implementing subsurface drains on 2.7 million hectares and open drains on 3.1 million hectares, has led organizational development for the past 30 years. By 2005, more than 75% of the horizontal pipe drains in the “planned” areas, and more than 95 % of the open drain areas, had been completed

(Carlos Garcés-Restrepo, 2005). The so-called "official" reuse of drainage water has increased from 2.6 billion m^3 in 1988/89 to 5.0 billion m^3 in 1998/99. In addition to the "official" reuse of drainage water, there is a significant amount (between 2.8 and 4.0 billion m^3) of "unofficial" drainage water being used by individual farmers throughout the region. There is no control on the amount of this unofficial reuse by farmers (Carlos Garcés-Restrepo, 2005). The NSDP canal is planned to discharge 4.45 billion m^3 water, of which 2.340 billion m^3 will be agricultural drainage water from the El-Serw (about 0.435 billion m^3), Bahr Hadous (about 1.905 billion m^3) and Farskour drains (to supply the rest of the amount of drainage water needed). The required amount of fresh water to meet the 1:1 ratio (fresh water: drainage water) is supplied from the Nile river. The information on total water resources of Egypt and the amount of discharge water from each drain is given in Table 1. The mean precipitation in Sinai is 200 mm, which is considered to be very high in Egypt. Most of the rain water goes to the sea and some causes occasional disasters. Thus, precipitation in Sinai is not considered to be a water source.

Table 1. Water resources supply in Egypt and Sinai Development Project

Egypt Water Resources	Supply (BCM)	Sector	Demand (BCM)	Sinai Water Resources	Supply (BCM)
Nile River	55.50	Agriculture	61.00	Damietta branch	2.11
Renewable GW*	5.50				
Non-Renewable GW	0.50	Municipalities	4.60	El Serw drain	0.435
Drainage Water Reuse:					
-Nile Delta	4.90	Industry	7.50	Bahr Hadous drain	1.905
-Nile Valley	4.95				
-Unofficial	2.80	Navigation	---	Faraskour drain	Drainage water deficit
Wastewater Reuse	1.00				
Effective Rainfall	1.00	Hydropower	---		
Desalinization	0.03				
Losses	3.00	Fisheries	---		
Total	73.18		73.10		4.45

*GW is ground water

Abou Rayana et al. (2001) reported that the groundwater with salinity level ranging from very high (TDS=20,000 mg l^{-1}) to low (TDS=300~700 mg l^{-1}). The groundwater with low salinity level is used for domestic and agriculture purposes. In the northern coastal areas, about 1,260 wells have been used to draw about 108,500m^3 d^{-1}water, of which 58,000m^3 d^{-1} is used to irrigate 4,134 ha of agricultural land and about 50,000 m^3 d^{-1} is for municipal use (Table 2).

Table 2. Discharge and total area irrigated from groundwater on the north coast of Sinai

Area	Number of wells	Daily discharge ($m^3\ d^{-1}$)	Total irrigated areas (ha)
El-Arish	195	51,500	2,142
Sheikh Zuwayid	147		244
Rafah	256	43,000	1,395
Bir El-Abd	662	14,000	353
Total	1,260	108,500	4,134

CROPPING PATTERNS FOR NSDP

For NSDP, three cropping pattern scenarios were examined: the planned cropping pattern as set out in the original project design, the actual cropping pattern being followed currently by farmers in the area, and a cropping pattern recommended for wise use of water taking into consideration the economic and cultural needs of the farmers and current availability of water resources. The project plan suggested different crop rotations for the three different soil types, namely clay, sandy and coastal soils, common in the area. On the farm level, farmers are required to divide their land in to three sections each having one of the phases of a specific three year crop rotation planned based on the soil type and irrigation system. For example, crop rotation with rice on clay soil helps to leach down the salts and consequently, controls soil salinity hazards. Similarly, the project planners suggest surface irrigation system for clay soil. Under sandy and coastal soils; sprinkler irrigation has been suggested for agricultural crops while drip irrigation was suggested for fruits.

Before the start of NSDP, this kind of crop rotation plan was prepared for the newly rehabilitated farmers (Fig. 1). Part of the project area (Tina plain and South of East Qantara) in North Sinai has been now developed and the farmers there have been advised to adopt the above mentioned crop rotation plan. Most of the crops which were being cultivated by the local farmers before the start of project were not included in the planned crop rotations.

Before the start of the irrigation canal construction for development of North Sinai in 1997, wheat, barley, tomatoes, and cantaloupe were the main winter crops and the main summer crops were tomatoes, cucumber, cantaloupe, and watermelon. But all these crops were not included in the planned crop rotation for that area. With the passage of time, farmers started including these crops in the rotation, not sticking to the plan. Therefore, re-assessment of the planned cropping pattern considering the interest of the local famers was needed. This was also important for the project planners because NSDP was designed to meet the water requirements of the target area based on the planned crop rotations rather than those actually being practiced by the farmers. A socio-economic study was recently conducted by Drainage Research Institute (DRI) and Water Management Research Institute (WMRI) of Egypt to assist the development of future agricultural plans for farmers in El-Tina Plain (DRI and WMRI, 2006). The result indicated that 67% of the selected farmers preferred agricultural crops such as cotton, rice, wheat and alfalfa, 21 % of the selected farmers preferred fruits, 8 % of the selected farmers preferred vegetables and only 4 % wanted to plant trees.

Based on the above survey done in 2006, the cropping pattern of local farmers before 1997, and the current interest of newly rehabilitated farmers in the area, a new recommended crop rotation pattern has been postulated and presented in juxtaposition with the originally planned crop rotations (Fig. 1). It can be noticed that the planned rotations have different combinations of crops than the crops cultivated by the farmers before 1997 as well as their current preference as indicated by the survey. For example, wheat and barley, which accounted for 92% of the total area under winter crops in Sinai area during 1997, have not been included under any soils type in the planned cropping pattern. Under recommended crop rotation plan, we suggest not only inclusion of wheat and barley, but also Egyptian cotton because of its high economic returns. To maintain soil fertility, crops such as clover (alfalfa) have also been included. Moreover, the land use has been increased to 178 % under the recommended cropping pattern as compared to 167 % under the rotations planned by the Project.

In the planned crop rotation, under clay soils, short clovers, onion, vegetables and sugar beet for winter and soybean, rice and sorghum for summer season were included. However, in the recommended cropping pattern, we have included wheat and barley for winter and cotton for summer season (Fig. 1). The introduced crops will meet the demand of local consumption, maintain the soil fertility, meet onsite farmer needs and take into consideration the current food security crisis in the country. Based on the recommended cropping pattern, Tina plain is recommended to have 66.7, 16.7 and 16.6 % of the irrigated area under cereals, fodder and vegetables, respectively.

On the sandy soils, planner suggested fruits, long-duration clovers, vegetables and potato. But we have included wheat, barley and short-duration clover for winter and potato and maize for summer season in the recommended crop rotation (Fig. 1). Based on these modifications, the pattern on sandy soil is recommended to have 43.3 % area under cereal crops, 20 % under fodder crops, 26.7 % under vegetable irrigated by sprinkler system, and 10 % under fruit trees to be irrigated by drip system.

Crop rotation planned for loamy soils included fruits, short clover, vegetable and sorghum. In the recommended crop rotation we have included wheat, barley and maize in addition to the planned crops (Fig. 1). Consequently, the cropping pattern on loamy soils is recommended to have 43.3% area under cereals crops, 26.7% under fodder crops and 20% under vegetables to be irrigated by sprinklers and 10% under fruit trees to be irrigated by drip system.

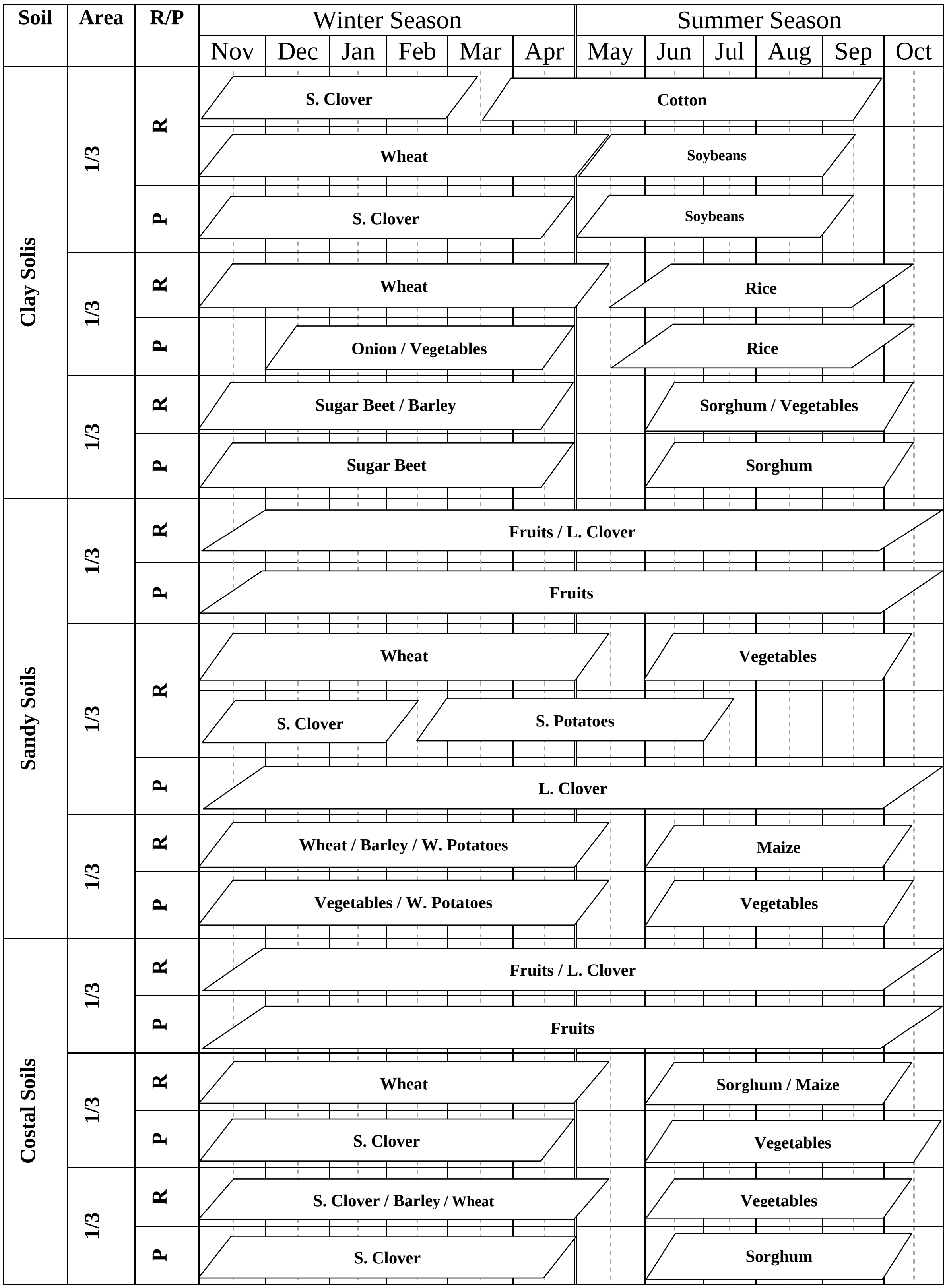

Figure 1. Planned (P) and recommended (R) crop rotation patterns for the North Sinai Development Project

Currently, Ministry of Agriculture and Land Reclamation is monitoring the cropping patterns. The government officially controls the area under rice and cotton cultivation. Rice growers need to obtain a cultivation permit from the Ministry of Water Resources and Irrigation (MWRI). These observations by the government will help to evaluate the recommended crop rotation in the area after a few years of application. It is worth mentioning that the cropping pattern will have to be reviewed every few years considering the interest (reaction/response) of the local famers and the change in the availability of water resources.

NSDP LAND ALLOCATION

As soon as the area is reclaimed, it is distributed among the big investors, small investors, and small farmers. Fifty percent of the land is allocated to big investors, 35% to small farmers and graduates and 15% to small investors. Table 3 presents the land allocation, reclamation and revegetation of land in the NSDP area until March 2007. Data show that the area used for cultivation by different stakeholders of Tina plain varied markedly from what was planned: small farmers (56.1%) > big investors (31.3%) > small investors (12.3%). In case of South Qantara, the distribution was: small farmers (54.5%) > big investors (26.2%) > small investors (19.3%). In general, 29.8 and 75.8 % of Tina plain and South of East Qantara areas were cultivated, respectively. It is clear from the data that the small farmers paid the most attention on the newly reclaimed soils and did maximum cultivation. Therefore, we recommend the reallocation of reclaimed lands to increase the percentage of land for the small farm holders.

Table 3. Allocation of privatized, delivered, cultivated, and prepared area (ha) in Sahel El Tina plain and south-east of Qantara to big and small investors and small holders under the NSDP up to March, 2007

Region	Category	Privatized areas	Delivered areas	Cultivated areas	Processed areas for Agric.	Prepared areas for planting	Categories allocated (%)
El Tina Plain	BI	7,560	7,560	1,327	1,665	4,575	50
	SI	2,110	2,110	525	532	1,053	15
	SH	4,536	4,536	2,381	1,187	968	35
	RF	42	42	13	-	2,9.4	-
Sahel El Tina		14,247	14,247	4,246	3,376	6,625	-
S of E. Qantara	BI	4,775	4,631	2,915	21	1,695	50
	SI	5,229	3,718	2,142	25.2	1,551	15
	SH	9,116	6,311	6,048	37.8	225	35
S of E Qantara		19,120	14,660	11,105	84	3,471	-
Total		33,367	28,907	15,351	3,460	10,096	-

BI = Big investors, SI = small Investors, SH = small Holders and RF = Research Farm

IRRIGATION WATER SALINITY

As the fresh water resources are limited, therefore, the area under NSDP was supposed to be irrigated with a mixture of drainage and fresh water in a ratio of 1:1. The required amount of drainage water is pumped into the fresh water (El-Salaam canal) from the Nile River. The suitability of reuse of drainage water for irrigation is determined by the amount and kind of salts, generally using with FAO guidelines (FAO, 1985).

The planning of NSDP was started in 1986 and was partially completed in 1997. Their decision to use the proportion 1:1 of fresh water to drain water was based on the data available up to 1997, but during the last few years changes have been observed in the amount of drainage water generated in the Nile Delta. The reduction, especially during 1993 and 1994, might be attributed to the adoption of better irrigation water management practices in the area. However, with the reduction in drainage water there has been a commensurate increase in the concentration of total dissolved solids (TDS). Figure 2 shows the average TDS values of El-Serw, Faraskour, and Bahr Hadous drains in the period from 1988 to 1998 ranged from 992 to 2,896 mg l^{-1} with an average of 1,341 mg l^{-1}. The highest values in the period from 1989 to 1994 were recorded in the month of February because of the lower volume of drain water discharged during this month. To determine the relationship between amount of discharge in ($m^3 s^{-1}$)(Q) and TDS concentration (ppm) in drainage water, a simple polynomial relationship was identified from the monthly drains discharge and TDS data of El-Serw, Farskour, and Bahr Hadous drains from 1988 to 1998 as shown below:

$$TDS = 0.725 Q^2 - 85.13Q + 3688 \quad (1)$$

As the degree of fit was very good (r^2 = 0.7114), this relationship can be used to predict the future water quality of the drainage water available for the Project.

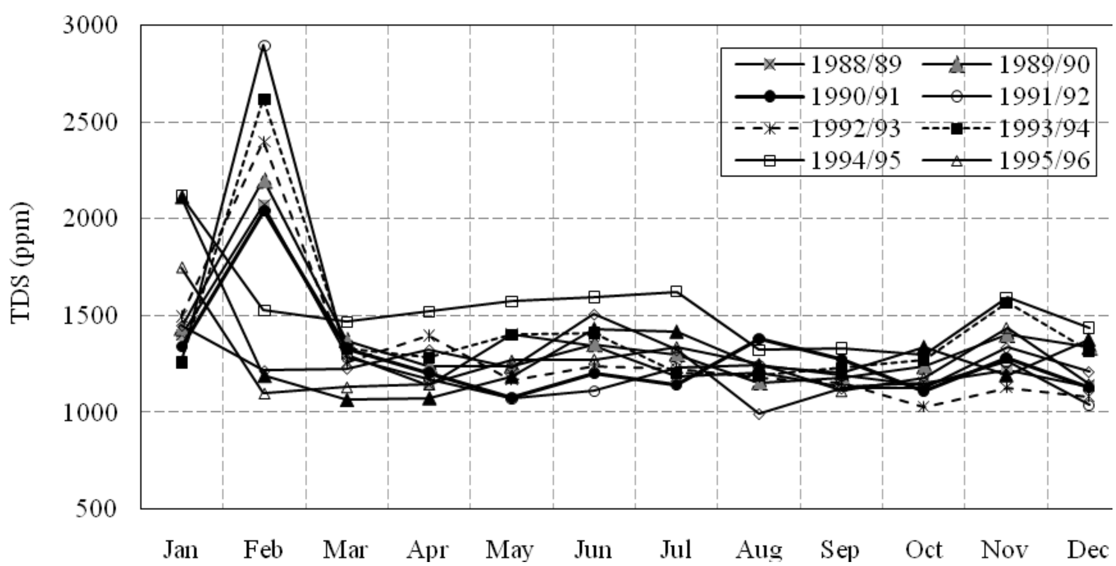

Figure 2. Monthly total dissolved solids (TDS) in NSDP drains during 1988-98.

