Meeting Irrigation Demands in a Water-Challenged Environment

SCADA and Technology: Tools to Improve Production

A USCID Water Management Conference

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USCID
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Edited by

Gerald A. Gibbens
MWH Americas, Inc.

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

Published by

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

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

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

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Preface

The papers included in these Proceedings were presented during the **USCID Water Management Conference**, held September 28 - October 1, 2010, in Fort Collins, Colorado. The Theme of the Conference was *Meeting Irrigation Demands in a Water-Challenged Environment***.** An accompanying book presents abstracts of each paper.

In today's economy, it is easy to forget about planning and implementing state-of-the-art technology and instead focus on "just getting by." However, continual **improvements in technology** provide the backbone in processes and systems to increase efficiency and provide protection from the vulnerabilities caused by antiquated methods. Technological advances affect all aspects of irrigation and water system operations, from engineering, planning and finance, to system operations and environmental protection. The Conference provided a forum for presentation and discussion of advancements in technology, and to demonstrate its application to all areas of irrigation and water resource system planning, engineering, operation and maintenance.

The Conference incorporated a special session dedicated to **Supervisory Control and Data Acquisition** (SCADA) systems. This session featured an exchange of ideas and information regarding state-of-the SCADA systems, building upon previous USCID conferences on this subject.

The authors of papers presented in these Proceedings are professionals from academia; federal, state and local government agencies; international 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.

Gerald A. Gibbens
MWH Americas, Inc.
Fort Collins, Colorado

Conference Chairman

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THE COLORADO SATELLITE-LINKED WATER RESOURCES MONITORING SYSTEM: 25 YEARS LATER

Thomas W. Ley[1] PhD, PE
Phil L. DeArcos[2]
Russell V. Stroud[3]
David G. Hutchens[4]

ABSTRACT

The Colorado Satellite-Linked Water Resources Monitoring System was initiated as a two-year pilot demonstration project in the early 1980's in Colorado's Arkansas River and Rio Grande River Basins. The system was formally established with funding from the Colorado Water Resources and Power Development Authority in 1985. By the end of 1985, an effective monitoring network of 150 stations had been established. The Satellite Monitoring System (or SMS, as it is now called) was turned over to the State Engineer's Office (aka the Colorado Division of Water Resources, CO DWR) to operate and maintain in October 1985. Today CO DWR operates and maintains over 500 satellite telemetry gage stations on rivers, streams, ditches and reservoirs around the State. In combination with satellite telemetry gaging stations operated by the USGS, and gage data from other State and local agencies in Colorado, water resources data from over 900 sites are available in near real time from the Colorado Surface Water Conditions web site (www.dwr.state.co.us). This paper will chronicle the continuing development of this important water resources management tool in Colorado, including changes in technology, information management and delivery, system expansion, coordination with other agencies, and the ever-increasing ways in which the data are used. Although not a SCADA system, many gages on the network provide dual benefit for collection of data for the SMS as well as for direct feed to SCADA systems operated by gage cooperators.

BACKGROUND

Colorado water law has its roots in the gold rush days of the late 1850's and early 1860's, when miners used water to work their claims regardless of the location of the claim relative to the water source. Due to the relative scarcity of water in the Intermountain West and the sporadic nature of the supplies, these early water use rights also were based on the concept of "first in time, first in right". As mining went through its boom and bust cycles, homesteading and development of agriculture followed closely behind. Prior to Colorado statehood in 1876, territorial laws were enacted allowing water to be taken from streams and rivers to lands "not adjoining the waterway", as well as recognition of rights of way to transport water across lands not owned by the owners of the water right.

[1] Chief, Hydrographic and Satellite Monitoring Branch, CO Division of Water Resources, thomas.ley@state.co.us
[2] IT Professional , CO Division of Water Resources, phil.dearcos@state.co.us
[3] Hydrographic Technician, CO Division of Water Resources, russell.stroud@state.co.us
[4] Electronics Specialist, CO Division of Water Resources, david.hutchens@state.co.us

The Colorado Doctrine, or the Doctrine of Prior Appropriation, recognizes: a) those that put the water to use first are entitled to get their water first during periods of water shortage, and b) water is a separate property right that can be sold separately from the land. This is opposed to the Riparian Doctrine that ties water use rights to the ownership of lands adjacent to the river or stream. The codification of fundamental Colorado water law is found in Colorado's 1876 Constitution, Article XVI, Sections 5, 6 and 7. These basically state: water within the State of Colorado is a public resource belonging to the citizens of the State; the right is recognized to divert unappropriated waters of any natural stream and apply that water to beneficial use with priority of appropriation determining who gets water first in times of shortage; and, the right is recognized to convey water across public, private and corporate lands upon payment of just compensation.

In 1879, the legislature created a part of Colorado's present water administration system. It provided for the division of the State into ten water districts, nine of these in the South Platte valley and one in the Arkansas. The position of Water Commissioner was created with this legislation for the express purpose of allocating and distributing water according to the doctrine of prior appropriation. The statute as passed by the legislature in 1879 did not provide for stream measurement.

In 1881, the Colorado legislature established the Office of the State Hydraulic Engineer. The purpose of this office was to assist in carrying out the provisions of certain portions of the irrigation laws passed at the same session, and to obtain important information by means of surveys and observations. Primary responsibility was the administration of water rights according to the appropriation doctrine, "first in time, first in right," by maintaining a list of water rights, on each stream, in order of priority. The priority of a water right is determined by both when the water was first diverted and put to a beneficial use and when the right was decreed by the district court. Additionally, the State Engineer shall: "shall make, or cause to be made, careful measurements and calculations of the maximum and minimum flow in cubic feet per second, of water in each stream from which water shall be drawn for irrigation, as may be best for affording information for irrigating purposes; commencing with those streams most used for irrigation; also to collect facts and make report as to a system of reservoirs for the storage of water, their location, capacity and cost; and he shall keep proper and full records of his work, observations and calculations."

These two early pieces of legislation formed the basis of the system of water administration still in use today: measurements of the amount of water in rivers and streams over time provide the data needed and used by water commissioners to administer water rights according to the State's Constitution. Early on this process was difficult. Only infrequent observations of the amount of water in various water courses were possible, only in a few locations, and these observations suffered from inaccuracy and imprecision. In 1883, Colorado's second State Engineer, E.S. Nettleton, designed and developed the Colorado Current Meter, cups or vanes rotating in a horizontal plane around a vertical axis, the speed of rotation of which could be directly related to the velocity of water impinging on the vanes. This design is the basis of the Price AA current meter still widely used today. This advance greatly improved the ability to accurately measure stream discharge. In 1884, Nettleton designed and developed a stream stage recorder for use at streamgaging stations to collect continuous records of stream stage, which could be used to compute records of streamflow. The State Engineer’s Office established some of Colorado’s earliest stream gaging stations during this period: Cache la Poudre at the Canyon Mouth (1881), Arkansas River at Canon City (1888), and Rio Grande near Del Norte (1889), and are still operated by this office.

In 1887, the State created the position of superintendent of irrigation, the forerunner of today’s division engineer, to supervise water commissioners within each division. By the beginning of the 1890's, many stream systems were over appropriated. The need to know stream flow rates over time and in many locations was becoming more widespread.

In 1969, the State legislature passed the Colorado Water Rights Determination Act. This legislation created the Colorado Division of Water Resources (CO DWR) as part of the Department of Natural Resources. The State Engineer’s Office was incorporated as the CO DWR. CO DWR is empowered to administer all surface and ground water rights throughout the state and ensure that water is administered according the State Constitution and court decrees. CO DWR employs approximately 257 professional engineers and geologists, information technology professionals, technicians, and support staff to administer water rights, to evaluate and issue water well permits, monitor stream flow and water use, inspect dams and wells for construction and safety, maintain databases of Colorado water information, represent Colorado in interstate water compact proceedings, evaluate impacts of and necessary mitigation for various water use activities, educate the public, and numerous other responsibilities.

Significant development has transpired over the 134 years since Colorado became a State, including development of major urban centers (particularly on the Front Range), economic development, and agricultural development. Interstate compacts and agreements were developed describing how water, which has its source in Colorado, would be shared with downstream States. By the later decades of the 20th century, heavy stress on Colorado’s limited water supply and on administration of that water supply was being experienced. Population growth has resulted in greater domestic demand for both surface and ground water. Colorado’s water administration has attempted to keep pace. Increasingly complex water court decrees, augmentation plans, exchanges, etc. have been developed and executed.

DEVELOPMENT OF THE COLORADO SATELLITE-LINKED WATER RESOURCES MONITORING SYSTEM

As discussed above, by the early 1980’s, Colorado water administrators were experiencing greater and greater need for timely and accurate water resources data at more and more locations Statewide. To help meet this need, a two-year demonstration project was designed and implemented in the Arkansas River and Rio Grande River basins, in which, continuous water resources data were collected at key gaging stations and provided in near real-time via satellite telemetry to decision makers. The project successfully demonstrated that water rights administration, hydrologic records development, flood warning, and water resources management could be significantly enhanced.

The Colorado Water Resources and Power Development Authority provided initial funding for this project pursuant to Section 37-95-107(5), C.R.S. (1983), by enactment of Senate Joint Resolution No. 20. The Colorado Water Resources and Power Development Authority has, as one of its goals, enhancement of water resources management in Colorado. The Authority provided funding for system establishment and its first year of operation at a total cost of $1.8 million in 1984.

The Authority awarded the contract, under competitive procurement, to the Sutron Corporation, Herndon, Virginia, in May, 1984. The original contract called for Sutron to provide a turn-key system including remote data collection hardware for 82 stations, receive site, central computer, and operating/applications software. In March 1985, the Authority approved an expansion of the monitoring network by an additional 68 stations. This effectively brought the statewide network to 150 stations. The system acceptance test was successfully run on August 8, 1985. The system was formally dedicated on October 4, 1985. At that time, the Authority turned the system over to the State of Colorado under the jurisdiction of the Office of the State Engineer.

Early System Description

The SMS allows the Division of Water Resources to collect, process, store, and distribute many kinds of environmental data transmitted from remote locations. The data set of interest to the Division is the water level at rivers, streams, diversion structures, and reservoirs. The SMS converts these raw water level values into several "products" of use to various "clients". The "products" range from raw data passed on to other computer systems to the official Hydrographic Records of mean daily stream flows. Clients include Division of Water Resources personnel and other water users wanting real-time administrative data, computer systems performing other analyses, and the varied user community of state and federal agencies, municipalities, canal companies, attorneys, and consulting engineers needing access to real-time and historic stream flow data.

The SMS consists of four primary sub-systems: 1) the remote station data measurement, collection, and transmission hardware; 2) the satellite communication links and transmission receive hardware; 3) the computer hardware and software systems; and 4) the computer-based hardware and software for making data available to users.

Data collection, measurement and transmission hardware was generally installed in existing stream, diversion, or reservoir gauging stations, and included on-site sensors, a programmable Data Collection Platform (DCP) and radio transmitter electronics, a power supply, and a radio antenna. The primary sensor for measurement of stream stage or water level was either a float actuated incremental shaft encoder operating in a stilling well hydraulically connected to the stream or reservoir, or, a manometer or other type of pressure transducer, or a direct discharge meter. Often air temperature sensors and other meteorological sensors were also present. The DCP is a programmable device that collects, processes, and stores data from up to 16 sensors. It also controls the timing of the satellite radio transmissions. Most sites are powered by 12-volt batteries re-charged by solar panels. If available on site, 120 volt AC power was used and converted to 12 volt DC current. Environmentally secure enclosures were used to protect the equipment from extreme weather and unauthorized access.

In the early years of operation, remote site hardware consisted of a Sutron 8004 DCP (Fig. 1) that would measure data every 15 minutes from a 0-5 volt shaft encoder and then transmit the values every four hours at a data transmission rate of 100 bps. Transmission time windows were one minute in length. The DCP was programmed using command driven software by connecting a portable computer via an RS-232 port. Very little diagnostic insight about DCP operational performance was provided. The 8004 was limited to storage of 32 data values per connected sensor. In most cases, this amounted to 8 hours of 15-minute data. With scheduled transmissions at 4-hour intervals, this provided replicate data in case of a missed transmission. A DCP could be programmed to detect if stream stage or water level conditions exceeded programmed threshold levels. When such conditions occurred, transmission of such random events on a separate channel for random messages could be enabled, providing real-time alarm warnings. A major operational issue was the need to maintain accurate time (GMT) in the DCP in order to keep satellite transmissions within the required transmission time window for the specific gage site. Many transmissions were missed due to incorrect GMT time entry, and, over time DCP clocks would drift. Additionally, transmission circuits would drift requiring bench re-calibration.

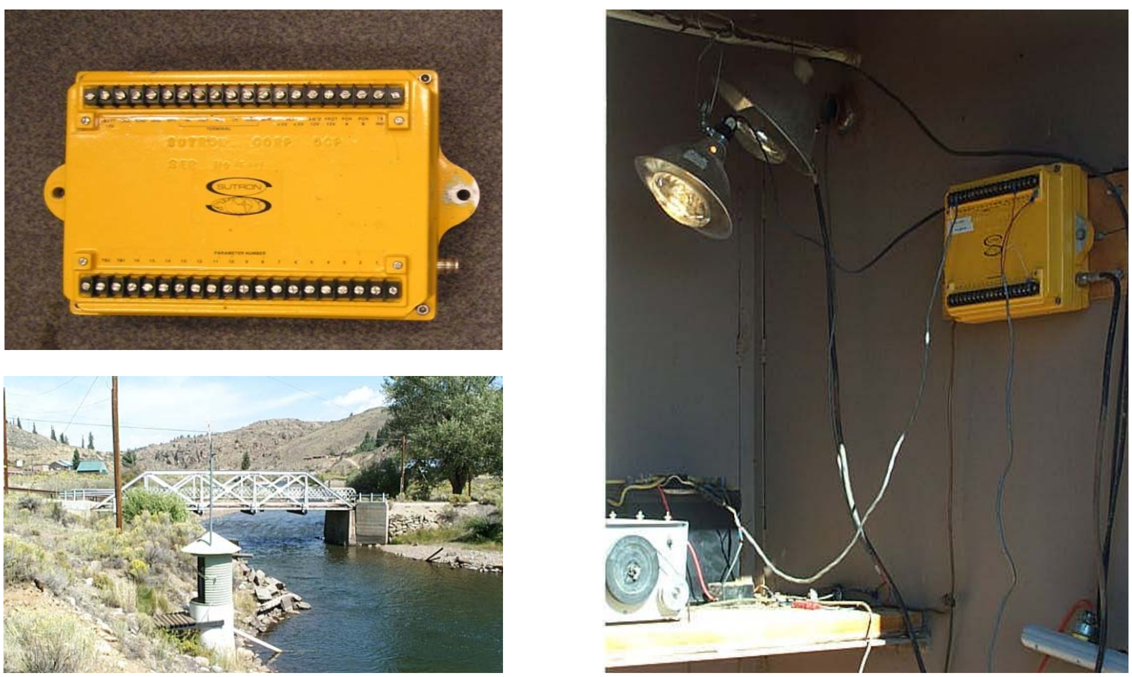

Figure 1. Early Colorado SMS DCP and gage installation.

The system was expanded in the 1990's using Sutron 8200 DCPs. The 8200 could measure and log data from several different types of shaft encoders and could store up to one year of data in internal memory. New bubbler-type pressure transducers were introduced in the field to replace mercury manometers. The DCP was programmed by menu driven software, but now had a one line display and front panel keypad for configuration and viewing of data. Many transmissions were still missed due to clock and transmission circuit drift.

The communications link for data transmissions from the remote site DCP is a Geostationary Orbital Environmental Satellite (GOES). This is a federal satellite operated by the National Oceanic and Atmospheric Administration-National Environmental Satellite, Data, and Information Service (NOAA-NESDIS). The GOES satellite is in equatorial, geostationary orbit 22,500 miles from the earth surface in space. The Division of Water Resources originally installed a Direct Readout Ground Station (DRGS) to receive this data directly from the GOES satellite. In the mid 1990's, this method was converted to what is called a local readout ground station which receives and processes data transmitted on a domestic communications satellite. The NOAA Data Collection System (DCS) receives all GOES transmissions at its Command and Data Acquisition Station at Wallops Island, Virginia then retransmits the data over one channel to a domestic communications satellite visible from all of North America. This satellite (DOMSAT) broadcasts back to earth with much more power than the GOES system. The more powerful signal allows use of a much smaller 1.8-m diameter antenna and much simpler electronics. Since the DOMSAT multiplexes all data on one channel data from any remote site can be received without additional electronics.

The first main computer used on the SMS was a Digital Equipment Corporation (DEC) VAX 4000-300. This system gathered data from the DRGS electronics and from the DOMSAT receive system running on a PC. Real-time software automatically processed converted, and stored the incoming data. The conversion calculations used the most up-to-date stage-discharge relationships for a given stream gage and hydrographic shifts, as determined by actual measurements, to reflect changes in the stream channel characteristics. The system processed meteorological information in a similar manner. Every morning the system processed the previous day's data and calculated mean values, minimums, maximums, and other statistics, placing the results in a separate database. To preserve the integrity of the data, the original raw satellite data were archived unedited in a separate database. An internally developed system extracted a subset of the original data for editing and hydrologic streamflow record development. Other programs allowed users to access data and to control the system.

Several methods of communications access and data dissemination were supported in the early years. Using a PC and a modem, users anywhere in the world, with proper authorization could access the system. In 1995, CO DWR installed newer, high speed 28.8kb modems. This provided users with a better level of service through much higher data transfer rates. Eventually applications were developed allowing users to connect to the system and access data through the Internet.

The Colorado Satellite-linked Water Resources Monitoring System received national merit awards in 1985 and 1986. The National Society of Professional Engineers selected the system as one of ten outstanding national engineering achievements for 1985. The

Council of State Governments selected the system as one of eight of the top innovative programs instituted by state government in the nation for 1986. At the time, Colorado was the only State in the nation to operate a statewide monitoring system of this type.

On-Going Development

The interest in real-time data collection for monitoring water resources and other natural resources data grew at an incredible rate due to the need for such data and the cost effectiveness of this approach to data collection, processing and dissemination. Table 1 shows the growth of the SMS at five-year intervals since inception. Various federal agencies (primarily the US Geological Survey), water conservancy districts, municipalities, and private entities operate satellite-linked data collection stations in Colorado in addition to the State-operated network.

Table 1. Growth of the number of gaging stations (operated by CO DWR and by other agencies) included in the Satellite Monitoring System since inception.

Year	CO DWR	USGS and Other Federal, State, Local Agencies	Total
1985	52	98	150
1990	57	101	158
1995	229	176	405
2000	324	264	588
2005	462	276	738
2010	518	384	902

During the past decade alone there have been significant advances in technologies employed in the SMS for data collection, data processing, and data presentation to end users. The year 2000 (Y2K) brought about the end of the use of the VAX main frame and DB2 database on the SMS due to incompatibility issues. At that time the satellite monitoring database was migrated to SQL Server 2000 and initial data processing was accomplished on a redundant set of workstations. Each workstation was connected to one of the satellite dish receivers at CO DWR. Data from the receivers was processed and decoded, and then the processed data was fed into both an internal data system, and out through a set of TCP/IP sockets. Alert, Decode, and Diagnostics sub-systems (hosted on the main application/database server), each ‘listened’ on their respective sockets for feeds from the decoding software. These received and then processed the data messages into the main database, where the processed information was used by other sub-systems and applications. The USGS and NCWCD sub-systems (hosted on the development server), received and processed data from their respective cooperator agencies and also stored the data in the main database.

The Data Processing sub-system performed additional calculations or summaries as necessary. This final processed data was then made available to the web reporting database, applications, and tools. Internal Data Viewing and Management Applications were used by CO DWR personnel to manage aspects of the Data Processing sub-system, check the status of field equipment, or retrieve real-time stream-flow results from the database archive. The Hydrologic Management System, a PC client-based software tool, allowed CO DWR hydrographers to update rating tables, shifts, and shift curves used when calculating streamflow results, and the SatMon Telemetry Editor allowed IT personnel to update decoding information. Real-Time Archive and Diagnostics Reporting Systems were intranet based web applications that allowed users to retrieve flow data from the database, as well as to check the status of field equipment by reviewing reports of the diagnostic data sent with each satellite transmission.

In 2000, a simple web site was created for public access to hydrograph displays and tabular data of current stream conditions and up to the last 10 days of historic data. Additional historic data requests required the user to contact CO DWR. In 2004, an internal Alert notification system was added so that specific threshold stream and reservoir conditions could be monitored and notification alert messages generated when thresholds were met or exceeded.

Several improvements were made to the data processing and presentation sub-systems during 2007-2008. These included:

- Extensive upgrade and re-formatting of the stream flow web site allowing enhanced viewing and analysis of current conditions and historic data
- Development of web-based applications for system administration
- Migration of the satellite monitoring database to SQL Server 2005
- Added gage data from a new cooperative program (discussed below) with water conservancy district gages for display on the CO DWR web site
- Upgraded satellite data decoding to a near industry standard LRGS process developed by Ilex Engineering. This new system can capture data from both satellite and/or Internet sources
- Developed and implemented Windows services to process incoming data to improve system stability and integrity
- Added historic data retrieval and analysis features to the web site
- Allowed users to define custom station lists

Current SMS Configuration

Due to near saturation use of available channels on the GOES satellite system, in 2001 NOAA-NESDIS began a process to convert from 100 bps transmissions within one-minute windows every four hours to “high data rate” transmissions at 300/1200 bps in 6 to 15 second windows every hour. This conversion process was formally implemented in 2003, and NOAA-NESDIS has allowed a 10-year period for upgrades. As a result the capacity of the GOES satellite system has increased significantly. For the CO SMS, upgrades have typically involved complete replacement of remote site equipment. Upgrade costs have been in the range of $4000 to $5000 per gage.

Currently, the typical configuration at CO DWR SMS gaging station consists of a Sutron Satlink2 high data rate (hourly transmissions at 300 bps) DCP along with a serial digital interface (SDI) shaft encoder or a bubbler type pressure transducer called a Constant Flow Bubbler. The Satlink2 DCP is programmed using Windows-based software. DCPs are typically configured to collect and log data every 15 minutes. Data are store in flash memory for up to 3 years. The Satlink2 provides the user the option of also installing up to four analog sensors (such as air temperature) and includes a separate input for a tipping bucket rain gage. Several gages in key areas are setup to log and transmit these additional parameters.

By virtue of the implementation of high data rate transmission and shorter time windows in which to successfully complete transmissions (6 to 15 seconds) DCP clock reliability has had to improve. This has been accomplished through use of GPS synchronization that acquires GMT time every hour to ensure accurate DCP clock time. Transmissions occur once every hour at an assigned time given by NESDIS. Four hours of data are transmitted each hour, with three of the four hours being redundant data.

The Satlink2 DCP may also be programmed for alert levels. High threshold alert levels are used to monitor potential flood threats, low threshold alert levels provide protection for low flow instream water rights, and rate of change threshold alerts are used to monitor flows at gages below reservoirs. Once an alert level is detected the DCP will then transmit data values on a separate random channel. These may be viewed real time on the web site or activate an alert messaging service described later.

Sutron has been the primary supplier of data collection platform and satellite telemetry equipment since the SMS was initiated in 1985. This attempt to standardize on equipment has resulted in the following benefits:

- equipment compatibility issues are non-existent or minimal
- staff efficiency in terms of training requirements is improved
- staff develop better understanding of equipment operation, maintenance and troubleshooting when from a single source rather than multiple sources,
- costs of ancillary equipment, parts, pieces, tools to support a single line of equipment rather than multiple lines are reduced
- diagnostics test equipment costs are reduced

CO DWR is currently in the final stages of a multi-year program to upgrade satellite equipment at gaging stations throughout Colorado to high data rate. It is expected the upgrade process will be completed during 2010. Part of the upgrade process has included installation of: a) proper grounding and isolation equipment to improve operational reliability at field sites, b) improved gage power supply equipment (better batteries and solar panels), c) more accurate 400 count per rotation SDI shaft encoders to replace older 200 count per rotation shaft encoders, and d) Sutron Constant Flow Bubblers to replace older bubbler type pressure transducers for better performance and operation diagnostics. Figure 2 presents photos of several upgraded gage stations showing the improved components.

Improvements and upgrades to the SMS data processing and presentation sub-systems have continued as well. Once data have been transmitted to the GOES satellite, the

Figure 2. Photos of CO DWR gaging stations showing equipment upgrades.

NOAA CDA station at Wallops Island decodes the data from the transmission and then makes it available in 2 ways: by rebroadcasting data to the domestic satellite (DOMSAT), and by streaming to the Internet where users may access and capture the data stream via a Local Readout Ground Station (LRGS). There are multiple LRGS stations around the country that access satellite transmissions through a Direct Readout Ground Station (DRGS) and make the transmissions available through an LRGS to the Internet.

Data messages are received at CO DWR through an LRGS. The LRGS is a Windows Server 2003 PC. It is configured to receive transmissions primarily through a DOMSAT receiver connected to the satellite dish on the Centennial Building. A new feature is if the receiver signal fails, then the LRGS will automatically switch to a TCP/IP connection and retrieves data messages through a USGS LRGS system (the Emergency Data Distribution

Network) in Sioux Falls SD. A second LRGS platform sits in a “hot-standby state” as an emergency backup. Figure 3 is a diagram illustrating the current configuration of hardware components used in the SMS from remote field sites to the LRGS server in Denver.

Data are decoded by the LRGS software and stored as text files on the local server. Each LRGS decodes and stores 30 days of data transmissions. Processing is performed by a series of applications running as Windows services. The Data Loader Service takes files decoded by the LRGS and pushes them to the SMS database. The LRGS server also runs applications as “Windows services” to retrieve and process data from cooperator agencies which, in turn, are stored in the SMS database. A USGS Data Service processes data from the USGS web site and stores the data. A NCWCD Data Service processes data via a web service and stores the data. The Data Processor service takes the initially processed data, and performs additional calculations such as discharge. A Diagnostics Service processes “raw” data from files decoded by the LRGS and pushes them to the SMS database. Data in these files is used to diagnose common problems with satellite transmissions. A separate windows service application performs additional data processing, and data is disseminated through a variety of means. Figure 4 is an illustration of the current configuration of computer hardware used to process and prepare data for presentation to end users.

Additional data processing systems and services have recently been implemented. The SMS Monitor Service is a Windows service that periodically checks each component in the data processing system. If any one component has failed to execute within a specified period of time, a notification email is sent to the system administrator. This service has added to the operational integrity of the system. The Alert System has been re-written as a Windows service which allows “subscribers” to be notified when transmitted data meets certain threshold criteria. These two services reside together on a Windows Server 2003 PC. In 2009, data analysis features were added to streamflow web site to replace an internal tool used by Water Commissioners called SatMon Tool. Also in 2009, a web service was created to provide data access by data cooperators on the SMS.

A few operational data processing statistics illustrate the volume of data handled by the SMS in its current configuration:

- 10,700+ satellite transmissions decoded per day
- 105,500+ data values stored per day
- 32,000+ diagnostics data values (signal strength, battery voltage, error codes, etc.) decoded per day
- 45,000+ data values from external providers processed and stored per day.

OPERATION OF THE SMS

The Hydrographic and Satellite Monitoring Branch of the CO DWR is charged with the operational responsibility of the SMS. The Branch’s primary efforts are directed towards collection and dissemination of accurate, high quality 'real-time' surface water (stream and reservoir) data to support CO DWR's water rights administration mission. The Branch currently operates and maintains nearly 520 gaging stations throughout Colorado, and coordinates with the USGS and other State and Federal agencies that operate approximately an additional 380 gaging stations in the State. Primary objectives

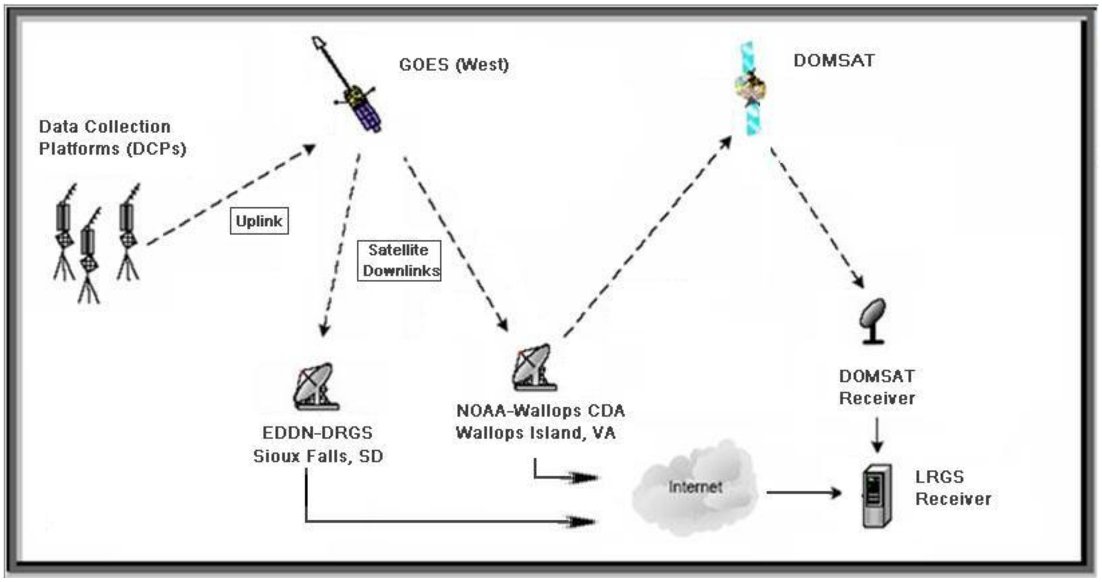

Figure 3. Diagram illustrating the hardware components of the Satellite Monitoring System.

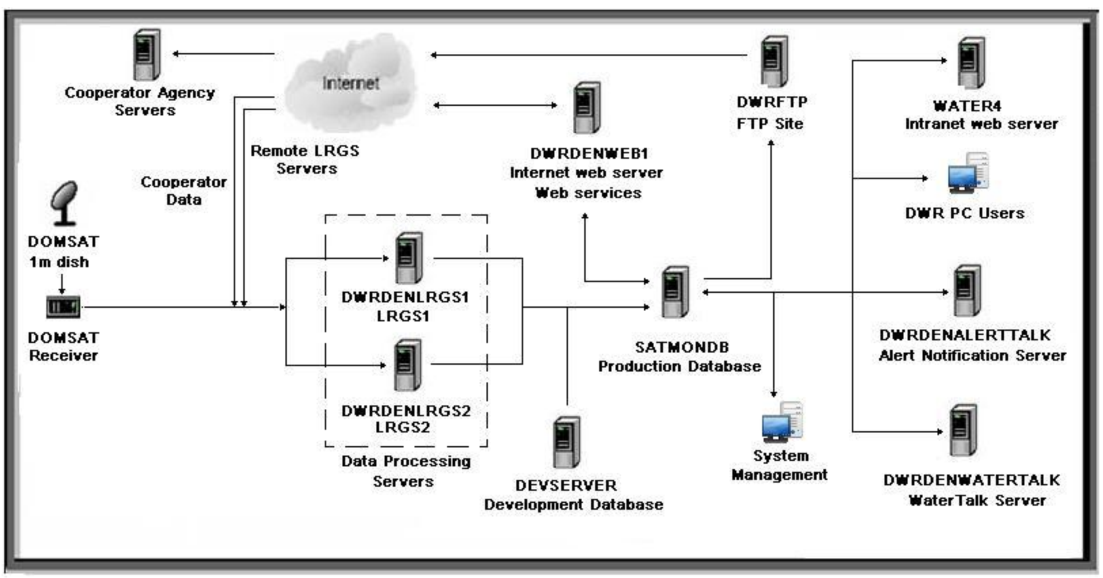

Figure 4. Diagram illustrating the hardware components of the Data Processing System.

of this work are: 1) to conduct streamflow measurements at stream gaging sites along the State's natural rivers and creeks, and at major ditch and canal diversions, to maintain accurate stage-discharge relationships and 2) maintain water level (stage) sensing and satellite telemetry equipment to minimize operational downtime and missing data. The purpose of this work is to provide accurate water supply data at key locations to CO DWR water administrators, who, in turn, must distribute and allocate water according to the principals of allocation and public safety as established in the Colorado Constitution, court decrees, and Interstate Compacts while maximizing beneficial use.

Basic statutory authority vesting the State Engineer with streamflow measurement and monitoring responsibility is given in Colorado Revised Statutes (CRS) Section 37-80-102(1)(h), which gives the State Engineer general supervisory control over measurement, record-keeping, and distribution of the public waters of the state. Flow measurements are performed on rivers, streams, creeks, major ditch and canal diversions to support increased water administration accuracy and efficiency.

CRS Section 37-80-110(1)(i) authorizes the State Engineer to collect fees for water measurement work done by his office "for rating any ditch, canal, reservoir inlet or outlet, at the request of the owner thereof or of any agent or employee having control of the same". Section 37-80-117 requires owners/operators of canal and ditch diversions to cooperate with authorized hydrographers to regulate flows in the canal or ditch when it has been deemed necessary to perform rating measurements to make a rating of any weir or flume or measuring section of any canal or ditch.

CRS Sections 37-84-112 to 37-84-122 discuss responsibilities of water users and owners of ditches, canals, measurement structures, reservoirs and other facilities for diversion and use of water with respect to specifications, construction, and maintenance of such facilities. Section 37-84-114 requires the state engineer or division engineer rate the measuring flumes and weirs referred to in these sections, and maintain records thereof. Section 37-84-122 describes the penalties when any division engineer, or his deputy or assistant, willfully neglects or refuses, after being called upon, to promptly measure water from the stream or other source of supply into the irrigating canals or ditches, in his division.

Authority to house and operate the satellite monitoring system within the State Engineer's Office was given in CRS Section 37-80-102(10). Section 37-80-111.5(1)(c) created the satellite monitoring system cash fund and authorized the State Engineer to set and collect fees by rule and regulation for the use of the equipment and programs of the satellite monitoring system authorized pursuant to Section 37-80-102 (10). Moneys in the satellite monitoring system cash fund may be expended by the State Engineer for the purposes of Section 37-80-102 (10), subject to appropriation by the general assembly.

The Hydrographic Program is implemented substantially in accordance with the State of Colorado DWR Hydrographic Manual. This manual provides standard operating procedures to be followed by all CO DWR hydrographers and provides the basis for the technical guidance and administrative management for consistent, reliable and sound streamflow measurement and record development. Many of the standard operating procedures for streamflow measurement; gaging station design, construction and maintenance; and streamflow record development are directly attributable to US Geological Survey streamflow measurement and computation methods (USGS Water Supply Paper 2175: Measurement and Computation of Streamflow).

Maintaining database integrity is an important operations goal. Real-time data are of no value unless the data are accurate. Considerable effort is expended to ensure that remote hardware and sensors remain in calibration. While other entities operate about 43% of the stations in the State's monitoring network, they generally are not using the data to make real-time water administration decisions. This difference in the use of data makes efforts to keep equipment calibrated more difficult. Those entities more concerned with historic data do not have the same sense of immediacy as the CO DWR with its interest in water administration. State hydrographers visit SMS gage stations as frequently as every week, but generally at two to four week intervals. On-site flow measurements and any necessary adjustments to the equipment are made.

System diagnostics data help in monitoring the operation of the remote data collection hardware. Computer generated reports tabulate the transmission characteristics and a database analysis for each station for the previous day. Reports list the number of received, scheduled, and missed transmissions, any message length errors, transmission time errors, errors in transmission quality including power and frequency, any deficiency in remote power supplies, and the number of missing values and parity errors for each station. Remote equipment operating problems can be detected before they produce fatal errors.

Hydrographic field personnel receive training from the SMS Electronics Specialist in the operation and maintenance of system hardware. Training is directed at system diagnostics, hardware calibration, and basic repairs. Each Division is supplied with sets of replacement hardware. If a component malfunctions and cannot be repaired in the field, it is replaced and sent to the Electronics Specialist's repair facility in Denver. If repair is not possible there or if the item is under warranty, it is then returned to the manufacturer for repair.

DATA ACCESS

The system was developed as a tool to help the Division of Water Resources administer and enforce user water rights and interstate compact agreements. Software systems and tools for accessing and retrieving stream flow data have been developed to support CO DWR personnel, outside agencies and the public. These systems provide both real-time and historic stream-flow information by a number of different means and formats. Users can access data from the system by different avenues depending on their need.

Colorado Surface Water Conditions Website

Raw and processed data are available to users at the Colorado Surface Water Conditions web site (www.dwr.state.co.us). This website queries the SMS database and provides users with current surface water conditions and provisional, historic data (both graphic and tabular). In addition to stream flow data, many gaging stations provide other environmental parameters such as precipitation, air or water temperature. Also, many of the state's reservoirs are included in the system to provide water surface elevation and storage contents in acre-feet of storage. The current conditions web site is an ASP.NET 2.0 application that connects to the SMS database to generate on-the-fly data pages to the web user.

Since 2008, the web site has offered a number of important features for the retrieval and analysis of surface water data. A "My Stations" section was added to the web site that allowed users to create a custom set of gaging stations. This custom set allowed users to quickly view gaging stations of special interest. That same year a feature was also added to allow users the ability to "overlay" data from multiple gaging stations, or multiple years of data from the same station. This feature provides users with the ability to compare multiple data sets.

Most recently, a feature was added to allow users the opportunity to view statistical information from a set of gaging stations. Statistics include daily averages, 24 hourly values (for user defined 24-hour period), and daily minimum and maximum values. Users may download these statistical values for further analysis. In 2009, the web site had 4,671,884 hits.

Links are also provided to historic data for published stream flow gages on the Colorado Decision Support System website (http://cdss.state.co.us/DNN/default.aspx).

WaterTalk

The telephony based application WaterTalk, provides data via a call-in telephone based system. WaterTalk is an automated water information phone line used to access specific stream flow data at stream gages located throughout Colorado. The system is comprised of a Dialogic telephony card mounted in a PC running Windows Server 2003. The telephony application, Active Call Center, runs as a Windows service to monitor incoming calls from the Dialogic card. When a call is detected, a series of scripts are executed to "walk" the caller through the system and retrieve the desired information. In 2009, WaterTalk processed 75,475 telephone requests.

In the process, the caller dials into the system and selects one of seven valid water divisions in the State. The system verifies the water division selected, and then asks the user to enter the code number for a station identifier within that division. If a valid code was entered, the system returns information pertaining to that station, including the descriptive name, date and time of the latest data reading, and the value at that time. In addition to selecting a valid water division, a user may select division 0, which in reality returns the latest data value recorded in the Satellite Monitoring System. This allows administrators to remotely test whether the system is up to date and functioning properly.

webHMS Web Site

The SMS system includes a web site to provide administrative functions. The webHMS web site was developed to provide Hydrographic Branch personnel with a user interface for gaging station management. Via this interface, staff can assess system status and perform system administration functions. These include managing gaging station data processing including shift and stage-shift relationship activation, rating curve application, and setting of message flags regarding station data quality and status. Satellite telemetry setup and configuration including how the gage data are to be decoded can be performed. Staff can access and evaluate satellite transmission diagnostic data including remote site GOES transmitter operational status, remote site battery voltage, remote site self-timed and random transmission activity, etc. Statistical reports summarizing the status of the system can also be generated.

ColoradoWaterSMS Web Service

The ColoradoWaterSMS web service was created to expose data from CO DWR stream flow and climate stations throughout the State. The web service was developed using Visual Studio .NET and resides on the same web server as the current conditions web site.

The goal of this service is to expose useful non-proprietary, non-security-sensitive data to our cooperators and anyone else interested in consuming it, and allows the user to develop their own program to consume and display data. Web services are for machine-to-machine communications, exchanging XML messages between the entity requesting information (client), and the entity providing information by responding to these requests (server).

SYSTEM APPLICATIONS

Water Rights Administration

The primary utility of the Colorado satellite-linked monitoring system is for water rights administration. The availability of real-time data from a network of key gauging stations in each major river basin in Colorado provides an overview of the hydrologic conditions of the basin that was previously not available. By evaluating real-time data for upstream stations, downstream flow conditions can typically be predicted 24 to 48 hours in advance. This becomes an essential planning tool in the hands of the Division Engineers and Water Commissioners. The "river call" can be adjusted more precisely to satisfy as many water rights as possible, even if just for short duration flow peaks caused by precipitation events. Access to real-time data makes it possible to adjust the "river call" to match dynamic hydrologic conditions. If additional water becomes available, additional junior rights can be satisfied. On the other hand, if water supplies decrease, then water use can be curtailed to protect senior rights.

The administration of water rights in Colorado is becoming increasingly more complex due to increased demands, implementation of augmentation plans, water exchanges, transmountain diversions, and minimum stream flow requirements. For example, the number of water rights has increased from 102,028 in 1982 to over 173,000 in 2007, and increasing numbers of water rights has continued to the present. Water rights transfers approved by the water courts are becoming increasingly complex. This is especially evident where agricultural water rights are transferred to municipal use.

There is considerable interest in monitoring transmountain diversions, both by western slope water users and the eastern slope entities diverting the water. Transmountain diversion water is administered under different laws than water originating in the basin. In general, this water may be claimed for reuse by the diverter until it is totally consumed. Forty transmountain diversions are monitored by the SMS.

Water exchanges between water users are becoming increasingly frequent. These exchanges can provide for more effective utilization of available water resources in high demand river basins, but can be difficult to administer. The satellite-linked monitoring system has proven to be an integral component in monitoring and accounting of these exchanges.

Many municipalities and major irrigation companies have reservoir storage rights. Generally, these entities can call for release of stored water on demand. The Division Engineer must be able to delineate the natural flow from the storage release while in the stream. He/she then must track the release and ensure that the proper delivery is made. The SMS has demonstrated to be effective in this area.

The utility of the SMS in the administration of interstate compacts is an especially important application. The State Engineer has the responsibility to deliver defined amounts of water under the terms of the various interstate compacts, but not to over-deliver and deprive Colorado of its entitlement. Data collected from over twenty gage stations operated by both the CO DWR and the USGS are incorporated in the statewide monitoring network and utilized for the effective administration of these interstate compacts.

The majority of the large, senior water rights in Colorado belong to irrigation companies. These rights are often the calling right in the administration of a water district. The direct diversion rights exercised can affect significantly the hydrology of the river. Dozens of major irrigation diversions are monitored by the system.

Water rights have been acquired by federal and state agencies to guarantee minimum stream flow for both recreational and fisheries benefits. As well, instream flow water rights have been developed by the Colorado Water Conservation Board to ensure minimum instream flows are maintained in critical stream reaches around the State. The availability of real-time data is essential in ensuring that these minimum stream flows are maintained.

Hydrologic Records Development

Specialized software programs provide for the processing of raw hydrologic data on a real-time basis. Conversions such as stage-discharge relationships and shift applications are performed on a real-time basis as the data transmissions are received. Mean daily values are computed automatically each day for the previous day. Data values that fall outside of user defined normal or expected ranges are flagged appropriately. Flagged data values are not utilized in computing mean daily values. Missing values can be added and invalid data values corrected by the respective hydrographer for that station using data editing functions.

Data can be retrieved and displayed in various formats including the standardized US Geological Survey-Water Resources Division annual report format adopted by the Colorado Division of Water Resources for publication purposes. An advantage of real-time hydrologic data collection is in being able to monitor the station for on-going valid data collection. If a sensor or recorder fails, the hydrographer is immediately aware of the problem and can take corrective action before losing a significant amount of data.

It is essential to understand that real-time records can be different from the final record for a given station. This can be the result of editing raw data values because of sensor calibration errors, sensor malfunctions, analog-to-digital conversion errors, or parity errors. The entering of more current rating tables and shifts can modify discharge conversions. Corrections to the data are sometimes necessary to compensate for hydrologic effects such as icing. Human error can also result in invalid data. The final record for those gauging stations operated by non-state entities, such as the US Geological Survey-Water Resources Division, is the responsibility of that entity. Modifications to the real-time records for these stations are accepted by the State of Colorado.

The Hydrographic Branch develops historic streamflow records in coordination with other State and Federal entities and the water user community. At the conclusion of each water year, the State Engineer's Office compiles streamflow information and measurements conducted throughout the year for publication. Published streamflow records describe the mean daily discharge, the instantaneous maximum, lowest mean discharge, and monthly/ annual volumetric totals for a specific location on a river or stream. These annual streamflow records are computed using two critical sources of information: streamflow measurements made throughout the water year to calibrate the stage-discharge relationship at a specific site, and, the electronic record of stream stage collected by the satellite monitoring system. Using these data a continuous record of streamflow for the water year is computed. Streamflow records undergo a rigorous data quality control/quality assurance program to ensure the product is accurate. The Division of Water Resources Hydrographic program computes and publishes over 240 streamflow records annually. Published historical streamflow data are extremely valuable in support of water resources planning and management decision-making, assessment of current conditions and comparisons with historical flow data, and hydrologic modeling.

Water Resources Accounting

Currently, the SMS is being utilized for accounting for the Colorado River Decision Support System (CRDSS), the Colorado-Big Thompson Project, the Dolores Project, and the Fryingpan-Arkansas Project Winter Water Storage Program among others around the State. The ability to input real-time data into these accounting programs allows for current and on-going tabulations.

Dam Safety

Dam safety monitoring has developed in recent years into a major issue. Numerous on-site parameters are of interest to the State Engineer in assessing stability of a dam. At this time, the system monitors reservoir inflow, water surface elevation and reservoir release or outflow at more than fifty reservoirs in Colorado. These data provide a basis for evaluating current operating conditions as compared to specific operating instructions. The installation and operation of additional sensor types could provide essential data on internal hydraulic pressure, vertical and horizontal movement, and seepage rates.

COORDINATION AND COOPERATION

Formal streamgaging programs are administered by the CO DWR and the USGS Colorado Water Science Center, and have support from more than 60 cooperating organizations. Streamgaging programs are closely coordinated between the CO DWR and the USGS with funding and coordination assistance from the Colorado Water Conservation Board, to help ensure the data are comparable and easily accessible to everyone, including the provision of real-time data on the internet. Other organizations, including the U.S. Bureau of Reclamation, the U.S. Army Corps of Engineers, Northern Colorado Water Conservancy District, Denver Water, the cities of Aurora and Colorado Springs, and the Urban Drainage and Flood Control District, also collect streamflow information to support their project needs and make those data available to water users and managers. Coordination occurs on many levels; high level coordination, data chief coordination, and field staff coordination.

The CO DWR Director/State Engineer, the CWCB Director, and the USGS Colorado Water Science Center Director meet annually to discuss respective program and set policy directions that concern all entities. Topics include current projects, litigation involving water-quantification issues, and ongoing evaluations of the adequacy of the gage-network operations and coverage. Coordination of equipment purchases to upgrade streamgages is also discussed at these meetings. Coordination agreements allow the State to buy specialized equipment directly through the USGS Hydrologic Instrumentation Facility.

Coordination meetings also occur between the CO DWR Lead Hydrographers, the CWCB Gaging Coordinator, and the USGS Data Chiefs two times per year. These meetings enable our agencies to work cohesively and to effectively coordinate our work efforts at the operational level. Mutual objectives, opportunities, and conflicts are discussed and coordinated to facilitate better operations for all three agencies. Training opportunities are also shared between agencies at these meetings. Streamflow data coordination is one of the ongoing agenda items at the Data Chief Coordination meetings. Data are shared between the agencies and the public via websites and direct data feeds. Streamflow records from 15 gages sites operated by the CO DWR are reviewed and published by the USGS.

Day-to-day coordination occurs between the staff of all three agencies. Contact is made as needed and mutual support routinely is offered among the agencies. Help includes equipment repair and maintenance, and streamflow data troubleshooting. For example, if a hydrographer discovers a problem with another agency's gage while on site, a temporary repair will be made so data are not lost.

A recent cooperative program between CO DWR, Northern Colorado Water Conservancy District (NCWCD), Lower South Platte Water Conservancy District (LSPWCD), and Saint Vrain and Left Hand Water Conservancy District (SVLHWCD) has resulted in obtaining and presenting streamflow data from 65 additional gage stations at diversion, recharge sites, augmentation sites, and return sites for display on the CO DWR website. These gages are configured with Sutron Stage Discharge Recorders (basically a programmable shaft encoder with onboard datalogging and communications interface) and cell phone telemetry. Both the SDR unit as well as this cell phone telemetry paradigm were largely developed and refined by cooperative efforts between CO DWR and Sutron Corp. and NCWCD.

Data are transferred from the remote SDR sites to computer base stations in the NCWCD and LSPWCD offices on an hourly basis similar to the current SMS transmission interval and on-demand as needed, where the data is processed and made available so that the SMS system can access and transfer the data via an FTP service client. Data is then archived in CO DWR databases and displayed in a similar fashion to traditional SMS sites. Figure 5 is a photo of a cooperative program SDR/cell phone telemetry gage.

This system deviates substantially from the SMS system discussed earlier in that discharge computations are computed, processed, and logged wholly within the SDR unit rather than being computed based on parameters stored in the satellite monitoring database. Additionally, data transmission and data retrieval are not initiated from the field unit; rather the base computer stations call out and individually poll the sites at specified intervals. Special routines are in place to redundantly call a remote site if data transmission failed or if a data set is incomplete.

This program paradigm has proven to be a cost effective solution for obtaining data from multiple remote sites of mutual interest because of the lower initial capital inputs. As a result of the lower capital inputs and further development of the SDR units, simple automation has started to be installed or considered on some of these sites via the Sutron Ditch Master package.

Figure 5. Cooperative Program SDR/cell phone telemetry streamgage.

Another recent cooperative development has been to marry or merge multiple users of a gage to a single sensor capable of multiple data outputs (SDI-12 / RS-485 / SCADA). Historically, cooperative gages at which multiple users or entities were involved required multiple instruments to accomplish the same task due to their output requirements. Thus, a single gage may have several sensors performing the same task reporting to different systems. For example, a float-actuated shaft encoder would report stage values to a DCP via SDI-12, which is placed next to another float-actuated shaft encoder producing an analog signal to a Supervisory Control and Data Acquisition (SCADA) system. This paradigm caused the two data sets to differ, primarily due to instrument calibration issues. Moreover, many of the analog sensors had poor resolution.

Starting in 2007, a cooperative pilot program was developed embarked upon between the USBR and CO DWR within the East Slope of the Colorado Big Thompson (CBT) system, whereby gages that were cooperatively operated by the USBR and CO DWR were migrated to a single stage sensor system. Typical installations employed a Design Analysis Waterlog H-334 Absolute SDI-12 shaft encoder (65,536 counts/rev). The H-334 unit simultaneously produces a SDI-12 and analog (4-20mA) output. Stage determined via the optical/magnetic sensor determines stage in user defined units, and then scales and produces the output signal via an internal digital to analog converter. Subsequent installations within the CBT system have used a Sutron SDR-001-4 unit which can simultaneously produce output signals via SDI-12 and 4-20mA analog similar to the H-334 unit, but also maintains an internal log of recorded stage as well as all user interactions with the unit.

For sites employing a pressure transducer, the single sensor approach was accomplished by utilization of a Design Analysis H-416 SDI-12 to 4-20mA converter unit (Figure 6). The H-416 unit is designed to passively listen for to the SDI-12 bus for a user defined address and parameter. Once the SDI-12 value is captured by the H-416 unit, it scales and produces an output current based on user-defined threshold values.

Employment of the signal sensor paradigm has proven to be a positive solution for all parties involved. Data obtained via digital and analog avenues agree much closer than ever before. USBR staff had previously had to visit gages up to three times a week to ensure calibration now only weekly visits are made and adjustments are rarely needed.

Because of the success of this pilot program employed along the East Slope portion of the CBT project, cooperative USBR-CO DWR gages throughout the West Slope of the CBT, as well as Fryingpan-Arkansas projects have been, or are in the process of being converted to the single sensor-dual output paradigm[5]. Moreover, similar cooperative gages within the Denver Water, NCWCD systems have started to employ the techniques demonstrated within the East Slope CBT system.

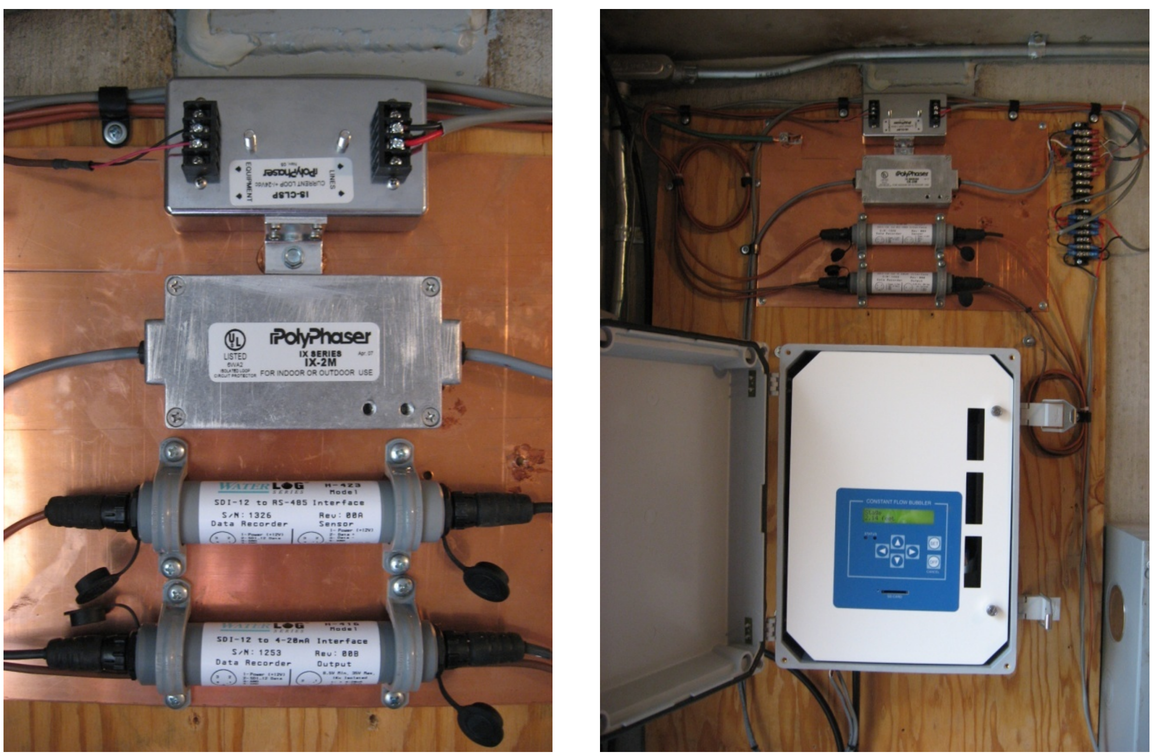

Figure 6. Photos showing a Sutron CFB connected to a Design Analysis H-416 SDI-12 to 4-20mA converter module.

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[5] The authors wish to acknowledge the efforts of Mr. Mark Henneberg, formerly Hydrologic Technician, Eastern CO Area Office, US Bureau of Reclamation, Loveland CO, and currently US Geological Survey, Grand Junction CO for his extensive work to make the single sensor-dual output paradigm a reality.

SUMMARY

The satellite-linked monitoring system (SMS) provides the Division of Water Resources, other State and Federal entities, and the water user community with access to real-time and historic stream-flow data from gauging stations across the State of Colorado. These data and software systems provide for more effective water rights administration, improved water resource management, computerized hydrologic records development, flood warning and other types of flow alert notifications.

ACKNOWLEDGMENTS

Many CO DWR staff have contributed to the success of the SMS over its 25-year history. While each of the authors has been involved with the SMS for 10 or more years, we wish to acknowledge the contributions and efforts of all involved, including John Kaliszewski, Chuck Schaffer, Greg Ibarra, Jeris Danielson, Jim McDanold, Dave Dzurovchin, Dick Poelker, Scott Veneman, Hal Simpson, Will Burt, Jack Byers, Doug Stenzel, Dick Wolfe, and all CO DWR Hydrographic staff from 1985 to present. The system would not exist without the on-going financial support of the CWCB.

USING STATE WATER LAW FOR EFFICIENT WATER USE IN THE WEST

Laura A. Schroeder[1]
Therese A. Ure[2]

ABSTRACT

The prior appropriation doctrine, as adopted by water codes throughout the western states, creates water rights based on the time of appropriation. Under the prior appropriation system, water users must put water to beneficial use without waste, and may not sit on their rights without actually using the water they are allotted.

Despite the superficial efficiency that the prior appropriation system espouses, the system is in fact highly inefficient. Water users are locked into antiquated practices without incentives to modernize their operations. The administrative process for changing water rights to more efficient uses acts as a roadblock to such action.

Western states have begun evolving their water codes to provide for more opportunities in water conservation and efficiency. This paper explains the background of the prior appropriation system, analyzes how the "pure" prior appropriation system creates water use inefficiency, and explores how certain states are bringing their water codes into the 21st Century.

INTRODUCTION AND BACKGROUND

A Brief History of Prior Appropriation

Irrigation is an essential element for living in the western United States. Archeological studies have shown evidence of early Indian irrigation projects in the West.[3] Spanish colonists utilized irrigation ditches in what are now Arizona and New Mexico during the 16th Century.[4] Along with the civilization of the western frontier came the water needs of those early populations, and harnessing the waters of the West through irrigation was the only way to support life in the arid climate.

Modern irrigation practices were developed as pioneers populated the West. First, Mormon settlers constructed community irrigation systems to support domestic uses, stock watering, irrigation, manufacturing and mining beginning in 1847.[5] Additionally, the California Gold Rush of 1849 brought miners out west, who diverted water while

[1] Partner and Founder, Schroeder Law Offices, P.C., P.O. Box 12527, Portland, Oregon, 97212, (503) 281-4100, schroeder@water-law.com.
[2] Managing Attorney, Reno, Nevada Office, Schroeder Law Offices, P.C., P.O. Box 12527, Portland, Oregon, 97212, (503) 281-4100, t.ure@water-law.com.
[3] WATERS AND WATER RIGHTS § 11.02 (Robert E. Beck ed., 3rd Edition, 2009).
[4] *Id*.
[5] *Id*. at § 11.02(b).

seeking their fortunes.[6] These larger populations developed customary local rules to govern water use, based on priority in time of use and actual use of the water.[7]

Most early settlement took place on federal lands without the express permission of the government. In order to support the settlement of the West, the federal government ratified the pioneers' actions through the Homestead Act,[8] the Mining Act,[9] the Desert Land Act,[10] and the Carey Act.[11] Through these federal acts, the federal government granted lands and water to citizens in order to provide incentives for easterners to move west and defend the new country.[12]

As western states joined the Union they adopted the water customs which were already present in the territories. Eighteen states currently follow the prior appropriation doctrine,[13] all of which adopted that system before the beginning of the 20th Century.[14] Although it was believed at the time of settlement that federal land patents included water rights,[15] the United States Supreme Court made it clear that settlers had to look to the states for the right to appropriate water.[16]

At first the prior appropriation system was a tenet of common law, enforced through the courts.[17] But quickly, western states adopted statutes that codified the prior appropriation system.[18] Now every western state has a water code that outlines the specificities of the prior appropriation system in the jurisdiction.

The "Pure" Prior Appropriation Doctrine

Water law is state law. Variations exist from jurisdiction to jurisdiction. However, the prior appropriation system has core elements which create a platform, upon which modern variations exist.

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[6] *Id*. at § 11.02(c).
[7] *Id*.
[8] 12 Stat. 392, Ch. 75 (1862).
[9] 14 Stat. 251, Ch. 262 (1866).
[10] 19 Stat. 377, Ch. 107 (1877).
[11] 28 Stat. 422, Ch. 301 (1894).
[12] WATERS AND WATER RIGHTS, *supra* note 3, at § 11.03(a).
[13] The eighteen prior appropriation states are: Arizona, California, Colorado, Idaho, Kansas, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington, Wyoming, and Alaska.
[14] WATERS AND WATER RIGHTS, *supra* note 3, at § 11.03(a). Note that riparian rights, the eastern system creating the right to use water based on proximity to the water source, existed in western states before the prior appropriation system. Some western states rejected the riparian system, and others found a way for both systems to coexist.
[15] *Id*.
[16] California Oregon Power Co. v. Beaver Portland Cement Co., 295 U.S. 142, 162 (1935).
[17] WATERS AND WATER RIGHTS, *supra* note 3, at § 11.04(b).
[18] *Id*. Not all states follow the prior appropriation doctrine for the use of groundwater; some use the rule of capture, and some follow riparian principles of reasonable use. *See generally*, WATERS AND WATER RIGHTS, *supra* note 3, at § 11.01.

The first core principle of the prior appropriation system is that the "first in time is first in right."[19] This principle creates a hierarchal system of junior and senior rights holders. Senior water users have rights to use water that are superior to the rights of junior users. The priority of water rights becomes exceedingly important in times of drought because juniors may not take water from a watercourse if there is insufficient supply to fulfill the seniors' rights.[20] Priority is established through application to the appropriate state agency for water appropriation.[21]

An applicant must show intent, diversion, and beneficial use to be eligible to appropriate the waters of a state. First, physical diversion of water from the source was originally required because actual diversion provides subsequent users with notice of a senior use.[22] Additionally, diversion requires funds and labor, which tends to show a serious investment to put water to actual use rather than speculate water resources.[23]

Second, the diverted water must be put to beneficial use. Most western states have nearly identical statutes that state: "beneficial use, without waste, is the basis, measure, and limit of a water right."[24] Traditionally, states only recognized 19th and early 20th century uses such as mining, irrigation, stock watering, municipal use, power creation, and industrial uses as beneficial.[25] Some western states have gone beyond the traditional scope of the doctrine to recognize additional beneficial uses, such as fish propagation, wildlife habitat, and recreation.[26] In order for a use to qualify as beneficial, the "type of use" must be socially recognized, and the "amount of use" must be that actually required by the use.[27] This principle was imposed to prevent speculation of resources, and ensure that precious resources were not wasted.[28]

Third, intent to divert the water and put it to beneficial use had to be shown. Intent may be inferred from diversion and application of waters to beneficial use.[29] Once intent is established through these actions, it relates back to the initial date of application.[30] Again,

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[19] Western Water Policy Review Advisory Commission, Water in the West: The Challenge for the Next Century § 5-4 (June, 1998) (hereinafter "Water in the West").

[20] MARC REISNER & SARAH BATES, OVERTAPPED OASIS: REFORM OR REVOLUTION FOR WESTERN WATER 63 (Island Press 1990).

[21] WATERS AND WATER RIGHTS, *supra* note 3, at § 12.02(a). As states adopted water codes, prior uses of water were recognized with priority dates correlating to historic use periods. *Id*.

[22] WATERS AND WATER RIGHTS, *supra* note 3, at § 12.02(c)(1).

[23] *Id*.

[24] Janet C. Neuman, *Beneficial Use, Waste, and Forfeiture: The Inefficient Search for Efficiency in Western Water Use*, 28 ENVTL. L. 919, 923-924 (1998).

[25] *Id*. at 927-8; Western Water Policy Review Advisory Commission, *supra* note 19, at § 5-4; REISNER & BATES, *supra* note 20, at 63.

[26] Neuman, *supra* note 24, at 927-8; Western Water Policy Review Advisory Commission, *supra* note 19, at § 5-4.

[27] *Id*.

[28] WATERS AND WATER RIGHTS, *supra* note 3, at § 12.02(c)(2).

[29] *Id*. at § 12.02(b).

[30] *Id*.

this requirement's purpose was to prevent speculation.[31] To appropriate water, the applicant must intend to use the water for a beneficial purpose.

An important innovation of western water law, as compared to riparian law in the East, is that water use is not limited to use on strictly riparian lands.[32] Water may be transported in ditches to distant lands and used for any beneficial purpose.[33] But despite this flexibility, water rights are narrowly tailored. A water right creates the right to use a fixed amount of water, at a specific time of year, on a particular parcel of land, for a definite use; no more and no less. The rights become appurtenant to the land on which they are put to beneficial use.[34]

Finally, water rights are subject to the "use it or lose it" principle.[35] If water is not continuously put to beneficial use, then the user risks loss of their right to appropriate. Loss may occur by common law or statute. The common law doctrine of abandonment requires both the "intent to abandon" and "actual relinquishment" of the right.[36] Statutory forfeiture of a right takes place when the appropriator fails to put the water to a beneficial use for a statutorily determined amount of time.[37]

INEFFICIENCIES CREATED BY THE PRIOR APPROPRIATION SYSTEM

Inefficient Principles Underlying Prior Appropriation

The core principles of the prior appropriation doctrine appear as if they would promote efficiency. The system creates a clear order of priorities for defined rights to water, and users must put water to a beneficial use, without waste. Those who fail to follow the rules lose their rights. However, the prior appropriation system arose from old mining customs, and from a time when water supply was larger than water demand. The prior appropriation system, in many ways, creates inefficiencies in modern water allocation.

The beneficial use requirement is not an efficiency-forcing standard.[38] Rather than requiring a certain level of efficiency in water use, the beneficial use doctrine takes a "customary approach."[39] The amount of water that was traditionally needed to satisfy a particular use, based on customary methods employed by the local community, will continue to satisfy the doctrine in the future.[40] The doctrine does not demand higher

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31 *Id*.
32 *Id*., at § 12.02(f).
33 *Id*. Note that many states have limitations on taking water outside of watershed or water basin boundaries. *Id*. Additionally, states have restrictions on using state water on lands outside the state borders. *Id*.
34 *Id*.
35 REISNER & BATES, *supra* note 20, at 63.
36 Sears v. Berryman, 623 P.2d 455, 459 (Idaho, 1981).
37 *Id*.
38 Neuman, *supra* note 24, at 960.
39 *Id*.
40 *Id*.

efficiency standards based on new innovations; it allows large amounts of water to be wasted through seepage and application, yet does not proclaim this "waste." The beneficial use doctrine creates inefficiency because it allows archaic practices to persist.

The "first in time, first in right" principle allows inefficient uses of water to carry on in perpetuity.[41] Additionally, abandonment and forfeiture can sweep in to divest a user of his rights if he does not put all the water he has a right to use to work continuously.[42] Combined, these two facets of western water law create disincentive to conserve water.[43] If a users increases his efficiency he gains nothing. In fact, he is out the cost of his investment and additionally loses his rights to use the water he saved. This system is inefficient because it forces users to continue wasteful practices, or lose a portion of their rights.

Roadblocks to Efficiency

The Coase Theorem, an economic theory, states that the market will create an efficient resource allocation if property rights are clearly defined and transaction costs are low.[44] When these prerequisites are met, efficiency will transpire, even if the initial allocation of rights was inefficient.[45] However, Coase equilibrium may not be possible in the current water system due to high transaction costs and ill-defined property rights.[46]

Transaction costs for water transfers can be extremely high. This is due, in large part, to the slow-moving wheels of the administrative process.[47] In the West, state agencies control the water appropriation process.[48] The agencies must approve new appropriations as well as changes to existing water rights. This typically involves application to the state agency, notice to other rights holders and the public, opportunity for comment, objection, and possibly a hearing, examination of the application by the agency in light of statutory requirements, and acceptance, rejection, or modification of the application.[49] This process can take many years to complete. Additionally, the states impose fees for submitting and

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[41] LAWRENCE J. MACDONNELL, FROM RECLAMATION TO SUSTAINABILITY: WATER, AGRICULTURE, AND THE ENVIRONMENT IN THE AMERICAN WEST 127-129 (University Press of Colorado, 1999).
[42] *See, supra* notes 35-37, and accompanying text.
[43] MACDONNELL, *supra* note 41, at 132.
[44] HENRY N. BUTLER & CHRISTOPHER R. DRAHOZAL, ECONOMIC ANALYSIS FOR LAWYERS 29 (Carolina Academic Press 2006).
[45] *Id*.
[46] C. Carter Ruml, *The Coase Theorem and Western U.S. Appropriative Water Rights*, 45 NAT. RESOURCES J. 169, 182 (2005).
[47] *Id*. at 175-80; Lawrence J. MacDonnell, *Transferring Water Uses in the West*, 43 OKLA. L. REV. 119, 121-122 (1990).
[48] Water is controlled by state agencies in all western states except for Colorado. Colorado uses a water court in place of an agency, but the water court performs the same functions as the agencies in other states. WATERS AND WATER RIGHTS, *supra* note 3, at § 11.04(b).
[49] Ruml, *supra* note 45, at 176-177.

reviewing applications, providing notice, and conducting hearings.[50] The time and expenses involved in appropriating water and changing water permits can be enormous.

Further, the prior appropriation system restricts the ability of water users to freely transfer and change water rights. No transfer or changed right may "injure" existing water rights.[51] Although this promotes clarity in private property rights, delayed or unforeseen injury may raise problems for a water user attempting to transfer or change a right. Further, water rights may be transferred to a new place of use,[52] but state statutes restrict transfers outside of the water basin of origin, outside of state boundaries, and outside of special districts.[53]

In addition, water rights are not clearly defined property rights. First, water rights may be subject to public rights in water through the Public Trust Doctrine. This doctrine, which is part of the common law passed down from England,[54] imposes on the states a fiduciary duty to protect public interests in water such as navigation, commerce, fishing, and bathing.[55] In a very progressive case, the California Supreme Court held that state water appropriations were void because they were issued without consideration of public trust interests.[56] The scope of the public trust is a very controversial issue, and its intricacies are too great to cover in this paper,[57] but it suffices to say that public rights in water interfere with private rights in water.

Second, water rights may be subject to federal rights through the doctrine of federally reserved water rights. Under the Property Clause of the United States Constitution,[58] the federal government makes rules and regulations with respect to property belonging to the United States.[59] The United States Supreme Court decided that when the federal government creates an Indian reservation, the creation impliedly includes the reservation of as much water as is necessary to support the land.[60] In *Winters v. United States*, although state residents had duly appropriated water under state law before an Indian reservation began to take water, those appropriations were held to be junior to the federal

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[50] *See, e.g.*, Oregon Revised Statutes ("ORS") § 536.050.

[51] A. DAN TARLOCK, JAMES N. CORBRIDGE, JR., & DAVID H. GETCHES, WATER RESOURCE MANAGEMENT 232-233 (Foundation Press, 2002). *See also*, WATERS AND WATER RIGHTS, *supra* note 3, at § 11.07.

[52] WATERS AND WATER RIGHTS, *supra* note 3, at § 12.02(f).

[53] *Id*.

[54] Charles F. Wilkinson, *The Headwaters of the Public Trust: Some Thoughts on the Source and Scope of the Traditional Doctrine*, 19 ENVTL. L. 425, 431 (1989).

[55] Illinois Central Railroad Co. v. Illinois, 146 U.S. 387, 452 (1892). The scope of the Public Trust Doctrine has been extended in some states. *See, e.g.*, Marks v. Whitney, 491 P.2d 374, 381 (Cal. 1971), and National Audubon Society v. Superior Court of Alpine County, 658 P.2d 709, 712 (Cal. 1983).

[56] National Audubon Society, 658 P.2d at 728-729.

[57] For a full description of the Public Trust Doctrine and its implications, *see* Wilkinson, *supra* note 51. For a critique of the doctrine, *see* James L. Huffman, *Speaking of Inconvenient Truths—A History of the Public Trust Doctrine*, 18 DUKE ENVTL. L. & POL'Y F. 1 (2007).

[58] United States Constitution, Art. IV sec. 3 cl. 2.

[59] *Id*.

[60] Winters v. United States, 207 U.S. 564, 577-578 (1908).

reserved water rights.[61] This doctrine has been extended to all federal land reservations, such as national forests, recreational areas, and wildlife areas.[62] Therefore, water appropriations may be subject to federal reservations without any notice of this fact from the onset.

Finally, water users may be hesitant to attempt to transfer or change a water right due to the risk of losing a portion of their right through abandonment. The historical use doctrine states that a transfer or change is limited to the amount of water that was historically used, regardless of whether the right holder has a "paper right" to divert a larger quantity.[63] Historical use and abandonment arguments may be raised whenever a water user seeks to transfer or change his water rights.[64] Thus, the doctrine deters water rights changes and transfers.

THE EVOLUTION OF THE PRIOR APPROPRIATION SYSTEM

Sources for New Standards

The prior appropriation system began in the courts as a common law regime.[65] As states joined the Union, state legislatures codified the common law and created permitting systems.[66] State agencies were given the authority by the legislatures to run the permitting systems and to create regulations to aid permitting and enforcement.[67] As a result, all three institutions, the courts, the legislature, and the agencies, have the ability to set new standards in western water law.

Judges have the ability to interpret statutory law and common law issues that come before the courts. Thus courts have the ability to forge new ground within the prior appropriation system. For instance, courts have the ability to determine what constitutes a beneficial use, and what practices cause prohibited waste. Interpretation of the laws and application to individual cases is an important power in bringing about new standards in the law.

State legislatures have the ability to change the laws by passing new statutes. For example, they can change forfeiture standards or appurtenance requirements. Additionally, legislatures have the power to set aside funds to aid conservation. They may raise money to provide incentives to users for saving water. These powers are instrumental in bringing about change in western water law.
Finally, state agencies have been delegated the authority to make regulations that set standards for water users. Agencies may define the intricacies of state statutes. As an

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[61] *Id*.
[62] Arizona v. California, 376 U.S. 340 (1964).
[63] *See, e.g.*, Orr v. Arapahoe Water and Sanitation District, 753 P.2d 1217, 1223-24 (Colo. 1988).
[64] *Id*. In a proceeding for change in place of diversion, the court found that the appropriation should be limited to the amount of water historically used. *Id*.
[65] WATERS AND WATER RIGHTS, *supra* note 3, at § 11.04(b).
[66] *Id*.
[67] A. DAN TARLOCK, JAMES N. CORBRIDGE, JR., & DAVID H. GETCHES, *supra* note 51, at 292-293.

illustration, an agency may define "waste," if left undefined by the legislature, and may even set metering or construction requirements to prevent waste. These sorts of requirements may be written into user permits, thus promoting conservation and efficiency one user at a time.

Evolving State Laws that Provide for Conservation and Efficiency

All western states have gone beyond the bare bones requirements of the "pure" appropriation doctrine. As demand for water resources grew, water uses began to compete with one another, and states had to provide means for settling conflicts and reallocating existing water rights.[68] In the modern era, because of growing demand, and over-appropriated water resources, many states have implemented policies that allow for better conservation and efficiency. This section provides examples of ways in which the "pure" prior appropriation doctrine has evolved in certain states to accommodate modern water allocation challenges.

Appurtenance Requirements Typically, appropriated water must be put to beneficial use on a specific parcel of land, to which the right to use water becomes appurtenant.[69] This requirement can lock water rights holders into inefficient uses of their water. Thus, some states have changed appurtenance requirements, allowing users additional flexibility to determine on which lands to put water to beneficial use.

In Oregon, the state allows water permit and water certificate[70] holders to change the place of use without lengthy administrative processes under certain circumstances. Permit holders may change their place of use to contingent lands, which they own or control, so long as there is no injury to other rights holders, and the permittee gives notice to the Water Resources Department 60 days before the change is made.[71] Most water right certificates may only be changed by detailed application to the Water Resources Department, notice by publication, and opportunity for objection and hearing.[72] Certificate holders who put water to use for irrigation, however, do not need to go through the application process if "the owner of the water right uses the water for incidental agricultural, stock watering and other uses related to irrigation use, so long as there is no increase in the rate, duty, total acreage benefited or season of use."[73]

Nevada has also changed traditional appurtenance requirements. Initially, waters put to beneficial use are "deemed to remain appurtenant to the place of use."[74] However, the

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[68] *See generally*, WATERS AND WATER RIGHTS, *supra* note 3, at § 11.07.

[69] *See* footnotes 32-34 and accompanying text.

[70] In Oregon, a water permit is issued after initial review of the appropriation application. The permit allows a user to divert water and put it to beneficial use. A water right certificate is then issued after the user perfects his water right by completing any needed construction and putting the water to beneficial use. ORS § 537.230.

[71] ORS § 537.211(4).

[72] ORS § 540.520(1)-(7).

[73] ORS § 540.520(8).

[74] Nevada Revised Statutes ("NRS") § 533.040(1).

state legislature has carved out an exception that is applicable to surface water users who receive water from federal reclamation projects. The exception allows such users to classify all lands under the same ownership, which are used primarily for agricultural purposes, as a single "farm."[75] Then, the user can apply to the state engineer to change his place of use to the "farm" rather than individual parcels of land.[76] In this way, a water user may alternate water use on different parcels of land, so long as the total amount used does not exceed the quantity laid out in the user's permit.[77] Although the initial classification as a "farm" requires an application to change the place of use,[78] thereafter the water user can enjoy great flexibility regarding where to apply his water.

Washington, like Nevada and Oregon, requires water users to apply to the Department of Ecology before making changes to the place of use of water.[79] However, the state allows seasonal or temporary changes in place of use with only the prior permission of a water master, rather than requiring users to undertake full change in place of use procedure.[80] This can save a water user both time and money. Additionally, Washington allows water users who own lands and water rights to rotate the use of water to which the group of users is collectively entitled.[81] This way, larger amounts of water may be put to use on different parcels in different years or during different seasons.

In Idaho, although changes in place of use usually require a water rights holder to apply to the Department of Water Resources,[82] when an irrigation district holds water rights, the place of use specified in the permit can encompass the entire irrigation district.[83] As a result, water may be used on any parcel of land within the district, and changes in place of use may be made without having to comply with change in place of use requirements.[84] This type of system is utilized in many western states.[85]

<u>Conservation and Salvaged Water</u> Under the "pure" prior appropriation doctrine, if a user implements conservation practices, and as a result uses less water, that user loses the right to use the saved water through abandonment or forfeiture.[86] This creates a disincentive for conservation. To cure this problem, some states have declared that conservation will not constitute abandonment or forfeiture.

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75 NRS § 533.040(7).
76 NRS § 533.040(4).
77 *Id*.
78 NRS §§ 533.325 and 533.345.
79 Revised Code of Washington ("RCW") § 90.03.380.
80 RCW § 90.03.390.
81 *Id*.
82 Idaho Code ("IC") § 42-222.
83 IC § 42-219(5).
84 IC § 42-219(7).
85 *See, e.g.*, ORS §§ 540.570 and 540.580; RCW § 90.03.380.
86 *See* footnotes 41-43 and accompanying text.

The Oregon legislature has declared that "conservation and efficient utilization of water benefits all water users, provides water to satisfy current and future needs through reduction of consumptive waste, improves water quality by reducing contaminated return flow, prevents erosion and allows increased in-stream flow."[87] In order to implement this policy, the state has established a voluntary program[88] under which "any person" holding a water right certificate may apply to the Water Resources Department for an allocation of "conserved water."[89] Conserved water results only from "conservation," which is defined as "the reduction of the amount of water diverted to satisfy an existing beneficial use achieved either by improving the technology or method for diverting, transporting, applying or recovering the water or by implementing other approved conservation measures."[90] Conserved water is the difference between the smaller of the quantity of water which is stated in the water right or that which was actually diverted through existing facilities,[91] and the quantity of water needed after implementation of conservation practices to satisfy the beneficial use.[92] The water user must apply within five years of implementing the conservation measure.[93] If approved, the water user is allocated 75 percent of the conserved water, and only 25 percent reverts back to the state for in-stream purposes or appropriation to new users. The water user may then sell the conserved water, or keep the water for his personal beneficial use.[94]

Likewise, Montana has declared it the policy of the state to "encourage the conservation and full use of water."[95] Therefore, the state has provided for those who "salvage" water to maintain full rights to such water for beneficial use.[96] To "salvage" means "to make water available for beneficial use from an existing valid appropriation through application of water-saving methods."[97] Holders of rights to salvaged water may make short-term leases of the water without prior approval from the Department of Natural Resources and Conservation.[98] All other uses of the right to salvaged water must be approved as a change to the water right.[99] The rights to salvaged water may also be sold or leased.[100]

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[87] ORS § 537.460(1). *See also*, Oregon Administrative Rules ("OAR") § 690-018-0010.
[88] ORS § 537.463.
[89] ORS § 537.465.
[90] ORS § 537.455(1).
[91] Note that this requirement is an application of the historical use doctrine. *See* footnotes 64-65 and accompanying text.
[92] ORS § 537.455(2).
[93] ORS § 537.470(2).
[94] ORS § 547.490.
[95] Montana Code, Annotated ("MCA") § 85-2-419 (2009).
[96] *Id*.
[97] MCA § 85-2-102(20).
[98] MCA § 85-2-419.
[99] *Id*. Changes to water rights must be approved through the procedures imposed by MCA §§ 85-2-402 and 85-2-436.
[100] MCA § 85-2-419. Water sales are dealt with in MAC § 85-2-403, and leases in MAC §§ 85-2-408, 85-2-410, and 85-2-436.

Washington also allows water users to conserve water without losing their rights in the water saved. Washington implemented its program due to water shortages and the ability of voluntary water transfers to alleviate those shortages, meet presently unmet needs, and provide for future water needs in the state.[101] Unlike Oregon and Montana, Washington's legislation provides authority to state to enter into contracts with water users to supply money to assist the funding of water conservation projects in return for conveyance of the net water savings to the state "trust water rights program."[102] The conveyance may take the form of a temporary transfer, permanent transfer, or lease.[103] Under the state trust water rights program, conveyed water is delegated for in-stream, irrigation, municipal, or other beneficial uses.[104] The water user may contract for how the water is delegated.[105] Additionally, the state may, with the consent of the water right holder, transfer rights to the water-banking program to provide water to third parties on a temporary or permanent basis.[106]

<u>In-Stream Water Rights</u> Traditionally, water had to be diverted from its source for a water user to claim a right to it.[107] Demands on water sources have continued to increase in every western state.[108] Therefore, states have begun to recognize in-stream water rights as beneficial.[109] Water users can take advantage of these programs to maintain their rights during periods of non-use.

In Oregon, any person can purchase or lease or accept a gift of an existing water right, or portion thereof, for in-stream use.[110] In order to accomplish this result, the state has declared that "using" a water right for in-stream purposes is a beneficial use.[111] Water rights holders may split their use of water by leasing a portion of their water rights, so long as the uses are not concurrent during the year.[112] A savvy water rights holder may wish to lease an unused portion of his rights for in-stream purposes in order to avoid loss of his rights to the water through abandonment or forfeiture proceedings.

In Utah, only the government[113] may purchase, lease, or accept as a gift a water right to be used for in-stream purposes.[114] Fishing groups, however, may file a fixed time change

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[101] RCW § 90.42.005.
[102] RCW § 90.42.030.
[103] *Id*.
[104] RCW § 90.42.040.
[105] RCW § 90.42.040(9).
[106] RCW §§ 90.42.100 through 90.42.130.
[107] *See* footnotes 22-23 and accompanying text.
[108] Western Water Policy Review Advisory Commission, *supra* note 19, at § 5-5.
[109] WATERS AND WATER RIGHTS, *supra* note 3, at § 13.05(a).
[110] ORS § 537.348.
[111] ORS § 537.348(2).
[112] ORS § 537.348(3). *See also*, OAR § 690-077-0079 for split season in-stream leasing requirements.
[113] "The government" includes the Division of Wildlife Resources or Division of Parks and Recreation. Utah Code ("UC") § 73-3-30(1)(a).
[114] UC § 73-3-30(2).

application in order to protect certain species of native trout.[115] Like Oregon, Utah has declared in-stream uses of water to be beneficial.[116] This departure from traditional western water law promotes conservation of water sources, and allows water rights holders to protect their rights from abandonment and forfeiture during periods of non-use.

Beneficial Use Requirements Beneficial use is typically determined on customary grounds.[117] If a certain amount of water for a certain use has traditionally been used in a local area, then that use is most likely considered a beneficial use by the relevant jurisdiction. However, following a customary approach can lead to inefficiency because new technologies and changed circumstances may make the amount of water previously used wasteful. For these reasons, states have begun to change how they determine whether a particular use is indeed beneficial, or just wasteful.

In Idaho, the legislature has determined the amount of water that is beneficial for irrigation. Users cannot divert more than one cubic foot of water per second for each 50 acres of land to be irrigated.[118] Additionally, users cannot store more than five acre-feet of water per year for each acre of land to be irrigated.[119] However, the legislature has merely created a presumption that water above the stated amount is wasteful. The presumption can be rebutted with evidence showing that a greater quantity of water is necessary for specific irrigation projects.[120] Although the state has strayed from the traditional conception of what constitutes beneficial use, courts must still look to local and community customary uses, rules and regulations, adopted by the majority of users from a common water source, to determine whether a larger quantity of water is in fact necessary.[121]

The Nevada state legislature has prescribed additional factors to be considered in beneficial use analysis beyond the traditional customary approach. For instance, the quantity of water must be limited to the amount with is “reasonably required” for the particular use.[122] To determine what amount of water is reasonable, the state engineer must consider the climate of the area, the duty of the water as established by decree or experimental work, the length of the growing season, the type of crop to be grown, reasonable transportation losses and evaporation losses, and any other information and data available.[123] Through this process, the state can reduce waste and increase efficient allocation of water resources.

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[115] UC § 73-3-30(3).
[116] UC § 73-3-30(7).
[117] *See* footnotes 38-40 and accompanying text.
[118] IC § 42-202.
[119] *Id.*
[120] *Id.*
[121] IC § 42-220.
[122] NRS § 533.070.
[123] *Id.*

CONCLUSIONS

Water in the western United States is a scarce, yet essential resource. The prior appropriation doctrine developed during a time when water supply surpassed water demand. Therefore, many of the tenets of the "pure" prior appropriation doctrine are out of touch with the realities of modern water needs in the West.

Although an evolution in western water law is desperately needed to bring forth efficiency in water allocations, the states have been slow to waiver from the basic principles espoused by the prior appropriation doctrine. These principles are enshrined in both the laws of the western states and in western culture.

Despite the long precedence of the "pure" prior appropriation doctrine, states have begun, one by one, to make small departures from that system. These changes to the traditional doctrine have been driven by necessity. Only through conservation and efficient water use practices can the West sustain its current growth patterns and be plentiful in the future.

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ON-FARM STRATEGIES FOR DEFICIT OR LIMITED IRRIGATION TO MAXIMIZE OPERATIONAL PROFIT POTENTIAL IN COLORADO'S SOUTH PLATTE BASIN

Stephen W. Smith[1]

ABSTRACT

Farming, in many ways, is more complex and technically demanding than ever before. Just one example of this complexity is related to the population growth along the Front Range of Colorado and within the South Platte Basin. Municipalities, desperate to identify and solidify their future water supplies that will sustain continued population growth and produce a "safe yield" of water are frequently looking toward agriculture as a water supply source. Often enough, farms are acquired outright and the water rights are parted off 100% to be changed over to municipal use. This is often referred to as "buy and dry."

The purpose of this paper is to show that successful farming operations can be continued while benefiting from a proportional parting-off of the water right's established consumptive use (CU). The CU of a given water right is established through an engineering study which evaluates and details the historic use of the water right. Historic cropping patterns, acreages, and irrigation methods must be considered in the study. Once the CU is established and vetted through the Colorado Water Court, the CU for that water right becomes decreed – a known quantity. This then allows for more comprehensive consideration as to how that CU water might be used to economic advantage in the future. Specifically, a future water use might be to continue farming but to lease or sell a proportion of the CU to municipal interests. This same general idea might also apply to a ditch company getting involved in planning, controlling, and administering an overall service-area-wide program.

Once actual CU water quantification is fully understood, consideration can be given to a comprehensive package of farming practices which become the underpinning of future agriculture operations for farmers interested in availing themselves of such a change. Practices may include changes to cropping patterns, consideration of alternative crops, deficit irrigation, improved irrigation application efficiencies, and improved management and monitoring / control using the newest technologies. Optimization software is under development to assist farmers and ditch companies as they consider the viability of operational changes.

[1]Founding Partner, Regenesis Management Group, 2442 S. Downing St., Suite 250, Denver, CO 80210. Graduate Student, Civil & Environmental Engineering Dept., Colorado State University, Fort Collins, CO. Email: swsmith@regenmg.com.

INTRODUCTION

In 2003, the State of Colorado initiated a planning effort called the Statewide Water Supply Initiative (often termed “SWSI” and pronounced “swa - zy”) for the purpose of projecting water supply needs for each of Colorado’s river basins in 2025. For the South Platte Basin (Figure 1), the SWSI report forecast a population growth of 65% which equates to 2,000,000 people by 2025 and an associated water supply need of 400,000 acre feet. The South Platte is already over appropriated. Transbasin transfers and new storage are essentially no longer feasible because of permitting obstacles. The prevalent presumption is that the 400,000 acre feet will likely come from irrigated agriculture. This dynamic is also playing out in other states in the West and other basins in Colorado in the form of municipal acquisition of farms and water. The water is then 100% removed from the farm and the use of the water is changed to municipal and industrial (M&I) use. The farm is dried up into perpetuity. This process is often referred to as “buy and dry.” Even some of the municipalities who have availed themselves of this practice are saying publically that they do not want to continue with the practice because of the impact on the rural community and the cumulative negative push back from many sectors. Some municipalities are actively looking for alternatives to what has come to be called “buy and dry.”

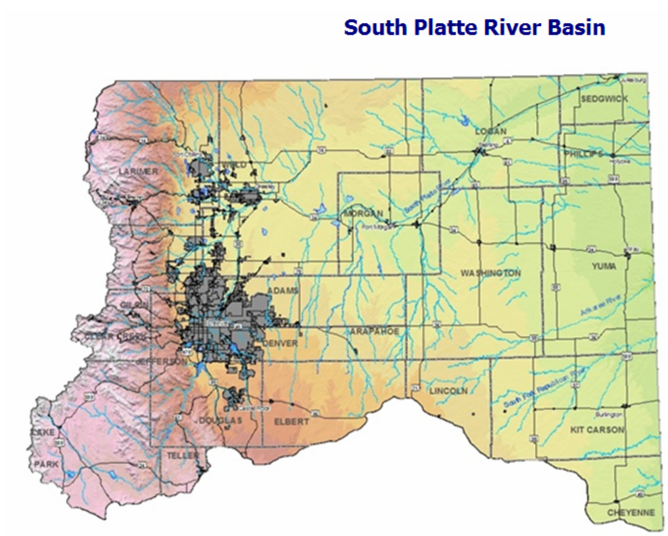

Figure 1. The South Platte River Basin in northeastern Colorado.

An alternative to buy and dry in the Arkansas Basin of southeastern Colorado is manifest in the form of the Super Ditch Company. The Super Ditch is a recent, for-profit farmer-managed entity that represents the collective interests of eight ditch companies by offering a rotational fallowing option to their constituent farmers. A municipality or water district may contract with The Super Ditch to deliver a prescribed amount of CU water over a specified period of time. The CU water is made available through rotational fallowing. Farmers can evaluate a number of options suitable to their specific circumstance and make it known to Super Ditch management that some proportion of their land is available to be fallowed. Some operational issues are still under

consideration, and as of now, no wet water has been delivered. However, a letter of intent to contract has been executed between Super Ditch and the Pikes Peak Regional Water Authority according to published newspaper reports in The Pueblo Chieftain.
A somewhat similar approach but differently organized is in the early stage of development and vetting in the South Platte Basin. With this program, farmers can initiate a desktop analysis of their farming operation, evaluate future “what if” operations, and consider the cumulative effect of changed practices. The analysis facilitates viewing their consumptive use (CU) water as a block from which they may evaluate an incremental parting off of some proportion of the CU. The ultimate goal, depending on several intertwined factors, may be to lease or sell a portion of their CU or to at least consider that option. The lease of a proportion of the CU could become a steady and predictable revenue stream for the farmer over the term of the lease. By evaluating alternatives which may include a full package of changed practices, the farmer can at least evaluate the potential for this change. Does it work for them or not? The answer to that question is an individual decision but at least the option can be fully evaluated using a decision support system and optimization. Changed farming practices represent a business decision, of necessity, but a decision underpinned by sound engineering and economics.

The relevant technical literature uses many terms for “limited irrigation” or “deficit irrigation.” The terms are often used interchangeably. It was noted at a recent deficit irrigation workshop that there is ambiguity in the terms but it was suggested that “deficit irrigation” may be preferred by many. Marshall English at Oregon State University has recently defined deficit irrigation as irrigation that allows stress in a significant fraction of a field at some times during the season. Freddie Lamb at Kansas State University notes that he defines deficit irrigation as an irrigation level under the expectation of reduced crop yield with economics justifying the deficit. The term “limited irrigation” herein will refer to a reduction of water applications through a combination of practices, one of which may be deficit irrigation.

The history of basic research in this area is long and dates back to the 1970s. Early work was primarily intended to show the basic potential for water conservation. The more recent work is driven by drought response demands, desire to predict climate change impacts on crop production, and the possibility of revamping individual farming operations for maximizing profit as opposed to maximizing yield.

The current definitive research in the western U.S. is being conducted by Derrel Martin and Ray Supalla at the University of Nebraska, Norm Klocke at Kansas State University, Tom Trout with the USDA-ARS Water Management Unit in Fort Collins, Colorado, and Marshall English at Oregon State University. Several of these research efforts have resulted in Excel-based optimization routines including the Water Optimizer program developed at the University of Nebraska and the Water Allocator program developed at Kansas State University.

THE SOUTH PLATTE BASIN CIRCUMSTANCE

The South Platte Basin has become a focus and "poster child" of many of the interrelated problems associated with population growth. Cities and towns along the Front Range have varying water portfolio amounts in what is referred to as "safe yield" water to serve growing populations. There is often a desperation mentality that makes the municipal water managers grasp at all alternatives – conservation, new storage, leak detection, fines for water wastage, water conservation programs, public information programs, and aggressive water acquisition. In the water acquisition realm, the City of Thornton clandestinely bought up Northeastern Colorado farms in 1986 with the explicit purpose to eventually dry up those farms and move water south to Thornton for future water supply needs. All of this creates a lot of angst, distrust, and uncertainty in the water community and the community at large. Periodic drought conditions and climate change discussions magnify all of this.

As noted in the 2004 SWSI report:

> "Nearly two-thirds of the increase in the state gross demand by 2030, approximately 409,700 AF, will be in the South Platte Basin. Of the 409,700 AF of increased water demands in the South Platte Basin, the majority of the demand is proposed to be met through existing supplies and water rights and through the implementation of identified projects and processes. However, there are still some anticipated shortfalls expected in certain portions of the basin. The identified shortfalls will be the focus for supply alternatives developed for the basin."

Todd Doherty with the Colorado Water Conservation Board noted in a recent Colorado Water Institute newsletter that "most of the (water for population growth) will be met through three main water supply strategies: conservation, agricultural transfers, and new water supply development." He goes on to say "if these new water supply projects are not built, future water demands will have to be met mostly through a combination of agricultural transfers and conservation.

ESTABLISHMENT OF HISTORIC CONSUMPTIVE USE

There is no intent herein to fully describe the engineering or the legal process of formally establishing the consumptive use of a water right in Colorado. However, for the purpose of framing the change case effort which requires a study of historic CU, it is worthwhile to describe a few pertinent aspects of the process.

The need for establishing the CU of a water right must first exist. If farmers have beneficially used a water right decreed for irrigation for a long period, then they can continue to use the water right in that way indefinitely with no need to define or quantify CU. An evaluation of CU is generally driven by a change in the type of use, place of diversion, or the quantity of water diverted. Because the engineering study to establish historic consumptive use is costly, it is unlikely that anyone would take on the effort without justification. That said, it is important to note that someone else holding the same water shares (i.e. same ditch company) can initiate a change case, establish CU through the court process, and Colorado's Water Court will likely view that change case as being a "ditch-wide" analysis and therefore affecting all the shareholders of that right whether they participated in the change case or not. This subtlety can be extremely important.

The historic water deliveries and season of use are easily found in the data base of the South Platte Decision Support System (http://cdss.state.co.us/DNN/default.aspx) . Historic cropping data and irrigated areas are not so easily found. One must investigate vintage aerial photography from multiple sources, locate and check publically available Farm Service Agency documents and records, talk to landowners and irrigators, and otherwise undertake a time consuming effort to understand the past. Sometimes the ditch company's board members and board or annual meeting minutes can provide useful historic information. Historic irrigation practices, estimates of irrigation efficiency, and delivery efficiency (canal seepage) also come into play with the CU calculations and must be determined or estimated.

A water balance of the canal or the farm is a useful means of understanding the sources and the destinations of water. The Figure 2 one-line diagram shows how the water balance plays out from the river diversion and downstream to the on-farm distribution system and provides some context of common terms.

Basically, what this illustrative graphic shows is what happens to water once it is diverted into a ditch or canal for irrigation purposes. The character of some of the water changes as one moves downstream in the canal. Some would say colloquially that the "color" of the water changes, a reference to where the water came from, or where it is bound, or what is its decreed use.

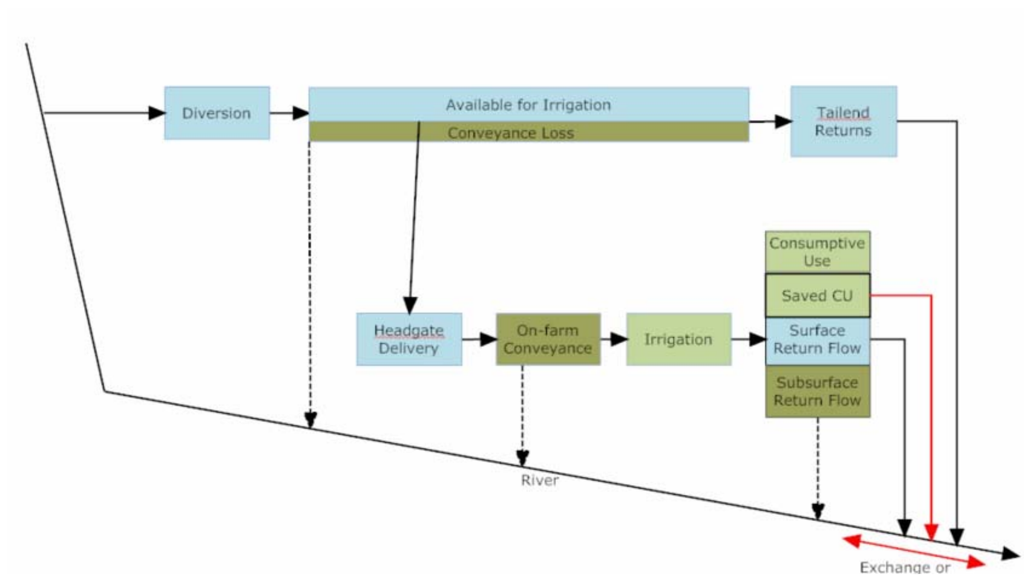

Figure 2. Depiction of the elements of surface water delivered to the farm via canal.

After diversion into an earthen canal, the diverted flow immediately begins to diminish because of conveyance losses, the most notable of which is seepage. Other losses are attributable to phreatophytes and evaporation. Seepage can be quite significant especially over the full length of the canal and is likely the highest loss in earthen canals. Seepage returns to the river as subsurface flows and the time it takes to actually arrive at the river is a function of distance from the river and characteristics of the alluvium and this can vary over the length of the canal as well. With a water right change case, this historic return flow pattern must be maintained into the future.

As we move downstream through the canal, some water returns to the river via the end of the canal as wastage or operational spill. Some canals have historically diverted a generous amount of water to assist with canal operations. It is easier to deliver equitable flows to canal headgates, especially those at the end of the canal, if the canal is flowing nicely with excess water that can be returned to the river for other downstream users.[2]

Continuing to refer to Figure 2, a headgate delivery to the farm has similar water balance characteristics as with the main canal but the headgate delivery likely represents the point at which the company's delivery responsibility ends and the individual farmer's responsibility begins. Downstream of the headgate, there are often on-farm conveyances from which there are losses, and again, those loses are most notably seepage. Once we deliver water to on-farm irrigated fields, and the associated irrigation systems, the key elements of irrigation water can be identified as consumptive use, the surface return flow, and the subsurface return flow. Within the consumptive use amount, there is a proportion of that consumptive use that may be appropriately termed "conserved" or "saved" or "set-aside" CU and this amount is the water that might be considered for its higher economic value.

In Figure 3, the average historically diverted water to the farm is characterized as consumptive use, surface return flow, and subsurface return flow. Crop consumptive water use is the amount of water transpired during plant growth plus what evaporates from the soil surface and foliage in the crop area. The portion of water consumed in crop production depends on many factors including whether or not water availability is limiting evapotranspiration plus soil texture, crop varieties, and so on.

[2] This practice is becoming less common as canals come under scrutiny for "sweeping the river" and taking the full flow of the river even if they are decreed to do so.

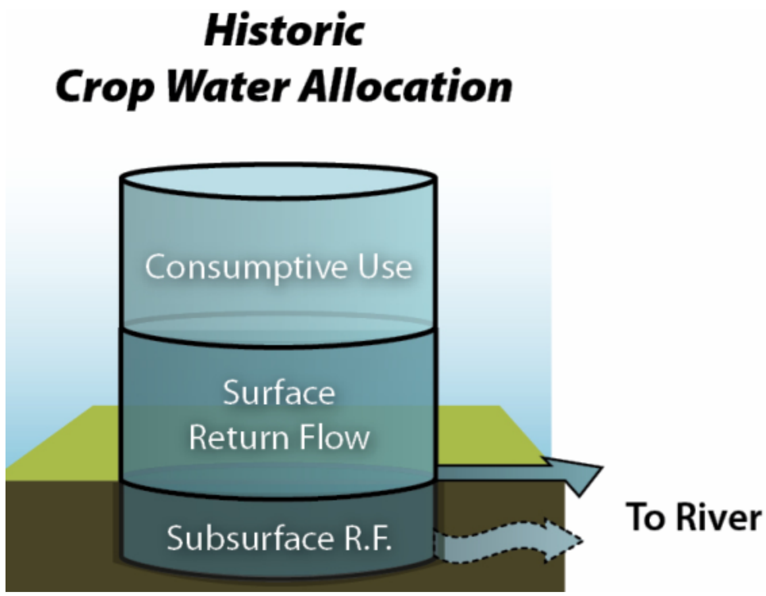

Figure 3. Depiction of the primary named use of water delivered to the farm.

Once an estimated or a fully decreed consumptive use (CU) is known for a given water right, it opens up potential to consider options for how the CU might be utilized differently in the future. The consumptive use can be allocated to new use priority or some balance between old and new priorities. The consumptive use can now be viewed in terms of an on-farm CU water budget. A new use of the CU might be to part off a portion of the water to a municipal or environmental water user.

As an example, consider a farming operation that is typified as follows:

- 150 acres irrigated.
- Surface water supply is owned to include 10 shares in a ditch company that, on average, delivers 30 acre feet per share or 300 acre feet total.
- The CU has been established via a ditch-wide analysis of the shares and the right. The decreed CU is 10 acre feet per share.
- A local municipality is offering $500 per acre foot of CU water on a long-term lease arrangement.

In this example, the farmer has 10 shares times 10 acre feet per share or 100 acre feet of CU water available in an average year. Maybe the farmer wants to consider parting off half of that water, or 50 acre feet of CU water. A lease of the water to a municipality would provide a low risk revenue option and a predictable revenue stream ($25,000 / year) into the farming operation.

Planning for the use of the remaining 50 acre feet of CU water can now be considered by management. Planning must include appropriate consideration to each component of the water right. Historic return flows must be maintained and this applies to the full water right just as if no CU water had been parted out. So, farms can be operationally changed in a significant way or crops may be converted to dryland crops or fields fallowed to reduce the amount of CU water that is used. Monitoring and reporting of operational changes is likely to be precisely mandated in any change case decree. The State of Colorado has become much more stringent in the last decade and requiring of more data and more timely, even real time, data.

It is important to note that a lease to a municipality probably includes a guarantee for delivery of a certain amount of water each year. This would be defined in contractual terms but would probably be a commitment to deliver an agreed upon amount of water regardless of the impact on the farming operation in that year. In other words, the farmer will be required, under contract, to take the shortage in any given year. A drought year or years could result in the necessity for the farmer to deliver the agreed upon amount of water regardless of the impact to the farm. Severe drought conditions may result in curtailed farming during drought years so as to meet the obligation to the municipality.

A somewhat bigger picture view of this circumstance is shown in Figure 4 which indicates surface irrigated fields and again identifying colored water. Downstream of the river diversion the canal seepage contributes to return flows to the river. After water is diverted at the farm headgate, water flows down furrows and the portion that does not infiltrate to the soil becomes tailwater and returns to the river as surface return flows. Deep percolation below the crop root zone is subsurface return flow.

Flow measurements are indicated in Figure 4 at the river diversion, downstream of the farm headgate, and on the tailwater return ditch. In the past some or all of these flow measurements were not necessary and not undertaken due to hydraulic structure and data collection costs. In the future, and under a substitute water supply plan or a water right change decree, all of these flow measurements will be mandated along with the reporting.

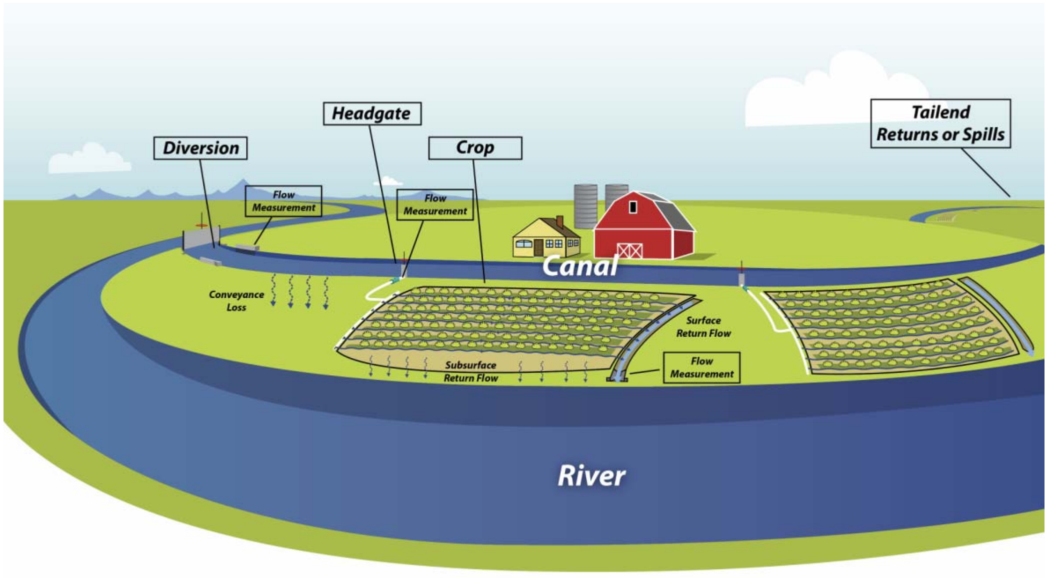

Figure 4. A graphic depiction of a river diversion, canal, and elements of on-farm water delivery. In the future, flow measurements at the points noted will likely be required in a water court change decree and the State Engineer will monitor real time data and monthly reports which collectively will indicate conformance with a decree.

POTENTIAL FOR CHANGING FARMING PRACTICES AND MONITORING USING A DECISION SUPPORT SYSTEM

Once a farmer or group of farmers (possibly a farmer cooperative) understands the amount of consumptive use water that is available to them through their water rights, consideration can be given to a new mix of water uses for the remaining portion. These uses can be evaluated within a CU water budget which can be optimized for a given year. This water budget would logically have basic characteristics as follows:

- Monthly and annual time basis and potentially covering multiple years.
- Recognition of multiple water sources and their respective season of use.
- Water allocations by fields and crops.
- Consumptive use allocation.
- Approach to return flow replacements at the river.

In many instances, the water right was historically used to grow the crops that were prevalent in the area. On the South Platte, the predominant crops are corn, wheat, dry beans, grass hay, alfalfa hay, and truck crops. Consideration can be given to the practices, or more likely the combinations of practices, that adhere to an annual CU water budget. In any given year, practices may include:

- Deficit irrigation.
- Crop rotations and introduction of new crops.
- Permanent or rotational fallowing.
- Dryland farming.
- Continued full irrigation of selected crops.
- Combinations or permutations of the above.

A new decision support system is under development by a team lead by Regenesis Management Group located in Denver, Colorado. This program is contained within an internet-delivered software package known as Sustainable Water & Innovative Irrigation Management™ or SWIIM™. SWIIM™ is intended to be used for farmer-considered planning but also as a monitoring and reporting system into the future should practice changes be implemented.

SWIIM™ is a tool for farmers to use in evaluating potential operational changes to conserve CU. More specifically, SWIIM™ is:

- A package of technologies under one umbrella software program.
- A decision support system (DSS).
- A farm operations simulation.
- An optimization program for evaluating alternative farm operational strategies.
- A database, monitoring, and reporting system following implementation of a strategy or strategies.

Primary planning and modeling features of SWIIM™ are:

- GIS-created user inputs of all inputs such as field configurations that are geographic in nature.
- Prompting for inputs for past operational costs.
- An underlying database containing all planning level data.
- Optimization routines (non-linear programming) to evaluate alternatives.
- Reports to assist in considering a package of changed practices to compare future practices with the historic past and with one another.

Primary implementation, monitoring, and reporting features of SWIIM™ are:

- On-farm monitoring of soil moisture and other site specific parameters such as wind speed and precipitation.
- Integration with weather station networks and existing SCADA systems.
- Reports to management.

- Reports to the State Engineer's Office (SEO) to meet their regulatory requirements for timely and a suitable amount of confirming data.
- Field confirmation of changed irrigation practices.
- Aerial (low level periodic flights) confirmation of changed irrigation practices and evapotranspiration rates.
- Satellite (LandSat) confirmation of farm level, ditch-wide, and regional evapotranspiration rates and monitoring or affirmation of deficit conditions on larger fields.

SUMMARY

Agriculture to urban water transfers can be affected in various ways. Alternatives to "buy and dry" appear to have validity and are under development. The Super Ditch Company in the Arkansas Valley of southeastern Colorado was formed to offer farmers land fallowing options. It is intended that a collection of consumptive use water sources can to be leased to needful municipal interests. In the South Platte Basin of northeastern Colorado, research is being conducted and optimization and planning software is under development to assist farmers in considering technology and changed farming practices also intended to provide options. Farmers interested in continued farming operations while availing themselves of a new predictable revenue stream are considering these options. With consumptive use water is parted out, historic return flows to the river must be maintained. None of these technology options have been decreed by the Colorado Water Court system and it will likely be several years before a change case with high technology features receives its day in court.

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KNOWLEDGE MANAGEMENT FOR THE 21ST CENTURY

John Winchester, P.E.[1]

ABSTRACT

According to the US Bureau of Labor Statistics and the Office of Personnel Management, 40% of America's workforce will be eligible to retire in 2010 (Greene, 2005). Some jobs will be difficult to fill, meaning that there may not be anyone to train before a person retires. If we fail to transfer our institutional knowledge to the next generation, career-scale knowledge will be lost. Knowledge management systems will preserve institutional knowledge, plus allow future engineers quickly find the information they need.

One of the best ways newer employees can learn from more experienced staff members is by shadowing. However, shadowing only works for planned changes in personnel and is not an option for sudden, unexpected departures. This is a significant factor because younger employees change jobs more frequently than earlier generations of workers did. Therefore preservation of knowledge is critical, regardless of the age or intentions of an organization's employees.

Knowledge preservation has been tried using audio, video and written media. With today's technology, preservation of engineering knowledge is most likely to be document based because written documents can be stored and searched very efficiently.

Document management options include filing cabinets, searchable databases, linked documents, document management software and facilities maintenance programs. Because water resources projects commonly have a spatial aspect, map-based software provides many advantages over other systems. Developing a knowledge management system entails identifying key documents, facilities, relationships and operations; converting the information to a useable format; and organizing the documents so they can be searched electronically.

Knowledge management systems can be populated in large sections with concerted effort, or over time by regularly dedicating staff time to the task, or by building the management system by adding knowledge as staff work on projects.

INTRODUCTION AND BACKGROUND

Purpose and Scope

The purpose of this paper is to raise awareness of the need for knowledge management systems, to describe the basic types of systems currently available, and to provide several example web sites.

[1]President, High Country Hydrology, 825 South Broadway, Suite 10, Boulder, CO 80305; john@highcountryhydrology.com

Background

In the days when children took over the family business, whether the farm, the store or a trade, the younger generation typically worked beside their parents for several years, and in the process learned how to run the business. This tradition has changed as people have the financial and social opportunity to choose a different career than their parents. In today's mobile world, institutional knowledge should stay with the organization and not the individual worker.

Due to a variety of factors the typical length of employment is getting shorter. Workers now feel less loyalty toward employers and may be more willing to move from one job to another. This creates problems for employers in areas such as water management organizations, because without a knowledge management system, employees leave with valuable institutional knowledge that is very difficult, if not impossible, to regain. This is particularly important as long-term key employees reach retirement age, because the replacement workers are likely to have been in the organization for less time than their predecessors, and will likely not stay in the position as the person they are replacing. The converging trends of shorter lengths of employment make knowledge management and retention a critical issue for the present time.

KNOWLEDGE MANAGEMENT

The Objective of Knowledge Management

The objective of a knowledge management system is to record knowledge held by current employees, and store it in a form so that future employees can easily find and access that knowledge. This enables future employees to learn institutional knowledge more quickly than if they had to mine the file drawer themselves, therefore permits them to be more productive, which in turn allows the company to retain benefit from the time and money invested in the current employee.

The Question of What Knowledge to Preserve

The first question to address in a discussion of knowledge management is exactly what information should be preserved. This is important because different information is best stored in different formats.

For example, is the knowledge documentary in nature, describing why something was done the way it was done? Documentary information is likely to be reviewed only occasionally and will likely be viewed in its entirety. Consequently this information can be stored in a variety of formats, including written paper or electronic documents, audio or video interviews. It is also less important that this information be searchable. For example, to preserve the engineering knowledge gained from designing the Concorde SST, engineers were interviewed on video tape before they left so the knowledge of how to build a supersonic passenger plane would not be lost.

Or, is the information most likely to be referred to on a regular, even if infrequent basis?

This material should be stored in such a way that it can be searched, such as searchable electronic text files.

Or is the information about how a job is to be performed, in which case the material should be organized by topic, preferably with decision trees and summary lists of subtasks to be completed.

Or is the information more spatial in nature? Information about infrastructure, easements, water rights and other location-specific documents can be organized and even stored in map-based software.

Fundamental #1: How you choose to store information depends on who is going to use it and what purpose they are going to use it for.

The Issue of Preservation

Another aspect of knowledge management is the level of risk the organization willing to take that the information could be lost. Loss can happen in several ways: destruction of the archive documents themselves; losing the ability to read electronic documents when software or hardware becomes obsolete; or simply losing the knowledge that the documents or files exist, which is arguably worse than knowing they existed and then losing physical access to them.

If an organization chooses to store its information in an electronic format, it is important that the organization have a rigorous plan in place to make sure that all documents are updated to a current software version and state of the art hardware format on a regular basis. Continually moving the data – which likely includes word processing documents, spreadsheets, cadd drawings, databases and photos – helps ensure that they will be accessible in the future. However, for a continual modernization program to be successful, it is necessary that all important files be included. For example, if a spreadsheet was used to develop interim data, the interim spreadsheet has to be updated, or the process will likely be lost.

Fundamental #2: Safe storage of electronic files is not enough to ensure readability in the future. Electronic files must be repeatedly saved to current file formats or they may be lost to software or hardware obsolescence.

Cornerstones of a good Knowledge Management System

The purpose of knowledge management is three-fold: First, to encourage the transfer knowledge from the individual to the institution. Second, provide a mechanism so that knowledge may be found and used by others. And third, the management system should suggest relevant information to the user, particularly about details of which the user may not be aware.

Knowledge Transfer: While some individuals may be very conscientious about documenting what they do and why they did it a particular way, some are not. Institutions concerned with knowledge management should build in procedures and a corporate culture that encourages the transfer of knowledge as it is generated.

Usability: A good knowledge management system will have two key usability features. First it will have an interface that is intuitive for at least 95% of the potential users. Making the interface simple to use allows it to be used by people with a wide variety of computer skills, which in turn has two immediate benefits: first, the person looking for information will be able to search and find the information that is of particular interest to the situation at hand. Having a user friendly interface also means that a person with less technological skill can use the management system. Second, some systems, such as those based in facilities maintenance software, require someone with specialized computer skills to pull information. These systems are useful, but require more staff time to operate. Particularly in the current economic climate, systems requiring excessive staff time are probably impractical.

Suggestible Nature: A good knowledge management system will not only identify the information the user is looking for, but will suggest related material. The ability to suggest related material helps ensure that the user is aware of all information pertinent to the topic being researched. This is particularly important for new employees, who may not be aware of areas of past work. For example, a new employee may not be aware of an operational agreement negotiated with another water user, and a good knowledge management system would make the employee aware of the agreement.

Fundamental #3: A knowledge management system makes it easy to put information in as a normal course of doing business, and makes it easy to find and retrieve that information at a later time.

Key Features for Water Resources Organizations

The key features of knowledge management systems are based on the three objectives described above. The four key attributes are: First, the interface must make it easy to both find and retrieve information. Second, the subject matter must be easy to locate. Data and information must be arranged in a logical fashion so people looking for specific information can readily find it. Third, specific information must be easy to find. This means the information must be searchable. And fourth, information must suggest itself to the user, so it will be found even if the user is not looking for that particular piece of information.

Ease of Use: The user interface must make it easy to both store and retrieve information, or it won't get used. This is particularly important for areas where new information continues to be generated, less important for organizations where the institutional knowledge remains fairly static.

In either case, it should be easy for users to document their work. It should be easy for employees to add documents, data and short explanatory notes to the system. It should also be easy for employees to not only add documents, but to add relevant information to the index. The alternative is to have a dedicated person add the documents, which not only requires that person's time, but also means that there will be some lag between when the documents are created and when they are added to the system. Ideally, a worker will add a document just as soon as it is completed. Workers who are asked to frequently use an unfriendly system will not want to do it, while workers who use the system only infrequently may be unable to remember the nuances of how the system works.

If the system is easy to use, not only will employees add their documents, but they will also use the system themselves as a reference tool for past work. This is the ideal situation, because the workers will learn through use how to file things so they can be found, how to best index documents, and what sort of documents, data and notes are the most valuable for future reference.

<u>Logical Organization:</u> Today's technologically savvy users expect the technology to be user friendly. For example, Apple doesn't include a user's manual with its phones or mp3 players, but rather designs its devices with the objective that users will not need a manual. Users expect technology to be intuitive, and companies like Google, eBay and Amazon make large investments to have their sites anticipate what users want and not just what they ask for.

In the past, the state of the art knowledge management system included filing cabinets with a paper list of contents. This system has three main drawbacks. First, the user has to know that a document exists before they can look for it. Tables of contents commonly have only one entry per document, so if the user doesn't look for and recognize the right entry, they will not be able to find the document. For example, if a facility has multiple names, such as the Charles Boustead Tunnel in the Fryingpan-Arkansas system, a user, particularly an inexperienced user, who is looking for one entry may not recognize the facility if it is listed under another name. Unlike a paper-based system, a good knowledge management system will include the ability to attach multiple terms to a single record.

<u>Searchability:</u> The power of today's technology is the ability to search documents. A knowledge management system should not only organize data, but allow for documents to be searched for specific text strings. This should include legal documents, agreements, raw data, as well as non-text file formats such as spreadsheets and drawings.

If the knowledge management system does not allow the user to search documents directly, it should, at the very least, list documents that the user can / should open and search as a separate process. For example, someone looking for flow rate limitations in a water rights decree may have to read multiple sections just to find the particular numbers they are looking for. A good knowledge management system will include the ability to search documents. Today, this typically means that documents are stored in an electronic format that includes text-based information, for example, an original word processing document or searchable .pdf, rather than a .tiff or .pdf image file.

<u>Related Material is Suggested:</u> A good knowledge management system should suggest

what data, information, legal documents or institutional knowledge is available for structures or facilities that are owned or otherwise used by your organization. This could include information on:
* water rights
* operational agreements
* leases of facilities or water rights
* knowledge of day to day operations, including key contacts
* maintenance schedules for equipment or facilities
* emergency procedures

For example, water rights decrees and stipulations, intergovernmental agreements and operational procedures should all automatically be returned when a user researches a particular structure.

Practical Options

Currently there are three practical options for computer-based knowledge management systems;
1. Searchable / browsable document indexes
2. Web based document management
3. Map based systems

Searchable document indexes can be built using linked .pdf or office suite files, where the user creates an index of files, and then the index entries are linked to the source documents. If the .pdf files are created as searchable text documents, this system fulfills the basic requirements of being easy to operate, easy to update and easy to search. Most offices have the necessary software, such as MS Word or WordPerfect, or with a minimal investment can purchase a .pdf file creator. Unlike word processor or spreadsheet files, .pdf files have the advantage that they cannot be inadvertently changed while someone is browsing through them. The disadvantage of linked indexes is that unless the index is very carefully planned, the system will not suggest related material to the user.

Web-based document managers are simply web pages that allow the user to organize documents by topic using html language. The advantage of these systems is that almost every computer user is familiar with how to navigate web pages. The disadvantage is that if the index is broken up into multiple web pages, there is no way to search all the subpages automatically. A single page might work for organizations with only a few dozen documents, but when many hundreds or thousands of documents are involved, a single page can become overwhelming to browse through. Typically web indexes are broken down by topic, so the user can navigate through several layers of web pages to find the documents of interest. Web-based systems typically require someone with above-average computer cabability to create and maintain.

Map-based systems organize documents by geographical area. This is particularly useful for documents that relate to a specific location, such as a water right. This allows the user to quickly grasp where previous work has been done.

There are many levels of user interface, with the more complex interfaces typically providing more power to the user. Map-based systems have the advantage that a user can browse a geographic area and see locations that have documents associated with them. Software options include GIS software, facilities management software, graphics-based web pages, and hybrids such as Google map. Map-based systems typically require a technologically advanced person to set up and maintain, but can frequently be operated by all levels of user.

Potential Pitfalls

While there are many advantages of putting your information into a knowledge management system, there are also risks. First, there is the risk that your information could be accessed by those wishing to cause you, your organization, your customers or the public in general harm or embarrassment. For example, information on infrastructure could be used to determine how to disrupt operations. Institutional knowledge could be used to discover weaknesses in water rights or planning processes, and could be used to disrupt strategic planning. Documents containing institutional knowledge could be used to identify processes or activities which could be construed as approaching the fringe on legality. To prevent this sort of security breach, document control and computer security is paramount.

A knowledge management system could also make it easier for the public to locate and find information subject to Freedom of Information Act (FOIA) requests from public entities. If the existence of a system is made public, there could be a FOIA request for the system and all its documents. Sensitive documents should be protected by attorney-client privilege. In these cases, the knowledge management system can refer to the documents, even if it is in an abstract manner. While laws vary by location, one possible option for sensitive documents is to have a consulting attorney or engineer host the knowledge management system, so the documents, because they are on a network belonging to a private corporation, are not subject to FOIA.

If documents are stored in an editable format such as a word processing or spreadsheet software, the “documents of record” could accidentally be modified, causing confusion later. While there is an advantage to keeping an editable version in the original format for future use, it is also worth considering whether regularly accessed documents should be stored as non-editable documents, such as pdfs. With these documents, there is no chance the document can be inadvertently changed.

Online Examples

There are numerous knowledge management systems in use today. The following map-based versions illustrate some of the variety of the software platforms and user interfaces available. While several of these examples have physical scales that are orders of magnitude larger than would be applicable for a typical water organization, they do show some of the potential possibilities for linking various types of maps, databases and documents.

The Oklahoma Water Resources Board maintains an on-line water resources database for the state. This system allows users to view different layers (ground water, surface water, land cover, water rights, water supply, etc.). In addition, the user can select color aerial photos, topographic maps or shaded relief maps as the background for the map.

This system was developed in-house by OWRB staff with ESRI products, and took approximately a person-year to assemble and populate. Less computer-savvy users may find this interface somewhat intimidating because of its complex nature. Go to the following url and click on Custom Map Viewer.

http://www.owrb.ok.gov/maps/server/wims.php

Summit County Colorado has built an on-line map-based database that allows the public to access data from the assessor's office. In addition to displaying information at various levels of detail, this map allows the user to query the assessor's database by address, description, owner, or county schedule number or PPI number.

This database displays the lots, and selecting the information icon and then clicking on the lot brings up a box with detailed information about the owner, lot size, improvements, etc. The interface on this database is less complex than the one used by the Oklahoma Water Resources Board.

http://maps.co.summit.co.us/arcmap1/Run.htm

The State of New Mexico Water Rights Reporting is an on-line, map-based system that is written in html code. The map links index pages which in turn link to forms filled in from a database. The forms are only as complete as the supporting database, and in many cases the fields have not been completely populated.

http://nmwrrs.ose.state.nm.us/nmwrrs/sub.html

The Digital Atlas of Montana is also html-based, using a combination of clickable maps and forms that guides the user to the information they are looking for. This site has the advantage that you can choose how you locate the data you are interested in, whether by county, stream, township/range, or other parameter.

http://maps2.nris.state.mt.us/mapper/

The Oregon Water Rights Mapping Program is a map-based information system that allows the user to find information on water rights users. This interface is fairly easy to navigate and provides tabular data filled in from a database. The code could undoubtedly be changed to include links to documents in addition to data fields.

http://gis.wrd.state.or.us/apps/map/owrd_map/

The Smartmap was built as a basic proof of concept that a knowledge management system could be built using Google map. The advantage of this system is that the user interface has been refined by Google to be user friendly. The user constructs data files that are read by the map engine to display markers, lines and text balloons. These in turn can be linked to any file the user has access to.

This system does not have a search function, but relies on the user's visual acuity to determine that there are related documents available. If desired, it is possible to construct a search feature that would look at keywords, titles or document text.

The Google licensing agreement says that Google map can be used for any legal purpose, so long as the data files are available to the public. This allows other Google map developers the opportunity to use code developed by other users. This means that you cannot host a Google map behind a firewall. What you can do though, is to put the html code up on a publicly available site, but put the data files used to populate the map and in a password protected directory. In addition, the files that the map links to can be placed on a secure server behind a firewall so they cannot be accessed without authorization. This allows the user to satisfy the Google license while also protecting the information from public view.

www.smartmap.highcountryhydrology.com

CONCLUDING OBSERVATIONS

In addition to learning what documents are important to keep, organizations should set clear expectations about what types of documents are not worth keeping. Draft reports, preliminary calculations and outdated analyses should all be discarded rather than archived. From a legal perspective, e-mail records should be carefully scrutinized to make sure they do not include any material that could be taken out of context or that could be used by opposing entities against the organization.

There is a saying, "software will come and go, but data is forever." A knowledge management system should be developed with the expectation that it will eventually be replaced by another system. The information committed to the system should be easily retrievable and exportable to a commonplace format. As a general rule, software with proprietary data formats should be avoided. In addition to being able to store information, knowledge management systems should be able to import and export data easily.

There should be a conscious effort to migrate information from one software to another as products gain and lose public favor. For example, documents written in WordStar should have been converted to other formats such as Word Perfect or MS Office when users realized WordStar was on the decline.

Developing a knowledge management system can preserve institutional knowledge, reduce the learning time for new employees and enable employees to be more agile and responsive to inquiries for specific information.

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ECONOMICS OF GROUNDWATER MANAGEMENT ALTERNATIVES IN THE REPUBLICAN BASIN

Raymond J. Supalla[1]
Christopher L. Thompson[1]

ABSTRACT

In 2005 the State of Nebraska, in cooperation with local Natural Resources Districts (NRD's), implemented policies to reduce irrigation in the Republican Basin to comply with the Republican Interstate Compact. These policies limit the amount of water which irrigators can apply over a five year period. In this paper an optimization program called Water Optimizer was used to analyze the optimal irrigation management responses to these limitations and to estimate the cost to irrigators and the Basin economy. The optimal strategy was found to be deficit irrigation in most cases, with no reductions in irrigated acres until allocations were reduced to less than about 70 percent of unrestrained requirements. If optimal strategies were followed and average weather occurred, it was estimated that under current polices annual costs would be $27 per affected acre, or $278 per acre foot change in applied water to reduce irrigation. When expressed in terms of the primary policy objective, which is to reduce consumptive use, costs were found to average $344 per acre foot of decrease in evapotranspiration (ET) from irrigation. The aggregate economic effects since the control policies were implemented, however, were found to be small relative to the total regional economy. Favorable weather, high crop prices and improved agricultural technologies have mitigated much of the expected adverse impact of irrigation reductions on the regional economy.

INTRODUCTION AND BACKGROUND

In 1998 Kansas sued Nebraska and Colorado alleging that they had violated the Republican River Compact by allowing the proliferation and use of thousands of wells hydraulically connected to the Republican River and its tributaries, thus adversely affecting the amount of stream flow reaching Kansas. The states of Colorado, Kansas and Nebraska settled this lawsuit in December 2002. The Settlement Agreement required Nebraska and Colorado to significantly reduce their consumptive use from irrigation to levels that met Compact entitlements. Nebraska's entitlement is 49 percent and Colorado's 11 percent of total Republican Basin consumptive use. Compliance is defined as a five year moving average, except in dry years when compliance is measured on a two or three year moving average basis. This paper addresses the economics of policy options used by Nebraska to comply with this Agreement.

Under Nebraska law, surface water is administered by the Nebraska Department of Natural Resources (NDNR) following the Appropriation Doctrine of first in time, first in right, and groundwater is administered by Natural Resources Districts (NRD's) using a correlative rights approach. The Republican Basin encompasses three NRD's, called the

[1] Raymond J. Supalla and Christopher L. Thompson are Professor and Research Associate, respectively, Department of Agricultural Economics, University of Nebraska – Lincoln.

Lower Republican NRD (LRNRD), the Middle Republican NRD (MRNRD) and the Upper Republican NRD (URNRD) (Figure 1)[2]. Each of these NRD's has worked with the NDNR to develop management plans that reduce irrigation to meet Compact requirements. This paper presents estimates of the on-farm cost of limiting irrigation using these management plans, assuming that irrigators optimally respond to the associated regulations. It also addresses the regional economic consequences of the reductions in agricultural production which have resulted from reduced irrigation.

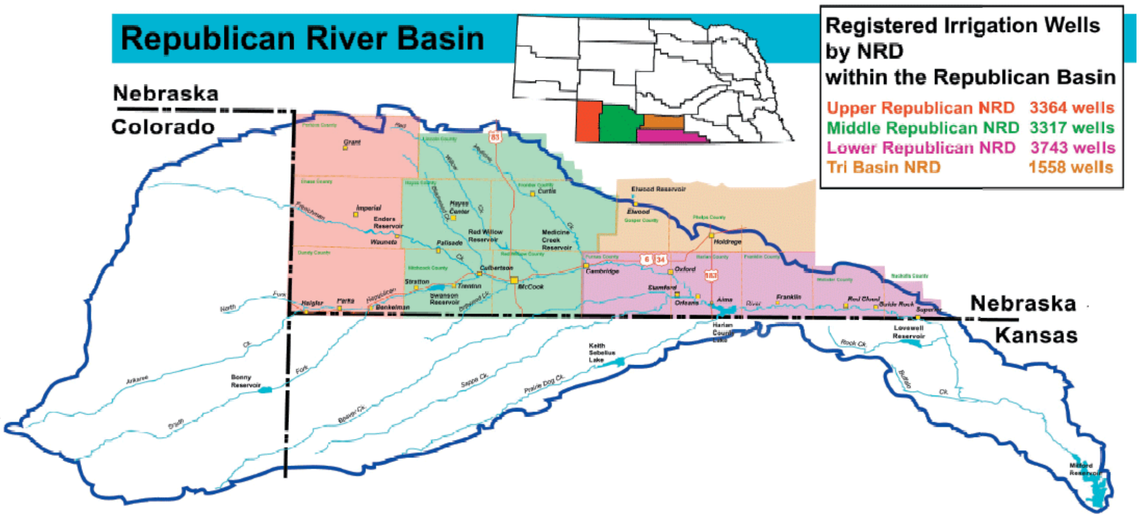

Figure 1. Map of the Republican River Basin.

DESCRIPTION OF THE REPUBLICAN BASIN

The Republican Basin begins with the North Fork and South Fork Republican rivers in the high plains of northeastern Colorado. These rivers meet to form the major trunk of the Republican immediately southeast of Benkelman, Nebraska. The Republican River then flows generally eastward along the southern border of Nebraska, passing through the Swanson and Harlan County reservoirs before curving southward into Kansas. Growing season rainfall varies from 16 inches at the western edge of Nebraska to 28 inches at the east end of the Basin. Elevation ranges between 3,284 feet and 1,598 feet above mean sea level.

Agriculture in the Basin is a mix of irrigated crops, dryland crops and rangeland. There are about one million certified irrigated acres in the Basin, distributed across the URNRD (435,337), the MRNRD (310,168) and the LRNRD (325,876)[3]. The major irrigated crops are corn (60%), Soybeans (17%), wheat (5%) and other (18%). There is about 1,450,000 acres of dryland crop production in the Basin, consisting primarily of wheat in the west and a corn-soybean rotation in the east. Historically there has also been a significant amount of dryland grain sorghum produced throughout the Basin, but grain sorghum acreage has decreased substantially in recent years. Dryland wheat is usually produced in

[2] The Tri-Basin NRD is also partially located within the Republican Basin, but the Settlement Agreement did not require it to reduce consumptive use from irrigation.
[3] Producer reported irrigated acres are certified as accurate estimates of historical irrigation by NRD staff.

a two year summer fallow–wheat rotation or in a three year eco-fallow rotation of corn-fallow-wheat.

About 65 percent of the irrigated land is irrigated with sprinkler systems, primarily center pivots, and 35 percent with gravity systems, primarily gated pipe (Table 1). About 10 percent of all irrigated land receives some surface water, although most surface watered acreage also receives supplemental groundwater. Over 95 percent of the total water applied comes from groundwater. Total irrigation water applied in the Basin averaged 1.1 million acre-feet per year during the five years prior the Settlement Agreement, with average per acre applications of 14.7, 12.0 and 8.9 inches in LRNRD, MRNRD and URNRD, respectively.

Table 1. Irrigated Acres, Irrigation System Type and Water Pumped, Pre-Settlement Baseline

	Irrigated Acres	**% Distribution by System**	**Water Pumped (Acre-feet)**	**Average Application In./Acre**
Upper Republican NRD				
Sprinkler	407,778	93.7	498,044	
Gravity	27,559	6.3	33,709	
Total	435,337		531,753	14.7
Middle Republican NRD				
Sprinkler	134,375	43.3	134,317	
Gravity	175,793	56.7	175,162	
Total	310,168		309,479	12.0
Lower Republican NRD				
Sprinkler	130,533	40.1	97,051	
Gravity	195,343	59.9	145,238	
Total	325,876		242,289	8.9
Total Republican Basin				
Sprinkler	672,686	62.8	729,412	
Gravity	398,695	37.2	354,109	
Total	1,071,381		1,083,521	12.1

METHODS AND PROCEDURES FOR ESTIMATING ON-FARM COST OF IRRIGATION REDUCTIONS

The on-farm cost of reducing irrigation was estimated using Water Optimizer, which is a non-linear optimization model developed at the University of Nebraska (http://wateroptimizer.unl.edu). This model computes the profit maximizing irrigation management strategies when both water and land are constrained. It determines the optimum crops to produce, the optimum amount of water to apply to each crop and the optimum number of acres to irrigate. The on-farm cost of irrigation reductions was defined as the difference in net economic returns for two different water supply levels, assuming that irrigators maximize profits as determined with the Water Optimizer model. The major inputs that determine the profit maximizing strategies include crop water requirements, comparative crop yields, crop prices, production costs and irrigation costs.

Crop Water Requirements

The estimated production functions which define the relationship between water applied and grain yields are probably the most important inputs to this analysis. Most of the economic effects stem directly from how crop yields change as the amount of water applied is reduced. Production functions were estimated separately for central locations within each NRD, for four irrigated crops (corn, soybeans, wheat and grain sorghum), assuming the most typical irrigation system (center pivot sprinklers at a water use efficiency of 0.75), and a medium soil having a water holding capacity of 1.5 inches per foot of rooting depth.

Estimating the water applied versus crop yield production functions required four critical inputs for each case: non-irrigated yield, maximum irrigated yield, maximum irrigation requirement, and water use efficiency. The parameter values used in this analysis were the same as those developed for general use in Water Optimizer (See http://wateroptimizer.unl.edu for data sources and procedures) and are shown here in Table 2.

Each of the production functions used in Water Optimizer and in this analysis were defined as

$$Y = Y_d + \left(Y_m - Y_d\right)\left(1 - \left(1 - \left[\frac{I_a}{I_m}\right]\right)^{1/\beta}\right) \tag{1}$$

Where:
Y = grain yield in bushels per acre
Y_d = non-irrigated yield
Y_m = maximum yield from a fully watered crop
I_a = irrigation water applied, inches
I_m = irrigation water applied for maximum yield, inches
β = water use efficiency, assumed to be 0.75

Source: Martin (1989).

Production functions describing how crop yields respond to water applied are graphically depicted in Figure 2, for the four major crops at a representative location within the MRNRD, using input data from Table 2. Note that crop yield response to water diminishes as more and more irrigation water is applied. Recognizing the presence of diminishing returns to water is of crucial importance for understanding the economic effects from reduced irrigation. The profit maximizing irrigator logically continues to apply successive amounts of water to a crop as long as the additional water will produce a net economic gain. The first inch of water applied to a crop produces a large economic gain, whereas the last inch applied may cost as much as the value of what it produces.

Table 2. Crop Water Requirements[a]

	LRNRD	MRNRD	URNRD
Corn			
Non-Irrigated Yield	**83.7**	**62.8**	**50.2**
Max Irrigated Yield	**213.4**	**209.4**	**201.3**
Irrigation Needed for Max Yield	**12.7**	**15.2**	**16.7**
Wheat			
Non-Irrigated Yield	**55.6**	**52.9**	**49.1**
Max-Irrigated Yield	**73.5**	**78.9**	**83.2**
Irrigation Needed for Max Yield	**5.0**	**7.5**	**10.0**
Grain Sorghum			
Non-Irrigated Yield	**72.9**	**58.9**	**50.7**
Max-Irrigated Yield	**139.5**	**139.5**	**139.5**
Irrigation Needed for Max Yield	**10.0**	**12.7**	**14.2**
Soybeans			
Non-Irrigated Yield	**37.3**	**29.1**	**21.0**
Max-Irrigated Yield	**66.6**	**64.5**	**57.6**
Irrigation Needed for Max Yield	**10.8**	**13.0**	**14.2**

[a]All estimates assume a center pivot system and a water use efficiency of 0.75. The representative values for each NRD were based on available estimates for centrally located counties, Franklin for the LRNRD, Red Willow for the MRNRD and Chase for the URNRD.

Crop Prices, Production and Irrigation Costs

The crop prices used for corn, wheat, grain sorghum and soybeans were based on futures market prices for December 2010, with basis adjustments to reflect average Nebraska prices (Table 3). These prices also closely correspond to the price forecasts available from the Food and Agricultural Policy Research Institute (FAPRI, http://www.fapri.iastate.edu/) and from the Economic Research Service, USDA (http://ers.usda.gov/).

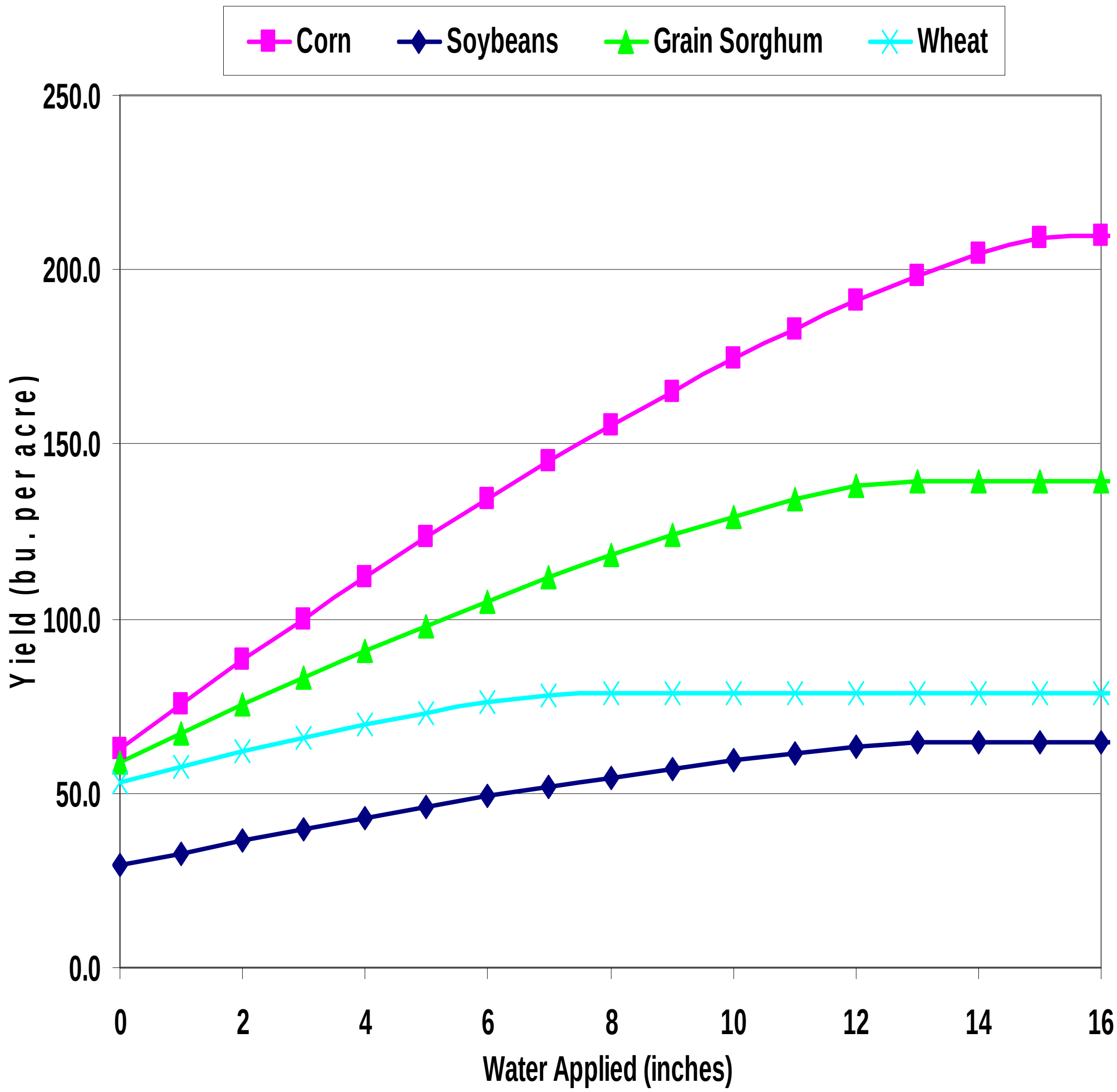

Figure 2. Production Functions for Corn, Soybeans, Grain Sorghum, and Wheat, in the Middle Republican NRD

The crop production costs used in this analysis were estimated for the Water Optimizer model based on 2010 Nebraska crop budgets data produced by the Department of Agricultural Economics, UNL (Wilson, 2010). The costs for each crop include yield dependent costs and other variable production costs (Table 3). Yield dependent costs include all costs that vary with crop yield. Grain handling, drying grain and nitrogen fertilizer were the main yield dependent costs. Other production costs included those costs associated with producing a crop which were variable in the sense that they could be avoided if the crop was not produced, such as seed, chemicals, fertilizer and field operations. Costs which are unaffected by how the land is managed, such as overhead and management charges, insurance, taxes and some depreciation costs were not considered. Irrigation costs were addressed as a separate category.

Table 3. Crop Prices and Production Costs

	Crop Prices	Yield Dependent Costs[a] ($/bushel)	Other Variable Costs Except Irrigation[b] ($/acre)
Corn	**3.76**	**.37**	**271.77**
Wheat	**4.99**	**.33**	**196.12**
Grain Sorghum	**3.20**	**.61**	**182.36**
Soybeans	**9.08**	**.08**	**164.16**

[a] Includes all costs that vary with yield such as grain handling, grain drying and nitrogen.
[b] Includes costs for seed, chemicals, fertilizer, labor, field operations and use related depreciation. Costs which are not affected by what crop is produced, such as overhead and management charges, insurance or taxes are excluded.

Irrigation costs depend on irrigation system type, feet of lift, pressure required and energy cost. Within the Republican Basin irrigation costs range from about $2.00 per inch for a gravity system, a shallow well and an electric pump, to about $8.00 per inch for a center pivot requiring moderately high pressure, pumping from a deep well and using a diesel pump. This analysis used a mid range cost of $5.50 per inch.

OPTIMUM MANAGEMENT STRATEGIES WHEN WATER IS LIMITING

When water becomes the limiting input, producers have three basic management options, deficit irrigate, plant crops that use less water and/or irrigate fewer acres. The profit maximizing practices at different levels of available water were analyzed in detail for Red Willow County, which is in the MRNRD and centrally located within the Republican Basin. We found that if water was unrestricted and rainfall was normal, producers would grow 80 percent corn and 20 percent soybeans, applying 15.2 inches to corn and 12.9 inches to soybeans, resulting in average water use of 14.8 inches per irrigated acre.[4] The optimal strategy, if the available supply of applied water was reduced by less than 30 percent of the combined requirement for both crops, was to deficit irrigate. It was not optimal to begin reducing irrigated acres until the amount of water available for corn was less than 13 inches, which is 85 percent of the full corn requirement, and the amount available for soybeans was less than 8.5 inches, which is 65 percent of the full soybean requirement. It was never profitable to produce lower water using crops such as grain sorghum or wheat at any water supply allocation (Table 4).

Deficit irrigation is clearly a preferred management strategy when one expects average weather, or has a sufficiently large multi-year allocation to compensate for less than expected rainfall during the season. A 20 percent reduction in applied water, for example, would cost irrigators $36 per acre if they followed deficit irrigation practices and $50 per

[4] Irrigated soybean acreage was limited to a maximum of 20 percent to more realistically represent current practices.

Table 4. Optimal Management Strategies when Applied Water is Controlled, Red Willow County

Optimal Crop Choices[a]							
Allocation Level (% of Demand)	**Allocated Amount (In./Acre)**	**Corn Acres (% of all)**	**Water Applied to Corn (In/Acre)**	**Soybean Acres (% of all)**	**Water Applied to Beans (In./Acre)**	**Dryland Acres[b] (% of all)**	**Total Net Return ($/Acre)**
100	14.8	80	15.2	20	12.9	0.0	$352
90	13.3	80	14.0	20	10.5	0.0	$339
80	11.8	78	13.0	20	8.5	2.4	$316
70	10.3	67	13.0	20	8.5	13.5	$290
60	8.9	55	13.0	20	8.5	24.8	$264
50	7.4	44	13.0	20	8.5	36.2	$238
40	5.9	32	13.0	20	8.5	47.5	$212
30	4.4	21	13.0	20	8.5	58.9	$186
20	3.0	10	13.0	20	8.5	70.3	$160
10	1.5	0	0.0	20	7.4	80.0	$134
0	0.0	0	0.0	0	0.0	100.0	$100

[a]The cropping pattern was restricted to a maximum of 20% soybeans to reflect current production practices.

[b] Optimal dryland crop was eco-fallow, a corn-fallow-wheat rotation.

acre if they fully irrigated both crops by reducing irrigated acres. However, if the irrigator does not have a remaining allocation that is large enough to compensate for rainfall risk, then the optimal strategy may be different. Rainfall risk is not a factor as long as the irrigator has enough water remaining in his multi-year allocation to compensate by applying more irrigation water than planned when rainfall is less than average. Similarly, if rainfall is more than average the produce can meet the optimal outcome by applying less irrigation water than planned and carrying the surplus forward to a future year, or by irrigating as planned resulting in higher than expected yields. Rainfall risk becomes a factor only if the producer is approaching the end of a multi-year allocation period and does not have enough water available to compensate for below average rainfall.

The effects of rainfall risk were evaluated for an optimal management strategy which incorporated deficit irrigation, and for a full irrigation strategy. For this analysis it was assumed that in higher than average rainfall years the irrigator would not decrease his planned irrigation level unless total available water exceeded crop requirements. The findings indicate that deficit irrigation is substantially better at capturing the upside of rainfall variability, with no significant differences on the downside, when compared to a full irrigation strategy. If you plan to deficit irrigate, rather than choosing to fully irrigate by putting your limited water on fewer acres, then when rainfall is above average the net returns from the deficit strategy are much higher than those from a fully watered strategy (Figure 3). Downside rainfall risk is very similar for both the deficit irrigation and fully watered strategies. Hence, deficit irrigation appears to be an even more strongly preferred strategy when rainfall risk is considered.

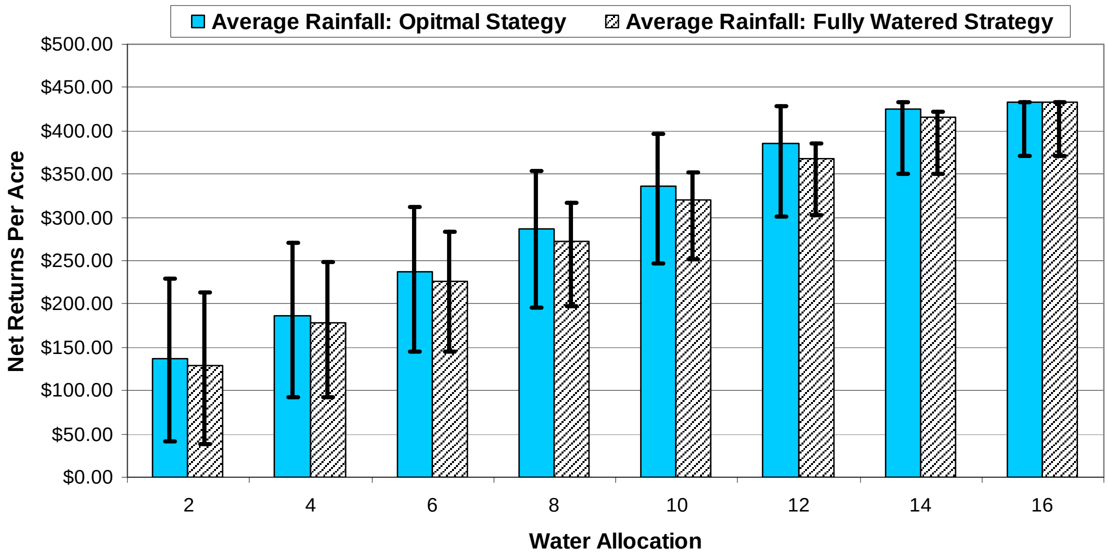

Figure 3. Distribution of Net Returns Depending on Management Strategy and Rainfall Amounts in Red Willow County Nebraska

Assuming profit maximizing behavior and no adjustments for risk, net returns over variable costs were estimated to range from $160 per acre with a three inch water supply, to $352 per acre at a full water supply of 14.8 inches, given the conditions described for Red Willow County (Table 4). This means that a reduction from 14.8 to 3.0 inches would cost irrigators $192 per acre (352-160 = 192), or an average of $16.27 for each one inch reduction in applied water. Cost per inch of reduction increases substantially as the reduction in available water gets larger, with the first 10 percent reduction in applied water costing $9.00 per inch, and the final 10 percent costing $17 per inch (Table 5).

What is most important from a producer perspective is the cost of reducing the amount of water that can be applied, because that is how the regulations are currently administered. The appropriate policy variable, however, is cost per unit change in evapotranspiration (ET) from irrigation, because the policy objective is to reduce the effect of irrigation on consumptive use in the Basin. When optimal management practices are followed and regulations are administered based on applied water, the cost of reducing ET from irrigation was estimated to range from $26 per inch at a 20 percent reduction in applied water to $22 per inch for large reductions (Table 5).

Table 5. On-farm Cost of Reducing Applied Water and ET, by Allocation Level

Allocation (% of Demand)	Allocation Amount (In./Acre)	Change in Applied Water (In./Acre)	Change in ET from Irrigation (Ac./Inches)	Change in Net Returns ($/Acre)	Cost of Reducing Applied Water ($/Inch)	Cost of Reducing ET ($/Inch)
100	14.8					
90	13.3	1.4	0.5	$13	$8.90	$24.27
80	11.8	2.9	1.4	$36	$12.46	$25.89
70	10.3	4.4	2.6	$62	$14.16	$23.99
60	8.9	5.9	3.8	$88	$15.00	$23.23
50	7.4	7.4	5.0	$114	$15.50	$22.84
40	5.9	8.8	6.2	$140	$15.84	$22.60
30	4.4	10.3	7.4	$166	$16.08	$22.43
20	3.0	11.8	8.6	$192	$16.26	$22.32
10	1.5	13.3	9.8	$218	$16.41	$22.29
0	0.0	14.7	11.1	$252	$17.11	$22.76

CURRENT AGGREGATE ON-FARM COSTS FROM REDUCING IRRIGATION

The management plans currently in place in the Republican Basin specifically restrict the amount of water that can be pumped per certified irrigated acre and acknowledges the need to reduce irrigated acres, especially in dry years. The Lower Republican NRD (LRNRD), Middle Republican NRD (MRNRD) and Upper Republican NRD (URNRD) restrict irrigation withdrawals over the next five years to 45, 60 and 67.5 inches, respectively. Irrigators may manage their allocations however they want over a five year period. There are no restrictions on what crops can be produced, how they are irrigated, or on how much water can be pumped in a single year. A limited amount of water not used during the five year allocation period can be carried forward to subsequent periods, but exceeding the five year allocation by essentially borrowing from subsequent periods in not allowed. Since 2005 there have been temporary retirements of irrigated acres under the federal CREP and EQIP programs and through the occasional purchasing of annual irrigation rights by the NDNR, but no well defined long-term land retirement program is in place.[5]

[5] CREP is the acronym for the federal Conservation Retirement Enhancement Program, which has been used in the Basin to pay farmers for converting irrigated land to conservation uses that do not involve any dryland or irrigated crop production for a contract period of 10 to 15 years. EQIP is the acronym for Environmental Quality Improvement Program, which has been used for paying farmers to convert land from irrigated to dryland crop production for a period of three years.

Cost of Reduced Pumping Allocations

The aggregate costs from the current allocation program depend on the economic factors discussed above, on how many acres have been affected by pumping limits, and by how much water was being applied before the limits were imposed. The first step in the analysis consisted of estimating how much water was being applied before the current regulations were imposed. This was done using historical well pumping distributions which depict the percentage of the wells which pumped more or less than particular amounts, expressed in inches per acre. A log normal distribution was assumed based on work by Martin (Martin,2004). Log normal distributions were estimated for each NRD by inputting the mean historical pumping level and then varying the standard deviation until the total area under the distribution curve matched NRD estimate of historical average annual volume pumped by all wells. These pumping distributions were used to determine how many acres historically received more water than the current allocation (Table 6).

The second step consisted of using Water Optimizer to compute optimal net returns for regulated and non-regulated water levels, for typical conditions in each NRD. Typical conditions were defined based on centrally located counties within each NRD. Franklin, Red Willow and Chase counties were used to represent the LRNRD, MRNRD and URNRD, respectively. County level data defined the irrigation requirements for each crop, as described in Table 2. Typical irrigation system characteristics and economic variables were assumed to be the same in each location and the same as those used above for evaluating alternative management practices.

On-farm costs resulting from the current allocation levels in each NRD were estimated at $20.7 million per year for the entire Republican Basin, which is an average of $27.43 per affected acre.

Table 6. On-farm Cost of Current Allocation Programs

	Net Returns at Current Allocation ($/Acre)	Prior Net Returns ($/Acre)[1]	Acres Affected by Regulations	Cost of Regulations ($/Acre)	Cost of Regulations Total
Lower Republican NRD	$341.24				
Historical Use					
9.0 to 10.5 Inches		$354.41	48,881	$13.17	$ 643,763
10.5 to 12.0 Inches		$374.85	39,105	$33.61	$1,314,319
12.0 Inches or More		$379.14	74,951	$37.90	$2,840,643
Totals			162,937	$29.45	$4,798,725
Middle Republican NRD	$318.74				
Historical Use					
12.0 to 13.5 Inches		$331.24	31,107	$12.50	$ 388,838
13.5 to 15.2 Inches		$350.34	27,915	$31.60	$ 882,114
> 15.2 Inches		$352.06	96,152	$33.32	$3,203,785
Totals			155,174	$28.84	$4,474,736
Upper Republican NRD	$270.53				
Historical Use					
Regulated @ 14.5 Inches		$296.70	435,337	$26.17	$11,392,769
Republican Basin Total			753,448	$27.43	$20,666,230

[1]For the Lower and Middle Republican NRD's, acres receiving less than the unrestricted requirement were evaluated at the midpoint of the indicated range in water applied, and acre receiving the average irrigation requirement or more were evaluated at the required amount.

For the Upper Republican NRD, all irrigators were assumed to be using their previous allocation of 14.5 inches before the current regulations were implemented.

Per acre costs were very similar for each NRD, which is perhaps a reflection of a general desire to implement policies which distribute the economic burden of meeting Compact requirements fairly evenly across NRD's. However, it important to note that the Compact costs estimated for the URNRD reflect the fact that they had an allocation program in place before obligations to meet Compact in-stream flow requirements became an issue. If costs for the URNRD were estimated relative to an unregulated state, as they were for the LRNRD and MRNRD, they would have been much higher.

In addition to thinking in terms of costs per acre, it is useful from a policy perspective to consider on-farm costs in terms of dollars per unit reduction in water applied or consumed. Estimated on-farm costs for current allocation policies average $278 per acre foot change in applied water ($20,700,000/74,293 =$278) and $344 per acre foot change in ET from irrigation ($20,700,000/60,006 = $344). The costs per acre foot change in ET from irrigation are higher than the costs per acre foot change in applied water, because the reduction in ET averages about 80 percent of the reduction in applied water for the current allocation programs in the Basin.

Farm Level Cost of Reducing Irrigated Acres

Irrigated land retirement is an alternative method of reducing irrigation. This could be accomplished by leasing or purchasing irrigation rights and the cost is theoretically equal to the difference in net returns with and without irrigation water, expressed in annual terms or as a capitalized value. Land retirement costs are very difficult to estimate, however, because whereas allocation rules apply to all acreage, retirement costs depend on what land is retired. If the land retired is in the eastern part of the Basin where rainfall is higher, the difference in annual net returns between irrigated and dryland is about $150 per acre at current crop prices, but this difference increases to over $250 per acre at the western end of the Basin. These values are for lands having typical productivity and irrigation costs. If one was able to retire irrigated land beginning with the least productive land in the highest rainfall areas, the farm level costs would be well below the estimate of $150 per acre, per year. These costs would be incurred by irrigators if acres were reduced using regulations without compensation, or by general taxpayers if compensation were paid.

Retiring irrigated land by leasing or purchasing irrigation rights is the most cost effective way of reducing ET from irrigation, assuming that no excess compensation is paid[6]. If acreage controls were used to reduce ET from irrigation in the central part of the Basin, the change in ET would be about 11.1 inches per acre and the cost would depend on the productivity of the land involved. If producers were forced to retire some part of their irrigated acres, the cost to them for typical pivot irrigated land in Red Willow County would be about $200 per acre for a one year shift to dryland, assuming current crop prices and a reduction in land taxes of about $50 per acre. This translates to a cost of $18.00 per inch, or $216 per acre foot of reduction in ET, compared to a cost of over $325 per acre foot to achieve the same result with allocation in the same location.

OBSERVED IMPACTS FROM ALLOCATION POLICIES: 2005-2009

The above discussion addresses expected farm level effects of reduced irrigation in a weather normal year. How does this compare with what the Basin has actually experienced since post Settlement Agreement regulation began in 2005? In particular, have we seen the expected reductions in agricultural production and regional economic activity?

The estimated effect of allocation on net farm income of $20.7 M., expressed as net returns over variable costs, represents a change in agricultural production of about $14 M., with the difference accounted for by reduced farm input costs. Although this total is not insignificant in absolute terms, it amounts to less than five percent of the total value of irrigated crop production in the Basin, which makes the aggregate impacts difficult to

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[6] Voluntary willing buyer and willing seller land retirement plans often result in payments well in excess of what is required to make the producer equally well off.

detect. A review of Basin wide trends in the value of agricultural production shows that agricultural values increased substantially after 2005, due primarily to crop price increases (Figure 4). When crop prices were held constant at their 10 year averages, Basin production was found to be nearly constant across most of the past decade. The inability to observe an impact in Figure 4 from regulations adopted in 2005, may be due to the fact that in the five years before 2005 growing season rainfall averaged 3.3 inches less than what has been experienced since 2005, at three representative weather stations. If adjustments were made for rainfall, the data would suggest some decline in production due to reducing irrigation, but still a very small change compared to the total.

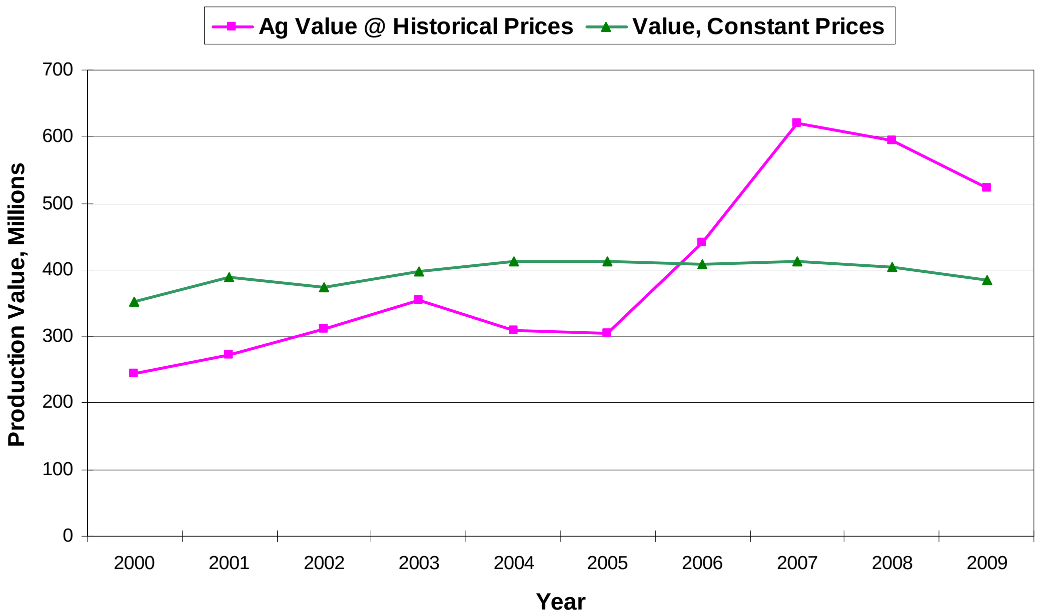

Figure 4. Republican Basin Agriculture Production Trends

One rather good measure of the effect of changes in irrigated agriculture on total regional economic activity is sales tax revenue. Sales taxes are levied on most consumer products, except services and some agricultural inputs. Sales tax trends in the Republican Basin show slower growth rates compared to what occurred in other rural areas or at the state level in recent years, but the Republican Basin economy has not experienced an absolute decline since the post Compact Settlement regulations were imposed in 2005 (Figure 5). This is due in part to the fortune of reasonably good weather and to the technologies that have led to increased grain yields and improved production efficiencies over time.

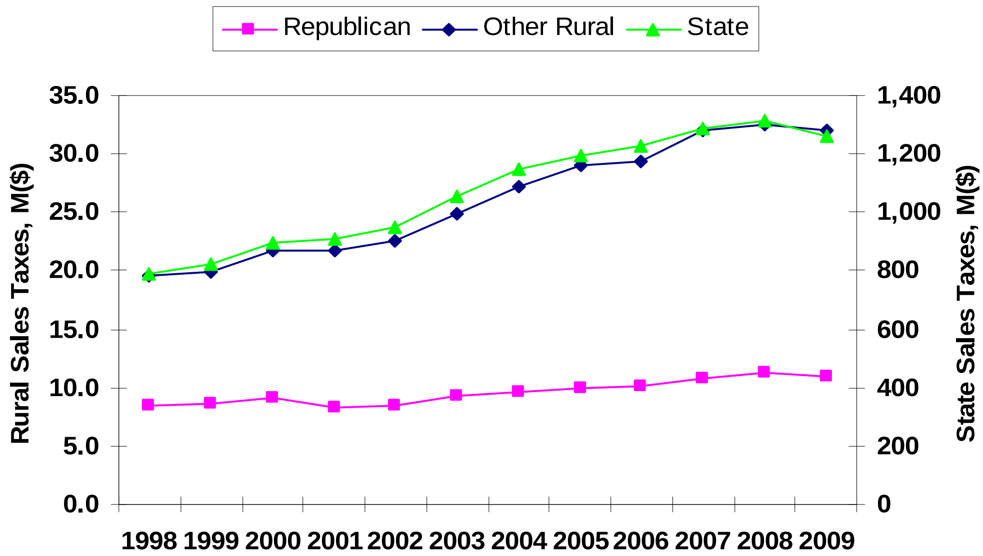

Figure 5. Nebraska Sales Tax Revenue, by Region

SUMMARY AND STUDY LIMITATIONS

This study addressed the economic consequences from policies designed to reduce irrigation in the Nebraska Republican Basin. It was found that the optimal strategy was to deficit irrigate, if the available supply of applied water was reduced by less than 30 percent of the combined requirement for both crops. It was not optimal to begin reducing irrigated acres until the amount of water available for corn was less than 85 percent of the full corn requirement, and the amount available for soybeans was less than 65 percent of the full soybean requirement. It was never profitable to produce lower water using crops such as grain sorghum or wheat at any water supply allocation. If optimal strategies were followed and average weather occurred, the cost of reducing irrigation by limiting applied water was estimated at $27 per affected acre, $278 per acre foot change in applied water, and $344 per acre foot of decrease in ET from irrigation, under current polices and economic conditions. It was also found that ET from irrigation, which is the major policy objective, could be achieved much cheaper if an acreage retirement policy was used, especially if the policy procedures led to retirement of the least productive land. The observed effects on the total Basin economy of the regulations adopted in 2005 were found to be surprisingly small. This is due in part to favorable weather, high crop prices and improved agricultural technologies.