Water samples were also taken by Hafez et al., (2008) along the main El-salaam and El-Sheikh Gaber canals (carrying blended water), to analyze the soluble cations, anions, EC, sodium adsorption ratio (SAR) and pH by using standard laboratory methods (Table 4). The SAR of water was computed to obtain an indicator of potential soil sodification using the following equation:

$$SAR = [Na^{+}]/\sqrt{([Ca^{2+}]+[Mg^{2+}])/2} \quad (2)$$

Table 4. Chemical properties of the irrigation and drainage water and soil of NSDP (Hafez et al., 2008)

Location	pH	EC (µmhos)	SAR	TDS (mg l^{-1})	Cation (meq l^{-1}) Na^{+}	K^{+}	Ca^{2+}	Mg^{2+}	Anion (meq l^{-1}) HCO_3^{-}	Cl^{-}	SO_4^{2-}
1	7.9	680	32.7	967	195	9	62	34	277	266	138
2	7.8	1400	32.7	967	195	9	62	34	277	266	138
3	7.9	1400	34.6	678	206	9	62	36	231	271	123
4	7.7	3200	69.0	2092	512	14	96	78	291	687	412
5	7.8	4000	74.0	2556	613	16	121	98	352	973	371
6	7.8	3800	75.6	2506	609	16	114	94	322	943	449
7	7.2	1500	75.3	2513	612	16	116	92	328	943	512

where, Na^{+}, Ca^{2+} and Mg^{2+} are expressed in meq l^{-1}.

Seven sites were selected for water sampling from intake of fresh water into El-Salaam canal namely; 1) at intake of El-Salaam canal (Nile river), 2) at 17.0 km from intake point (before blending at El-Serw drain), 3) at 18.0 km from intake point (after blending at El-Serw drain), 4) at 47.2 km from intake point (after blending at Hadous drain), 5) at 87.0 km from intake point (before Suez Canal Siphon), 6) at 0.50 km from intake point of El-Sheikh Gaber canal (after Suez Canal Siphon), and 7) at 25.0 km from intake point of El-Sheikh Gaber canal. The SAR was minimum (32.7) at fresh water intake point of El-Salaam canal (Nile river) and the SAR values increased to 75.3 at the last sampling point (25.0 km from intake point of El-Sheikh Gaber canal), which were higher than the accepted SAR value (14) for irrigation water (FAO, 1985). Similarly, the EC also increased from the intake point (680 µmhos) to the last sampling point (1500 µmhos).

The data clearly show that the TDS values are fluctuating near the upper limits in locations 4, 5, 6 and 7. Abu-Zeid (1988) and Kotb et al. (2000) defined the criteria for mixing drainage and fresh water on the basis of drain water TDS. They suggested different blending ratios for different TDS values of drain water. At a TDS of <700 mg l^{-1} the drainage water can be used directly, at 700-1500 mg l^{-1} TDS it should be blended with fresh water at 1:1 ratio, at 1500-3000 mg l^{-1} TDS blending should be at 1:2 or 1:3 ratio, and at >3000 mg l^{-1} TDS, the drainage water was not recommended for use. Based on this classification it is clear that the TDS values are nearing the upper limit, even exceeding the limit in some cases (1994). Therefore, it can be inferred that the use of blending ratio of 1:1 would not be a pragmatic approach for sustainable agricultural development under NSDP. In the scenario of water shortage in drains and increasing TDS level in blended water, there will a need to increase the fresh water input in El-

Salaam and El-Sheikh Gaber canals. It is suggested that the currently used blending ratio of 1:1 be replaced by a ratio of 1:2 ratio. Additional Nile water needed for this purpose could become available from the water saved through irrigation improvement projects (IIP and IIIMP) in the Nile Delta in Egypt and/or implementation of upstream water conservation projects for the entire Nile River basin that will also increase the availability of Nile water for all the other Nile River basin countries.

CONCLUSIONS

Attention must be given to measures that minimize short- and long-term effects of elevated salinity of irrigation water on soil productivity. Based on the salinity results, it is recommended to use it by mixing Nile water and drainage water at a 2:1 ratio. In case of serious fresh water shortage, irrigation with Nile water and drainage water at 1:1 ratio could be applied temporarily. The consumption of wheat in Egypt has increased by 4% from 2006 to 2008 and demand has been met by increasing imports by 7%. To augment domestic wheat production, there is a need to include wheat in the crop rotation now to be recommended to the farmers in the NSDP area. It is expected that such an introduction of wheat in the project area will result in a production of 391,000 tons of wheat each year. Also, the cropping pattern will have to be reviewed and readjusted every few years based on the socioeconomic, food security and water resource availability in the Project area. For the rapid and lasting development in NSDP area, it is recommended to revise the allocation policy for the reclaimed lands and increase the percentage allocation for the small farm holders over the level originally planned in the project.

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DRIP IRRIGATION DESIGN TO AID GRASS ESTABLISHMENT ON RAILWAY FORMATION STEEP SLOPES

Yeboah Gyasi-Agyei[1]

ABSTRACT

Embankments and cuttings are integral parts of rail and road networks that support the economy of every country including Australia. Water induced soil erosion from the steep slopes (batters) of these civil engineered structures costs tax-payers in terms of ongoing operation and maintenance of the land transport networks. Also the environment is degraded and sediments transported from sites have the potential to pollute the nearby water bodies downstream. Development of a cost-effective drip irrigation system that sources water from either an existing pressurized water main or a temporary excavated pond/ dam (with solar or petrol pump) to supplement the unpredictable natural rainfall for quick grass establishment is an integral part of the HEFRAIL Project strategies developed. This paper presents the hydraulic modeling effort for the drip irrigation lateral network. Estimated hydraulic model parameters of commercially available pressure compensating laterals are given. A few examples of irrigation network bays based on the basic subunit of 3 laterals placed at the top section of the batters are presented. Simulation results have shown that for the fire-fighter petrol pump used on the HEFRAIL Project, a bay consisting of a maximum of 4 subunits can be run at the same time to ensure that the emitter pressures are within the pressure compensating range. For sites where more than 4 subunits are required, multiple bays are set up with controllers to schedule irrigation.

INTRODUCTION

Upper layers of soils in much of the area of the Bowen Basin coal deposits in Central Queensland (CQ) are generally highly dispersive. The steep slopes (batters) required for earthworks within the narrow corridors of the export coal rail network are therefore particularly susceptible to water erosion, resulting in sediment transport and siltation of waterways. Some of the embankment and cutting batter erosion problems within Queensland Rail (QR) corridors are highlighted in Figure 1. In Australia soil erosion problems are not confined to CQ only, but they abound all over the country. Wherever soil is exposed there is erosion potential and the risk is aggravated by the steepness of embankment and cutting batters. Traditionally embankments have been designed and constructed without due regard to the hydrological processes and effects on the environment.

High maintenance costs, train delays due to speed restrictions and increasing environmental degradation persuaded QR to fund extensive research into cost-effective and sustainable methods of erosion control in this ecologically sensitive area. This twelve-year collaboration between QR and CQUniversity (CQU), under the banner of HEFRAIL Project, has produced integrated systems to optimize the establishment of

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protective grass cover on steep slopes using fast growing non-invading plant species accepting of local conditions. Development of a cost-effective drip irrigation system that sources water from either an existing pressurized water main or a temporary excavated pond/ dam (with solar or petrol pump) to supplement the unpredictable natural rainfall is an integral part of the strategies developed (Gyasi-Agyei, 2003, 2004ab). This paper first presents the hydraulic modeling effort for the drip irrigation laterals and networks. Estimated hydraulic model parameters of commercially available pressure compensating laterals are given in the following section. A few irrigation network examples based on the basic subunit of 3 laterals placed at the top section of the batters are then presented. In the same section the simulated hydraulic system curves of the example networks are superimposed on the operating performance curves of the fire-fighter petrol pump used on the HEFRAIL Project to determine the limit of subunits that can be run at the same time.

Figure 1. Examples of erosion problems within QR corridors (left: rill erosion on embankment batter; right: eroded sediments choking culverts)

HYDRAULIC MODELING

Single Lateral

Figure 2 shows a single lateral having inlet pressure head H_0 and discharge Q_0, and equal emitter spacing s. The discharge q_i (L.h^{-1}) from an emitter i is determined by the rating curve

$$q_i = kH_i^x \tag{1}$$

where H_i (m) is the pressure head in the lateral at the emitter i, x is the emitter discharge exponent characterizing the flow regime and emitter type, and k is emitter discharge coefficient. Several approaches have been adopted in the literature for the hydraulic analysis of drip irrigation laterals (Wu and Gitlin, 1975; Warrick and Yitayew, 1988; Yitayew and Warrick, 1988; Kang and Nishiyama, 1996; Vallesquino and Luque-Escamilla, 2002). The Forward-Step Method (Hathoot et al., 1993, 2000; Gyasi-Agyei, 2007, 2009a), which takes into account the velocity head change and a proper selection of the friction coefficient f_{i+1} formula based on the Reynolds number, is used to solve downstream pressure heads as

$$H_{i+1} = H_i + \frac{3}{2gA^2}\left[Q_i^2 - Q_{i+1}^2\right] - \left[\frac{8s}{\pi^2 g D^5} f_{i+1} + \frac{\alpha}{2gA^2}\right] Q_{i+1}^2 - s s_o \tag{2}$$

where s_o is the constant slope of the lateral (positive for uphill and negative for downhill), A (m^2) is the cross-sectional area of the lateral, D (m) is the lateral internal diameter and g (m.s^2) is the acceleration due to gravity. The emitter head loss coefficient α term in Eq. (2) caters for the local head loss due to emitter insertions. For the pressure compensating case (x=0), q_i=k, $Q_0=k.N$ and $Q_{i+1}=k.(N-i)$ lead Eq (2) to be expressed as

$$H_{i+1} = H_i + \frac{3k^2}{2gA^2}(2N - 2i + 1) - \left[\frac{8s}{\pi^2 g D^5} f_{i+1} + \frac{\alpha}{2gA^2}\right] k^2 (N - i)^2 - s s_o \tag{3}$$

where N is the number of emitters in the lateral (Gyasi-Agyei, 2009b). The friction coefficient f_{i+1} is obtained by solving the Colebrook-White equation which is a function of Reynolds number and pipe diameter for a smooth pipe. Q_1 is used to evaluate the friction coefficient f_1. With Eq. (3) H_1 is estimated and the calculation is repeated for the next emitter downstream until the last emitter. Thus for a given value of H_0 and the hydraulic parameters α and k, the pressures along the lateral can be estimated.

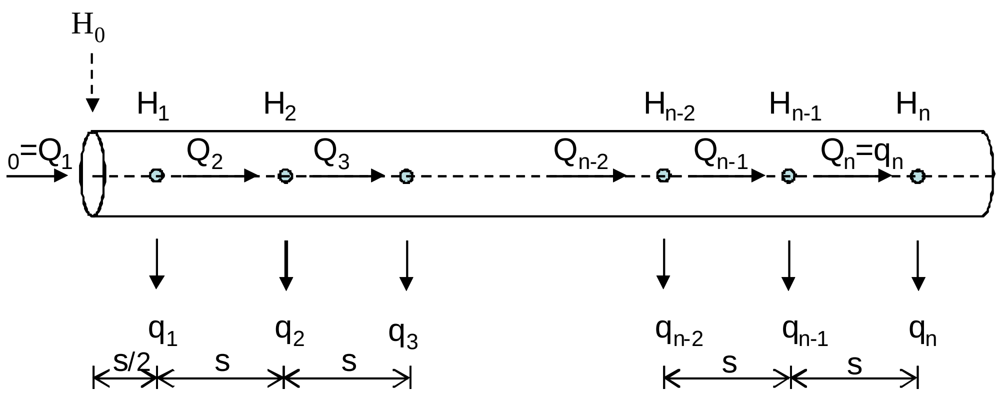

Figure 2. Single drip lateral

Subunit of Multiple Laterals

Similar concepts used for a single lateral are used for the subunit (Figure 3) simulation. The subunit inlet discharge Q_{SU} is a unique function of the top lateral inlet pressure H_{0N}. Given H_{0N}, Q_{0N} is estimated as explained for the single lateral case. Since Q_{0N} is the same as the discharge through the top submain, H_{0N-1} is estimated using the Backward-Step energy formula

$$H_{0i-1} = H_{0i} + f_{Si}\frac{8L_{Si}}{\pi^2 g D_{Si}^5} Q_{Si}^2 + L_{Si} s_{oSi} + k_{eSi}\frac{Q_{Si}^2}{2gA_{Si}^2} \tag{4}$$

where L_{Si} is the length of pipe *Si* between the laterals. The last term represents changes in geometry and fittings head losses with k_{eSi} being the total upstream coefficient for pipe *Si*. The remaining symbols are as previously defined. Knowing H_{0N-1}, Q_{0N-1} can be estimated and added to Q_{0N} to obtain the discharge in the submain S_{N-1}, Q_{SN-1}. The process is repeated for the next lateral and submain backwards until the subunit inlet pressure H_{SU} and discharge Q_{SU} are estimated. Hence pressure H_{0N} can be optimized to match the given Q_{SU} and simulated Q^*_{SU} subunit inlet discharges. Therefore, it is a problem of finding the root (H_{0N}) of a non-linear equation formulated as

$$Q_{SU} - Q^*_{SU}(H_{0N}) = 0 \tag{5}$$

satisfying the conditions given in the single lateral case.

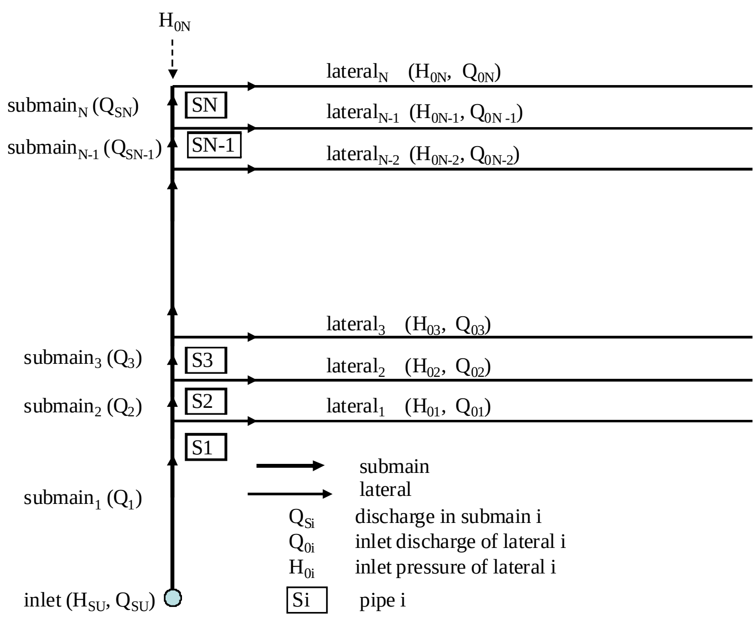

Figure 3. Single irrigation unit

<u>Multiple Subunits</u>

Consider Figure 4 which consists of 4 subunits joined to the main pipeline to form a single irrigation bay. Each subunit requires only the inlet pressure (H_{0i}) of the top lateral to estimate the pressure and discharge at the inlet of the subunit. From hydraulic principles, pipes flowing away from a junction should have the same upstream pressure equal to the downstream pressure of the pipe flowing into the junction. To satisfy the continuity principle, the total flow into a junction must equal the total flow out of the junction. Therefore the problem can be formulated into a system of *M* (equal to the number of subunits) non-linear equations with *M* unknowns (the inlet pressures of the top laterals of the *M* subunits). Hence

$$\begin{aligned}
&\text{at junction 0:} \quad Q_{IB} - Q_{p1}(H_{01}, H_{02}, H_{03}, H_{04}) = 0 \\
&\text{at junction 1:} \quad H_{0SU1}(H_{01}) - H_{p2up}(H_{02}, H_{03}, H_{04}) = 0 \\
&\text{at junction 2:} \quad H_{0SU2}(H_{02}) - H_{p3up}(H_{03}, H_{04}) = 0 \\
&\text{at junction 3:} \quad H_{0SU3}(H_{03}) - H_{p4up}(H_{04}) = 0
\end{aligned} \tag{6}$$

where H_{piup} is the upstream pressure of main pipe *i*, H_{0i} is the inlet pressure of the top lateral of subunit *i*, H_{0SUi} is the inlet pressure of subunit *i*, and Q_{pi} and Q_{IB} are the discharges in pipe *i* and the total of the irrigation bay, respectively. Again the conditions given in the single lateral case must be satisfied. The system of non-linear equations is solved to determine the pressures and discharges within the network (Gyasi-Agyei, 2007).

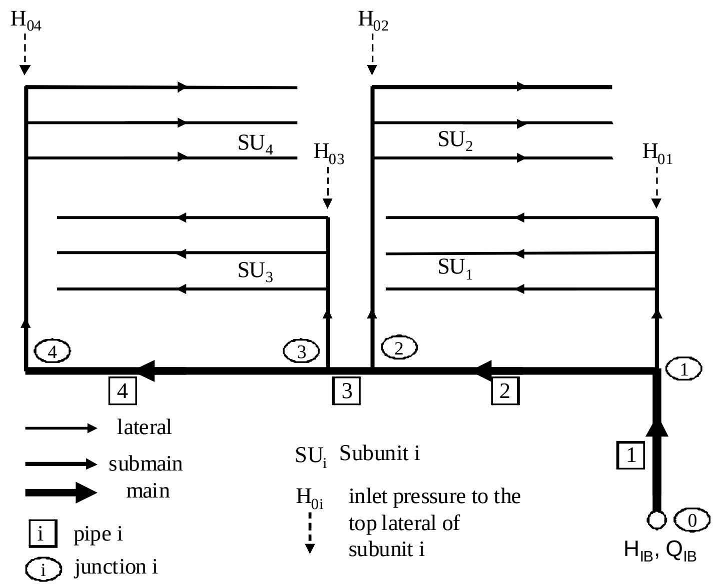

Figure 4. A single irrigation bay with multiple subunits

PARAMETER ESTIMATION

A 13 mm diameter pressure compensating dripline commonly used in Australia is adopted for the railway application. It is moulded from low-density polyethylene for flexibility and durability. The emitters are enclosed and inseparably welded to the inside wall of the tubing as it is extruded in the manufacturing process. It is manufactured with different emitter spacings and nominal discharges. However, the 300 mm spacing and 2 L/h nominal discharge was selected because of past experience (Gyasi-Agyei, 2007). 100 m rolls were purchased from the shelf and tested on a 110 m long, 300 mm wide, and a constant slope of 1% (downhill), temporary timber platform constructed on a lawn at CQUniversity Rockhampton campus. Data consisting of total inlet discharge and pressures at 13 locations on each lateral were gathered to estimate the hydraulic parameters.

The Metropolis algorithm (Kuczera and Parent 1998), a Markov Chain Monte Carlo method, of the NLFIT software (Kuczera, 1994), was used to estimate the parameter uncertainty (Gyasi-Agyei, 2009b). Figure 5 and 6 present the empirical posterior marginal distribution and the covariance of the parameters, respectively. The parameters are unimodal and strongly correlated, with mean and standard deviation values of k (2.0617, 0.0641) and α (1.3686, 0.1184). These calibrated values are used in the railway application simulations.

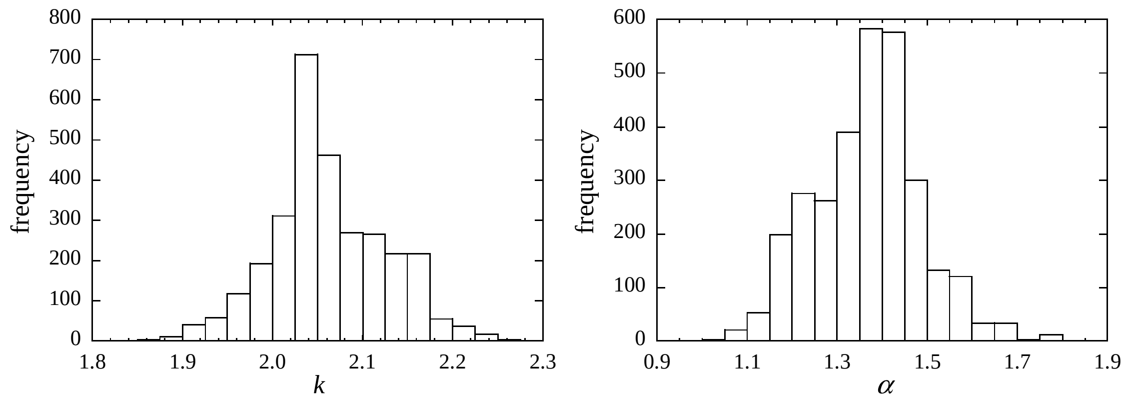

Figure 5. Posterior marginal distribution of parameters generated by the Metropolis algorithm

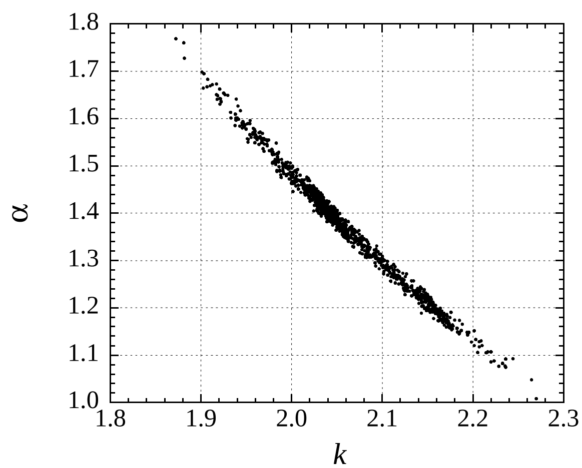

Figure 6. Covariance of the model parameters

RAILWAY EMBANKMENT APPLICATION

Figure 7 shows typical railway embankment geometry. The designed batter slope is 1 (vertical) to 1.5 (horizontal) giving an angle of 34^o to the horizontal. Embankment heights could be as high as 10 m giving a batter slope length of up to about 20 m. To save cost irrigation is normally concentrated on the top 3 m of the batter identified as the critical section for grass establishment to spread runoff minimizing soil erosion impact. Therefore, 3 lateral rows at the top of the batters at 1m spacing constitute the basic irrigation lateral unit. Irrigation networks are designed from this basic unit tailored to suit the batter areas to be irrigated for grass establishment. A typical 6 m high railway embankment batter was used to specify the geometrical layouts in the case studies. Figure 8 shows a few examples of the potential layouts. It is assumed that the pressure head on the pump is zero with it sitting at the bottom of the embankment with 20 m of 38 mm poly pipe mains connecting the 6.5 hp fire-fighting petrol pump (used in the HEFRAIL Project) to the 25 mm poly pipe sub-mains. Table 1 presents the pipe characteristics for a bay of 4 subunits entered into the software to simulate pressures and discharges throughout the network of laterals.

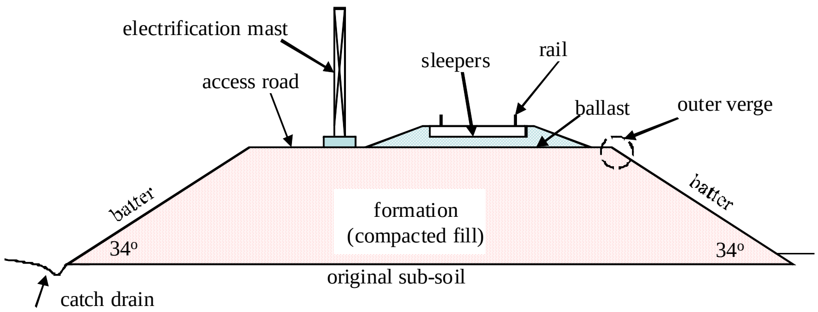

Figure 6. Railway embankment geometry

Inlet discharges and pressures through these example bays of lateral networks were simulated to develop the system curves which were superimposed on the pump to develop the pump performance curve in Figure 9 (left). An important design criterion is that the pressures within the laterals should stay within the operating pressure compensating range (8.5 m – 40 m). As seen in Figure 9(left), provided the pressures within the laterals are within the compensating range the total flow for a given network should be constant. This figure shows only scenarios where the minimum emitter pressure is greater than the threshold value of 8.5 m. As the number of laterals increases, the minimum and the maximum emitter pressures decrease for a fixed inlet pressure (Figure 9, right). Charts similar to Figure 9 can be used for quick design of lateral networks. For the pump with performance curve shown in Figure 9, a bay 4 subunits for the geometry considered is the maximum for the emitter pressures to stay within the pressure compensating range.

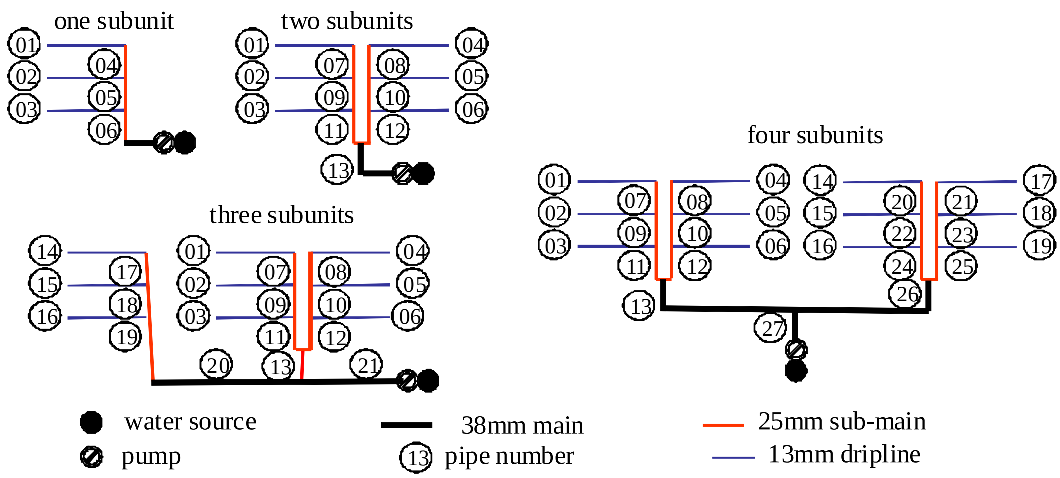

Figure 8. Examples of bays of lateral networks for railway batter applications

Table 1. Pipe Characteristics of a Bay of 4 subunits

No	Type	upstream node	downstream node	length (m)	upstream elevation (m)	downstream elevation (m)
1	1	7	1	100.0	6.00	6.00
2	1	9	2	100.0	5.44	5.44
3	1	11	3	100.0	4.89	4.89
4	1	8	4	100.0	6.00	6.00
5	1	10	5	100.0	5.44	5.44
6	1	12	6	100.0	4.89	4.89
7	2	9	7	1.0	5.44	6.00
8	2	10	8	1.0	5.44	6.00
9	2	11	9	1.1	4.89	5.44
10	2	12	10	1.0	4.89	5.44
11	2	13	11	8.6	0.00	4.89
12	2	13	12	8.6	0.00	4.89
13	3	27	13	100.0	0.00	0.00
14	1	20	1	100.0	6.00	6.00
15	1	22	15	100.0	5.44	5.44
16	1	24	16	100.0	4.89	4.89
17	1	21	17	100.0	6.00	6.00
18	1	23	18	100.0	5.44	5.44
19	1	25	19	100.0	4.89	4.89
20	2	22	20	1.0	5.44	6.00
21	2	23	21	1.0	5.44	6.00
22	2	24	22	1.0	4.89	5.44
23	2	25	23	1.0	4.89	5.44
24	2	26	24	8.6	0.00	4.89
25	2	26	25	8.6	0.00	4.89
26	3	27	26	100.0	0.00	0.00
27	3	28	27	20.0	0.00	0.00

Notes: pipe type: 1-lateral(13 mm), 2-submain(25 mm), 3-main(38 mm).

CONCLUSIONS

Water induced soil erosion from the steep slopes (batters) of railway formation (embankment and cuttings) within the coal export network of Central Queensland, Australia, costs tax-payers in terms of ongoing operation and maintenance. Cost-effective drip irrigation system that sources water from either an existing pressurized water main or a temporary excavated pond/ dam (with solar or petrol pump) is an integral part of strategies for quick grass establishment to combat the erosion problems (HEFRAIL Project). This paper has presented the hydraulic modeling effort for drip irrigation lateral networks tailored to suit the batter areas to be established with grasses. The case study is on commercially available pressure compensating laterals, hydraulic model parameters of which have been calibrated. A few examples of irrigation network bays based on the basic subunit of 3 laterals placed at the top section of the batters have been presented. Simulation results have indicated that for the fire-fighter petrol pump used on the HEFRAIL Project, a bay consisting of a maximum of 4 subunits can be run at the same time to ensure that the emitter pressures are within the pressure compensating range. For sites where more than 4 subunits are required, multiple bays are set up with controllers to schedule irrigation. Optimum design of irrigation networks of laterals will save costs for large projects.

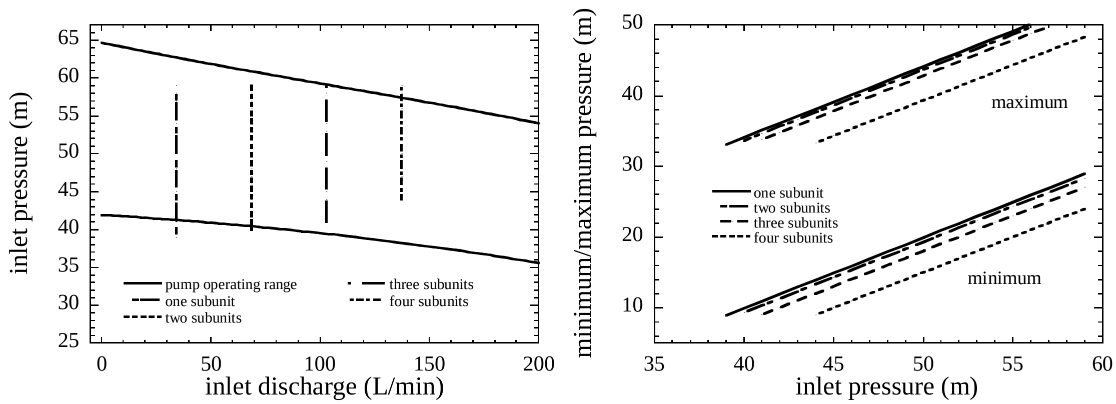

Figure 9. Lateral network systems and pump performance curves (left); minimum/maximum pressure within laterals for given inlet pressures (right)

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ALTERNATIVE ENERGY FOR MICRO-WATER SYSTEMS ON THE NAVAJO NATION

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Loren Crank[4]
Terry Battiest[5]

ABSTRACT

Over the last 2 years, the Navajo Nation and Federal professionals have been working on small-scale, solar-powered water projects for extremely isolated homes in Utah and Arizona. It has been estimated that nearly 8,000 Navajo reservation homes are currently without reliable utilities, and many have to travel long distances for food. One solution to this problem is the coordinated use of alternative energy systems attached to recreational vehicle (RV) water technologies. The systems are very "green" and very much in line with current Federal initiatives. Several prototypes have been constructed as a proof of concept and as laboratories for improving engineering designs. A major component of the water/power/food systems is real-time monitoring.

BACKGROUND

A commitment was made by the Federal government in 2002 under the United Nations Millennium Development Goals for improved access to safe drinking water and basic sanitation in Indian Country. Specifically, the U.S. committed to reduce the number of tribal homes lacking these amenities by 50 percent by the year 2015.

It is estimated that 7,850 homes on the Navajo Nation are without reliable water and 7,525 are without adequate sewer facilities. Many of these are also without commercial power and the residents have to travel long distances over rough roads for food because of their isolated locations in rural, arid Arizona, New Mexico, and Utah. The Indian Health Service (IHS) and Navajo Tribal Utility Authority (NTUA) will not be able to provide services to many of these homes anytime in the foreseeable future because of geographic and cost constraints. At stake is the traditional culture of the Navajos. As they move into subdivisions to obtain "modern" services and conveniences, they are increasingly separated from their pastoral heritage.

Conditions for these tribal members in isolated locations are becoming increasingly dire as the cost of energy and food escalates. Hauling water and shopping for food are increasingly expensive. For some, propane usage is also not a viable option. Gardening

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and small-scale farming are becoming a necessity, further putting pressure on limited water supplies. As for small-scale farming, which has been a staple of the Navajo heritage, much knowledge has been lost.