It is important to note that the results from this analysis reflect current crop prices, a very simplified approach to representing the diversity of irrigation operations in the Basin, and assumed optimal irrigator responses to water limiting regulations. Estimated costs would be quite different if alternative assumptions were made, although the estimates are believed to represent midrange outcomes for current economic conditions.

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EFFECTS OF POLICIES GOVERNING WATER REUSE ON AGRICULTURAL CROPS

Jeffrey Pfeifer[1]
Leeann De Mouche[2]
Dr. Rhonda Skaggs[3]
Dr. Adrian Hanson[4]

ABSTRACT

The state of New Mexico is located in the Chihuahuan Desert, an environment characterized by high aridity and a very limited water supply. New Mexico's water is supplied by both rivers and underground aquifers with the Rio Grande serving as the principle source of surface water throughout the state's central corridor. Recycled wastewater has been recognized as a promising source of "new" water throughout the world and in the arid western United States. However, recycled wastewater has yet to be exploited in New Mexico due to current regulations and technological limitations which make it infeasible to employ recycled water in agricultural uses. In order to meet future water needs, New Mexico needs to revise the distribution of testing responsibilities between producers and consumers of recycled water. Technology currently used to treat recycled water in the state also needs to be upgraded in order to guarantee its safe use on crops.

New Mexico is in the process of increasing the efficiency of recycled water production and use but the state still needs more investment and regulatory changes in order to achieve sustainable and higher levels of wastewater reclamation. The use of recycled water for green space irrigation has increased in southern New Mexico. Clear evidence of this increasing trend is the recent construction of a wastewater reclamation facility on Las Cruces' East Mesa. The majority of the water treated at this facility, water which originates in the Jornada Aquifer, will be used for green space irrigation, and as a result will not end up being returned to the Rio Grande. Las Cruces, New Mexico's second largest city, has a rapidly growing population and diversifying economy, and is regularly included on lists of most desirable places to retire, livable small cities, etc.

The objective of this paper is to describe the current water resource situation in southern New Mexico, compare and contrast New Mexico and California regulations regarding recycled water, and provide recommendations for improved recycled water regulations in New Mexico.

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[1] Graduate Assistant, New Mexico State University, MSC 3169, New Mexico State University, P.O. Box 30003 Las Cruces, NM 88003; Jeffp@nmsu.edu
[2] Water Resource Specialist, New Mexico State University, MSC 3AE, New Mexico State University, P.O. Box 30003 Las Cruces, NM 88003; ldemouch@nmsu.edu
[3] Professor, New Mexico State University, MSC 3169, New Mexico State University, P.O. Box 30003 Las Cruces, NM 88003; rskaggs@nmsu.edu
[4] Professor, New Mexico State University, MSC CE, New Mexico State University, P.O. Box 30003 Las Cruces, NM 88003; athanson@nmsu.edu

INTRODUCTION AND BACKGROUND

Sources of Water in Las Cruces, New Mexico

Las Cruces, New Mexico is located in south-central New Mexico in the northern part of the Chihuahuan Desert. New Mexico is split from north to south by the Rio Grande, which traverses several rapidly growing metropolitan areas located along the central spine of the state and is the primary source of water for agricultural irrigation in the region. This river is primarily fed by snowmelt from Colorado's southern Rocky Mountains.

New Mexico is a prior appropriation state which means that water rights are established using the "first in time-first in right" principle (Center, 2001). Agricultural water rights are old, well established, and are facing the challenges which arise from growing demand for water by non-agricultural users as well as increasing demand for water by relatively new crops with high levels of consumptive use. The need for more water for agricultural irrigation in New Mexico forces farmers into difficult situations. Farmers must either buy water rights or wet water from other farmers or agricultural water rights holders or use an alternative "new" source of water. Currently all the water that flows down the Rio Grande is fully appropriated which means there are few sources of "new" water. Buying water rights or wet water can be very expensive, and in some cases the cost may be higher than the value of additional crop yield. Furthermore, many cities and local governments are aggressively purchasing water rights in order to secure a future supply of potable water for municipal and industrial (M&I) users. The added competition from M&I users for water rights means that agricultural water users now have relatively less bargaining power in water market transactions.

Groundwater is New Mexico's other important source of drinking water, and one which will be critical to the future of agriculture as well as overall economic and population growth throughout the state. Ground water comes from several underground aquifers, and like surface water is regulated through the New Mexico Office of the State Engineer (OSE). The state engineer has declared 33 underground water basins throughout New Mexico (Center, 2001). The Jornada Aquifer is located along the east side of Las Cruces and is believed to currently hold over 100 million acre-feet of water in the underground storage basin. The Jornada Aquifer (the Mesilla Bolson is the primary drinking water aquifer for Las Cruces) is recharged at a rate of 5,350 acre-feet per year; this is a source of concern because higher volumes of water are annually removed from the aquifer (Creel, 2007). The OSE monitors the extraction of water through limitations on wells. Persons seeking to use groundwater must be granted approval by the state in order to drill and extract the water for use (Center, 2001). The well permitting process requires that a report be sent to the OSE explaining the beneficial use of the water. Upon completion of the beneficial use inspection the OSE will issue a license to appropriate water to that person (Center, 2001).

One of the main concerns about the Jornada Aquifer is that the groundwater that is non-consumptively used is then cleaned and discharged into the Rio Grande. This arrangement adds water to the Rio Grande that otherwise would never end up in the river.

Unlike other aquifers in New Mexico and Texas the Jornada Aquifer is not recharged from the nearby Rio Grande (Creel, 2007). While the current situation contributes to surface water flows in the Rio Grande, the non-consumed groundwater is effectively lost from the Jornada Aquifer forever. The wastewater which remains after M&I pumping of Jornada Aquifer groundwater is currently not reused; however, the City of Las Cruces could use available technology to treat the wastewater and make it acceptable for food crop irrigation, green space irrigation, or other beneficial uses.

New Mexico has not fully utilized water reuse technology in the past; however, the state recently began allowing recycled water to be used for aquifer storage and recovery. State statues (§19.25.8, Natural Resources and Wildlife Administration and Use of Water—General Provisions Underground Storage and Recovery paraphrase) cover the administration and use of water for the purpose of underground storage and recovery (USR). The 1999 Act passed by the New Mexico Legislature allows governmental entities to store surplus supplies of water underground and to withdraw the recoverable amount at a later date for use by the governmental entity. The Legislature found that by passing this act groundwater recharge, storage, and recovery have the potential to: 1) offer savings in the cost of capital investment, operation and maintenance, and flood control and may improve water and environmental quality; 2) reduce the rate at which groundwater levels will decline and stress the aquifer; 3) promote conservation of water; 4) serve the public welfare of the state; and 5) lead to a more effective use of the state's water resources. With this said the effort, efficiency, and process to actually acquire the permit for underground storage and recovery would probably take a sufficient amount of funds and years of time. (State of New Mexico, 2001)

Presently the City of Las Cruces is in the last phase of construction on a Class 1A reclamation plant. This plant will allow the city to clean up to one million gallons of wastewater per day. Presently the non-potable water will be used to irrigate a golf course, high school football field, and several parks. The city has looked into the possibility of USR, but has found that certain barriers exist and limit their capability of USR. Barriers are political in nature but most deal with the fact that there is a need for accountability of stored water and there is a strong need for hydrological modeling. Both of these barriers are expensive and time consuming, although they are not insurmountable.

In recent drought years the Village of Cloudcroft, New Mexico has found itself in critical need of additional M&I water. The Village of Cloudcroft stated that during years of drought it was necessary to truck in approximately 20,000 gallons per day during their peak summer tourism season. (Livingston Associates, 2008) In 2007, Cloudcroft received a $600,000 grant from the State of New Mexico Governors Water Innovation Fund to help fund the village's new $2 million water reuse system. The state of the art system employs a second generation membrane bioreactor (MBR) and gravity fed reverse osmosis system to treat wastewater flows that after treatment exceeds drinking water quality standards. The treated effluent is discharged into a man-made reservoir rather than pumped into a large body of water such as an aquifer. The reservoir serves as a raw water source for the town's drinking water treatment system (Livingston Associates, 2008). This process of developing the treatment system has been very long and tedious, but designing and permitting the system is one of the first steps in the process of developing reclaimed water supplies statewide. Overall New Mexico remains very restrictive with respect to the guidelines and regulations affecting recycled water. In order to use recycled water the producer and the user are heavily regulated, required to produce numerous documents, and continuously test water quality. In many cases it is not economically beneficial or feasible to use recycled water because of the rigid regulatory environment, numerous restrictions, and barriers.

WATER REGULATIONS AND POLICY: NEW MEXICO VS. CALIFORNIA

New Mexico Recycled Water Regulations

Water users throughout New Mexico have not taken full advantage of technology and research that has been conducted within the wastewater reclamation industry. New Mexico has seen the neighboring states of Texas and Arizona embrace readily available and proven water technology designed to help arid regions cope with limited water supplies. Clearly, if New Mexico is to meet the water challenges which will result from population growth and economic expansion, the state cannot afford to fall behind. The need for modernized, reality-based water policy is evidenced by the state's current recycled wastewater classification scheme. New Mexico has four recycled wastewater classes which range from Class 1A to Class 3. The following table describes the four classes and what each class of water can be used for.

Table 1. Uses of Recycled Water by Class Allowed in New Mexico (Utilities, 2007)

Class of Recycled Waste Water	Approved Uses
Class 1A	**Includes usage on all classes listed below:** No setback limit to dwelling unit or occupied establishment
	Backfill around potable water pipes
	Irrigation of food crops
Class 1B	**Includes usage on all classes except 1A:** Impoundments (recreational or ornamental)
	Irrigation of parks, schools yards, golf courses
	Irrigation of urban landscaping
	Snow Making
	Street Cleaning
	Backfill around non-potable piping
	Toilet Flushing
Class 2	**Includes usage on class 2 & 3:** Concrete mixing
	Dust control
	Irrigation of fodder, fiber, and seed crops for milk-producing animals
	Irrigation of roadway median landscapes
	Irrigation of sod farms
	Livestock watering
	Soil compaction
Class 3	**Includes usage only for class 3:** Irrigation of fodder, fiber, and seed crops for non-milk-producing animals
	Irrigation of forest trees (silviculture)

Class of recycled wastewater 1A is the highest standard of treated water in New Mexico. It is approved for the irrigation of food crops; however, the edible portion of the crops cannot come into direct contact with the recycled water. Based on this stipulation cabbage, onions, chile peppers, lettuce, and other vegetables produced in southern New Mexico cannot be irrigated using recycled water. This stipulation does allow other crops produced in the region, such as pecans and corn silage, to use recycled water, although other regulations make it very difficult to do so economically. Wastewater in New Mexico is monitored very strictly at both the reclamation plant and at the point of use. Recycled wastewater has strict quality tolerances that must be met in order to meet Class 1A standards. These Class 1A tolerances are presented in Table 2 below.

Beyond testing by the recycled water producer at the treatment plant, the water must also be tested at the point of use. For example, if a farmer uses recycled water to irrigate their field or orchard, the water must be tested at the point of use. This testing requirement is an extra burden for agricultural irrigators and is a disincentive to the use of recycled water in crop production.

Table 2. New Mexico Water Quality Requirements for Class 1A Recycled Wastewater (Utilities, 2007).

Class of Recycled Wastewater	**Wastewater Quality Parameter**	**Wastewater Quality Requirements**		**Wastewater Monitoring Requirements**	
		30- Day Average	**Maximum**	**Sample type**	**Measurement Frequency**
Class 1A	Biochemical Oxygen Demand (BOD)	10 mg/l	15 mg/l	Minimum of 6-hour composite	3 test/week at major WWTP[1] 1 test per 2 weeks at minor WWTP
	Turbidity	3 Nephelometric Turbidity Units (NTU)	5 Nephelometric Turbidity Units (NTU)	Continuous	Continuous
	Fecal Coliform	5 per 100ml	23 per 100ml	Grab sample at peak flow	3 test/week at major WWTP 1 test/week at minor WWTP
	Ultraviolet UV Transmissivit y	Monitor only	Monitor only	Grab Sample or reading at peak flow	Record values at peak hourly flow when fecal coliform samples are collected

[1] Major waste water treatment plants (WWTP) are plants that clean one million gallons or more per day and minor WWTP are ones that produce less than one million gallons per day.

California Recycled Water Regulations

Every U.S. state has different regulations regarding acceptable levels of wastewater treatment, permitted treatment processes, and allowable uses for recycled water. The state of California is a leader in exploitation of recycled water in a variety of applications.

The California Department of Public Health Title 22 Regulations determine the uses for recycled water. Recycled water treated to the tertiary level can be used to irrigate food crops, including edible root crops, parks and playgrounds, schoolyards, residential landscaping and public golf courses (State of California, 2009). California regulations allow treated wastewater to be used in agricultural irrigation, public green space irrigation, and aquifer recharge or storage. Table 3 describes California's regulatory system for recycled water.

Table 3. California Permitted Recycled Water Uses (California, 2009).

Class of Reclaimed Waste Water	**Approved Uses**
Disinfected tertiary recycled water	Irrigation of crops in which edible portion comes into contact with the water
Un-disinfected secondary recycled water	Orchards in which the water has no contact with the edible portion
	Vineyards where water has no contact with edible portion
	Non-food bearing trees
	Fodder and fiber crops and pasture animals not producing milk for human consumption
	Seed crops not eaten by humans
	Food crops that must undergo commercial pathogen – destroying processes
	Ornamental nursery stock with no human contact 14 days after last irrigation with reclaimed water

California's policy of allowing the use of disinfected tertiary recycled water in irrigation of crops where the edible portion is in contact with the water means that state can take full advantage of recycled wastewater. California leads the nation in the production of high quality fruits, vegetables, and specialty crops. The future of these crops in the state depends on the availability of a safe and consistent supply of irrigation water. California agriculture has benefitted from technology development and research done on wastewater reclamation, and as a result now firmly includes recycled water within its short and long-run water resource planning. Due to continued water shortages and expected increases in demand for water in California, the use of recycled water will continue to play an important role in California agriculture. Other California industries also currently use recycled water, with varying degrees of dependence on the recycled supplies. The energy industry, public utilities, and prevention of sea water intrusion rely heavily on recycled water in California. The table below describes the requirements for disinfected "2.2 recycled water." Water recycled at the 2.2 parts of total coliform bacteria/milliliter standard and which has been oxidized and disinfected can be used to irrigate edible food crops if the crops do not have contact with recycled water.

Table 4. Quality Requirements for Recycled Waste water in California (California, 2009).

Class of Recycled water	Wastewater Quality Parameter	Wastewater Quality Requirements		Measuring Frequency
		30- day average	Maximum	
Disinfected secondary 2.2 recycled water	Total coliform organisms	2.2 per 100ml	23 per 100ml	Once daily
	Turbidity	2 NTU	5 NTU	Continuous
	Treatment process must contain coagulation			

Disinfected secondary "23 recycled water" is treated water that never surpasses a total of 23 per 100ml of coliform organisms and does not meet the requirement of the 2.2 per 100ml for a 30 day average. This level of treatment allows water to be used for public areas and seed and fodder production but not for edible food production (California, 2009).

California requires the producer/supplier of the recycled water to test and assure that the treated water meets regulatory standards. These regulations give the recycled water producer the primary responsibility for water quality, rather than the treated water consumer. California also allows manufacturers to demonstrate using a standard protocol that the standard can be met consistently. Use of a certified technology then reduces the testing burden for the water producer. As a result, barriers to the use of the recycled water are reduced.

The assignment of recycled water quality responsibility to water producers has resulted in California's status as a leading state in the use of recycled water. In 2006-07, California used 14,118 acre-feet of water in agricultural irrigation. Recycled water used in Los Angeles County alone totaled 94,750 acre-feet in the same year; figure 1 below illustrates the distribution of recycled water use in Los Angeles County in 2006-07. Almost 50% of the recycled water used in Los Angeles County was used in USR, thus contributing to the long-run sustainability of water supplies in the region (MIT, 2010). By comparison, as of 2008, there was minimal recycled water used in USR anywhere in the state of New Mexico. The City of Albuquerque Public Works Department stated that a pilot project was conducted in Albuquerque (2007-2008), but this project has been discontinued (Yuhas, 2009).

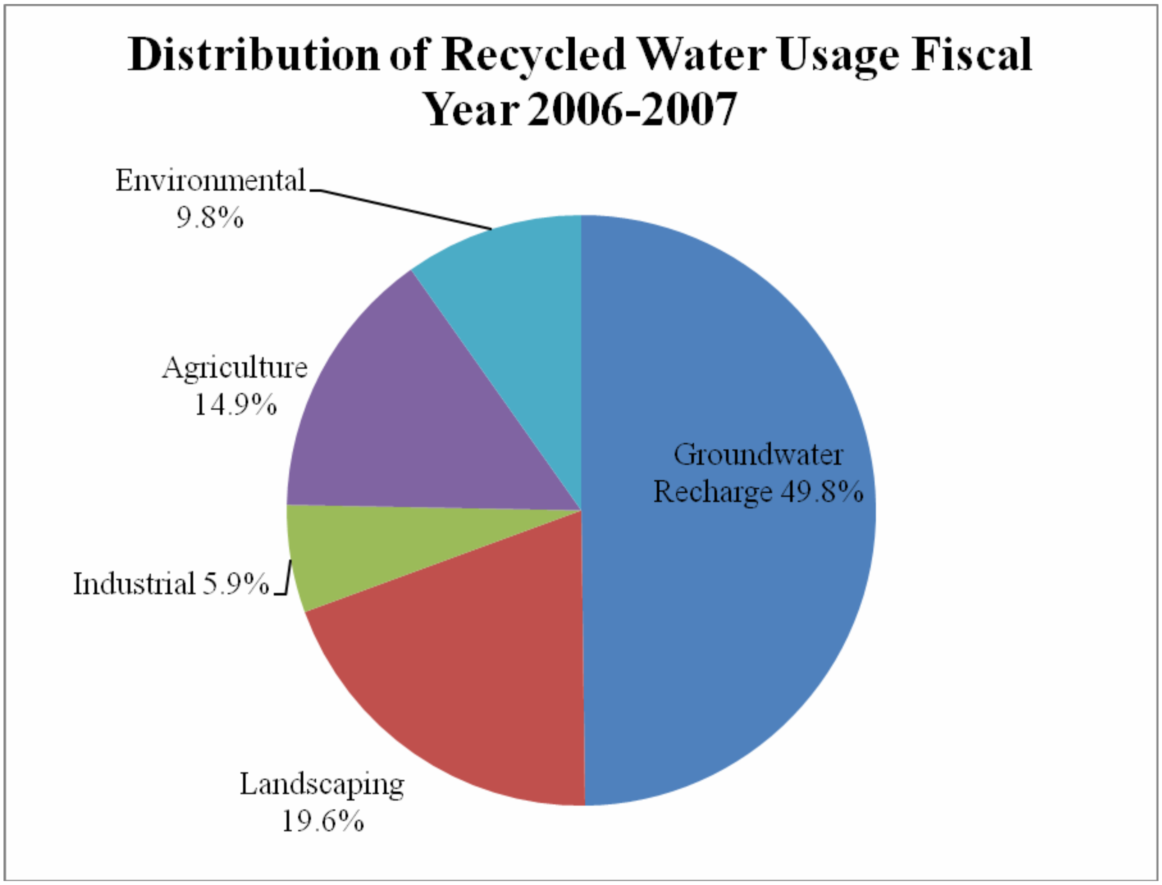

Figure 1. Recycled Water Use in Los Angeles County, California, 2006-07 (MIT, 2010).

INCREASING RECYCLED WATER USE IN A WATER-SHORT REGION

Technology and Improved Regulations

New Mexico has not taken full advantage of technology development and research that has been conducted to ensure the safety of recycled water. The majority of water currently used for irrigation in the southern half of the state comes from the Rio Grande with the remainder coming from groundwater. The region's surface water is fully appropriated, and future M&I water supplies in the region will likely be developed from reallocating surface water away from agricultural users. Expansion of irrigated agriculture in the region is thus constrained by water availability now and in the future. Groundwater supplies in the region are also limited and subject to competition from M&I users. Not all aquifers in the region are replenished by surface water flows, and mined groundwater is a significant source of water for many of the region's users. Thus, recycled wastewater represents a rare opportunity to expand existing water supplies in a water-short region.

As of 2010 New Mexico's regulations do not allow recycled water to be used in the production of food crops where the edible portion of the crop is in direct contact with the water. Wastewater reclamation plants in New Mexico need to consider adopting new technology that will enable them to treat water to disinfected tertiary levels. This technology would allow communities or utilities to treat their wastewater to the level required for comprehensive agricultural use and provide an additional source of revenue for the wastewater producers.

The use of recycled water on pecan orchards in southern New Mexico should be urgently considered. A recent study conducted in Florida examined the effect of using irrigated recycled water on citrus orchards. The study focused on whether fruit yield, quality, and foliage health and density decreased or increased. Results from the study indicated that citrus yields were affected along with leaf concentration by the recycled water. The tonnage of fruit harvested increased but the actual number of fruit picked decreased. Overall, yields (by weight) increased due to the increase in fruit size while fruit quality was also higher. The study also found that soil quality was not compromised as a result of irrigation with recycled water. Researchers concluded that when wastewater is treated effectively and fertilizer is adjusted accordingly, plants are not harmed and fruit yields are not compromised (Morgan, 2008). There is however an anecdotal account of small wastewater treatment plant effluent being used to irrigate pecans with no loss in yields or quality. However there are no studies being performed in this orchard, nor is there easily available verification of anecdotal accounts.

New Mexico's recycled water regulations should be modified to reflect the reality of current and future water shortages. Revising water testing responsibilities to align with California regulations would increase the willingness of New Mexico agricultural irrigators to use recycled wastewater. With consistent, robust demand for the recycled water, producers would have increased incentives to invest in proven treatment technologies.

Benefits of Using Recycled Water

Recycled water use has many benefits. The primary benefit of recycled water use in New Mexico would be increased sustainability. The use of recycled water would allow residents of the state to reduce the rate of use and preserve fresh water in the underground aquifers, thus allowing that water to be banked for the future. The underground aquifers in the state are an important and reliable source of water, and thus need to be conserved for as long as possible. The use of recycled water would reduce aquifer drawdown and increase the length of time the aquifers could be economically pumped. Recycled water could also contribute to aquifer recharge in some areas.

Wastewater reclamation would also contribute to improved water quality throughout the region, as wastewater which is now returned to the Rio Grande is minimally treated and ultimately applied to crops after it enters the river and joins the surface water flow. The quality of recycled water treated to higher standards would be of higher quality than the region's current surface water supply which includes irrigation return flows, minimally treated wastewater from numerous municipalities, as well as rainfall runoff and other underground flows hydrologically connected to the river. Surface water quality throughout the Lower Rio Grande Valley would be improved by keeping contaminates such as heavy metals, endocrine disrupters, and other biologically active agents out of the river system as a result of the higher-level treatment processes.

Securing a Sustainable Water Future

Without the use of recycled water, the state of New Mexico is limiting its water resource sustainability. Future population and economic growth, as well as agricultural irrigation, all depend on adequate water supplies. California's track record in wastewater reclamation provides a model for New Mexico and other arid, water-short regions to emulate. Policy and regulatory changes are essential if New Mexico is to take full advantage of existing wastewater supplies. It is critical that state regulations require the majority of water quality testing be conducted at the treatment facility by the recycled water producer rather than at the point of use by the recycled water user. Relieving the burden of testing from agricultural irrigators would increase the likelihood that these users will actively seek out and use recycled water in crop production. Treating recycled water to a higher quality would ensure robust demand for the water by providing a safety assurance to agricultural irrigators and make the water acceptable for application to higher value food crops. Recycled water treated to a higher quality is a more valuable input for agricultural producers, and thus would be worth more to food crop irrigators than to forage or other lower valued crop producers.

California has demonstrated that wastewater reclamation and the application of recycled water to food crops is safe and economically feasible. Consumers throughout the United States currently consume fruit, vegetables, and specialty crops produced in California, and by their actions, are demonstrating that using recycled water to irrigate food crops is acceptable.

CONCLUSION

New Mexico is located in an arid desert environment where water is scarce. New Mexico has two sources of water: rivers and underground aquifers. The Rio Grande traverses the middle of the state and provides irrigation water to thousands of agricultural irrigators. Rapidly growing cities and towns located in the state's Lower Rio Grande Valley will soon withdraw surface water for M&I uses. Surface water is fully appropriated, groundwater is already extensively used throughout the region, and there are virtually no untapped water supplies available. However, recycled wastewater use is an option which would supplement existing water supplies, support future population growth, and contribute to a sustainable water future in the region. Unfortunately, New Mexico currently enforces strict regulations that inhibit both development of recycled water supplies and demand for the recycled water by agricultural users.

Policy and regulations related to the use of recycled water in crop production in New Mexico must be changed; California regulations provide a template for the changes. Regulatory changes are necessary in order to expand the use of recycled water on crops. Without regulatory change, there is little incentive for investments in water reclamation technology that treats waste water to the levels required for higher valued uses (e.g., food crop irrigation). The use of recycled water in New Mexico would relieve the pressure on underground aquifers, increase downstream water quality, provide a reliable source of water to agricultural irrigators, and enhance water resource sustainability in the region.

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FLOW CALIBRATION OF THE BRYAN CANAL RADIAL GATE AT THE UNITED IRRIGATION DISTRICT

Gabriele Bonaiti, Ph.D.[1]
Eric Leigh[2]
Askar Karimov[3]
Guy Fipps, Ph.D., P.E.[4]

ABSTRACT

In an effort to improve the management of the Bryan Canal, the United Irrigation District in South Texas installed a radial gate in place of a pre-existing vertical slide gate structure with the objectives of establishing telemetry and remote control capabilities, and providing the District the ability to control the gates based on flow.

This paper discusses the calibration of the radial gate for flow based on the head differential and gate opening. Details are provided on the equipment and instrumentation used, which included pressure transducers for upstream and downstream water levels, gate opening sensor, and doppler and velocity flow meters. The calibration of the doppler flow meter will be discussed along with the methods used to determine actual radial gate opening from sensor data and the problems caused by hysteresis.

Flow rate was calculated from the head differential across the gate and gate opening using a submerged orifice equation. By adjusting the discharge coefficient, the equation was calibrated in such a way that total calculated flow matched the total measured flow. The flow data was further analyzed for individual flow events. Data was collected continuously over three months. This paper discusses the process of analyzing data and determining the conditions for which the equation is valid.

INTRODUCTION

Study Area

United Irrigation District (District) is located in the southernmost region of Texas, commonly known as the Lower Rio Grande Valley (Valley). The District is one of the 28 irrigation districts that calls the Valley home (Fig. 1). The District covers 37,800 acres of which 47% has now been lost to urban expansion, and holds 57,000 acre-feet

[1] Extension Associate, Department of Biological and Agricultural Engineering, 2117 Texas A&M University, College Station, Texas 77843-2117; gbonaiti@ag.tamu.edu
[2] Extension Associate, Department of Biological and Agricultural Engineering, 2117 Texas A&M University, College Station, Texas 77843-2117; eleigh@tamu.edu
[3] Extension Associate, Department of Biological and Agricultural Engineering, 2117 Texas A&M University, College Station, Texas 77843-2117; akarimov@ag.tamu.edu
[4] Professor and Extension Agricultural Engineer, Department of Biological and Agricultural Engineering, 2117 Texas A&M University, College Station, Texas 77843-2117; g-fipps@tamu.edu

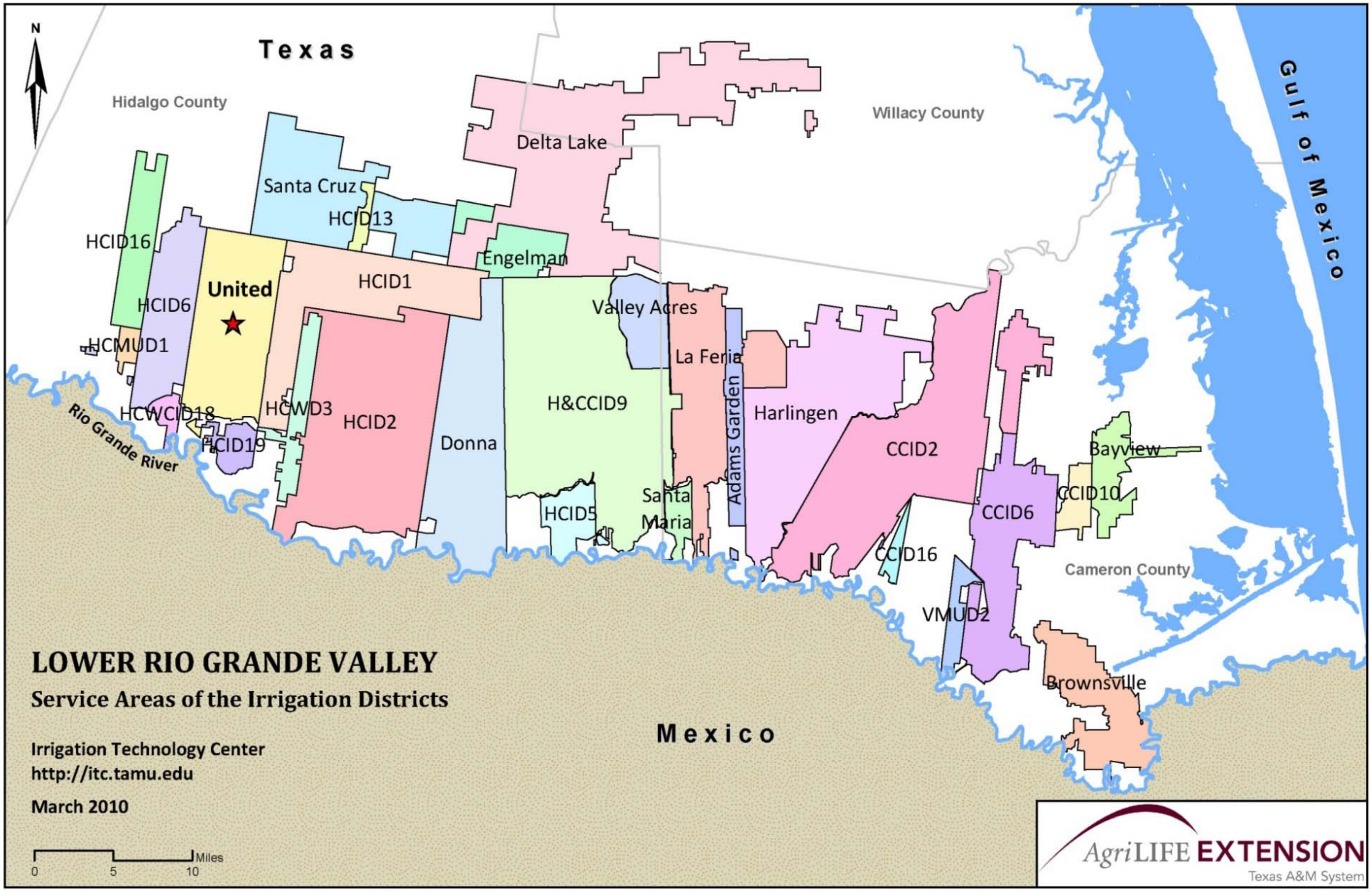

Figure 1. Service areas of the irrigation districts in the Lower Rio Grande Valley of Texas.

of Class A water rights from the Rio Grande River. The District distribution network is made up of approximately 50 miles of lined and unlined canals and 115 miles of gravity fed pipeline, with small hydraulic gradients.

The District's Bryan Canal is the main artery for the eastern portion of the District, delivering approximately 10,000 acre-feet/yr of irrigation water and 23,000 acre-feet/yr for municipal consumption to Sharyland Water Supply Company and the North Water Plant for the City of McAllen. The canal begins near the District office, just upstream of the third re-lift pump station, and flows east off the main canal and along Mile 2 N Road. On average, the Bryan canal carries 30% of total water distributed by the District.

Project Description and Objectives

In 2007, as part of the Irrigation District Engineering and Assistance (IDEA) program of the Irrigation Technology Center, we initiated a demonstration project with United Irrigation District to improve the efficiency of Bryan Canal by replacing the head vertical slide gate (Fig. 2) with a new radial gate (Fig. 3).

Figure 2. Pre-existing head slide vertical gate structure of the Bryan canal.

Figure 3. New radial gate and structure.

The objectives of the project were to:

- Establish telemetry and remote control capabilities
- Give the District the ability to control the gates based on specific water levels and flow rate set points
- Demonstrate the use of SCADA equipment and control systems

The pre-existing vertical slide gates and structure were in poor condition (Fig. 2). Only two of the three gates were operable and the bottoms of all the gate slots were blocked with concrete, providing a limited range of control. The radial gate was recommended to the District due to the known advantages of needing a small force for lift and operation, and good hydraulic discharge characteristics that are more favorable when calibrating a gate to serve as a flow measurement device (Bos, 1976; Wahl, 2004).

METHODS AND MATERIALS

Site Description

Bryan Canal is a trapezoidal concrete-lined canal with a capacity of 225 cfs with cross-section dimensions of 7 feet deep, 18 feet top width, 4 feet bottom width, and side slope of 1:1. The new housing for the radial gate is a rectangular structure 24 feet long and 10 feet wide. The gate has a radius of 7 feet, vertical height of 7 feet, and pinion height of 3.5 ft. Its opening ranges from 0 to approximately 5 feet. The gate leaf edges have hard bar-shaped rubber seals. All these structural details have a relevant influence on the calibration procedure (Wahl, 2005).

Equipment and Instrumentation

Pressure transducer sensors were positioned to record/measure the upstream and downstream water levels of the gate. The gate can be operated manually or remotely with the use of a built in gate position sensor in the actuator. A doppler flow meter (Argonaut-SW) was installed downstream of the radial gate and mounted on the bottom of the canal. A Campbell Scientific CR 1000 datalogger and a SDM-CVO4 control module control and record all activities at the site and are hard-wired to the District office. A schematic of the instrumentation installed to monitor flow is shown in Fig. 4.

For the calibration analysis, flow data was continuously recorded from January 13, 2009, through April 5, 2009, for a total of 80 days. The polling interval for the datalogger programming was set to 5 seconds. Data was automatically averaged every 30 minutes.

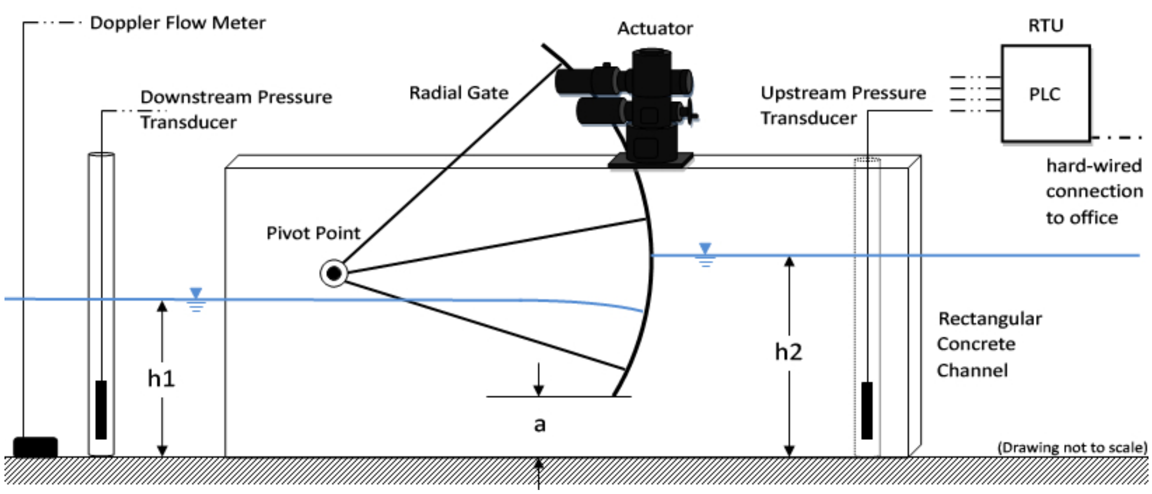

Figure 4. Instrumentation installed in the Bryan canal radial gate to monitor flow.

<u>Water Level Sensors</u> Two Keller America Acculevel pressure transducer sensors were installed as shown in Fig. 4. The upstream sensor was placed 10 feet from the gate pinion in a two-inch PVC stilling-well built into the vertical wall of the radial gate's rectangular control structure. The downstream sensor was housed 30 feet from the gate pinion in a 16-inch PVC stilling-well with the bottom open to the canal flow.

Actuator The actuator used for this project is an AUMA multi-turn actuator (Model SA 10.1-54B/GSD100.3) with built in 4-20mA input/output control signals. It features a single phase motor, 120 VAC, 60 Hz, 2 gear train limit switch with 8 contacts, a dual position potentiometer, and a RWG position transmitter (4-20mA DC output). The District purchased the actuator, and AUMA engineers helped with original calibration and set up.

Doppler Flow Meter The Argonaut-SW specifications state that it is accurate to ± 0.1% for water level when used in depths less than 16-feet and has an accuracy of ± 1% of water velocity for velocities up to 16 feet/second. The meter was installed in the middle of the canal about 30 feet downstream of the gate structure, and readings were recorded in 2-minute intervals.

Field Equipment Verification and Calibration

Current Meter vs. Doppler Meter Flow Verification We performed a series of flow measurements using Price Type AA current meter to verify the readings from the Argonaut-SW flow meter. Tests were carried out with maximum and very low flow. The measurement cross section was immediately upstream of the Argonaut-SW position. The USGS recommended procedures were followed, using the two-point method in measuring the velocities at 20% and 80% of total water depth of the canal cross-section (USBR, 2001).

Calibration of Vertical Gate Opening vs Actuator Position and Data logger Input The control range of the actuator (4-20 mA) was set to 0-100% scales, which corresponds to 0-5 ft of gate opening. The gate was then operated to different vertical opened positions based on a graduated input percentage set in the data logger during both the opening and closing to the gate. The chosen gate positions were every 0.5 ft of theoretical vertical opening. At each percentage, the actual vertical opening of the gate and the position of actuator were measured.

Flow Estimation

The submerged orifice flow equation was chosen to establish a head-discharge relationship for the Bryan radial gate. This equation is derived from the general Bernoulli equation used to estimate flow through an underflow gate, and is applicable to radial gates in case of slow and very submerged flow (Ghetti, 2006), which may be written:

$$Q = a * L * C_q * \sqrt{2 * g * (h_1 - h_2)} \tag{1}$$

Where:
Q = discharge
C_q = discharge coefficient
a = gate opening
L = gate width
g = gravitational constant

h_1 = upstream level
h_2 = downstream level
h_1 - h_2 = head differential (Fig. 4)

As suggested by USBR (2001) and Buyalski (1983) "approaching flow should be tranquil…10 average approach flow widths of straight, unobstructed approach are required." The old gate structure might therefore have slightly affected the accuracy of results.

In this study, Equation (1) was fitted to the measured flow data in order to calibrate the gate. To evaluate the accuracy of flow calculated with Equation (1), we used the coefficient of determination (R^2) for the regression functions on all data, and the relative sample standard deviation for individual events. In the latter case, we treated the calculated flow and the measured flow as two samples from a population normally distributed, with the goal to calculate the error on estimating the real flow with the two methods, calculated as:

$$s = \frac{1}{\bar{x}}\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2} \qquad (2)$$

Where:
s = relative sample standard deviation
N = number of samples
x_i = sample
$\bar{x}$ = mean of all samples

RESULTS

Current Meter vs. Doppler Meter Flow Verification

Maximum measured flow reached 116 cfs and a velocity of 1.7 feet/second, which was well under the Argonaut-SW factory accuracy limits. In all tests carried out the average flow rate measured with the Argonaut-SW was 3% less than the average flow rate measured with the current flow meter. The Argonaut data was therefore corrected according to the finding.

Calibration of Vertical Gate Opening vs Actuator Position and Data Logger Input

Actuator position signal vs gate opening The correlation between actuator position signal and gate opening differed depending upon whether the motion was set upward or downward. So, at a given actuator position the gate opening was greater when the gate was operated upward compared to downward (Fig. 5). This hysteresis phenomenon accounted for up to 0.1 ft difference, corresponding to about 4.4 cfs. Data from two measured series of observations on upward and downward motion were fitted by 2nd degree polynomial regression. Both equations are used depending upon whether The identified equations were used to convert actuator signal into gate opening.

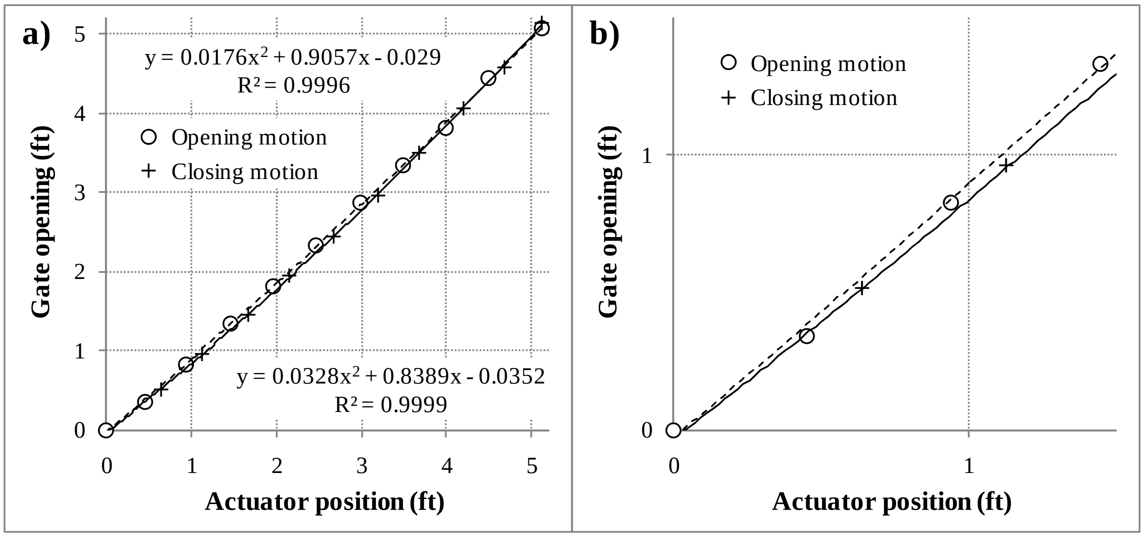

Fig. 5. Hysteresis identified between Actuator position and Gate opening: a) full gate opening range; b) detail for observed gate opening range.

Data logger input percentage vs Actuator position The correlation between gate opening input percentage and actuator position reading differed depending whether it was moving upward or downward. So, at a given gate opening input percentage the actuator position reading was lower when the gate was operated upward compared to downward (Fig. 6). This second hysteresis phenomenon was up to 0.5 mA, corresponding to 0.16 ft, and to 7.1 cfs in average. Thus, for gate calibration, the actuator readings were used instead of the data logger input.

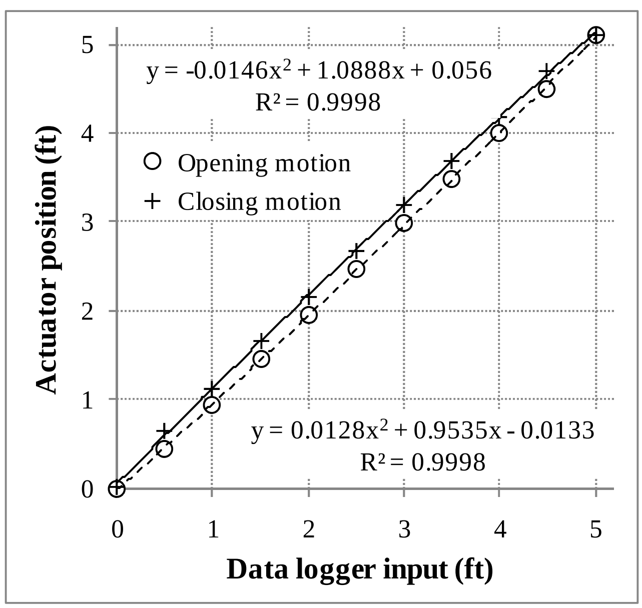

Fig. 6. Hysteresis identified between data logger input and actuator position.

Calculated and Measured Flow Rate

The radial gate was completely closed every Friday, except twice in the second half of February. There were an average of about four gate movements per week greater than 2 inches, mainly Monday through Wednesday, and the maximum observed opening was 1.5 feet. Downstream level was, in the average, one (1) foot lower than the upstream level, and such that flow conditions were always submerged. Table 1 summarizes the range in conditions that were observed.

Table 1. Range in conditions that were observed.

Parameter	Abbreviation	Max	Average	Min
Opening (ft)	a	1.5	0.5	0.0
Upstream level (ft)	h_1	7.0	5.4	3.9
Downstream level (ft)	h_2	5.4	4.2	2.2
Upstream level - Downstream level (ft)	h_1-h_2	2.8	1.2	0.0

The calibration process proceeded as follows. First, Equation (1) was re-written with the values corresponding to the dimensions of the radial gate:

$$Q = a * 10 * C_q * \sqrt{2 * 32.174 * (h_1 - h_2)} \tag{3}$$

Where:
Q = discharge,
a = gate opening,
h_1 = upstream level,
h_2 = downstream level.

Next, by trial and error, we selected values for C_q and solved Equation (3) until the cumulative flow converged with the measured values. A single discharge coefficient C_q = 0.71 was found to be able to predict all events, and matched measured flow with an average error of 3.2 % (Fig. 7).

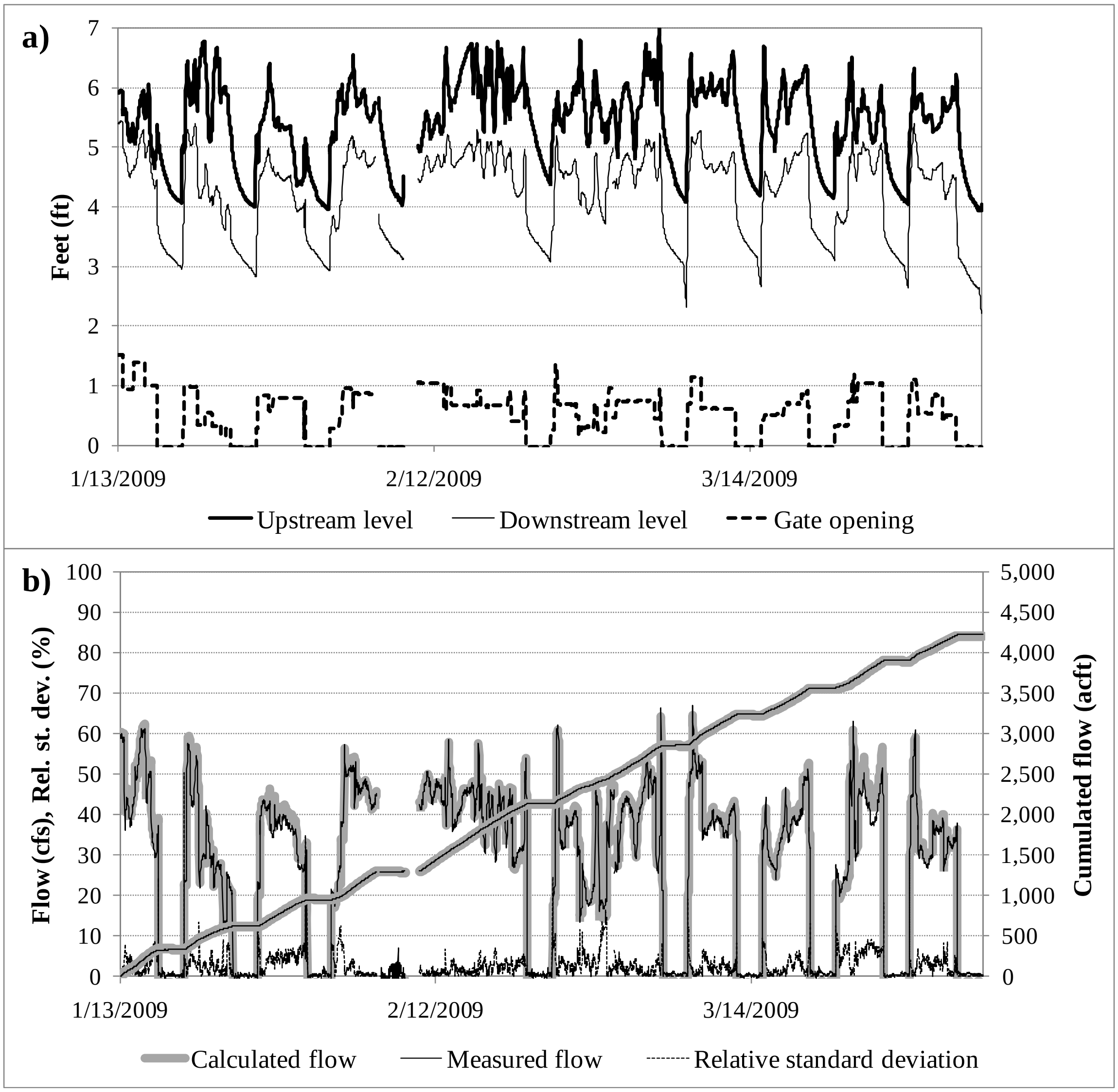

Figure 7. a) Gate opening and water level upstream and downstream the gate; b) Comparison of calculated flow and measured flow.

The relation between individual events of measured and calculated flow was well fitted by a linear regression function, as shown in Fig. 8. By comparing these events before hysteresis correction, we were able to identify two separated groups of data corresponding to opening and closing motion of the gate (Fig. 9). The linear regressions fitting the two groups of data were tested for parallelism, and the slopes resulted statistically different from each other.

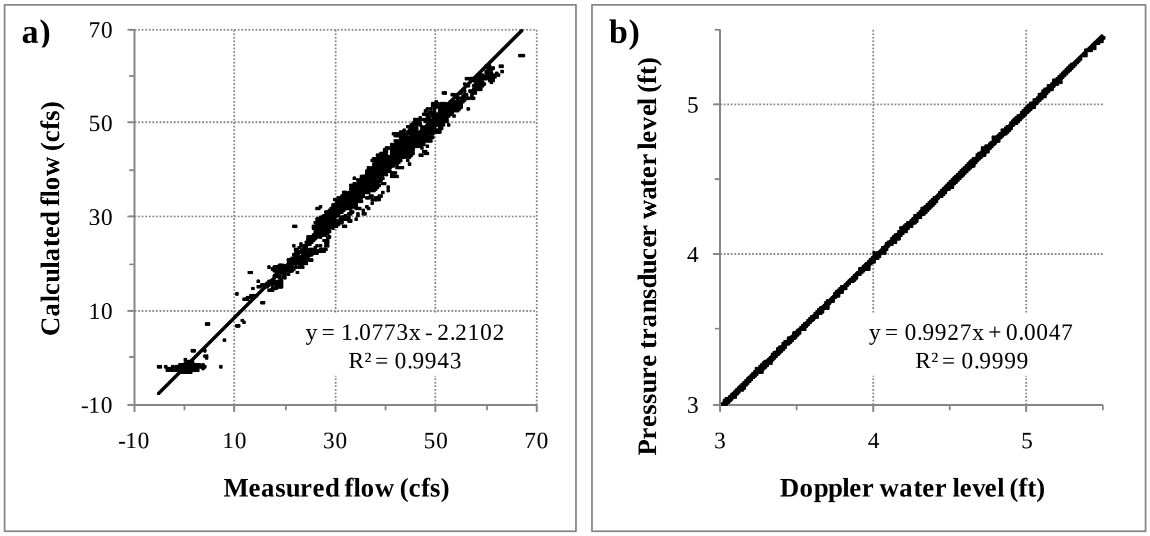

Figure 8. a) Calculated vs measured flow for individual events. b) Comparison of water level measured with doppler flow meter and pressure transducer.

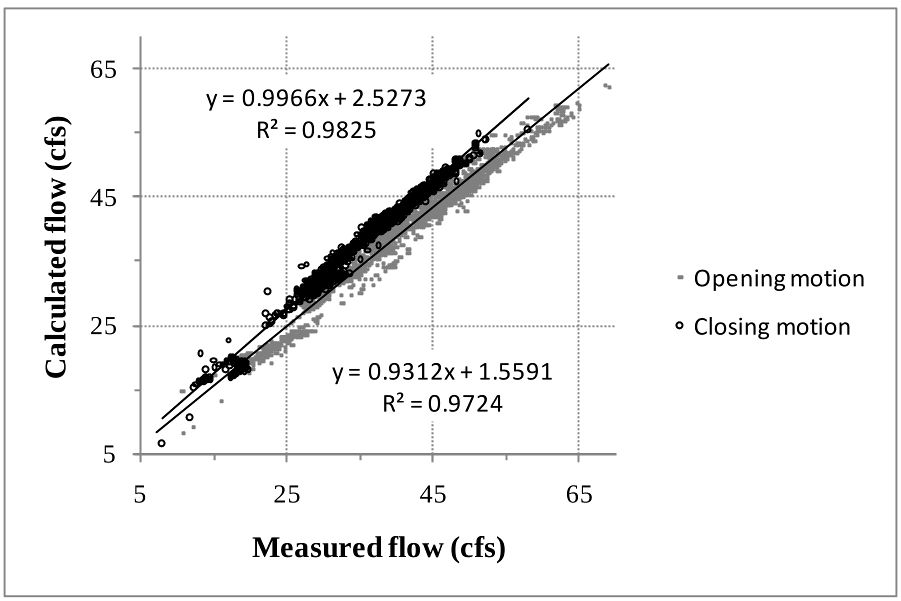

Figure 9. Identified groups of data corresponding to opening and closing motion of the gate by comparing calculated vs measured flow before correction for hysteresis.

CONCLUSIONS

The gate was calibrated for flow by inputting data on gate position and head differential across the gate into the submerged orifice equation. The coefficient of discharge (Cq) was adjusted to 0.71 in the equation for the total calculated flow to match the total measured flow of the doppler flow meter. A good correlation was found between each calculated flow event (every 30 minutes) and the corresponding measured doppler flow data. This correlation was described by a linear regression with slope equal to 1.08 and a R^2 equal to 0.994.

The doppler flow meter (Argonaut-SW) was very useful in the process because of the high accuracy and large amount of data obtained in a short period of time. The curve obtained is only valid for the flow conditions observed in this study. Such conditions were:

1) gate opening <1.5 ft;
2) gate always under submerged flow condition, with downstream level >2.2 ft, with maximum head differential 2.8 ft;
3) maximum flow 68.9 cfs.

Further calibration is needed for other ranges of flow.

A problem of hysteresis was identified in the gate position management. This was due to a difference between input and out signals to and from the actuator, and between the actuator signal and the real gate opening. While the former was not a factor in the flow calibration process because only the output signal of the gate setting was used, the latter required the use of separate equations to convert actuator signal into gate opening whether the motion was upward or downward.

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CONSIDERING CANAL POOL RESONANCE IN CONTROLLER DESIGN

Albert J. Clemmens[1]

ABSTRACT

The Integrator-Delay (**ID**) model (Schuurmans et al 1999) is a simple model of canal response that is used for design of various canal controllers. It describes the change in water depth at the downstream end of a canal pool as a function of flow changes at the upstream and downstream gates. Canal pools are characterized by a **Delay** time and a backwater surface area (**Integrator**). This model works very well for canal pools where water is flowing under normal depth conditions for a portion of the length, or where there are drops. For canal pools where the upstream flow depth is influenced by the downstream flow depth (that is, where canal pool is under backwater) the ID model often does not properly represent the water-level response. Changes in gate flows often cause a step change in water level. Schuurmans (1997) and Miltenburg (2008) propose the use of filters to account for this step change (ID-F), where the filter effectively causes a delay in response. Litrico and Fromion (2004) proposed the IDZ model, where a gate flow change causes a step change in downstream water level, after which the water level response follows the integrator of the ID model. The IDZ model does not fully account for resonance. An IDZ model with Filtering (IDZ-F) is proposed to account for additional resonance. In this paper, we compare the resulting water level response when the ID-F and IDZ-F models are used to design canal controllers for canal pools under backwater. It is shown that controllers designed with the IDZ-F model provide slightly better control than when designed with the ID-F model, although differences are not significant.

INTRODUCTION

Canal controller design requires a mathematical model of canal pool response. Most canal control methods rely on a linear model of canal pool response. Schuurmans (1997) suggest that there are two types of canal pools: 1) pools in which flow is governed by normal depth for some length at the upstream end and under back water at the downstream end and 2) pools which are entirely under backwater. For 1), Schuurans, et al (1999) propose the use of the Integrator-Delay (ID) model to describe canal response. The ID model determines the response of the water level at the downstream end of the pool to changes in gate discharge at either the upstream or downstream end. Resonance is usually not a problem for this type of canal pool. The model has two parameters: a delay time, τ, generally associated with the section under normal depth, and a backwater surface area, A, which functions as the integrator of the flow change. Clemmens and Schuurmans (2004) use state-transition equations to describe the ID model and then use Linear Quadratic Regulator (LQR) design to develop canal controllers. For 2), Litrico and Fromion (2004) propose the Integrator-Delay-Zero (IDZ) model to predict the water level response associated with canal pools under backwater. They use the same integrator and delay as in the ID model. The Zero essentially describes the influence of the celerity

[1] Center Director, U.S. Arid Land Agricultural Research Center, USDA/ARS, 21881 N. Cardon Lane, Maricopa, AZ 85138 bert.clemmens@ars.usda.gov

wave on the water level response. The purpose of this paper is to develop state-transition equations for the IDZ model and to compare canal controllers developed with the ID and IDZ models (with filters).

ID MODEL

The ID model assumes the water level at the downstream end of a pool responds linearly to changes in flow from steady state. It assumes immediate response to downstream flow change and a delayed response to upstream flow change. The ID model in continuous form is:

$$y_j(t) = y_j(0) - \frac{tQ_j}{A_j} \qquad t \le \tau_j$$
$$y_j(t) = y_j(0) + \frac{(t-\tau_j)Q_{j-1}}{A_j} - \frac{tQ_j}{A_j} \qquad t > \tau_j \tag{1}$$

where y is water depth at the downstream end of a pool, Q is discharge, j represents the pool number and the gate at the downstream end, t is time, τ is the delay time for a wave to travel from the upstream to the downstream end of a pool, and A is the backwater surface area of a pool.

A discrete form of the ID model is:

$$\Delta y_j(k+1) = \Delta y_j(k) - \frac{\Delta t}{A_j}\Delta Q_j(k) \qquad t \le \tau_j$$
$$\Delta y_j(k+1) = \Delta y_j(k) + \frac{\Delta t}{A_j}[\phi_{0j}\Delta Q_{j-1}(k) + \phi_{1j}\Delta Q_{j-1}(k-1) + ...] - \frac{\Delta t}{A_j}\Delta Q_j(k) \qquad t > \tau_j \tag{2}$$

where Δ represents the change in conditions over one time step, Δt, and φ are weighting coefficients that describe the water level slope change at each time step. The φ coefficients for any pool j sum to one. If a delay time falls in the middle of a time step, a portion of the water surface slope (and associated water level increase) occurs. The rest of the water surface slope is added at the next times step so that future water level slopes match the ID model slope ($\Delta Q/A$). The follow expression defines the φ terms for any pool j:

$$\tau = 0 \qquad \phi_0 = 1 \quad \phi_1 = 0 \quad \phi_2 = 0 \quad \dots$$
$$0 < \tau < \Delta t \qquad \phi_0 = \frac{(\Delta t - \tau)}{\Delta t} \quad \phi_1 = \frac{\tau}{\Delta t} \quad \phi_2 = 0 \quad \dots$$
$$\Delta t < \tau < 2\Delta t \qquad \phi_0 = 0 \quad \phi_1 = \frac{(2\Delta t - \tau)}{\Delta t} \quad \phi_2 = \frac{(\tau - \Delta t)}{\Delta t} \quad \phi_3 = 0 \quad \dots \tag{3}$$
$$2\Delta t < \tau < 3\Delta t \qquad \phi_0 = 0 \quad \phi_1 = 0 \quad \phi_2 = \frac{(3\Delta t - \tau)}{\Delta t} \quad \phi_3 = \frac{(\tau - 2\Delta t)}{\Delta t} \quad \phi_4 = 0 \quad \dots$$
$$\dots$$

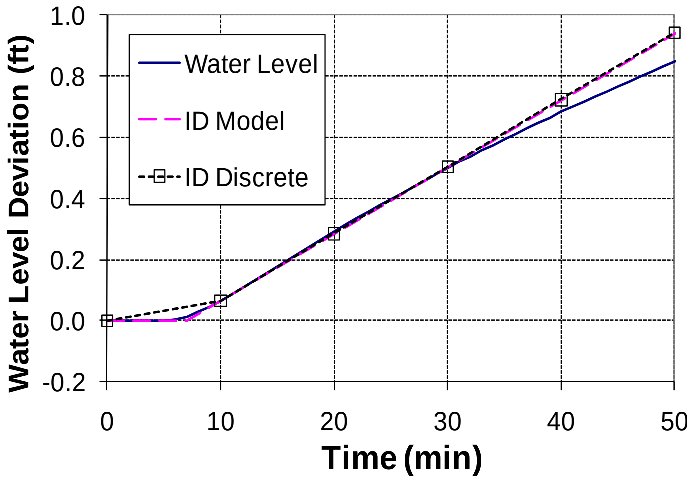

Figure 1. ID model in discrete and continuous form fit for canal pool CD-12. Step change in upstream discharge.

Eqs (2) and (3) were used by Clemmens and Schuurman (2004) to develop state-transition equations as input into controller design as Linear Quadratic Regulators (LQR) [linear model with quadratic penalties]. Figure 1 shows the downstream-water-level response in a canal pool for a step increase in flow at the upstream gate. The water level was computed from simulation with Sobek (2000). This pool does not display resonance. The ID model shown was fit by trial and error. Changes in cross section with depth cause the model to deviate from the simple ID model. The water level shown is for canal pool CD-12 at the Central Arizona Irrigation and Drainage District (CAIDD), Eloy, AZ. The pool has a bottom width of 4 ft, side slopes 1.5:1 (horizontal to vertical), slope 0.0012 m/m, length 3025 ft, a downstream set point depth of 5.05 ft, and a capacity of 110 cfs. The flow change was 5.5 cfs, and the backwater area was 0.346 ac. The ID discrete model in Figure 1 shows the water surface slope which is initially shallower than the ID model because of the discrete data points used (i.e., every 10 minutes). The change in slope is reflected by values of φ. The delay time, τ, for this model is 7 minutes, giving $\varphi_0 = 0.3$ and $\varphi_1 = 0.7$. Thus the initial slope of the response curve is 0.3 times the slope of the ID model.

ID-F MODEL

In canal pools under backwater, the dynamic wave created from an upstream flow change arrives suddenly at the downstream end, causing a sudden change in water level there. This can cause difficulty with water-level controllers. Schuurmans (1997) proposed the use of proportional-integral (PI) controllers with filtered water levels (PI-F) to assure control stability. This is currently the primary method for dealing with resonance in the design of canal controllers. A linear filter is used where

$$y_f(k) = F_c y_f(k-1) + (1 - F_c) y(k) \tag{4}$$

where $y_f(k)$ is the filtered water level at time step k and F_c is the filter constant. The filter constant is determined from

$$F_c = e^{-T_s / T_f} \tag{5}$$

where T_f is the filter time constant and T_s is the time step for water level sampling. For Schuurman's (1997) PI-F controller based on the ID model, T_f is found from

$$T_f = \sqrt{\frac{AR_p}{\omega_r}} \tag{6}$$

where R_p is the resonance peak height, ω_r is the resonant frequency. The resonant frequency is 2π divided by the time for a wave to travel the length of a pool and back. Any disturbance in a canal pool causes a wave. These waves travel at the speed of celerity

$$c = \sqrt{gD} \tag{7}$$

where g is the acceleration of gravity and D is the hydraulic depth (area divided by top width). The wave travel time can be estimated from

$$\tau_r = \tau_z + \tau_{zu} = \frac{L}{v+c} + \frac{L}{v-c} \tag{8}$$

where L is the pool length, v is the average flow velocity, τ_z is the time for the wave to travel to the downstream end, and τ_{zu} is the time for the wave to travel to the upstream end. Then $\omega_r = 2\pi / \tau_r$.

The filter causes a delay in the water level response, which can be estimated from

$$t_{delay} = \frac{F_c}{1-F_c} T_s \tag{9}$$

For controller design, this delay time is added to the ID model time delay. The filter constant computed above based on Eq. 6 is for Schuurmans' PI-F controller, and may or may not be appropriate for other controllers.

Figure 2 shows the simulated (Sobek 2000) downstream-water-level response in a pool for a step increase in flow at the upstream gate. This canal pool clearly shows resonance. The ID model is fit to the long-term response. The oscillations of the water level around the ID model line indicate resonance. The response in Figure 2 is for pool CM-1 for the Central Main Canal of CAIDD, which has a capacity of 900 cfs, bottom width 12 ft, sides slopes 1.5 to 1 horizontal to vertical, length 17,119 ft, slope 0.00013 ft/ft, downstream water level set point depth 11.0 ft. The step change was 35.3 cfs.

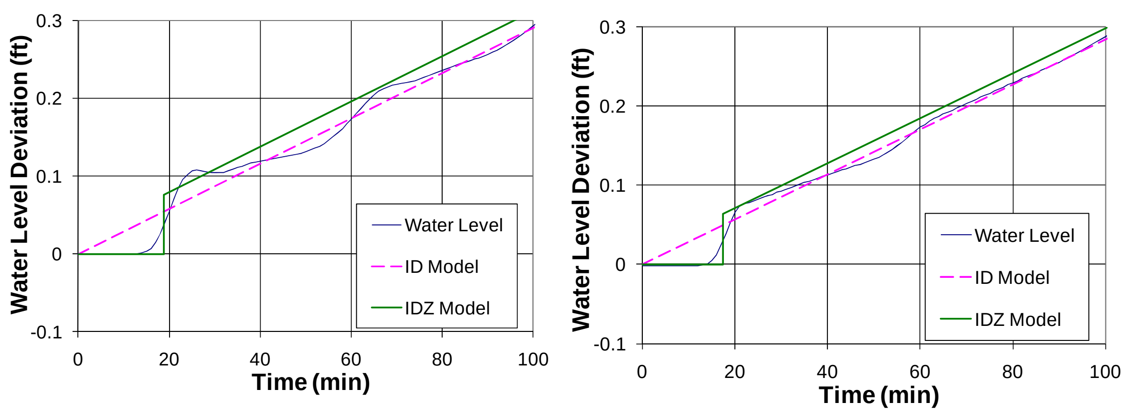

Figure 2. IDZ model in discrete and continuous form for canal pool CM-1 at a) 20% and b) 50% flow. Step change in upstream discharge.

IDZ MODEL

Litrico and Fromion (2004) proposed the IDZ model to account for the sudden rise in water level that occurs for pools which are under backwater, as shown in Figure 2. They developed a set of frequency-based relationships to describe the IDZ model. A time-based version in continuous form is:

$$y_j(t) = y_j(0) - \left(\frac{t}{A_j} + p_{22}\right)Q_j \qquad t \le \tau_{zj} + \tau_j$$
$$y_j(t) = y_j(0) + \left(\frac{t - \tau_{zj} - \tau_j}{A_j} + p_{21}\right)Q_{j-1} - \left(\frac{t}{A_j} + p_{22}\right)Q_j \qquad t > \tau_{zj} + \tau_j \tag{10}$$

where τ_{zj} is the wave travel time through pool j (Trd in Eq.8), and p_{21} and p_{22} are the transfer function for the sudden change in downstream water level for a change in upstream and downstream flow, respectively.

The height of the water level above the ID model line in Figure 2 (i.e., the first cycle) is an indicator of the resonance peak, although a higher wave would result if the input (upstream flow change) were cycled at the resonance frequency. The IDZ model response shown in Figure 2 was computed with equations for p_{21} and p_{22} from the Litrico and Fromion (2004). Note that for the lower flow rate, the peak height was under predicted. (This is not unexpected. Litrico 2010, personal communication). And this model over-predicts long-term changes in water level response. I also found that the estimates for this step height were very sensitive to estimates for the downstream water surface slope. Thus I decided to determine p_{22} and p_{21} based on matching the ID model, and then account for the additional resonance with a water level filter, as in the ID-F model. This approach can be considered a filtered IDZ model, or IDZ-F.

IDZ-F MODEL

For step changes in upstream discharge, we assume that the IDZ-F model steps up to the ID model line when the wave arrives. The step height is thus

$$\Delta y_j(step) = \frac{\tau_{zj}}{A_j}\Delta Q_j \tag{11}$$

Thus $p_{21} = \tau_z / A$. For a change in discharge at the downstream gate, the solution is less obvious. If we assume that the backwater area equals the pool length times the top width ($A_j \approx L_j B_j$) and that celerity is much larger than the average velocity ($\tau_{zj} \approx L_j/c_j$) substituting these relationships into Eq. 11 gives

$$\Delta y_j(step) \approx \frac{\Delta Q_j}{B_j c_j} \tag{12}$$

(This matches the solution for p_{22} by Litrico and Fromion (2004) for a Froude number of zero.) Figure 3 shows simulation results (Sobek 2000) where a step change in downstream discharge of 17.2 cfs (0.5 m^3/s) was made in pool CM-1. Initial flow was 450 cfs (50% of capacity). The value of the step change computed for p_{22} from Litrico and Fromion (2004) was 0.0272 ft. Eq (12) gives 0.0269 ft. The initial drop in level is well predicted (Figure 3). For simplicity, we can use Eq. 11 for changes in either the downstream or upstream gate.

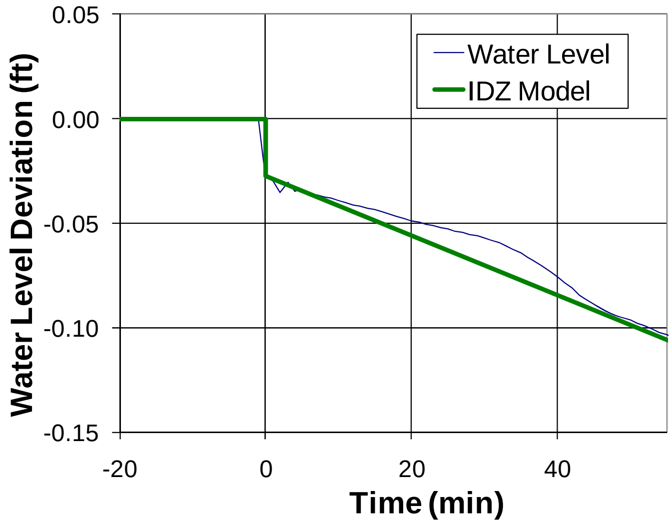

Figure 3. IDZ model response for CM-1 at 50% flow. Step change in downstream discharge.

A discrete version of the IDZ-F model is:

$$\Delta y_j(k+1) = \Delta y_j(k) - \left(\frac{\Delta t + \tau_{zj}}{A_j}\right)\Delta Q_j(k) + \frac{\tau_{zj}}{A_j}\Delta Q_j(k-1) \qquad t \le \tau_{zj} + \tau_j$$

$$\begin{aligned}\Delta y_j(k+1) = \Delta y_j(k) &+ \frac{\Delta t}{A_j}[\phi_{0j}\Delta Q_{j-1}(k) + \phi_{1j}\Delta Q_{j-1}(k-1) + ...] \qquad t > \tau_{zj} + \tau_j \\ &- \left(\frac{\Delta t + \tau_{zj}}{A_j}\right)\Delta Q_j(k) + \frac{\tau_{zj}}{A_j}\Delta Q_j(k-1)\end{aligned} \tag{13}$$

The last term in the first of Eq. (13) brings the water level slope back to the ID model after the initial shock from moving the downstream gate. The filter delay is included in τ_j.

The following equation defines the φ terms for the IDZ-F model for any pool *j*. This version of the IDZ-F model is essentially a piece-wise linear model of dy/dt over time, where the response over the duration of one time step is linear. The functions described by φ essentially changes dy/dt. The slope dy/dt returns to the simple ID model after the step increase.

$$\begin{aligned}
&\tau_f + \tau = 0 && \phi_0 = 1 \quad \phi_1 = 0 \quad \phi_2 = 0 \quad \ldots \\
&0 < \tau_f + \tau < \Delta t && \phi_0 = \frac{(\Delta t - \tau)}{\Delta t} \quad \phi_1 = \frac{\tau}{\Delta t} \quad \phi_2 = 0 \quad \ldots \\
&\Delta t < \tau_f + \tau < 2\Delta t && \phi_0 = 0 \quad \phi_1 = \frac{(2\Delta t - \tau)}{\Delta t} \quad \phi_2 = \frac{(\tau - \Delta t)}{\Delta t} \quad \phi_3 = 0 \quad \ldots \\
&2\Delta t < \tau_f + \tau < 3\Delta t && \phi_0 = 0 \quad \phi_1 = 0 \quad \phi_2 = \frac{(3\Delta t - \tau)}{\Delta t} \quad \phi_3 = \frac{(\tau - 2\Delta t)}{\Delta t} \quad \phi_4 = 0 \quad \ldots \\
&\ldots
\end{aligned} \tag{14}$$

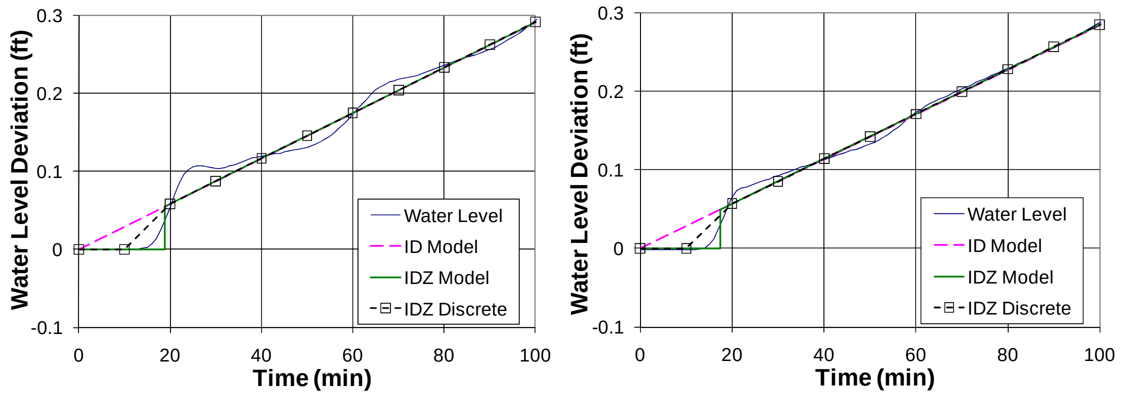

Figure 4. IDZ-F model in discrete and continuous form fit for canal pool CM-1 at 50% flow. (Filter time delay not shown).

Eqs. (3) and (14) are very similar. The only difference is that τ_{zj} influences the time step in which the step increase in water level occurs, while τ has essentially the same influence as in the ID model. A large difference occurs if τ_{zj} is large. Values of the first non-zero φ-term can be larger than unity, but the second non-zero φ-term is then negative to bring the sum back to unity, which brings the water level slope back to the ID model slope. An example of the step change for the discrete IDZ-F model (without filter delay) is shown in Figure 4, for the same scenario as given for Figure 2.

CONTROL EXAMPLE

The details of the Central Main Canal, the delay times and the filter constants are presented in Clemmens and Strand (2010). The parameters for the ID model were determined from steady-state simulation with Sobek (2000). For the ID-F model, filters were designed with the procedures of Schuurmans (1997). The filter delay for the ID-F model response was 14 minutes for all but pool 3, which had a delay of 8.7 min. For the IDZ-F model, we used a much smaller filter, essentially for antialiasing, with a 4.4

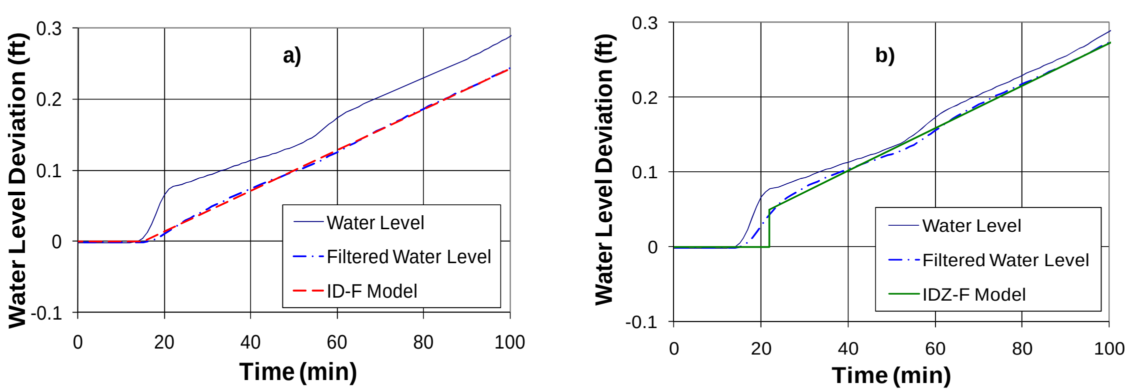

Figure 5. Water level response to upstream flow changes for pool CM-1 at 50% flow. a) Filtered water level and delayed ID-F model (14 minute delay) and b) Filtered water level and delayed IDZ-F model (4.4 minute delay).

minute delay. Figure 5 shows the approximate match between the filtered water level for pool CM-1 and the ID-F and IDZ-F models. These models fit the filtered water levels pretty well.

Downstream-water-level controllers were developed with the procedures of Clemmens and Schuurmans (2004) with either Eqs (2) and (3) for the ID-F model or Eqs (13) and (14) for the IDZ-F model. Controller tuning (i.e., tradeoffs between water level deviations and flow rate changes) was the same for both. Steady flow was established, and a turnout in pool CM-5 was suddenly increased by 17.6 cfs (0.5 m^3/s) without knowledge by the controller. Figures 6 and 7 show the water level response for these controllers. Overall, both controllers performed well. The controller designed with the IDZ-F model had a smaller deviation in water level than ID-F. However, the difference was not great. This is expected, since this controller had the most mechanistic response and shorter filter delays. Deviations in neighboring pools differed somewhat in which controller responded better. A more careful analysis of filter constants and tuning would be required to give a more definitive comparison.

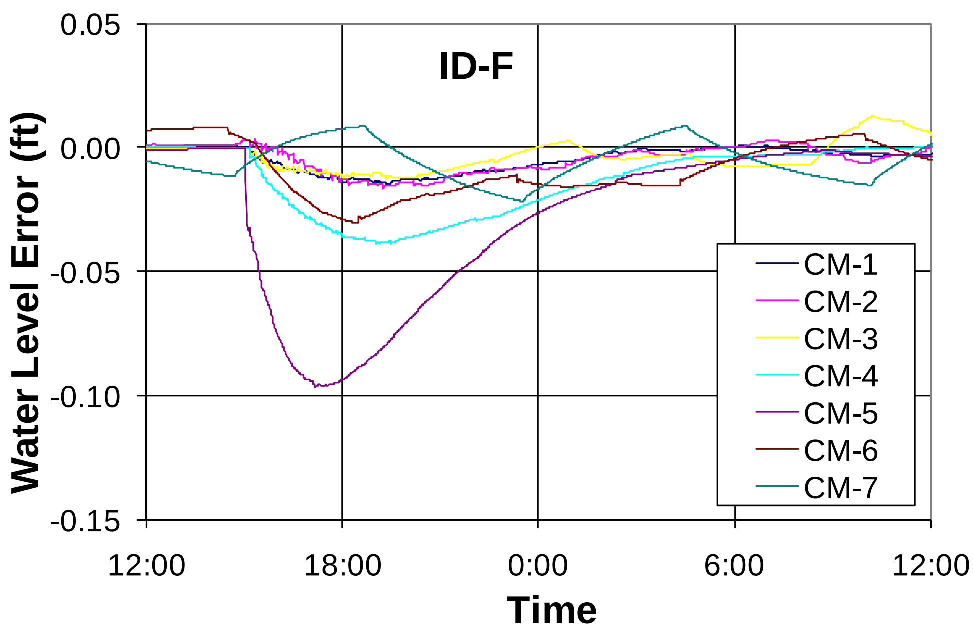

Figure 6. Response of water level to disturbance in pool CM-5: controller designed from ID-F model. (14 minute filter delay).