POSSIBLE SOLUTIONS

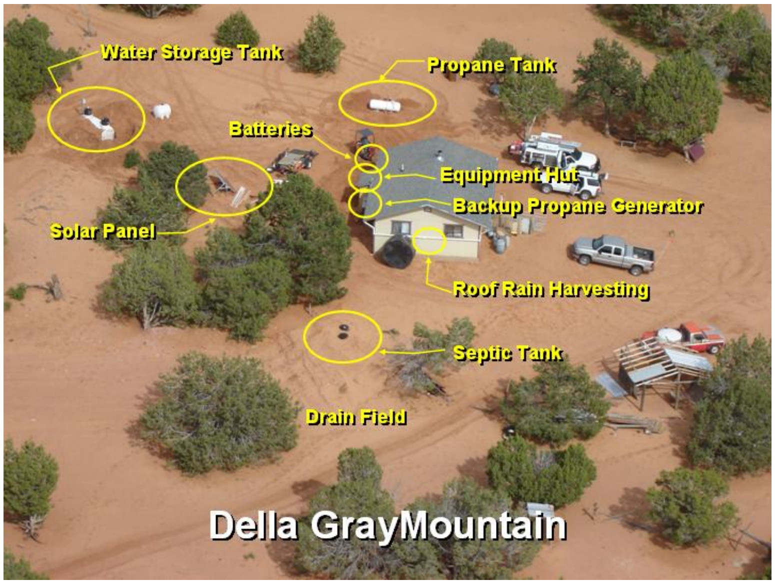
At the Federal, Tribal, and non-governmental organization (NGO) levels, there are multiple agencies and organizations involved in looking for solutions. Federally, there are IHS, Natural Resources Conservation Service (NRCS), Bureau of Indian Affairs (BIA), USDA Rural Development, Environmental Protection Agency (EPA), Sandia National Laboratories, Bureau of Reclamation (Reclamation), and others. At the Tribal level, there are Navajo Department of Water Resources (NDWR), NTUA (power and water are separate groups), Navajo Housing Authority (NHA), plus 120+ individual Chapters and several local water user associations. NGOs involved include the Rural Assistance Center (RAC), Rural Water Technology Alliance (RWTA), Engineers Without Borders (EWB), DesignBuildBluff (DBB), and Hearts and Hands in Action, just to name a few. At some level, many of the agencies and organizations have agreed to assist in finding solutions, but each has a separate mission with limited authority, which makes holistic solutions difficult. Reclamation is in a unique position to provide comprehensive water/power/food/housing solutions.

One solution that shows great potential is technology: photovoltaic (PV), wind, battery, RV, hi-tech micro-gardening, rainwater harvesting and grey water, and composting, all attached to real-time monitoring and control systems.

PROTOTYPES

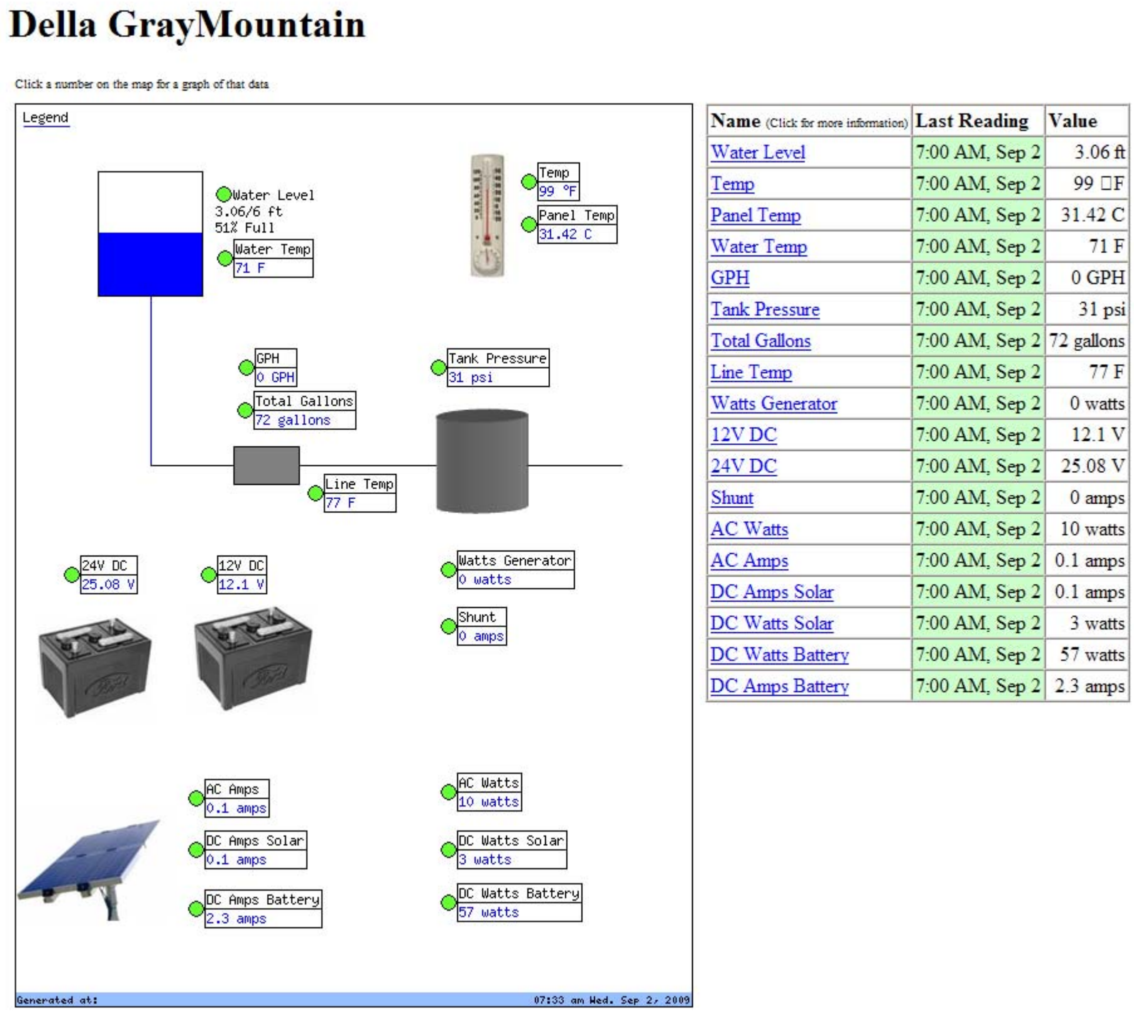
<u>Della GrayMountain Prototype</u>

As a preliminary proof of concept, a first-cut prototype was installed by Reclamation (Provo Area Office) and the Navajo Mountain WUA in the home of 92-yr-old Della GrayMountain, of the Navajo Mountain Chapter on the Utah/Arizona border, northeast of Page, AZ (Reclamation, 2008). Groundwater was not an option, so her system is cistern based, and is a combination of PV, RV, and propane technologies (see Photograph 1). With the prototype installed, Della's home now has indoor water and power (see Photograph 2). For example, her bathroom is now fully functional, where it previously had no water. Her water and electrical system is monitored hourly using a data-logger and cell-phone communications linked to a web page (see Figure 1). This latter feature is important for evaluation and troubleshooting (and hopefully improving sustainability). Della does not speak English.



Photograph 1. General layout of Della GrayMountain's water and electrical power system

Photograph 2. Della GrayMountain testing her recently installed water system



Name (Click for more information)	Last Reading	Value
Water Level	7:00 AM, Sep 2	3.06 ft
Temp	7:00 AM, Sep 2	99 □F
Panel Temp	7:00 AM, Sep 2	31.42 C
Water Temp	7:00 AM, Sep 2	71 F
GPH	7:00 AM, Sep 2	0 GPH
Tank Pressure	7:00 AM, Sep 2	31 psi
Total Gallons	7:00 AM, Sep 2	72 gallons
Line Temp	7:00 AM, Sep 2	77 F
Watts Generator	7:00 AM, Sep 2	0 watts
12V DC	7:00 AM, Sep 2	12.1 V
24V DC	7:00 AM, Sep 2	25.08 V
Shunt	7:00 AM, Sep 2	0 amps
AC Watts	7:00 AM, Sep 2	10 watts
AC Amps	7:00 AM, Sep 2	0.1 amps
DC Amps Solar	7:00 AM, Sep 2	0.1 amps
DC Watts Solar	7:00 AM, Sep 2	3 watts
DC Watts Battery	7:00 AM, Sep 2	57 watts
DC Amps Battery	7:00 AM, Sep 2	2.3 amps

Figure 1. Web page for monitoring della's water and power system

After the original installation, several improvements and enhancements were made to Della's system. The solar panel bank was enlarged from 330 watts to over 800. A water collection system was added to the roof of the house, with the water to be used for the stock watering. An ultra-violet water treatment unit is currently being added to the culinary water system. The GrayMountain water/power installation provided the opportunity for a wide variety of professionals to make recommendations for possible improvements.

Maude Crank Prototype

As a result of the GrayMountain prototype, several engineering design enhancements were developed internally, while others have been suggested by cooperators. For example, NTUA power staff recommended that we standardize their current PV/wind model, which has eight 110-watt panels and gel-cell batteries. This and other enhancements (point-of-use water heater, 12-VDC system for the lights in an adjacent 2-room rock house which is used, among other things, for weaving traditional rugs) were implemented at the home of Maude Crank, also at Navajo Mountain. Additionally, Maude and her two daughters have a small pasture and orchard which will benefit from an elaborate water harvesting system (see Photograph 3) and improvements to their micro-irrigation system. The Crank prototype is also monitored hourly.

Photograph 3. installing water harvesting system on the crank's rock house. The solar-panel is for a 12-VDC lighting system

Mary TallMan Prototype and Neighbors

There are four additional houses near the GrayMountain home which could benefit from water and power systems. A third prototype is currently being installed at the home of Mary TallMan. Mary, who suffers from dementia and does not speak English, desired to move from Tuba City, Arizona, back to her ancestral home at Navajo Mountain. Her 45-year-old rock home is being remodeled and retrofitted with indoor water (also cistern based) and power (solar) to facilitate home care. Much of the work on her home is being accomplished by volunteers from EWB. Her adjacent *hogan*, where she enjoys spending much of her time, has been equipped with a 12-VDC lighting system.

Near the GrayMountain/TallMan homes are three additional houses. One is currently lived in and two are being repaired in preparation of habitation. There is a one-room rock house, a two-room house (no bathroom or kitchen), and a small 2-bedroom rambler. Because the 5 houses are grouped together, it is anticipated that shared communications will be used for the real-time monitoring of any improvements.

Other Potential Study Areas

Several other Navajo homes have been identified for possible comprehensive water and power systems. NRCS, IHS, Utah Navajo Steering Committee, and Navajo Mountain WUA have provided a list of potential future customers. There is one area in Utah—Paiute Mesa—with 12 homes that because of its extremely isolated location will not receive piped water or commercial electricity anytime in the foreseeable future. This location presents a unique opportunity for future study.

Reclamation has also been involved peripherally with NRCS is development of artesian and shallow wells in the northern portion of the Navajo Nation. The non-flowing wells are equipped with solar-powered submersible groundwater pumps. Early applications were used for stock watering, but the feasibility of using these for micro-irrigation and gardening is currently being evaluated, particularly in the Mexican Water Chapter area southwest of Bluff, Utah.

MODULAR APPROACH

What Reclamation and the other groups have been developing is a holistic modular approach to making improvements to homes, involving the following modules:

- PV/wind/propane power system with inverter
- Water supply, storage, and pressure
- Rainwater collection and grey water
- Water treatment (UV and/or filter)
- Micro-irrigation and stock watering
- Septic tank and drain field (or composting system)
- Real-time monitoring (and possibly control)

Several private companies have expressed an interest in assisting, including AMD Architecture, Campbell Scientific, StoneFly Technology, and WesTech. Utah State University (USU) has agreed to sign on as a cost-share partner, and is interested in the application of micro-dataloggers to this project. Sandia National Laboratories has provided three monographs which describe the Navajo experience with PV technologies (Coots, 2009; Mar, 2009; Martinez, 2005). One of the monographs encourages the use of real-time monitoring for improving customer service and enhancing sustainability (Martinez, 2005).

NEW HOME DESIGNS

Another potential cooperator is DBB, an NGO that yearly constructs a unique "green" home in the northern portion of the Navajo Nation (see Photograph 4). This is accomplished using students from the University of Utah's architecture department. Working with DBB would provide an opportunity to merge the above concepts into new homes. DBB is particularly interested in the real-time monitoring opportunities. Once real-time communications are installed, there are several other uses that can be developed for the data-logging system, including: monitoring indoor conditions, appliances, outdoor weather, status of the propane system, condition of elders living alone for movement (door sensor, rug weight sensor, motion detector), etc.

Photograph 4. A design build bluff home located south of Bluff, Utah. Note the large water harvesting structure over the roof.

At the University of Arizona, students designed a simple rainwater harvesting system for the casita shown in Photograph 5 (located at Biosphere 2 near Tucson). The cistern system is designed to provide adequate water for a small drip irrigation system and to flush one toilet. During a one-inch rainfall, around 1, 025 gallons of water can be collected. Two 2,500-gallon cisterns provide enough water storage to last for several dry months.

Photograph 5. water collection system on casita at Biosphere 2. Circular tank is a water storage cistern.

Another more extreme style of self-contained home (see Photograph 6) has been constructed near Taos, New Mexico, at Earthship (Reynolds, 1993). These troglodyte homes have solar panels and rainwater harvesting systems on the roofs. They re-circulate the water collected twice. The first iteration, which is used in sinks and tubs, is treated through indoor gardens which can be used for growing food, and the second iteration is used to flush the toilet.

Photograph 6. Constructing a troglodyte house at Earthship (near Taos), New Mexico. The home is designed to be water and energy independent.

Elements of the above homes will be included in future retrofits and new home construction on Navajo demonstration sites.

RECOMMENDATIONS AND CONCLUSIONS

Two of the principal concerns that need to be addressed during future projects are: (1) the high initial installation costs (in part because of the logistics involved); and, (2) issues related to long-term sustainability and OM&R. Reclamation, USU, NDWR, and others are working toward a resolution of these two issues.

While the Navajo home projects are not the typical Reclamation dam-and-reservoir type of project, it can be viewed as such. They are nothing more than getting water and power (and improving micro-scale irrigation) to western customers in need, consistent with Reclamation's mission. In the aggregate they look like a Reclamation project with a non-traditional water and power supply, and a hi-tech irrigation delivery system. These technologies have the potential to greatly improve conditions for thousands of isolated homeowners in the Navajo Nation.

Water harvesting and water-efficient irrigation have been an integral part of Native American culture for over 1,400 years. This ancient technology when combined with modern solar and RV technologies will greatly assist the Navajo people with maintaining their pastoral heritage.

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VALIDATING AND ESTIMATING YIELD OF IRRIGATED POTATOES USING AERIAL MULTISPECTRAL REMOTE SENSING

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ABSTRACT

High resolution multispectral airborne and satellite data can be used to improve crop yield models by taking into account areas of soil and crop growth variability within a field and their impact on crop water use and yield. Various remote sensing-based vegetation index (VI) yield models using airborne and satellite data are restricted to grain crops like barley, corn, wheat, cotton, sugarcane, and others. So it becomes important to validate and extend the VI-based model for tuber crops like potato taking into account significant parameters that affect the final crop yield. This study involved the use of high-resolution multispectral aerial remote sensing in validating and extending an existing statistical vegetation index yield model developed for a potato crop. Spot yield samples collected from potato fields in the year 2005 were used in testing an existing model. Each yield sample was identified based on soil and crop growth patterns in the study field with a 3.63-m by 3.03-m size. The existing potato yield model developed by Jayanthi (2003) is based on the integrated Soil Adjusted Vegetation Index (SAVI) and assumes optimal irrigation water management. As potatoes are highly sensitive to water stress, maintaining optimal soil moisture in the root zone is required to obtain high-quality yields and profit. An improvement to this model is obtained by conducting a soil water balance in the root zone of the crop and incorporating actual evapotranspiration (ET) into the yield model as a method to improve yield predictions.

INTRODUCTION AND BACKGROUND

The food for a growing world population is largely dependent on production agriculture. Increasing food production has become the focus of research in most developing countries. The crop management system generally called precision agriculture relies on geospatial information which is intended to expand the prospects of agricultural crop production by adopting innovative approaches and technologies. Also, variability is known to exist in many agricultural fields. The causes of crop growth variability in an agricultural field might be due to tillage operations, influence of natural soil fertility, topography, crop stress, irrigation practices, incidence of pest and disease, and others. Effective management of the crop variability within the field can enhance financial returns by improving yields and farm production, and reducing production costs. Multispectral remote sensing plays a major role in precision agriculture due to its ability to detect crop growth conditions on a spatial and temporal scale, as well as its cost effectiveness. Multispectral remote sensing helps by exploring the crop biophysical data,

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namely vegetative development, photosynthetic activity, biomass accumulation, crop evapotranspiration, and crop production. This technology can help the crop growers to understand the expected yield of certain crops prior to harvest in order to make crop management and production-related decisions for maximizing field productivity and market gains.

In general, crop yield estimation can be done either by collecting ground samples from the field or by using various crop growth yield prediction models. Each method has its own pros and cons in accurately predicting crop yield. Ground-based yield prediction is time consuming, difficult and expensive. On the other hand, crop growth models sometimes become non-transferable to other cropped areas due to difficulty in incorporating the specific crop growth conditions. Remote sensing-based crop yield estimation techniques have been widely used in recent years. This method, unlike ground-based methods, is very easy to handle, not laborious, and most of all it provides accurate results of crop yield estimation. Remote sensing of crop yield can be broadly grouped into two classes (Moulin et al. 1998): crop process or simulation models and spectral vegetation index-based statistical yield models.

Crop process or simulation models involve mathematical functions of various crop physiological factors such as photosynthesis, respiration, and relative growth rate to describe the crop growth changes under various climatic and environmental conditions. These models assimilate climate, soils, crop, and environmental factors to predict the crop response functions such as phenology and biomass accumulation (Wiegand and Richardson 1990). Crop process model gives accurate estimations for small and homogenous fields but is less reliable to estimate yields for areas with non-uniformity and different agro climatic zones. The model can be complicated as it needs several detailed inputs for simulation and makes the calibration process tedious to perform. On the other hand, statistical models are developed based on the relationship between crop yield and various crop physiological parameters. Moulin et al. 1998 regressed crop yield obtained on the basis of a standard sampling technique with a spectral vegetation index in combination with standard weather variables to predict crop yields.

Remote sensing-based statistical yield models can be sub-grouped into two classes: (1) (ordinate) peak VI-based yield models; and, (2) area (under VI curve) based yield models (Jayanthi 2003). For vegetation index-based models, the VI (vegetation index) values at full cover are regressed over yield with different dates for maximum correlation. The area under VI curve-based yield models is determined either by integrating the VI during critical growth stages or by integrating the entire area under VI curve and then curve-fitting as a function of crop yield (Benedetti and Rossini 1993; Quarmby et al; 1993; Labus et al; 2002; Kalubarme; 2003).

Single date VI-yield models are very simple and constructed based on the assumption that spot yields are independent and randomly distributed covering the entire range of crop yield variability. As these models are easy to construct, they have been widely adopted; however, many factors like delayed crop season, high VI values may limit their performance, leading to unreliable yield estimation. Also, these models are not precise in estimating yields of indeterminate crops such as potato, sugar beet, and others due to the fact that these crops have a vegetative growth curve with no pronounced peak VI, and the final yield is related to the duration of the green leaf area, not only to the peak leaf area index (LAI). On the other hand, the area under VI yield models has proved to be successful in estimating crop yields as it covers the entire crop growing season. Jayanthi (2003) correlated SAVI (Huete 1988) with the hand-dug samples of potato for two varieties and the different combinations of SAVI developed were regressed with collected yield samples. The results showed that integrated SAVI over the entire crop period had good correlation with crop yield. The author also suggested that minimum of three airborne flights acquiring images during early stages of vegetative growth, prior to full cover and peak vegetative cover were needed to develop a reliable VI yield estimate (r^2 = 84%) and showed that predicting yield would be accurate with the maximum number of flights. However, the study did not involve actual evapotranspiration in the yield model as the research fields were well irrigated and well managed.

Most of the studies involving crop yield model predictions are done assuming that there is no water stress on the fields. Water stress in the fields is a major factor that affects yield and it is directly related to crop evapotranspiration. Crop yield versus ET relations are highly influenced by soil water levels in the root zone. Tuber crop like potato is highly sensitive to water stress. Considering the large production investments involved and in order to obtain a high profit, extreme care should be taken to maintain optimal soil moisture in the root zone. Tuber crops like potato and sugar beet are widely cultivated in certain areas on northwestern United States. In states like Idaho, Oregon, and Washington, potato accounts for more than 80 percent of the irrigated areas and 30 percent of the national irrigated areas (Wright and Stark 1990). Various VI yield models using airborne and satellite data are restricted to grain crops like barley, corn, wheat, cotton, sugarcane, and others. In areas with soil and crop growth variability, high-resolution satellite and aerial data are used to improve the crop yield models. There are hardly any references in the literature citing the development of VI yield models for potato using both airborne and satellite images.

This paper presents the use of high-resolution multispectral aerial remote sensing to validate and extend an existing statistical vegetation index yield model developed for a potato crop. Spot yield samples collected from potato fields in the year 2005 were used to test an existing model. Each yield sample was identified based on soil and crop growth patterns in the study plot with a 3.63-m by 3.03-m size. Soil adjusted vegetation index (SAVI) seasonal profiles corresponding to the spot yield locations in high-resolution aerial imagery (0.5 m pixel resolution) were generated. The existing potato yield model, developed by Jayanthi (2003), is based on the integrated Soil Adjusted Vegetation Index and assumes optimal irrigation water management. As potatoes are highly sensitive to water stress, maintaining optimal soil moisture in the root zone is required to obtain high-quality yields and profit. The study also involved estimating daily ET conducting a soil water balance in the root zone based on basal (Kcb) and reflectance-based (Kcr) crop coefficient methods for a sample study field and compared in preparation for further improving the potato yield model.

METHODS AND MATERIALS

Study Area

The data for this research were collected from the potato fields of Cranney Farms Inc., Oakley, Idaho. It is located in a semi-arid environment with summer months averaging 80°F and monthly average precipitation of an inch of rain during the summer. The study area has predominantly silt loam and closely related soils. The average values of permanent wilting point and field capacity are 160 mm/m and 320 mm/m, respectively. The total area occupied by potato fields in Cranney Farms in the year 2005 was approximately 3,500 acres. The crop growth season ranges from April to September. Five varieties of potato were cultivated in Cranney Farms, namely Russet Burbank, Rangers, Gem, Western, and Alturus.

Image Acquisition and Processing

Airborne Multispectral Imagery The images from the Cranney Farms fields were acquired using the USU airborne digital remote sensing system available through the Remote Sensing Services Lab at USU. The system consists of three Kodak Megaplus 4.2 mega-resolution digital cameras filtered for spectral observations in the green (0.548-0.552 μm), red (0.668- 0.676μm), and NIR (0.798-0.804 μm) bands of the electromagnetic spectrum. The images were captured in 8 bits with special digitizing boards mounted in personal computer on board the aircraft, controlled with specially-designed software. The airborne multispectral images in the year 2005 were acquired over different fields throughout the growing season, namely on July 8, August 4, and August 25.

Image Processing The binary files acquired on the aircraft were first converted to tiff format images. The individual green, red and NIR images were first registered to one another, layer stacked, and corrected for the vignetting effect to remove the illumination fall-off at the edge of the images. The preprocessing and processing of images was done using the ERDAS Imagine software. The images were geo-rectified using differentially-corrected GPS-based ground control points taken over the fields with sprinkler irrigation systems and also in the center of the pivots.

Calibration of Airborne Multispectral Imagery The images were calibrated in order to convert the pixel digital numbers in the images in to reflectance. Calibration of acquired aerial imagery is usually done by standard reflectance panel approach. But in this study it was not practical due to complications in setting up a panel in the region of the potato pivots close to Oakley, Idaho, also taking into consideration the distance to Logan, Utah. Pathak (2005) used an alternative solution of developing a relationship between solar irradiance measured over the panel and solar radiation measured with an Eppley pyranometer installed in a weather station at Kimberly, Idaho, that was located approximately 30 miles to the west of the monitored center pivots. The radiance was measured over a standard Halon panel with known bi-directional reflectance properties using an Exotech 4-band radiometer. The solar irradiance was estimated from the radiance measurements over a standard reflectance panel as follows:

$$[E] * \cos(\theta) = [\pi * L_p] / [R_p (0^o / \theta)] \quad (1)$$

where E is the irradiance at time of the panel measurement in Wm^{-2} and L_p is the average radiance over panel, wm-2sr^{-1}. R_p (0^o / θ) represents the bi-directional reflectance of the panel at nadir point and cos(θ) denotes the cosine of the solar zenith angle at the time of measurement .The estimated [E] * cos(θ) was then plotted against the solar irradiance measured with Eppley pyranometer and finally the relationship was developed through statistical curve fitting. The relationship developed by Pathak (2005) was used in the current study for calibrating the airborne images. The radiance over the panel at the time when the image was acquired is given as below

$$Lp = (E * \cos(\theta) * Rp) / \pi \quad (2)$$

where E is the estimated irradiance developed from the relationship, W m^{-2}. The multispectral images obtained were calibrated to radiance images using the calibration coefficients developed for the USU airborne system. Eventually, the images were transformed to reflectance images using the standard relationship:

Image Reflectance / Image Radiance = Panel Reflectance / Panel Radiance (3)

From the above equation, Image Reflectance was derived as:

Image Reflectance = (Panel Reflectance / Panel Radiance)*Image /Radiance (4)

Spot Yield Data Sampling

The study was performed at two levels, namely point yield level and whole field level. The total yield and potato quality data from each of the fields was provided by Cranney Farms. The point yield data were selected based on the spatial variability in the crop growth pattern within the fields that were monitored, and that were visible in the aerial multispectral imagery. The yield sampling locations were selected based on the crop growth profiles that falls into four categories, namely: (i) rapid growth-prolonged maturity and senescence; (ii) slow growth-prolonged maturity and senescence; (iii) rapid growth-short maturity; and, (iv) slow growth-short maturity, as observed in the airborne imagery. Each yield sample consisted of all the potatoes hand-dug from a (4-row, 10-ft transect) 3.63-m by 3.03-m area. The total tuber yield sample was weighed in the field, immediately replaced in the rows, and covered with the excavated soil. A differential GPS unit was used to identify the coordinates of the location within a 10 cm positional accuracy. The yield sample collection data were collected from two fields during 2005 (HF 12 and OI1).

Validation of VI-Yield Models

The hand-dug yield locations were translated into areas of interest (AOIs or the polygons digitized on computer screen) using ERDAS Imagine 9.0. These AOIs were accurately positioned over the geo-rectified images with the help of GPS coordinate readings and field observations. The corresponding average soil adjusted vegetation index statistic was determined from the pixels within the AOIs. The calculation procedure for calculating SAVI and integrated SAVI in this study is as follows:

$$SAVI = \frac{(NIR - RED)(1 + L)}{(NIR + RED + L)} \quad (5)$$

where NIR and RED represent near infra-red and red reflectances; and, L is an adjacent factor to account for the noise caused by soil background under changing vegetation cover conditions. The factor L decreases with increasing vegetative cover. For very low vegetative cover, L = 1 and for higher vegetation densities, L = 0.25. A factor of 0.5 was used for intermediate vegetation. For this study, an L factor of 0.5 was used.

$$ISAVI = \frac{0.5 * \sum\left\{\left[(SAVI_j - SAVI_{baresoil}) + (SAVI_i - SAVI_{baresoil})\right] * (DOY_j - DOY_i)\right\}}{\sum (DOY_j - DOY_i)} \quad (6)$$

where ISAVI represents integrated SAVI determined by the integration of the area of trapezium formed between SAVI and the day of year (DOY). The suffixes i and j represent the previous and present dates of aerial image acquisition. $\Sigma\ (DOY_j - DOY_i)$ represents the total crop growth season, which is the number of days the crop stood on the ground.

Soil Water Balance in the Study Area

Using the weather and irrigation data, a soil water balance was conducted in one of the study fields to obtain crop daily ET based on basal and crop reflectance based crop coefficient methods and compared. The soil water balance model used in this study to assess the soil moisture in the crop root zone is as follows:

$$SW_{j+1} = SW_j + I + P - ET_c - DP \quad (7)$$

where SW represents the available soil water, j and j+1 denotes the soil water content in the current time and a succeeding time j+1. I represents the irrigation amount applied and P indicates the precipitation. ET_c represents the crop evapotranspiration, and DP is the deep percolation.

The daily reference crop ET was computed using the 1982 Kimberly-Penman method. The crop ET was calculated using both the conventional basal crop coefficient (K_{cb}) and reflectance based crop coefficient (K_{cr}) method. A brief description about both methods are given below.

Basal Crop Coefficient Method Wright (1982) proposed this method of estimating the total crop ET at any given time. The theory behind this method is as follows:

$$ET_{crop} = K_c \times ET_{ref} \quad (8)$$

$$K_c = K_{cb} \times K_a + K_s \quad (9)$$

$$K_a = \ln(A_w + 1)/\ln(101) \quad (10)$$

$$K_s = (1-K_{cb})\,[1-(t_w/t_d) \times 0.5] \times f_w \quad (11)$$

where K_{cb} is the basal crop transpiration coefficient; K_a is the coefficient (dimensionless) that represents plant stress due to soil moisture deficit; and, A_w is the percentage available water (100 % at field capacity and K_a =1). K_s represents the soil evaporation coefficient; and, t_w indicates the time after rain or irrigation in days, whereas t_d is the time for the soil to dry, in days.

Canopy-Based Reflectance Method The theory behind this method is that the SAVI can be scaled to represent the basal crop coefficient and is sensitive to the actual crop growth conditions in the field (Bausch and Neale 1987; Neale et al. 1989). K_{crf} is the reflectance-based crop coefficient obtained through linear transformation of SAVI corresponding to bare soil and SAVI at effective full cover with the basal crop coefficient (K_{cb}) values corresponding to bare soil and effective full cover (EFC). The resulting transformation is:

$$K_{crf} = \frac{[(SAVI - SAVI_{baresoil})(K_{cbEFC} - K_{cbBaresoil})]}{(SAVI_{EFC} - SAVI_{baresoil})} + K_{cbBaresoil} \quad (12)$$

The remote sensing-based K_{cr} for this study was derived using the equation developed by Jayanthi et al. (2007) and the equation is as follows

$$K_{crf} = 1.085 \times SAVI + 0.0504 \quad (13)$$

RESULTS AND DISCUSSION

Validation of the Spot Yield Data

The image acquisition for the 2005 season occurred at different growth stages of the potato crop. A better relationship can be achieved by considering the entire growth duration of the crop and relating the yield with integrated area under the SAVI curve over time. The estimated yield for three dates was obtained using integrated SAVI yield model developed by Jayanthi (2003). The existing ISAVI model is:

$$\text{Yield (kg/m}^2\text{)} = 16.456 * \text{ISAVI} - 1.752 \qquad (14)$$

The integrated SAVI from the three dates (July 08, Aug 04, Aug 25) of airborne multispectral images was generated and statistics were extracted from the sample AOIs in the study plots. Estimated yield was obtained using Eq. 14. The estimated yield was then compared with the actual

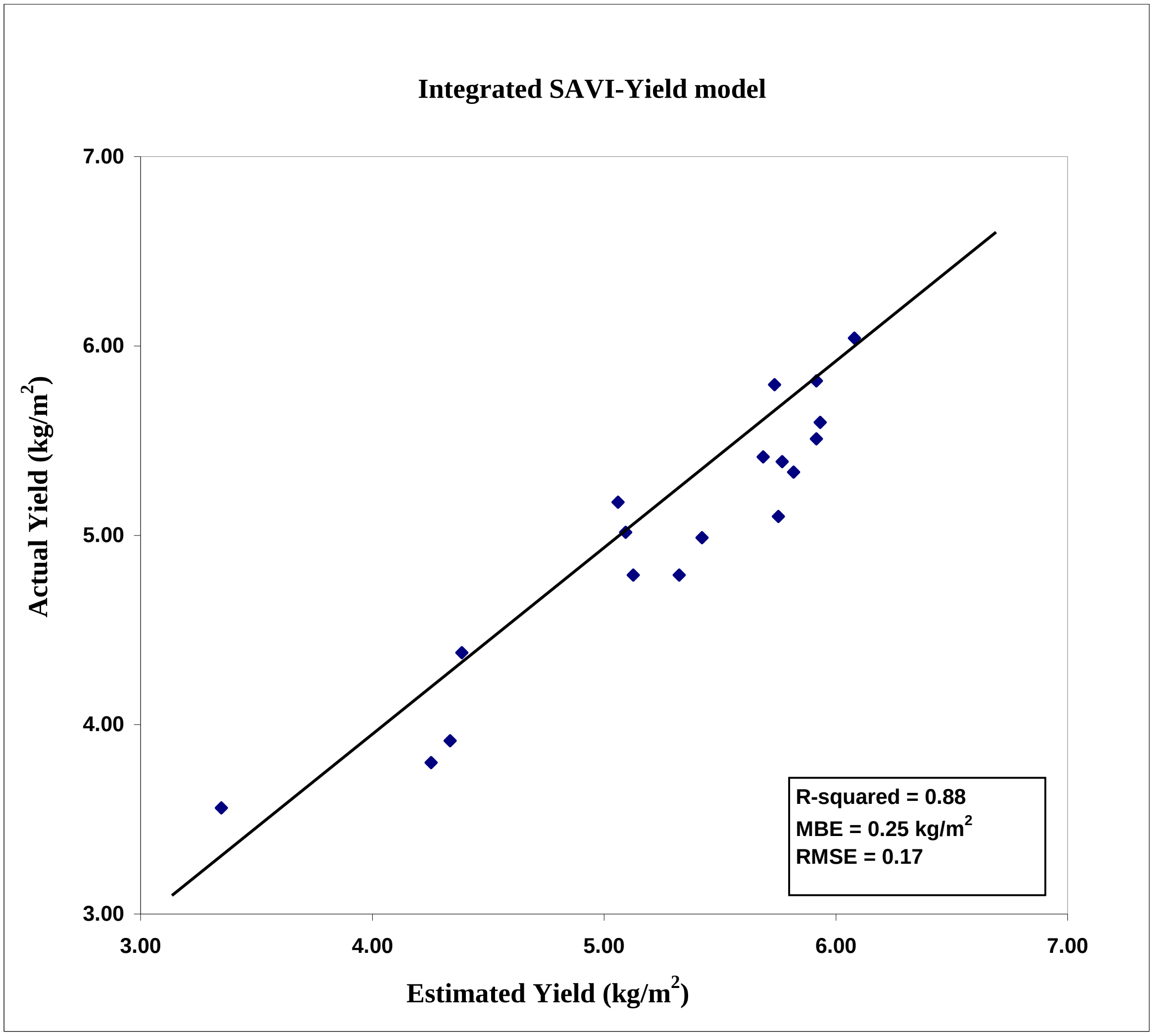

Figure. 1. Comparison between Estimated and Actual Yield using a Three-date Model

yield harvested from the field at different sampling locations. Figure 1 shows the comparison between actual and estimated yield indicating a considerable overprediction by the model most of the time with a mean bias error (MBE) of 0.25kg/m^2 and root mean square error (RMSE) of 0.17. The reason may be due to the calibration of the imagery, which was done in a different way using the relationship between panel radiance and Eppley-based solar irradiance developed for 2004 data by Pathak (2005) instead of using the panel reflectance data on the day of image acquisition.