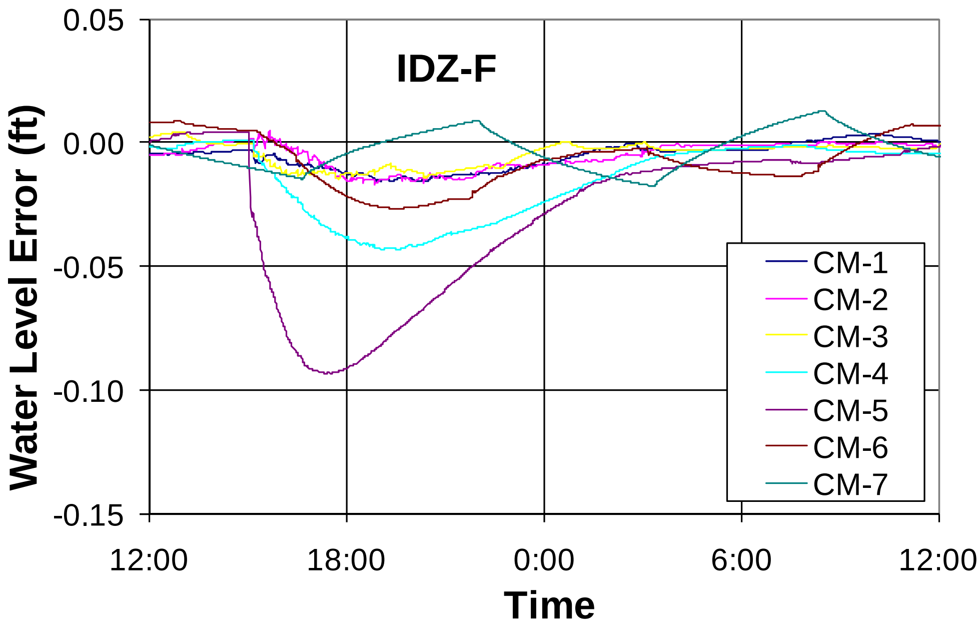

Figure 7. Response of water level to disturbance in pool CM-5: controller designed from IDZ-F model. (4.4 minute delay)

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SYNTHETIC CANAL LINING EVALUATION PROJECT

Eric Leigh[1]
Askar Karimov[2]
Guy Fipps, Ph.D., P.E.[3]

ABSTRACT

Irrigation districts in the Lower Rio Grande Valley of Texas have been experimenting with an assortment of synthetic canal lining materials, looking for more cost-effective methods for rehabilitating old, deteriorating canals. The synthetic canal lining materials are showing promise, but little information exists on the relative performance between different products. In 2005, we initiated a program to track the long-term effectiveness and durability of these lining projects and to document the damage caused by such factors as UV damage, animal traffic, intentional and unintentional vandalism. A summary of our results from the first four years of inspections are presented. Inspections for the linings are currently being updated for 2009-2010. Additionally, this paper provides documentation on canal lining installation and maintenance procedures, along with suggested considerations when planning a lining project. This paper also discusses future collaborative efforts underway for the testing and evaluation of synthetic canal liners.

The best performers were the two types of synthetic liners (PVC and polyester) with a protective barrier of shotcrete, which have shown no problems to-date. The noticeable difference between the two types of liners was the ability of the polyester to hold the shotcrete in place on the canal sidewalls. The PVC liner required an additional support system using a wire mesh overlay serving as the attachment between the material and the shotcrete.

The performance of synthetic liners without a protective barrier varied dramatically. One important factor was the location of the project. Liners located in high traffic areas (people and animals) showed significantly more damage than those installed in remote areas. The PVC alloy is the toughest of the 4 liners installed without a protective barrier, is more difficult to cut and less likely to be damaged by unintentional vandalism. We also observed that liners carelessly or improperly installed were more susceptible to intentional and/or unintentional damage.

INTRODUCTION

Water Losses from irrigation canals can be significant, and water districts are looking for more cost-effective methods for rehabilitating old, deteriorating canals other than relining

[1] Extension Associate, Department of Biological and Agricultural Engineering, 2117 Texas A&M University, College Station, Texas 77843-2117; eleigh@tamu.edu
[2] Extension Associate, Department of Biological and Agricultural Engineering, 2117 Texas A&M University, College Station, Texas 77843-2117; akarimov@ag.tamu.edu
[3] Professor and Extension Agricultural Engineer, Department of Biological and Agricultural Engineering, 2117 Texas A&M University, College Station, Texas 77843-2117; g-fipps@tamu.edu

with concrete or replacement with pipelines. Synthetic canal lining materials are showing promise as an alternative to more costly methods, but little information exists on the relative performance between different products, or on installation and maintenance procedures needed to ensure long life.

Since 1999, irrigation districts in the Lower Rio Grande Valley of Texas have been experimenting with an assortment of canal lining materials. In 2005, we initiated a program to track the long-term effectiveness and durability of these materials and to document installation and maintenance procedures which will help ensure good performance. Each lining project was inspected multiple times to document the effects of such factors as UV damage, animal traffic, intentional and unintentional vandalism, and normal irrigation district operational and maintenance activities. A summary of the results from the first four years of inspections are presented in this report.

MATERIALS AND METHODS

Lining Materials

Six different lining materials have been installed in seven irrigation districts of the Lower Rio Grande Valley of Texas. Table 1 provides a list of material types and generic descriptions of each. Unlike the other materials, the polyurethane was manufactured on-site during installation using specialized equipment. The locations of the lining projects are shown in Figure 1. In 1999, Hidalgo County Irrigation District No. 1 initiated a program that included four types of liners installed in 27 segments.

Table 1. Description of each lining material's composition.

Material	Description
Polyester with protective barrier	A geocomposite consisting of two layers (top and bottom) of 8 oz/yd^2 nonwoven polyester bonded to an olefinic copolymer geomembrane, 20 mil thick. The protective barrier consists of 2-3 inches of shotcrete.
PVC with protective barrier	Non-reinforced Poly Vinyl Chloride (PVC). The protective barrier consists of a wire mesh with 2.5 inches of shotcrete.
Polypropylene	A reinforced polyester scrim 16 oz/yd^2 between polypropylene layers, 24 mil thick.
PVC Alloy	A polyvinylchloride blend, reinforced with a polyester scrim, 40 mil thick.
EPDM Rubber	A non-reinforced EPDM (ethylene propylene diene monomer), 45 mil thick.
Polyurethane	Two layers of 3-oz/yd^2, heat-bonded, non-woven geotextile saturated with liquid polyurethane, 40 mil thick.

Evaluations and Site Inspections

During each site inspection, projects were given a condition rating ranging from “excellent” to “serious problems” as defined in Table 2, and photographs and other information were collected to document observed problems. Our original plan was to conduct inspections every six months. However, little change was observed over this time period, and succeeding inspections took place annually as follows:

- February 2005
- September 2005
- September 2006
- December 2007

Conducting inspections during the winter months when water levels tend to be the lowest have proved to be the most effective.

Table 2. General performance ratings for canal liners.

Rating	Definition
Excellent	0%: no damage and no maintenance required
Good	0 – 5%: mild damage to top anchor and canal interior 1 to 2 significant repairs needed per year
Fair	5 – 20%: mild damage to top anchor and canal interior 3 to 5 significant repairs needed per year
Poor	20 – 50%: mild damage to top anchor and canal interior 6 to 10 significant repairs needed per year
Serious Problems	50 – 100%: mild damage to top anchor and canal interior 10 > significant repairs needed per year

Note: Percentages are based on the linear length of the lining project

Seepage Loss Tests

Before and after seepage loss tests were conducted for Project #5 in Figure 1 using the ponding test method. In this method, earthen dams are constructed at either end of the test segment. The test segment is then filled with water, and the rate and total water losses are measured over a 24–48 hour period (Leigh and Fipps, 2009). The time-line for these tests was as follows:

- pre-lining test - September 2002
- lining project completed - October 2004

- first post-lining test - November 2004
- second post-lining test - July 2005.

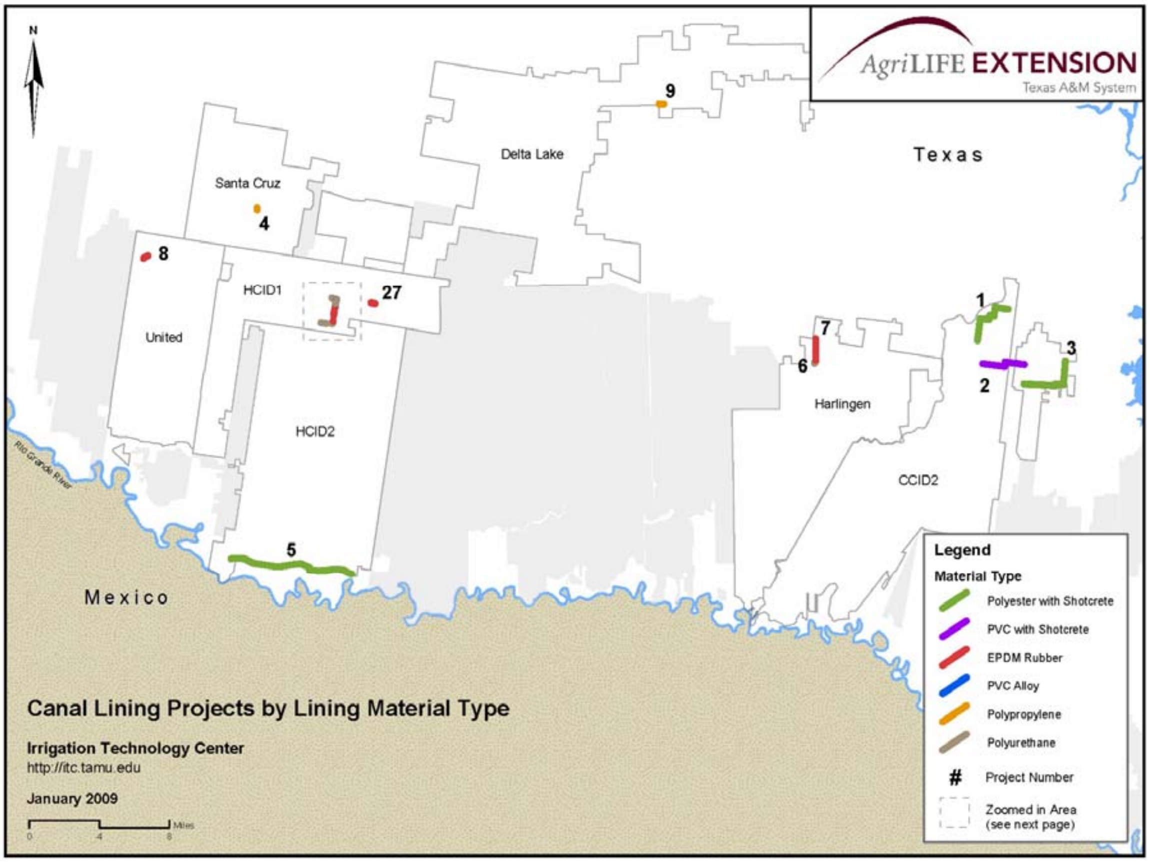

Figure 1. Lining Projects by Material Type

RESULTS AND DISCUSSION

The results of our evaluations are summarized in Table 3. Projects are grouped into lining projects *<u>with</u> a protective barrier* and projects *<u>without</u> a protective barrier*. Without question, liners with a protective barrier performed the best and have required no maintenance, while the performance of the liners without a protective barrier has varied significantly.

Table 3. Range of the performance rating results by lining material			
Material	No. of Projects	Total Miles	Rating
with a protective barrier			
Polyester with	4	14.47	Excellent
PVC with shotcrete	1	2.61	Excellent
without a protective barrier			
Polypropylene	2	0.36	Excellent to Good
PVC Alloy	3	0.05	Excellent to Good
EPDM Rubber	8	2.04	Excellent to Serious
Polyurethane	9	1.42	Excellent to Serious

Liners with a Protective Barrier

The best performers were the synthetic liners with a layer of shotcrete. This system is effective as the liner reduces seepage losses dramatically, while the layer of shotcrete prevents damage to the liner. Five projects extending over about 17 miles were implemented using this system with two different liners: polyester and PVC. The protective barrier consisted of 2 - 3 inches of shotcrete as shown in Figure 2.

To-date, these projects show no evidence of problems and have required no maintenance. No difference in performance was observed between the two types of liners. Hairline cracks developed in the shotcrete on a small stretch of Project #5, but no related problems have been observed.

Figure 2. Polyester canal liner with a 3-inch protective barrier

An important consideration with this system is the ability of the shotcrete to adhere to the liner. The polyester liner has a rough surface to which the shotcrete readily adheres to, while surface of the PVC liner is slick, and a wire mesh must be used.

In seepage loss tests, we found that this lining system reduced seepage losses by 94% after eight months (Leigh and Fipps, 2006). Details are as follows:

- before lining, loss rate = 1.36 gal/ft^2/day (134 ac-ft/mi/yr)
- one (1) month after installation, loss rate = 0.27 gal/ft^2/day (24 ac-ft/mi/yr)
- eight (8) months after installation, loss rate = 0.09 gal/ft^2/day (8 ac-ft/mi/yr)

Liners without a Protective Barrier

The performance of the liners without a protective barrier has varied significantly. Exposed liners are obviously more susceptible to damage caused by UV light, animals, and vandalism, as well as damage caused by the districts' mowers and maintenance activities. However, the amount of damage varied by the location of the project. Liners in remote areas have performed much better than those in urban or high traffic areas.

Installation and maintenance of the liners also appears to explain some of the variation in performance of these projects as discussed below. Another consideration with exposed liners is the potential damage that machinery can cause during normal district mowing operations and while cleaning out aquatic vegetation and sedimentation (Figure 3).

Figure 3. Aquatic vegetation and sedimentation clogging a farm outlet pipe

In general, of the four types of materials, the polypropylene and PVC alloy liners have been more durable and have experienced less damage. The performance of the other two liners, EPDM rubber and polyurethane varied significantly. While some projects are still in excellent condition, others have serious problems or have failed completely. Details are discussed below by type of liner.

<u>Polypropylene</u> In two lining projects, polypropylene was applied on existing concrete canals. To-date, these two lining projects are in excellent condition, with no visual damage. Yet, for one of these projects, we have concerns with the large amount of wrinkles which occurred during installation. Wrinkles can reduce water flow, accelerate sedimentation, and provide loose material that can easily be damaged.

For the project shown in Figure 4, concrete sections approximately 1-foot wide were poured on top of the liner at a spacing of 500 feet. The rational is that the concrete sections will help keep the liner in place and provide access points for sediment removal. Our conclusion is that long-term evaluation is needed to determine if such sections are useful for these purposes.

Figure 4. Concrete sections poured on top of a polypropylene liner

PVC Alloy Three short sections of PVC alloy were installed in 1999, ranging in length from 38 to 148 ft. This material has performed well, requiring little maintenance, with no major damage observed. However, cuts and tears have occurred in the exposed area of the liner (Figure 5) which could develop into larger problems if not taken care of in a timely manner. The overall performances for these small test segments are excellent to good.

Figure 5. PVC Alloy liner damaged on the exposed area

EPDM Rubber The performance of the eight projects using EPDM rubber has varied significantly. Two projects are in good to excellent condition, while the remaining six ranges from fair condition to serious problems, with one totally failing. EPDM rubber is very susceptible to vandalism and punctures caused by animals. It also appears that many cuts and tears initially occurred on the exposed areas where there is the most human and animal traffic (Figure 6). Unless repaired in a timely manner, these tears may lead to increasing amounts of damage (Figure 7).

Figure 6. Cuts/tears in a rubber liner

Figure 7. A rubber liner damaged possibly due to vandalism

<u>Polyurethane</u> During 1999 - 2000, nine short sections were lined with polyurethane, totaling 1.42 miles. The current condition of these projects varies from excellent to serious problems, with one section a total failure. Observed problems include the liner falling off the canal walls which was likely caused by a combination of severe UV damage (Figure 8), material defects, and vandalism. In some segments, the top layer of the material has peeled off, while in others, the entire liner has worn off (Figure 9).

Unlike the other liners, the polyurethane was manufactured on-site by specialized machinery, and requires that the chemicals used to be properly handled. Several problems occurred during its manufacture and installation, including inconsistency in product thickness, which may account for the large variation in performance. In addition, little to no maintenance has occurred since installation.

The location of the section does not appear to be a factor. For example, projects 17, 18, 20, and 21 are all continuing test segments; while projects 17 and 21 are in excellent shape, projects 18 and 20 have serious problems.

Figure 8. Polyurethane liner is shown hanging off the canal wall.

Figure 9. Residue left from a deteriorated polyurethane liner

CONSIDERATION WHEN PLANNING NEW LINING PROJECTS

The installation procedures and equipment requirements vary from material to material, with details available from each manufacturer. Proper installation and maintenance is necessary for avoiding or reducing problems that may contribute to accelerated deterioration of the material.

Lining Installation

Important installation considerations include:

- the methods used to overlap and mend/seam the layers of lining material together
- the methods used for attaching the material to the canal walls, around structures, and to the top of the levee (top anchor)
- the total width of the liner and extension on top of the levee in relation to the normal and maximum operating depth of the canals

Liners need to be properly installed and stretched in order to prevent wrinkles. Wrinkles not only look unprofessional, but make the liner more susceptible to damage. Glues, liquid rubbers resin, tar and types of metal pins are used to secure the material around the structures and at the joints (Figures 10).

Figure 10. Glues being applied to the joints of a polyester liner.

In one of early lining projects, the liner size was not planned properly to overlap and extend onto the top of the levee (Figure 11). As seen in Figure 12, the operating depth of the canal was higher than the top of the liner. The water eventually got underneath this liner and caused it to float.

Figure 11. Canal liner installed too low on the levee

Figure 12. Water level higher than the canal liner installed

Most damage has occurred on the exposed areas of the liner and top side walls of the canal. Figure 13 shows a cut made with a sharp object (probably intentional vandalism) verses Figure 14 could have been a case of unintentional vandalism. In areas where kids are playing, swimming in the canals, or being mischievous, intentional and unintentional vandalism will occur. Vultures have been reported to pick at the seams on the EPDM Rubber; animal hoofs can cut some liners.

Figure 13. Horizontal cuts likely due to vandalism on the canal sidewall

Figure 14. Vertical cut or tear on canal side wall caused unintentionally

Use of a Protective Barrier

While the initial costs of a lining project using a use of a protective barrier such as shotcrete are higher, these costs may be offset by the reduction in costs of maintenance and repairs over the life of the project. An important consideration is the ability shotcrete to adhere to the liner. The polyester material has small fibers (similar to the harden side of Velcro) to which the shotcrete will stick when sprayed on to the liner (Figure 15). On the other hand, the PVC liner has a smooth texture to which the shotcrete will not stick, and a wire mesh needs to be used on the top of the liner to provide grip and added reinforcement. This application also increases labor and cost.

Figure 15. Shotcrete being sprayed onto the fibrous polyester liner

Maintenance

A regular inspection and maintenance program is important so that repairs can be completed on a time basis. Once a tear or cut starts, it will tend to expand or be susceptible to further damage until it is repaired. Districts should consider having their personnel trained to performed the repair and maintenance which sometimes requires specialized equipment, and similar glues and adhesives used during the installation process (Figures 16 and 17). Removing sediment from lined canals may be more difficult due to the limitations of using heavy machinery, and may require increased manual labor (Figure 18).

Figure 16. A district maintenance crew repairing a damage section of lining

Figure 17. Repair of the liner joints around a structure with glue

Figure 18. Sedimentation at the bottom of a lined canal

CONCLUSIONS

The best performers were the two types of synthetic liners (PVC and polyester) with a protective barrier of shotcrete, which have shown no problems to-date. All five projects using a protective barrier were rated with a score of excellent since installation. The use of a protective barrier can extend the life of the lining project by preventing inadvertent damage and discouraging vandalism. The noticeable difference between the two types of liners was the ability of the polyester to hold the shotcrete in place on the canal sidewalls. The PVC liner required an additional support system using a wire mesh overlay serving as the attachment between the material and the shotcrete.

The performance of the synthetic liners without a protective barrier varied dramatically, ranging from excellent to having serious problems. Some were found to be more susceptible to such factors as installation problems, unintentional damage and vandalism.

Most of the damage to the synthetic liners occurred around the exposed areas of the liner near the top anchor attachments and top side walls of the canal. If the damage is not repaired in a timely manner, small tears can grow into larger ones. In general, exposed synthetic liners need more frequent inspections and regular maintenance.

In conclusion, the initial costs of a canal lining project will vary depending on the type of material and whether a protective barrier is used. For that reason, when planning a project, especially in areas of high traffic (animals and pedestrians), the district should consider if the short-term costs of adding a protective barrier will be more cost-effective compared to the long-term costs that will be incurred due to maintenance and repairs from the lining being damaged.

FUTURE COLLABORATIVE EFFORTS

Collaborative efforts are underway to assess more geosynthetic canal lining materials. Texas AgriLife Extension engineers and the Specialty Products division of Firestone are demonstrating three reinforced geomembranes with Adams Garden Irrigation District. The three lining materials included: 300 feet of Green TPO-R 0.060", 110 feet of Black Reinforced EPDM 0.045", and 160 feet of Black Reinforced fpp-R 0.045". During installation, the Extension engineers monitored and evaluated the installation techniques and materials used. The joining methods of the materials and sections were done using the overlap method and TPO QuickPrime tape along with a six inch wide standard unsupported QuickSeam Coverstrip. Further testing methods are being assessed such as tear and puncture testing methods used in the geosynthetic market today.

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SOUTH PLATTE DITCH COMPANY ─ DEMONSTRATION FLOW MONITORING AND DATA COLLECTION PROJECT

Tom Gill[1]
Charles Bartlett[2]

ABSTRACT

The Prior Appropriation Doctrine formulated in early-day Colorado as a means of appropriating water used primarily by the mining industry became the framework of water law for most states of the western United States. Colorado has also been a front-runner in establishing legal recognition of the hydraulic connection between surface streams and the tributary aquifers in within stream basins. Colorado's Water Right Determination and Administration Act of 1969 was passed to integrate administration of groundwater pumped from tributary aquifers with the administration of diversions from surface streams. The impact of the 1969 act on well users was magnified by a 2001 Colorado Supreme Court ruling, (Empire Lodge Homeowner's Association vs. Moyer), subsequent to which eastern Colorado water users that depend at least in part on groundwater wells have faced a dramatic increase in requirements for measuring and recording water flows.

A case-study is presented documenting an effort spearheaded by the South Platte Ditch Company (SPDC) in northeastern Colorado with objectives of improving flow measurement capabilities and of simplifying data collection and data management tasks. After an initial season with two field sites, representing SPDC's first experience with electronic flow monitoring equipment, the district quickly recognized that integration of electronic technologies represented a steep learning curve, and saw evidence that significant mutual benefits could be realized if multiple small districts like themselves (along with individual irrigators) could jointly establish and utilize a wireless data collection network.

A grant to fund a broader scale demonstration project was awarded to SPDC by the Colorado Water Conservation Board (CWCB) in late 2005. The key objective of the project is to enable water users to make water management decisions – including augmentation of stream flows to offset depletions due to past well pumping – based on real-time data. In the aftermath of the 2001 Empire Lodge ruling, well augmentation requirements are being quantified based on "worse-case" projections using data whose availability is typically lagged a month or more. Cooperating partners in the demonstration project include the South Platte Ditch Co.; shareholders of the Johnson and Edwards Ditch Co.; the Lower South Platte Water Conservancy District; the Colorado Division of Water Resources; US Bureau of Reclamation; Control Design Inc. along with limited support of other water entities and equipment manufacturers.

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[1] Hydraulic Engineer, US Bureau of Reclamation, USCID Member
[2] Project Coordinator, Irrigator, Board Member of South Platte Ditch Company

BACKGROUND

Colorado’s Water Right Determination and Administration Act of 1969 (1969 Act) brought operation of wells pumping from tributary aquifers under the Prior Appropriation Doctrine that is the basis for Colorado water laws governing diversion of water from surface streams. The 1969 Act was passed in recognition of the hydraulic connectivity between surface streams and alluvial aquifers in a stream basin whereby pumping of wells with junior water rights creates injuries to senior surface water rights holders on a time delayed basis. The 1969 Act called for well owners to secure water supplies that could be used to augment surface flows to repair injuries “in time and in place” that would otherwise be inflicted on senior water rights as a result of well pumping.

As a potential augmentation supply, the idea of developing groundwater recharge systems emerged. At times when available stream flow exceeded calls by established water right holders, flows could be diverted from the surface stream and routed to a point it could be allowed to percolate through the soil profile and “recharge” the alluvial aquifer. This would have the effect of augmenting surface flow on a delayed basis in the inverse manner in which well pumping depletes surface flow on a delayed basis.

The South Platte Ditch Company (SPDC) was a cooperative partner in a demonstration pilot groundwater recharge project initiated in 1972. Other participants in the project included the now defunct Groundwater Appropriators of the South Platte River Basin Inc. (GASP), Colorado State University (CSU), and the Colorado Division of Water Resources, (CDWR). In a continuation of the pilot project, SPDC eventually secured one of the most senior recharge diversion rights along the South Platte River with a priority date of 1974. During the early years of operation, return flows from the SPDC recharge project that were projected to augment surface flow at times when surface flow was insufficient to meet demands were leased to the GASP organization on an annual basis. SPDC irrigators who also operated wells enrolled their wells in GASP to administer augmentation needs. During this period, flows in the SPDC recharge project were documented using paper-chart flow recorders.

A 2001 Colorado Supreme Court Ruling, Empire Lodge Homeowner’s Association vs. Moyer, (Empire Lodge Ruling) dramatically shifted how the 1969 Act would be administered by the State Engineer’s Office within the CDWR. Accounting for well usage and the projected delayed injury to surface flows, along with the monitoring of stream augmentation to repair well pumping injuries has subsequently been held to a higher degree of precision both in terms of timing and location. A culture of accounting for flows on a monthly or even seasonal basis lacked the type of data availability needed to adjust rapidly to new operational constraints.

Wells that were able to remain in operation have done so for the large part by furnishing augmentation supplies to meet “worse-case” scenarios by which – even in an unusually dry year when greater than normal pumping might be required and when less than normal recharge accretions and/or other augmentation sources might be available – the well owner could demonstrate the capability of offsetting any stream flow injury with sufficient augmentation supplies.

Flow meters on wells are required to be recorded daily, but are reported monthly to the Office of the State Engineer. Paper chart recorders are being replaced with electronic data loggers that record flow information in 15 minute intervals, but most of these units require periodic on-site data downloads. The steep increase in data management tasks for the State Engineer's office bears little resemblance to modest staffing increases. As a result there is a time lag on the order of months between the point in time at which a piece of flow information is recorded and the time at which processed information from the State Engineer is in the hands of the decision maker seeking to ensure his well is appropriately augmented. Under this operating scenario, well depletions are typically over augmented using projections generated from the most recent available – but a month or more old – data. Progressive irrigation managers have recognized access to real-time flow data as potentially a key aspect for long-term economic viability of irrigated operations along the Colorado South Platte Basin.

PROJECT STARTUP

During the spring of 2005 an SPDC board member contacted an engineer at Reclamation's Hydraulics Investigations and Laboratory Services Group (HILS) in Denver seeking information on electronic flow measurement data collection equipment. As a demonstration project, HILS agreed to install a low cost system that had been developed in-house for an application at the East Bench Irrigation District in Montana. The device which HILS staff called the Continuous Flow Meter (CFM) was assembled using a programmable logic controller with integral display module that was marketed as a hobby robot controller.

An analog signal from any of a range of readily available electronic level sensors could be linked to the controller and calibrated to measure water level. A simple program written in a BASIC programming language would first apply calibrated slope and offset constants to an equation to calculate water level. This level value was then input into a power equation with calibration constants appropriate for the flow measurement structure at which the unit was installed. A desired measurement time interval (i.e. 15 minutes) input into the CFM program would trigger a measurement cycle. Once a flow rate had been calculated, a volume increment was determined based on the measured flow and the elapsed time from the previous reading. This volume increment would be added to a previous running total value. With each reading cycle, the most recently measured flow depth, flow rate, and total volume would be displayed on the CFM.

CFM units were installed at two locations on the SPCD recharge system to operate in parallel with existing Stevens paper chart recorders. A key shortcoming of the CFM for this application was the limited on-board memory which was insufficient for storing data logged values. The State Engineer's requirement of logging flow values at 15 minute intervals could not be met with this equipment. Approximately a month after installation both CFM units were removed.

DATA LOGGING AND TELEMETRY

During the same time frame the SPDC demonstration project was being initiated, HILS engineers came in contact with Control Design Inc. (CDI) of Placitas NM. CDI produces units that consist of a programmable logic controller coupled with a proprietary communications modem plus a communications radio operating on UHF frequency. Upon learning of the SPDC demonstration project, CDI offered use of equipment for two field sites plus two office base units for the 2005 season.

The CDI programmable controllers are designed around radio communications operation. All available on-board memory, including memory available for data logged values, is configured as Modbus registers. CDI worked with HILS engineers to develop a flow monitoring program for the demonstration project. A software program provided by CDI named Project 3 was installed on a Windows-based computer at a SPDC office site as well as at the Lower South Platte Water Conservancy District (LSPW CD) in Sterling CO. Project 3 can be configured to direct CDI base units to periodically poll field sites and download accumulated logged data values. Retrieved data is then stored on the computer hard drive in an Excel compatible .csv data file.

CDI units were installed on the SPDC recharge system at the two sites where the CFM units had previously been. Figure 1 shows the installation at the original G2 flume. This site marks the beginning of the reach of the Sandhill ditch for which SPDC receives recharge credit for canal seepage losses. Figure 2 shows the Sandhill pond installation.

Figure 1. 2005 Photo of the SPDC G2 Flume

Figure 2. 2005 Installation at the SPDC Sandhill Pond Entrance

During 2005 operations, the CDI equipment provided a promising level of performance with regard to performing on-site functions and in reliably performing data transmission tasks. Performance of third-party level sensors on the other hand was somewhat sporadic. The ultrasonic “down-looker” level sensors that were being used at both sites repeatedly lost accuracy at temperatures approaching freezing.

Another system “snag” encountered during 2005 was related to attempting to collect data at two office locations. The Project 3 software which is available for download from CDI’s web site was developed for systems with a single data-collection node. As field sites were polled by an office base unit, Project 3 would reset the field units to write the next data in the initial Modbus register of register field designated for data logging. Unless a second base attempting to retrieve the same data did so before the subsequent 15 minute data cycle, or else some data registers would be overwritten. It was deemed important for the CDWR or an entity acting on CDWR’s behalf (i.e. LSPWCD) to receive direct transmission of recharge project field data. At the same time, it was important for SPCD to also have real-time access to the field data to ensure that all fields sites are functioning properly at any point in time.

Overall, SPDC recognized significant value in benefits it could realize from electronic flow monitoring coupled with a reliable wireless data telemetry system. The limited-scope of the 2005 demonstration project left SPDC interested in seeking a means of extending the demonstration to develop a framework for a network that could potentially be beneficial for multiple water using entities in the area.

EXPANDED DEMONSTRATION PROJECT

Following the 2005 irrigation season, SPDC board members that had worked closely with the demonstration project approached two neighboring districts to see whether there might be support for a multi-district effort to seek funding support from the Colorado Water Conservation Board (CWCB). After receiving an affirmative response from the boards of both neighboring districts, a funding proposal was submitted to the CWCB. During the CWCB November 2005 board meeting, $100,000 in grant funding was awarded to the project over a three year period.

Shortly after grant funding was approved the project encountered controversy. One of the neighboring districts notified SPDC that they had decided not to participate in the demonstration project. Issues linked to the ramifications of the Empire Lodge ruling and the subsequent demise of GASP represented a strain on resources of the district and of individual shareholders. The other partnering district notified SPDC that some of their shareholders had entered into an option agreement for sale of ditch company shares. Those shareholders whom had entered the option agreement did not want wireless monitoring equipment installed at sites owned by them or on district owned sites.

Following these developments, an agreement was negotiated with CWCB whereby the scope of the CWCB-funded project would include monitoring locations within the SPDC system, plus key control structures that SPDC planned to look at automated or remote manual operating capabilities. In addition, willing shareholders in the Johnson & Edwards Ditch Company (J & E) agreed to install radio/control equipment on wells designated through water court as Alternate Points of Diversion to J & E surface rights, and at recharge facilities owned by participating J & E shareholders.

Ironing out these controversies consumed considerable time. A contract for the grant funding was finally issued by CWCB in April 2007. At that point in time, CDI notified project participants that the company was developing an upgraded product line that would be specifically geared toward low energy consumption for solar charged applications. In addition, the new product would be developed entirely “in-house” to eliminate quality control issues CDI had been experiencing with circuit boards developed for CDI by a contracting electronic design firm. New CDI units would not be available till late 2007.

After weighing factors including comparative product affordability, the high level of technical support that had been provided, and the “fit” of CDI product capabilities with project operational needs led SPDC and J & E participants in the demonstration project decide to delay start-up of installations with CWCB assisted funding until the new CDI product line was in production. The first new units were installed in the fall of 2007 at the SPDC main flume, and at the SPDC G2 and Sandhill Pond recharge sites.

A project task funded by SPDC was replacement of the G2 flume. The previous flume was a trapezoidal flume constructed of sheet metal. The trapezoidal flume lacked lateral support members and over time the sides had been pushed in to the point where calibrations for the “as-fabricated” cross sectional geometry were no longer valid. Additionally, backwater effects on the trapezoidal flume resulted in it operating under excess submergence at flow rates commonly encountered at the site. A new ramp-type long throated flume was constructed at G2 in September of 2007. Figure 3 shows the completed installation at the new G2 flume.

Figure 3. New Ramp-Type Long-Throated Flume at the SPDC G2 Site

During 2008, radio/control equipment was installed at additional recharge sites on the SPDC recharge system, and at one site on the J & E recharge system. A new base unit was installed at the Lower South Platte Water Conservancy District (LSPWCD) office in Sterling CO. CDI radio/control units were also installed on four J & E alternate point of diversion wells. At all recharge sites, redundant recording devices are in place.

At the SPDC main flume and the J & E recharge site, Sutron Stage & Discharge Recorder (SDR) units are installed. At the remaining SPDC recharge sites, Stevens type F chart recorders are installed. Both the Sutron SDR units and the Stevens type F recorders utilize float and pulley type level sensors. In an effort to minimize variability between recording technologies, multi-turn potentiometers were installed on the Sutron and Stevens equipment to serve as level sensors for the CDI radio/control units.

Each of the J & E alternate point of diversion wells was already equipped with McCrometer propeller meters. In order to provide electronic input signal for the CDI radio/control units, pulse output modules were installed on the McCrometer meters. Translation of pusles into flow rate was calibrated by starting with a McCrometer-supplied “K” factor then comparing the electronic totalized flow with the totalized value on the mechanical McCrometer over extended run time. The K factors have adjusted in an effort to achieve outputs as nearly synchronized as possible.

Level measurement accuracies are a point of focus. With the open channel sites, it is a straight-forward task to identify slope and offset values for the electronic sensors (multi-turn potentiometers linked to a float & pulley apparatus). With these calibrated constants, the radio/control equipment is able to make an accurate a determination of water level, and in turn of flow within the accuracy limits of the flow measurement structure. There is greater uncertainty in the monitored pump flow. Propeller meter measurement accuracy is difficult to verify without installation of an independent flow meter of known accuracy in series with the propeller meter. Thus the system being employed on the J & E alternate point of diversion wells is presently limited to the unknown accuracy of installed propeller meters.

A potentiometer installed on a Stevens type F recorder is shown in Figure 4. A kit available from Stevens enables a multi-turn potentiometer to be installed in the gear mechanism of the type F recorder. Others who have utilized this kit report that they typically needed to reset the offset on the potentiometer every time a new paper chart is loaded, as it is common practice to loosen the thumb screw that tightens the pulley to the shaft it rotates to adjust the chart to the existing flow level. For this project it was reasoned that by attaching directly to the pulley, the relationship between float elevation and potentiometer rotation would remain constant despite these chart-setting adjustments.

Figure 4. A Potentiometer Mounted to a Stevens type F Recorder Pulley

After installing the pulley-mounted potentiometers, it became apparent that not only do chart installers loosen the thumb screw for adjustments, lifting the beaded float cable off the pulley is another commonly employed practice. SPDC has encountered repeated instances of the potentiometer offset getting off a distance equal to one or multiple times the distance between bead notches in the pulley after CDWR staff had installed new paper charts. Presumably this will be a problem that goes away as CDWR develops a confidence level in the radio/control monitoring and telemetry system and agrees to discontinue the redundant datalogging using paper charts.

Figure 5 shows a McCrometer meter with pulse output module installed on a well discharge pipe. The pulse output generator is installed at the base of the mechanical meter. Installing this module requires a shaft extension for the mechanical meter as well as longer screws to secure the mechanical meter to the meter base.

Figure 5. A Pulse Output Module Installed on a McCrometer Meter at a J & E Well

Despite the availability of on-site electrical power, all radio/control installations in the project are powered using solar charged systems. This was done to eliminate the potential of damaging surge voltage coming in through power supply lines. The CDI radio/control units feature an on-board charge controller to maintain battery voltage within an appropriate range.

In addition to the flow monitoring and logging functions the radio/control units are currently performing, they may be programmed to perform expanded functions in the future. The capability exists to perform tasks such as monitoring of pump panel fuses, panel or motor temperature, timed startup and/or stoppage of the wells, remotely controlled well startup or stoppage, etc. Figure 6 shows the radio/control unit installation at a J&E well site.

Figure 6. A CDI Radio/Control Unit Installed in the Pump House Shown in Figure 5

FLOW CONTROL

During 2009, the first gate automation site was added to the SPDC demonstration project. A lateral that serves approximately one-third of SPDC acreage, referred to as the "Company Lateral", branches off near mid reach of the main SPDC canal. Flow entering the Company Lateral is controlled by a vertical slide gate. Lateral flow is measured at a flume located approximately 70 yards below the gate. The gate is automated to maintain a target flow rate. CDI radio/control units were installed at both the gate and flume sites. The flume unit reads the water level and calculates a flow rate every 60 seconds. The gate unit calls the flume site to obtain current data and determines whether or not a gate adjustment is called for at 3 minute intervals.

The gate was previously operated by turning a hand-wheel about a threaded rod attached to the gate leaf. A chain drive system was installed to motorize the gate. The rim of a 50 tooth sprocket sized for #50 roller chain is attached to the underside of the gate hand wheel. A 20 rpm gear drive 12 volt DC motor with a 12 tooth sprocket is mounted to the top of the gate frame. Gate position is monitored using a multi-turn potentiometer linked to a gear that engages in the gate stem threads. Limit switches are installed to interrupt the motor circuit as a redundant safety limit to software limits programmed into the control unit. Figure 7 shows the Company Lateral Gate with motorization equipment installed.

Figure 7. Gate Automation Equipment at SPDC Company Lateral Headgate

SPDC may adjust the gate by multiple means. A new target value may be entered at the District office using a PC linked to the base radio unit. SPDC also has a mobile radio/control unit marketed by CDI as the "Ditch Rider Unit". Following on-screen prompts and providing inputs using the six button keypad, the ditch rider can check current conditions and/or enter a new target value from his pickup. While on-site, a new target may be input following on-screen prompts and using keypad inputs on the field CDI unit at the gate site. On-site toggle switches also allow changing control from auto to manual. In manual an on-off-on toggle is labeled for raise-off-lower positions. And finally, should there be a power or motor failure, by removing a safety guard over the gate wheel and disconnecting the roller chain, the site may be reverted to hand operation in minutes.

In 2010, a new motorized overshot gate was installed in a previously stop-log controlled bay at a spill structure just upstream the SPDC main flume. SPDC plans to automate the overshot gate to maintain a target canal bay water level. A three-bay check structure immediately downstream from the spill gates currently features three hand-wheel operated vertical slide gates. SPDC plans to motorize one of these gates and install gate position sensors on all three. Once this is completed, a CDI radio/control unit will control automation of the overshot gate to maintain a target upstream water level and calculate gate-measured spill discharge. The same CDI unit will control the motorized gate in the adjacent check to maintain a target flow rate at the SPDC main flume. Figure 8 is a photo of the overshot gate in the SPDC spill structure.

Figure 8. Newly Installed Overshot Gate at the SPDC Spill Structure

FIELD DAYS

SPDC and the participating J&E shareholders have hosted annual field days open to all interested parties in 2008 and 2009. A September date is currently being targeted for a 2010 field day. Figure 9 is a photo of the 2008 field day field tour.

Figure 9. 2008 Field Day Tour Stop at the SPDC Main Flume

LONG-DISTANCE NETWORK BACKBONE

During 2009, a component was added to the demonstration phase of the project to look at potential benefits of a system extending beyond the SPDC and participating J & E shareholders. A task to demonstrate the transmission range that can be provided by the CDI equipment was carried out by establishing a series of repeater stations. Key additions were repeater units on towers owned by KCI, a local internet provider based on Sterling CO.

A CDI radio/control unit was installed on a KCI tower on the west edge of Fort Morgan. From this site, it is possible to communicate with the SPDC office to the east, and with a CDI repeater station that the Northern Colorado Water Conservancy District (NCWCD) has established approximately 20 miles east of its office complex at Berthoud CO.

A second repeater was installed at what KCI calls its Peetz tower approximately 30 miles northeast of Sterling. From this site, it is possible to communicate to the west with the SPDC office. This site was also be contacted to the east from Julesburg during a radio check using a mobile “ditch rider” unit.

Installation of repeaters at the two KCI towers provides the capability to transmit information from Julesburg to the NCWCD office via repeats at the Peetz KCI tower, the SPDC base, the Fort Morgan KCI tower, and the NCWCD repeater. Remote sites that have been linked to this extended network include a recharge measurement site on the Morgan Ditch system, and a recharge well owned by Roth Brothers near Goodrich. Figure 10 is a map showing nodes of this communication path.

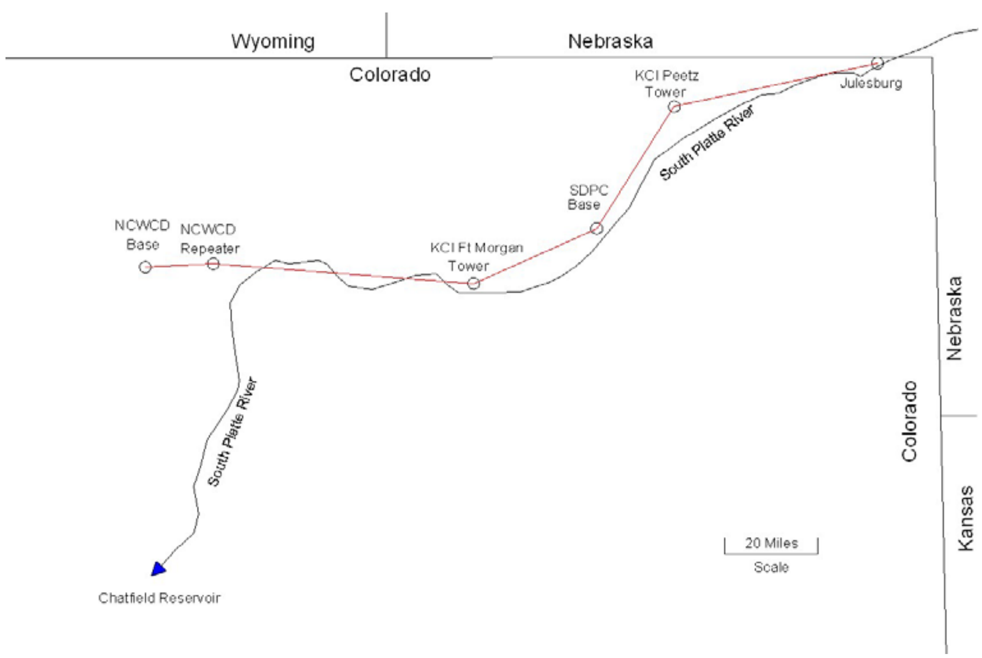

Figure 10. Extended Communications Network Radio Pathway

CURRENT PROJECT STATUS AND FUTURE PLANS

The three year project term defined in the CWCB grant contract ran through April, 2010. As of January 2010, approximately half the funding made available by CWCB had not been spent. As per agreements made at the project outset, there has been some modification of project tasks by mutual agreement of project participants and CWCB staff. The large remaining portion of unspent funds is due in part to some lower than budgeted equipment costs, along with utilization of surplus solar charging equipment made available by Reclamation. In addition, the project has fallen behind schedule on various tasks, as labor requirements that represent in-kind contributions by participants have exceeded estimated time needed.

In early 2010 CWCB granted the project a two year extension. Among remaining tasks is installation of a CDI radio/control unit at the SPDC river diversion. This unit would be linked to a pneumatically operated overshot gate on the river dam and to a similar gate in the canal mouth. SPDC plans to use gate-measured flow passing the spill structure as feedback for automated or remotely operated adjustments of the river diversion structure. Other installations planned include additional SPDC recharge monitoring sites, additional J&E alternate point of diversion wells, monitoring of an SPDC ditch pump and monitoring flow of an SPDC well utilizing pressure differential at a pipe diameter reduction.

In addition to remaining planned field installations, project participants are developing a plan to revise the data collection/data management aspect of the project. Attempts to enable polling of field units by multiple entities have come up against multiple constraints. Present plans are to set up an internet server at the SPDC base site and handle data collection exclusively through the SPDC base unit. Retrieve data would be logged and stored on-site in addition to being posted on the internet server.

For control functions and daily operational monitoring tasks, a second radio frequency will be employed along with a second radio/control unit to be installed at the SPDC base. The data collection base radio/control unit will control all direct communications with field sites. The most recently acquired data from field units along with a field-site generated time stamp will be passed to the secondary (or control and daily operations) radio/control base. Remotely entered control set point adjustments will either be entered directly into the secondary base, or radio transmitted to the secondary base from the mobile ditch rider unit, then passed from the secondary base to the primary base for transmission to field sites.

Similarly, alarm conditions detected by field units will read as part of the data polling process by the primary base. Alarms will then be passed to the secondary base. As alarm conditions are detected, the secondary unit can directly pass alarm information to mobile ditch rider units. A third-party alarm system linked to digital output ports of the secondary base unit will also be able to send out alarm messages by phone or by voice or pager radio systems.

SUMMARY

SPDC and participating partners have been able to develop a framework for a system that can significantly improve capabilities to manage and more efficiently use irrigation water supplies. The CWCB grant has enabled participants to develop a system that addresses issues unique to their needs and the regulatory environment in which eastern Colorado irrigation districts operate.

One aspect that may have been less than fully appreciated by project participants at the outset is the amount of time that a project of this nature might require. Some of this can be attributed to the versatility of the radio/control devices being utilized. As CDI founder Jim Conley has jokingly stated to project participants on multiple occasions, "Unfortunately, there isn't very much you can't make this equipment do." As the equipment capabilities become more fully appreciated, it is difficult to resist trying to incorporate additional tasks. Much time gets tied up developing and field testing programs that will "do more things". As the programs being developed become more complex, the debugging process seems to become exponentially more time consuming.

At present the SPDC demonstration projects includes numerous loose ends. At the same time, equipment configurations and programming that have been developed as part of this project will be readily transferable to other projects. To wit, flow monitoring and gate control algorithms utilized on this project are being utilized by Reclamation and others on irrigation systems distributed over several western US states. The loose ends aspect is likely to persist as long as creative minds are looking for better ways to do things. Each accomplishment seems to open up a myriad of previously unconsidered possibilities.

THE CASE FOR DITCH-WIDE WATER RIGHTS ANALYSIS IN COLORADO

Donald O. Magnuson[1]
Stephen W. Smith[2]

ABSTRACT

In Colorado, the pressures on the historic native water rights are tremendous. Senior water rights that have been in place since the 1800's are now frequently changed to accommodate transfers to municipal and industrial use or an environmental use. Senior water rights are also frequently changed as well augmentation is added as a water use. In order to begin a change case in Colorado Water Court, the historic consumptive use (CU) of the water right must be established through an engineering study. Various historic use records, assumptions, period of record, and other elements of the engineering study come under intense scrutiny by objectors in the case and by the Court.

Most commonly, ditch companies actually hold the decreed water right and each shareholder in the ditch system owns a proportional amount of that right based on their share holdings. For example, one share out of one hundred shares issued represents one percent ownership of the company and one percent of that water right. In the past, change cases have been initiated, and a new change decree fully adjudicated, in consideration of only a portion of the outstanding shares under the ditch system using what is known as a parcel specific analysis. Issues arise with this in that the amount of shares owned and used to irrigate a certain amount of irrigated ground can vary from one farming operation to another. The pros and cons associated with doing a full ditch-wide analysis of the water right are discussed.

INTRODUCTION

The South Platte Basin has become a focus and "poster child" of many of the interrelated problems associated with population growth and the municipal hunt for growth-driven water. Cities and towns along the Front Range have varying water portfolio amounts in what is commonly referred to as "safe yield" water to serve their growing populations out to a prescribed date. There is often a desperation mentality in play that forces municipal water managers to grasp at all alternatives – water conservation programs, new storage, leak detection, fines for water waste, public information programs, and aggressive water acquisition. As can be imagined, no community wants to be chronically short of water and no administrator wants to be responsible for not securing a suitable amount of water for the future.

Specific to the South Platte Basin, and as noted in Colorado Water Conservation Board's 2004 Statewide Water Supply Initiative report:

[1] Manager, New Cache La Poudre Management Co., Lucerne, Colorado. E-mail: don@newcache.com .
[2] Founding Partner, Regenesis Management Group, 2442 S. Downing St., Suite 250, Denver, Colorado 80210. E-mail: swsmith@regenmg.com .

> "Nearly two-thirds of the increase in the state gross demand by 2030, approximately 409,700 AF, will be in the South Platte Basin. Of the 409,700 AF of increased water demands in the South Platte Basin, the majority of the demand is proposed to be met through existing supplies and water rights and through the implementation of identified projects and processes. However, there are still some anticipated shortfalls expected in certain portions of the basin. The identified shortfalls will be the focus for supply alternatives developed for the basin." (Colorado Water Conservation Board. *et al.* 2004)

Todd Doherty, program manager with the Colorado Water Conservation Board noted in a recent Colorado Water issue that "most of the demand (water for population growth) will be met through three main water supply strategies: conservation, agricultural transfers, and new water supply development." He goes on to say "if these new water supply projects are not built, future water demands will have to be met mostly through a combination of agricultural transfers and conservation" (Doherty 2010).

In recent U.S. congressional hearing, Jennifer Gimbel, Director, Colorado Water Conservation Board, offered the following expert testimony:

> "The projected growth in the South Platte River basin will create water supply challenges for the agricultural community. The basin currently irrigates approximately 830,000 acres. Since 2001, the basin has seen a decline of approximately 100,000 irrigated acres due to well curtailment, urbanization and urban transfers. The basin will likely lose 40,000 to 50,000 acres as a result of urbanization. An additional 160,000 to 280,000 acres is expected to be lost due to agricultural to municipal transfers--combined this could equate to a 25% to 40% reduction in its irrigated acreage in the basin by the year 2050. There are several projects working through the federal permitting process that could assist in helping to minimize the loss of irrigated agriculture. Those projects include Halligan-Seaman Project, Moffat Collection System Project, Windy Gap Firming Project, Northern Integrated Supply Project (NISP) and Chatfield Enlargement Project. However, comments from the Environmental Protection Agency suggest that agriculture dry-up is the least environmentally damaging alternative to most of the proposed projects. This conclusion ignores the environmental benefits of the irrigated acreage itself, as well as the return flows, riparian environment and wetlands that are created"(Gimbel 2010).

Clearly water to serve the anticipated population growth, and the well augmentation needs anticipated in the South Platte and other areas of Colorado, is going to be a significant issue over the next few decades and water right change cases are likely to abound.

WATER RIGHTS IN COLORADO

Colorado was the first state to develop a system of water rights and laws based on the prior appropriation system. The underpinning of the system is “first in time, first in right.” So, if you were the first to divert the water from a stream, then you are the first priority on the river, and so forth. Calls on the river are satisfied according to the priority or priorities enjoyed by the water right holder. This approach, started in the mid-1800s, has worked quite well for Colorado and other western states that operate under the prior appropriation system (Schempp 2009).

In the late 1960’s, a State of Colorado statute legally recognized that tributary ground water is hydrologically connected to surface water[3]. Consequently, both ground water and surface water are administered under Colorado’s prior appropriation system. Colorado’s water supply can come from either surface or tributary ground water sources, both of which are governed in the same way.

When water rights are changed, the CU must be established through an engineering analysis and subsequent report that accompanies the change case and the ultimate change decree (Jones and Cech 2009).

HISTORIC CONSUMPTIVE USE ANALYSIS

The amount of the CU per share really establishes the water right in Colorado whether that CU has been quantified and decree or not. The historic diversions at the river headgate are a vital part of the historic record but the understanding of the historic CU is indicative of the value of the water right. The diverting of water at the river headgate has not only established the priority and gross volume of the diversion water right, but arguably and more importantly, the beneficial use of the water has established the volume of the water consumed under that water right.

As an overly simplified example, consider two 500-acre farms with different water rights. One farm as been historically irrigated with 3,000 acre feet of water diverted from the river, while the other farm has been irrigated with 2,000 acre feet of water diverted from the river. Both farms have historically grown corn and let us assume the CU for corn is 2 acre feet per acre or 1,000 acre feet for either of the 500-acre farms. So, the CU for each farm is identical. The farm that diverted 3,000 acre feet returns more water to the river than the other farm as either surface return flows or a subsurface return flows. The consumptively used water <u>is the same</u> in either case considering the area is 500 acres and the crop is corn. Hence, the water right is the same for both farms.

(Pease 2010) notes these overview requirements about water rights transfers:

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[3] When this paper refers to ground water, reference is made to tributary ground water that is hydrologically connected to surface water in streams and rivers. This should not be confused with deep, closed basin ground water, which is not regulated by the prior appropriation system in Colorado.

> Often a transfer of water has unknown impacts on downstream users, or at least an impact that is difficult to quantify. A water right should contain the following information:
>
> - a diversionary amount
> - a consumptive amount
> - the point of diversion
> - the purpose of use
> - place of use
> - the priority date of the right.
>
> Also important, but often omitted from water rights are, the time of year during which water can be diverted from a water course, and the size and location where return flows reenter the system. A change in any of these attributes can negatively impact downstream users.

The need and justification for establishing the CU of a water right must first exist. If farmers have beneficially used a water right decreed for irrigation for a long period, then they can continue to use the water right in that way indefinitely with no need to define or quantify CU. An evaluation of CU is generally driven by a change in the type of use, place of diversion, or the quantity of water diverted. <u>Because the engineering to establish historic consumptive use is time consuming and therefore costly, it is unlikely that anyone would take on the effort without justification.</u>

DITCH-WIDE VERSUS SMALL PARCEL (SHARE BLOCK) ANALYSIS

A historic consumptive use analysis can be accomplished for a single parcel (shareholder) or a subset of the full shareholder group in a parcel specific analysis, or it can be done for the full service area of the Company, which is referred to as a ditch wide analysis.

In a case commonly known as the "Jones Ditch Case" (See *In Re Water Rights of Central Colorado Water Conservancy District*, 147 P.3d9 (Colo. 2006), the Supreme Court stated that a ditch wide analysis is preferred. Unfortunately, the court did not elaborate as to why a ditch wide analysis is preferred. Even though the decision leaves considerable room for speculation and future litigation might bring clarification, to date, both approaches for calculating CU are legally valid.

The issues are exemplified by the histogram depicted in Figure 1. At some time in the distant past, with many ditch companies, there might have been rather narrow distribution of shares for a given acreage of land. Over time, especially over a 100-year plus timeframe, some farmers may have sold shares and others may have bought shares within the company and under the confines of the service area of the ditch. This is normal and represents a perfectly legal and acceptable means of selling and buying shares within an irrigation mutual company – willing seller and willing buyer. The reasons for the movement of shares within the company is not material but the exchanges were likely driven by one shareholder's need to sell an asset to raise cash and another shareholder's desire to increase their water holdings. The primary point here is that some farms, through this process of buying and selling, can become water short and others water long.

Figure 1 shows an example of the disparity that result. The average consumptive use for this example is 28 acre feet per share if a ditch-wide analysis were conducted. By contrast if a group of water short shareholders initiated a change case, then their quantified CU per share would be higher, and if a group of water long shareholders initiated a change case, then the CU per share would be less than the average.

Refer to Table 1 for a summary of reasons, from the shareholder perspective, as to why a parcel analysis or a ditch wide analysis is preferred. A summarizing question for consideration is this: the stockholder owns a pro rata interest in the water right. The stockholder pays a pro rata portion of the operating expenses through assessments. So, why would the stockholder have anything other than a pro rata interest in the CU given that CU is the true measure of the water right?

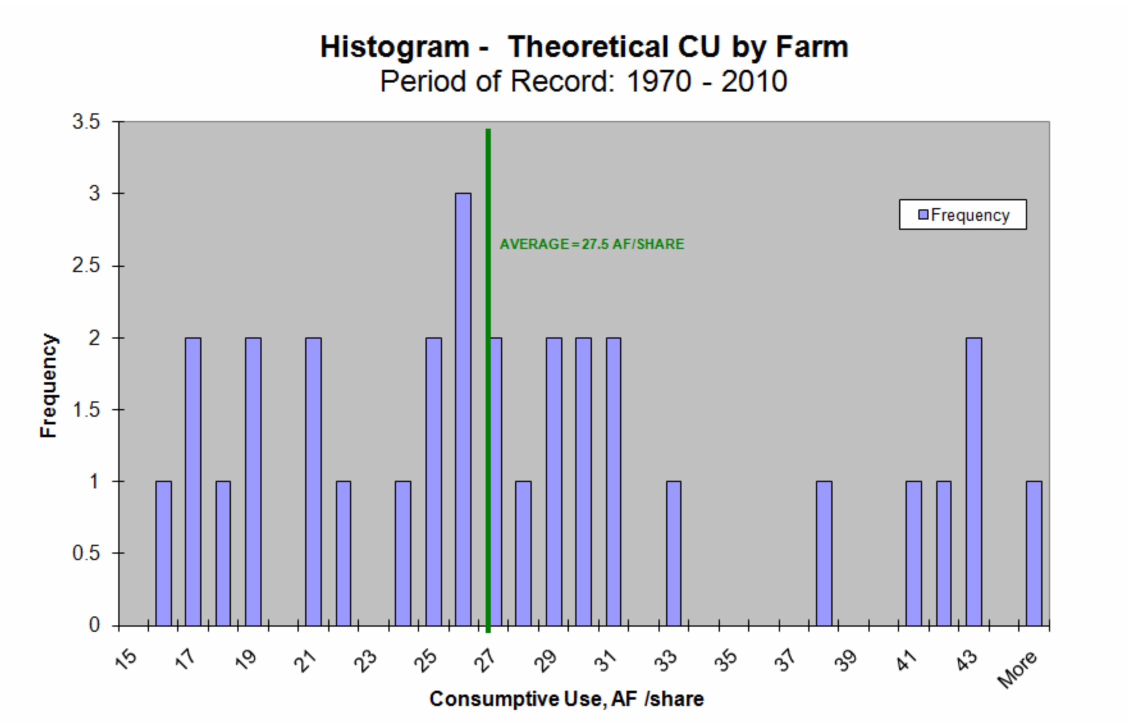

Figure 1. A histogram depicting the variability that can result due to willing seller and willing buyer exchanges of company stock over time. In this example, the average CU per share is 28 AF/share but outliers show the variance that is possible.

Table 1. The primary pros and cons of a ditch-wide versus a parcel specific (share block) analysis of CU.

PARCEL SPECIFIC ANALYSIS	DITCH WIDE ANALYSIS
CU varies from parcel to parcel (share to share)	CU equal for every share
Dry up acres vary for every parcel or share (but limited to parcel involved)	Dry up acres equal for every share
Cheaper analysis short term	Market develops for surplus dry up acres
Exposes stockholders to multiple inaccuracies from different sources in differing analyses	More expensive analysis short term
Often done using river diversion record and not headgate deliveries	Opens system to easier changes in the future
Favors those with fewer shares per acre	Favors those with fewer acres per share
Favors those who improved irrigation facilities (if they increased the acres irrigated)	Favors those who paid the expenses historically
Favors those who sold off water	
Shareholders may not be aware that a parcel level change may affect their CU per share	All shareholders are informed and participants in the change case
Requires the company to be involved in multiple analyses with multiple engineers and attorneys.	More indicative of the intent and spirit of a mutual ditch company

SUMMARY

In consideration of a parcel specific analysis of CU versus a ditch wide analysis of CU, the summary points are these:

1) A change of shares by any stockholder has the potential to adversely impact another or all stockholders if not properly accomplished.

2) There are pitfalls with either approach if you view the question from strictly the point of view of the water long versus the water short shareholder.

3) A more magnanimous approach in asking "what's best for the irrigation mutual company as a whole?" is probably preferred.

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BORE WELLS – A BOON FOR TAIL END USERS

Rajeev Kumar Goyal, M.I.E.[1]

ABSTRACT

The efficiency of an irrigation engineer can be well judged from the canal water available at tail ends of the canals under his control. But often he finds it difficult to maintain authorised share of water at tails. In India position is particularly precarious during rice sowing period, which is monsoon season, i.e. rainy season in India at that time. It is the peak demand period for canal water. A deficit monsoon coupled with water theft makes it very difficult for authorised share to reach at tail ends. On the other hand, a good rain can cause tails to get flooded. It causes great loss to tail end users.

This problem can be solved to some extent with the help of bore wells or dug wells, dug along the canal, more of them in the last one third of the length of the canal. These dug wells will act as rechargers of ground water during the period when there is excess of supply of water in the canals by diverting excess water to these bore wells, and will act as boosters during short supply by drawing this water through tube wells and mixing it with canal water. Though conjunctive use of tube wells along with canal water is being practised since long, this technique of first recharging aquifers with surplus canal water and then withdrawing this recharged ground water through tube wells during peak demand period, is particularly useful where ground water is otherwise brackish and is unfit for use.

INTRODUCTION AND BACKGROUND

Through this paper, an effort has been made to visualize how such a system can be developed, maintained and operated, what should be the design parameters, what problems can occur, what can be the solutions for such problems etc.

Punjab, which is known as food basket of India, is having the most developed Canal System in India. The green revolution has been possible only due to such a well developed canal system. Multipurpose projects like Bhakhra Dam project, Pong Dam project, Ranjit Sagar Project has made it possible to develop such a vast canal network. Some famous canals flowing through Punjab are Indira Gandhi National Canal, Bikaner Canal, Upper Bari Doab Canal, Bhakra main Line Canal, Sirhind Canal etc. These canals has made Punjab a basket of grains. These canals take off from Harike Headworks, Madhopur Headworks and Nangal Headworks. Figure 1 on the following page shows one such canal of vast network of canals in Punjab.

[1]Sub Divisional Officer, Punjab Irrigation Department, Rajuwala canal sub Division, Rajuwala (Faridkot), Punjab (INDIA)E-mail : goyal_rkg2003@yahoo.com

Figure 1. Photo of a canal in Punjab

Apart from canal network, a large number of tube wells are drawing underground water to fulfil water requirement of ever demanding crops. The over utilization of underground water has rendered water level to go down to drastic levels, resulting into 59 blocks out of 118 blocks of Punjab being declared as Black. In Faridkot, Mukatsar, Moga, Bathinda, Mansa, Ferozepur Districts of south Punjab, the underground water is becoming unsuitable for irrigation as over exploitation of underground water leaves behind brackish water due to increased concentration of salts in residual water.

A number of studies has been conducted to know the characteristics of ground water in this area and most of the results are shocking for the farming sector in particular and general public at large. The quality of underground water has gone so down that it is resulting into large number of health problems like spurt in cancer patients and such other medical problems. The percolation of pesticides into ground water has also resulted into rendering underground water unfit for irrigation or human use.

All this has increased dependence of farming sector more on canal water. This has increased pressure on irrigation men as they are now asked for every fluctuation in canal water. The over dependence on canals has resulted into more cases of water theft also, which hinders proper regulation of water. All this results in large fluctuations in canal water at the tail ends. Figure 2 below depicts shortage of water at tails.

Figure 2. Tails with short supply of water

Several existing canal irrigation systems suffer from inadequate water supplies. The available supply for instance is often less than half the amount needed for intensive agriculture. The total quantity of irrigation water is neither adequate nor satisfactory & in time. This calls for other measures to augment the available supplies. Tube wells are commonly used for conjunctive use of surface and ground water. The conjunctive use of surface and ground water can take form of augmenting canal supplies by direct pumping of ground water through augmentation tube wells or direct use of ground water during periods of low canal supplies or canal closures. It can also take the form of irrigating a part of the canal command area exclusively with ground water.

The conjunctive use of surface and ground water has been in practice in India to a limited extent. The practice has been prevalent in the Cauvery delta in Tamilnadu, the Godawari canal system in Maharashtra, Yamuna canal system in Haryana and parts of Punjab. In the Cauvery delta, privately owned filter points have been constructed on a large scale to raise paddy seedlings early in June before the canal system is opened. The filter points also provide irrigation to the rice crop after the canals are closed, thus ensuring a rich harvest. Some farmers also raise summer crops of cotton or ground nut with the help of filter points and give irrigation support to sugarcane crops.

In U.P. conjunctive use of surface & ground water started as early as 1930, when batteries of tube wells were installed in the tail end of some of the Ganga canal in Meerut District to meet great demand for water during low canal supply. In western Yamuna canal system in Haryana, tube wells have been constructed along the canal bank to augment canal supplies and lower the ground water table.

Tube wells are commonly used for conjunctive use of surface water and ground water. During their canal water turns, farmers pump tube well water into the canal to augment supplies to their fields. Farmers use a cluster of strainers to capture the canal seepage from shallow depths & pump it to mix with canal water for irrigation orchards. Farmers realized that they cannot pump for long periods at a stretch because brackish water would be pumped out after long period. But at times you need to pump water for longer durations. In such cases, to solve the problem of brackish water being pumped out after long periods, recharging of aquifers with surplus canal water could be effectively used. This will help in recharging of aquifers with good quality of water, thus increasing time period for pumping.

Another remedy to fluctuation in canal water as well as a solution to ever decreasing water table in this area has been found in Dug wells or bore wells being dug along the canals as well as at other common village lands. The runoff of excess rainfall, as well as excess canal water during lean demand period of canal water, is fed to these dug wells. Good results have been received from them, which are very encouraging. But this method is still in the early stage and a lot needs to be done in this regards. For this we will first study various types of recharge dug wells, their suitability in various circumstances, their design parameters, various arrangements to use this recharged ground water to supplement short supply of canal water at tail ends etc.

TYPES OF DUG WELLS/ RECHARGE SHAFTS

These are the most efficient and cost effective structures to recharge the aquifer directly. These can be constructed in areas where source of water is available for some time or perennially. Following are suitable site characteristics and design parameters:

- If the strata is non caving, it can be dug manually.
- If the strata is caving, proper permeable lining in the form of open work, boulder lining should be provided.
- The diameter of the well/shaft should normally be more than 2m to accommodate more water and to avoid eddies in the well. In the areas where water is having silt, it should be filled with boulder, gravel and sand to form an inverted filter. The upper-most sandy layer must be removed and cleaned periodically. A filter should also be provided before the source water enters the shaft.
- If the water is put directly into the recharge well through pipes, air bubbles are also sucked into the shaft through the pipe, which can choke the aquifer. To avoid this shaft should be lowered below the water table.

The advantage of the dug wells is that it requires only a small piece of land and water losses are less as it can be constructed close to the canal. Old unused wells can also be used for the purpose. Even operational bore wells can also be used as recharge shafts. It saves extra investment. Due to simple in design, it is easy to use even ever excess canal water flow is available for a limited period only. The effect is fast and immediately delivers the benefit.

Further these can be constructed in two different ways ─ vertical and lateral.

Vertical Shafts

The vertical recharge shaft can be provided with or without injection well at the bottom of the shaft. The recharge shaft without injection well is well suited for deep water levels (up to 15m bgl), if clay is encountered with in 15 m, effective if there is less vertical natural recharge and it is effective with silt water also by using inverted filter. The rate of recharge depends upon on the aquifer material and the silt content in the water. The depth and diameter of the dug well depends upon the depth of aquifer and volume of water to be recharged.

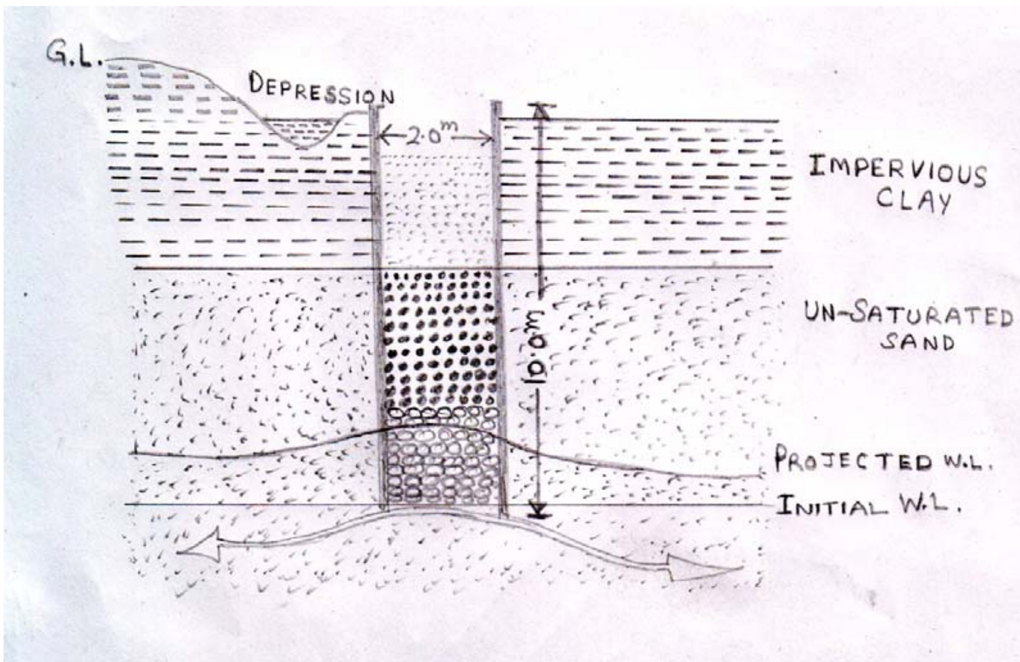

Figure 3. Vertical dug well/recharge shaft without injection well

This type of recharge shaft has been constructed at following places and good results have been received at all these places:

- Brahm sarovar, Kurukshetra – Silt free water
- Dhuri Drain and Dhuri link drain, District Sangrur, Punjab
- Nurmahal Block, Punjab

Vertical shaft with injection well

In this technique an Injection well of 100-150 mm diameter is constructed at the bottom of shaft piercing through the layers of impermeable horizon to the potential aquifers to be reached about 3 to 15 m below the water table. Such a structure is ideally suitable for very deep water levels (more than 15 m), aquifer is overlain by impervious thick clay beds etc. The injection well with assembly should have screen in the potential aquifer at least 3-5m below the water level. The injection well without assembly is filled with gravel to provide hydraulic continuity so that water is directly recharged into the aquifer. Depending upon the volume of water to be injected, number of injection wells can increased to enhance the recharge rate. The efficiency of such well is very high and recharge can go up to 15 lps at certain places.

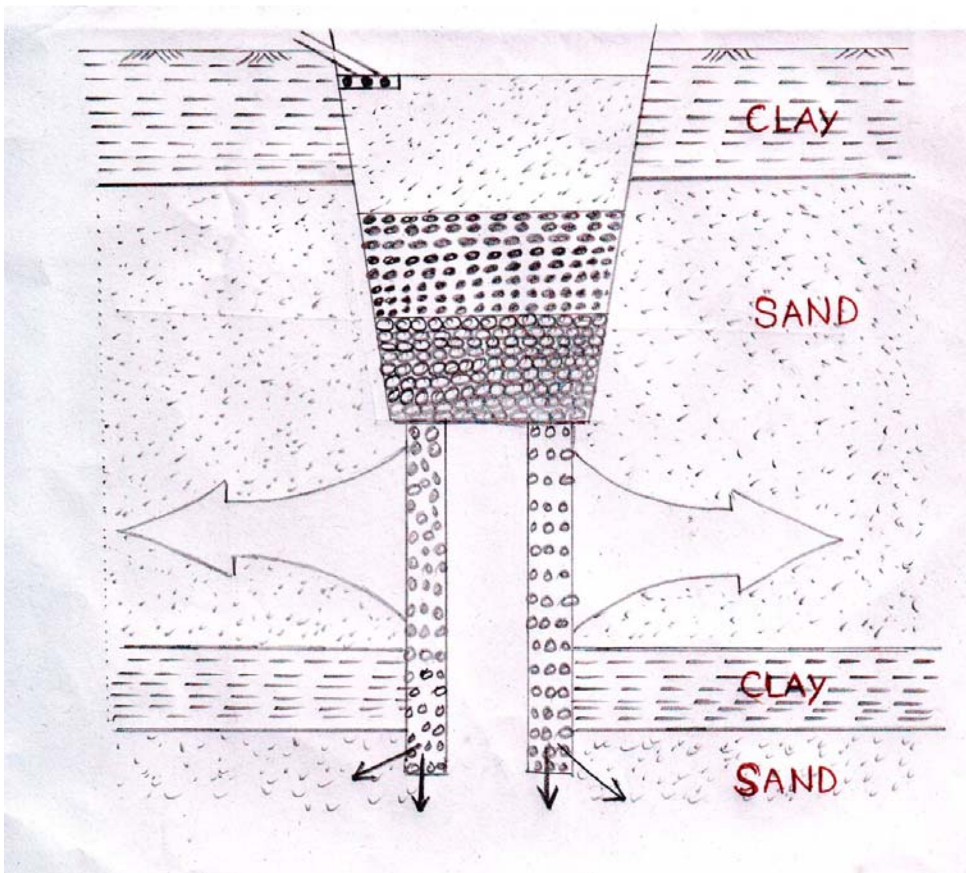

Figure 4: Recharge shaft with injection well

Such structures have been constructed at the following places in Punjab

Injection well without assembly:

- Dhuri drain, Sangrur district, Punjab
- Khana block, Ludhiana district, Punjab
- Samana block, Patiala district, Punjab

Injection well with assembly:

- Dhuri link drain, Sangrur district, Punjab
- Kalasinghian, Jalandhar district, Punjab

Lateral recharge shaft

Such a structure is ideally suited where permeable sandy horizon is within 3m below ground level and continues up to the water level – under unconfined conditions. The copious water available can be easily recharged due to large storage and recharge potential. It is well suited for silt water. These are constructed by excavating a 2 to 3 m wide and 2 to 3 m deep trench, length of which depends upon volume of water to be handled. These can be constructed with or without injection wells.

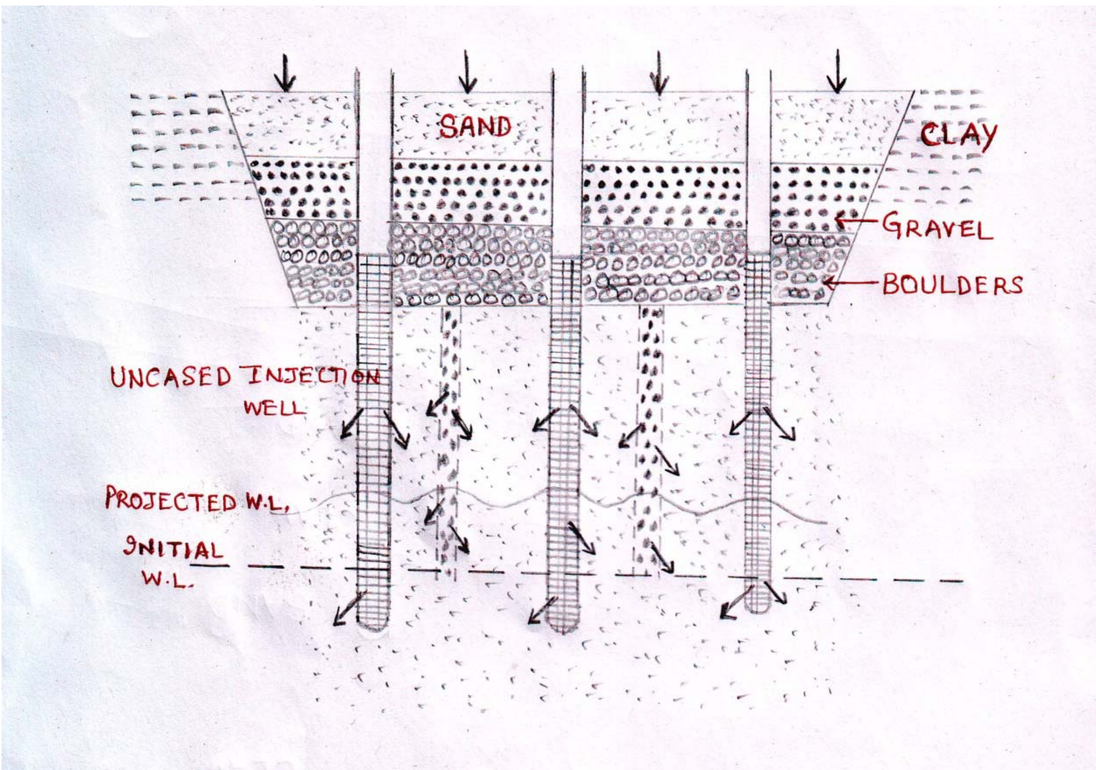

Figure 5. Lateral recharge shafts

This type of structures has been constructed at the following places:

- Dhuri drain with 6 injection wells (length 300 m)
- Dhuri link drain with 3 injection wells (length 250 m)
- Samana block Punjab - 4 lateral shafts with injection wells

CASE STUDY

Village Mukand Singh Wala falls in Hithar area of Faridkot District in Punjab. Hithar area is notorious for shortage of water. The land profile is such that on top of the soil is sandy strata, the depth of which varies from 5 m to 10 m, which is followed by an impervious layer of clay which is about 10 to 20 m wide. Due to sandy strata at the top, any rainfall or irrigation water fed to fields goes down very fast leaving fields again dry. And the clay strata beneath does not allow rain water to recharge underground water which lies below impervious clay strata. Due to this, the underground water is brackish and hence unfit for use. Figure 6 below depicts various layers of soil in one typical section:

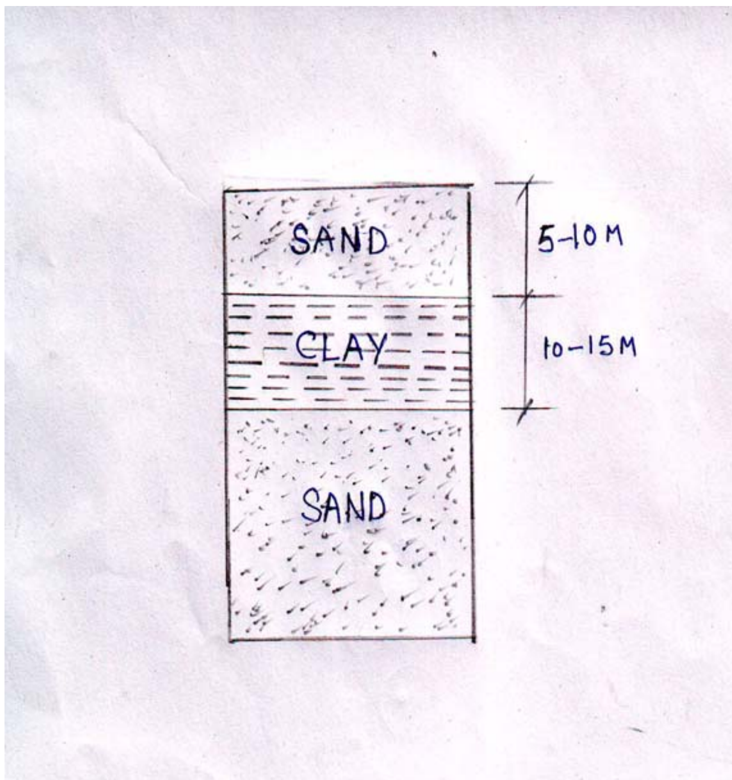

Figure 6. A typical section of Earth profile at Village Mukand singh wala

This village is supplied canal water for irrigation through Golewala distributary. Golewala distributary, which has a design discharge of 290 cusecs at the head, has a length of 40 km and combined length of minors off taking from it is 75 km. Hence it is a big canal system which feed about an area of 1,00,000 acres (Approx.) or say 40,000 hectares. This canal system suffers from chronic shortage of water at tail ends. The quantity of rainfall is also less than desired. Due to brackish nature of under ground water, the conjunctive use of underground water is not use full. So, it was decided to dug a recharge well adjacent to canal with depth about 50 m, going well down the impervious layer. A vertical recharge shaft with dia of 2 m was dug 25 feet away from the canal, so that canal does not face any breach or any other harm in future due to the recharge well. It was dug near outlet R.D.115000-L of Golewala distributary adjacent to an already existing tube well with an idea that recharged underground water will be pumped through this tube well and mixed with canal water flowing through the water course of outlet R.D. 115000-L.

To save recharge well from any future choking with silt water, inverted filter with layers of sand, gravel and boulder has been laid. A special open flume outlet has been made in the canal with crest at full supply level, Width of outlet (Bt) being 60 cm (2 ft). So that whenever there is excess supply in the canal, extra water available automatically flows into recharge well. The seepage from canal as well as surface runoff during rainy season also helped in recharge of the aquifer below the impervious layer.

The tube well has a casing of 15 cms and delivery pipe of 10 cms capable of supplying about 1.0 cusecs of water with depth of 50 m, reaching down to recharged aquifer. The tube well was about 25 m away from recharging well and water from it was directly fed to the water course carrying water from outlet R.D. 115000. The plan showing location of recharging well and the tube well with respect to the Golewala Distributory and the water course of outlet R.D. 115000 is shown below.