Soil Water Balance

Root zone soil water balance was conducted for one of the sampling locations in the study field taking into account all irrigation and rain inputs and water used by the plants through evapotranspiration. Figure 2 compares the actual ET estimated based on K_{cb} and Kcrf methods throughout the season. From the graph it can be observed that the ET estimate by both the methods have the same trend throughout the season. Generally, Kcrf-estimated ET values are higher than those estimated by the K_{cb} method. However, there are times when the Kcrf-based ET values are lower than those estimated by the K_{cb} approach towards the end of the season. This could be due to lower or no application of

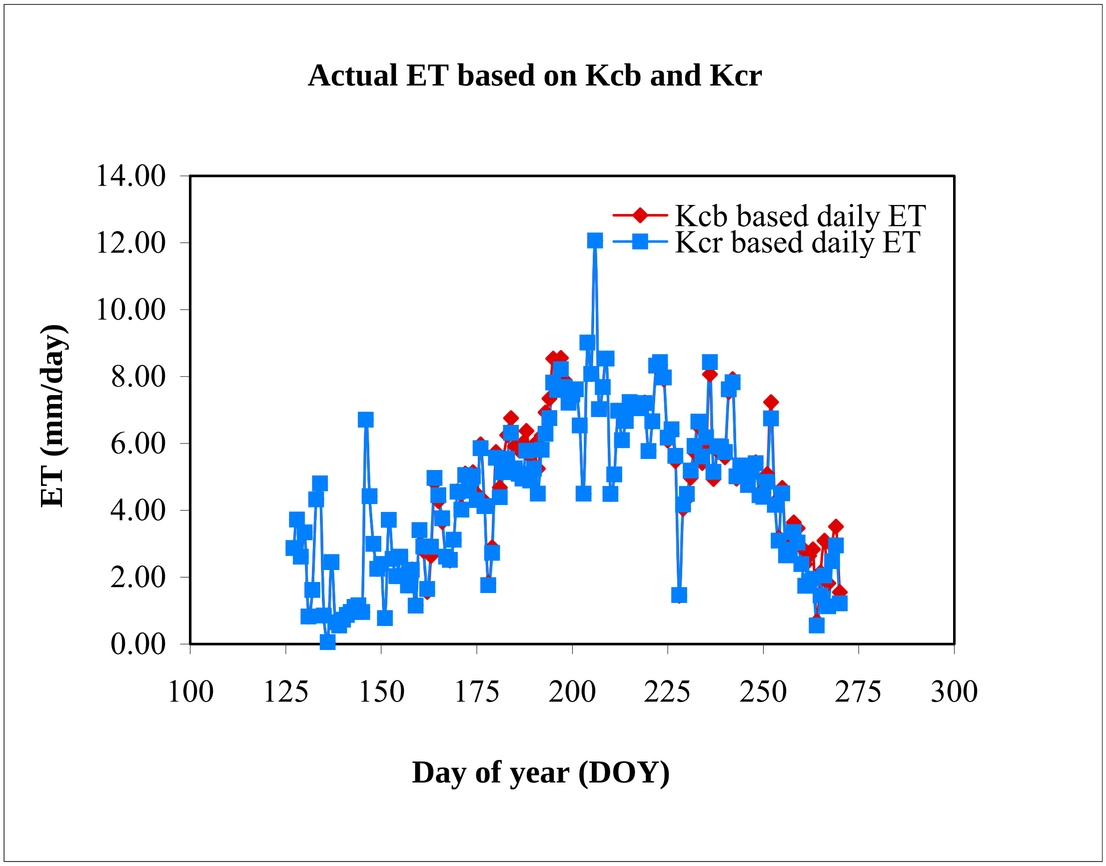

Figure 2. Temporal profile of K_{cb} and K_{cr} based Actual ET

water during these periods. This agrees well with the findings reported by Jayanthi (2003) in which a lower application of water resulted in lower ET estimates by the Kcrf method.

SUMMARY AND CONCLUSIONS

This paper presents the use of high-resolution multispectral aerial remote sensing to validate and methods to extend an existing statistical vegetation index yield model developed for potato crop. Spot yield samples collected from potato fields in the year 2005 were used in testing an existing model. Spot yields were collected from center-pivot irrigated potato fields of Cranney Farms Inc., Oakley, Idaho, during the 2005 summer season. Soil-adjusted vegetation index (SAVI) seasonal profiles corresponding to the spot yield locations in high-resolution aerial imagery (0.5 m pixel resolution) were generated and used for validating the existing single date and integrated SAVI model developed by Jayanthi(2003). Actual spot yields collected were regressed with the estimated yields. The three-date model was found to have best correlation with the yield compared to the single-date model. This highlights the need of image acquisition throughout the crop growing season to study soil and crop growth variability, crop vigor during maturity, and variable rates of senescence.

A soil water balance study in the crop root zone was conducted for one of the study fields to estimate the actual crop ET based on k_{crf} and K_{cb} approach and was compared. The results based on both the methods agreed well throughout the season. The model by Jayanthi (2003) was developed under optimal irrigation management by the farmer, with no moisture stress in the root zone. As potatoes are highly sensitive to water stress, maintaining optimal soil moisture in the root zone is required to obtain high quality yields and profit. Actual ET has been shown to be directly related to yield, thus including it as a parameter in the model should strengthen the model statistically. The factor ET_a/ET_{max} has been shown by previous research (Doorenbos and Kassam, 1979; Stewart et al, 1977) to explain variability in yield on the ground. In other words, ET_a/ET_{max} might be useful in explaining additional variance in the remote-sensing yield model. Further research is needed to confirm the relationship between Y/Y_{max} and ET_a/ET_{max}, and to develop a new crop yield model involving actual ET and remote sensing information.

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ENERGY BALANCE EVAPOTRANSPIRATION ESTIMATES OVER TIME FOR THE SOUTHERN SAN JOAQUIN VALLEY

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Deepak Lal[2]
Byron Clark[3]
Grant Davids[4]

ABSTRACT

Water resource planning requires knowledge of changes in consumptive water use by crops and natural vegetation over time. Remote sensing offers the promise of a consistent methodology to obtain consumptive use and other water resource data over large areas at regular intervals. SEBAL® (Surface Energy Balance Algorithm for Land) uses data gathered by satellite-based sensors to compute evapotranspiration (ET) and biomass production. ET is computed as the residual of the energy balance at the Earth's surface.

Growing season ET (April through October) was computed for 2002 and 2005 using SEBAL for the area covered by Landsat Path/Row 42/35 of the Southern San Joaquin Valley in California. Growing season ET for this area, selected smaller areas within it and selected crops, where reliable cropping records were available, was compared to annual and seasonal precipitation.

INTRODUCTION

Hanson (1991) estimated that about 67 percent of the precipitation falling on the United States, returns to the atmosphere through evapotranspiration (ET). After precipitation, ET is the most significant term in the water cycle. ET varies according to weather and water availability conditions in discernable regional and seasonal patterns. Quantifying ET is important to develop a thorough understanding of the hydrologic process and knowledge about the spatial and temporal rates of water movement. This understanding and knowledge is critically important for water resources planning and management. Matyac (2005) also stresses that improving our understanding of evapotranspiration is the key to improved water management. Further indicative of the need for evapotranspiration data, Hutson, et. al (2005) asserts that many individuals and organizations require reliable water use data to support research and policy decisions.

The objective of this paper is to further the knowledge and understanding of the spatial and temporal variations in ET by examining regional and seasonal patterns in ET.

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Regional ET computations are extremely data intensive and time consuming. To obtain regional ET estimates in a convenient and cost-effective manner, ET was computed as the residue of a surface energy balance utilizing satellite-based remotely sensed data together with ground-based weather station data. The SEBAL® (Surface Energy Balance Algorithm for Land) model, the most extensively used and validated surface energy balance model, was used to estimate ET for this analysis.

SEBAL THEORY

The sun's net radiation reaching the Earth's surface balances with soil, sensible, and latent heat fluxes according to conservation of energy at the Earth's surface. Taking into account the latent heat of vaporization and density of water, latent heat flux can be converted into ET flux (volume of water per unit area per unit time). ET flux can be estimated as a closure term from estimates of the remaining fluxes (Equation 1).

$$ET_a = \frac{1}{\lambda \rho_w}\left[R_n - \left(G + H\right)\right] \qquad [1]$$

where λ is the latent heat of vaporization of water, ρ_w is the density of water, ET_a is the actual crop ET, R_n is the net radiation flux at the Earth's surface, G is the soil heat flux, and H is the sensible heat flux.

The SEBAL model estimates actual crop ET (ET_a) from the energy balance by applying radiative, aerodynamic, and energy balance physics in 25 computational steps. Multispectral satellite imagery with a thermal band is used to calculate ET_a at the pixel-scale. Required input data include radiances in the visible, near infrared, and thermal infrared regions sensed by earth observing satellites; spatially interpolated ground based weather data from agricultural or other weather stations; and land use data describing general vegetation types, when available. Knowledge of specific crop types is not needed to solve the energy balance. SEBAL avoids the need for absolute calibration of the surface temperature of each pixel by utilizing a unique internal calibration for each image to estimate sensible heat flux between the surface and the atmosphere. A detailed explanation of the algorithm is provided by Bastiaanssen et al. (1998). Continuing refinements to the model include the use of digital elevation models for radiation balances in mountains (Allen et al., 2001), an improved albedo function (Tasumi et al., 2005), advection corrections, an improved soil heat flux relation, and an improved relation for surface roughness for momentum transport.

Recent validations of SEBAL, summarized by Bastiaanssen et al. (2005), have shown seasonal ET_a results generally fall within five percent of seasonal ET_a determined from reliable ground-based measurements. ET_a results from the 2002 SEBAL analysis used in this paper were compared to lysimeter measurements on alfalfa and peaches (Cassel, 2006) and surface renewal measurements on tomatoes (Roberson, 2006). In each comparison, the difference between the SEBAL ET_a and the ground-based estimates was five percent or less (Figure 1).

Input Data

A combination of satellite, ground based-meteorological, topographic, and land cover classification data are utilized to quantify spatially distributed ET_a. For this study, these datasets were obtained from the U.S. Geological Survey (USGS) and CIMIS. These data are described in greater detail in the following paragraphs.

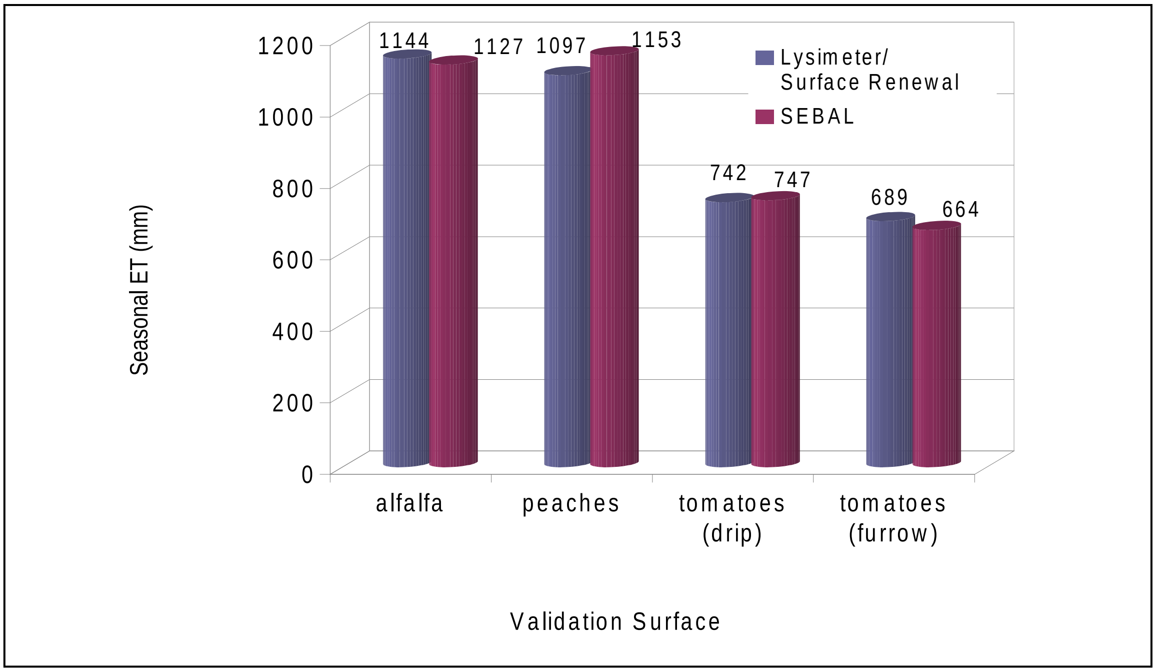

Figure 1. Seasonal SEBAL ET_a Results Compared to Lysimeter and Surface Renewal Results

Satellite Images. Seven Landsat 7 ETM and seven Landsat 5TM multispectral images encompassing the period from April to October for Path 35/Row 42 were obtained from USGS for 2002 and 2005, respectively (Table 1). Cloud-free images were selected to achieve a temporal frequency of one image per month for each growing season.

Table 1. SEBAL Datasets Used for Growing Season ET Analysis

Region	Satellite Platform	Row/ Path	Thermal Resolution	Image Dates	Images
Southern San Joaquin Valley (2002 season)	Landsat 7 ETM	42/35	60 m	4/12, 5/14, 6/15, 7/17, 8/2, 9/3, 10/5/2002	7
Southern San Joaquin Valley (2005 season)	Landsat 5	42/35	120 m	4/12, 5/14, 6/15, 7/17, 8/18, 9/19, 10/5/2005	7

Meteorological Data. Measurements of incoming solar radiation (R_s), relative humidity (RH), air temperature (T_a) and wind speed (WS) were available as hourly averages for the time of image acquisition. Daily (average for the image date), and period (average for the days represented by an individual image) measurements were also available. Twenty-three CIMIS stations falling within or on the edge of the study area were used to develop a weather surface prior to the SEBAL image processing. Weather data were quality checked according to the guidelines specified in Appendix-D of the ASCE Task Committee Report on the Standardized Reference Evapotranspiration Equation (Allen et al., 2005).

Weather data were spatially interpolated using MeteoLook, a collection of algorithms developed to interpolate point weather observations based on the surface and terrain characteristics coupled with physically-based models (Voogt, M.P., 2006). Processes that influence surface weather conditions such as elevation, surface roughness, albedo, incoming radiation, land wetness, and distance to water bodies are represented in MeteoLook. This improved spatial distribution of weather data improves the ability to estimate surface conditions influencing the surface energy balance and the ability to estimate spatially distributed reference ET.

Landuse Data and Digital Elevation Model (DEM). A generalized landuse map from the National Land Cover Dataset (NLCD) for 1992 was obtained from USGS and combined with available land use data from the California Department of Water Resources (CDWR) and Kern County to estimate obstacle heights for different surfaces within the study area. These data have been developed by various means including analysis of Landsat images along with inspection of aerial photographs and ground-surveys.

A DEM of one arc-second resolution (approximately 30 meter resolution) was obtained from USGS and was used in SEBAL to incorporate the effects of the slope, aspect and elevation into the energy balance.

RAINFALL AND REFERENCE ET

As general indicators of surface water supply availability, the California Department of Water Resources (CDWR) defines San Joaquin River Basin water years types based on the measured unimpaired runoff of four rivers. The four rivers are Stanislaus River inflow to New Melones, Tuolumne River inflow to New Don Pedro, Merced River inflow to New Exchequer and San Joaquin River inflow to Millerton. The water year type was below normal and wet for 2002 and 2005, respectively. The precipitation during the water year in 2002 was less than half the precipitation in 2005 (Table 2). The CIMIS reference ET ranged from four to nine percent greater for the April through October growing season and the water year (October through September), respectively for 2002 compared to 2005. These data indicate that 2002 was a year with less available soil moisture and a greater ET demand compared to 2005.

Table 2. Rainfall and Reference ET (Average of Selected CIMIS Stations in the Landsat Scene) in 2002 and 2005

Time Period	Precipitation (in)		Reference ET (in)	
	2002	2005	2002	2005
Water Year (Oct - Sept)	6.1	14.0	58.90	53.96
Annual (Jan - Dec)	6.1	11.0	58.80	55.24
April - Oct	1.0	2.5	48.03	46.04

ET COMPARISONS

The Landsat scene encompasses all of Kings County and parts of Kern, Tulare and Fresno Counties (Figure 2). The mean ET across the agricultural area of the Landsat image was about four inches higher in 2002 compared to 2005 (Table 3). The standard deviation was also higher indicating greater variation in ET across the agricultural areas of the image. Although all of the agricultural area requires irrigation to be productive, every year some area is not irrigated. These non-irrigated areas would be expected to have ET roughly equal to or slightly less than the precipitation in both images, on average. On the other hand, the irrigated areas will have close to the crop water requirements in both images unless water availability becomes a factor. Given the greater rainfall in 2005, the difference between the irrigated areas and the non-irrigated areas is greater in the 2002 image leading to a greater variation in ET as indicated by the greater standard deviation. The portion of Tulare County is on the eastern side of the San

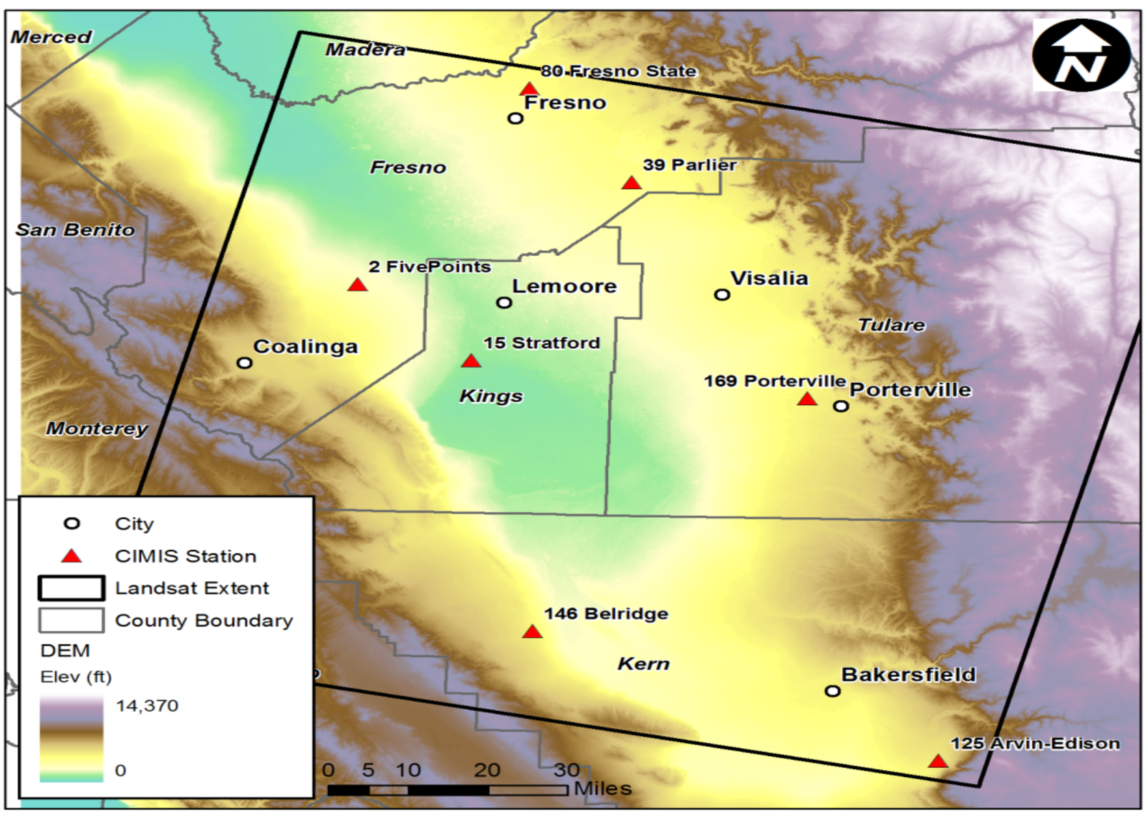

Figure 2. Southern San Joaquin Counties Encompassed within the Landsat Scene

Table 3. Seasonal (April through October) ET Statistics for the Agricultural Area within the Landsat Scene

Region	Area (ac)	Mean ET (in)		Difference in Mean ET (in)	Std. Dev. (in)	
		2002	2005	2002 & 2005	2002	2005
Landsat Image	2,889,645	31.39	27.17	4.22	13.96	11.66
Kings County	630,642	29.93	25.52	4.41	14.56	10.83
Part of Kern County	757,299	28.06	27.34	0.72	15.11	13.62
Part of Tulare County	687,967	36.99	31.18	5.81	12.02	9.61
Part of Fresno County	736,211	31.46	25.05	6.41	11.84	10.87

Joaquin Valley and has the highest average ET. Kings County, west of Tulare County on the western side of the San Joaquin Valley has much lower ET. The portion of Kern County has the lowest ET in the image.

Agricultural areas not irrigated during the study period are expected to have ET less than the total precipitation (Table 4). Using this criteria to identify land that was not irrigated in 2002 and 2005 indicated that non-irrigated area in 2005 was about 148,000 acres (five percent) more than in 2002. Most of this area was located on the west side of the Valley.

Table 4. Agricultural Area with ET Less Than Precipitation

Region	Area (ac)	Area in 2002 with ET < 6 in (ac)	Area in 2005 with ET < 11 in (ac)	Area in 2002 with ET < 6 in (%)	Area in 2005 with ET < 11 in (%)
Landsat Image	2,889,645	174,813	322,892	6.05	11.18
Kings County	630,642	57,248	79,388	9.08	12.59
Part of Kern County	757,299	71,045	115,987	9.38	15.32
Part of Tulare County	687,967	2,013	17,978	0.29	2.61
Part of Fresno County	736,211	30,848	94,789	4.19	12.88

Field boundaries and crops were obtained for Kern County from the County Agricultural Commissioner's office for 2002. The top five crops produced in terms of acreage were almonds on about 132,000 acres, followed by cotton on 92,000 acres, alfalfa and alfalfa mixtures on 75,000 acres, pistachios on about 54,000 acres and wheat on about 51,000 acres (Table 5). Alfalfa and alfalfa mixtures had the highest April through October average ET at just over 39 inches followed by almonds at about 34 inches. All crops, except alfalfa which was about the same, had slightly higher average ET in 2002 compared to 2005.

Given the ET_a computed by the SEBAL model, a "lumped" crop coefficient can be computed as ET_a divided by the reference ET. The SEBAL model computes a reference ET for each pixel in the image based on the FAO 56 (reference) Penman-Montieth equation and spatially interpolated weather parameters. This "lumped" crop coefficient combines the pristine crop coefficient (K_c) and the stress coefficient (K_s) into a single

Table 5. Seasonal (April – October) ET for the Five Crops Covering the Most Area in Kern County

Top Five Crops by Area in Kern County	Area (ac)	Mean ET (in)		Std. Dev. ET (in)	
		2002	2005	2002	2005
Almonds	131,967	34.58	33.97	12.89	16.29
Cotton	92,018	35.71	32.49	11.12	6.99
Alfalfa & Alfalfa mixtures	75,155	39.16	39.17	12.66	8.56
Pistachios	54,124	25.73	25.31	14.10	15.45
Wheat	50,825	28.52	26.24	14.97	9.64

term (K_{cs}). The mean seasonal K_{cs} for almonds, cotton and pistachios is essentially the same for both 2002 and 2005, indicating that the level of average water stress was about the same for the two years. Conversely, the mean K_{cs} is 14 and 9 percent lower for alfalfa and alfalfa mixtures and wheat, respectively in 2002. This represents increased water stress on alfalfa and wheat crops in 2002, the dry year.

Four alfalfa and four almond fields were selected as an example of intra-field, inter-field and inter-year ET (Figures 3, 4 and 5). At the time the aerial photo (Figure 3) was taken in June 2005, it appears that the two north alfalfa fields were fallow. However, the 2002 ET results indicate that these two fields had more ET than the south fields in 2002 (Figure 4).

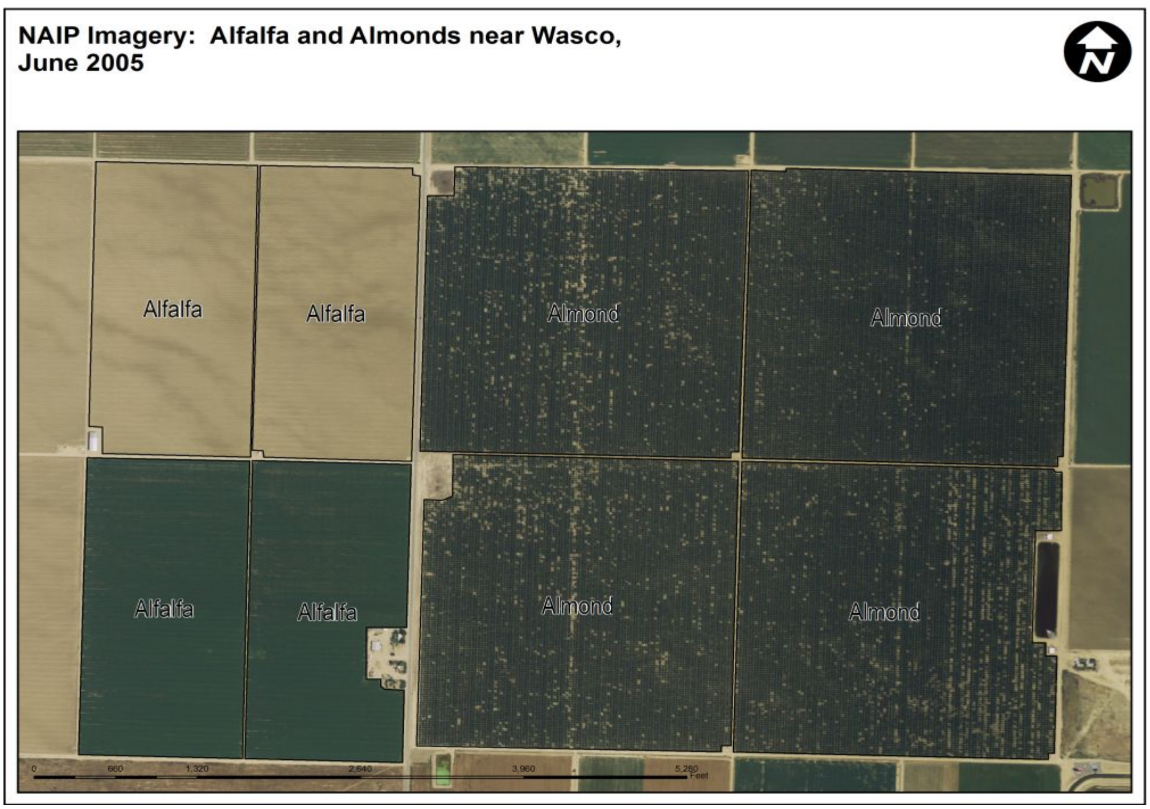

Figure 3. Aerial Photo of Selected Alfalfa and Almond Fields near Wasco, California

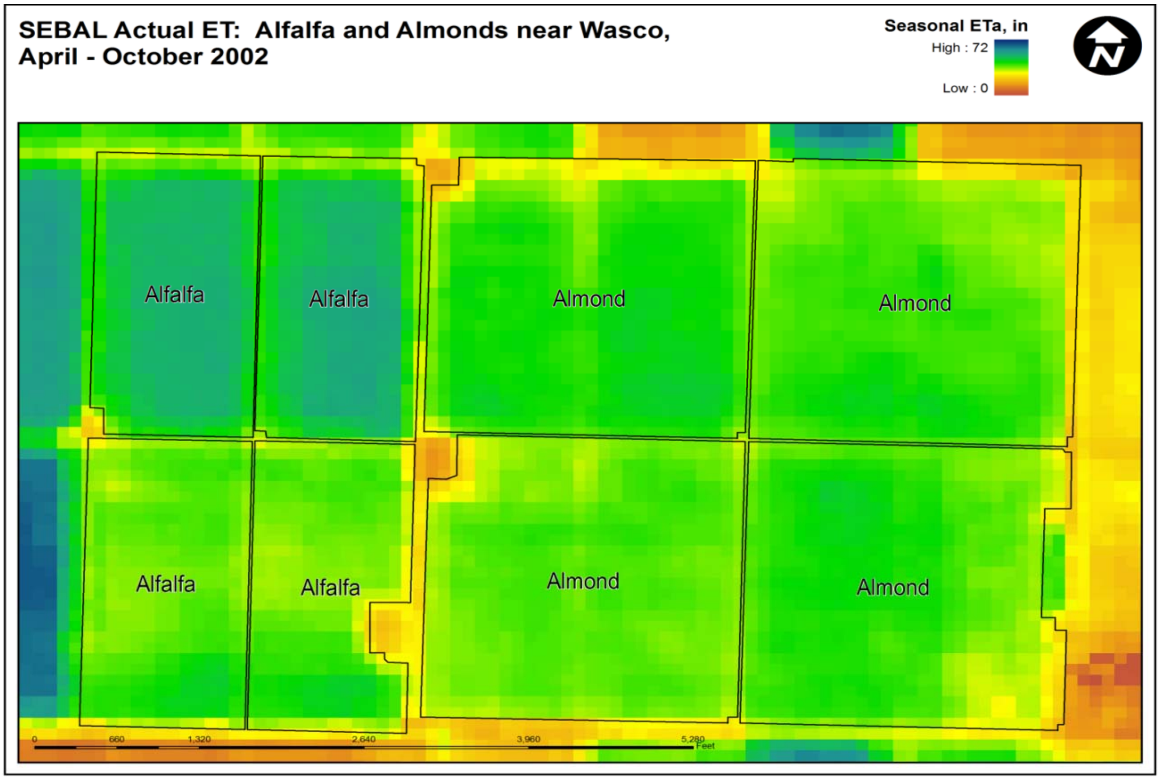

Figure 4. ET of Selected Alfalfa and Almond Fields near Wasco, California

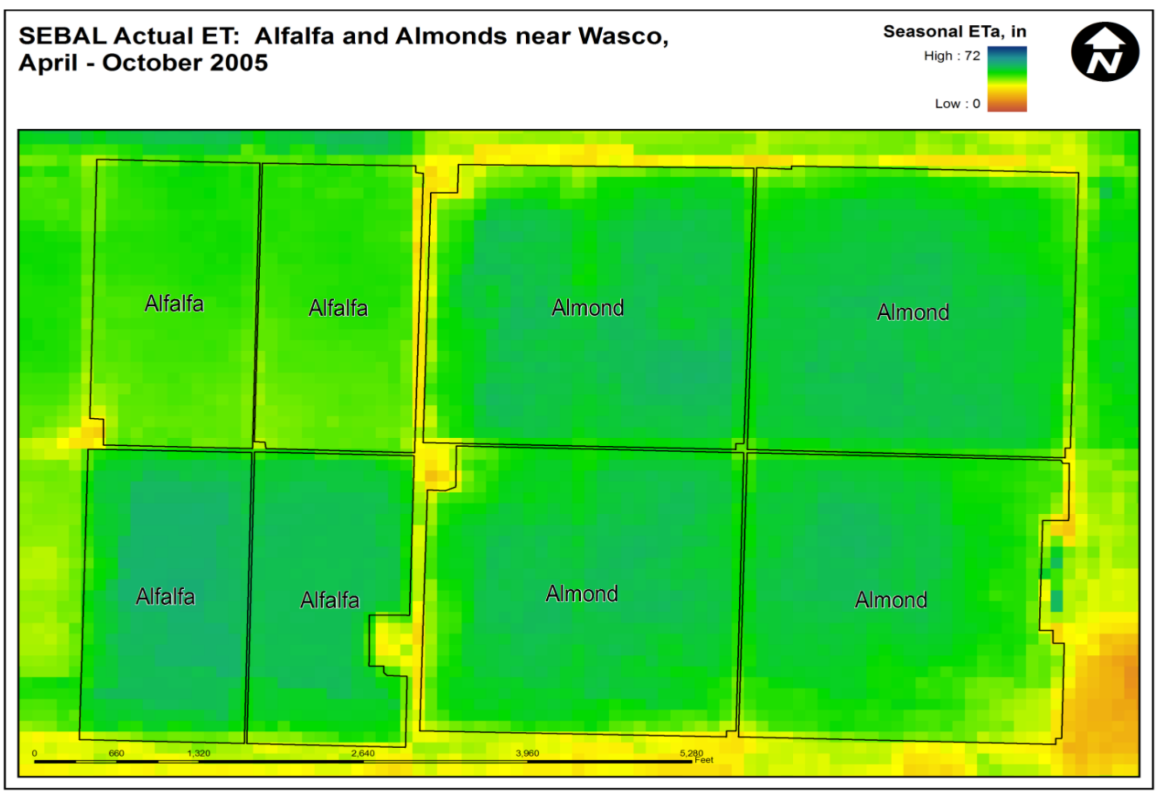

Figure 5. ET of Selected Alfalfa and Almond Fields near Wasco, California

However, the 2005 ET results (Figure 5) show greater ET in the south two alfalfa fields as one would expect based on the aerial photo. All four almond fields consumed more water in 2005 than in 2002.