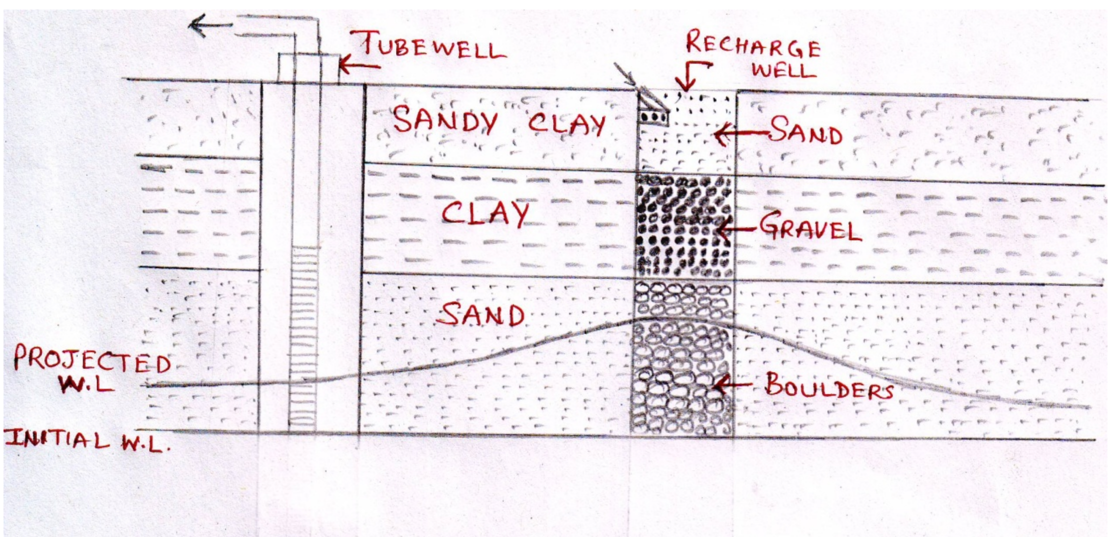

Figure 7. Picture showing section of recharge well and tube well

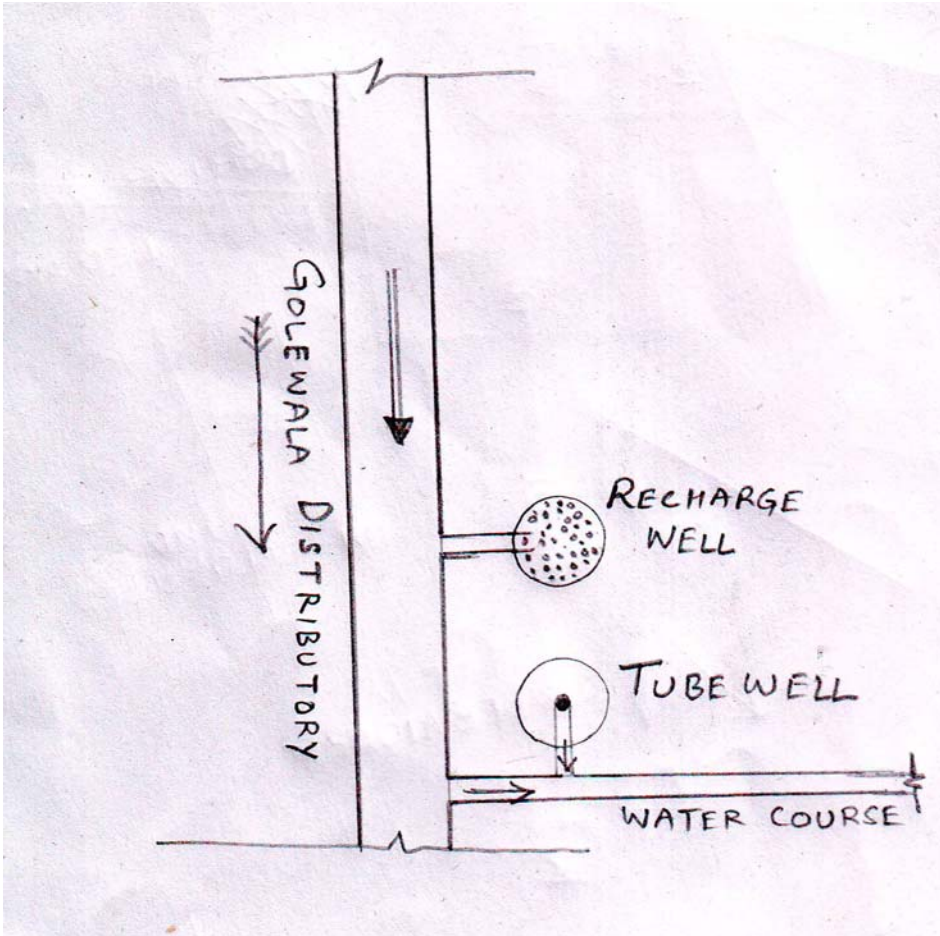

Figure 8. Picture showing plan of recharge well and tube well

Under the guidelines of Command area development authority (CADA), the shareholders of each outlet has formed individual water user associations, which deal with construction and maintenance of the water course of that particular outlet including all its branches. Initially each shareholder as per his land holding on that outlet, contributes 10% share of total budget and rest is contributed by centre government through CADA. The operation and management of the present system was also handed over to the same Water user association.

The construction of recharge well was completed by September 2008. From the end of October 2008, recharge well started receiving excess canal water through the special out let. A few rains in winter also helped recharge well to receive water to recharge aquifer below the impervious layer. During the period from November 2008 to March 2009, the water level of underground water rose by one foot. The recharge shaft got surplus canal water, rainfall runoff as well as seepage from canal running along, to recharge the aquifer. Due to limited demand of water during this season (Wheat season), the running of tube well was not much required. This helped the aquifer to be charged to a good extent, so as to be useful in the coming rice sowing season.

It was in the beginning of June 2009, when the sowing of Rice (PADDY) started, that necessity to run tube well was felt to augment low supplies of canal water in the water course of out let RD 115000-L. Due to delay in Monsoon over the region, the flow of water at the tails has reduced to half. Hence the full running of tube well was started. The tube well water was mixed with canal water flowing in the water course. This helped shareholders to receive full share of good quality water. This continued for the full month of June till the rains started in the beginning of July. This improved the situation of water in the canal at the tail end. The running of tube well was reduced. During the whole of the paddy season, conjunctive use of under ground water was done along with canal water and the shareholders of outlet R.D.115000 received authorized share of water for the full season. This has helped the production of the rice to increase on an average by 15% as compared to last year.

Advantages of the System

- Loss of crops at tail ends due to shortage or excess supply of water reduced.
- Shareholders received full share of water for irrigation regularly.
- Best suited to circumstances where underground water is otherwise unfit for conjunctive use, but with the recharging of aquifer with canal water and rainwater, it allows underground water to become fit for use.

SUMMARY

From the above discussion, we can well find out that to reduce fluctuations of canal water at tail ends, bore wells or recharge dug wells are a boon which help in mitigating woes of farmers by controlling both – excess and short supply of water in canals at the tail ends. Conjunctive use of underground water by pumping is possible only where quality of underground water is good. So to have a good quality of underground water, the best solution is to recharge such aquifers with the help of recharge shafts of different types as per requirement. The alternate use of bore wells, i.e., first for recharging the aquifers and then for withdrawing water from them can help in a big way to mitigate problems of tail end users. So we can well say that bore wells are a boon for tail end users.

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IRRIGATION EFFICIENCY AND WATER USERS' PERFORMANCE IN WATER MANAGEMENT: A CASE STUDY ON THE HERAN DISTRIBUTARY SANGHAR, SINDH, PAKISTAN

Bakhshal Lashari[1]
Rubina Siddiqui[2]

ABSTRACT

This study focuses on water use efficiency and water user's role in maintenance of the system for sustainable irrigated agriculture. The parameters assessed were water delivery to water users, water distribution, water use efficiency and farmers' role. The relevant data were collected in the field and through a literature survey.

Analyses of data indicate that DPR during the season varied from 1.0 to 1.60. The middle reach received slightly more than the head reach, and in the tail reach it varied from 0.6 to 1.80. Furthermore, water distribution among watercourses was also variable. The 7L- head watercourse received 30 to 82 percent more water than its design discharge (Q_d). The downstream watercourses (16R and 18AT) also received up to 183 percent more discharge than Q_d. However, the mid-reach watercourses (9AR and 13R) received the design share or less, though the flow of water was greater. In spite of unfair distribution there were no complaints from the water users about unequal distribution because there was enough water for everyone.

Furthermore, result indicated that total water supply was 6.62 mm/day and the crop water requirement was between 2.54 and 3.56 mm/day in the Rabi (winter) crop season. Thus, the total loss of water was estimated as 46 percent. This was also verified by estimating seepage losses in watercourses and the distributary, which were 4.5 percent and 26 percent, respectively.

However, the role of the Water Users Associations (WUA) in the maintenance of the distributary was significant. They collectively desilted the channel at a cost of about US$ 0.25 (Pak Rs. 21) per acre of land, which improved the head-tail water delivery performance ratio from 3.53 to 2.55 (Lashari and Murray-Rust 2002). But the maturity index has indicated that only 12.5 percent of the WUAs were at a sustainable level (Lashari et al. 2009).

INTRODUCTION

The Sindh is the second most populous province in Pakistan. With a growth rate of 2.8%, the total population is estimated at 41.2 million in the 23 districts of the Sindh. The population density in the Sindh is about 243 persons per sq km.

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[1] Professor, Institute of Irrigation and Drainage Engineering, Mehran University University of Engineering and Tech Jamshoro, Sindh Pakistan; bakhshall@yahoo.com.
[2] Research fellow, International Water Management Institute, Pakistan.

About 68% of the rural population depends on agriculture, which employs over 46 percent of the labor force and accounts for more than 60 percent of foreign exchange earnings. Pakistan's economic development is, therefore, directly linked to the progress of the agriculture sector. The Sindh's contribution to Pakistan's agriculture GDP is 23% with its contributions of major products as: wheat 21%, cotton 23%, livestock 28%, sugarcane 31%, rice 42%, and marine fish 70%.

There are two growing seasons: the summer (Kharif) season, from May to September, and the winter (Rabi) season from October to March. Annual cropping intensities vary significantly across canal command areas. The average annual cropping intensity in the province is about 67%.

The average water use in the Sindh from 1991 to 2009 was estimated at 40.5 MAF, which includes more than 95% for agricultural purposes and the remaining 4-5 percent for domestic and industrial use. Groundwater abstraction for agriculture has been estimated about 5 MAF/year. The extraction of groundwater is being made by deep and shallow tube wells, and there are more than 50,000 tube wells.

The cultivable command area (CCA) is about 12.6 million acres. About 3.33 million acres are classified as fallow, which could be brought under cultivation if irrigation water were available. The actual irrigated area varies from year to year depending on the availability of canal water, with an average of 9.35 million acres. The irrigation system below the barrages comprises 14 feeders and main canals and 1,462 branch canals, distributaries, and minors.

The inequitable distribution of water, an unreliable supply of irrigation water, inefficient cropping patterns, lack of coordination among irrigated agriculture stakeholders, and lack of investment for the re-modeling of the irrigation system are major obstacles in conserving and efficiently managing water resources in the Sindh (Azad 2003). In the Sindh, the average irrigation efficiency is about 30 to 35 percent and water logging and salinity is a serious problem. Consequently, the yield of major crops is reduced by about 40-50 percent (IUCN 2007).

To improve irrigation water management, to produce enough food for future generations within at least the limits of existing water resources, and to deliver water in an equitable and reliable way to the users, the irrigation management strategies which define rights and responsibilities, and penalties, for violations of the rules, and when irrigation water is insufficient to meet limited crop demand, should be considered to achieve the highest possible economic return (Perry 2001; Schneekloth et al. 2001; Wahaj et al. 2000).

The actual water distribution pattern in the Sindh have failed to meet the targets agreed upon at the start of each season. There are different water deliveries to different sub-systems in Pakistan. Head-end (upstream) areas receive significantly more water than their share, while tail-end (downstream) areas receive comparatively less (Kijne et al. 2002; Vander Valde 1991).

In order to solve the irrigation and drainage problems, the Government of Pakistan adopted a new program to establish a self-sustaining irrigation and drainage system. This involves: (a) transforming Provincial Irrigation Departments into Provincial Irrigation and Drainage Authorities (PIDAs); (b) creating Area Water Boards (AWBs); and, (c) organizing farmers into Farmer Organizations (FOs). Under such reforms, all provinces established irrigation and drainage authorities through Acts passed by the assemblies in their respective provinces. This was called the PIDA act of 1997. This was, in fact, the first major move to introduce participatory irrigation management throughout the country.

Since the establishment of the Sindh Irrigation and Drainage Authority (SIDA), three AWBs have been formed: Ghotki Feeder Canal Area Water Board, Nara Canal Area Water Board, and Left Bank Canals (Fuleli and Akram Wah Canals) Area Water Board (Fig. 1). Additionally, 369 Farmer Organizations (FOs) which are at the third tier on the SIDA system, have been formed and formal IDMT Agreements have been made with 315 FOs. This research study focuses on irrigation water management and the water user's role in maintenance of the system

MATERIAL AND METHODS

Study Area

The study was conducted at Heran Distributary which is an off-take from the Nara main canal at the Sukkur Barrage. Under the institutional reforms program water users association (WUA) was formed on the Heran distributary command area in 1998. The irrigation management transfer (IMT) of the distributary to WUA was made on 2002, and since then WUA is responsible for water distribution, water fee collection, and maintenance of the distributary. The location map and salient features of the distributary are given Fig. 1 and Table 1.

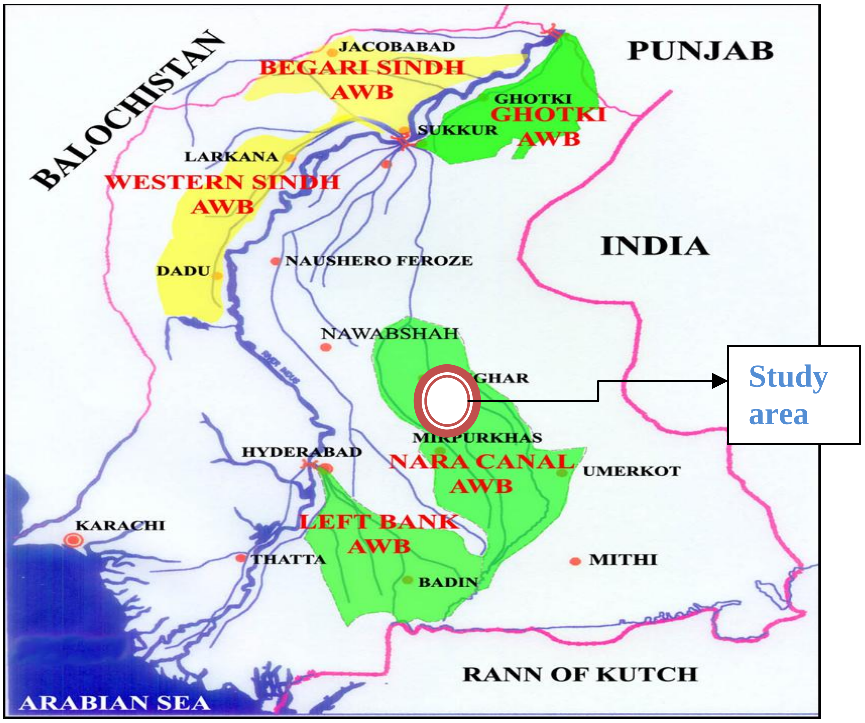

Figure 1. Location Map of Heran Distributary, Sanghar.

Table 1. The Salient Feature of Heran Distributary, Sanghar

Description	Value
Design Discharge (cfs)	62.5
Distributary Length (ft)	34,800
Number of Watercourses	31
Number of Lined Watercourses (one-third of length)	31
Crop Command Area (acres)	15,410

Data Collection

To obtain discharges at the head, middle, and tail reaches, flow measurement gauges were installed and calibrated. Similarly, the outlet structures of sample watercourses were calibrated. The discharges were recorded on a daily basis for all three gauges and all five sample watercourses for the period from October 15, 2007, to March 15, 2008 (winter crop season 2007-08). Crop data were surveyed for four sample watercourses representing head, middle, and tail reaches. Other data, such as metrological information and organizational management, were also collected in the field, as well as from the concerned departments. Using the CROPWAT model, potential ET was calculated for the distributary command area. The literature was surveyed to assess the role of farmer organizations established at different times by different organizations.

RESULTS AND DISCUSSIONS

Water distribution. Figure 2 explains the supply to the distributary at head and distribution along the length of channel.

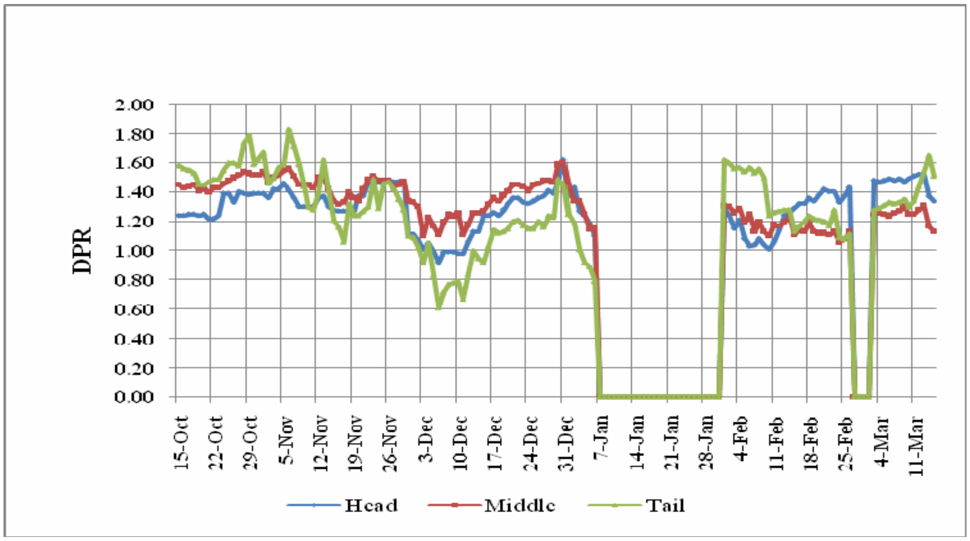

Figure 2. Water Distribution along the Channel Length

Observed data show that the delivery performance ratio-DPR (DPR is defined as ratio of actual discharge to designed discharge) at head of the distributary was between 1.0 – 1.6; at the middle it was slightly higher than at the upstream end (head), and at the downstream end (tail) the variation was from 0.6 to 1.8 during the Rabi season of 2007-08. The main reasons for such variation in the head, middle, and tail reaches were mismanagement and excessive supply of irrigation water. The canal was closed for maintenance from January 7-31, and there was a rotational closure of the distributary from February 27 to March 3 due to water shortage.

Table 2 describes the water distribution among watercourses along the channel length during the Rabi season of 2007-08.

Table 2. Water Delivery Performance Ratio (DPR) in Sample Watercourses

Month	Delivery Performance Ratio (DPR)				
	7-L	**9-AR**	**13-R**	**16-R**	**18-AT**
October	1.64	1.11	0.95	2.83	1.4
November	1.61	1.02	0.86	1.95	1.13
December	1.45	0.88	0.75	1.82	0.76
January	1.29	0.9	0.7	1.44	0.89
February	1.47	0.88	0.82	1.35	1.42
March	1.82	0.73	0.88	2.12	1.45

Results indicate that 7L- head watercourse was getting 30 to 82 percent more water than its designed discharge (Q_d). The tail reach watercourses (16R and 18AT) were also receiving up to 183 percent more discharge than Q_d. However, the middle reach watercourses (9AR and 13R) were taking nearly the design share (or less), though the flow of water was more in this reach. In spite of unfair distribution there were no complaints from the water users for unequal distribution of water because there was enough for everyone.

Cropping pattern. The major crops of the Rabi season were wheat, fodder, and vegetable, and the annual crops were sugarcane and gardens, as shown in Tables 3 and 4.

Table 3. Cropping Patten of the Sample Watercourses for the Rabi Season (2007-08).

Crops	Cropping Pattern in Percent				
	7-L	**9- AR**	**13- R**	**18 AT**	**Average**
Wheat	64.2	61.5	56.2	60.7	60.6
Sugarcane	7.2	5.4	11.2	4.4	7.1
Fodder	12.8	6.1	14.4	14.6	12
Oil Seed	14.5	24.4	17.6	9.8	16.6
Vegetables	1.4	1.1	0.6	4.6	1.9
Garden	00	1.6	0	5.8	1.9

Table 4. Cropping Pattern in the Rabi Season for Different Years in the Hearn Distributary Command Area.

Crops	**(1995-96)**	**(1999-2000)**	**(2007-08)**
Wheat	65.6%	64.8%	60.6%
Sugarcane	8.8%	9.4%	7.1%
Fodder	15.7%	13.9%	12.0%
Orchard & Gardens	3.7%	7.2%	1.9%
Vegetables	6.1%	4.7%	18.5*

*includes oil seed and vegetable data

The cropping pattern from 1995 to 2008 indicates that wheat, sugarcane, and fodder were cultivated on almost equal areas. Nevertheless, vegetable increased 3-4 times in 2008 and garden crops declined in 2008. In fact, wheat is a stable crop, fodder is needed for livestock, and sugarcane is a cash crop. Thus, farmers always prefer to keep these crops as constant and regular crops, while vegetables vary from year to year depending on market prices, and gardens were damaged due to water logging and salinity.

Water supply (WS) and crop water requirement (CWR). Figure 3 depicts the actual water supply to the distributary and calculated crop water requirements based on cultivated area and crop types.

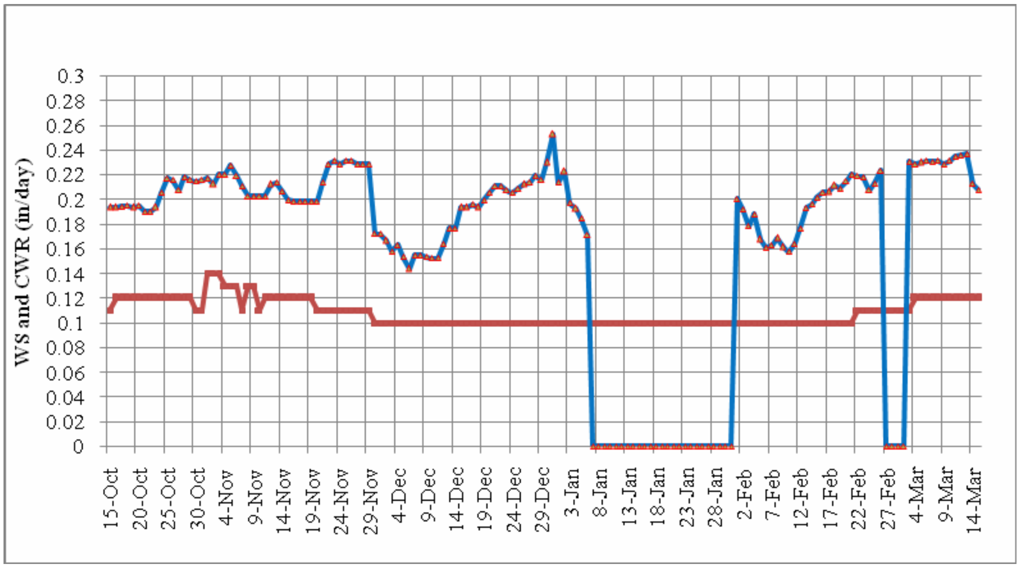

Figure 3. Water Supply and Crop Water Requirements in Rabi 2007-08

Analysis has indicated that the average supply at the head end of the distributary was 0.26 inch (6.62 mm) per day and the crop water requirement was between 0.10 inch (2.54 mm) per day and 0.14 inch (3.56 mm) per day from the beginning to the end of the cropping season. Thus, the values clearly demonstrate that the water supply (WS) was more than the crop water requirements (CWR). It is noted that the distributary was closed for canal maintenance from January 8 to 31, and was closed from 27 February to 3 March due to water shortage.

Seepage losses. Figures 4 and 5 discuss seepage losses in distributaries and watercourses in Pakistan and the study area. In the Heran distributary the seepage losses were about 4.5 percent and its watercourse seepage losses were 26 percent. The losses in the distributary were small due to adequate maintenance, while the watercourses were poorly maintained in the earthen portions, and sections at some places were wide and overtopping was common. Also, animal movement in the watercourses was noticed. The trend of seepage losses in distributaries and watercourses in Pakistan is almost the same except for a few cases.

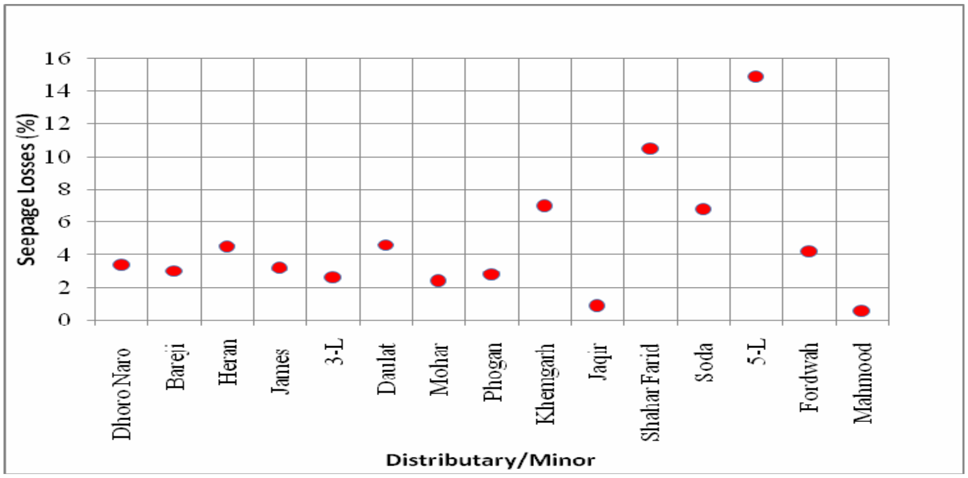

Figure 4. Seepage Losses in Distributary/Minor in Pakistan

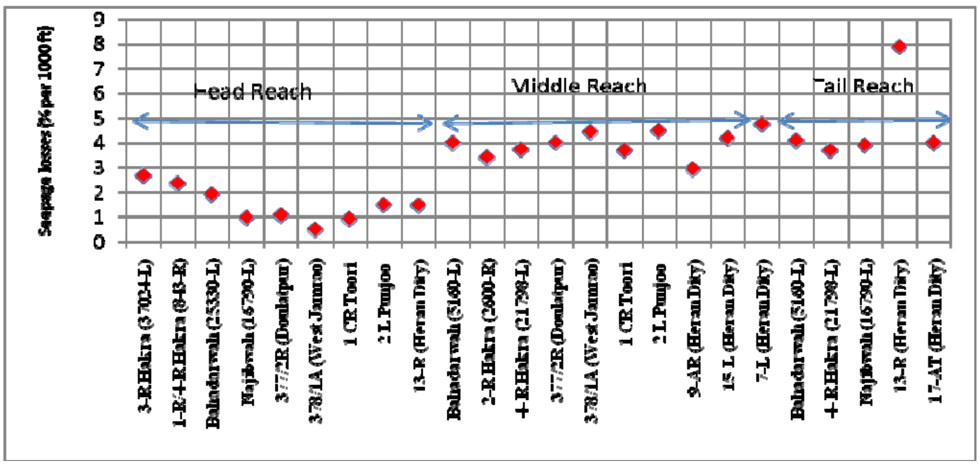

Figure 5. Seepage Losses in H-M-T Reaches of Watercourses

Net water balance. Figure 6 demonstrates the net water balance. Results show that except for the month of January, the excess of water was from 27 M ft^3 to 59 M ft^3 in the Rabi season. Thus, the total seasonal excess amount of water (+ net balance) was about 131 M ft^3. This excess amount not only contributes to the water table depth and water logging, but also reduces crop yield and creates water shortages to the tails of the overall network of irrigation system in the Sindh. The problem of water logging can be assessed through Fig. 7.

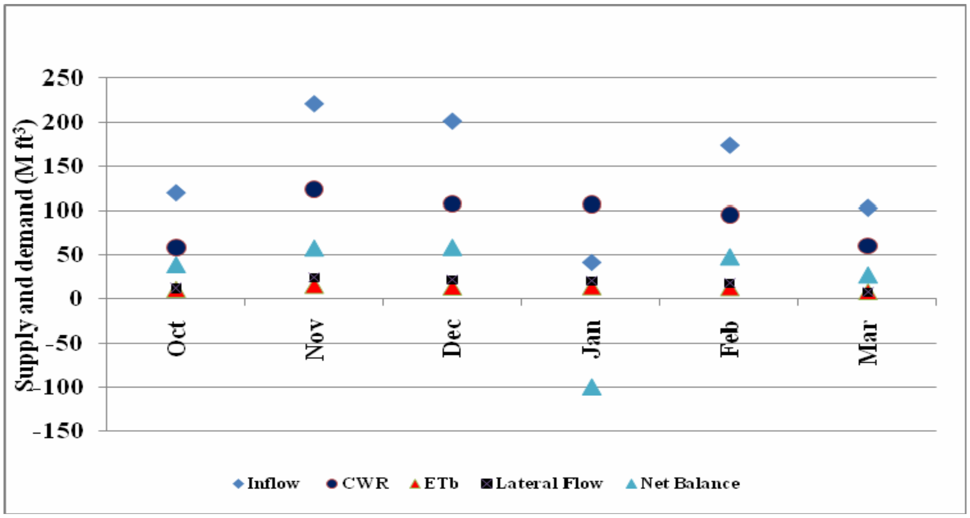

Figure 6. Net Water Balance in the Distributary Command Area

In the Sindh province, due to losses from the irrigation network and over-irrigation in the fields, water logging and salinity problems are very serious. The assessment was done from 1998 to 2009, which has indicated that in 1999 the waterlogged area, with a water table depth of 0-5 ft, was 5.43 million acres, which drastically reduced to about 0.64 million acres due to drought conditions from 1998-2001. However, the variation has been continued from year to year as indicated in Fig. 7.

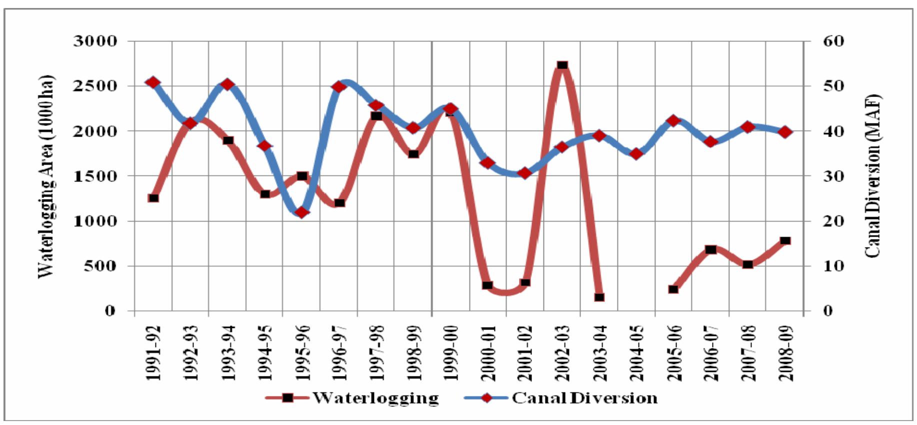

Figure 7. Waterlogging in Sindh Province

Sustainability of Farmer Organizations. The maturity index (organizational, conflict resolution, financial, O&M, environment, and capacity aspects) of 160 out of 369 FOs in the Sindh were determined. It was found12.5 percent of the FOs are at a sustainable level, 55 percent the FOs are at a stable level, 25 percent of the FOs are fragile, and 7.5 percent are weak (Lashari et al. 2009).

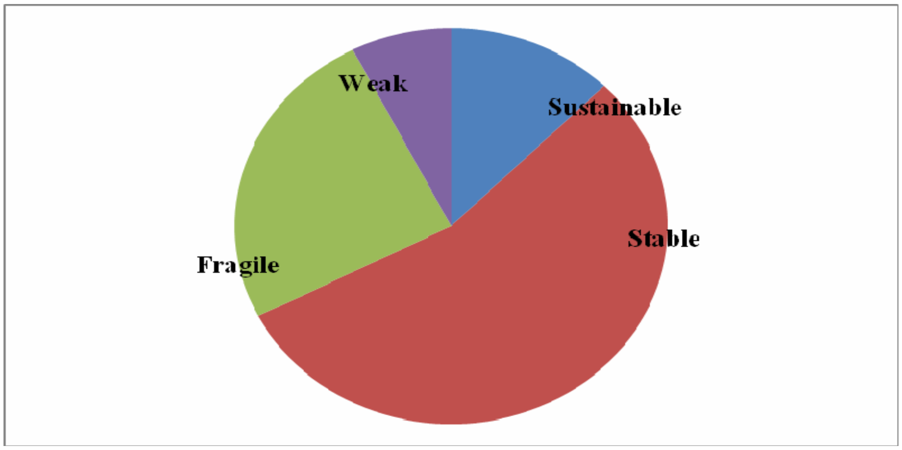

Figure 8. Farmer Organizations (FOs) strength in Sindh

The pilot project on farmer-managed irrigation systems carried out on the Heran distributary by International Water Management Institute (IWMI) has indicated that the FOs carried out remarkable maintenance of the distributary in which they collectively desilted the channel at a cost of about US$ 0.25 (Pak Rs. 21) per acre of land and improved the head-tail water delivery performance ratio from 3.53 to 2.55 (Lashari and Murry-Rust 2002).

SUMMARY AND CONCLUSIONS

Supply to the distributary was almost double the design discharge, but distribution among water users was observed to be unfair and no water users complained about unfair distribution. The reasons were an abundant supply of water and the fact that everyone was obtaining some water illegally. This increased supply not only impacted the efficiency of the system, but also decreased the crop yield and increased water logging in the command area of the distributary and throughout the Sindh province of Pakistan. Also, it was noticed during the study period that the downstream ends of the irrigation system of the Sindh suffered from an acute shortage of water.

The institutional reforms in the Sindh have not yet proved to be effective in providing equitable, reliable, and adequate supplies to cultivable lands for enhancing agriculture productivity and sustainable development. The FOs which were formed are still in the learning and capacity-building stages and cannot achieve the set objectives of efficient management of irrigation water, though there have been some FO success stories.

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INITIATING SCADA PROJECTS IN IRRIGATION DISTRICTS

Askar Karimov[1]
Eric Leigh[2]
Guy Fipps[3]

ABSTRACT

Delivering water efficiently through distribution networks is a priority for irrigation districts but often is a difficult goal to achieve. SCADA shows promise of improving operational efficiency, increasing flexibility in the amount and timing of water deliveries, and reducing spills and other losses in distribution networks.

However, implementing SCADA in a district for the first time is a difficult process. Districts often do not understand or are distrustful of the technology. They often do not know or understand how their system actually operates, thus making it difficult to design SCADA systems and to determine operational parameters and control algorithms.

Selecting equipment that is easy to integrate into district operations is not a simple decision. Simple tasks such as selection of sensors and communication hardware become time consuming because of the need to explain advantages and disadvantages of each component. District boards of directors are normally reluctant to spend money, which further complicates the process. Once SCADA is installed, district personnel have to be trained on how to use the equipment to perform daily operations.

In this paper we discuss the process of implementing SCADA projects for the first time in a district that had no previous experience with such technology or control systems. The paper will cover both hardware aspects as well as human consideration, and discuss some of the many lessons learned.

INTRODUCTION

Implementation of SCADA technologies for irrigation districts to improve real time water measurement, and control and monitoring have been significantly increased in recent years. This is partly due to the cost of SCADA hardware, software and operation and maintenance that is becoming cheaper, and the availability of funding to implement such projects. However, challenges remain on the implementation process. Many irrigation districts in Texas have little experience using such technology and need training on selection, setup, operation, and maintenance of SCADA equipment.

[1] Extension Associate, Texas A&M University, 201 Scoates Hall, 2117 TAMU, College Station, TX 77843; akarimov@tamu.edu
[2] Extension Associate, Texas A&M University, 201 Scoates Hall, 2117 TAMU, College Station, TX 77843; eleigh@tamu.edu
[3] Professor and Extension Agricultural Engineer, 207B Scoates Hall, 2117 TAMU, College Station, TX 77843; g-fipps@tamu.edu

Out of the 28 irrigation districts that reside in the Lower Rio Grande Valley (LRGV) of Texas, only a handful of those districts have implemented various levels of SCADA. For the most part, many of the districts operate completely technology free; gates and pumps are controlled manually based on a combination of experience, water levels, and the use of the spill structures. The canal riders operate the gates based on the logic that a certain number of turns of the gate wheel equal a "head" of water. The only mandatory flow measurement takes place at the main intake pumps on the Rio Grande River, which is required by Texas Commission on Environmental Quality (TCEQ).

The Irrigation District Engineering and Assistance (IDEA) team of The Irrigation Technology Center has been working with several irrigation districts to implement SCADA demonstration projects in an attempt to familiarize them with the use of the technologies.

The IDEA team has learned about different types of hardware and software regarding to SCADA through training courses, conferences, and several visits to the districts in California, Oklahoma, Colorado and Texas where these systems have being utilized in daily operations. In addition, the IDEA team has gained valuable experience designing and implementing SCADA demonstration projects with Hidalgo County Irrigation District No.6 (HCID6 or 'District') and United Irrigation Districts and through the collaborative work with other districts and their consulting engineers.

In this paper we discuss the process of implementing a SCADA project for the first time in HCID6 of Texas, which had had no previous experience with such technology or control systems. The paper will cover both hardware aspects as well as human consideration; and discuss some of the many lessons learned.

BACKGROUND

Hidalgo County Irrigation District No.6 is located at the most southern tip of Texas in an area called the Lower Rio Grande Valley (LRGV). The LRGV has been experiencing significant urban growth over the past decade causing considerable fragmentation of the agricultural lands and putting increased pressure on the irrigation districts to improve overall water use efficiency. Of the counties that comprise the LRGV, Hidalgo County had the highest percent increase in urban area with 35% (Leigh et al., 2009). Figure 1 shows Hidalgo County Irrigation District No.6 with distribution network and expansion of urban area.

The District, located in the western part of Hidalgo County, has authorized water rights of 40,729 acre-feet of water from the Rio Grande River and serves approximately 18,900 acres, as well as provides raw water for industrial and municipal uses. The distribution network consists of approximately 23 miles of main and 41 miles of secondary and tertiary lined canals, and 60 miles of gravity fed pipelines. In addition, there are three main re-lift stations on main canal and several small lift stations throughout the district. The District operates two reservoirs at the start of the main system: Walker (116 acre) and District Lake (60 acres), which are maintained in maximum storage capacities to absorb changes from municipal and irrigation demands.

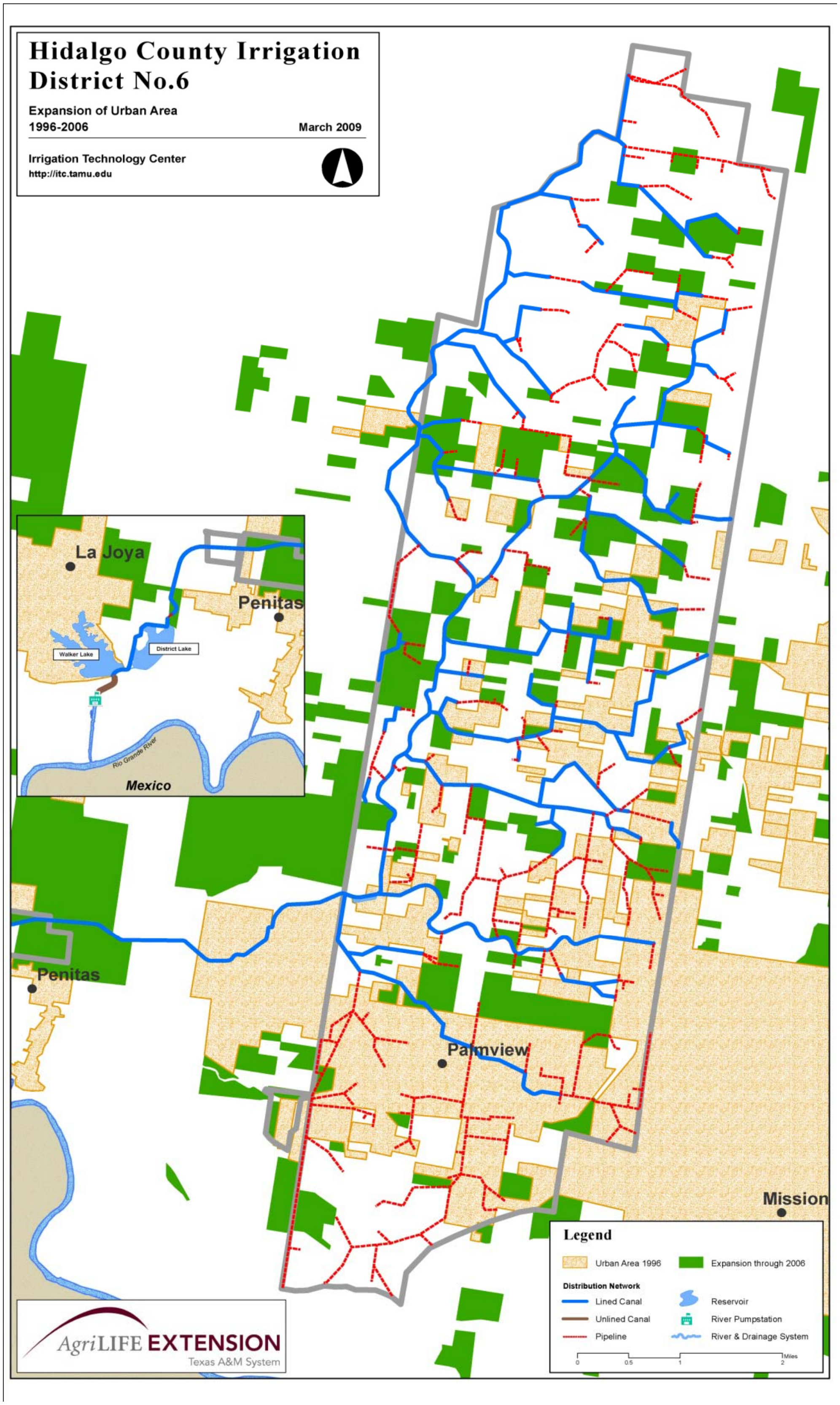

Figure 1. HCID 6 service area with urbanization

PROJECT DESCRIPTION

During large rainfall events, the District must release excess water out of the two reservoirs, more specifically Walker Lake, and back into the main canal to prevent flooding of the surrounding neighborhoods. The water level in the main canal is normally kept at the same level as the reservoirs and also requires lowering. A steel 36-inch round slide gate (refer to as the "emergency gate") near the main pumping plant must be opened in order to drain the water from the main canal and back into the Rio Grande River.

While the reservoir gates are relatively close to the district employee's home who manages the area, the emergency gate is located several of miles away. The unpaved roads to the gate can become impassable during rain events, requiring the district employee to walk, often at night, to open the gate.

The district manager requested assistance from the IDEA team on combating the problem. He understood theoretically that some type of automatic control system could be used, but did not know about the specific types of equipment, components, or setup requirements that would be needed. The IDEA team first worked with the district to understand their overall goals and to evaluate potential project sites.

Next, the team developed a range of options including the hardware, software, telemetry equipment and the control logic for the system that would provide the best benefit for remote and automatic control operations. The project was divided into two phases: Phase I: design and implement a SCADA system for the emergency gate on the main canal; Phase II: implement the developed SCADA system (from Phase I) for the gates of Walker and District Lakes.

METHODS AND PROCEDURES

Hardware and Software

Actuator AUMA brand actuators were selected for use in these projects. A basic 1/3 horsepower actuator is used at the emergency gate site. One horsepower actuators with built-in 4-20 mA gate position feedback are used for the radial gate at Walker Lake and the vertical slide gates at the District Lake.

Programmable Logic Controller (PLC) A SCADAPack controller by Control Microsystems are used for all project sites. These PLCs have 14 digital and 8 analog inputs with 2 additional analog output ports. This brand was chosen due to its current use by other districts and their engineers.

Water Level Sensor A Stevens float and pulley with 4-20 mA output signal are used as water level sensors on the main canal, and Walker and District Lakes. They are enclosed in a 24-inch PVC pipe that serves as the stilling well. A float and pulley sensor was chosen due to the easy of calibration, installation and use, as well as low operation and maintenance cost. In addition, vandalism was the main factor on eliminating the use of ultrasonic sensors, and the high salinity content of the water prevented the use of pressure transducers.

Communication system A dedicated phone line was set up as main telemetry system between RTU and Master station while site evaluations for radios were investigated. Once a clear line of sight was verified, 915 MHz Transnet (also known as a spread spectrum) radios were selected for the telemetry system (Figure 2).

Operation Parameters Control logic for the gate had to be developed in order to maintain normal water levels in the system during flooding situations. The main challenge was to determine a water level set point for automatic control of the gate. Since this emergency gate is located on the main canal next to the main pump station, the water level set point cannot overlap with high water level in the canal during peak irrigation season, as it would create an artificial emergency situation. Therefore, all frequency of high water level scenarios had to be considered in order to develop optimal operation parameters for the gate.

Programming In the region, Ladder logic and C are commonly used in programming the input and output signals from hardware into PLC in other districts. We worked with a local consultant engineering company to finalize control logic that was developed using C language.

Human Machine Interface (HMI) ClearSCADA of Control Microsystems was used as HMI software, which resides on a dedicated computer at the district office. The other software used in the region are LookOut and Wonderware. ClearSCADA was chosen because of costs, availability of local technical support, ease of use, interface and simple graphical displays. The LookOut software was eliminated due to the lack of local technical support, while Wonderware needed a specialist for initial integration due to complexity of the software.

Implementation

Remote Terminal Unit (RTU) Three Nema enclosure boxes were installed at the emergency gate, and at Walker and District Lakes; one for the PLC, radio, power converter and terminal blocks, and the other for the main power supply (Figure 3). The actuator was installed, wired and programmed into PLC, along with radios.

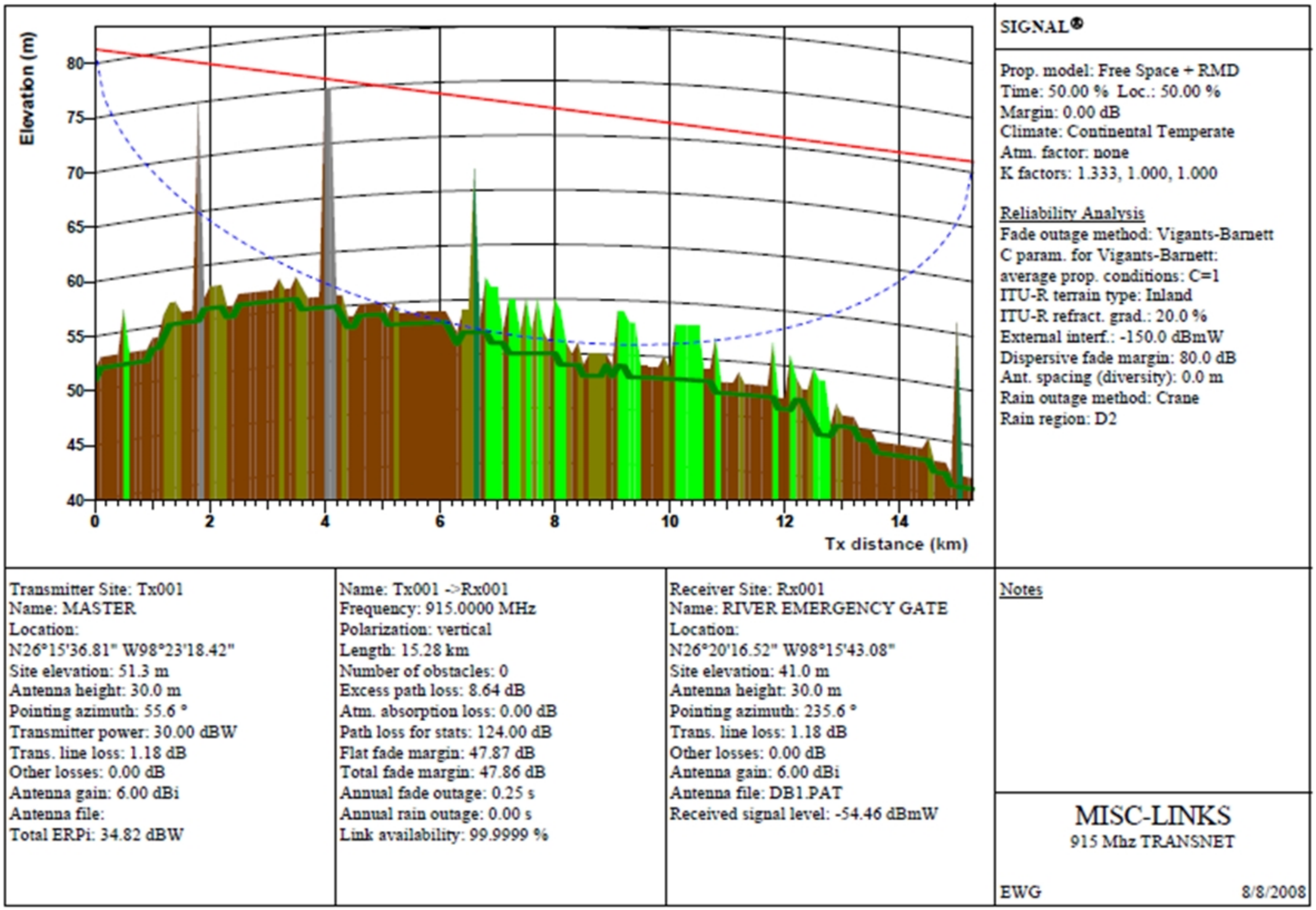

Figure 2. Determination of line of sight using SIGNAL software

Figure 3. The Remote Terminal Unit (RTU), which consists of PLC, radio, power converter, fuses and terminals and actuator at the Emergency Gate site.

Radio Telemetry System Line-of-sight availability for radio communication was determined using SIGMA software which generated detailed recommendation based on latitude/longitude coordinates of the Master station and RTU. Based on the software results, we used a 30 db Yagi antenna at a height of 30 ft at the RTU and a 7 db Omni antenna at a height of 40 ft at the Master station. We also established the available range of communication using diagnostics software of the radio.

For the emergence gate site, the radio signal at the site ranges from -92 db to -97 db where -40 db is the best and -120 db is the worst. But according to technical specs of this particular radio, the max range is -100 db.

Control Logic Control algorithm for the gate was developed for remote and automatic control options based on a pre-determined water level set point. Since the main purpose of the project was to release excess amount of water from Walker Lake during heavy rains, the emergency set point was based on the maximum water level reading at the lake. Both Walker and District lakes had staff gauges that were calibrated to sea level.

The district operates both lakes at a maximum level of 132.2 ft. If rainfall occurs, the lakes can handle another depth of 4 inches (free board) before it spills over into a residential area surrounding Walker Lake. Therefore, based on the managers' recommendation, we developed a control logic based on the 132.2 ft pre-set water level, the "emergency level". When water level exceeds 132.2 ft, the PLC receives a signal from the water level sensor and sends a signal to the actuator to open the gate. The gate stays open until water level at the canal drops to 132.1 ft, and then closes.

<u>Master Station</u> The master station consists of a radio and antenna to receive and send signal to/from remote sites and a dedicated computer, which hosts the ClearSCADA HMI software. All the register addresses in PLC, such as gate position, water level readings and set points, and automatic/remote control options were programmed into HMI software. Graphical displays showing real-time operation and monitoring, and alarming capabilities were implemented into the HMI in a simple manner so the district personnel can easily understand and utilize the system efficiently (Figure 4 and 5).

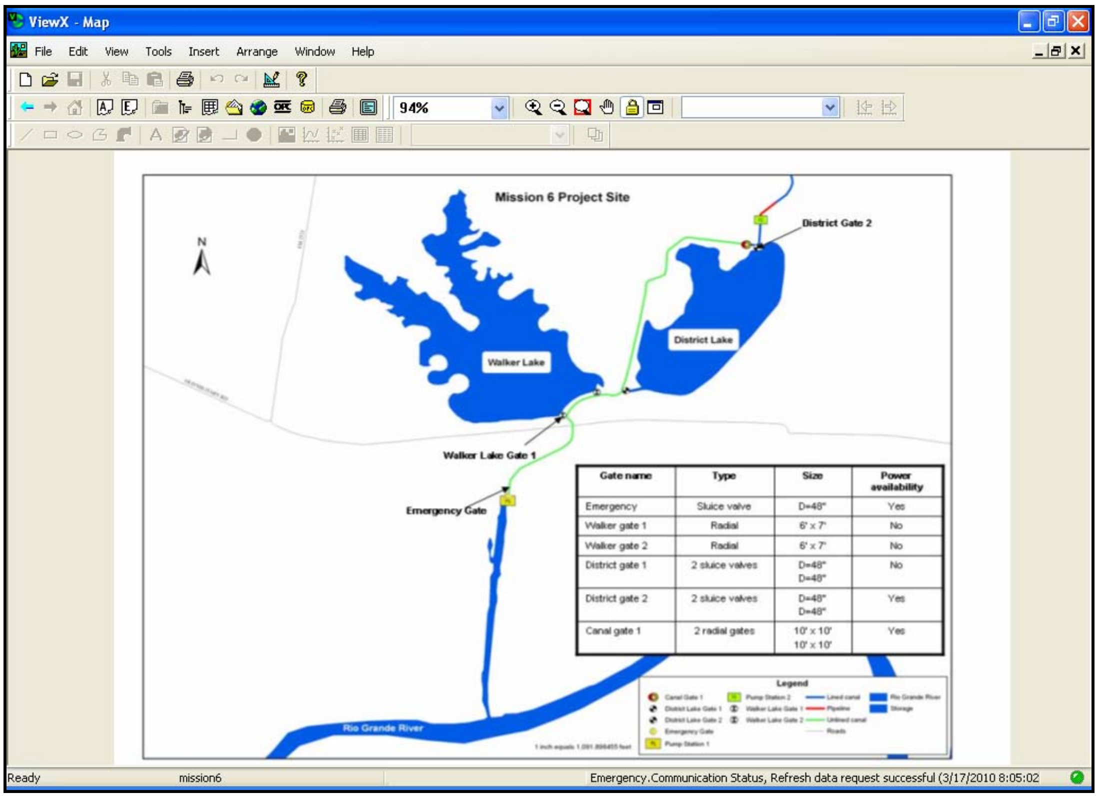

Figure 4. Remote Terminal Units at emergency gate, Walker and District Lakes on HMI software display on district computer at the office.

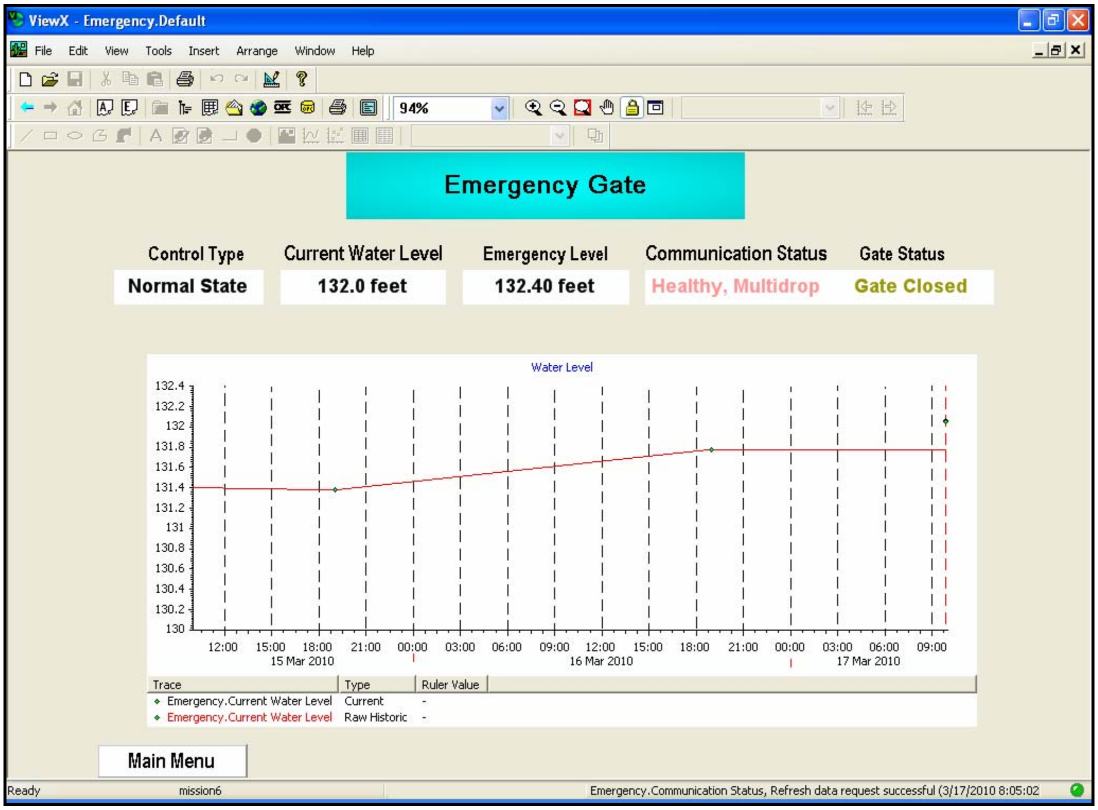

Figure 5. Emergency gate RTU display and control on Clear SCADA at the office computer

<u>Test of the system</u> We performed series of control scenarios to test reliability, accuracy and correctness of logic to control the gate. For instance, an artificial flood situation was created to test reliability of automatic control with increasing water level set point to examine how gate supposed to react to the given command from the sensor. As soon as water level reading exceeded the emergency set point of 132.2 ft, the gate opened immediately and stayed open until set point was decreased below 132.1 ft.

The system was also tested for remote control operation by simply changing control type on HMI without changing water level set point. This option is particularly designed and programmed for high water level in the canal system during which max water is pumped from the river to meet the demand at downstream water users. In that case, the district personnel will change the control type from automatic to remote on HMI to eliminate flooding in the system.

<u>Training District Personnel</u> We provided training on operation and use of HMI software, since this gate is designed for automatic control purpose; it's not operated frequently. In addition, wiring diagrams for actuator, sensor, radios and power for RTU along with customized manuals on operation of HMI and radios were provided.

RESULTS AND DISCUSSION

At the start of Phase I, the actuator installed for the emergency gate had initial operational problems due to the rust build up on the stem, threads, and guide frame from infrequent use. In the beginning we thought that the gate supports and stem were not capable of supporting the torque force from the actuator. Additional steel supports were added to the structure but the problem persisted. For further evaluation, the concrete section containing the gate was then blocked from the main canal and drained. After the rusty condition of the gate was determined as the problem, the district personnel cleaned and applied grease to the gate components.

The installation of the equipment for the RTU sites, which included the water level sensors, actuators, spread spectrum radios, and PLCs were successfully installed. The next decision was to decide on the programming language to be used for this project. The SCADAPack PLC can use several languages including ladder logic and C/C++.

We initially had limited programming experience, so we worked in close collaboration with other districts and their consulting engineering companies whom had similar SCADA systems. The consultants provided example programming codes using the C language and assisted us on understanding of the functions involved.

During the implementation of Phase II, we ran into problems with the calibration of the actuator at Walker Lake that controls a small radial gate. The gate feedback position signal of the actuator was giving false readings because the wrong potentiometer was installed. The AUMA sales representative made some initial miscalculations when during the specification process. We contacted AUMA for assistance. The company sent an engineer to work with us to solve the problem. The potentiometer was replaced and the actuator was properly calibrated.

The next problem was due to lightning events that occurred at the Walker Lake RTU site. One of the analog inputs on PLC board along with fuses and a water level sensor was damaged and the team replaced water level sensor and PLC.

The final problems were encountered at the District Lake RTU site during the installation of the radio system. We had a series of problems on gaining line-of-sight. The initial tests showed that signal strength was at -110 db, and not within the optimal signal range between -40 and -100 db, not allowing any communication to the master station. The antennae height was then raised from 30 feet to 40 feet, which increased the signal strength to an achievable range between -98 db to -100db. While this is still not a desired range, we have future plans to add a repeater station for signal strength improvement. But so far the district has not had any problems with radio communications.

A summary of the lessons learned from problems experienced during the process of the project:

- Need proper evaluation of existing equipment before proceeding to next task
- Understanding the use of the programming language

- Ordering proper equipment (i.e. lightening protection, actuator components)
- Proper planning out the installation of equipment
- Establishment of suitable line of sight for radio telemetry system
- Calibration of actuators and water level sensors

CONCLUSIONS

The money is the essence for the implementation of any kind of project whether it is SCADA or rehabilitation of canals and pipelines. But the Board of directors most of the time are unwilling to spending money for these small SCADA demonstration projects due to the cost, mistrustful of technology, fear of the cost for operation and maintenance of the system and etc.

We had been working with several districts in the region on design and implementation of SCADA projects for various applications. However, most of the districts are willing to work and they do understand importance of technology on improvement of water delivery efficiencies in the conveyance systems.

In addition, most of the districts are experiencing shortages on number of canal riders who perform daily operations of gates, turnouts and pumps. Most of the canal riders are about to retire but districts are having hard time on recruiting new canal riders. This seems to be one of the biggest problems in near future.

We learned many lessons throughout design and implementation phases of SCADA projects. But when working with irrigation districts other issues arise including:

- Districts not installing the equipment as provided in project plans
- Lack of understanding and seeing the overall project goal (slows down project implementation)
- Lack of education on the cost, time and efforts need for each project
- Not understanding the importance of being involved on all aspects of the project, including learning how to use to control systems

This was one of the successful projects that we have implemented so far. Another part of the success of this project was due to the district manager's willingness to spent money to combat the flooding problems in his reservoirs; the board members were also very supportive.

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USE OF GIS AS A REAL TIME DECISION SUPPORT SYSTEM FOR IRRIGATION DISTRICTS

Gabriele Bonaiti, Ph.D.[1]
Guy Fipps, Ph.D., P.E.[2]

ABSTRACT

GIS technology has been utilized in the past years by drainage and irrigation districts mostly for organization of spatial data, and as decision support system. However in some cases, GIS has not reached its full potential due to such factors as lack of interest after initial set up, effort required for and the high costs of keeping the system updated, and a disconnect with daily management.

This paper discusses the development of a real time GIS decision support system for the Brownsville Irrigation District of Texas (District). The objectives were to provide the District with a simple tool that would improve the management of water orders, allow access of data by landowners through the internet, and to improve the availability of pump flow data from the existing SCADA system. An important component of the project was to interact and train District personnel. The final product of the project is a website, where water orders and pump operations information are displayed in real-time, along with links to related historical data, and other information.

The activity resulted in an expanded interest on the use of GIS as a real time decision support system by District personnel, the identification of solutions for limits in the existing database, and recommendations for further improvement. In this paper, we present the steps that were taken with District personnel to set up the system, the website features, and the initial benefits that have been identified by District personnel and the manager.

INTRODUCTION

Water conservation in the irrigation districts of the Lower Rio Grande Valley of Texas has been a key challenge for more than a decade. Hence, new technologies and water management strategies have been implemented. GIS is one of the technologies that have been introduced in irrigation districts, and has been used primarily for mapping and planning purposes (Fipps and Leigh, 1998, Fipps and Leigh, 2003, Leigh et al, 2009). GIS has not reached its full potential, due to such factors as lack of interest after initial set up, high costs of upgrades and keeping the system updated, and a disconnect with daily management.

[1] Extension Associate, Department of Biological and Agricultural Engineering, 2117 Texas A&M University, College Station, Texas 77843-2117; gbonaiti@ag.tamu.edu
[2] Professor and Extension Agricultural Engineer, Department of Biological and Agricultural Engineering, 2117 Texas A&M University, College Station, Texas 77843-2117; g-fipps@tamu.edu

A demonstration project started in June 2009 by the Irrigation District Engineering and Assistance (IDEA) program of the Irrigation Technology Center, in collaboration with the Brownsville Irrigation District (District). The general objective was to improve the use of GIS in managing pump operation data, which are monitored with a Supervisory Control And Data Acquisition (SCADA) technology, and water account data.

The District is one of the smaller of 28 irrigation districts in the Lower Rio Grande Valley (Figure 1). The irrigated land is about 4,200 acres, typically using the flood irrigation method, and the most common irrigated crops are corn, soybean, sugarcane, and orchards. Water is pumped from the Rio Grande River, and delivered to the fields by means of re-lift pumps and a network of pipelines under low pressure. Pump operation data are continuously measured and remotely monitored with a SCADA system. Water sales are recorded daily in a water account database, with the support of manual meter readings. The GIS is mainly used to create maps representing total yearly water sales, and distribution network features.

Objectives

The objectives of the project were to:

- Improve access to existing pump operation and water account data, both from District office and via the internet
- Enable landowners and growers to access their data directly
- Use GIS to link different sources of data and to serve as interactive display tool
- Interact and train District personnel

We carried out three main activities:

- Analysis of pumps operation and water orders management
- Education and GIS training program
- Establishment of a Web GIS Pilot Project

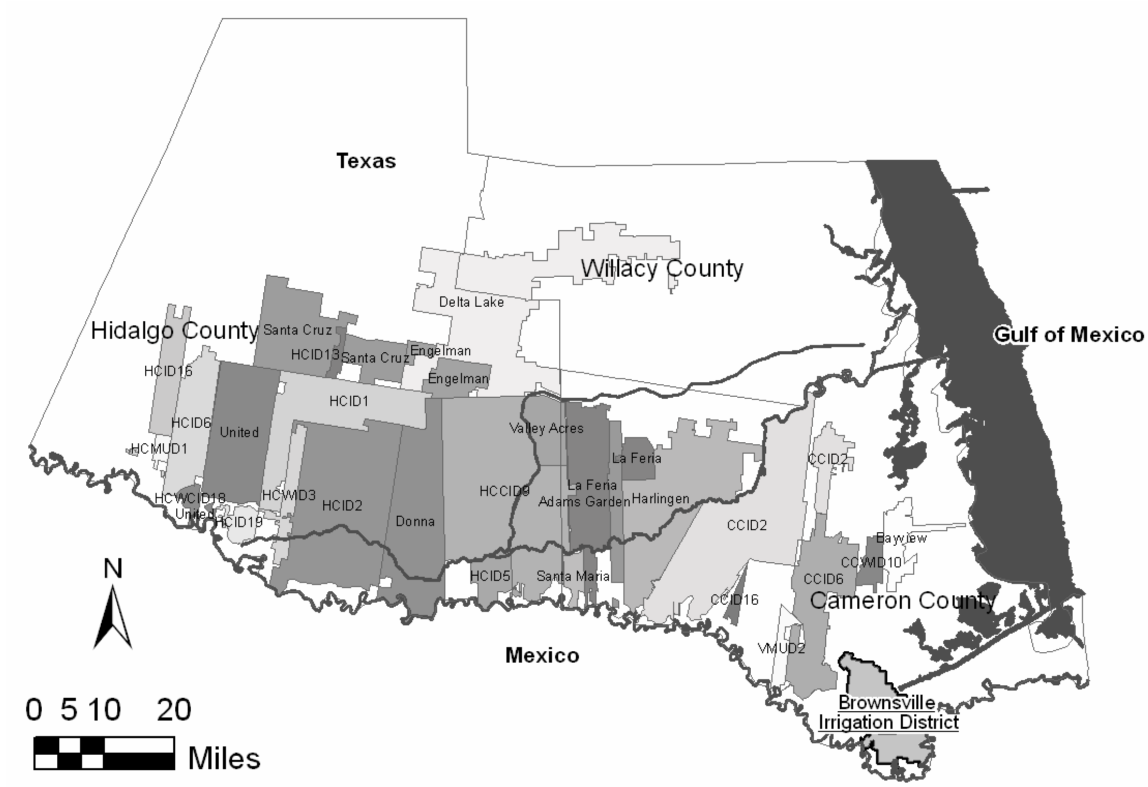


Figure 1. Service areas of the irrigation districts in the Lower Rio Grande Valley of Texas.

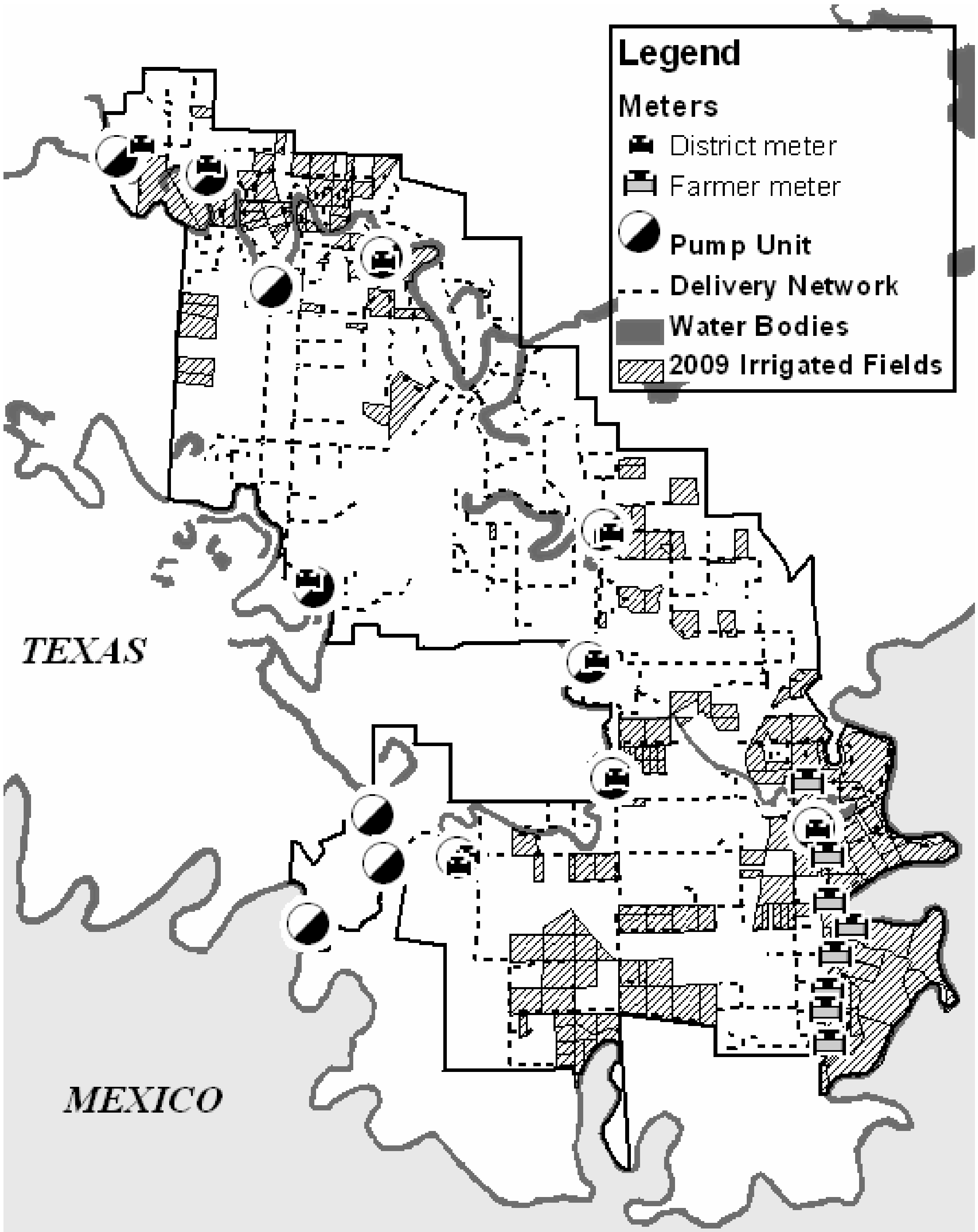


Figure 2. Pump stations and delivery network in the Brownsville Irrigation District.

ANALYSIS OF PUMPS OPERATION AND WATER ORDERS MANAGEMENT

District's Internal Computer Network

We examined the District's internal computer network to ascertain if and how computers are interconnected, how data is stored, what software is used for data acquisition and management, and the level of training of District personnel on the use of computer systems and associated software. Data recorded at the District office were identified, along with storage and use details. We also determined what type of information District personnel considered the most useful and what improvements were desirable.

The District's pumps are equipped with remote terminal units (RTUs) for remote control. The pumps are operated remotely with SCADA software, which is installed on a personal computer (PC1) disconnected from the internal network (Figure 3). The SCADA unit polls the RTUs for water data of the canals from where water is pumped, equipment status (whether pumps are on and off), flow rate, and cumulated flow.

Water account information is stored in the server, and is updated daily from a personal computer (PC2) with the database management software FilePRO (Figure 3). The District manages water orders by selling "water tickets," which specify detailed information such as date of purchase and delivery, amount of water sold and delivered, name of land owner and grower, crop. The water accounts database is frequently not updated in a timely manner with water ticket information, particularly the dates of order and delivery. However, water ticket information for a few of the largest farms is kept more current on a third computer (PC3). GIS database is also managed and stored on PC2.

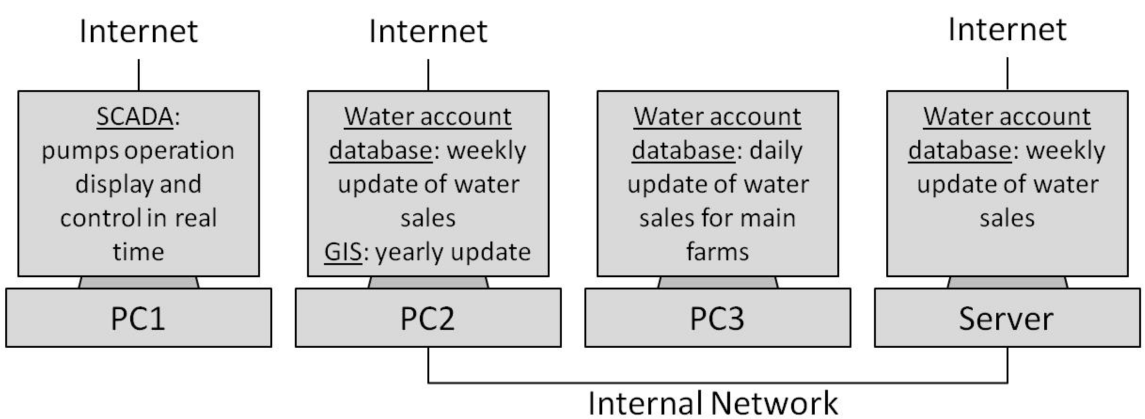


Figure 3. Schema of pump and water orders database management. Communication is missing between some sources of data.

Identified Problems and Recommended Changes

The most evident problem was a missing communication link between different sources of data. Internet access was, nevertheless, ensured to three out of four computers. Some modifications to database settings (e.g. output data formatting) can only be done by contractors, which leads to a strong dependency on the contractor and ties the hands of the District staff.

A list of the problems and recommended changes were compiled (Table 1) for the District, some of which were addressed during the Web GIS Pilot Project.

Table 1. A sample of the identified problems and recommended changes.

	Problems	Recommended changes
Water account database	• Output data are in an encrypted format	• Add routine that converts output in a text file format, or converts to a different database product
	• Update of water tickets is done weekly	• Update water tickets information daily
	• Irrigated fields ("locations") are missing in the water account database	• Add "location," ensuring the use of the same code as in the GIS database.
	• Daily updates of water sales are recorded in a standalone computer (no connection to the internal network)	• Record data in the water account computer (PC2)
	• Information on planting date, harvest date, and irrigation method are missing	• Require the canal rider to record this information and update them daily in the database
SCADA	• District personnel do not know how to access stored data	• Convert output into a text file format with the desired frequency
	• No communication with the internal network	• Connect to the internal network
GIS	• Current shape files are not usable with available alphanumeric information and other IDEA Team shape files	• Re-project to common spatial references; add fields to host new information; edit at scale equal or larger than 1:10,000; snap network and update it
	• Water orders area differ from water account area (sub areas, mistakes on drawing, over selling, confusion of order between accounts, etc.)	• Frequently update maps with information on location, turnouts, and cultivated parcels, encourage the identification of irrigated fields with grower
	• "Locations" recorded by canal rider differ from water account boundaries	• If the location is larger, use this name to identify the account; if it is smaller, use it to split account
	• Daily updates of water sales are recorded in a standalone computer (codes in the spread sheet not compatible with GIS)	• Modify files to meet GIS requirements, or record data in the water account computer (PC2)

EDUCATION AND GIS TRAINING PROGRAM

The education and GIS training program was designed to help District personnel and contractors to better use available tools, and to learn new ones. Meetings, GIS classes, demonstration sessions, and field tours were the activities carried out as face-to-face sessions (Table 2). Correspondences by regular mail and email, and phone calls, are not reported in the table, but were used extensively.

Table 2. Face to face education and GIS training program.

	Meetings	Demonstrations	Classes	Field tours
NUMBER OF EVENTS	9	6	2	3
PEOPLE (counted for each event):				
District manager and personnel	11	8	2	1
Water account database contractor	1			
SCADA contractor	1	2		
TOTAL	13	10	2	1
HOURS (hours x people)	28	10.5	5	7

Meetings

Meetings were organized to foster discussions with the manager and District personnel, and to identify expected outcomes. Those discussions focused on improvement need for database organization and access.

To obtain useful results, we met frequently and spent a considerable amount of time discussing the current organization, proposed tools, and specific aspect to be developed. This allowed for both, District and IDEA Team personnel, to understand each other vision, and to carefully evaluate proposed changes.

GIS Classes

The project required that District personnel learn two key skills in GIS database management. Therefore we organized two classes to teach staff how to use basic and some advanced tools available in the ArcGIS ArcView software, and to set up procedures for the Web GIS Pilot Project.

Demonstrations

During the first session, we introduced the manager and District personnel to ArcGIS Server web applications, and demonstrated how the Districts data could be managed with this extension of ArcGIS. In the following session, we designed and taught a tool that could effectively help the District manage pump operation and water orders through ArcGIS Server web applications. The features of this tool are described below.
Sessions were also organized for the SCADA contractor upon his request. We introduced him to the ArcGIS Server web applications, and to the ongoing Web GIS Pilot Project at

the District. After the demonstrations, the contractor expressed his intention to continue GIS education, in an effort to improve further technical assistance.

Field Visits

Several field visits were conducted by the canal rider in order to bring the IDEA Team up to speed on the distribution network system. The visits were useful for understanding the type of field activities carried out, and gave the canal rider the opportunity to explain in detail his work methods.

WEB GIS PILOT PROJECT

The Web GIS Pilot Project was organized in the following steps:

- Ensuring correct data format and features
- Transfer of files in real time from District computers to the IDEA Team server
- Storing and processing of received files
- Creation of GIS projects to synthesize data
- Creation of Web GIS projects for remote access

Data Format and Features

Some changes had to be made to the database structures in order to use them in the Web GIS Pilot Project. A routine was added by the SCADA contractor in PC1 to output and save data in a CSV file format every 15 minutes. Data older than a week are overwritten; in this way the size of the file is kept limited for faster transfer.

In the same way, the FilePRO daily output was set up to be automatically converted to CSV format. The size of this file is not an issue since transfer is only needed once a day.

For PC3, minor changes were made in the spread sheet files to limit errors in the data entry process (e.g. introduction of drop down lists) and to facilitate the exchange of files (e.g. limiting of number of new workbooks).

Finally, spatial references were added to the feature classes in the GIS database, together with identification codes enabling joining with other databases. This allowed for water account detailed boundaries to be added (Figure 4). A procedure was set up in collaboration with the District personnel for ensuring frequent updates of class features.

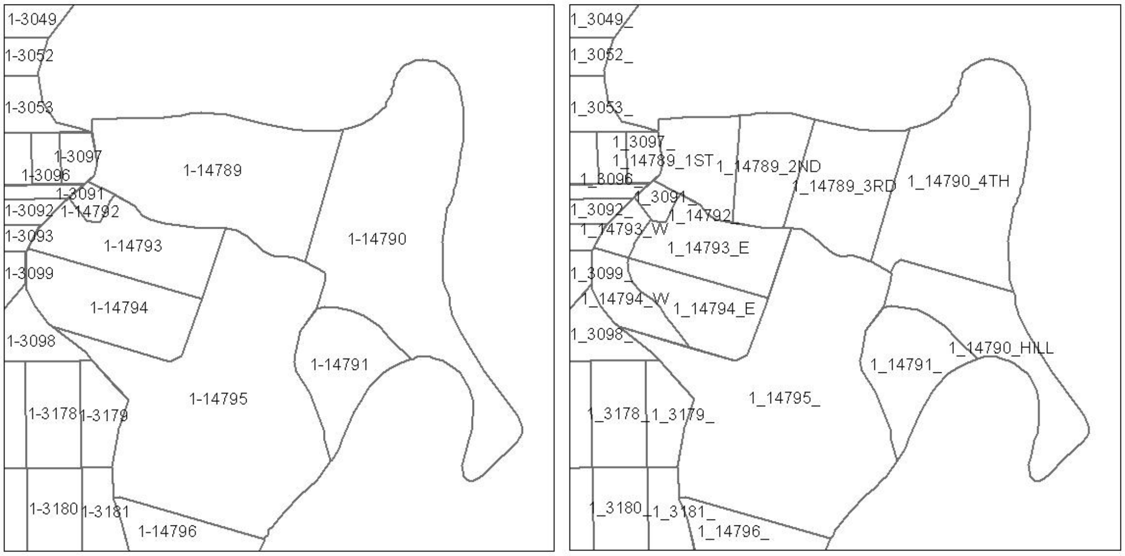


Figure 4. Water accounts were split to display orders in the specific fields. Canal rider can check if water is allocated correctly.

Transfer of Data

Internet access was added to PC3. Then Secure Shell Protocol (SSP) was installed on each computer containing needed files and set up to automatically transfer files from the District computers to the IDEA Team server. Pump operation data were set to be transferred every 15 minutes, while water sales and GIS data were transferred daily.

Processing of Data

A set of automatic routines were set up on the IDEA Team server to process received data. The objective was to create a new, simplified database, and to create queries to extract the most useful information (e.g. current flow rate, last water ticket order, pending water tickets, cumulated ordered water for each field for a selected year, historic database). This data is stored in a SQL Server database. ArcGIS feature classes were converted to geodatabases using ArcGIS ArcInfo, and are manually modified every time there is an update.

Centralized GIS

ArcGIS is used to retrieve all spatial data received and all related information from the database. New maps are created using the feature classes sent by the District combined with those possessed by the IDEA team (roads, soil properties, cities, etc.). Maps are set to automatically update when new attribute data is received.

Web GIS Access

Data is organized to be accessed, displayed and downloaded through the Internet according to the needs of the District manager and personnel. This was done by publishing the new maps as “services” and “web applications,” using the ArcGIS Server software, and by linking historical data. Meter readings and District personnel web pages are password protected. Data access, display and download are set up differently for the growers/landowners than for District personnel, to better manage permissions and security issues. Pump operation and water account management in the Web GIS Pilot Project is shown in Figure 5.

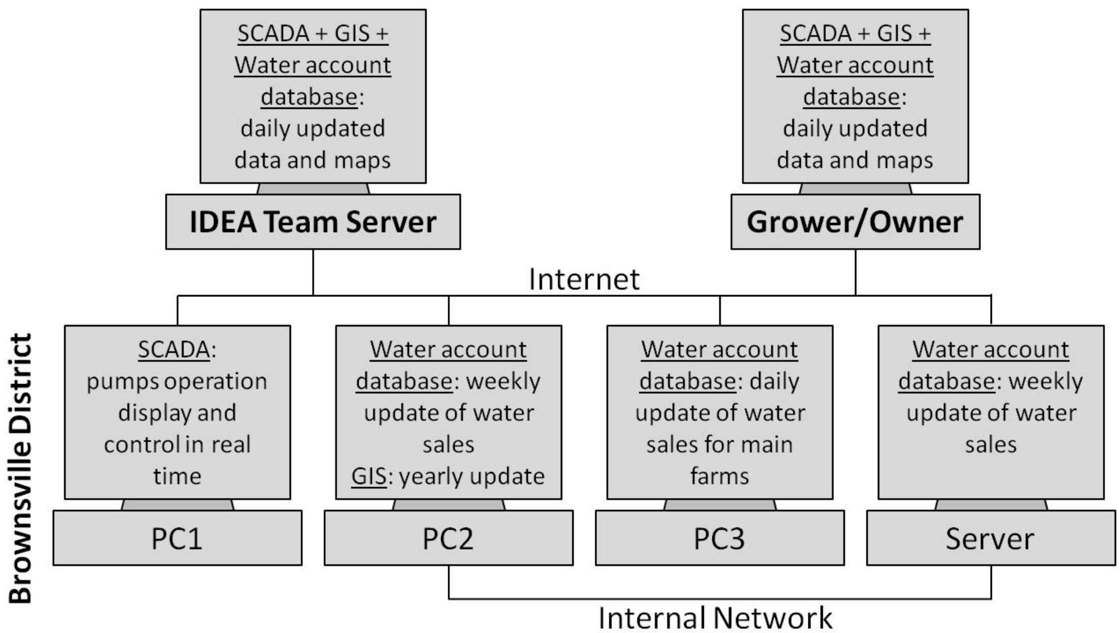


Figure 5. Database management in the Web GIS Pilot Project. Data and maps are shared through the Internet.

Grower/Landowner The grower and the landowner can open a dedicated interactive map (web application) on the District webpage (Figure 6). From the webpage, the grower/landowner can query the flow meter on their land and check the latest readings, which are updated every 15 minutes, without having to call the canal rider. With a different query, they can locate their fields, and find related information on water tickets. Each query requires a password, which was mailed to the grower/owner. Visualized information can also be printed. The map includes useful feature and images, such as delivery network, roads, District boundaries, and aerial photograph (Figure 7).

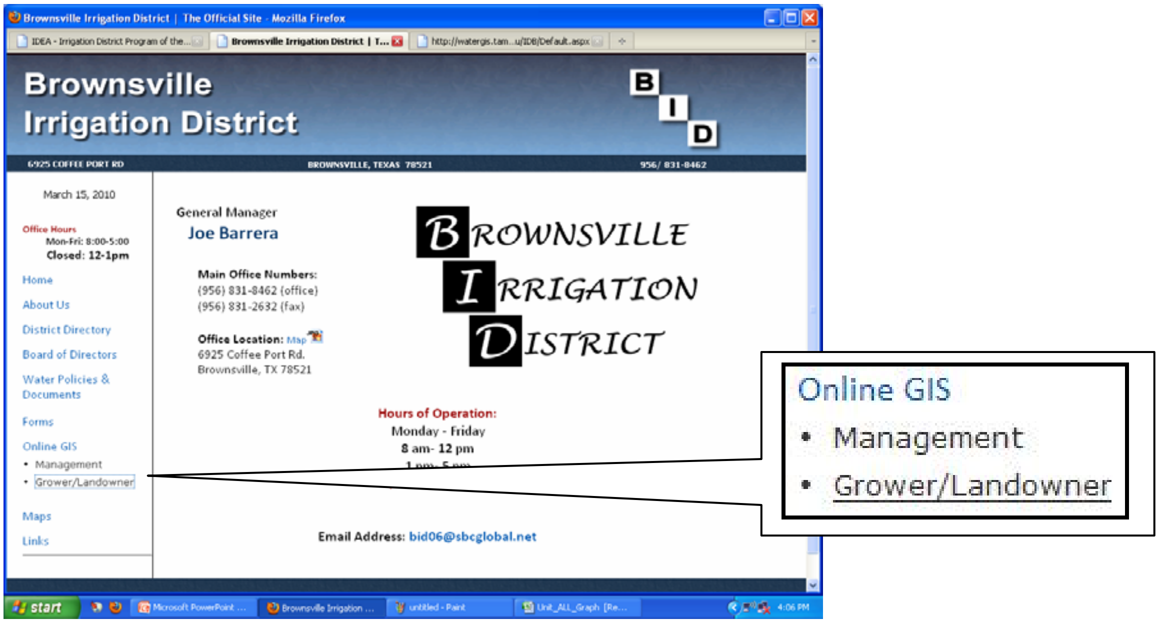


Figure 6. The Grower/Landowner can open a dedicated web application from the District Web page.

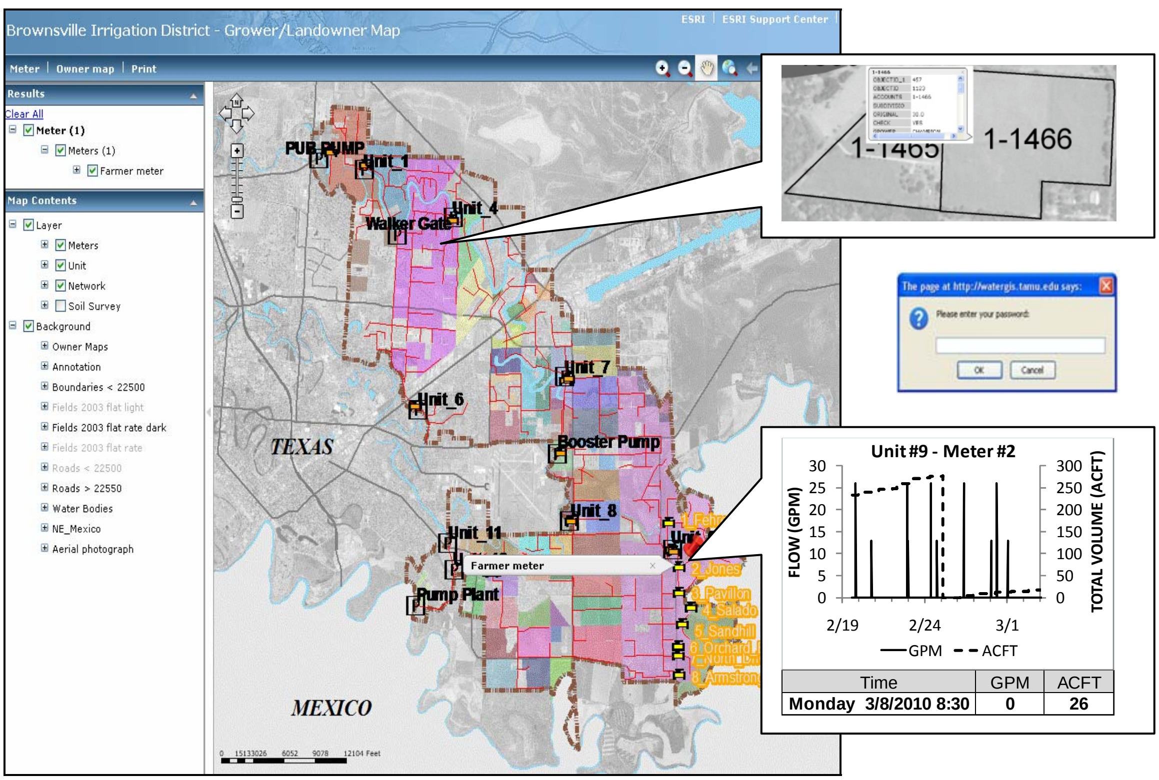


Figure 7. Personal information is retrieved from the Grower/Landowner web application.

District Personnel From the District webpage, District personnel are redirected to another webpage, where they can choose to access real time or historical data. The access to this page is password protected.

The web page shows current operating pumps, related flow and water body levels, along with a link to the data from the last week of operation. The map includes information on other useful features and images, such as delivery network, roads, District boundaries, and aerial photograph (Figure 8).

Real time water sales are displayed in the same web application, and queries are set to find the desired field in the map. Options for queries include searching by water account number, owner name, or grower name (Figure 9).

Finally, all historical data regarding pump operation and water orders can be accessed from a different webpage. Data is in a spreadsheet format, and may contain further elaboration as requested by the District personnel (Figure 10).

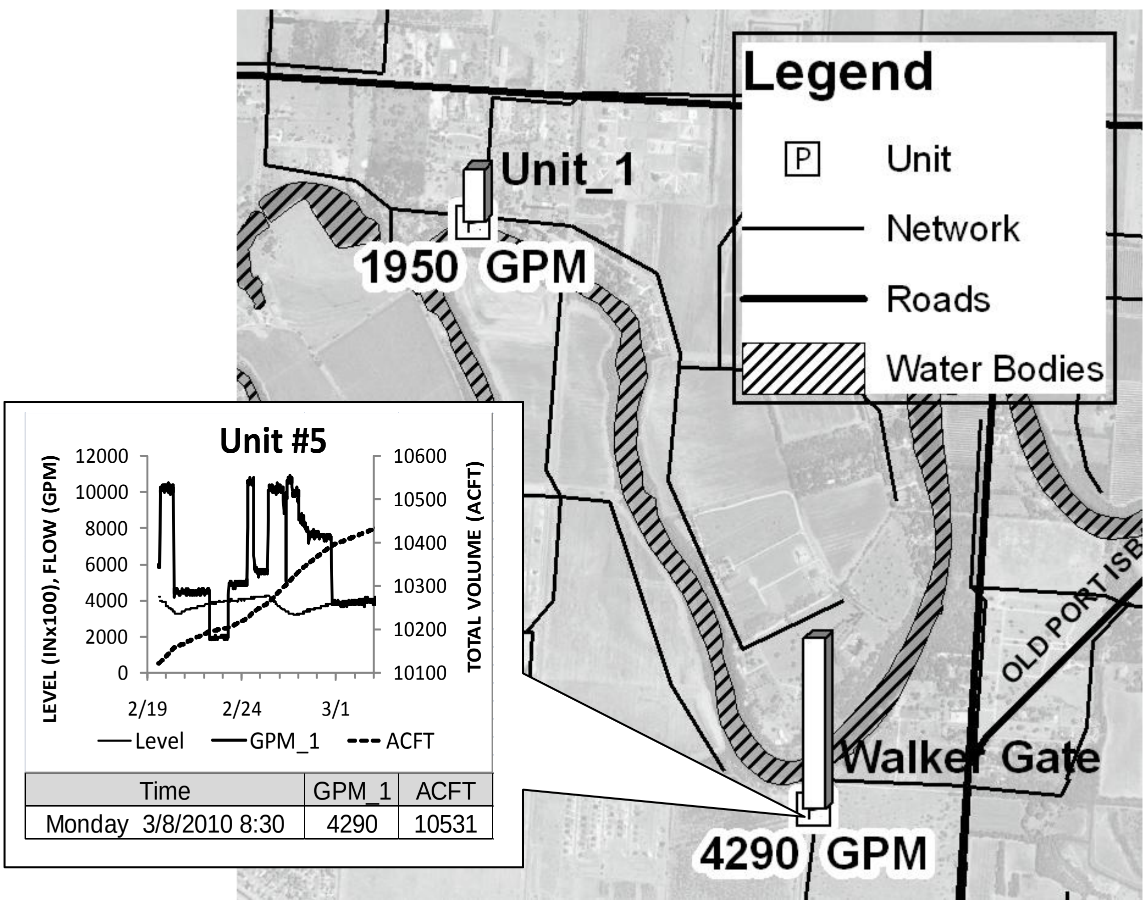


Figure 8. Pump operation real time and historical data accessed by District personnel.

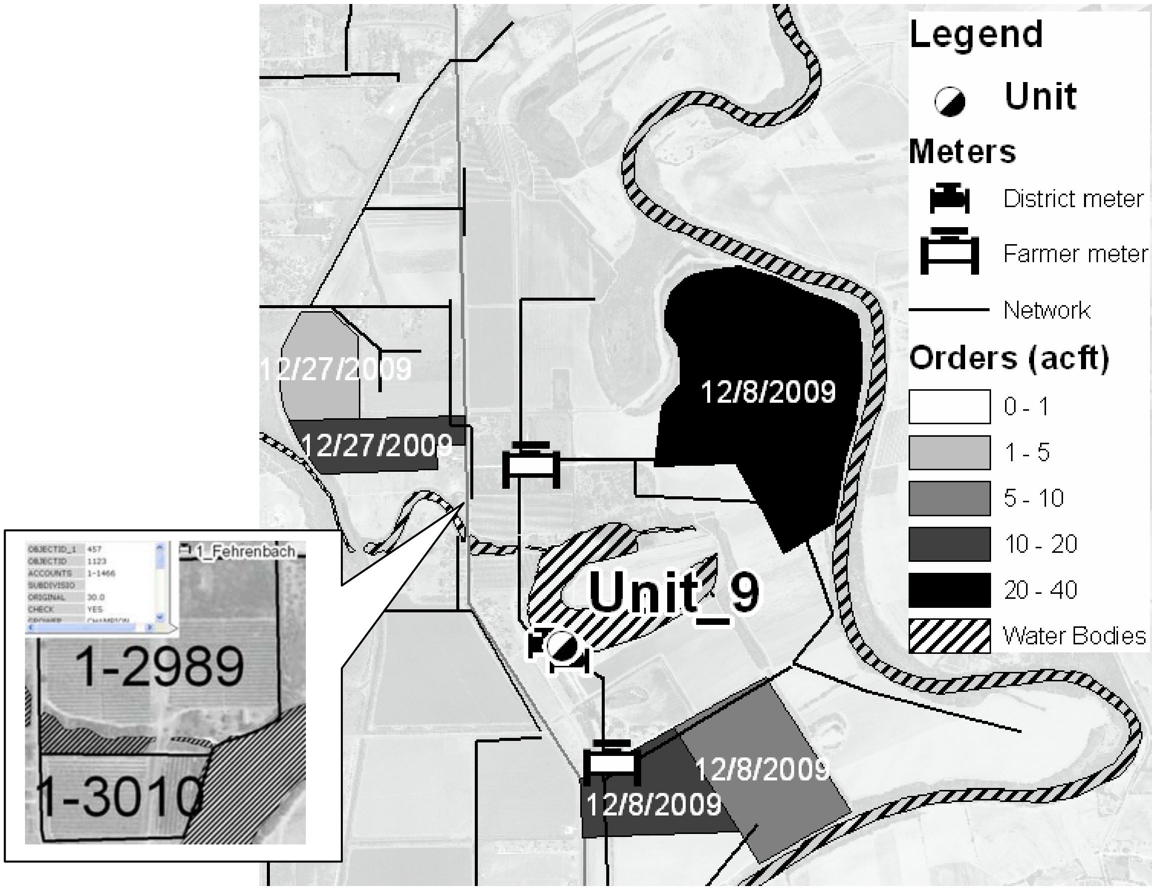
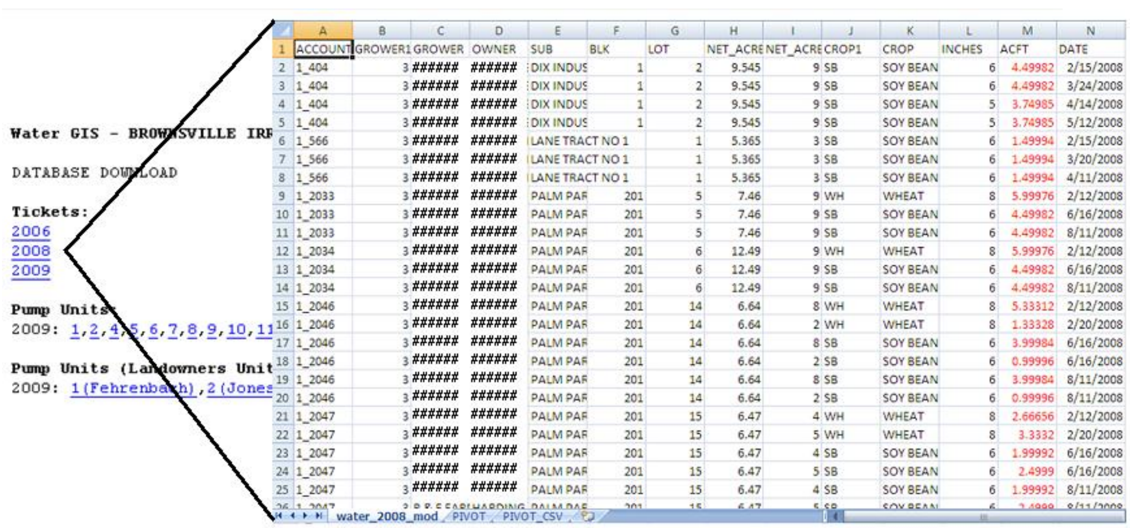


Figure 9. Water ticket sales and water account database accessed by District personnel.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	ACCOUNT	GROWER1	GROWER	OWNER	SUB	BLK	LOT	NET_ACRE	NET_ACRE	CROP1	CROP	INCHES	ACFT	DATE
2	1_404	3	######	######	DIX INDUS	1	2	9.545	9	SB	SOY BEAN	6	4.49982	2/15/2008
3	1_404	3	######	######	DIX INDUS	1	2	9.545	9	SB	SOY BEAN	6	4.49982	3/24/2008
4	1_404	3	######	######	DIX INDUS	1	2	9.545	9	SB	SOY BEAN	5	3.74985	4/14/2008
5	1_404	3	######	######	DIX INDUS	1	2	9.545	9	SB	SOY BEAN	5	3.74985	5/12/2008
6	1_566	3	######	######	LANE TRACT NO 1		1	5.365	3	SB	SOY BEAN	6	1.49994	2/15/2008
7	1_566	3	######	######	LANE TRACT NO 1		1	5.365	3	SB	SOY BEAN	6	1.49994	3/20/2008
8	1_566	3	######	######	LANE TRACT NO 1		1	5.365	3	SB	SOY BEAN	6	1.49994	4/11/2008
9	1_2033	3	######	######	PALM PAR	201	5	7.46	9	WH	WHEAT	8	5.99976	2/12/2008
10	1_2033	3	######	######	PALM PAR	201	5	7.46	9	SB	SOY BEAN	6	4.49982	6/16/2008
11	1_2033	3	######	######	PALM PAR	201	5	7.46	9	SB	SOY BEAN	6	4.49982	8/11/2008
12	1_2034	3	######	######	PALM PAR	201	6	12.49	9	WH	WHEAT	8	5.99976	2/12/2008
13	1_2034	3	######	######	PALM PAR	201	6	12.49	9	SB	SOY BEAN	6	4.49982	6/16/2008
14	1_2034	3	######	######	PALM PAR	201	6	12.49	9	SB	SOY BEAN	6	4.49982	8/11/2008
15	1_2046	3	######	######	PALM PAR	201	14	6.64	8	WH	WHEAT	8	5.33312	2/12/2008
16	1_2046	3	######	######	PALM PAR	201	14	6.64	2	WH	WHEAT	8	1.33328	2/20/2008
17	1_2046	3	######	######	PALM PAR	201	14	6.64	8	SB	SOY BEAN	6	3.99984	6/16/2008
18	1_2046	3	######	######	PALM PAR	201	14	6.64	2	SB	SOY BEAN	6	0.99996	6/16/2008
19	1_2046	3	######	######	PALM PAR	201	14	6.64	8	SB	SOY BEAN	6	3.99984	8/11/2008
20	1_2046	3	######	######	PALM PAR	201	14	6.64	2	SB	SOY BEAN	6	0.99996	8/11/2008
21	1_2047	3	######	######	PALM PAR	201	15	6.47	4	WH	WHEAT	8	2.66656	2/12/2008
22	1_2047	3	######	######	PALM PAR	201	15	6.47	5	WH	WHEAT	8	3.3332	2/20/2008
23	1_2047	3	######	######	PALM PAR	201	15	6.47	4	SB	SOY BEAN	6	1.99992	6/16/2008
24	1_2047	3	######	######	PALM PAR	201	15	6.47	5	SB	SOY BEAN	6	2.4999	6/16/2008
25	1_2047	3	######	######	PALM PAR	201	15	6.47	4	SB	SOY BEAN	6	1.99992	8/11/2008

Figure 10. Historical data can be downloaded by District personnel as spreadsheets.

CONCLUSIONS

In collaboration with the Brownsville Irrigation District, an education and demonstration project was implemented to use GIS in managing pump operation, and water account data.

Problems and recommended changes in managing data were identified. The most relevant problems were an incomplete connection link between computers, a formatting of output data not suitable for GIS applications, and a missing relation between irrigation water orders and irrigated fields.

A Web GIS Pilot Project was established which also addresses some of the identified problems. GIS training sessions were organized to ensure effectiveness of introduced changes. As a result of the Project, real time and historical data can be retrieved from GIS applications through the internet and owners and growers can access their personal water account and meter reading information, reducing need for help from District personnel.

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INTERACTION OF ADVANCED SCIENTIFIC IRRIGATION MANAGEMENT (ASIM) WITH I-SCADA SYSTEM FOR EFFICIENT AND SUSTAINABLE PRODUCTION OF FIBER ON 10,360 HECTARES

Nabil Mohamed[1]

ABSTRACT

Efficient drip irrigation of 10,000,000 fast-growing Pacific Albus trees in the water-challenged environment of Easter Oregon, US; requires not only a massive and complex computerized water distribution system but also an efficient and economical methodology to manage and deliver the water to the trees. The Greenwood Resources Boardman Tree Farm (GWR BTF) achieves this by interacting its Advanced Scientific Irrigation Management (ASIM) program with its state-of-art Irrigation Supervisory Control and Data Acquisition (I-SCADA) system to achieve high irrigation and economical efficiencies. Also within this ASIM / I-SCADA system combination is an elaborate automated soil moisture sensing operation and an original and innovative methodology incorporating a customized Advance Hydraulic Balanced Irrigation Scheduling (AHBIS) program, which enables smooth and steady hydraulic operation of 101 pumps at 23 major pump stations. Additionally, the BTF I-SCADA system operates pivot irrigation on 1,930 hectares (4,770 ac) of very high-value agriculture crops, including organic crops.

Boardman Tree Farm offers a show-case example where the latest technology and human ingenuity are utilized to drip irrigate vast areas of land, while at the same time minimizing the use of scarce water and energy resources and maintaining a sustainable and economical rate of fiber production for use in BioEnergy, Paper and Solid Wood production.

INTRODUCTION

In the semi-arid part of Easter Oregon, US, where less than 20 cm (8 in) of total annual precipitation occurs, exists the world's largest contiguous drip irrigated farm of 10,360 hectares (25,600 ac), managed by Greenwood Resources (GWR), and known as the Boardman Tree Farm (BTF) (Figure 1).

At BTF, 10,000,000 fast-growing Pacific Albus trees are irrigated by a massive and complex computerized water distribution system. Cost of pumping water is a major crop production cost, so a very aggressive and determined effort is made to operate the irrigation system efficiently and cost effectively. To achieve high irrigation efficiencies BTF uses Advanced Scientific Irrigation Management (ASIM) program, automated soil moisture sensing and one of the most advanced and sophisticated Irrigation Supervisory Control and Data Acquisition (I-SCADA) systems in the world. Additionally BTF

[1] Water & Energy Resource Engineer, Greenwood Resources Boardman Tree Farm, 77200 Poleline Road, Boardman, OR 97818, nabil.mohamed@gwrglobal.com, www.greenwoodresources.com

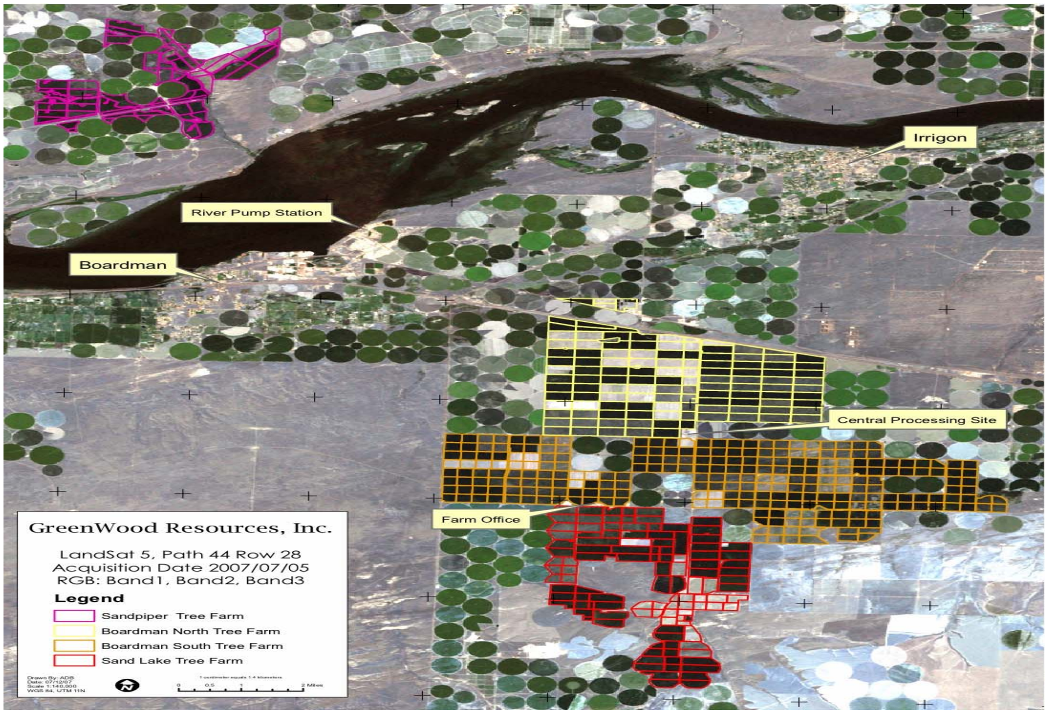

Figure 1. Satellite image of Boardman Tree Farm (BTF) in Eastern Oregon showing both the drip and pivot irrigated lands. Included also is the GreenWood Resources Sand Piper Tree farm located in Washington state and north of Boardman.

utilizes original and innovative methodology incorporating customized Advance Hydraulic Balanced Irrigation Scheduling (AHBIS) program, to create individual block irrigation schedule regimes. These irrigation schedule regimes provide precise irrigation together with a smooth and steady pump stations hydraulic operation.

One of the success stories of BTF's excellent water management practices is the demonstrated ability to irrigate with such accuracy (+/- 1 minute) and precision that the central 60 cm (2 ft) wide soil strip between the three meter (10 ft) wide tree rows always remains dry. This level of water application efficiency is unparalleled on such a grand scale anywhere else in the world!

The BTF overall tree management strategy emphasizes the use of the most efficient water delivery methods via drip irrigation and automation. Together with the use of the highest quality tree clonal material and the continuous monitoring of crop vigor and health, BTF aims to become the lowest cost producer of high quality sustainable wood fiber products. The Pacific Albus trees at BTF are grown on an eleven to fourteen-year rotation. For disease control and other reasons, multiple clones of Pacific Albus trees are used to add genetic diversity. Each clone has its own characteristic needs for water and fertilizer and unique production quality and quantity. Pacific Albus trees are known to grow more than five centimeters (2 in) a day during peak growth and have growth rings more than three and a half centimeters wide (1.5 in). The trees are harvested at an average sustainable rate of one tree every 16 seconds. For BioEnergy fiber production the trees are harvested every two years, for paper chip production the trees are grown for six to seven years and for solid wood the trees are harvested at twelve to fourteen years of age. It is a dynamic harvest plan which adjusts to market needs in order to maximize economical returns and production efficiencies at the Saw Mill located within BTF.

PROJECT FACTS

Boardman Tree Farm (BTF)

The BTF consists of two main units - North/South Boardman Tree Farm and the Sand Lake Tree Farm. In the North/South BTF, 7,500,000 fast-growing Pacific Albus trees are irrigated by a massive and very technically complex automated water distribution system. The large tree acreage is operationally divided into 369 individual irrigated blocks, each ranging in size from 16 to 28 ha (40 to 70 ac), which are fed by 13 different pumping stations from two independent farm water supply distributions; which also supplies water to other various crops on 1,930 ha (4,770 ac) under pivot irrigation. The extensive irrigation pipe network consists of 805 km (500 ml) of buried pipe 4 to 183 cm (1.5 to 72 in) in diameter and 23,100 km (14,330 ml) of drip tube with nearly 20,000,000 emitters. The 13 pumping stations have 70 irrigation pumps with a total of 22,640 kW (30,350 HP), producing peak flow capacities of 689,000 lpm (182,000 gpm) and a capacity to produce 992,000,000 lpd (262,000,000 gpd). Single pump capacities range from 1,900 lpm to 121,000 lpm (500 to 32,000 gpm) with pump motors ranging in size from 22 to 746 kW (30 to 1,000 HP).

North/South Tree Farm together with the Sand Lake Tree Farm, collectively form the BTF and cover 104 square km (40 sq ml) planted with 10,000,000 Pacific Albus trees on 10,360 ha (25,600 ac). Additionally there are a combined total of 2,225 ha (5,500 ac) of various high value crops including organic crops under pivot irrigation but on a non-GWR ownership. Both the trees and the pivot crops are irrigated by 23 major pump stations through 101 pumps. BTF peak pumping capability of 28,420 kW (38,100 HP) can deliver in excess of 852,000 lpm (225,000 gpm) with a capacity to produce 1,226,000,000 lpd (324,000 gpd). This very large volume of water is feed via nearly 27,000,000 emitters to the trees through an astounding 30,622 km (19,028 ml) of drip line, which is about ¾ the circumference of the earth. The 250 sand media filters in the irrigation system gives BTF the largest concentration of operational sand media filters in the world (Figure 2). Even though it is one of the largest rural water distribution systems in the state of Oregon, GreenWood Resources Drip irrigation System (GWRDIS) has the capacity to pump enough water per day to serve three cities the size of Portland, the largest city in the state of Oregon. The BTF with its present size of 10,360 ha (25,600 ac) is the world’s largest irrigated fiber farm and the North/South BTF is one of the largest contiguous drip irrigated farms in the world. BTF is also a world leader in large-scale drip irrigation efficiency.

Figure 2. BTF I-SCADA Remote Terminal Unit (RTU) with sand media secondary filters.

Irrigation Supervisory Control and Data Acquisition (I-SCADA) System

BTF irrigation practices cover a huge area and are very complex and demanding, thereby requiring a very sophisticated control and monitoring system. BTF state-of-art I-SCADA system controls and monitors 250 pumps, 369 irrigation blocks, 1254 automated valves and 46 center pivots. BTF's I-SCADA system consists of two master processors and a single computer installed with Human Machine Interface (HMI) software, all interacting together with the 153 Remote Terminal Units (RTU) (Figure 2). All communications to the RTU's is done by Spread Spectrum radio telemetry on two totally independent licensed radio frequencies. This I-SCADA system is designed to remotely control valve(s) or pump(s) within a radius of 24 km (15 ml) from the Operator Interface Terminal (OIT) at the office. All I-SCADA system remote field actions occur within two seconds of operator command, with full control acknowledgement within 5 seconds of command initialization from the OIT. Irrigation system operations can be remotely, or manually, programmed and stored at multiple locations on the I-SCADA system such as the OIT, master processors and the RTU's. I-SCADA system real time data is stored on a sequential database. Some data is stored every minute, and is then plotted for trends and also analyzed to improve BTF irrigation performance and methodologies.

IRRIGATION

Survival of Pacific Albus trees at BTF is largely dependent on irrigation water. In the semiarid environment during peak evapotranspiration rates, the project's irrigation system cannot adequately provide the trees high daily water consumption. Additionally for some tree clones the timing of irrigation is also important, therefore requiring random daily irrigation start times. Growing trees under these conditions and in sandy soils is a challenge in itself, further compounded with the fact that any cessation of irrigation for more than 15 hours causes a detrimental reduction in yield or even death of trees! Therefore reliability of the BTF irrigation system is very crucial.

BTF's pumping energy cost of nearly $4,000,000 for an irrigation season of less than eight months is a major operational cost for tree production; so achieving a high pumping efficiency is crucial task of the BTF I-SCADA system.

With all these tough environmental and tree demands, has forced BTF to implement very sophisticated and reliable water management practices. With 369 individual blocks, that cycle irrigation as much as four times a day, irrigation scheduling is also a hydraulic nightmare.

There are basically two major irrigation challenges facing the BTF:

1) Water deliverance from the source to the trees.

Every irrigation project has its challenges and the challenges faced by BTF, especially in water deliverance are not unique except for its very large scale of operation. BTF met these challenges by spending adequate resources to ensure the delivery of water is not an issue in tree production. Senior water rights, upgrading/changing of existing water deliverance facilities by using the latest and appropriate technology with "good" engineering were the keys. Once the deliverance system was installed, a state-of-art I-SCADA system was installed to control and monitor the whole BTF irrigation system. This I-SCADA system provided the ability to "spoon feed" the trees with specific amounts of water and fertilizer.

2) Water management and irrigation scheduling.

In the areas of water management and irrigation scheduling, BTF faces challenges that are huge, ongoing and very complex that require unique solutions involving collectively the I-SCADA system and the use of multiple customized and in-house software. Additionally these challenges are made even more demanding as they affect the whole economics of the BTF operation.

The I-SCADA system tackles these daunting challenges of water management and irrigation scheduling by interacting together with sophisticated and customized Advanced Hydraulic Balanced Irrigation Scheduling (AHBIS) software. This AHBIS program generates an I-SCADA operational code file with nearly 12,000 individual block irrigation schedules with random daily irrigation start times and hydraulically balanced. The I-SCADA / AHBIS program interaction allows BTF to micromanage irrigation scheduling at the individual 16 to 28 ha (40 to 70 ac) block level.

Hydraulic Balanced Irrigation Scheduling (HBIS) is an original and innovative methodology of creating individual block schedule regimes that leads to a smooth and steady pump station hydraulic operation. This methodology is incorporated into a customized highly sophisticated Advance Hydraulic Balanced Irrigation Scheduling (AHBIS) program that optimizes irrigation schedule regimes, such that no pump changes are necessary during a period of a particular irrigation schedule regime. This also leads to steady canal withdrawal rates at the pump stations thereby assisting the irrigation district to have an efficient canal operation. It also allows the operation of a very large complex irrigation system without the use of expensive and very complex pump automation programs. The AHBIS methodology improves pumping energy efficiency with tangible pump energy savings, decreases irrigation system wear and greatly improves human resource allocations. This “smooth” operation of the irrigation system is “easy’ on the irrigation hardware of the system and lessens the work load of the irrigation team members as their interaction with the I-SCADA system is normally only limited to reacting to its remote pager alarm message(s). This hydraulically smooth operation is what enables the I-SCADA system to become a “stand alone” system.

ADVANCED SCIENTIFIC IRRIGATION MANAGEMENT (ASIM) PROGRAM

1. The BTF water management goal, for economical and environmental reasons, is to ensure that the water pumped by the irrigation system is the right amount for the trees – “no more no less”.

2. The goal of applying only the absolute minimal amount of water that the trees need, lead to the development in-house of sophisticated and comprehensive Advanced Scientific Irrigation Management (ASIM) program. This ASIM program is operated on weekly basis throughout the irrigation season.

3. The weekly ASIM program starts from weather data collected from the local AgriMet station(s) (Figure 3). AgriMet stations are a satellite-based network of nearly 75 automated agricultural weather stations located mainly in the Pacific Northwest and are operated and maintained by the Bureau of Reclamation. The AgriMet weather data is analyzed together with weather forecasts from three independent sources, including a customized weather forecast provider. Further computation and analysis with a 22 year historical local weather database, leads to a prediction of Evapotranspiration (ET) and Growing Degree-day (TG) rates for the coming 10 days. The ET and TG information is then input into in-house Pacific Albus crop models, which result in an accurate and repeatable scientific approach to predicating water demands for each age group of trees. Collectively this *predicated water demand* is the accumulated amount of water to be pumped by the BTF irrigation system and is the right amount of water that the trees actually need for the coming week.

4. Nearly 375 automated soil moisture sensors provide real time soil moisture readings at various locations and depths around BTF. The soil moisture data is collected by I-SCADA and stored in a sequential database. Analysis of the soil moisture data provides information if any adjustment to the soil moisture reservoir in the soil is required. The goal of BTF, for optimum economical growth of the trees, is to maintain greater than 80% available soil moisture in the root zone. The automated soil moisture sensors also monitor the irrigation water encroachment to the central 60 cm (2 ft) wide soil strip between the three meter (10 ft) tree rows; which according to state water right rules has to always remain dry. A detailed soil moisture evaluation status (increase/decrease) at each

field, including other analysis, is done at this stage of the ASIM program and a *soil moisture* report is created.

Figure 3. "HERO" AgriMet station located North boundary of BTF.

5. The *predicated water demand* per tree age group is converted to *hours of irrigation* operation and is presented to the Water Group of BTF team for acceptance and modifications. The present and extended weather forecast, extended and historical ET and TG graphs and the *soil moisture* report are also presented at the same time. This is a major decision of the week and one that impacts greatly on the economics of BTF. Debate is done on issues such as; if water demands for a particular age group of tree need any adjustment, date and time for the start of the next irrigation schedule, pump availability and water quality issues such as system flushes. Water Group members provide input on irrigation hour's adjustments per age group and clone, special irrigation requests, single or multiple block runs, daily to every third day schedules, number of cycles per day, system flushes and special water regimes for experimental testing and harvesting. A report with the final decision on the *hours of irrigation* for each age group and other irrigation parameters is then prepared and forwarded onto the next stage of ASIM program.

6. The information from the *hours of irrigation* report is then input into an in-house software program and hours adjusted due to higher or lower emitter flows in comparison to design flows. Additional adjustment to the hours is made due to the BTF Deficit Irrigation program. After computation a determination of the expected water demand at each pump station and the expected withdrawal rates from the irrigation canal is made. Pump selection per pump station for efficient water delivery is also computed and relayed to the irrigation team for confirmation on availability of the selected pump(s) to the I-SCADA system. The expected water withdrawal demand from each of the irrigation canal pump stations is then relayed to the irrigation canal company 24 hours before the new schedule goes into place. The final output of this stage of ASIM program is an

irrigation demand file that is forwarded to the next step of the ASIM program for encoding into the I-SCADA system.

7. For actual I-SCADA implementation of the planned hours of irrigation, a six-day irrigation schedule regime for each of the 369 individual blocks is created from the *irrigation demand* file by the AHBIS program. It is a tedious and complex process of laying out an irrigation schedule that provides not only the irrigation needs of each block precisely but also covers the block flush requirements, has random daily irrigation start times and maintains a steady hydraulic demand at all times at each pump station during the duration of the irrigation schedule. The output of the AHBIS program is the *BTF irrigation schedule code* file, consisting of nearly 12,000 individual block irrigation and/or flush schedules over a six day period. This irrigation schedule regime allows the BTF irrigation team to micromanage irrigation at each block level to within +/- of a minute, for a high precision and accurate irrigation of the Pacific Albus trees.

8. The *BTF irrigation schedule code* file is then transferred, via Ethernet, to I-SCADA master processor which in turn remotely transfers, via radio, to the 93 RTU's for implementation at field level. The I-SCADA OIT displays the new irrigation schedule and system flushes of each block, keeps track of its real time operation as it progresses and stores the data in the database every minute. An 18-page report on the new daily irrigation schedule for the next six day run is the final output of the weekly ASIM program at BTF. This irrigation schedule report is then disseminated to the BTF irrigation team.

9. When the weather conditions change enough to affect the trees predicted water demand, the ASIM program is run again and a new *BTF irrigation schedule code* file created. Major structural failures with the BTF irrigation system can also cause a change in the water regime and thereby initiate a new partial, or full, ASIM program run.

10. If the water demand for the trees does not change over a six-day period, the I-SCADA system will automatically repeat the previous week's irrigation schedule.

OTHER IRRIGATION EFFICIENCY PRACTICES

Beside the use of ASIM and AHBIS programs together with the I-SCADA system, BTF utilizes other important practices for achieving high overall irrigation efficiencies. These practices include:

1) Use of an award winning design for closed-loop drip irrigation system together with pressure compensated emitters to achieve the highest possible irrigation application efficiencies.
2) Use of Variable Frequency Drive (VFD) motors, Real-Time innovated pump selection guides at the I-SCADA OIT for single and multiple pumps operations, Real-Time data of energy usage per unit of water pumped and combined with on-line pump testing; all collectively help improve irrigation pumping energy efficiencies.
3) Use of extensive Real-Time flow and pressure monitoring at pump station and block levels, enables high irrigation uniformity efficiencies.

4) Complex localized RTU programming at each block level to enable hydraulic Self Recovery of the irrigation system in case of partial lose of pumps or pumps stations. This Self Recovery allows partial irrigation to occur minimizing the downtime effects of an irrigation system failure.
5) Use of sophisticated “auto-pump shut-off” RTU programs for maintaining system integrity when irrigation system fails. This is combined together with extensive Real-Time alarm/pager system to alert operators of an irrigation situation that would affect irrigation performance or efficiency.
6) Use of satellite multi-band imagery and aerial Infra Red (IR) information to assist in improving irrigation uniformity efficiencies.

CONCLUSION

With the use of innovative irrigation water management ideas and methodologies, together with precise and accurate application of irrigation amounts, BTF farm achieves high overall on-farm irrigation efficiencies in excess of 95%. The BTF offers a show-case example where latest technology and human ingenuity are utilized to drip irrigate vast areas of land, while minimizing the use of scare water and energy resources while maintaining a sustainable and economical rate of fiber production for use in BioEnergy, Paper and Solid Wood production. At BTF the use of Advanced Scientific Irrigation Management (ASIM) program, State-of-Art I-SCADA system, extensive automated soil moisture monitoring, multiple weather sources, Pacific Albus crop curves and the use of complex customized and in-house software, allows BTF to adequately irrigate its trees very efficiently and so maintain its position as a world leader in large scale drip irrigation efficiency.

With its innovative and sophisticated drip irrigation technology, BTF can help lead the world in advancing the spread of large-scale drip irrigation projects. Implementation of drip irrigation technology is ever so much important in today’s times, where some countries social and economical survival may very well depend on migrating from less water efficient irrigation systems to more water efficient drip irrigation systems, allowing optimum use of their scarce and diminishing water resources.

ACKNOWLEDGEMENT

Appreciation is extended to the GreenWood Resources Inc. and its Boardman Tree farm Team, whose members devote tireless efforts in seeking higher levels of efficiency in producing low cost, sustainable and eco-friendly fiber and wood products.

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

Nathi Manana[1]
Luis Garcia[2]
Kristoph-Dietrich Kinzli[3]
David Patterson[4]
Ramchand Oad[5]
Nabil Shafike[6]

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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[1]Graduate Research Assistant, Colorado State University, Fort Collins, CO; kosinathi.manana@colostate.edu
[2] Professor and Department Head, Department of Civil and Environmental Engineering Colorado State University, Fort Collins, CO; garcia@engr.colostate.edu
[3]Assistant Professor, Whitaker School of Engineering, Florida Gulf Coast University, Fort Myers, FL; kkinzli@FGCU.edu
[4] Research Associate, Colorado State University, Fort Collins, CO; pattersd@engr.colostate.edu
[5]Professor, Department of Civil and Environmental Engineering Colorado State University, Fort Collins, CO; oad@engr.colostate.edu
[6] Hydrologist, New Mexico Interstate Stream Commission, Albuquerque, NM; nabil.shafike@state.nm.us

INTRODUCTION

Irrigated agriculture in the Western United States has traditionally been the backbone of a vibrant rural economy. The climate in much of the American West in characterised by low annual rainfall amounts of 8-14 inches, which is conducive only to dry land farming. Irrigated agriculture requires extensive water diversions and systems of canals and laterals. Topography in the West is characterized by north to south mountain ranges, such as the Rocky Mountains, which accumulate significant snowfall. These mountain ranges interrupt the movement of precipitation in the west to east storm tracks causing rain deficit shadows in the plains on the lee side of the mountain ranges. The snowmelt hydrograph, which has a duration of approximately 100 days, provides direct diversion of water on to the irrigated farms, with excess runoff stored in reservoirs allowing for irrigation throughout the summer crop-growing season. Of the total available surface water, irrigated agriculture uses (diverts) 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 (diverts) 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 River and its tributaries, including the Rio Chama River. 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 chili, the latter 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 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 instream 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 satisfy its irrigator's requirements 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.

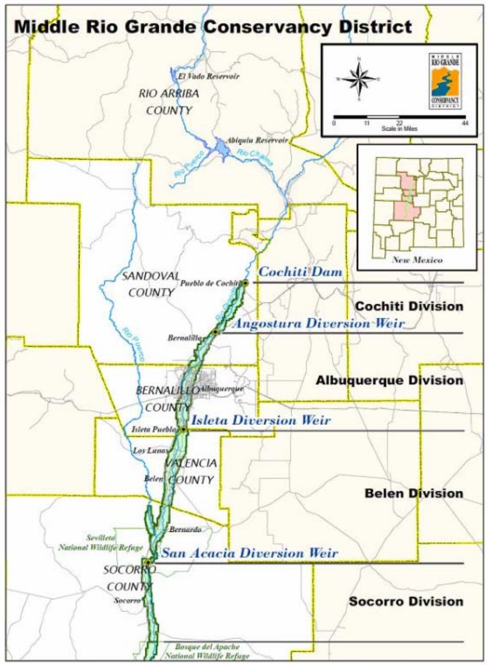

Figure 1. Middle Rio Grande Conservancy District (MRGCD)

Decision Support Modelling of Irrigation Systems

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.

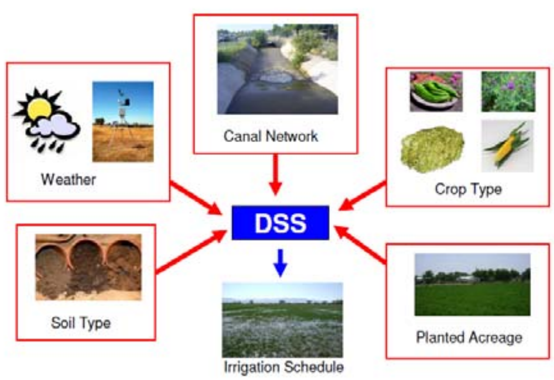

Figure 2. Conceptual View of a Generic SWD DSS

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).

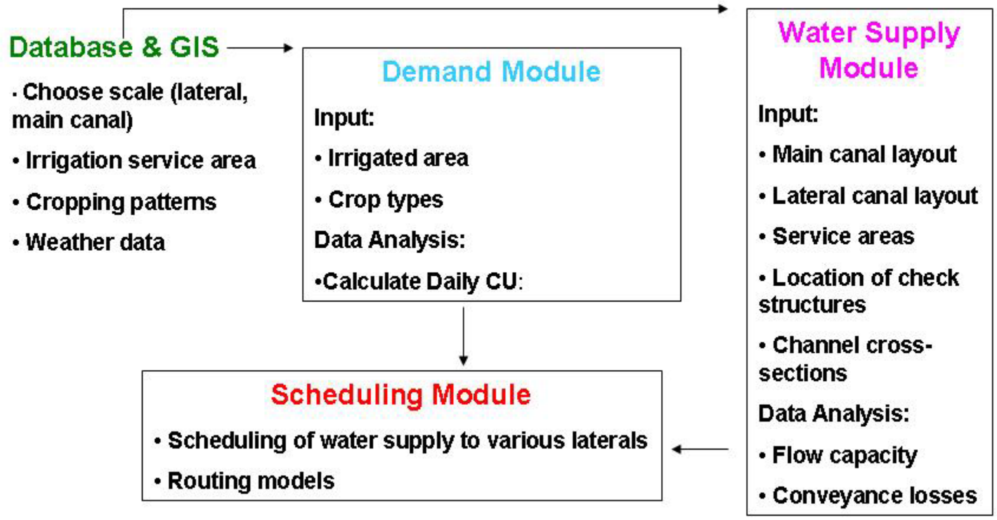

Figure 3. DSS Structure Displaying the Three Modules and Database (Kinzli, 2009)

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.

<u>Supply Network Module.</u> 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.

<u>Irrigation Scheduling Module.</u> 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.

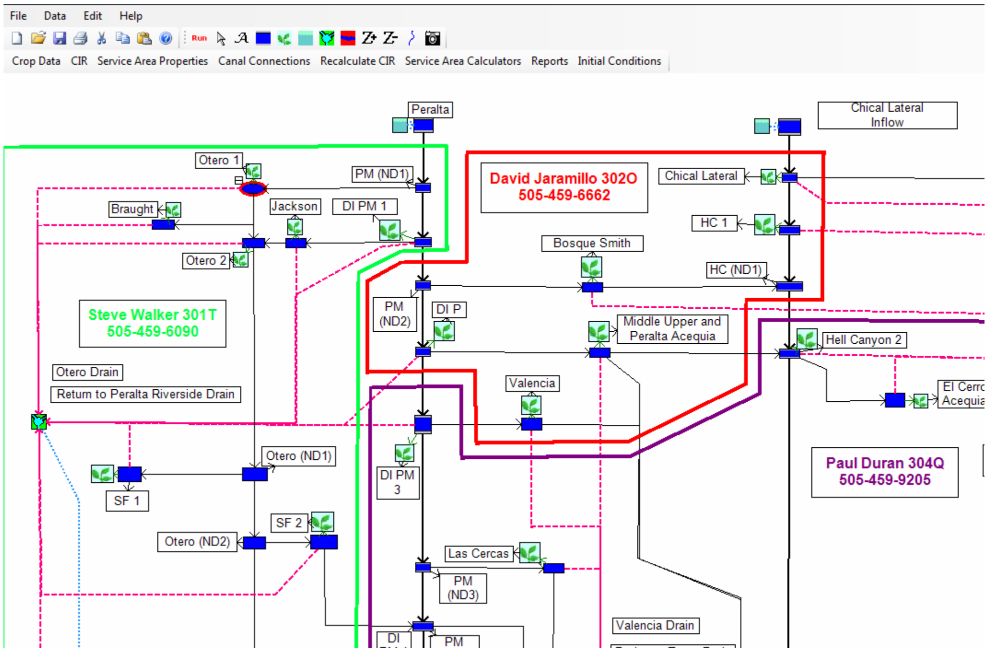

Figure 4. Representation of DSS Supply Network (Kinzli, 2009)

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

Water Measurement Structures

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 and accuracy 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 (Kinzli, 2009)

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).

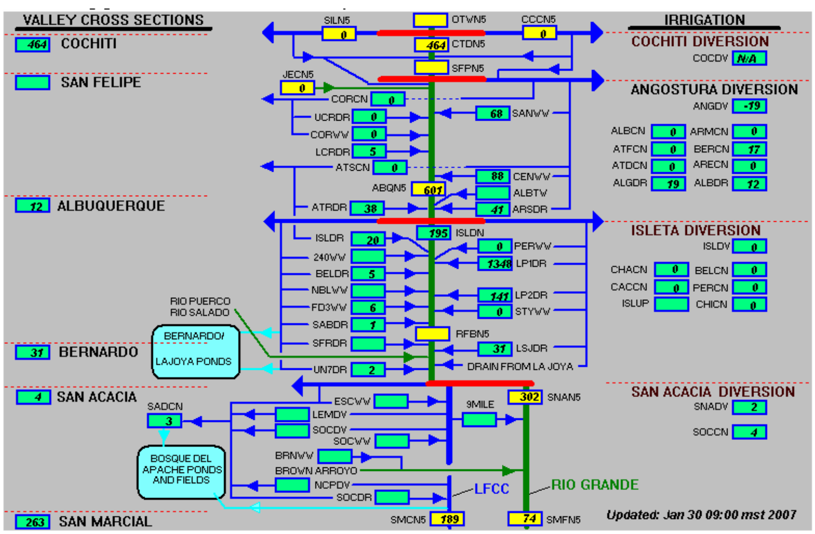

Figure 7. MRGCD Telemetry Network

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.

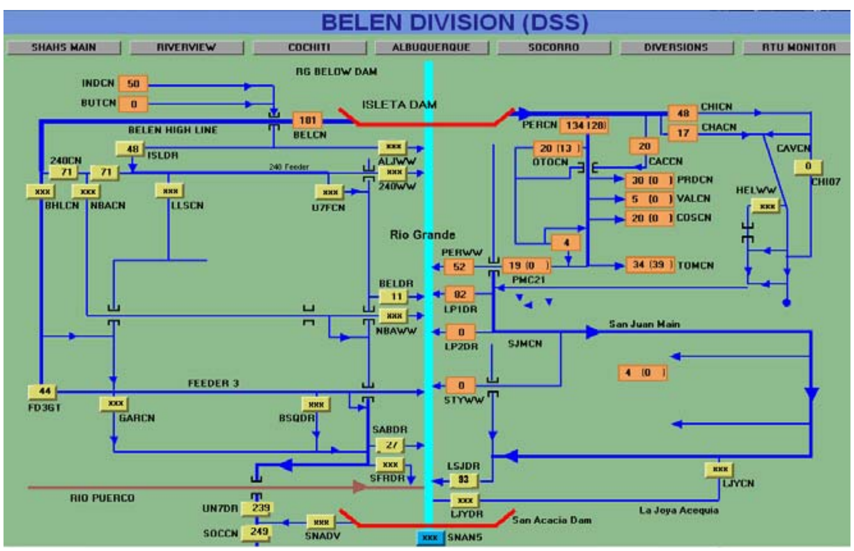

Figure 8. MRGCD SCADA Screen with Actual Deliveries and DSS Recommendations

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.

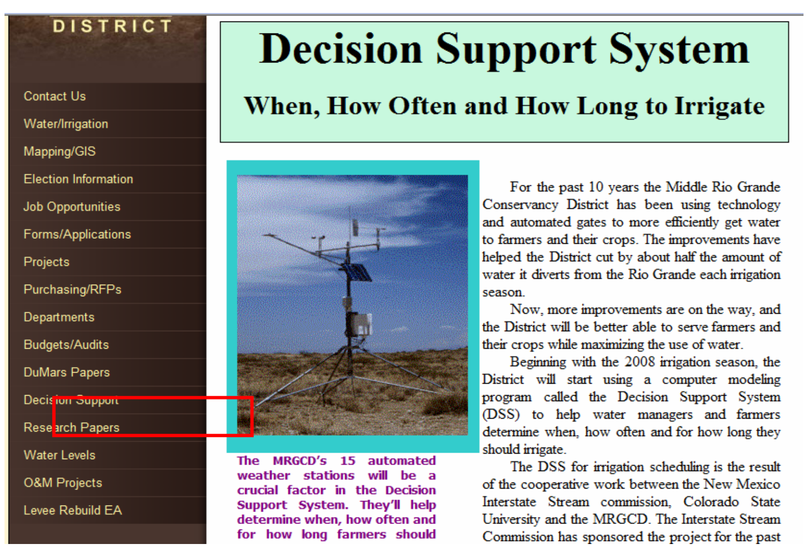

Figure 9. Article Explaining DSS on MRGCD Website

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.

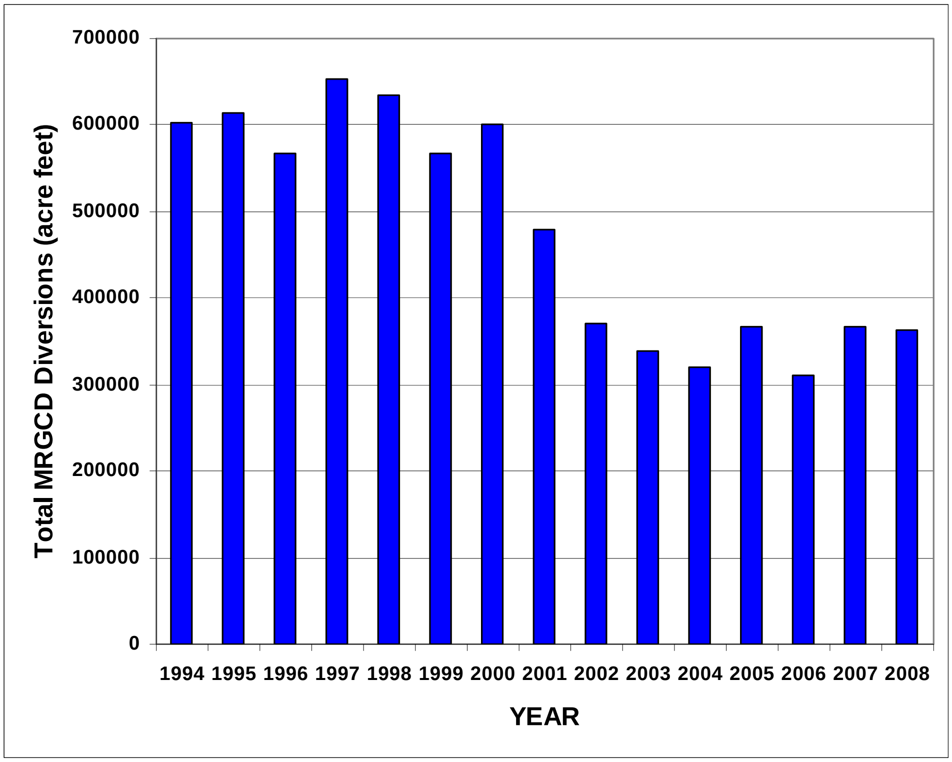

Figure 10. MRGCD River Diversions by Year

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.

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COST-EFFECTIVE SCADA DEVELOPMENT FOR IRRIGATION DISTRICTS: A NEBRASKA CASE STUDY

Clinton Powell[1]
Tom Gill[2]

ABSTRACT

Irrigation districts across the West face economic hardship brought about by increased maintenance costs, reduced water supplies, and a shortage of skilled labor. One opportunity for a district to offset these challenges is by implementing a Supervisory Control and Data Acquisition (SCADA) system. However, historically these systems have been out of the reach of smaller and less-affluent districts because of the large capital outlays required for adoption.

Reclamation's Nebraska-Kansas Area Office in cooperation with Reclamation's Hydraulic Investigations and Research Laboratory is working with the Bostwick Irrigation District in Nebraska to create a monitoring and control system suitable to the needs of a small irrigation district with limited resources. Specifically the project has focused on low acquisition and installation costs, district driven solutions to SCADA operational issues, and minimization of technical expertise for maintenance purposes.

This paper chronicles the efforts to develop a SCADA solution for the Bostwick Irrigation District in Nebraska that meets each of these needs through innovative product choices, materials fabrication, and low-cost solutions. Current project status and future project direction are discussed in context of the District's operating environment in light of the complex issues facing all the water users in the Republican River Basin upstream from Kansas.

BACKGROUND

The Bostwick Division was authorized in December of 1944. The Bostwick Division is comprised of two sub-units, Bostwick Irrigation District in Nebraska that currently serves approximately 20,500 acres in Nebraska, and the Kansas-Bostwick Irrigation District currently serving approximately 62,000 acres. Harlan County Lake, a multiple use water storage and flood control facility constructed by the US Army Corps of Engineers (USACE) on the Republican River near Republican City NE serves as storage for both the Nebraska and Kansas Bostwick Districts. Lovewell reservoir on White Rock Creed provides additional storage for the Kansas-Bostwick District.

Nebraska Bostwick Irrigation District is geographically in the middle of the area that was the focus of recent US Supreme Court litigation among Kansas, Nebraska and Colorado regarding use of Republican River Basin water resources. In 2004 with Harlan County

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[1] Agricultural Engineer, US Bureau of Reclamation, Nebraska-Kansas Area Office, Water Conservation Program; clintonpowell@usbr.gov
[2] Hydraulic Engineer, US Bureau of Reclamation, Hydraulic Investigations and Laboratory Services Group; tgill@usbr.gov

Lake at approximately one-third normal storage capacity, no water was delivered to District shareholders for the first time since water delivery operations were initiated in the 1950's. 2005 was again a water short year and for the second consecutive year, no deliveries were made to Nebraska Bostwick irrigators. With return of precipitation in the basin to rates closer to the historical norm, Nebraska Bostwick water deliveries resumed in 2006 and have continued through 2009. Going into the 2010 season, Harlan county lake is at full storage, which bodes well for normal deliveries in 2010

With these recent uncertainties in its operations, Nebraska Bostwick has been aggressive in enhancing water conservation capabilities in their delivery network. The District has taken advantage of the comparatively high elevation of the Franklin Canal relative to the delivery areas served by laterals off the Canal and in Spring, 2010 is completing a multi-year project to replace multiple open laterals with buried pipe. In an effort initiated in 2009, Nebraska Bostwick began to integrate electronic control and radio communications equipment which will enable local automation and/or remote operation and monitoring of structures in the canal system. The control/communications project is the focus of this paper.

PROJECT SCOPE

All field locations included in initial phase of Nebraska Bostwick's control/ communications project are located on the main stem of the District's Franklin Canal. The Franklin Canal runs along the north side of the Republican River beginning at the turnout gates just below Harlan County Dam. The canal continues for almost 47 canal miles eastward paralleling the Republican River along the north side of the valley. The upper end design capacity of the Franklin Canal is 230 ft^3/s.

Sites selected for equipment installation are ten check structure along the canal reach between Harlan County Dam and Red Cloud NE. The selected checks represent approximately every third check structure. Distance in canal miles between instrumented checks ranges from a low of 2.1 miles to a high of 5.6 miles. The average distance is approximately 3.6 miles.

Lands under Nebraska Bostwick are subject to frequent intense and often localized thunder storms. As a result, irrigators routinely need to drop scheduled deliveries on short notice. Additionally, storm water runoff can lead to significant unanticipated canal inflows. Throughout its operating history, Nebraska Bostwick has experienced significant spillage losses due to impacts of weather events.

Primary among upgraded capabilities being sought by the district were 1) improved delivery reliability, and 2) the capability to utilize in-canal storage to limit spillage losses. Additional benefits such as reduced vehicle mileage and staff travel time required to monitor the system were considered secondary to improving system performance and enhancing water conservation.

To meet District objectives, Reclamation engineers worked with District staff to develop a plan for equipping the ten designated check structures for local automated upstream level control with the capability to adjust target levels either onsite, or remotely.

Additionally, Reclamation engineers attempted to develop a methodology for using the installed gates as a flow measurement device to determine flow passing the instrumented check structures.

EVALUATION OF EXISTING STRUCTURES

The ten selected checks represented two general design configurations. The upper seven checks were each three-bay structures. The two outer bays were stop-log controlled and the center bay was a vertical slide gate. None of the gates were motorized. District staff indicated that the vertical slide gates had remained in closed position at all times for as far back as presently employed personnel could remember. The District opted to rebuild existing gates prior to installing the control and communications equipment. Since district staff was tied up on the project of converting open laterals to buried pipe, the District contracted with a local welding shop to construct new gates for the seven upper three-bay structures. Figure 1 is a photo of the three-bay 5.4 check

Figure 1. Reclamation Engineer Clinton Powell (L) and Nebraska Bostwick Manager Mike Delka Inspect the 5.4 Check in February, 2009

The three checks lower on the canal that the District selected for motorized gate operation initially had no gates installed. Each of these sites was a two-bay structure with stop-log control in each bay. The District staff fabricated new vertical slide gates to install in one of the stop-log bays at each of these checks. Figure 2 shows the 34.2 check site.

Figure 2. Nebraska Bostwick 34.2 Check in February 2009

RADO PATHWAY CHECK

In March of 2009, Reclamation engineers worked with Nebraska Bostwick personnel to test radio transmission signal strength. Radio/control units manufactured by Control Design Inc. (CDI) were selected for the tests based on the successful performance of their equipment on other projects. Compared to other available alternatives, CDI equipment was cost effective and demonstrated good signal strength. For the tests, an antenna was temporarily installed on the communications radio tower at the District's Red Cloud office. A battery-powered radio was connected to the antenna at the tower base. A second antenna was attached to a ten-foot mast and taken to each check structure, beginning with the site nearest Red Cloud and working outward. A second battery powered radio/control unit programmed with a calibration algorithm to determine receiver signal strength indicator (RSSI) levels was linked to the field antenna.

Communications with the Red Cloud office were tested at successively further west sites until a site was reached at which a reliable link could not be established. At that time, the field antenna was taken to the District's Franklin office and temporarily installed on the Franklin communications radio tower to attempt direct contact with Red Cloud. Attempts to make direct contact between the office sites were unsuccessful. To continue the tests, the antenna at Red Cloud was taken down and mounted to the ten-foot mast to use at remaining field sites in checking communications linkage with the Franklin Office. The later tests showed that communications from Franklin were possible with the westernmost check that could be contacted from Red Cloud, and with all of the rest of the field sites west from that point plus the gate house at Harlan County Dam.

Based on findings of the radio pathways testing a comparatively simple radio network was sufficient to establish communications among all sites and both offices without including any dedicated repeater sites. Each office base could be programmed to communicate directly with field sites within its range. The system was designed such that for out of range sites, each office would repeat first through the field site (the 28.6 check) that could directly communicate with both offices. A second repeat could be made through the base at the other office, then back to the selected field site. Built-in networking configuration tools in the CDI equipment enables each unit to perform as a base or as a field Remote Transmission Unit (RTU) and simultaneously function as a repeater. Figure 3 is a sketch of the project layout showing relative positions of Harlan County Lake, instrumented check sites, the Franklin and Red Cloud offices, along with the check site that also functions as a repeater.

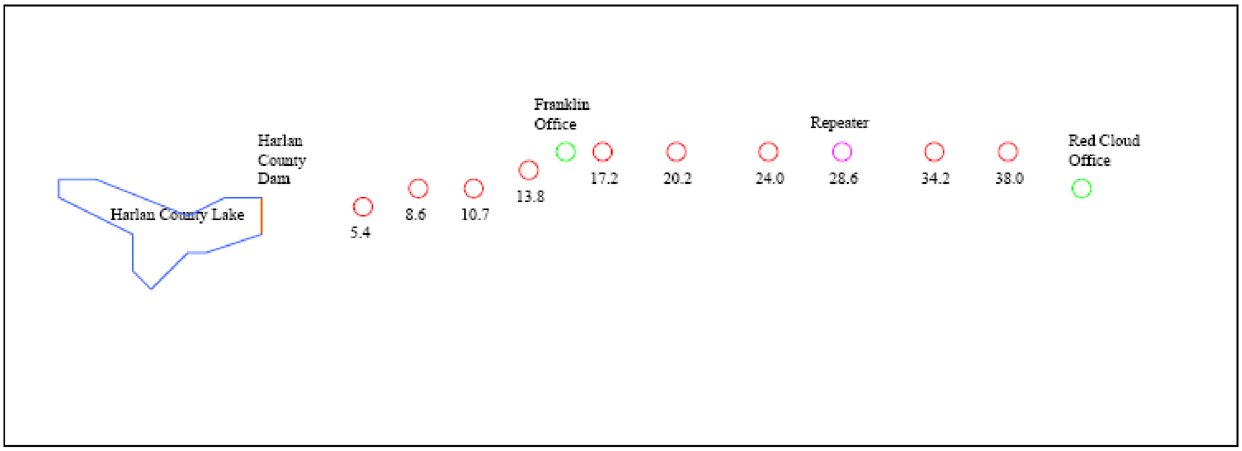

Figure 3. A Layout Sketch of Approximate Locations of the Radio/Communications Sites.

A sense of scale may be derived from Figure 3 from check identifier names. The identification number for the Franklin Canal checks represent the number of canal miles they are located from the gate house below the Harlan County Dam. It should be noted in the context of the discussions on radio transmission paths that the landscape throughout the project area can be characterized as rolling hills. Much of the radio pathway being utilized is not line of sight.

GATE MOTORIZATION

Nebraska Bostwick considered a range of gate motorization alternatives. Prior to embarking on this project, two members of the District staff participated in a Reclamation-sponsored Canal Modernization Workshop held in February of 2009 in Hot Springs SD. During the workshop, staff of the Belle Fourche (SD) Irrigation District reported on their canal modernization project that included using linear actuators on previously hand-operated gates. Belle Fourche has also installed commercially produce canal gate actuators produced by Limitorque. Information was also presented on a chain drive gate motorization that was developed by Reclamation over a decade ago that has been in service over an extended time period at sites in multiple states.

For reasons of simplified installation and for the attractive affordability offered, the District opted to motorize the vertical slide check gates using linear actuators. Availability of units with built-in travel limit switches as well as built in positions sensors were perceived as key benefits over the chain drive option. From an affordability standpoint, the linear actuators are almost an order of magnitude lower in cost than commercial actuators.

The new gates, which were either built by District staff or by a contractor, were configured during construction for linear actuator operation. In lieu of the threaded rods previously used to lift gates, a short section of smooth shaft was affixed to the gate on the lower end and has a clevis-type connector for linkage to the linear actuator on the upper end. The function of this rod is to keep all components of the linear actuator above the water surface at any gate position.

2009 INSTALLATIONS

New gates were installed at each of the selected check sites in early June prior to the initial water-up of the system. Tubing and protective conduit for bubbler level sensors were also installed at check structures prior to watering up the system. Each site was equipped for upstream and downstream level measurement if submergence conditions are present.

Installation of linear actuators, along with batteries, solar charging systems, and manual operation toggle switches began prior to water-up and continued through out much of the irrigation season. Limitations on the time commitments of Reclamation staff proved to be a bottleneck in completion of this task. Reclamation's staff was primarily responsible for calibration and testing of electrical and electronic components. At sites where gate motorization was not yet functional, canal stage adjustments were made by adjusting stop logs in bays adjacent to the gated bays, in the same manner the system has been operated in previous years. Figure 4 shows the final stages of hardware installation at the 20.2 check. Figure 5 is a photo of the same site from a different angle.

Figure 4. Reclamation Engineer Clinton Powell Making Wiring Connections on the Linear Actuator at the Nebraska Bostwick 20.2 Check

Figure 5. Completed Hardware Installation at the Nebraska Bostwick 20.2 Check

CONTROL SYSTEM COMPONENTS

As noted earlier, bubbler level sensors were selected to measure upstream canal pool level. Downstream levels are needed for gate flow measurement where submergence is present. The bubbler equipment employs a single bubbler setup plumbed through a bi-directional solenoid valve to enable the same sensor to measure water level at two locations. The installation was made easier because CDI had previously provided a board with all components needed for this multiple level bubbler sensor for use with a submerged flume measuring system Reclamation has been field testing in Arizona.

This multiple location bubbler level sensor was a cost competitive alternative for measuring two levels. The bubbler technology also eliminates water quality concerns associated with use of submersible pressure transducers, functions effectively without a stilling well, and does not require the temperature compensation that is often needed with ultrasonic level sensors.

Gate operation circuitry that Reclamation (and others) have utilized at multiple DC powered canal gate installations utilizes triple-pole, double-throw plug-in relays with relay contacts located in a sealed chamber filled with inert gas. Two relays are utilized for each gate. When a relay coil is energized, two of the normally open triple pole contacts close to complete both the ground and positive legs of the gate motor circuit. The coil energizing circuit utilizes normally closed contacts on the third pole of the companion relay. Thus when one relay coil is energized, all normally closed poles are opened. It is not possible to simultaneously energize both relay coils.

CDI has created a circuit board with sockets for the plug-in relays that utilize the same circuitry as hand-wired installations Reclamation has used successfully along with diodes to protect against reverse current flow resulting from collapsing fields as circuits are switched. An additional feature built into the CDI boards are terminal connections for installation of toggle switches to switch control from the on-site programmable logic controller (PLC) to hand operated toggle switches to raise and lower gates.

The CDI radio control units are assembled as a single unit consisting of a programmable logic controller, a modem and the radio. The current product line which was introduced in 2007 may be configured with or without an on-board 4 x 20 display and with or without an on-board 6 button keypad. At similar installations where CDI equipment has been utilized, an on-site user interface has proven to be a desirable configuration. Figure 6 shows installation of control equipment at a Nebraska Bostwick check site with remotely located display and 4 x 4 keypad.

Figure 6. Control Components (upper enclosure) and
User-Interface Components (lower enclosure)

A drawback to the on-board display and keypad is that if these user interface components are frequently accessed, there is high potential for the enclosure cover to be insufficiently closed and sealed leading to issues with moisture and/or insects disrupting function of electronic components. For the Nebraska Bostwick project, external display and keypad components are located in a separate electrical enclosure to reduce potential for exposure of sensitive electronic components to the elements. To further isolate sensitive components from potentially corrosive agents, the battery is housed in a separate enclosure on the opposite side of the pole from control equipment.

2010 PROJECT STATUS AND FUTURE PLANS

During the 2009 irrigation season, as linear actuators along with batteries and charging systems were installed, ditch riders adjusted the motorized check gates manually using toggle switches (seen in Figure 6 below the display and keypad face plate). The upstream level control programming will be installed in the CDI units and tested during the 2010 irrigation season.

After manually operating the motorized gates in 2009, the ditch rider staff is in favor of a program to upgrade all stop log bays with gate structures. The District recognizes the advantages of the configuration of the three-bay checks in the upper reaches of the Franklin Canal whereby the center vertical slide gate enables passage of bed sediments while flow passing over stop logs on the side bays can enable much of the floating debris to also pass the structure.

To maintain the ability to pass floating debris, overshot gates were identified as the preferred alternative for upgrading stop-log bays at checks where vertical slide gates already exist. Following a scoping-level investigation of prices for commercially available overshot gates, the District opted to participate in a Reclamation Science and Technology Program research project that is seeking to develop guidelines for overshot gates that irrigation districts can self-construct. The research project is focused on structures that can be fabricated as “drop-in” units for existing stop-log structures.

In this effort the District has constructed overshot gates to install in stop log bays at three of the checks where motorized slide gates were installed in 2009. Similar to the motorization alternative selected for vertical slide gates, the overshot gates will also be operated by DC powered linear actuators. Based on a projection of forces that will act on the gates, two actuators with gear heads linked by a drive shaft will be used to operate the gates.

As operation of the overshot gates is incorporated into the automated upstream level operation, the algorithm will call for coarse adjustments to be accomplished with overshot gate movements while small adjustments will be made with vertical slide gate movements. Once the automation system is functional, water level target adjustments may be entered on-site following on-screen prompts and keypad input, or remotely via radio. Manager Mike Delka sees the District expanding this modernization effort at an affordable rate until ultimately all main canal checks have similar automated or remote operating capability. Figure 7 is a photo of the District’s 28.6 check where motorized gates have been installed in previously stop-log controlled bays by the beginning of the 2010 irrigation season.

Figure 7. Vertical Slide and Overshot Gates at the 28.6 Check
Both Motorized using DC Linear Actuators

SUMMARY

For an initial experience with integration of electronic control and communications equipment into canal operations, the scope of Nebraska Bostwick's project represents a comparatively ambitious step. The seemingly boldness of the initial project scope is tempered considerably when considered in the context of current operating realities including the complete shut-down of deliveries in 2004 and 2005. Improving the District's water management capabilities to enable more efficient delivery operations is a key focus for District staff and producers alike.

The situation Nebraska Bostwick finds itself in is similar to the plight of many irrigation systems throughout the western United States. Many water users are being faced with the alternative of seeking affordable means of stretching limited water supplies, or risk being unable to afford to remain viable. The approach Nebraska Bostwick has selected is to rely on in-house talents and develop new in-house capabilities to the extent possible to make adoption of new technologies in system operations an affordable process that can help sustain the District with limited reliance on external expertise.

INTEGRATED HYBRID RADIO COMMUNICATIONS NETWORKS

Dan Steele[1]

ABSTRACT

Farms and water irrigation districts with geographically dispersed operations can collect and report data with a single solution. Sometimes this approach makes sense. However, other times integrating additional technologies offers significant benefits that can easily and more cost-effectively be incorporated into a single network. This paper will offer specific ways to set up and deploy hybrid networks to drive maintenance/monthly costs down, which directly impacts financial obligations; decreases polling cycle times; reduces the time needed to identify and rectify problems within the network; and, eliminates locations where the network is reliant upon a single communication component and thus vulnerable to failure.

INTRODUCTION AND BACKGROUND

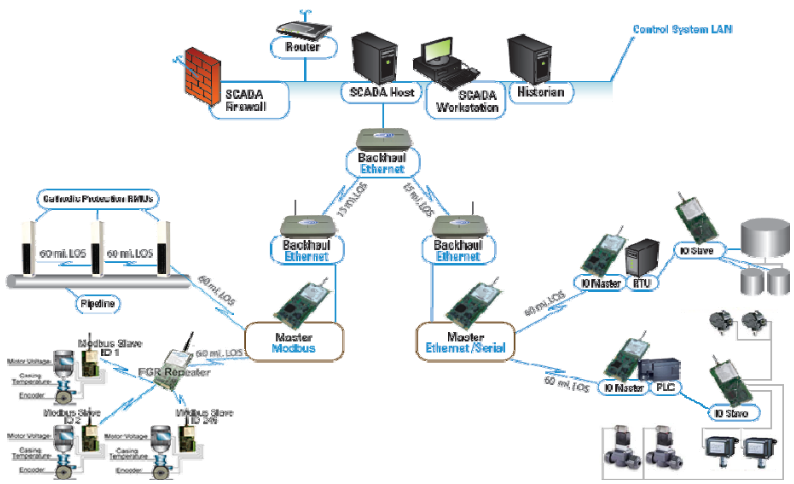

Figure 1. Hybrid radio network example.

Small-to-large family or corporate farms, municipal water and wastewater utilities or water conservancy or irrigation districts with remote operations (such as those in the farming and irrigation water industry), can select one technology, one source or one vendor to collect, retrieve and report data to assess the status of their operations. Sometimes, this type of approach makes sense. However, other times integrating multiple technologies offers significant benefits that can easily and more cost-effectively be incorporated into one cohesive network. This can be done by using a combination of

[1] Business Development Executive, FreeWave Technologies, Inc., 1880 S. Flatiron Court Suite F, Boulder, CO, 80301, dsteele@freewave.com

different technologies and in some cases, different vendors, based on a mix of data requirements which are unique to each network owner.

The days of building large, unmanageable networks are behind us. In the past, the building of large elaborate radio networks may have been the way a company or farm might demonstrate its vast expertise and deep knowledge base. However, today there are options that allow us to consider better manageability, expandability, cost and speed. Hybrid networks, for example, can include microwave, satellite or cell phone-based technologies along with licensed or unlicensed land-based systems.

Achieving Compatibility

These technologies all can be made compatible with one another by the selection of standard communications protocols, such as Modbus, which is now common, and allows information from many different devices to be sent back to a PLC/RTU or the computer host software. In addition, the use of Ethernet devices is much more prevalent today than ever before. MPEG-4 video cameras, IP-based PLC's or RTU's and radios with Ethernet and Serial ports are commonplace now. The need to add more speed and still be able to "talk" to the older radios usually makes sense, and the end device may not have a requirement for IP or Ethernet and serial data, therefore the use of existing technology is the prudent thing to do while still decreasing the SCADA software polling time.

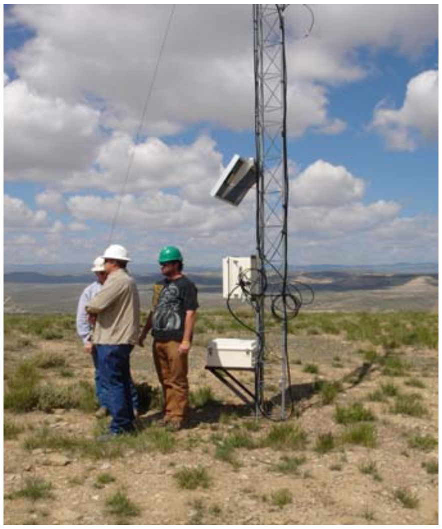

Figure 2. Selecting the best repeater site and adding additional hardware takes time and study to ensure the best results.

Microwave radios in both the unlicensed and licensed band have dropped dramatically in price while they have increased the speed or capacity with which they can transmit data. New microwave radios using the 2.4 and 5GHz unlicensed bands are easy to set up and often incorporate integrated radios with a patch antenna or have external antenna options for longer range. The fact that they are IP-based makes it easy to add other IP or Ethernet radios on the network. These networks can branch out and pick up the serial devices that may be added to the new IP network or "hybrid network," which can have serial, IO, low-to-medium and high-speed Ethernet all on the same communication network.

No one system can effectively collect data from multiple locations and deliver it to offices over a widespread area and many companies are in need of a solution for this type of data collection. However, by combining technologies, users can create a seamless data stream from several locations and share data over a LAN or WAN with multiple users. The end result is more effective and efficient management of their network, increased reliability through reduced downtime – all at a much more affordable price. The other key benefit is the ability to use IP-based diagnostics that can view or see the entire network and how well it is working and bring back alarms if something changes due to lightning, grounding, equipment failure or vandalism. The use of IP-based or hybrid networks allow for "over the air" equipment changes or firmware updates from the host location instead of having to travel to each site. This saves a lot of labor costs and time that could be deployed elsewhere. The bottom line is that the owner of these networks is more efficient and can access the network from any location with Internet access.

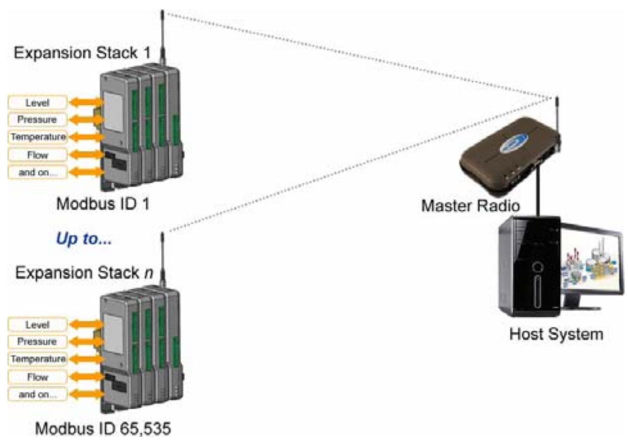

Figure 3. Serial-based SS radio IO system gathering field inputs and sending them back to a host computer via Modbus protocol.

The speed of the newer microwave radios is incredible – 300Mbps or more isn't uncommon and even the spread spectrum hopping radios are over 1 Mbps now. In the old days, 9600 baud was fast at the PLC/RTU site and now it is common to even have serial connections up to 115kbps and/or Ethernet ports for higher speed devices. The biggest factor contributing to the appetite for speed is driven by new applications, such as sending images, video and data over the network and the use of real-time monitoring and control. The use of some IP devices that use a lot of bandwidth has created a demand for speed, and streaming full motion video is another high-bandwidth application that is becoming common for security monitoring.

The reason for using a hybrid system might simply be narrowed down to costs and the fact that even though some of the older hardware is slower, it still works. The sites that some of these devices are connected to can live with the speed they currently have. This allows users to just replace those units when they fail in the future, or when they have the financial resources to do so.

Benefits of High-Speed Networks

Installing high-speed networks in areas where users have existing, older radio technologies in the same geographical area requires a lot of thought and engineering to ensure the system will work as designed. If network owners are replacing older and slower devices with newer ones then they have to understand that speed comes with a price. The low-speed radios can transmit and receive at very long distances because they are using smaller bandwidth and have higher sensitivity. The high-speed radios use large chunks of bandwidth and different RF modulation schemes to transmit data. Sensitivity will be less and the distance that users can transmit effectively is also less. Users may be able to add higher gain antennas – but the price goes up dramatically and then they need to worry about wind and tower loading. The other big difference is the need for 100 percent line of site and total Fresnel zone clearance for the high-speed radios to work. Users also may need to use different coaxial cable or use POE (Power of Ethernet) cable to the radio and antenna outdoor unit (ODU) from an indoor unit (IDU) that adds more cost to the installation and two devices or more at each site. The other thing to consider is that routers or switches will need to be deployed to manage how the Ethernet traffic is directed from the host.