COMPARISONS TO OTHER REGIONAL WATER USE ESTIMATES

The USGS compiles and publishes nation-wide estimates of water use every five years. For the 2000 report, the most recent available, water use was defined as water withdrawals (Hutson, et al., 2005). Water withdrawal is defined as "water removed from the ground or diverted from a surface-water source for use." The report acknowledges that a portion of these water withdrawals is "released" from the point of use and thus becomes available for further use.

In 2000, irrigation water withdrawals for irrigation in Kings County were estimated to total 1.66 million acre-feet (3.25 acre-feet per acre) (Hutson, et al., 2005). The CDWR estimates a total crop ET of 1.31 million acre-feet (2.56 acre-feet per acre) (CDWR, 2009). The SEBAL model results estimate a total crop ET of 1.57 and 1.34 million acre-feet for the April through October growing season in 2002 and 2005, respectively.

CONCLUSIONS

Total ET in 2002 and 2005, respectively dry and wet years with regard to surface water supplies, was essentially the same for agricultural lands in the southern San Joaquin Valley. For the year 2002, the increased evaporative demand, as indicated by the higher reference ET, and the lower available soil moisture resulted in increased water stress on lower value crops. This increased water stress was indicated by the lower seasonal K_{cs} as compared to the 2005 year. Accurate quantification of ET is extremely important because water consumed as ET is not available for reuse. The SEBAL model provides extensive data sets quantifying spatial and temporal patterns in ET, greatly increasing knowledge and understanding of the consumptive use of water to support more informed water resources planning and management

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AQUALASTIC® CANAL REPAIR SOLUTIONS FOR URBAN, RURAL, DEGRADED AND LEAKING IRRIGATION CANALS

Jill Winfield[1]

ABSTRACT

The AquaLastic® Canal Repair System is a solution for severely degraded, leaking and potentially leaking concrete irrigation canals.

AquaLastic® was developed in response to an industry need, by two individuals from Washington State who thought of taking a known polyurea substance and developing it in specific ways to meet the unique, worsening conditions of aging irrigation systems.

Today, over 6 million linear feet of AquaLastic® has been applied to Western irrigation canals and the AquaLastic® technology has performed to flawless standards ever since the first installation over eight years ago. At Quincy Columbia Irrigation District, WA, it remains as effective in the canal as the day it was installed, even though AquaLastic® has since gone through subsequent product and application improvements.

There are many irrigation districts that have substantially benefited from AquaLastic®. These districts saved large dollar amounts when compared to other methods of canal repair or replacement, and AquaLastic® also stopped water leaks, thereby recouping much of the cost of installation via water sales that would otherwise have been lost.

AquaLastic® is an example of how products developed for other industry areas have, and continue, to be adapted in productive and useful ways for other uses.

INTRODUCTION AND BACKGROUND

AquaLastic® began over a quick lunch break on a windswept highway in Washington State.

Tom Matheson (Matheson Painting) and Jim Powers (Powers Equipment) were discussing the emergency situation at a nearby canal company. A main, high capacity feeder canal was leaking. The pressing fear was that the leaks might rapidly worsen and flood a populated area below the canal.

Tom Matheson's industrial painting company was, at the time, sealing metal gates using a polyurea product and the two men discussed applying the material to the cracks in the concrete canal liner.

They suggested it to the irrigation district's manager as a *temporary* solution to the impending emergency and he gratefully agreed. A few months later, with the temporary solution still perfectly in place, AquaLastic®, formerly known as Hydrolastic, came into being as a canal repair product.

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[1] Technical Representative, Cairo Canal Solutions LLC; President, Cygnet Enterprises Northwest Inc.

That was more than eight years ago and today, the original application site remains perfectly intact.

Several product revolutions and nearly a decade later, the AquaLastic® Canal Repair System remains the leading method of concrete canal repair throughout the northwest irrigation states and is rapidly growing in demand in many more states, including California, Utah, Arizona, New Mexico and Nevada. AquaLastic® is exclusively distributed worldwide by Cygnet Enterprises Northwest Inc. in partnership with Cairo Canal Solutions LLC.

The AquaLastic® name has also developed to be described as the AquaLastic® Canal Repair System. It was quickly understood that applicator experience and skill is an essential element of efficient use of polyurea substances on concrete for underwater applications and that other products, such as fillers, can be utilized to increase the places that AquaLastic® can be used to save money and prolong the life of canals, flumes and ditches.

These other products are a variety of state of the art industrial sealers and fillers that enable the experienced application crew to enhance the operation by chasing-down and filling and securing voids and leakage channels underneath and behind concrete panels.

As Dick Hapaala, Senior Engineer at Ch2M Hill remarked about an AquaLastic® installation crew that worked on a badly degraded flume at Union Gap ID in WA: “Those guys made it look easy, but on studying them at work, I saw that it takes experience and a high level of skill to do it right.”

AquaLastic® has been developed to offer a number of unique qualities. The most important of these is the product elongation factor of nearly 900% and its adhesive qualities and tensile strength. However, even the unique qualities of the AquaLastic® polyurea are only valuable when applied by experienced applicators with years of experience handling the materials. Polyureas are a two-part component application, mixed at the nozzle, and any movement off ratio, however slight, will greatly affect the performance and longevity of the material. An experienced applicator knows exactly how AquaLastic® should look, feel and perform and knows instantly if there is a change.

Later, we look at three different canal systems where Certified Applicator skills and the AquaLastic® Canal Repair System came together to make tremendous, cost-saving improvements to different canal situations.

AquaLastic® being applied using high pressure application equipment

AquaLastic® the Product

AquaLastic® is a state-of-the-art, high performance, sprayed, plural component pure polyurea elastomer. This system is based on amine-terminated polyether resins, amine chain extenders and MDI prepolymers. It provides a flexible, resilient, tough, monolithic membrane with good water and chemical resistance. It is applied using high pressure application equipment.

DRY PROPERTIES* @ 70 mils (1.77 mm)*	
Tensile Strength ASTM D 638	3400 psi (23.63 mpa) Avg
Elongation @ 77°F (25°C)	867% Average
Hardness (Shore A) ASTM D 2240	87 (0s)
Hardness (Shore D) ASTM D 2240	41 (0s)
Tear Resistance ASTM D 624	398 PLI (69.69 KN/m) Avg
Perms (MVT) ASTM E 96	.107
Service Temperature	-40°F - +200°F
	-40°C - +93°C

Figure 1. Dry Properties of AquaLastic®

Key Features of AquaLastic®

- 100% solids. No solvents, No VOC's
- Fast set: Handle in two minutes or less.
- Hydrophobic, therefore unaffected by damp, cool surfaces during application
- Proprietary adhesion enhancing additives ensuring excellent bond strength to concrete
- Extended tack time to allow deep surface penetration
- High temperature stability up to 250° F (121 °C) with intermittent temperatures up to 300° F (148 °C)
- High abrasion resistance
- ASTM E84-97a and complies with NFPA and UBC Class 1 Fire Rating

CANAL CASE STUDY 1 — ROZA IRRIGATION DISTRICT, WA

Roza Irrigation District AquaLastic® Application

Background

There were two sections of the main canal, approximately 3,598 linear feet that had been leaking excessively due to a large number of cracks caused by expansion and contraction from freeze-thaw cycles that rendered the concrete non-water tight. Once the water escaped through the cracks it entered drains under the concrete liner that were originally intended to carry water away from the liner. The amount of water that was leaking was known via a water meter.

Escaping water was metered at this point

The objective was to eliminate enough seepage to make application of the product, AquaLastic®, cost-effective once the next water shortage year came to pass. To do this, the project would have to eliminate at least 88% of the seepage.

The project entailed sandblasting a three to four inch strip each side of all the cracks and clearing the canal of debris. This work was carried out by the AquaLastic® Certified Applicator and the crew then applied approx 80 – 100 mils of AquaLastic® to the cracks, bridging the gaps to create a water-tight seal to eliminate the leakage.

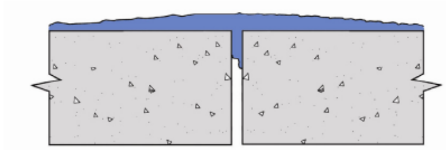

Figure 2. AquaLastic® bridges cracks to accommodate expansion and contraction from freeze-thaw and cool-heat cycles.

Upon Completion

Prior to the start of the project, the estimated water loss was approximately 1,220 acre-feet per irrigation season. After the completion of the project, not only did AquaLastic® eliminate 99% of the seepage, far exceeding the required 88%, but during the following 2007 season, the total water loss was approximately 14 acre-feet, for a net savings of 1,206 acre-feet. This saving is equal to $145,500 annually and so the project more than paid for the application costs during the next drought season when the additional water could be marketed.

The metered site after AquaLastic® application. No water can be seen.

CASE STUDY 2 — THE BOISE PROJECT, ID AND URBAN CANALS

Urban development encroaching on canals

Background

Irrigation Districts have some special situations to deal with, such as when canals pass through urban areas. In many cases, canals were constructed before any urban residential or industrial construction. A main canal managed by the Boise Project Board of Control, Idaho flows right through the center of Boise and numerous residential areas. Some real estate agents have even gone so far as to describe the properties as 'water front'. Managers of The Boise Project have, as a consequence, wrestled with a number of problems concerning the proximity of urban build-up to their canals. In one such case, they were dealing with the problem of water leaking into the basement of a house that was situated well below canal level.

Photo taken from the backyard of the house. The canal flows above the level of the house behind the constructed retaining wall.

The Boise Project chose to utilize AquaLastic® in an experiment to try to establish where the water was originating from. The possibilities were that it was leaking out of the immediate canal stretch, from a different part of the canal, or flowing from the heavily 'watered' yards of an upscale residential area above the far side of the canal. As there were a number of cracks in the walls of the main canal and a large gap between the wall and floor and the first step in the elimination process was to seal them.


The canal prior to application


The canal during application

AquaLastic® crack sealer was applied to the stretch of canal most likely to be leaking, in spring ’07. The Boise Project’s own maintenance team undertook sandblasting the crack areas prior to application. The largest cracks between the walls and the bottom of the canal were filled first with specially selected industrial foam filler and then the coating was applied by AquaLastic® Certified Applicators to form a water-tight seal over the top.

The canal was very carefully scrutinized by teams from both organizations to ensure that every crack had been sealed.

After irrigation start-up, it was found that water was still leaking into the house. Manager, Paul Deveau said at the time: “We are very disappointed for the homeowners, but also now very confident that the water is coming from elsewhere. It is a process of elimination to find out where it is coming from and this has been a good start.”

The following year, The Boise Project contracted the application of additional AquaLastic® to other areas in the same urban canals as part of their ongoing canal maintenance program.

The Boise Project New York canal

AquaLastic® has become a leading choice for the repair of urban canals where breaching would have particularly disastrous consequences.

Kennewick Irrigation District in Kennewick, WA has many parts of its system where urban development, industrial and residential, has encroached on aging canals. As a consequence, the management took the decision to use AquaLastic® on a rolling program and many miles have now been completed with potential urban flood areas treated as a priority.

A recent canal break in an area not yet treated with AquaLastic® caused severe problems for the district, demonstrating the potential consequences. In this case, farmland was flooded rather than housing, but the emergency reinforced the potential reality of a breach in a populated area of the City of Kennewick.

Photo courtesy of KNDU.com

Extract from KNDU.com website. *"KENNEWICK, Wash. - Crop owners and Farmers are wondering when water will come after a Kennewick Irrigation District canal broke Monday.*

The brake [sic]couldn't have come at a worse time. With the record heat and no water, orchards and crops have little to depend on and little time to survive.

John Pringle of Pringle Orchards in Kennewick has thousands of apple trees in danger of drying out……"

CASE STUDY 3 — FLUME AT NAMPA AND MERIDIAN IRRIGATION DISTRICT, ID

Degraded high level flume photographed early spring '08

The flume exhibited advanced deterioration in all areas with damaged joints and exposed aggregate.

Manager of Nampa and Meridian Irrigation District, John Anderson estimated that the flume was losing 25 Miner Inches or 1 Acre Foot per day. Water was visibly leaking and there was severe spawling on the concrete.

He explained that the Irrigation District had patched-up the flume many times and within one irrigation season, the patches were peeling away.

Example of patch peeling away

A complete re-build had been considered at a cost of $0.75- $1 million. A repair was effected with the AquaLastic® Canal Repair System in late spring of 2008 at a cost of around $80,000.

The repair process included several steps before AquaLastic® was applied to the entire surface area. The flume was sandblasted throughout the inside circumference and across the top of the sides. It was then patched with a polymer cement and primed with Epoxy paint.

Several processes took place before AquaLastic® was applied

The flume is completed and ready for re-watering at a fraction of the cost of replacement

John Anderson says there have been no visible leaks throughout the irrigation seasons of 2008 and 2009 and that the flume over-wintered well in Idaho’s harsh winter weather with no observed problems associated with the AquaLastic® coating.

NEW AQUALASTIC® LOW PRESSURE SYSTEM (ALPS)

Irrigation Districts can now undertake many of their own concrete canal repairs with the new, state of the art AquaLastic® Low Pressure System (ALPS).

The System allows districts to safely handle and apply a proven polyurea using their own maintenance crew, giving them the flexibility to repair areas of canals in selected places where a high pressure application with a Certified Applicator is not necessary.

Extensively tested on irrigation canals in the North West, the AquaLastic® Low Pressure System consists of a low pressure, self-contained system that is so compact, it will fit into the back of a standard sized pick-up and even onto the back of an ATV. The unit is mounted on wheels for easy loading and maneuvering into vehicles or directly into canals or onto access roads and tracks. Complete with a central heating system and elongated heated hoses, it is designed for use in canals any time of the year, including low temperature winter conditions.

Initial ALPS field tests took place with the help of several irrigation districts in winter 2008. Based on those trials, several modifications to the system were engineered and recent field tests have demonstrated the ease of operation and effectiveness of the system.

ALPS uses state of the art polyurea technology from the AquaLastic® product suite. AquaLastic® *high pressure* has a flawless 10+ year history with no product failure, in irrigation canals. This is due to its unique properties that have been optimized over many years for the specific requirements of irrigation canal systems. Many of these unique advancements exist in the low pressure polyurea which is so well developed, that it meets many of the standards currently found in other high pressure polyureas advertised on the market, that are more expensive to apply.

Use of ALPS requires a very short training program that covers equipment start-up, shut-down, and minimum maintenance requirements.

The ALPS equipment is highly affordable to purchase and a rental option is also available, making it especially approachable for smaller districts that might wish to utilize the technology in their concrete ditches.

ALPS is not intended as a direct replacement for the AquaLastic high pressure applications that have been used to repair major problems in canals and flumes and completed by experienced, AquaLastic® Certified Applicators. It is an additional option that is particularly suited to repair smaller canals and ditches and also as an emergency repair option that is especially beneficial for urban canal systems where unforeseen water leaks have potentially disastrous consequences.