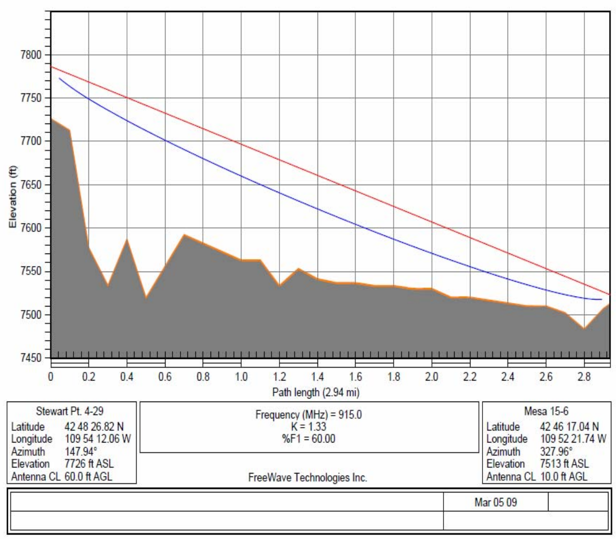

Figure 4. Example of a computer-generated path test showing the location, antenna distance, antenna height, radio path and Fresnel zone clearance.

Ethernet-based networks are faster and allow for remote diagnostics, over the air firmware upgrades and new hardware options that can be added to the network. PLC’s or RTU’s with Ethernet ports can be added instead of serial port devices. Increased bandwidth allows security video camera systems to be easily added to the network and IO devices can be viewed at the host computer. Network design may require more research and engineering up front, but the payoff is speed, enhanced capabilities and compatibility with existing hardware. Computer-generated path surveys and network designs should assist in the process, but actual site visits, tower inspection and/or construction may be required. If network users deploy licensed technology, they will have to apply for licenses with the FCC and will have renewable fees to keep track of and pay.

Implementing a Hybrid Network

There are several potential approaches to implementation. Users can start small, pay as their radio network grows, and add hardware a little at a time, or they can do a complete overhaul. The choice is dependent on their urgency, financial budget and needs. A few of the radio manufacturers may offer "free" assistance with the network design and engineering and will help with some of the design requirements and radio settings. Users should be careful though, do their homework and choose a company that will be there to help them *after* they buy the equipment and will support them when they have installed the hardware and software. Here are some guidelines in summary to consider:

- Does the product/company have a track record?
- Are the radio products field-<u>proven</u> and <u>reliable</u>?
- Will the SCADA data be secure?
- Will the hardware perform in harsh environments?
- How does the radio product interface to hardware (PLC's/RTUs) and sensors, and is the programming easy to do?
- What are the limitations of the technology?
- Are the manufacturer's radios backwards-compatible with older hardware?
- Is this technology being over-sold?
  - (over the air speed vs. actual data throughput)
- What diagnostics software is available and is it user friendly?

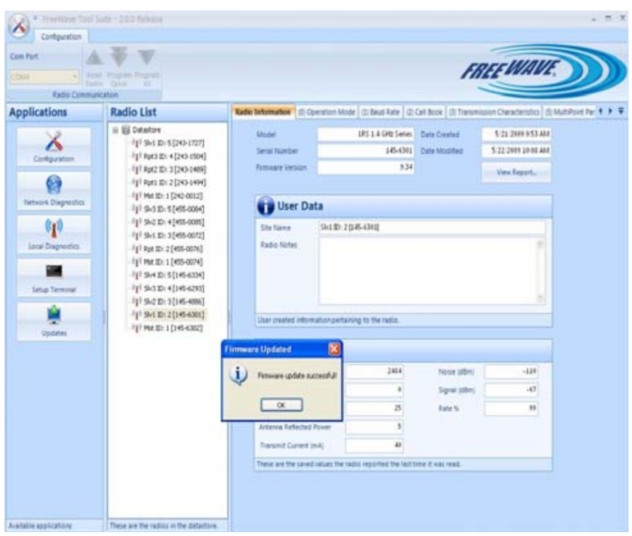

Figure 5. FreeWave Technologies Toolsuite Software

The radios should be easy to set up, program and maintain. They also should provide diagnostic information to show the health of the network, thresholds, alarms and offer the capability to import and export information – all at the users fingertips. These features and software should be included at no cost to the end user and updates to the software or radio firmware should be included at no charge. The field technicians should be able to maintain the network and add to it painlessly and have a record of any changes or updates stored in the computer host.

In addition, diagnostics tools are one of the most important parts of the system, as they allow one to know how well the network is working, and they give the ability to troubleshoot and fix small problems before they might take an entire network or sub-network down. The ability to see if anything has changed after a thunderstorm or other weather factors will be easy to detect.

CONCLUSION

When it comes to communication networks, especially those within geographically dispersed or remote locations, a single solution for monitoring critical-data is not always an option. By combining different technologies, such as microwave, satellite or cell phone technologies with either licensed or unlicensed systems, users can create a seamless data stream that is fast and cost effective. In addition, many users have deployed an Ethernet backbone to combine the mutiple technologies into a single network. These types of networks are high-speed and satisfy the increasing need for real-time data. With proper engineering and installation, this type of network will provide the ulitimate network management system that a single solution cannot.

INTEGRATING FISH SCREEN REQUIREMENTS, FLOW MEASUREMENT, LEVEL CONTROL, AND SCADA ─ WHAT WORKS

Dr. Kenneth B. Schuster[1]

ABSTRACT

In the State of Washington, metering of open channel and pressurized pipe systems is a requirement of the Water Code. Adequate and approved fish screens are also a requirement of the Fish and Wildlife Code. Submergence of fish screens needs to be maintained between 65% and 85% through all ranges of diversion.

Three requirements need to be satisfied. Those are: 1) the measuring device complements the fish screen, 2) the agency(ies) responsible for the fish screen recognize the compatibility of the measuring device with the operation of the fish screen, and 3) users are confident the device measures accurately and meets regulatory requirements for accuracy in measuring and reporting their water use. Partially-contracted submerged orifices have proven to meet the three requirements.

Automated monitoring and control provides for timely adjustment of the rates of diversion for maintaining submergence on the fish screens, provide sufficient water for fish bypass at the screens, and adequate flows in the irrigation canal. Users do not need to make several trips per day to check on and make manual adjustments. SCADA using the Internet not only provides remote control of the system on a real time basis, it also enables automatic reporting of water use to regulatory agencies automatically at pre-determined intervals, and view-only access can be granted to other interested parties.

INTRODUCTION AND BACKGROUND

The State of Washington Fish Screen Program

Most open channel irrigation systems diverting water from the main stems of rivers in the fish-critical watershed resource inventory areas (WRIAs) of the State of Washington are medium to small[2] in size, with the majority of small users located on tributaries to the main stems. The tributaries are important for recovery of salmonid fish species because at the very least they serve as refuge for fry and smolts, providing escapement from predators such as fishes, piscatorial birds, etc.

In many situations, the small canals themselves serve ideally as refuge. The purpose of fish screens is to prevent fry and smolts from access to the entire diversion channel where survival is not likely and instead return them to the river or tributary via a fish bypass structure. For water diversions using either open channel or pumps, an adequate and

[1] Water metering advisor, Watch Technologies, 4330 Fish Hatchery Rd. Grants Pass, OR 97527, kschuster@q.com

[2] For purposes of this paper, medium size means diversions diverting between 20 to 100 cfs. Small size means diversions less than 20 cfs, the majority of which divert less than 5 cfs.

approved fish screen is a requirement of the Revised Code of Washington (RCW) 77.57.040. Open channel systems must also have an adequate fish bypass return. Fish screens must satisfy design criteria. The two types of screens used on most medium and small sized diversions in Washington are rotary drum and flat plate screens. Structures housing fish screens are also constructed to operate a paddlewheel that either turns the rotary screen to prevent plugging with trash or operates a brushing device on flat plate screens to remove trash from the screen as water passes through the fish screen into the open channel. Electric power may be used if power is readily available at relatively low cost. In most cases paddlewheels are used.

Design Criteria for flat plate with paddle-wheel driven rotary wiper and paddle wheel-driven rotary screens (Washington Department of Fish and Wildlife) The critical design criteria for all fish screens are an approach velocity of 0.4 feet per second or less and sweeping velocity of 0.4 feet per second or higher. Submergence of screens is important for ensuring that 1) approach velocity of water through the screen does not exceed 0.4 feet per second to prevent impingement of fry and smolts against the screen, 2) sweeping velocities parallel to the screen are equal or greater than the 0.4 feet per second to guide fry and smolts to the bypass channel, and 3) smolts cannot jump over the fish screen and into the diversion channel. A bypass flow between 10% and 15% of consumptive use is required at all times when smolts migrate, but can be lower after migration, particularly when stream flow declines.

Rotary fish screens must be submerged at 65% - 85% of screen height to maintain criteria for approach and sweeping velocities. The range of 65% - 85% submergence on flat plate screens is also required. However, there may be exceptions for flat plate screens for varying rates of diversion if it can be shown that the criteria for approach and sweeping velocities are maintained. For example, the level of submergence in a particular structure for a flow of 25 cubic feet per second would be higher than for a flow of 10 cubic feet per second, provided that criteria for approach and sweeping velocities are satisfied.

The State of Washington Water Metering Program

Surface water diversions in the State of Washington are required by RCW 90.03.360 to measure the instantaneous rate of flow (Qi) and the total volume of water (Qa) diverted and to report usage annually to the Washington Department of Ecology (Ecology) per Washington Administrative Code (WAC) 173-173-020(a). WAC 173-173-020(a) requires measuring on all diversions from waters in which the salmonid stock status is depressed or critical, as determined by the Washington Department of Fish and Wildlife. Sixteen watershed basins have been so designated.

Defining the Problem

The problem was, and is, the need to satisfy two objectives simultaneously, flow measurement and fish screening. It is challenging to do both effectively. The agencies responsible for the installation of fish screens, the U.S. Fish and Wildlife Service, Washington Department of Fish and Wildlife, and U.S. Bureau of Reclamation, implemented fish screening before Ecology began implementing the water measurement requirement. Few of those diversions included an adequate measuring device or method, and fish screens were installed without considering the need for flow measurement in the design.

The problem manifested when the Yakima County Superior Court (the Court) adjudicating surface water rights in the Yakima River basin issued a Pendente Lite Order[3] on 13 October 1994 requiring surface diversions on the main stem rivers (Yakima, Naches, and Tieton Rivers) in the Adjudication of the Yakima River Basin to measure and report water use to the U.S. Bureau of Reclamation (the Bureau). Acceptable measurement methods included standard weirs, Parshall flumes, velocity meters, pressurized pipe meters, stable rated section with a staff gauge and rating table, or other acceptable methods or devices. Most diversions relied on a rated section with a staff gauge, with the Bureau providing monthly flow measurements to verify the rating curve.

The Court issued another Pendente Lite Order[4] on 15 September 2005 requiring <u>all</u> surface water diversions with a conditional final order to install water measuring devices and to begin recording and reporting water use to Ecology. The Order included diversions on tributaries to the main stems, of which most did not have measuring devices or fish screens. Holders of water rights then began asking Ecology about water measuring devices that would satisfy the requirements for accuracy in WAC 173-173-020(a). Diversions associated with the Bureau did have accurate methods of measuring and the technical expertise to maintain accuracy. However, the Bureau did not have enough manpower to verify rating curves used by users on the main stems at sites not associated with the Bureau. For that reason, those users were not comfortable that the rated section method provided the accuracy required in the metering rule because they did not possess the expertise themselves to verify rating curves. Few users on the tributaries to the main stems had any measuring device or method, and most of those that did were using inadequate methods.

The requirement to have fish screens compounded the overall challenge when the agencies responsible for prioritizing diversions that needed fish screens had to convince owners of surface diversions that a fish screen was needed. Funds and technical expertise for designing and installing fish screens were provided with the understanding that, once installed and operating, the daily operation and maintenance were the responsibility of the owners of the diversions. In general, while owners did not like the idea that they "were told what to do," they did cooperate.

Many were frustrated about the need for daily maintenance. Without daily maintenance, accumulations of trash on the fish screens impacted the operation of the fish screens because enough water was not passing by the paddle wheels to keep either the rotary screen or brushes on the flat plate screens operating and reduced the amount of water

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[3] State of Washington, Department of Ecology v. James J. Acquavella, et.al., No. 72-2-01484-5 (Yakima County Superior Court 1994).
[4] State of Washington, Department of Ecology v. James J. Acquavella, et.al., No. 72-2-01484-5 (Yakima County Superior Court 2005).

delivered that the user needed. Then came enforcement to measure and record the instantaneous rate of diversion and the total quantity diverted and submit those records of use to Ecology annually. If the users had to measure and also "put up" with fish screens and problems associated with screening, they wanted a solution that reduced the work the two requirements imposed on them.

There is an unintended and significant benefit of fish screen structures for measuring water that was used to advantage and reduce that workload. Fish screen structures are constructed level and of sufficient size and depth that conditions of approach flow for accurate measuring are easily met. Because the fish screen serves as a baffle, the velocity of approach of water to the measuring device is 0.5 cfs or less, usually less. That benefit was not realized until the need for developing a solution that concurrently measured water and satisfied the operational requirements of fish screens and reduced the workload that both requirements imposed on water users.

<u>Preferred location for measuring rates of diversion into open channels</u>

The preferred location for measuring rates of diversion is below fish screens regardless of the method of measurement. If the location is above the fish screen, all water is measured as consumptive use. Bypass flow is in reality non-consumptive, but allowance for bypass flow returned to the river or tributary is problematic, is seldom done, and so is counted as consumptive use. Measuring water below the fish screen eliminates that problem and only actual consumptive use is measured.

Sharp- or broad-crested weirs measure water accurately when conditions of approach and depth of water in the weir pool are optimal. Weirs must also operate with downstream submergence below critical flow limits, but that is not often a problem. However, with sharp- or broad-crested weirs it is difficult to maintain a relatively constant level of submergence on a fish screen because of changes in water levels imposed by weirs as flow rate changes regardless of whether a weir is located above or below the fish screen. Daily fluctuations in water levels on rivers and tributaries cause similar problems. Stop logs placed below fish screens are used to maintain submergence, but often do not work as well as intended without impacting rates of diversion, which can cause tension between the user and agencies responsible for the design and installation of fish screens. For instance, if the rates of diversion increase, then stop logs should be removed, or if rates of diversion decrease, stop logs should be added. Removing or adding stop logs is not done, which usually results in the fish screen operating outside the preferred range of submergence.

<u>Solving the Problem</u>

Six conditions needed to be met: 1) accurate measurement and delivery of water to the user, 2) proper operation of fish screens to keep the screens free of trash, 3) steady flow of water through the fish screen, 4) maintain adequate depth in the fish screen structure to maintain submergence of the fish screens between 65% and 85% submergence, with 75% submergence generally ideal, 5) maintain adequate flow through the fish bypass to provide enough water for smolts and fry to return to the river or tributary, and 6) assurance to the agencies that the proposed measuring solution would not impact operation of the fish screens and that performance of fish screens would be enhanced.

The solution developed was: 1) install a partially-contracted submerged orifice for measuring water, 2) install a regulating gate below the orifice to control the amount of water diverted into the open channel and use the difference in head across the orifice to calculate flow, and 3) install automation and SCADA control using the wireless Internet. Figure 1 is a generic left hand plan view of the fish screen structure, showing the location of the orifice plate, regulating gate, fish screen, and the fish screen bay, forebay, and orifice bay. The right hand version is a mirror image of the plan view shown. The plan is modified to fit individual diversions whether made of concrete or steel.

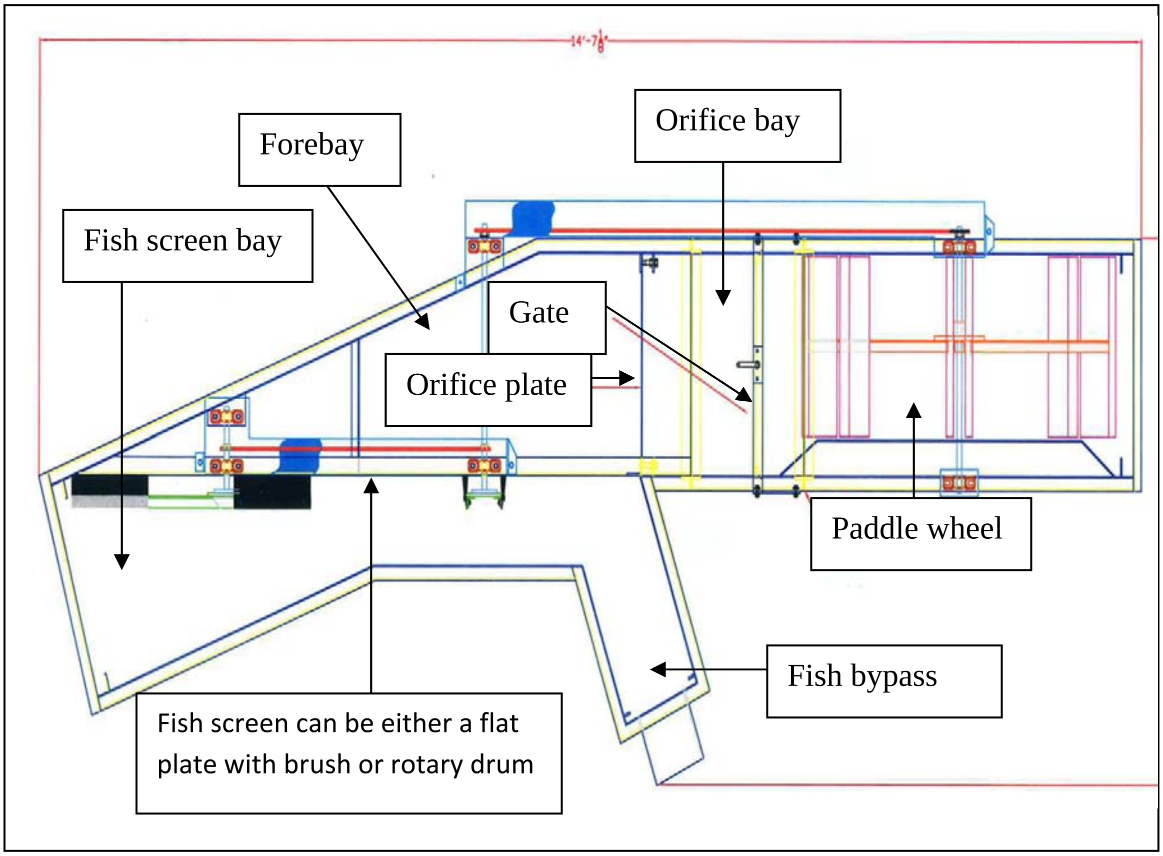

Figure 1. Plan view of fish screen structure with submerged orifice and regulating gate.

<u>Why Select a Submerged orifice</u> The objective is to create conditions within the fish screen structure that ensure a fish screen stays submerged within the desired range of submergence and to accurately measure water. A submerged orifice is ideal as conditions very similar to a constant head orifice can be duplicated within the fish screen structure. Very stable rates of diversion are maintained by managing for a water level in the pool that varies no more than the desired range of submergence of 65% to 85%.
The two primary advantages are 1) submerged orifices are accurate for measuring water, and 2) for fish screens, the depth of water in the forebay is easier to maintain (US Bureau

of Reclamation). Because the water level in the forebay rises or lowers at a rate slower than the level of water in the orifice bay as rates of diversion change, submergence on the fish screen is maintained between 65% - 85%. In essence, the forebay serves as a regulating reservoir. The larger the forebay, the more effective the forebay serves as a regulating reservoir.

Operationally, there are three factors critical to success in using a submerged orifice to obtain optimum results discussed above. First, the regulating gate below the orifice must be properly operated to maintain a stable water surface that only varies within the 65% - 85% range of submergence on the fish screens most of the time. Second, the height of the orifice should be kept as short as possible in relation to the width. For instance, a four square foot orifice should be perhaps four feet wide and one foot high as compared to a two foot by two foot orifice. It is easier to maintain the depth of water in the forebay at least 2.5 times higher than the height of the orifice if the height of the orifice is kept low. Third, the area of the orifice should be as small as possible to obtain higher resolution for measuring, which also improves the ability to maintain the optimum depth in the forebay and thereby maintain submergence on the fish screen. A fourth option is that an operational spill should, when feasible, be included that would begin spilling water when the level of submergence on the fish screens begins to exceed 75% to aid in controlling water levels on the screen rising higher than 85% as much as possible.

<u>Automation and SCADA</u> Automation and SCADA provide what has shown to be a dramatic improvement in operating and managing small and medium size diversions. Automation and SCADA enables 1) level control in the fish screen bay to maintain 65% to 85% submergence and to raise and lower a level control gate within the fish screen bay to assist in maintaining the desired level within the fish screen, 2) communication with and automation of the diversion head works to open and close the gates to maintain the level of submergence consistent with the amount of water needed for the consumptive use, 3) automation to raise and lower the regulating gate to maintain the desired rate of diversion into the open channel, and 4) establishing wireless Internet communication for remote control of the entire system by the water user. Level control in the forebay is particularly important because of the lag time on open channels for water to reach the fish screen structure when rates of diversion are changed, or when water levels in the river or tributary increase or decrease and affect the rate of diversion, as typically occurs in a 24-hour period. Two systems are discussed below.

THE PACKWOOD CANAL DIVERSION

The Packwood Canal diversion is a 25 cfs diversion on the Yakima River. Its diversion channel to the fish screen is approximately one-half mile in length. The fish screen is a flat screen approximately four feet high and fifty feet long. Brushes clean debris from the screen, including leaves, small twigs, and growths of algae. The brushes are operated by a paddle wheel which is turned by the force of water passing through the paddle into the delivery canal.

The slope on the channel below the paddle wheel is 0.0002 %, which for design purposes is virtually flat. Under most operating conditions the paddlewheel did not turn sufficiently to operate the brushes to clean the fish screen. The fish screen structure also was not designed with flow control and measurement in mind, as diversions to the canal for irrigation were regulated manually with check boards.

It was possible to maintain a depth of four feet in the fish screen structure, so a submerged orifice was a perfect fit for meeting the needs of all parties concerned. The orifice provides flow measurement, and an automated undershot gate for regulating flows was added in the orifice bay in front of the paddle wheel; it now provides adequate velocity to operate the brushes consistently under all flows and controls the amount of water diverted to the canal for irrigation.

Figure 2 shows how the two operational spill outlets now control depth in the forebay (Figure 2). Excess water is returned to the river via two return channels, one for the passive spill and one for the automated spill, the same channel used for the fish bypass located at the downstream end of the structure next to the automated spill outlet.

Figure 2. Packwood diversion structure showing passive operational spill, automated operational spill, submerged orifice, and automated gate in front of paddlewheel

The Packwood Canal was completely automated and tested in 2009 (the diversion head works was not automated). Check boards in the passive spill were set to 3.8 feet, at which point water would begin to spill over the boards into its return channel. The automated gate was also set to maintain the depth of water at 3.8 feet. When the depth exceeds 3.8 feet, the automated spill gate lowers to spill water and continue to spill water to maintain the desired depth. When water is spilling and depth drops to less than 3.5 feet, the gate raises to maintain depth at 3.8 feet. The goal is to maintain a range of depth of 3.5 to 3.8 feet on the fish screens, so a dead band of 3.5 to 3.8 feet is allowed. If depth drops below 3.0 feet, the system alarms the manager who then has to go to the head works and open the head gate.

An Internet connection via radio was designed for remote communication and control for the manager of the system. A webpage (Figure 3) for the human-machine interface (HMI) was designed to the user specifications so that operation of the entire system could be monitored and controlled remotely. The system is powered by solar panels. The system functioned as designed and met all expectations and requirements of the owners and other interested parties, and could be monitored anywhere using the wireless Internet.

Protocols for automatically transmitting data on instantaneous and total flow to Ecology will be established for the 2010 irrigation season.

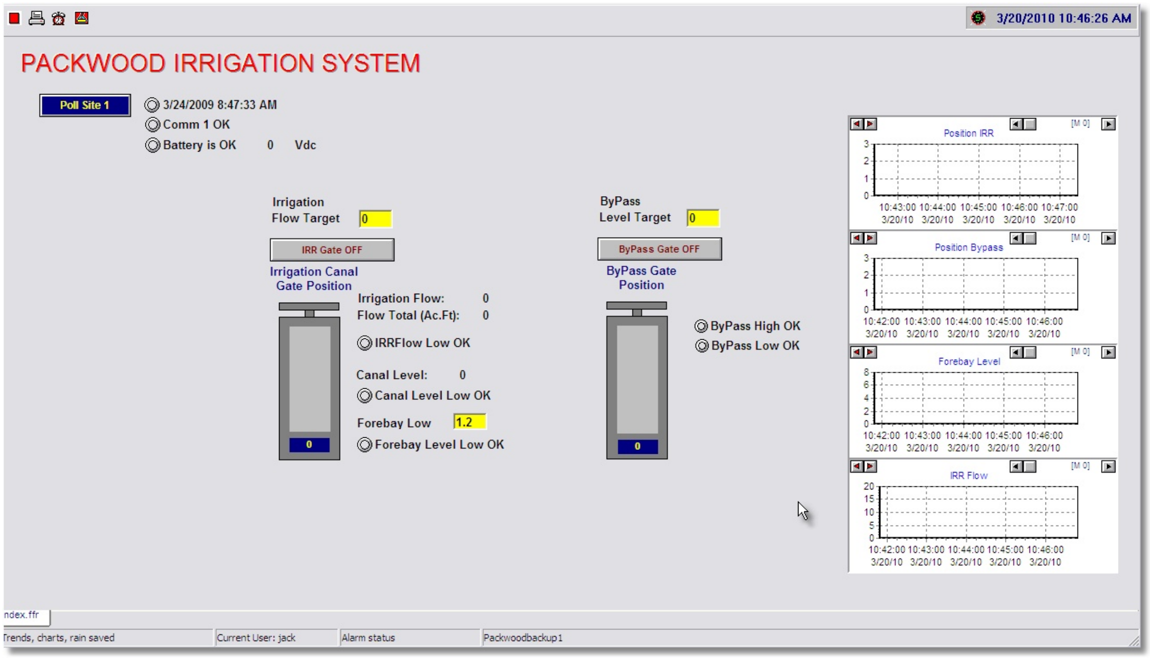

Figure 3. Internet screen HMI for the Packwood Canal showing flow, forebay level, gate position, target level, battery power, and continuous instantaneous and total flow

Equipment installed at the fish screen structure consisted of the submerged orifice, an undershot regulating gate in front of the paddlewheel behind the submerged orifice, the drop-down gate for the automated spill, 2 each WEGS automatic gate controllers, two solar assemblies for the automated gates, 2 each WER3 RTUs with software for automating the gates, and two stilling wells and pressure transducers. The remote terminal unit contains the RUG 3 controllers for connecting the sensors, display data, and control gate operations, and the radio and solar charge controller.

Equipment for the base station consisted of one WE1111 900 MHz radio assembly (1W), one WE900Y 900 MHz Yage 9dbi antennae, one WER5** RTU WEMDM modem board, one WER5 RTU with software for Modbus interface, one PC server and software, router and Internet interface, WE1111900 MHz Radio Assembly (1W), and one WEA901 – 900 MHz 5 dbi Omni antenna with mast and bracket.

THE NESBIT DIVERSION

The Nesbit diversion is a 3.5 cfs diversion off of Cherry Creek, a tributary to the Yakima River. Cherry Creek is a tributary that has a lot of potential as a salmonid-bearing stream, especially as habitat for spawning and rearing of salmonids, primarily salmon. An old, not fish-friendly diversion dam was removed in 2009 and replaced with a series of in-stream rock weirs to raise the level of the creek for the farmer to obtain water from the creek. A flat plate, rotary brush fish screen structure was modified to incorporate a bottom contraction-suppressed rectangular submerged orifice (Figure 4). The fish screen and automation are installed and diversion will be operational for the 2010 irrigation season.

Figure 4. Nisbet diversion showing the completed structure, automated regulating gate after the submerged orifice, flat plate fish screen and location of staff gauges for determining head differential between forebay and orifice bay.

The fish screen structure now serves two purposes instead of just preventing fry and smolts from ending up in the irrigation system. It now integrates the capability for measuring water. The submerged orifice serves three purposes – maintaining the desired depth on the fish screen, measuring water, and providing sufficient velocity of water through the paddle wheel to reliably turn the rotary brushes to keep the screen free of trash and other debris.

The irrigation system draws water from one other source, an irrigation company. The irrigation company supplies extra water through a pipeline for the irrigator when flows in Cherry Creek are too low for the irrigator to receive a full supply of water. The SCADA system controls and measures that water as well. When supply from the creek is insufficient, the system lets in enough water from the second source, the pipeline, and provides the extra water needed. Equipment for automation and SCADA consisted of three gate controllers, one WT RUG 5 RTU, 2 automated gates (one six-inch and one 12-inch), one Watch Technologies custom gate for controlling flows through the orifice bay for irrigation, 3 level transducers, and software.

LESSONS LEARNED

There were a number of lessons learned when working with water users and agencies concerning fish screens, water measurement, automation, and SCADA. Those were:

1. First and most important, speak the language of the user to avoid being separated by a common language.
2. FOLLOW THE K.I.S.S. PRINCIPLE. Complexity will not sell. Most, if not all, small- and medium-sized systems have neither the personnel nor technical skills needed to understand and maintain technically complex SCADA systems. They do not have the money to hire permanent staff nor time to develop the individual skills needed, and most of them are not interested in doing so. Simplicity and ease of

understanding of the system and information, the end product provided, is important to them.

3. Develop an empathy with the people purchasing and using the system and discuss with them in detail what they want the system to provide. Commensurate with that is understanding and appreciating the obligations they have as water users regarding meeting any requirements of the water codes under which they operate and problems they have with the existing diversion and delivery system that automation and SCADA can help them resolve.
4. Explain to the users that at best it will take at least a year's worth of experience with the system after installation to work out the "bugs" and get the system operating to their satisfaction. It often takes at least one irrigation season to identify and fix problems and the next season to become comfortable with it.
5. NEVER, NEVER let the pressures under which users operate affect the service being provided. And, they are not interested in the pressures which you, the provider, may be suffering.
6. The customer is always right, provided you have obtained all the pertinent information from the customer that is needed (see 3, above).
7. Lastly, and no less important than the six points above, inter- and intra-agency bias and disciplinary bias was, and remains, a major problem to resolve. The focus has to be for an interdisciplinary, interagency solution, which is and remains perhaps the most difficult persuasion.

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ACCOMPLISHMENTS FROM A DECADE OF SCADA IMPLEMENTATION IN IDAHO'S PAYETTE VALLEY

Brian W. Sauer[1]
Ronald Shurtleff[2]

ABSTRACT

Irrigated agriculture began in southwest Idaho's Lower Payette Valley in the 1880's. By 1900, over 30,000 irrigated acres had been developed, served by a system of over 20 canals diverting natural flows. High springtime river flows were often reduced to a trickle by August. Two Bureau of Reclamation dams were built to provide supplemental storage and to bring another 53,000 acres into production.

Like many early canal systems, the Payette Valley canals were built with only a few manually operated water control structures or water measurement devices. Diversions were difficult to control due to variable river flows and much water was wasted. Water rights were difficult to administer, due to the lack of accurate water measurement. In dry years there were often disputes among users on different canals as natural flows declined.

In 1997, the first canal headworks in the Payette were automated, utilizing solar power and simple off-the-shelf components. The success of this single project encouraged more irrigation entities to improve water control capabilities utilizing SCADA. New control structures were built and automated and communication links were put in place to monitor canal operations and to update water accounting.

Today, there are over 40 automated control gates, 14 telemetered water measurement sites, and 11 new water measurement structures. Diversion data daily and accurately account for water use in the basin. Telemetry has enabled canal operators to monitor facilities and to respond quickly to changing water needs or emergency situations. Canal systems in the valley are being operated more efficiently, reducing both diversion rates and operational spills. This more efficient operation has helped to improve water supply reliability. These changes have also served to bring a greater sense of cooperation to water users throughout the Payette Valley.

BACKGROUND

Early Irrigation Development

The Payette River and its tributaries drain approximately 3200 square miles in the west central mountains of Idaho (Figure 1). On average, the river produces over 2 million acre-ft of water per year. Much of the basin is unregulated, with no dams or storage

[1]Hydraulic Engineer, U.S. Bureau of Reclamation, Snake River Area Office, 230 Collins Road, Boise, ID 83702, bsauer@usbr.gov .
[2]Watermaster, Water District #65, 102 North Main Street, Payette, ID 83661, waterdist65@srvinet.com .

reservoirs. Flows vary greatly between the peak runoff season in May and June and the lowest flow periods in August and September.

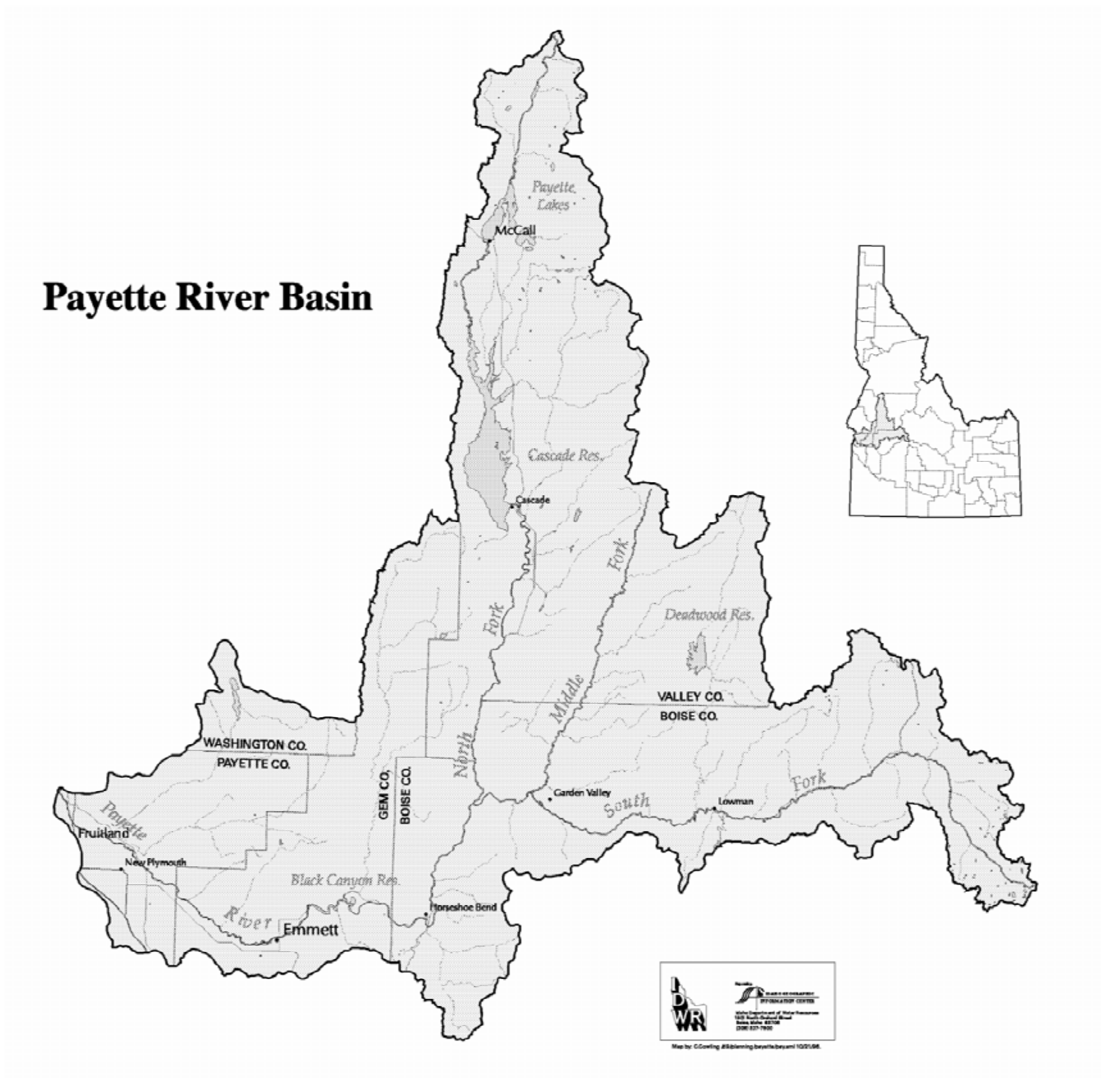

Figure 1. Map of the Payette River Basin

The Payette River was named for Francois Payette, a French-Canadian fur trapper who was one of the first people of European descent to settle in the Payette River area. Payette ventured east from Fort Astoria in 1818, and from1835 to 1844, he headed the Hudson's Bay Company's Fort Boise which was located near the mouth of the Payette River. As settlers moved into the valley in the 1870's, irrigated agriculture sprung up along the lower the Payette Valley. Many of the farmers grew produce for the many new gold mines in the surrounding mountains.

Irrigated acreage in the valley expanded in the 1880's as more canals were constructed. While the high elevation snow in the basin generally provided good water supplies until mid-summer, low late-summer river flows limited the irrigation development in the area.

By 1900, approximately 13,000 irrigated acres were in production. Following its creation in 1902, the U.S. Reclamation Service (later the U.S. Bureau of Reclamation) identified an additional 59,000 acres that could be irrigated from the Payette River with construction of adequate water storage.

Black Canyon Diversion Dam, 183 ft high and completed in 1924, was the first Reclamation facility built in the Payette basin. This facility was constructed to divert water into a “high line” canal which could serve much of the remaining irrigable land on the south side of the river and to pump water to Emmett Irrigation District lands on the north side of the river. Work began in 1936 on the south-side Black Canyon Main Canal and a gravity distribution system to 28,000 acres and was completed in 1940. An additional 25,200 new acres were added to the Black Canyon Irrigation District in 1949 with the completion of the large C-Line Pumping Plant.

Since reservoir storage was essential to expansion of irrigated lands in the Payette Valley, Reclamation then completed Deadwood Dam, a concrete arch dam with 154,000 ac-ft of storage on the Deadwood River, in 1931. Cascade Dam, a zoned earthfill dam on the North Fork of the Payette with 646,000 ac-ft of storage, was completed in 1948. The largest amounts of storage space in the two reservoirs were purchased by the Black Canyon Irrigation District (240,000 ac-ft) to irrigate the “new” project lands and the Emmett Irrigation district (62,000 ac-ft) to supplement their existing natural flow rights. These facilities, along with several smaller, privately constructed storage dams in the basin, provided stored water for late season irrigation and for the development of additional irrigated acres.

Late 1900’s Developments

Irrigation water supplies were plentiful in the Payette Basin throughout most of the1950’s and 1960’s. All of the water users had natural flow rights under Idaho’s prior appropriation statutes and some also had reservoir storage. These rights, however, had not been formally adjudicated by the state and were not closely monitored. In some years, particularly during low flow periods in late summer, there was some friction between the two largest water users, Emmett and Black Canyon Irrigation Districts who divert their water at Black Canyon Diversion Dam, and the smaller canal companies that diverted water below the dam. Many of these “lower valley” irrigators felt that even though they had senior water rights they were sometimes short of water due to excessive diversions by the two “upper valley” users. Still, in most years, water supplies were adequate.

In 1977, much of the Pacific Northwest was subject to extreme drought conditions. This resulted in the first water shortages in the Payette Valley since the construction of Cascade Reservoir. This brought about several changes in the way water was managed. First, an emergency Payette River watermaster was appointed by the Idaho Department of Water Resources (IDWR) to monitor the irrigation diversions and to administer the water rights in the basin during the drought. This drought period also prompted two of the lower valley canal companies, the Farmers Cooperative Irrigation Company and the

Lower Payette Ditch Company, to purchase available storage in Cascade Reservoir to help weather future drought periods. Other water users, including the Noble Ditch Company and Emmett Irrigation District later purchased Cascade Reservoir storage.

Shortly thereafter, IDWR began the adjudication process to formally quantify and validate all of the water claims in the Payette Basin. This process brought about further changes. Several of the lower valley canal companies filed water right claims to the irrigation return flows in the numerous open drains that carry irrigation return flows back to the lower reaches of the river. Until this time, this supplemental water was mostly taken for granted. Also, with several of the lower valley canal companies purchasing supplemental reservoir storage, a water bank was established in the Payette Basin. This enabled reservoir spaceholders to lease their unneeded stored water to other water users on an annual basis. A similar water bank had been working for many years in Snake River basin in southeastern Idaho.

Additional drought years in the early 1990’s caused more water shortages, prompting IDWR to strongly encourage the Payette water users to establish a permanent state-sanctioned water district, Water District #65, to fund a permanent watermaster to monitor all of water rights in the basin and administer the water bank. This was endorsed by the Bureau of Reclamation. By this time, Reclamation was beginning its effort to provide releases of stored water to supplement natural river flows in the Snake and Columbia Rivers for downstream migration of endangered salmon smolt. This water came from uncontracted storage in Reclamation reservoirs in the Snake River basin as well as water leased from private reservoir spaceholders through established water banks in the basin.

IRRIGATION SYSTEM IMPROVEMENTS

The drought years in the early 1990’s also caused several of the canal companies and irrigation districts in the Payette Valley to examine their facilities and operations to see where changes could be made to improve operational efficiencies. Upon reflection, several items came to the forefront. Many of the older distribution systems had limited water control capabilities and much water was lost to operational spills. In some cases, more water than necessary was diverted from the river in order to maintain adequate canal levels to make irrigation deliveries. In other cases, diversions into the canal fluctuated with changes in river flows. Antiquated or poorly-maintained headworks structures made it difficult to regulate canal inflows.

Since nearly half of the Payette River basin is not regulated by dams, flows in the lower valley can vary significantly when mountain snows are melting. These canal fluctuations often caused either too much or too little water to be delivered. Additionally, most diversions were measured using rated canal sections which “shifted” or changed calibration during the irrigation season. This made it difficult for canal operators and the watermaster to accurately determine actual canal flows.

The First Projects

In 1996, the District #65 watermaster and representatives of the Farmers Cooperative Irrigation Company (FCIC) contacted the Bureau of Reclamation's Snake River Area Office in Boise, ID, about some efforts by Reclamation's Denver Technical Service Center (TSC) and Provo Area Office to develop low-cost, solar powered systems to control and monitor canal facilities. The FCIC wished to reduce operational spills by automating its "Squeeze Gate" structure which regulates flows into the company's 30 mile-long main canal, located near Emmett, ID. FCIC applied for and received a cost-share grant from Reclamation's Water Conservation Field Services Program for the project. With financial and technical assistance from Reclamation, the three 5'-wide x 8' high steel slide gates were automated prior to the 1997 irrigation season.

The hand cranks on each of the three gate operators were replaced with a 30:1 chain drive and connected to a 1/10-horsepower 12-volt DC gearmotor. Power for the motors was supplied by a 30-watt solar panel and 2 deep-cycle batteries. Water level sensors were placed in the canal upstream and downstream of the structure. The system was controlled by a Campbell Scientific CR10 data logger. The data logger was connected via modem to an existing telephone line that was buried beside the canal. The site was programmed to maintain a desired downstream water level which was correlated with the canal's gauging station another half-mile downstream of the control structure. The controller was accessed either on-site or by telephone using a laptop or desktop computer and Campbell Scientific's PC208 software. Installation took approximately five days. Figure 2 shows the Squeeze Gate structure following SCADA installation.

Figure 2. Farmers Cooperative Automated "Squeeze Gate" Structure

After some typical startup bugs, the system worked well throughout the 1997 irrigation season. In addition to maintaining steady flows at the head of the FCIC main canal, the SCADA capabilities permitted canal operators to make flow changes remotely, saving untold time and pickup miles. With this capability, canal flows could be changed remotely from the FCIC shop in New Plymouth, 20 miles from the site. This enabled operators to remotely make flow changes late at night which would ensure that the proper amount of water reached downstream irrigators the first thing the next morning.

The success of the Squeeze Gate project led to other similar projects in the Payette Valley. Prior to the 1998 irrigation season, the Reed Ditch constructed a ramp flume at the head of its 50-cfs canal and replaced a check board regulating structure with an automated Armtec overshot gate (Figure 3). This site also used a CR10 controller but utilized analog cellular telephone telemetry. Also, following the 1998 season, the Lake Reservoir Company used the same technology to facilitate remote operation of three 12-ft wide radial gates at Lardo Dam in McCall, Idaho. This site, which regulates the outlet of Payette Lake, is approximately 100 miles from the Company's office in Payette, ID.

Figure 3. Automated Armtec gate regulates the Reed Ditch diversion

<u>Types of projects</u>

At present, there are approximately 50 SCADA sites within the Payette River valley. Individual sites may have unique configurations or operational objectives, but all use the same basic technologies, including Campbell Scientific dataloggers, solar power, and small 12-volt DC motors. The sites can be categorized as follows:

<u>Automatic flow control</u> - Many of the projects have established automatic and/or remote control at key water control structures. The main objective of these projects has been to stabilize and regulate downstream canal flows. To date, eight Payette River diversions, with capacities ranging in size from 30 to 1200 cfs, have been automated. This has enabled canal operators to accurately regulate canal diversions despite fluctuations in

river flows. At most locations, existing gates and operators were adapted to automatic operations with minor modifications. At one site it was necessary to replace two old wooden gates before they could be automated.

The largest automated river diversion is Black Canyon Irrigation District's 30-ft wide radial gate at Black Canyon Diversion Dam. Due to limited freeboard in downstream flume sections, the district has installed redundant downstream water level sensors for better control and monitoring. The Emmett Irrigation District has automated the turnouts for two distribution laterals near the tail end of their main canal to compensate for variable flow conditions.

Water level control – Several of the early canal systems were constructed with few in-line check structures. Here, the only way to regulate canal levels at delivery points was to spill water into drainage channels at various points along the canal. The Farmers Cooperative Irrigation Company and the Noble Ditch Company have automated existing slide gates at numerous spill locations. The FCIC, the Noble and the Lower Payette Ditch Companies have replaced check boards with automated Langemann overshot gates at existing spill locations. In addition to water level control, the design of these gates also permits the companies to easily measure the spills at these sites.

In order to better control canal levels, both the FCIC and the Lower Payette Ditch Company have constructed check structures at lateral turnout locations along their main canals. The Farmers Cooperative Canal was originally constructed without control structures in the canal in order to permit logs harvested in the upper part of the Payette basin to be floated down the river and then 20 miles down the canal to a sawmill near the town of New Plymouth. During the late season when natural river flows declined and canal flows were reduced, the canal company would typically pile large rocks and concrete rubble below some turnouts to check up the water levels. The rocks were then removed after the irrigation season.

Both of the aforementioned canal companies have constructed a series of check structures to control down the length of their main canals. The checks all use a similar single overshot gate design, with the gate leaf operated by a cable hoist. Three of the FCIC's checks have installed SCADA for automatic level control (Figure 4). The company's remaining six overshot checks have been motorized, lacking only an RTU and communication components to be able to operate automatically. Lower Payette has installed 7 check structures in its main canal, all motorized but not currently automated.

Figure 4. Automated check structure on the Farmers Cooperative Canal. Structure utilizes check boards (left) and automated overshot gate (right) to control water levels.

Water measurement and accounting improvements – Idaho water laws require that all irrigation diversions must have some type of measurement to allow the Department of Water Resources monitor water use and assure compliance with state water rights. The state watermaster for each river basin is charged with measuring and recording water use data to determine an accurate accounting of irrigation diversions. Most of the Payette diversions were originally measured using rated canal sections which needed frequent calibration to maintain accuracy. Typically, the watermaster would only be able to visit each site once or twice a week to measure and record flows. In order to provide more accurate measurement of their diversions, several canal companies in the basin have replaced existing rated sections with ramp flumes. Since 1998, nine rated sections, ranging in capacity from 3 to 300 cfs, have been replaced by ramp flumes. At several sites, flow data from recently constructed ramp flumes is used as input for automated diversions.

The controllers at the automated sites have datalogging capability, so it is a simple matter to record flow data and obtain an accurate accounting of diversions and spills. Typically flow data is recorded every 15 minutes. Since many of the automated sites have telephone or radio communication, the watermaster is able to download data from these sites on a daily basis via the communication link. This enables the watermaster and the canal companies to monitor their water use daily. Currently the Payette River watermaster is able to download 15-minute flow data from 23 sites in the basin. Downloads are performed automatically early each morning during the irrigation season. Data from 13 of these sites are used as input to the IDWR water accounting program for Water District #65.

Communications – When the SCADA installation process began, telephone technology was the primary communication method. Most of the automated sites were connected to nearby buried telephone lines. At more remote locations, analog cellular telephones were used. Most of the sites used a modem that transferred data but also could be programmed to relay information to the operator using a synthesized voice. The audio feedback was helpful to the novice SCADA system operators. They could monitor the site conditions remotely without the need for a computer. Most of the sites were programmed to automatically dial out and send an alarm to the operator in the event of certain unusual circumstances, such as high or low water levels or a non-responsive automated control gate. With voice capabilities, the operators could be informed of the nature of the problem over the phone.

In several locations, direct FM radio communications are used to transmit data between two automated sites, such as a control gate and a downstream flow monitoring site. As the number of SCADA sites increased, the water users began looking at ways to reduce communications costs. Radios were installed at some of the sites with telephone communications, enabling those sites to communicate with new radio-only installations. This eliminated the need for an additional phone and its monthly service charges. Newer technology also enabled radio sites to serve as repeater stations for other radio sites. The remaining cell phones have been converted from analog to digital technology. However, the new digital cell modems no longer have the voice synthesis capabilities. System operators access their remote sites via office computers or with laptops and cell phone modems in their pickups.

Currently, water users in the Payette and Water District #65 are working together to develop a valley-wide radio network that will eliminate most of the telephone communications. A radio communications site has been established at the Water District office and will also serve as a repeater site for much of the western part of the valley. The watermaster is currently working to establish another repeater site that will cover the eastern portion of the valley and can also communicate with the Water District office.

The Seven Mile Slough Project

The work on one area of the Valley, the Seven Mile Slough (Slough), provides a good example of multiple water user entities working together to improve water management through the use of SCADA and improved water measurement. The Slough is a seven-mile-long side channel of the main Payette River, located near Letha, Idaho. The Noble, Reed and Letha Ditches and several smaller irrigation canals divert from the Slough. In the 1920's the water users on the Slough constructed a concrete structure with three radial gates at the head of the Slough to regulate inflows from the river. In addition to Payette River water, the Slough can receive up to 70 cfs of water from a large open drainage channel, known locally as the Government Drain. The drain and the diversion structure, known as The Barrels, were constructed in the 1940's by the Bureau of Reclamation to alleviate high water tables caused by upslope irrigation. The Idaho Department of Fish and Game has asked the irrigators on the Slough to maintain a minimum 35-cfs flow downstream of the last irrigation diversion.

The Noble Ditch Company (NDC) operates the Slough headworks and also has the largest irrigation diversion on the Slough. Prior to the Slough project, Noble Ditch flows were highly variable. Flow variations in the river caused variable flows into the Slough, resulting in too much or too little water being diverted into downstream canals. Variable inflows of drain water at the Barrels caused additional fluctuations in the Slough, exacerbating the problem. All of the water control structures on the Slough were manually operated and required constant monitoring to maintain steady canal flows. To assure sufficient water in the downstream reaches, the NDC would generally divert extra water into the Slough. Any flows above the 35-cfs minimum, however, are unused and are essentially wasted. This wasted water is charged against the water accounts of NDC and the other water users on the Slough.

To improve the measurement accuracy on their main canal, the NDC constructed a ramp flume at the head of the Noble Ditch in 1997. Following the 1997 irrigation season, the NDC worked to automate the Noble Ditch headworks, using similar technology as the Farmers Cooperative. Utilizing financial and technical assistance from Reclamation's Snake River and Provo Area Offices, NDC automated one of the two slide gates at the head of the ditch (Figure 5). The site was solar powered and had cell phone telemetry. Flows were measured at the downstream ramp flume.

Figure 5. Noble Ditch headworks structure

In early 1998, the Reed Ditch Company, the second largest diversion on the Slough, also constructed a ramp flume at the head of their main canal. The Reed project automated the diversion, replaced a check-board structure with a solar-powered Armtec overshot gate, and also installed cell phone telemetry. Both projects worked well during the 1998 irrigation season, and eliminated much of the variability in canal flows.

The following year, the NDC and other water users on the Seven Mile Slough tackled the problem of excess tailwater at the downstream end of the Slough. Before the 1999 season, the NDC automated two of the three radial gates on the control structure at the head of the Slough (Figure 6). A 30-ft wide ramp flume was constructed in the channel below the control structure to assure accurate flow measurement (Figure 7). The NDC also took steps to regulate inflows to the Slough from the Government Drain. A Langemann overshot gate was installed at the Barrels site to control water levels in the Drain and regulate diversions into the Slough. Another ramp flume was constructed to measure these diverted flows. The overshot design of the control gate permits measurement of the remaining drain flows. Additionally, a second Langemann gate was installed at the last diversion on the Slough to automatically control upstream water levels and to measure flows passing back to the river (Figure 8). Cell phone telemetry permitted the NDC and the watermaster to accurately measure and control the flows in the Slough.

Figure 6. Seven Mile Slough Headworks Structure

Figure 7. Ramp flume at the head of the Seven Mile Slough

Figure 8. Langemann Gate at the last diversion on the Seven Mile Slough.

These projects significantly enhanced the efficiency of the operations by reducing flow fluctuations and operational spills (Figure 9). The work done on the Seven Mile Slough demonstrated how relatively simple and inexpensive technologies could be used to improve water management in the Payette Valley. It also demonstrated how multiple entities could pull together to accomplish common objectives.

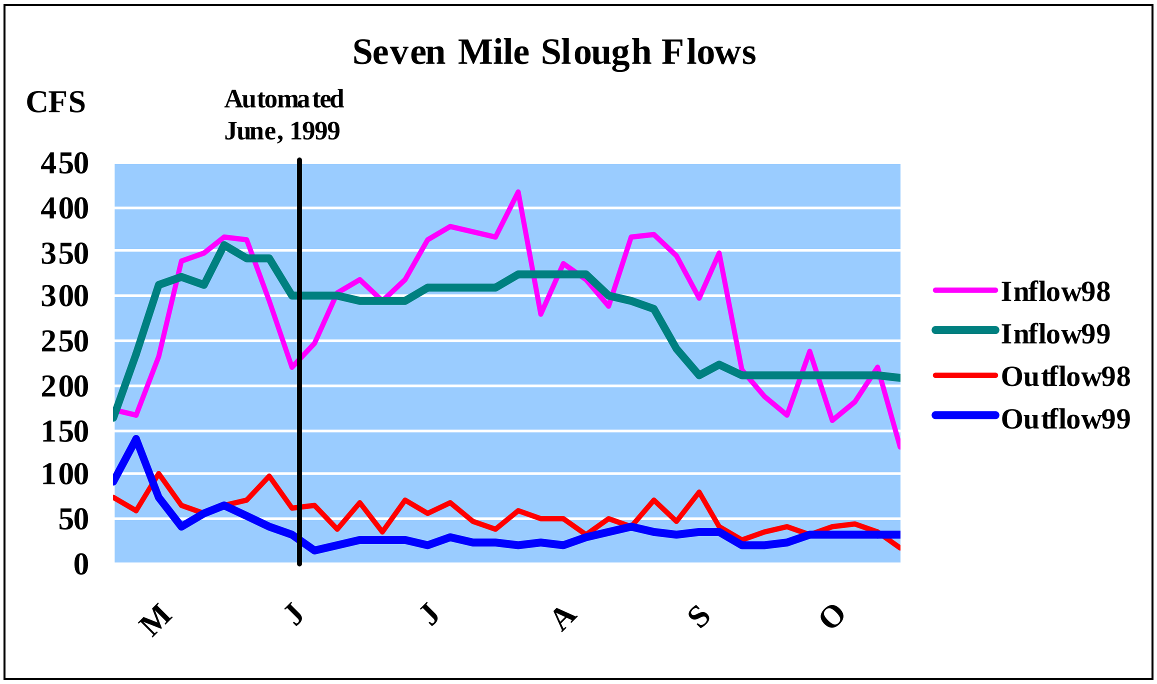

Figure 9. Seven Mile Slough inflows and outflows before and after automation at the headworks and the end check.

BENEFITS

Since 1997, water users in the Lower Payette Valley have installed over 40 automated water control sites, 14 water measurement sites with telemetry, and 11 new water measurement structures. Many of these projects received technical and financial assistance from the Bureau of Reclamation's Water Conservation Field Services Program. Some new control gates were installed in the process, but in many cases, original gates were used with only minor modifications. Nearly all of the sites are using the same technology, Campbell Scientific RTU's, solar power, and telephone or radio telemetry.

Over the years, the RTU software and hardware has been updated and analog cell phones have been replaced with digital technology or radio communications, but the simple, "do-it-yourself" methodology has proved successful. Now, even much of the RTU programming is being done by the water users, with some occasional outside assistance. Several of the key benefits of these projects are:

<u>Improved water use efficiency</u> - The SCADA and measurement improvements have reduced overall water use in the valley, primarily by providing canal operators with the tools to reduce operational waste. Comparisons of current, late-summer flows below Black Canyon Dam with historic flows show that irrigation demands in the lower valley can be met with nearly 200 cfs less water. This is primarily due to improved control and better water measurement. Better control of canal flows has also provided more constant farm deliveries, which likely has improved the efficiency of on-farm irrigation

applications. Improved water use efficiency has also helped water users to better weather the inevitable drought years.

Improved water accounting – Improved measurement of diversions and spills helps to assure accurate accounting of water use. Flumes have eliminated errors caused by calibration "shifts" of rated canal sections. Telemetry and continuous data recording allows the watermaster to provide most water users with accurate water use information on a daily basis rather than once or twice a week.

Making water available for other uses - More efficient water use has also enabled Payette irrigation districts and canal companies to make reservoir storage water available for other uses through the basin's water bank. In years with adequate supplies, reservoir space holders can raise revenue by leasing stored water to others. In Water District #65, much of the leased water is used by the Bureau of Reclamation to augment river flows for ocean-bound salmon smolt in the lower Snake and Columbia Rivers. In 2009, Payette water users leased approximately 166,000 ac-ft of stored water to Reclamation for flow augmentation and an additional 10,000 ac-ft for in-basin irrigation uses.

Revenue for capital improvements - Lessors of water receive a payment of $2.00 per ac-ft for stored water used within the Payette basin and $11.80 for stored water used outside of the basin. (The price differential is due to in-basin leases having a higher refill priority than out-of-basin leases in the subsequent water year.) Many of the SCADA projects have been partially funded with this revenue. Additionally, Water District #65 receives a $1.00 per ac-ft administration fee for all leased water. The Water District makes most of this money available as grants for the irrigation districts and canal companies in the basin to help fund distribution system improvement projects.

Reduced operating costs – Once SCADA systems are in place, system operators are able to monitor their conveyance systems around the clock. The ability to check the status of key locations of the system at a glance and to make flow changes remotely reduces travel and man-hours. Alarm capabilities of the systems can notify operators of potential problems before they get severe and enable them to respond more quickly.

Increased cooperation – One of the unanticipated benefits of the SCADA projects in the Payette Valley has been increased cooperation between many of the canal companies and irrigation districts. As the projects were being developed, ideas and experiences were being shared among the entities. Designs for control structures and gate operators were developed and shared. As the number of sites has expanded, the water user entities have begun working together to develop a valley-wide radio telemetry network to reduce communication costs and improve the reliability. The Water District and the watermaster are a common point of contact for all of the entities and have become keys to this cooperation.

SUMMARY

Irrigated agriculture has been an important part of southwest Idaho's Lower Payette Valley for over one hundred years. Natural river flows and stored water from Bureau of Reclamation reservoirs is conveyed to over 80,000 acres of farmland through a system of over 20 canals. Most of the canal systems were constructed in the late 1800's and were built with only a few manually operated water control structures and few water measurement devices. Only part of the Payette River is regulated by dams, resulting in highly variable river flows. This variability made irrigation diversions into canals difficult to control. Water diverted into canals was often wasted due to the lack of accurate water measurement at diversion points and the lack of water control within the distribution systems.

A series of dry years in the early 1990's prompted water users in the Payette Valley to evaluate updating and improving their canal systems to improve operational efficiencies. In 1997, the first canal headworks in the Payette were automated, utilizing solar power and simple off-the-shelf components. The success of this single project encouraged more canal companies in the valley to take the leap into the SCADA world. With assistance from the Bureau of Reclamation, Payette water users began to improve their water measurement and also began improving control capabilities throughout the distribution systems. New control structures were built and automated. Communication links were put in place to monitor critical locations on canals around the clock.

These improvements, initiated by a dozen different irrigation districts and canal organizations, have resulted in the installation of more than 40 SCADA sites where irrigation water is controlled and/or measured. Telemetry has enabled canal operators to monitor facilities around the clock and to respond quickly to changing water needs or emergency situations. Improved water measurement has enhanced the operators' ability to manage their water resources. With these improved capabilities, canal systems in the valley are being operated more efficiently, diversion rates have been lowered and operational spills have been reduced. This more efficient operation has helped to improve carryover reservoir storage and increased the amount of water made available in the basin's water bank. Moreover, these enhancements have served to bring a greater sense of cooperation to water users throughout the Payette Valley.

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LOW COST LINEAR ACTUATORS FOR CANAL GATE CONTROL

Blair L. Stringam[1]
Tom Gill[2]

ABSTRACT

Electric linear actuators are a reliable, cost-effective alternative for operating canal gates as part of a canal modernization program. These units have been successfully utilized to upgrade existing gates or at new gate installations (vertical slide gates and overshot gates). They are commonly available with built-in travel-limit switches and position indicators. The cost and range of sizes available reflect an economy of scale in their production that is far better than that of components designed exclusively for irrigation system use. For canal gates, they are often used in manual control installations as well as fully automatic or remote-manual control. Using these components helps to make canal operation convenient and safe. These actuators have been proven rugged, reliable, comparatively simple to install, and cost effective in ongoing field demonstration projects. They can significantly reduce the cost of equipment in a canal modernization project without sacrificing functionality or reliability.

INTRODUCTION

As irrigation districts seek to upgrade control capabilities on canal systems, one of the initial items to consider is whether to rehabilitate existing control structures or replace them with all new equipment. Unless an outside funding source is present, limited available funding typically dictates that districts maximize use of existing facilities. Many districts have opted to motorize existing gate structures as an affordable alternative to replacing existing gates with commercially produced gate systems that can be automatically or remotely operated.

A linear actuator is a device that can be a cost effective alternative that can be used as a commercial gate actuator. It consists of a long acme-threaded shaft housed within an outer metal tube, a nut attached on one end of a smaller inner metal tube, a gear box, and a motor. The motor can be AC or DC powered. They are used in many industrial applications, medical applications, recreational vehicles, satellite dish movement mechanisms etc. Linear actuators are designed to move different loads and have varied operational spans. As a result of the wide range of applications in which linear actuators are used, the price range at which they are available reflects an economy of scale ($400 - $1000 per actuator) not frequently encountered in products targeted for the irrigation system market.

[1]Associate Professor, Dept of PES, New Mexico State University, MSC 3AG, PO Box 30003, Las Cruces, NM, 88003-8003 (blairs@nmsu.edu)
[2] Hydraulic Engineer, US Bureau of Reclamation, Mail Code 86-68460, PO Box 25007, Denver, CO 80225-0007 (tgill@usbr.gov)

Linear actuators are available in different load ranges and for different travel spans. Operational safety and feedback features that may be available include overload protection such as torque limiting clutches and/or thermal switches. For irrigation applications it is desirable for actuators to have travel limit switches and position sensors. Overload protection components are usually not required as this function may be economically accomplished by installing a fuse or circuit breaker in the control circuitry external to the actuator. Having built-in limit switches and position indicators enhances affordability and reduces the complexity of on-site tasks required for motorizing a canal gate. An example of an actuator with built-in limit switches and position indicator is shown in Fig. 1.

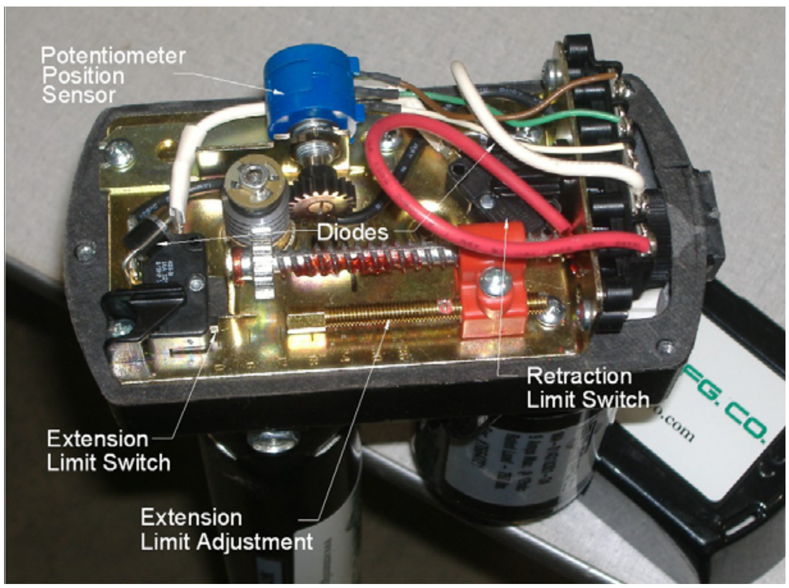

Figure 1. 12 Volt DC linear actuator with limit switches and position sensor

DC powered actuators such as the one shown in Fig. 1 are equipped with a diodes and limit switches to protect the motor and power supply in case the actuator is run to the end of its operating range.

Linear actuators are commonly available with either analog (potentiometer) position sensors or digital (pulse output) position sensors. Pulse output sensors are sometimes more readily available and may be less costly. A disadvantage with pulse sensors is that gate position must be re-established each time a programmable controller operating the gate is powered down and powered back up. This is due to the fact that gate position is tracked by keeping count of pulses – a task that cannot be performed while the controller is powered down. With an analog output position sensor the magnitude of the analog signal will correspond to a specific gate position. This relationship will not change unless the linkage between the linear actuator and the gate is moved. Even if the actuator is temporarily disconnected and the gate is moved manually, as long as the actuator is reconnected using the same linkage positions, the analog-signal-magnitude/gate-position relationship will remain the same.

Linear actuators are produced by numerous manufacturers, though not all offer specific features or operational ranges that may be desired for operating canal gates. In some cases the manufacturers may have excessive lead times. Functional suitability and timely availability are important factors for consideration in comparing linear actuators from different sources.

When selecting a linear actuator, it is recommended that the load capability of the actuator surpasses the required load capability by about 20 to 30 percent. This can account for any unforeseen changes in the loading of the actuator. For example, a linear actuator may move a slide gate for typical operating conditions, but unanticipated accumulation of debris may increase the loading on the gate movement mechanism. If there is a portion of the year that the canal is not used, corrosion on the irrigation structure will also increase the loading on the actuator. If a linear actuator is overloaded, the actuator will move slowly or possibly not move at all. Unless circuit overload protection is installed the motor will burn out. A well-designed system will include a fuse (or circuit breaker) located in the power supply circuit that will burn out (or trip) before damaging the actuator motor.

Obviously, the actuator should be selected so that it will meet the operation span requirements of the irrigation structure. An actuator with a greater-than-required span can work suitably by adjusting the limit switches to limit the operating range to the appropriate travel distance. Additional span length (within a manufacturer's standard production range) typically adds a minimal additional cost. For an irrigation district using linear actuators at multiple sites – not all of which have the same load and span requirements – it may be a cost-effective consideration over the project life to use actuators meeting the same specifications at all sites in order that a spare unit could be kept on hand as a replacement for any site, or in an emergency an actuator could be taken from a low priority site for use at a high priority site until a replacement unit is obtained.

Actuators that have limit switches incorporated into the device save in setup time, protect the switches from the environment, help protect the switches from vandalism, and in most cases cost less than installing external switches. If limit switches are not contained in the actuator unit, additional fabrication time is required to install limit switches on the control structure. Much of the cost advantage that can be realized by using linear actuators to motorize canal gates will be lost if the selected actuators do not have built-in limit switches and a built-in position sensor.

As with any electrical installation, the electrical components must be sized to meet the power requirements of the actuator. The switches and relays must be able to handle the current that is required to move the motor. This can be difficult if the actuator motor requires a current greater than 10 amps. There are relays and contactors that are designed to handle current loads that exceed 10 amps, but they are usually much more costly than simple "ice cube relays". As the power requirement of a location exceeds an amperage threshold in this range, not only does the cost of circuitry components escalate rapidly, the affordability and availability of linear actuator equipment with suitable load capacity becomes much less attractive.

SLIDE GATE APPLICATIONS

Slide gates are common water control devices that are used on canals throughout the United States and the world. Many of these gates have an actuation device that consists of a wheel that is connected to a threaded stem or some kind of leverage movement device such as the one in Fig. 2 on a canal in the Bard Irrigation District in California.

Figure 2. A vertical slide gate with a linear actuator installed

Large slide gates can be wide enough that it can be impractical to lift them from a single point. For wide gates, lifting from a single point can cause the gate to bind if both sides do not raise or lower at the same rate. Fig. 3 shows a gate on an eastern Idaho canal. This type of gate was effectively motorized using two linear actuators. The two actuator lift system serves to keep both sides of the gate moving at the same rate. In addition, the load being carried by each actuator is half the total load. This reduces the power requirement for each actuator. For this application the system is more cost effective than designing and installing a movement mechanism using one actuator.

Figure 3. Side by side large slide gates with two linear actuators on each gate

A problem with the type of configuration shown in Fig. 3 is keeping the actuators aligned with each other. Control engineers compensate for this problem by incorporating a subroutine in the control code that determines when the actuators are misaligned. If this occurs, the subroutine activates one actuator to realign the two actuators.

Another method of addressing the alignment issue when two actuators are being used on a vertical slide gate is shown in Fig. 4. For this configuration, bevel gear boxes are attached to the acme screw end of two actuators. A shaft connects the two gear boxes to ensure the acme screw rotation speed will be identical in both units. A single drive motor is shown in Fig. 4. A similar configuration with two motors – one attached to each bevel gear box is configured for installation on gates at the Nebraska Bostwick Irrigation District.

Figure 4. Actuators with bevel gear boxes for linking multiple drives

The US Bureau of Reclamation has been setting up field demonstration sites using linear actuators to move slide gates over the last decade. An objective of Reclamation's work has been to identify and refine methodologies for canal modernization in which irrigation district staff can play a primary role in implementation. Irrigation districts have been actively involved in installation and maintenance of modern technologies with limited reliance on costly consultants and/or integrators.

In work with Reclamation's Yuma Area Office, linear actuators are being used to operate gates at two prototype automated surface irrigation sites. Two sites are being set up in cooperation with the University of Arizona Extension Service on a field in the south of Yuma. A second field site is being set up in cooperation with the University of California Extension Service at a field in the Imperial Irrigation District in Southern California.

The sites near Yuma are on level basin fields, one at a citrus orchard and the second at an alfalfa field. At each site, water is turned out from a concrete-lined canal via large jack-gate turnouts, one gate per border section. Flow approaching the field is measured as it passes through a ramp-type long-throated flume. Flow rate and known border section geometry are utilized to determine appropriate cut-off time for water turned into a field section. A programmable radio/control unit operates linear actuators of the respective field section gates to start and stop flow into the border sections. Figures 5 and 6 show gates and actuators at the citrus grove and alfalfa field sites respectively.

Figure 5. Citrus grove turnout gate

Figure 6. Alfalfa field turnout gates

The Imperial Irrigation District automated surface irrigation site is a sloped field with three smaller "port" gates per border section installed in a concrete-lined canal. Two check gates are needed in the canal along this one-half mile wide field with twelve border sections. The control system being developed will utilize monitored flow rate along with advance rate feedback from the first two border sections plus monitored end-of-field runoff to determine appropriate cut-off times to stop flow in one border section and open gates for the next border. Figures 7, 8 and 9 show linear actuators installed on the port gates and on a check gate.

Figure 7. Linear actuator on turnout gate at the Imperial Irrigation District automated surface irrigation demonstration site

Figure 8. Linear actuator in operation on a turnout gate at Imperial Irrigation District automated surface irrigation demonstration site

Figure 9. Linear actuator on check gate at Imperial Irrigation District automated surface irrigation demonstration site

OVERSHOT GATE APPLICATIONS

There are a number of movement mechanisms that have been developed for the overshot gate. The first overshot patent was granted to R.A. Lang in 1890. The device was a chain suspended gate that doesn't have much relevance to today's irrigation requirements. UMA Engineering developed a cable and drum hoist overshot gate that it installed in several irrigation projects (Ayers, T.G. and Palmer, B.C.,1987). There have been more recent patents for irrigation applications (Aughton et. al., 2006. Langemann, 1994). These last two devices have been used extensively and are effective water level control devices for irrigation canals.

There are a number of benefits in using an overshot gate for water level regulation. Much like widely used stop log structures they effectively maintain comparatively steady upstream water levels due to the fact that flow rate passed downstream is a function of change in upstream head raised to the 1.5 power. (i.e. Modest upstream level changes result in significant changes in flow rate passed.) Adjusting an overshot gate is typically much simpler than inserting or removing stop logs. In addition, gates may be adjusted to any level within the operational range while stop log control is incremental, dependent on the dimensions of an individual stop log.

Safety concerns are also commonly associated with stop logs. As wooden stoplogs become saturated and swell it is common for them to become lodged in place. Methods such as cutting submerged stop logs with chain saws, or utilizing heavy equipment such as a backhoe to adjust swollen stop logs have been repeatedly reported by irrigation districts. For a combination of these reasons, upgrading existing check structures through installation of overshot gates is an improvement numerous irrigation districts have already done or are presently considering.

There are plenty of compelling reasons for an irrigation district to upgrade check structures by installing overshot gates. The greatest obstacle for most districts is cost of commercially available overshot gate systems. In recent field demonstration activities the authors have been independently involved in the development of overshot gate systems that could be self-constructed and installed by irrigation districts.

The steel fabrication equipment and skilled personnel needed to construct these gates are resources many irrigation districts already have in place as necessary capabilities for routine system maintenance. Self-fabricated structures can be a particularly cost effective option for irrigation districts in climates where there is an extended non-irrigation season.

Using a linear actuator to operate a gate enhances the cost effectiveness of a self-constructed overshot gate system. This is accomplished through simplified fabrication and installation tasks, and reduced up-front costs compared with alternative gate motorization options available. Prototype self-constructed overshot gates utilizing linear actuators were developed in cooperation with irrigation districts in Idaho and Oregon. Figures 10 and 11 show overshot gates constructed by irrigation districts that utilize linear actuators to operate the gates.

Figure 10. Self-constructed overshot gate in eastern Oregon.

Figure 11. Self-constructed overshot gate in eastern Idaho.

Presently, there are two concerns in this design. By extending a frame out at the edge of the gate and attaching the linear actuator, the mechanical advantage is reduced and a larger actuator has to be used. Alternative designs are being considered to improve the mechanical advantage. A second issue is the accumulation of debris around the gate. Debris collects between the gate leaf lift frame and the wall of the overshot. Ditch riders are aware of this and remove the debris as needed during the peak of the irrigation season. Similar gates using linear actuators were fabricated and installed in the spring of 2010 by districts in Colorado and Nebraska. These gates will include design modifications that address these concerns.

SUMMARY

Linear actuators can be a cost effective and reliable alternative for motorized operation of canal gates. Unlike technologies developed to exclusively target irrigation system structures, linear actuators have a wide range of industrial applications with a resulting economy of scale in production. A notable drawback that has been encountered is an insufficient weather-tight seal on motor and gearbox housing. Figure 12 shows a less elegant but effective weather protection system that a South Dakota district reports has eliminated this problem.

Figure 12. Linear actuator on a slide gate with an inverted bucket installed over the motor and gearbox to prevent moisture damage.

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CRITICAL SUCCESS FACTORS FOR LARGE SCALE AUTOMATION EXPERIENCES FROM 10,000 GATES

Tony Oakes[1]
Gino Ciavarella[2]
Remy Halm[3]

ABSTRACT

Canals have been the principal means of distributing irrigation water since the early civilisations. However, the performance of irrigation systems, which use approximately 70% of the available water world-wide, is being called into question. The technology used to control canals and hence their performance changed little until the second half of the nineteenth century when the early work on performance enhancement started with the first generation of activities focussed on automatic monitoring and regulation. This paper provides an overview of the experiences gained over the last 20 years in the application of technology to enhance the performance of large scale irrigation systems through improvements to monitoring and control. Improving the productivity of irrigated agriculture is seen as a critical initiative to double world food production by 2050. Improving the performance of irrigation canal systems is seen as a critical requirement to meet the future world food needs.

INTRODUCTION

Automation is defined as "The act of implementing the control of equipment with advanced technology; usually involving electronic hardware; "automation replaces human workers by machines"[1]. Numerous papers have been devoted to various aspects of automation of irrigation systems at previous USCID forums and likewise there is a plethora of information published in the academic literature about irrigation system automation.

This paper seeks to provide an overview of the author's collective experience gained over the last 20 years in the development and application of automation technology to the open channel irrigation sector, primarily in Australia but more recently in the USA, China, New Zealand, India, Vietnam, France and Italy. The focus is primarily on a holistic approach to transform irrigation systems from pre biblical design principles to be fast, flexible, responsive and efficient to provide a platform to sustain food production against a global background of declining water, agricultural land, energy and nutrient availability. The paper generally follows the directions documented in [2] and discusses the following topics

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[1] Rubicon Systems Australia Pty Ltd, 1 Cato Street, Hawthorn East, 3123, Australia (Anthony.Oakes@rubicon.com.au)
[2] Rubicon Systems Australia Pty Ltd, 1 Cato Street, Hawthorn East, 3123, Australia (Gino Ciavarella@rubicon.com.au)
[3] Rubicon Systems Australia Pty Ltd, 4563 Denrose Court, Fort Collins, CO 80524, USA (Remy.Halm@rubicon.com.au)

- Automation Conceptualisation
- Instrumentation
- Gates Actuation and Flow measurement
- Communications
- SCADA System Engineering and Control
- Human Considerations
- Performance Measurement

For a more detailed discussion on the business benefits of automation technology refer to Reference 3.

AUTOMATION CONCEPTUALISATION

The process of automating a single gate to meet a local objective such as maintaining an upstream or downstream water level or constant flow is a well documented and understood process. Invariably this process involves instrumentation to monitor water levels, usually on the upstream and downside side of the gate, some instrumentation to measure the position of the gate, a motor to drive the gate, and some electronics usually in the form of a commodity Programmable Logic Controller (PLC) or Remote Terminal Unit (RTU) to make the decisions about how to position the gate as a function of time to meet the underlying objective. Installations of this type require an energy source to drive the automation equipment with solar being a popular choice due to the remote location of installations, and communication to a central environment and/or other gates is becoming increasingly common practice.

For this simple standalone example there are many choices to be made about the technologies to best meet the automation needs with accuracy, stability, reliability, responsiveness, durability and total cost of ownership being key considerations. However, a more overriding consideration is usually how this automation equipment “fits” with the channel system and the “demands” the system places on the automation technology. In the case of a single standalone piece of equipment heuristic methods to configure and tune the automation are generally satisfactory.

However, the approach to automating large systems where there are potentially thousands of automated gates is a more demanding academic and practical challenge. In a network of automated gates the impact of control action at one gate can potentially impact on the control outcomes at many other gates. For moderately large systems it may be possible to compute the best position to set many gates to meet an overall control objective but in general with communication system constraints it is not practical to transmit these values to the field equipment at the required frequency given their remoteness. For these reasons we have chosen to distribute the control logic to the field equipment on the basis of the conceptualisation of a canal system as many concatenated blocks of the form depicted in Figure 1.

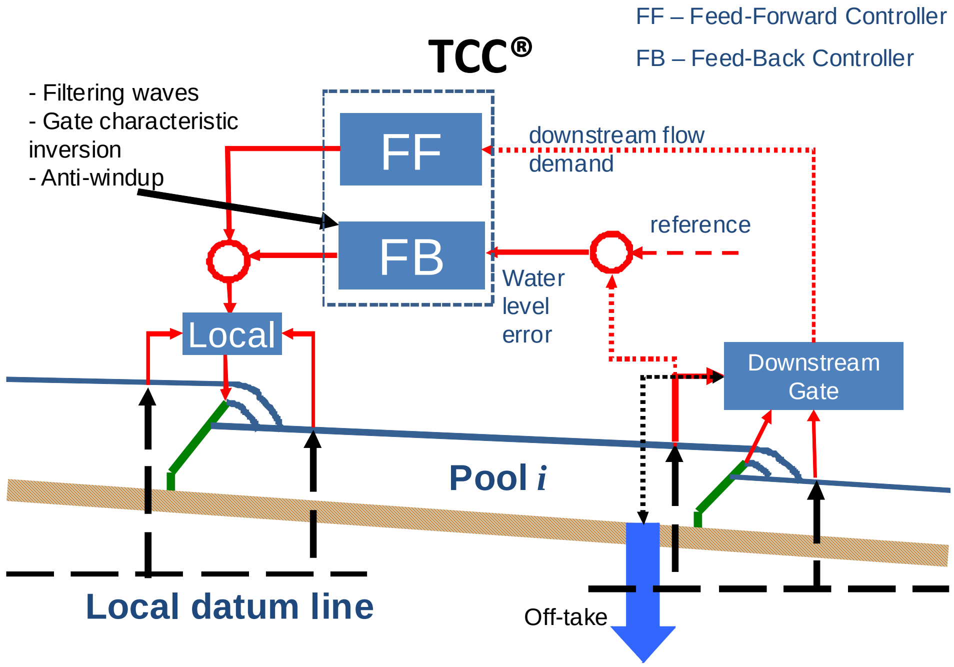

Figure 1. Conceptual Structure of a Pool

The authors contend that this conceptualisation of large networks is a critical factor in successfully deploying automation on a large scale.

INSTRUMENTATION

There is much to be said for the old adage that if you cannot measure it then you cannot manage it. The availability of cost effective and accurate measurement instrumentation has in our view hampered the development of large scale automation technology. An implication of the conceptual structure shown in Figure 1 is that flow leaving the pool at the downstream gate must be accurately measured if there is to be accurate control. It is contended that to accurately measure flow it is necessary to be able to accurately measure water levels, with millimetre precision. For this reason and in the absence of alternatives in the market Rubicon has developed unique water level measurement instrumentation based on acoustic technology, as depicted in Figure 2. The unique feature is the use of a precision calibrated reference mark that reflects the sound wave before the reflection from the water level surface. By processing the return signals and using the relationships shown in Figure 2 it is possible to precisely measure water level.

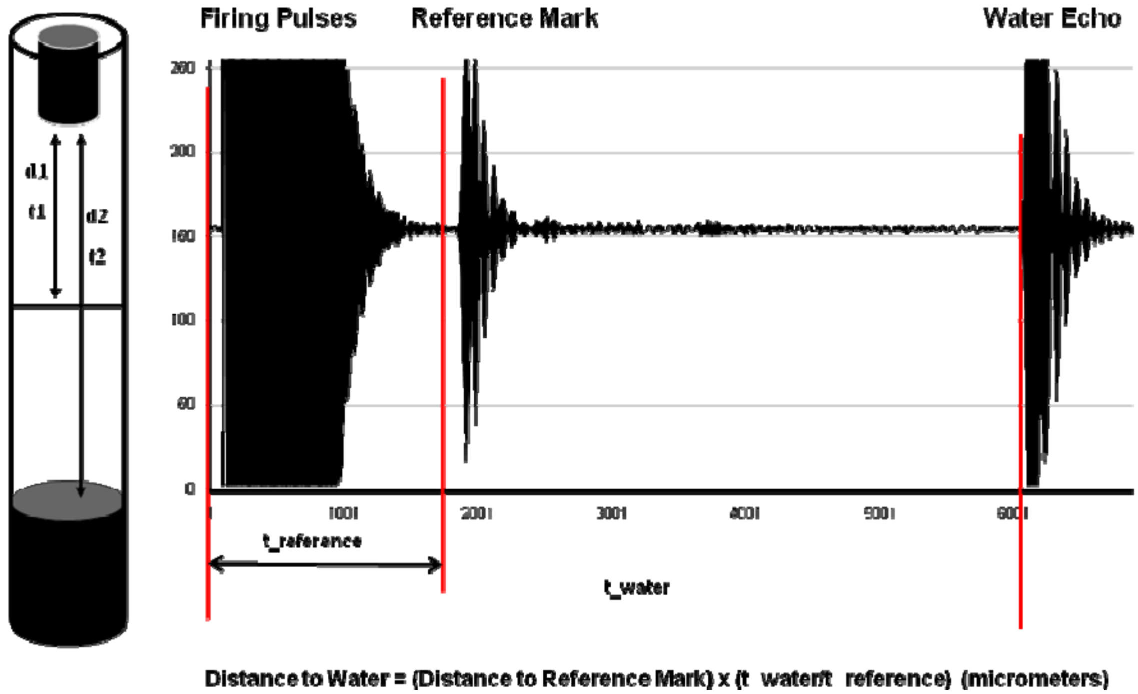

Figure 2. Self Calibrating Ultrasonic Water Level Instrument

This instrument in packaged as a standalone device but also embedded within the FlumeGate products as shown in Figure 4.

GATES ACTUATION AND FLOW MEASUREMENT

Rubicon has a generic gate control software product. This product been progressively developed since the company's formation in 1995 and has been implemented on hundreds of gates mainly in Australia, with a handful of sites in the USA. The design intent was to be able to retrofit to instrumentation and actuation equipment using industry standard interconnection methods like 4-20mA, 0-5 Volt, MODBUS and relay technology. Figure 3 shows an example from the USA. In this case the application was to automate a standalone spill gate site to "dump" water on the basis of high canal levels, utilising existing gate and lifting mechanisms but retrofitted with a Limitorque actuator, solar power supply, RTU and radio. This approach required extensive on site equipment installation and configuration and the software configuration requires the gate elevations to be surveyed and various calibration parameters computed and configured in the field for incorporation in the software.

Figure 3. Retrofitted Automation – New Cache La Poudre, Colorado, USA

Our experience is that this approach is really only viable when contemplating a small number of sites when the duty is primarily focussed around coarse control objectives where the errors associated with water level and gate position measurement are consistent with the capabilities of the plant.

However, when contemplating large scale automation of complete irrigation systems such as the Northern Victorian Irrigation Modernisation and Renewal Project [3] a more systematic approach to the control infrastructure is considered to be warranted. For this project FlumeGate technology was used to replace the existing in channel manual regulating equipment. The FlumeGate is a precision manufactured control and measuring device that has been specifically designed for network based control strategies such at that shown in Figure 1.

Critical Success Factors for supporting this strategy are

- High Duty cycle – the unique actuation and drive chain mechanism is designed for precise control and long life.
- The water level instrumentation is located within the gate frame providing stable and repeatable water level measurements.

- The flume nature of the gate design combined with precision instrumentation enables accurate flow measurements across free and submerged flow conditions.
- Standardised electronics and software featuring solid state fusing, digital instrument marshalling, encoder based gate positioning, motor soft starting combined with local keypad and display interface.

Figure 4. 9 FlumeGate™s at the CG No 8 Channel Offtake, Tatura, Australia

COMMUNICATIONS

Reliable communication is a clearly a critical success factor for reliable automation. The systems we have deployed are based on the following design principles;

- Most of the communications traffic is based on *report by exception* where the site broadcasts a message when a parameter value changes by an amount that is uniquely configured for each key variable at a site. An event driven communication architecture is a critical requirement for addressing scalability.
- Each control site communicates with its neighbouring site, independently of the central server – so called Peer-Peer communication.
- Each site must be capable of being solar powered and is typically configured with a 75 watt solar panel.
- For redundancy reasons, there are alternate communication paths to link the distributed communication nodes to the central office environment. Figure 5 shows a solar powered communication node.

Frequency Hopping Spread Spectrum (FHSS) radio systems are the technology of choice for most applications primarily because

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

Figure 5. Communications Node Site

SCADA SYSTEM ENGINEERING AND CONTROL

Our experience from managing large scale rollouts is that the following are critical success factors;

1. Standard software needs to be developed and maintained based on well understood IT system design and implementation methodologies. Our preference is to use standard programming languages like C/C++ and Java across the product range rather than RTU specific languages that are difficult to manage using code revision control systems.

2. The software needs to closely couple demand and supply i.e. it is considered essential that the demand imposed on the control system never exceeds the capacity. This Demand Management System is considered to be a critical aspect of any canal automation solution.
3. The systems must be able to be incrementally configured to support the transition from manual to automated operation.
4. The ability to configure systems dynamically without the need to shutdown or interrupt system operations.

HUMAN CONSIDERATIONS

The management of change is clearly a critical aspect of any transformation project such as canal automation. Firstly for irrigation district staff moving from manually planned and controlled systems to complete automation is a huge change. The skill sets for supervising and maintaining the automated systems are completely different and this needs to be formally addressed through a structured change management program. For irrigation district customers automation can deliver huge improvements in services. However, again because the extent of the changes can be dramatic, particularly for older farmers, it is essential that they be lead through this process and supported by informed and positive staff.

PERFORMANCE MEASUREMENT

Quantifying and measuring the performance of an automated canal system is not trivial. Control Engineers often like to measure performance within a framework like that shown in Figure 6. However, these principles are difficult to communicate to irrigation district staff and to incorporate into contract acceptance criteria.

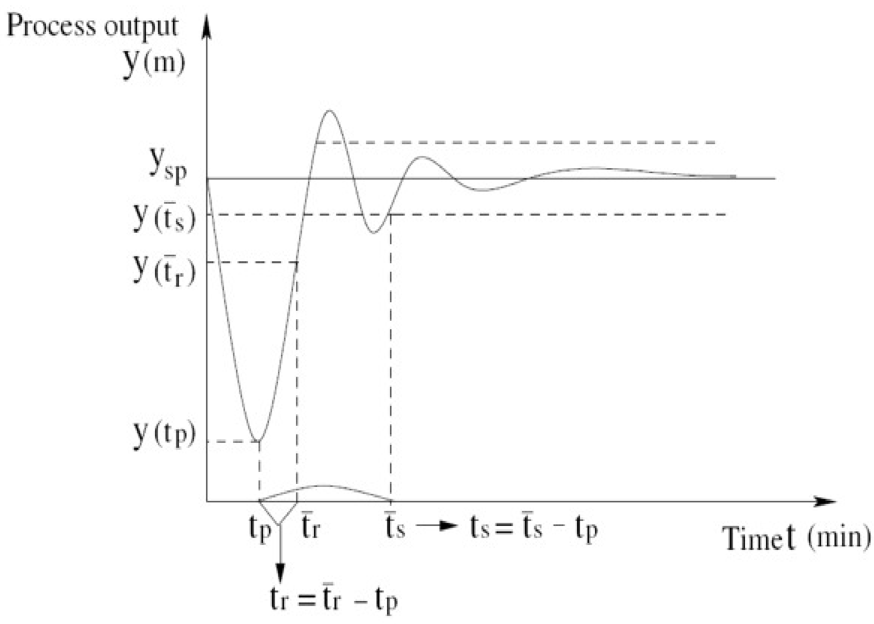

Figure 6. Characteristic Control System Process Response

Our experience for these purposes is that simpler measures shown below are more practical;

- Time water level deviates from set point
- Volume of water spilt from system
- Availability of plant (i.e. benchmark on down time)
- Deviation between time customer requires water and when it is delivered
- Deviation between requested and delivered flow rate

LEASONS AND CONCLUSIONS

Quite clearly the technology used for automating irrigation systems needs to be first class, well designed, robust, stable and cost effective. In developing evolutionary solutions for canal automation, a critical focus has been placed on technological innovation and standards. However, as the footprint of the implementations expands increasing focus is being placed on the human aspects associated with moving from a manually operated data poor situation to one that is automatic and data rich. It is absolutely critical for Boards of Management and Irrigation District managers to be able to define to customers what the costs and benefits of implementing canal automation may be and how such an investment will be assessed, measured and evaluated. A key success factor in a smooth transition to an automated irrigation system is preparing and implementing a sound Education/Information/Training program for both staff and customers in the use and maintenance of the systems. It is our experience that whole of life costs are a more significant consideration for customers than the initial capital cost of a system.

Irrigation in most parts of the world is under growing pressure to “lift its game” to perform better and use more productively, the large proportion of water allocated to it. There is now demonstrated experience that full automation can be successfully implemented to deliver significant performance improvements and enhanced customer services.

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MAPPING ET IN SOUTHEASTERN COLORADO USING A SURFACE AERODYNAMIC TEMPERATURE MODEL

José L. Chávez[1] Dale Straw[2]
Luis A. Garcia[3] Thomas W. Ley[4]
Allan A. Andales[5] Lane H. Simmons[6]
Michael E. Bartolo[7]

ABSTRACT

Accurate estimates of spatially distributed evapotranspiration (ET) using remote sensing inputs could help improve crop water management, the assessment of regional drought conditions, irrigation efficiency, ground water depletion, and the verification of the use of water rights over large irrigated areas.

In this study, ET was mapped using surface reflectance and radiometric temperature images from the Landsat 5 satellite in a surface energy budget algorithm driven by a surface aerodynamic temperature (SAT_ET) model. The SAT_ET model was developed using surface temperature, horizontal wind speed, air temperature and crop biophysical characteristic measured over an irrigated alfalfa field in Southeastern Colorado. Estimates of the remote sensing-based ET for a 4.0 hectare alfalfa field and a 3.5 hectare oats field, during the 2009 cropping season, were evaluated using two monolithic weighing lysimeters located at the Colorado State University Arkansas Valley Research Center (AVRC) in Rocky Ford, Colorado. Although the overall model performance was encouraging, results indicated that the SAT_ET model performed well under dry atmospheric and soil conditions and less accurately under high air relative humidity and soil water content conditions. These findings are evidence that SAT_ET needs to be further developed to perform better under a range of environmental and atmospheric conditions.

[1] Assistant Professor, Civil and Environmental Engineering Department, Colorado State University, 1372 Campus Delivery, Fort Collins, CO, 80523-1372; jose.chavez@colostate.edu
[2] Water Resources Engineer, 1313 Sherman St., Room 818, Colorado Division of Water Resources, Denver, CO. Phone (303) 866-3581 Ext. 8261, Fax (303) 866-3589; Dale.Straw@Naturenet.state.co.us
[3] Professor and Department Head, Civil and Environmental Engineering Department, Colorado State University, 1372 Campus Delivery, Fort Collins, CO, 80523-1372; luis.garcia@colostate.edu
[4] Chief, Hydrographic and Satellite Monitoring Branch, Colorado Division of Water Resources, 310 E. Abriendo, Suite B, Pueblo, CO; thomas.ley@state.co.us
[5] Assistant Professor, Soil and Crop Science Department, Colorado State University, C106 Plant Science Building, Fort Collins, CO, 80523; allan.andales@colostate.edu
[6] Research Associate, Arkansas Valley Research Center, Colorado State University, 27901 Road 21, Rocky Ford, CO; lane.simmons@colostate.edu
[7] Senior Research Scientist, Arkansas Valley Research Center, Colorado State University, 27901 Road 21, Rocky Ford, CO; michael.bartolo@colostate.edu

INTRODUCTION

In the Western United States as well as in other semiarid areas of the world, intensifying competition for limited water supplies between urban, industrial and agriculture uses continues to exert profound pressures on the agricultural sector. In the Western U.S., agriculture currently accounts for about 70 percent of consumptive water use, and its water rights are increasingly being transferred to municipal and industrial uses, while in-stream flow requirements for environmental purposes also threaten to curtail diversions for irrigation. Maximizing the services provided by available water supplies for multiple uses imposes an immense responsibility to improve agricultural water management and planning for potential future climate change and population growth.

Irrigation and rainfall water use as crop evapotranspiration (ET) varies spatially and seasonally according to weather and vegetation cover conditions (Hanson, 1991). Modeling variations in ET is essential for providing predictive capabilities to guide planning and management of water resources, especially in arid and semi-arid regions where crop water demand exceeds precipitation and requires irrigation from surface and/or groundwater resources. Remote sensing (RS) based ET methods have been found to be useful for deriving such information for the range of present conditions (Gowda et al., 2008; Choi et al., 2009).

Most RS ET models are driven by a land surface energy balance algorithm in which sensible heat flux (H) is estimated using the radiometric surface temperature (T_s), using a linear surface to air temperature difference function ($dT = a + b\ T_s$), obtained from satellites or airborne sensors. However, H may be over-estimated when T_s is used rather than the surface aerodynamic temperature (T_o) in the bulk aerodynamic resistance equation since T_s is typically larger than T_o. This result would affect the estimation of crop water use or ET since and over-estimation of H would mean an under-estimation of ET, when using the energy balance method, consequently irrigation amounts would be less than required. Therefore, resulting in crop water stress and yield reductions.

The objective of this study was to evaluate ET values obtained remotely, under different atmospheric and environmental conditions, using an empirically developed surface aerodynamic temperature model in southeastern Colorado.

MATERIALS AND METHODS

Study Area

The research was carried out at the Colorado State University (CSU) Arkansas Valley Research Center (AVRC) which is located near Rocky Ford, Colorado, in 2009. The site elevation is 1,274 m (above mean sea level), and its latitude and longitude coordinates are 38º 2’ N and 103º 41’ W, respectively. The soil type at the AVRC is Rocky Ford silty clay loam. The long term average annual precipitation is 299 mm, with May through August having the largest precipitation amounts. Figure 1 shows the location of the research site in southeastern Colorado (upper picture) and the location of the large and small weighing lysimeters (lower picture) at the CSU AVRC.

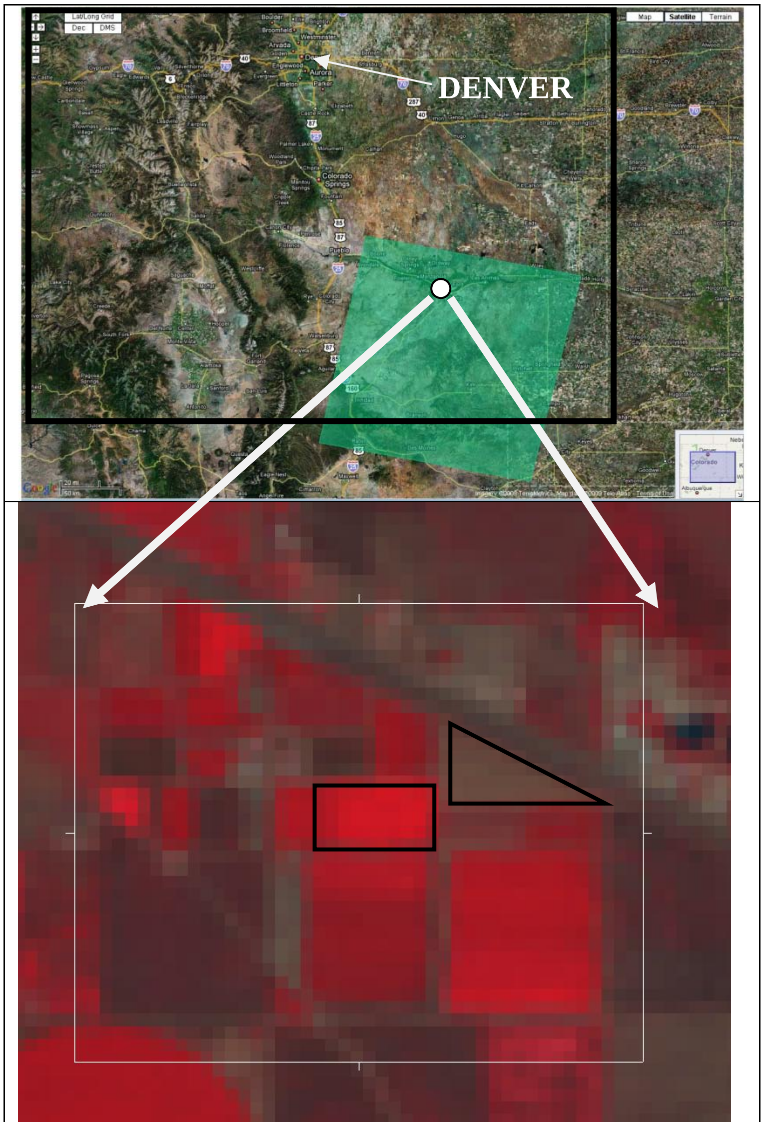

Figure 1. Location of research site (white dot) in southeastern Colorado (upper picture) and lysimeter fields location (lower picture), in a reflectance false color composite image, at the CSU AVRC facility near Rocky Ford, CO. The black rectangle shows the alfalfa field location (large lysimeter site) and the black triangle shows the location of the oat field (smaller lysimeter).

Lysimeter Characteristics

Remote sensing estimates of ET were verified by comparison with measured ET derived from a soil-water mass balance using data from two large monolithic weighing lysimeters. The CSU lysimeters were located in two fields. One field was a furrow irrigated 4.13 ha field (162 × 255 m) planted to alfalfa in 2007. The large lysimeter (3 × 3 × 2.4 m) was located in this field (Fig.2a). The second smaller lysimeter (1.5 × 1.5 × 2.4 m) was in a 3.12 ha triangular field (180 m long in the North-South direction and 350 m in the East-West direction) was planted to oats in 2009 (Fig. 2b).

The following sensors were installed at the large lysimeter site: one tipping bucket rain gauge (TE525, Texas Electronics, Inc., Dallas, Tex.), a horizontal wind speed/direction sensor at 2 m height (RM Young 03101 Wind monitor, Campbell Scientific, Inc., Logan, Utah), two additional anemometers at 2-m and 3-m height (RM Young Wind Sentry, Campbell Scientific, Inc., Logan, Utah), one air temperature/relative humidity sensor installed at a height of 1.5 m above ground (HMP45, Vaisala, Campbell Scientific, Inc., Logan, Utah), and another air temperature/relative humidity sensor (HMT331, Vaisala, Campbell Scientific, Inc., Logan, Utah) which was located in a "cotton" shelter along with a barometer (PTB101B, Vaisala, Campbell Scientific, Inc., Logan, Utah). In addition, a net radiometer [Q*7.1, Radiation and Energy Balance Systems (REBS), Bellevue, Wash.], two infra-red thermometers, (IRTS-P, Apogee, Logan, Utah), incoming and reflected photosynthetic active radiation (PAR) sensors (Model LI-191 Line Quantum, LI-COR Biosciences, Lincoln, Neb.), an albedometer (CM14, Kipp and Zonen, Bohemia, N.Y.), two pyranometers (an Eppley PSP and a LI200X-L21, LI-COR, Campbell Scientific, Inc., Logan, Utah), 14 soil temperature probes (107, Campbell Scientific, Inc., Logan, Utah), and four access tubes for soil water content readings using a neutron probe (model 503DR1.5, InstroTek Inc., Concord, CA) were installed at and near the lysimeter.

Remote Sensing Data

In this study, two images from the Landsat 5 Thematic Mapper (TM) satellite sensor were used. Landsat 5 produces images in seven bands from 520-600 nm of bandwidth in the visible (VIS) to 10,400-12,500 nm for the thermal band. The image pixel spatial resolution is 30 m for the VIS, near infra-red, and mid infra-red bands while the pixel size is 120 m for the thermal band (which the image supplier had re-sampled to 60 m). The temporal resolution is one scene every 16 days. The satellite sun-synchronous near-polar orbit altitude is 705 km which results in an image swath width of 185 km.

The two images were acquired on May 19 and July 7, 2009. The local overpass time was approximately 17:20 GTM (or 10:20 MST). The images were pre-processed according to the following steps: a) digital number (DN) conversion to radiance values, b) conversion of radiance values of visible and mid infra-red bands to top-of-atmosphere (TOA) reflectance, c) correction of TOA reflectance for atmospheric effects using the atmospheric radiative transfer model MODTRAN4 v3 (Berk et al., 2003), conversion of thermal radiance values to apparent surface radiometric temperature, correction of atmospheric effects on the apparent surface temperature using MODTRAN4 v3 to obtain the at-surface temperature value.

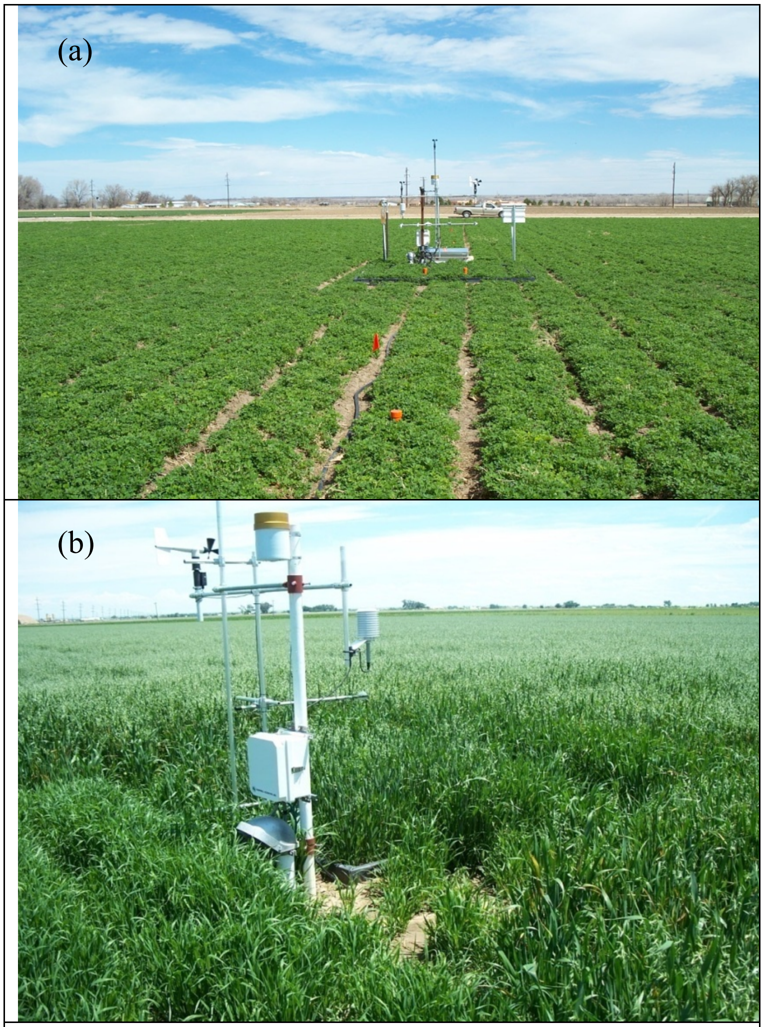

Figure 2. Large weighing lysimeter in an alfalfa field (a) and smaller weighing lysimeter in an oat field (b).

Weather, Crop and Soil Water Content Data

Weather data was collected from the instrumentation available at the lysimeter sites (see Fig. 2). Table 1 summarizes the 15-minute average recorded weather data as well as the alfalfa biophysical characteristics and soil volumetric water content (average soil moisture at a depth of 0.15-2 m).

Table 1. Weather data for DOYs 139 and 187 collected near the satellite overpass time.

DOY	T_a (ºC)	RH (%)	U ($m\ s^{-1}$)	BP (kPa)	R_s ($W\ m^{-2}$)	h_c (m)	LAI ($m^2\ m^{-2}$)	θ_v ($m^3\ m^{-3}$)
139	31.1	22.9	4.6	87.26	947.4	0.56	4.8	11
187	21.4	76.4	2.3	87.61	853.1	0.58	4.9	28

where, DOY is day of year, T_a is air temperature, RH relative humidity, U wind speed, BP barometric pressure, R_s shortwave incoming solar radiation, h_c crop height, LAI is alfalfa leaf area index, and θ_v volumetric soil water content.

It is worth noting the difference in the atmospheric and soil water content conditions on both days. DOY 139 is characterized by a dry surface and atmospheric conditions while DOY 187, on the contrary, is characterized by a near field capacity volumetric soil water content and very humid air.

Surface Aerodynamic Temperature based Remote Sensing ET Algorithm

The proposed RS-based ET algorithm uses a surface aerodynamic temperature (SAT_ET) model developed in Colorado (Chávez et al., 2010). The ET algorithm uses the land surface energy balance (EB, Eq. 1) to estimate instantaneous latent heat flux (LE) or evapotranspiration (ET_i) as a residual.

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

where R_n is net radiation, G is the soil heat flux, and H is sensible heat flux. Units in Eq. (1) are all in W m^{-2}, with R_n and G positive toward the crop/soil surface and other terms positive away from the surface.

Net radiation was estimated according to Monteith (1973).

$$R_n = (1-\alpha) R_s + \varepsilon_a \sigma T_a^4 - \varepsilon_s \sigma T_s^4 \tag{2}$$

where α is surface albedo, R_s is shortwave incoming solar radiation (W m^{-2}), ε_a is atmospheric emissivity, σ is the Stefan-Boltzmann constant (5.67E-08 Watts m^{-2} K^{-4}), T_a air temperature (K), and T_s is surface temperature (K). Both surface albedo and T_s are derived from the satellite multispectral imagery. Details on the remote sensing application of R_n can be found in Chávez et al. (2009a) and Chávez et al. (2005).

Soil heat flux was estimated according to Chávez et al. (2005).

$$G = \{(0.3324 - 0.024\ LAI) \times (0.8155 - 0.3032 \ln(LAI))\} \times R_n \tag{3}$$

Sensible heat flux was estimated using the bulk aerodynamic resistance equation (Eq. 4) and the surface aerodynamic equation (Eq. 5) developed by Chávez et al. (2010, 2009b).

$$H = \rho_a\, Cp_a\, (T_o - T_a) / r_{ah} \tag{4}$$

$$T_o = 1.5\ T_s - 0.53\ T_a + 0.052\ r_{ah} + 0.36 \tag{5}$$

$$r_{ah} = \frac{\ln\left(\frac{z_m - d}{Z_{oh}}\right) - \psi_h\left(\frac{Z_m - d}{L}\right) + \psi_h\left(\frac{Z_{oh}}{L}\right)}{u_* k} \tag{6}$$

$$u_* = \frac{u\,k}{\ln\left(\frac{z_m - d}{Z_{om}}\right) - \psi_m\left(\frac{Z_m - d}{L}\right) + \psi_m\left(\frac{Z_{om}}{L}\right)} \quad (7)$$

where ρ_a is air density (kg m^{-3}), Cp_a is specific heat of dry air (≈ 1,004.5 J kg^{-1} K^{-1}), T_a is average air temperature (K), T_o is average surface aerodynamic temperature (K), which is defined as the air temperature that occurs at a height equal to the zero plane displacement height (d, m) plus the roughness length for sensible heat transfer (Z_{oh}, m) height, and r_{ah} is surface aerodynamic resistance (in s m^{-1}) to heat transfer from d+Z_{oh} to Z_m (horizontal wind speed measurement height, m). Further, k is the von Karman constant (0.41) and u_* the friction velocity in m s^{-1}. Ψ_h( ) and Ψ_m ( ) are the atmospheric stability factors for heat and momentum transfer, respectively. L is the Monin-Obukhov stability length (m), and u horizontal wind speed at Z_m.

LE is converted to an equivalent water depth evapotranspirated (mm h^{-1}) using the following conversion formula:

$$ET_i = (3600 \times LE) / (\lambda_{LE} \times \rho_w) \quad (8)$$

where, ET_i is instantaneous remote sensing derived crop ET (mm h^{-1}), λ_{LE} is the latent heat of vaporization (MJ kg^{-1}), and ρ_w is the density of water (1 Mg m^{-3}).

Reference ET fraction (ET_rF) is the ratio of the crop ET_i to the alfalfa reference ET_{ri} that is computed from weather station data at overpass time (hourly average). Finally, the computation of daily or 24-h ET (ET_d), for each pixel, is performed as:

$$ET_d = ET_rF \times ET_{rd} \quad (9)$$

where, ET_{rd} is the cumulative 24-h alfalfa reference ET for the day (mm d^{-1}). Both ET_{ri} and ET_{rd} were computed following ASCE-EWRI (2005) procedures.

RESULTS AND DISCUSSION

ET maps for both DOYs 139 and 187 were produced for the Arkansas River Valley of southeastern Colorado (Fig. 3). In the maps, the location of the city of Rocky Ford and the location of the CSU AVRC lysimeter sites are indicated. For DOY 139 the maximum ET rate was 12.5 mm d^{-1} for well-irrigated crops, due to the large evaporative demand imposed by the atmospheric conditions. For DOY 187 the maximum ET rate was only 8.0 mm d^{-1} for well-irrigated crops due to the air high relative humidity, low air temperature, and calm winds.

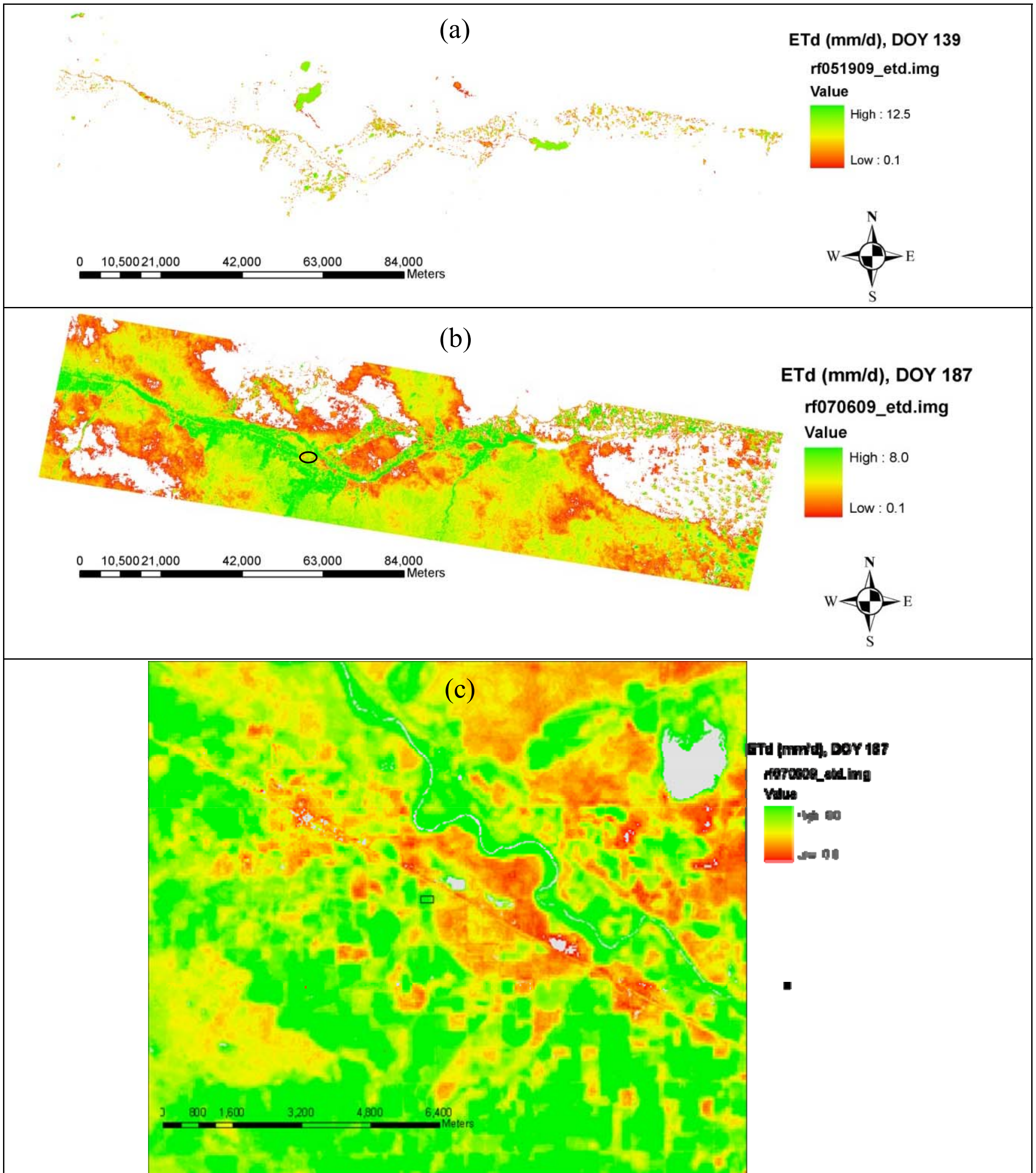

Figure 3. ET map for DOY 139 (a), ET map for DOY 187 (b) showing the location of Rocky Ford (oval), and (c) a closed-up of the ET map of DOY 187 showing the large lysimeter field (black rectangle).

The alfalfa hourly ET was estimated to be 0.45 mm h^{-1} at the time of the satellite overpass (17:20 GMT or 10:20 MST) while lysimeter measured ET was 0.47 mm h^{-1}. Therefore, the underestimation would be 4.3% when the lysimeter hourly alfalfa value of 0.47 mm h^{-1} was used as reference. Otherwise, the difference would be -0.52 mm h^{-1} or an underestimation of 53.6% when the ET_{ri} value of 0.97 mm h^{-1} ("potential hourly ET") was used as reference. This good agreement of estimated and measured hourly ET is not surprising because aerodynamic temperature in southeastern Colorado was modeled using weather and alfalfa data acquired under similar weather and soil water conditions of those encountered during DOY 139. The discrepancy in relation to ET_{ri} was due to soil water content not being at reference levels, i.e. the alfalfa was experiencing water stress which was not accounted for in the reference ET computation.

Estimated daily ET for the lysimeter alfalfa field for DOY 139 was 5.2 mm d^{-1} while the lysimeter measured an alfalfa water consumption rate of 4.6 mm d^{-1}. Thus, resulting in an overestimation of ET of 13% even though hourly ET resulted in a small underestimation of 4.3%, as explained above. The overestimation on daily ET was caused by the magnitude of ET_{rd} in the adopted extrapolation mechanism of hourly ET to daily ET. The "potential" ET rate (ET_{rd}) was 11.3 mm d^{-1} according to the standardized ASCE PM method; which may be an over estimation due to a higher air temperature and lower relative humidity values recorded under the "non-standard" soil water content conditions. Therefore, the daily alfalfa ET was slightly overestimated. Furthermore, using ET_{rd} as a reference, the alfalfa was evapotranspirating at a rate that was only 46.4% of the potential. This low ET rate was due to limitations imposed by the availability (lack of) of soil water on DOY 139. Average volumetric soil water content measured with a neutron probe to a depth of 2 m, inside and outside of the lysimeter box, was 11%.

For the oat field (small lysimeter field), on DOY 139, hourly ET was estimated to be -0.82 mm h^{-1} while measured ET was +0.82 mm h^{-1}. Extrapolation to a daily value resulted in a negative ET rate of 9.3 mm d^{-1}, while the measured value was +5.7 mm d^{-1}. This result was not a sign error, rather sensible heat flux was grossly overestimated (1,066.5 W m^{-2}) due to a very large surface temperature value (47.1 ºC) derived from Landsat 5 thermal imagery. The large surface temperature value was due to the Landsat 5 TM thermal pixel radiometric contamination at the location of the oat field. The Landsat 5 TM thermal pixel covered and area equal to 120 m × 120 m which may have caused radiometric contamination in the pixel covering the oat lysimeter field due to the incorporation of radiances from more than one surface type (i.e., temperatures from hotter adjacent areas, as roads, to the oat field site being averaged with surface temperatures from the oat field). As shown in Fig. 1(b), the oat field has a triangle shape and it was bound to the north and east by a road and by a fallow land to the south. Therefore, if a thermal pixel does not fully fall or is contained within the field then inevitably it will have average radiometric values including temperatures from surrounding areas. The maximum surface temperature on adjacent dry fallow fields was found to be 58.2 ºC. The oat field contaminated thermal pixels indicated a canopy temperature of 47.1 ºC. When the aerodynamic temperature was calculated it resulted in a value of 56.3 ºC, which is too large. Considering the surface aerodynamic properties of the oat field, every degree difference (overestimation) in surface aerodynamic temperature (due to pixel thermal contamination) caused an overestimation (error) of 0.98 mm d^{-1} in daily ET. Thus, the total net ET error of 15 mm d^{-1} (9.3 + 5.7 mm d^{-1}) meant that the actual aerodynamic temperature was about 41 ºC instead of 56.3 ºC. This T_o value would have resulted from a surface temperature (true) of 36.5 ºC (a difference of 10.6 ºC with the satellite sensed temperature of 47.1 ºC). This situation highlights a significant constraint of applying the SAT_ET model on fields having dimensions that not fully accommodate an entire satellite thermal pixel. Future research, in this regard, will include the concept of thermal pixel sharpening in which the thermal pixel radiometric and spatial resolutions are enhanced using information from other bands and/or other sensors (platforms).

For DOY 187, the remote sensing estimation of hourly alfalfa ET was 0.67 mm h^{-1}, lysimeter measured hourly ET was 0.76 mm h^{-1}, and "potential" ET_{ri} and ET_{rd} were 0.64 mm h^{-1} and 6.0 mm d^{-1}, respectively. The calculated ET_rF was 1.04 and the RS estimated daily ET was 6.2 mm d^{-1}; however measured daily ET was 7.4 mm d^{-1}. The error in the estimation of hourly ET was -14.3% while the daily ET error was -19.7%. This discrepancy to the lysimeter measured ET value is attributed to an overestimation of the aerodynamic temperature (26.8 ºC) which would have overestimated sensible heat flux (167.2 W m^{-2}) and therefore underestimated latent heat flux (455.1 W m^{-2} or ET 0.668 mm h^{-1}).

To verify this hypothesis an energy balance was performed at the lysimeter box using measured values of R_n, G and LE (LE from the conversion of measured hourly ET) in order to calculate the lysimeter derived sensible heat flux (37.5 W m^{-2}). Then, T_o was obtained, from inverting the bulk aerodynamic resistance equation, and was found to be 22.5 ºC. This value was 4.3 ºC less than the remote sensing-based T_o of 26.8 ºC. Furthermore, we used H data (66.8 W m^{-2}) from a Large Aperture Scintillometer (LAS), that was installed in the alfalfa field as part of another experiment, to compute T_o (23.5 ºC).
Therefore, on DOY 187 T_o was overestimated by 3.3 to 4.3 ºC (i.e., an error of 14 to 19%).

On DOY 187 no more oats were available at the small lysimeter field because the oat field had been harvested July 1st (DOY 181). Instead, the field contained a bare soil. At this location the remote sensing ET algorithm estimated an hourly ET rate of 0.12 mm h^{-1} and a daily ET rate of 1.13 mm d^{-1} while the corresponding lysimeter measured values were 0.29 mm h^{-1} and 2 mm d^{-1}, respectively. Hence, the estimation errors were -26.5% for the hourly ET and -14.7% for the daily ET. The discussion regarding thermal pixel contamination applies to the imagery acquired on DOY 187 as well. This means that high surface temperatures were employed in the T_o estimation in addition to the already recognized overestimation of the T_o model for the environmental and weather conditions encountered on DOY 187.

This result is evidence that the aerodynamic temperature model used in this study needs to be further refined incorporating a wider range of surface types (e.g., bare soils, fallow land, and crops at difference development stages), environmental, and atmospheric conditions to improve its performance.

CONCLUSIONS

A remote sensing ET algorithm (SAT_ET) based on surface aerodynamic temperature was applied to two satellite (Landsat 5) images. One image acquired May 19 (DOY 139), 2009 and the other July 6 (DOY 187), 2009. Weather conditions were very different on both days, on DOY 139 the air and the soil were dry and wind speed was high; while on DOY 187 the air and the soil was wet and wind speed was low. Under these conditions the aerodynamic temperature method performed better for DOY 139 with small errors (5.4%) in the estimation of the alfalfa daily ET. However, for DOY 187 the error was larger (-19.7%).

Therefore, the aerodynamic temperature model used in this study needs to be further refined incorporating a wider range of surface types (e.g., bare soils, fallow land, and crops at difference development stages), environmental, and atmospheric conditions to improve its performance. Nevertheless, overall, the results found in this study are very encouraging in that the aerodynamic temperature based energy balance algorithm has the potential to be effectively used in Colorado to monitor crop water use and improve regional water management.

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ALFALFA CROP COEFFICIENTS DEVELOPED USING A WEIGHING LYSIMETER IN SOUTHEAST COLORADO

Hamdan AlWahaibi [1]
Dale Straw[2]
Michael Bartolo[1]
Thomas Trout[3]
Allan Andales[1]
Lane Simmons[1]
Thomas Ley[2]
José Chávez[1]
Neil Hansen[1]

ABSTRACT

Weighing lysimeters are precise devices used to measure crop evapotranspiration (ET) and to develop crop coefficients. A weighing lysimeter was installed in the Arkansas River Valley of Colorado in 2006 to measure ET and develop crop coefficients of locally-grown crops. The lysimeter was filled with a 3 m × 3 m undisturbed soil monolith. Alfalfa (*Medicago sativa L.*) was planted in the lysimeter and in 4 ha of surrounding field in August 2007. Climatic data and soil conditions were measured using microclimate and soil sensors installed above and on the lysimeter. Furrow irrigation was applied to the monolith and surrounding field. Reference ET was calculated using the hourly ASCE standardized reference ET equation. Crop coefficients of alfalfa were calculated by dividing daily measured ET from the lysimeter by the corresponding daily total ASCE standardized reference ET. Four alfalfa cuttings occurred in both the 2008 and 2009 growing seasons. The results showed that the alfalfa growth, climate and precipitation were shaping crop coefficients. The first cutting cycle, which had slower growth due to climate, had lower crop coefficients, whereas later cutting cycles with rapid growth had higher crop coefficients. The maximum crop coefficients were below 1.2 in 2008 and at or above 1.2 in 2009. Precipitation interception by the alfalfa canopy increased evaporation and caused outliers in the crop coefficient values.

INTRODUCTION

Irrigation water management is an essential element of conservation and sustainability of water resources. Effective irrigation management depends on accurate estimates of crop water use which is needed for deciding when and how much to irrigate. Crop water use is defined as the water lost from crop and soil through the processes of transpiration and evaporation (evapotranspiration, ET).

Estimation of ET or water consumption is the foundation of irrigation scheduling for efficient irrigation management. Although many methods to determine ET are available, direct measurement using a weighing lysimeter is the most precise method for measuring crop water consumption. In a precision weighing lysimeter, ET is determined by

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[1] Colorado State University, Fort Collins, Colorado, 80523, USA
[2] Colorado Division of Water Resources, Pueblo, Colorado, 81004, USA
[3] USDA-Agricultural Research Service-Water Management Research, Fort Collins, Colorado 80526, USA
Corresponding author. Tel.: (970)491-6516; Fax: (970) 491-0564
Email address: Allan.Andales@colostate.edu

measuring the change in mass with an accuracy equivalent to a few hundredths of millimeters of water (Allen et al., 1998). The crop coefficient (Kc), which represents plant characteristics, is the ratio of the actual crop ETc to the reference evapotranspiration (ETr). Crop coefficients are widely used to determine crop water consumption and in determining when and how much water to apply with irrigation (Howell et al., 2006). Even though Kc values for most crops have been reported in the literature, developing them under local cropping practices and soil and climatic conditions is recommended for accurate irrigation scheduling because of variations in crops, climate and other environmental factors that influence ET. Whatever a reference ET method is used, there is proof that Kc values may not be transferable from one area to another (Evett et al., 1998). Crop coefficients that are currently used by the Colorado Division of Water Resources were measured at Kimberly, Idaho and Bushland, Texas (Berrada et al., 2008).

Alfalfa is one of the major and most valuable forage crops and has a high biomass yield potential in Colorado (Smith et al., 1999). Irrigated alfalfa has one of the greatest levels of seasonal water consumption among irrigated crops (Wright, 1988). Determination and application of accurate alfalfa crop coefficients could be a potential way to save water. This research was aimed to develop crop coefficients of alfalfa using a weighing lysimeter in the Arkansas Valley of Colorado.

MATERIALS AND METHODS

Experimental location

The experiment was conducted during 2008 and 2009 at the Arkansas Valley Research Center in southeast Colorado (latitude 38^o 2' 17.30", longitude 103^o 41' 17.60", altitude 1,274 m above sea level). It was carried out using a large weighing lysimeter constructed for evaluating the American Society of Civil Engineers (ASCE) standardized Penman Monteith (PM) equation and to compute actual evapotranspiration (ETc) and crop coefficients (Kc) for various crops under Arkansas Valley conditions. The lysimeter was filled with an undisturbed soil monolith with soil type being a Rocky Ford course loamy, mixed , superactive, mesic Aridic argiustoll. The soil pH and ECe are 8.2 and 0.78 dS/m respectively. The soil layers have bulk density and hydraulic conductivity ranges of 1.35-1.45 g/cm and 0.33-1.25 cm/hr, respectively.

Lysimeter design

The inner tank of the weighing lysimeter has dimensions of 3m x 3m x 2.4 m depth. Calibration of the weighing mechanism was done similar to the procedure developed by USDA-ARS at Bushland, Texas (Berrada et al., 2008) to convert the load cell output in mV/V to mass. The lysimeter load cell output was recorded every 10 seconds throughout each growing season. Fifteen-minute averages of the load cell data were used in the calculation of ETc. Based on the load cell calibration, a change of 1 mV/V in the load cell output is equivalent to a change of 76 mm of water in the lysimeter.

Climate and soil measurements

A weather station was installed at the lysimeter site to measure climate variables above and within the lysimeter. Variables included rainfall, wind speed, air temperature, solar radiation, barometric pressure, soil temperature, and soil heat flux. Berrada et al. (2008) described in detail the sensors and their placement. Climatic data were recorded every 15 minutes. Soil moisture in and near the lysimeters was monitored using a CPN 503 DR neutron probe at 20 cm increments up to 190 cm. Two access tubes were installed inside the monolith and four were installed immediately outside the lysimeter. The neutron probe was calibrated based on the Evett et al method (Berrada et al., 2008).

Alfalfa planting and irrigation

Alfalfa (*Genoa* variety) was planted mechanically in the field and by hand in the lysimeter on 9 August 2007 at a rate of 21.3 kg/ha. The soil monolith was irrigated manually to mimic the furrow irrigation of the surrounding field (158.5 m x 256.1 m). When flow in the field furrows reached the lysimeter, it was diverted around the lysimeter. Metered water was pumped into four evenly-spaced furrows (76 cm spacing) on the soil. The amount of water applied to the monolith was recorded. Alfalfa height was measured weekly. Alfalfa was harvested four times in both 2008 and 2009. Alfalfa in the lysimeter was harvested manually in June 11th, July 21st, September 1st and November 3rd in 2008 and in June 8th, July 15th, August 24th and October 5th in 2009.

Water balance

Water balance of the lysimeter for the 2008 and 2009 seasons was calculated based on the weight data using the equation:

$$ET = P + Irr - D - \Delta S \tag{1}$$

Where seasonal change in soil water content (ΔS) was calculated from water inputs [Precipitation (P) and irrigation (Irr)] and water outputs [Evapotranspiration (ET) and Drainage (D)].

Reference ET calculation

The American Society of Civil Engineers (ASCE-PM) standardized ETrs equation was used to estimate reference evapotranspiration on an hourly time step using climatic data obtained from the weather station.

$$ET_{rs} = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{C_n}{T + 273} u_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + C_d u_2)} \tag{2}$$

where:

ETrs = standardized reference crop evapotranspiration for tall surfaces (mm/h),

Rn = calculated net radiation at the crop surface ($MJ/m^2/h$),

G = soil heat flux density at the soil surface ($MJ/m^2/h$),

T = mean hourly air temperature at 1.5 to 2.5-m height (°C),

u2 = mean hourly wind speed at 2-m height (m/s),

es = saturation vapor pressure at 1.5 to 2.5-m height (kPa),

ea = mean actual vapor pressure at 1.5 to 2.5-m height (kPa),

Δ = slope of the saturation vapor pressure-temperature curve (kPa/°C),

γ = psychrometric constant (kPa/ °C),

Cn = 66; numerator constant for tall reference and hourly time step (K mm s^3 /Mg/h) and

Cd = 0.25 (daytime), 1.7 (nighttime); denominator constants for tall reference and hourly time step (s/m).

Units for the 0.408 coefficient are m^2 mm / MJ.

The ETrs calculated by ASCE-PM uses wind speed measured at 2 m height over smooth surface like clipped grass. The wind speed at the lysimeter was measured at 2m above alfalfa, which had variable height during the growing season. At most times alfalfa height was greater than clipped grass. The wind speed adjustment algorithmdescribed by Ley et al. (2009) was used to adjust wind speeds over variable height alfalfa to equivalent wind speeds at 2 m over grass.

<u>Crop coefficient (Kcr) calculations</u>

Crop coefficient values based on a tall (alfalfa) reference for the 2008 and 2009 seasons were calculated on a daily time step as the ratio between measured ETc from the lysimeter and the ASCE standardized ETrs.

$$Kcr = \frac{ET_c}{ET_{rs}} \tag{3}$$

where:

ETc = Actual crop evapotranspiration from lysimeter (mm/d)

ETrs = ASCE standardized reference crop evapotranspiration (mm/d)

The daily ETrs values were obtained by summing values calculated from the hourly version of the standardized equation for each 24-hour period. Crop coefficient curves for each alfalfa cutting cycle were fitted through observed Kcr values using FAO 56 methods (Allen et al., 1998), with some modification to fit observed Kc's for each growth stage.

RESULTS AND DISCUSSION

Seasonal Water Balance

Seasonal water balance for 2008 and 2009 is shown in Figure 1. Alfalfa use 1333 mm of water in 2008 and 1179 in 2009. The total water input (precipitation + Irrigation) was 1269 mm in 2008 and 1381 mm in 2009. There was no drainage in both seasons. The change in soil water content in 2008 was -64 mm. This indicates that alfalfa consumed 64 mm more water than that added by precipitation and irrigation. In 2009, the change in soil water content was +202 mm, indicating that alfalfa consumed 202 mm less water than that added by precipitation and irrigation. Alfalfa consumed more water in 2008 than in 2009 even though the total water added was lower than 2009. Higher water consumption in 2008 was primarily due to a longer growing season. The total growing season in 2008 was 215 days whereas 2009 was only 195 days.

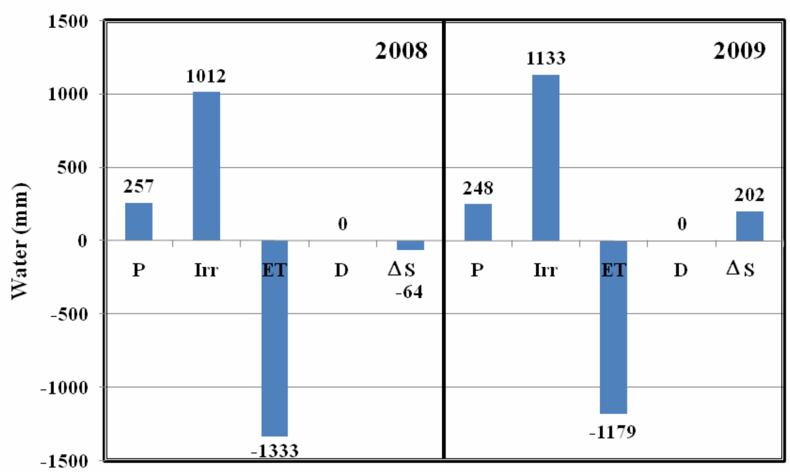

Figure 1. Seasonal water balance of the alfalfa grown in the lysimeter in 2008 (4/1/08 - 11/5/08) and 2009 (3/24/09 – 10/5/09).

Alfalfa Evapotranspiration

Daily alfalfa ET for both 2008 and 2009 season is shown in Figure 2A. Alfalfa ET fluctuations during the growing periods corresponded with similar fluctuations in reference ET (Figure 2B). Actual ET in 2008 was higher than in 2009 for the first cutting cycle because of greater atmospheric demand, which is reflected in the higher ETrs values in 2008. Maximum water use of alfalfa was around 14.0 mm/d for both 2008 and 2009 seasons. Average ET for 2008 and 2009 was 6.1 mm/d and 6.0 mm/d, respectively. In comparison, Evett et al. (1998) found that measured ET of alfalfa at Bushland, TX in 1996 and 1997 averaged 7.1 mm/d and 6.7 mm/d, respectively. They also found that the peak ET reached 16 mm/d for both years.

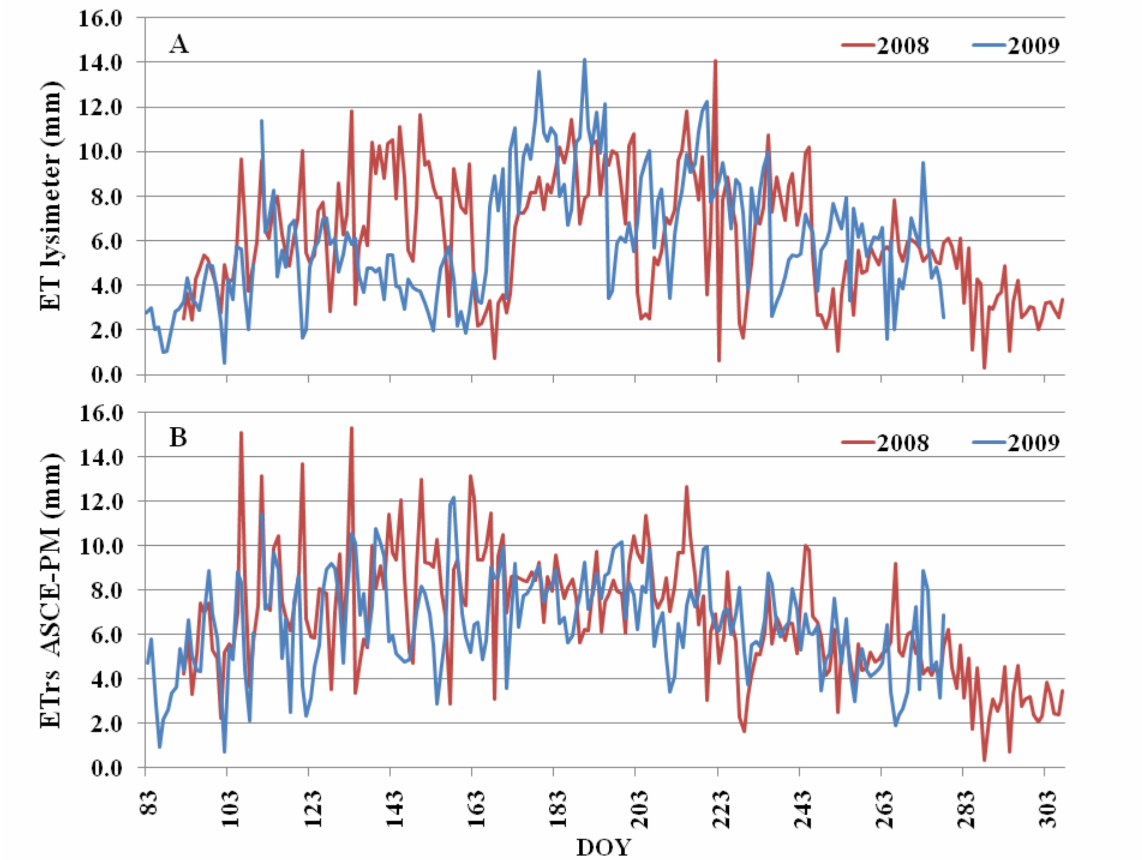

Figure 2. Actual alfalfa ET from lysimeter (A) and reference ET ASCE-PM (B) in 2008 (4/1/08 -11/5/08) and 2009 (3/24/09 – 10/5/09).

Alfalfa crop coefficients

Crop coefficients represent the effects of crop growth and condition on ET. The Kcr is low when the crop is in the initial growth stage or after cutting and increases as the crop develops, reaching a maximum value at mid stage. Figure 3 shows alfalfa crop coefficients for the 2008 and 2009 seasons as responding to crop growth. In the 2008 season, the first cutting cycle was not included because there weren't canopy height measurements that could be used for making wind speed corrections for ETrs calculations. It is obvious that alfalfa crop coefficients were low in the initial stage and increased as alfalfa height increased until reaching the maximum when the alfalfa height was at mid stage. The growth of alfalfa in the first and fourth cutting cycle was slower due to cooler weather and lower solar radiation.

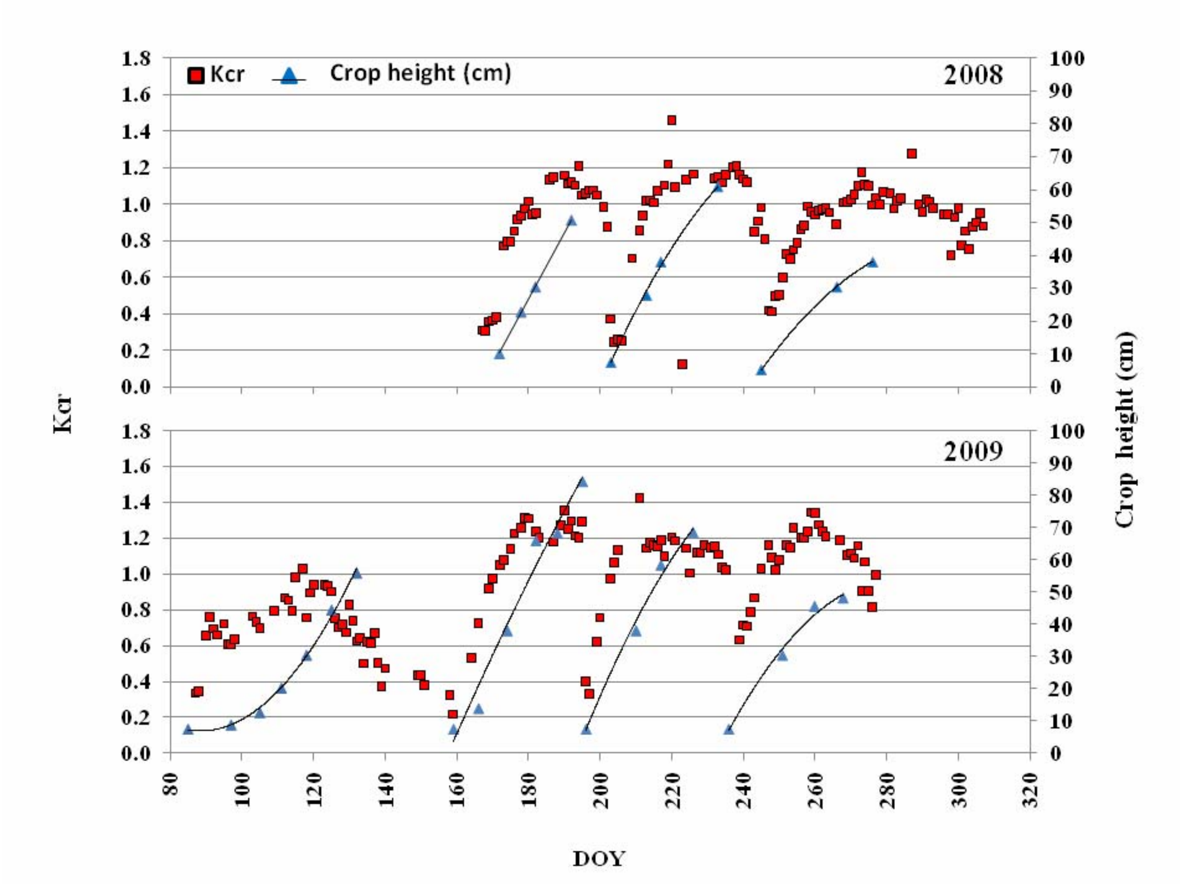

Figure 3. Alfalfa crop coefficients corresponding to crop height development in 2008 and 2009.

In general for all cuttings, maximum Kcr values were higher in 2009 than in 2008 (Figure 4). In 2008 the maximum Kcr values mostly remained below 1.2 whereas in 2009, maximum Kcr values were about 1.2 as shown in Figure 4. The Kcr values greater than 1.0 were due to ETc values from the lysimeter being higher than ETrs values from the ASCE standardized equation. However alfalfa crop coefficients based on ETrs should not persistently exceed 1.0, given the assumption that ETrs represents the theoretical upper limit for ET. The peak Kcr values reported here were higher than those reported by Howell et al. (2006) and Wright (1982). They found that the peak Kcr was near 1.0. However Howell et al. (2006) found that Kcr values did exceed 1.0 occasionally. In both years, the second and third cutting cycles had similar lengths of growing periods. In contrast, the fourth growing period in 2008 was longer than in 2009 that was reflected in the difference in shape of the Kcr curves. The first cutting cycles for both the 2008 and 2009 seasons were longer than other cutting cycles. The 2009 data showed that peak Kcr values in the first cutting cycle were lower than in later cutting cycles.

Figure 4 also shows the effects of rainfall on the crop coefficients. Crop coefficient values increased significantly during precipitation days. Precipitation tends to increase evaporation from bare soil during early growth stages when the alfalfa does not fully cover the ground. Precipitation also increases direct evaporation of rainfall that is intercepted by the crop canopy.

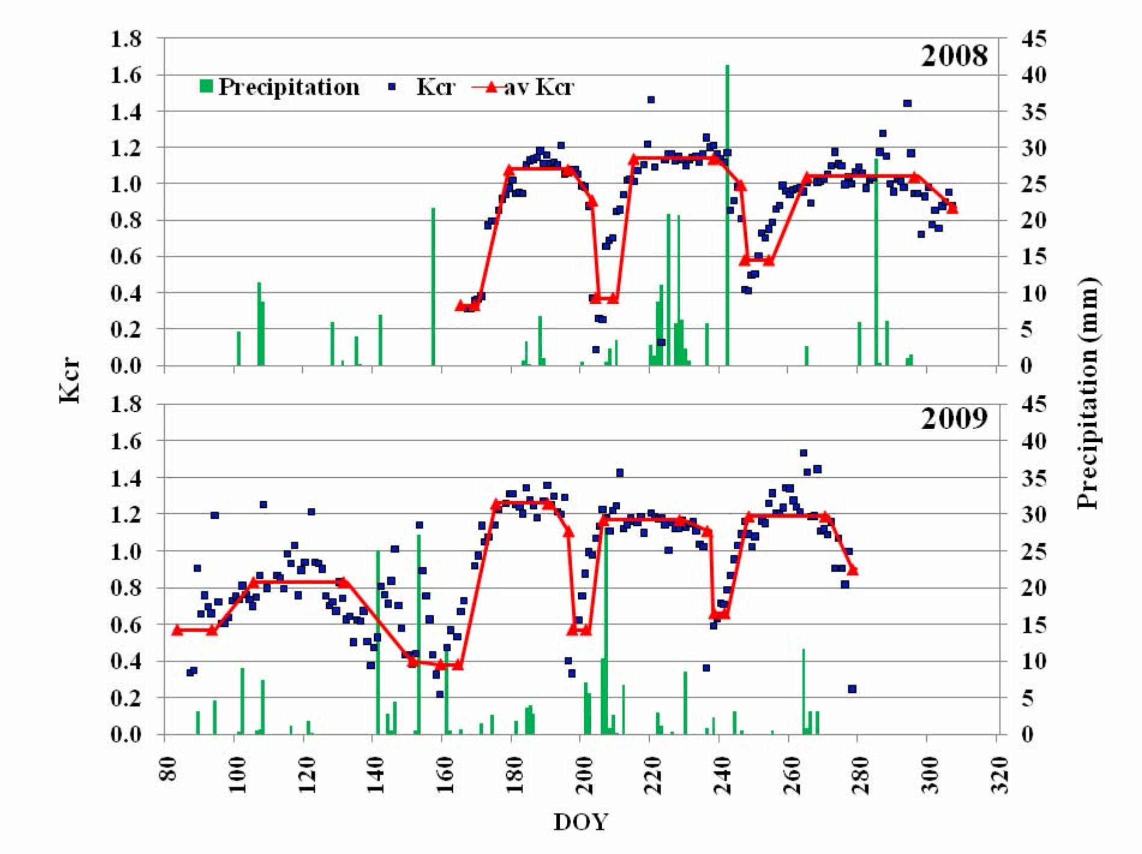

Figure 4. Alfalfa crop coefficients and precipitation in 2008 and 2009.

The peak Kcr values that were persistently greater than 1.0 lead us to believe that some energy actually available for ET is not being accounted for in our ETrs calculations. Further evaluations of the weather data inputs have to be made to determine why ETrs values were persistently less than ETc from the lysimeter during the latter periods of the 2nd, 3rd, and 4th cutting cycles. Possible causes may be under-estimation of net radiation (R_n) input to the ASCE standardized equation and the actual evapotranspiring surface of the lysimeter alfalfa being greater than the ground surface area of the lysimeter. The second possibility may occur when alfalfa at the perimeter of the lysimeter lodges and its canopy extends beyond the perimeters.

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TURFGRASS ET FROM SMALL LYSIMETERS IN NORTHEAST COLORADO

Mark A. Crookston[1]
Mary Hattendorf [2]

ABSTRACT

Small weighing lysimeters were planted to 11 different turfgrass varieties in 2010. Only one of the 11 turfgrasses selected was warm-season, the remaining 10 were cool-season. There are four replicates of each turfgrass. Results are compared to ETos calculated from an adjacent weather station using the standardized Penman-Monteith equation. The first season results from 44 small weighing lysimeters are presented.

Each lysimeter is centered in a 4 ft by 4 ft plot of the same grass variety. The lysimeters each consist of a PVC shell containing a 12-inch diameter free draining sandy loam soil core having a 20-inch rooting depth. The lysimeters are continuously weighed in-place by electronic load platforms connected to a data logger. Irrigation is applied via high uniformity sprinklers and measured through a flow meter monitored by a data logger. All turfgrasses receive the same irrigation treatment and are managed to avoid soil moisture induced stress. All grasses are mowed to the same height.

The purpose of the study is to quantify evapotranspiration of several varieties of turfgrass, under well watered conditions and with adequate fertility.

Differences in measured turfgrass evapotranspiration are included in the summary. Quantification of turfgrass ET with increased accuracy is especially important in regards to water conservation, agricultural to urban water transfers, and water rights administration.

INTRODUCTION AND BACKGROUND

Interest in different varieties of turfgrasses and their water usage has increased in recent years. Although general statements of lower water requirements are readily attached to some turfgrasses, quantitative assessments based on ETos from the standardized Penman-Monteith equation are rare. The use of lysimeters to directly measure turfgrass ET provides a defensible basis for quantifying and comparing actual water use. This information will provide municipalities with information needed in developing landscaping standards in support of efficient water use and conservation. It should also assist in more accurate quantification of irrigation return flows from urban landscapes and the in-stream flow credits claimed by Colorado municipalities under water rights administration.

[1] Manager, Irrigation Management Department, Northern Water, 220 Water Avenue, Berthoud, CO 80513; mcrookston@ncwcd.org
[2] Water Management and Conservation Specialist, Northern Water, 220 Water Avenue, Berthoud, CO 80513; mhattendorf@ncwcd.org

Previous Studies

Jensen et al. (1990) stated that “differences in grasses appear to be even greater than those for alfalfa, with clipping height having a pronounced effect on ET rates. In addition, large differences in peak period ET may exist between warm- and cool-season grass types . . .”

Feldhake et al. (1983) reported results from a three year turf study (1979 to 1981) of eight small weighable lysimeters at Fort Collins, Colorado. Mowing was two to three times per week with a height of 0.8 inches standard. Grasses included Merion Kentucky bluegrass (three years), Rebel tall fescue (one year), and common buffalograss (one year). Moisture levels in all lysimeters were maintained for maximum ET (irrigated three times per week). Reference ET was taken to be the measured ET from the Kentucky bluegrass lysimeters – irrigated three times/week, mowed to 0.8 inches, and maintained with adequate fertility (0.8 lbs/1,000 ft^2/month). In 1979 (July 13 to October 4), bluegrass mowed at 2.0 inches resulted in 13% higher ET. Concerns about oasis effects from the mini-plots with higher mowing height prompted observations using an infrared thermometer. These showed a “substantial temperature gradient” across mini-plot (8.2 ft x 8.2 ft) borders, but “essentially a constant temperature” inside a distance of 1.2 ft. In 1980 (June 20 to August 28), bluegrass with deficient fertility resulted in 14% lower ET. In 1981 (June 8 to August 16), tall fescue had 2% higher ET and buffalograss had 21% lower ET.

Brown et al. (2001) affirmed the following factors to affect turf water use and thus Kc: turf species and/or variety (cool-season – higher ET, warm-season – lower ET), canopy characteristics, mowing height (increased – higher ET, decreased – lower ET), nutrition (adequate – higher ET, deficient – lower ET), irrigation frequency (increased – higher ET, decreased – lower ET particularly for surface applied irrigation), and the procedure used to estimate ETo.

Jensen et al. (1990) also stated “an average ETr/ETo ratio of 1.2 to 1.25 may have been more representative of the 11 lysimeter sites evaluated” in ASCE Manual No. 70. This would provide a factor of 0.80 to 0.83 to convert alfalfa reference to a cool-season grass reference.

The University of Idaho REF-ET software recognizes that the ratio of ETr to ETo can range from 1.15 to 1.25, with 1.25 as the recommended default. This ratio provides a factor of 0.80 to covert alfalfa reference to cool-season grass reference, with an assumed grass height of 4.7 inches.

Jensen et al. (1990) included Table 6.11 that provided a ratio of 1.28 for 1982 Kimberly Penman ETr to lysimeter measured ET for clipped ryegrass (3-6 inches) for May through August at Kimberly, Idaho (1983-1984). This ratio would provide a factor of 0.78 to convert alfalfa reference to actual ryegrass ET. Their Table 6.9 provides the same 0.78 mean Kc factor for use directly with alfalfa reference ETr (120 days during mid-season).

Allen et al. (2007) converted the mean crop coefficients from Kimberly, Idaho for use directly with alfalfa reference ETrs obtained from the ASCE standardized Penman-Monteith equation. Their Table 8.7 provides an updated Kcs of 0.80 for perennial ryegrass during mid-season (60 days) and 0.55 for the beginning and end of season.

Devitt et al. (1992) provided monthly Kc values for over seeded perennial ryegrass in Las Vegas, Nevada. The basis was a two year study (1987 to 1989) of common bermudagrass over seeded with perennial ryegrass on three sites (two golf courses and one park). Each site was equipped with two vacuum drained lysimeters and a weather station. Ryegrass was over seeded the third week of September and reached mowing height the second week of October. The ryegrass was mowed to an average of 0.7 inches at the golf course sites and to two inches at the park site. For the November through April period (when ryegrass fully dominated) the average monthly Kc values from the golf course sites ranged from 0.43 in February to 0.81 in November, averaging 0.62. In contrast, the corresponding monthly Kc from the park site ranged from 0.33 in February to 0.60 in November, averaging 0.46. Reference ETo was calculated using the 1973 Penman equation. The significant increase in Kc at the golf course sites was largely attributed to increased fertility levels with 3 to 5 times the nitrogen fertilizer applied as compared to the park site. If the mowing height at the golf course sites had been two inches (same as the park site) further increased Kc factors may have resulted.

Hill (1998) reported a crop coefficient for turf of 0.56 applied to 1972 Kimberly Penman derived alfalfa reference. The applicable season was April-Oct (210 days). The basis was field research from two lysimeters in the Logan, Utah Country Club Golf Course during two seasons, 1991-1992.

Allen et al. (1998) provided a mid-season to end crop coefficient for cool-season turfgrass (bluegrass, ryegrass, and fescue with height of 2.4 to 3.1 inches) of 0.95 for FAO Penman-Monteith grass reference. The corresponding mid season to end crop coefficients for alfalfa hay were 1.20 and 1.15. The basis for these crop coefficients was a two year study (1971-1972) at Davis, California involving two large sensitive lysimeters planted to alfalfa and 'Alta' tall fescue grass. A procedure was provided for deriving a reference conversion ratio for more arid sites, such as Kimberly, Idaho. Application of this procedure results in a ratio of 1.24 for ETr at Kimberly to ETo at Davis. Consequently, also adapting the FAO-56 crop coefficients for cool-season grass to Kimberly, Idaho (Kc now equals 0.98) and combining with the ETr/ETo factor – provides a factor of 0.79 to convert ETr to cool-season grass ET for Kimberly.

Allen et al. (2007) updated the FAO-56 mean crop coefficient to 0.90 for cool-season turfgrass. Utilizing the 1998 procedure, this would provide factors of 0.75 to 0.78 to convert ETr for Kimberly to cool-season grass ET.

Ervin et al. (1998) reported crop coefficients of 0.70 (0.60 to 0.80) for Kentucky bluegrass and 0.60 (0.50 to 0.80) for tall fescue applied to 1982 Kimberly-Penman derived alfalfa reference. The basis was field research from a line source sprinkler irrigation study at Fort Collins, Colorado, 1993-1994. Mowing was twice weekly at 2.5

inches. This study showed that reduced irrigation levels did maintain acceptable turfgrass quality.

Brown et al. (2001) provided monthly Kc for over seeded 'Froghair' intermediate ryegrass that ranged from 0.78 in January to 0.90 in April. The basis was a three year study (1994-1997) in Tucson, Arizona utilizing two large weighing lysimeters with bermudagrass during June through September, which was then over seeded to ryegrass in October, with the November through May (180 days) data utilized to develop the ryegrass Kc. Reference ETo was calculated using the FAO-56 Penman-Monteith equation. Irrigation was daily and the ryegrass was mowed two times per week at a height of one inch.

Although many previous studies are in relatively close agreement for ET from well-irrigated cool-season turfgrass with adequate fertility, differences between cool-season turfgrasses is lacking. Additionally, the difference in mowing height and lack of reference to ETos from the standardized Penman-Monteith equation curtails their transferability from one region to another. The Northern Water lysimeter study will compare turfgrasses under the same climate conditions with similar mowing heights to the standardized Penmen-Monteith ETo at Berthoud, CO.

MATERIALS AND METHODS

In 2009, Northern Water commenced construction and installation of a 30-ft x 30-ft study plot for turfgrass lysimeters within its Conservation Gardens at its headquarters in Berthoud, Colorado. The turfgrasses were seeded starting May 28th and finishing June 2nd, 2010.

The lysimeter plot was divided into 4-ft x 4-ft sub-plots, separated by 1-inch x 6-inch PVC plastic composite decking/edging material. This edging clearly delineates the subplots and helps prevent the spread of one grass variety into another subplot. It also provides support for foot traffic by study technicians without damage to turf or compaction of the soil. Turfgrasses were planted into 44 of the 49 sub-plots, with the four corners and center sub-plots excluded from the study, but planted to a bluegrass blend to maintain fetch. The lysimeter plot was divided into four blocks, with each block containing 11 randomized sub-plots with lysimeters, one of each turfgrass variety included in the study. Consequently, the study includes four replicates of each of the following 11 turfgrasses:

Kentucky bluegrass blend:
- 50% - Rampart
- 25% - Touchdown
- 25% - Orfeo

Drought hardy Kentucky bluegrass:
- 33% - Rugby
- 33% - America
- 33% - Moonlight

Fine fescue blend:
- 25% - Covar Sheep
- 25% - Intrigue Chewings
- 25% - Cindy Lou Creeping Red
- 25% - Eureka Hard

Reubens Canada bluegrass

Tall fescue – Major League blend

Ephraim crested wheatgrass

'Low Grow' mix:
- 29% - Creeping Red fescue
- 27% - Canada bluegrass
- 24% - Sheep fescue
- 16% - Sandburg bluegrass

Perennial ryegrass - Playmate blend

Texas hybrid bluegrass blend:
- 50% - Reveille
- 50% - SPF 30

'Natures Choice' - Arkansas Valley mix:
- 70% - Ephraim Crested wheatgrass
- 15% - Hard fescue
- 10% - Perennial ryegrass
- 5% - Kentucky bluegrass

Blue gramma – buffalograss mix:
- 70% - Blue Gramma
- 30% - Buffalograss

EQUIPMENT

The weighing platform for each lysimeter includes a Revere PC6-100kg-C3 load cell transducer. Each load cell is connected to one of three AM 16/32 multiplexers, each connected to a Campbell Scientific CR10X data logger. Figure 1 is a diagram of the small turfgrass lysimeters and their arrangement within the lysimeter plot.

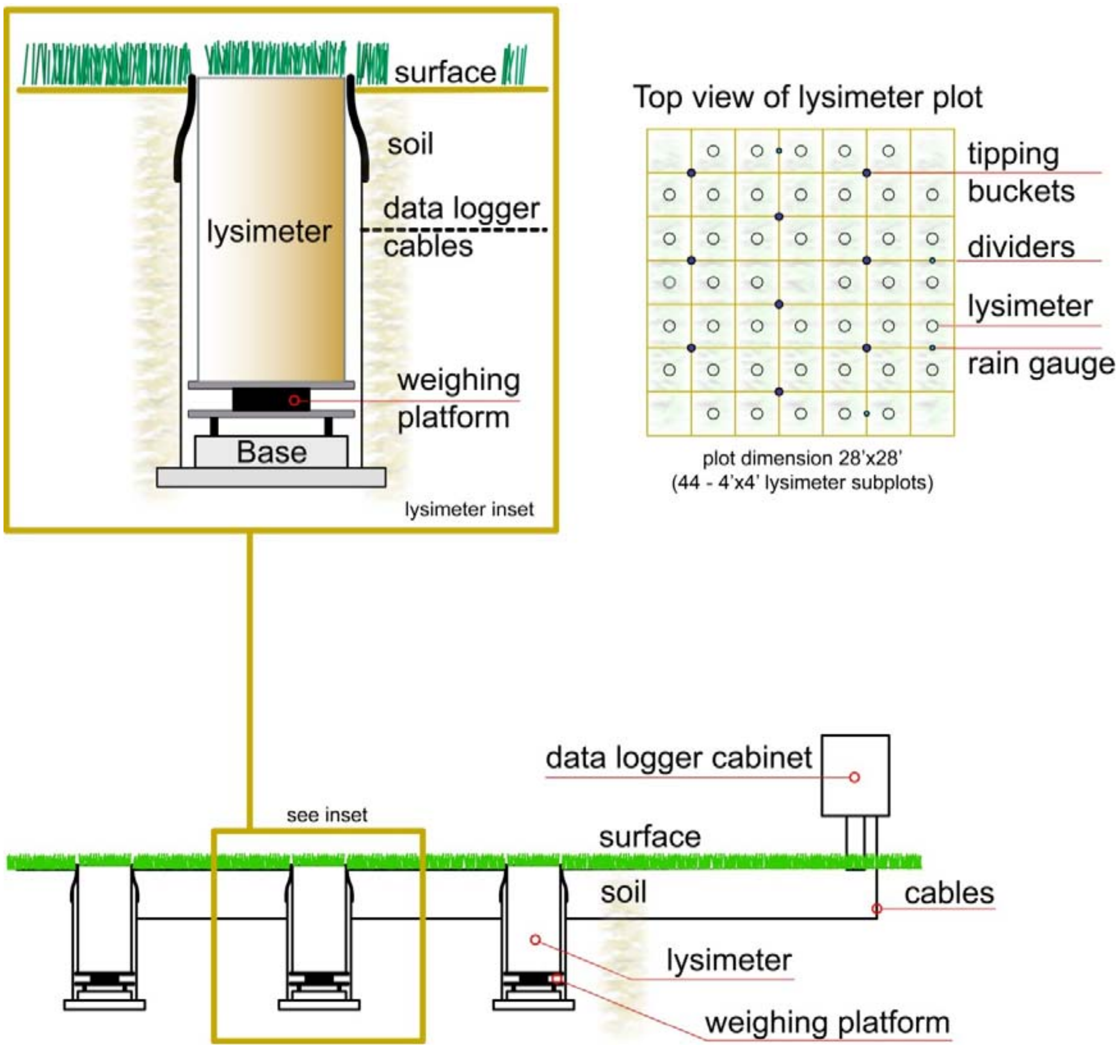

Figure 1. Diagram of Small Turfgrass Lysimeters

Every three seconds a measurement is taken from each load cell and these measurements are averaged every 60 seconds. This one minute average is time-stamped and stored in the data logger at the end of each 15-minute period. Stored data is automatically downloaded every 15 minutes to a desktop PC via an RF401 spread-spectrum radio. Differences in lysimeter weight are calculated as the difference in the measurement at the end of each hour. These hourly values are compared to calculated ETos obtained from the REF-ET software (http://www.kimberly.uidaho.edu/ref-et/) utilizing data from the adjacent Campbell Scientific ET-106 weather station. The weather instruments are each calibrated annually.

The weighing platforms for each lysimeter were calibrated in-place (without the lysimeter) in September 2009 over their full load range using steel weights. They were again re-calibrated in-place during 2010, but only over their operational range (from dry soil to wet soil). No problems were identified during the re-calibration and all weighing platforms were measuring lysimeter weights properly.

The entire lysimeter plot is on a single irrigation zone using MP Rotator 2000 sprinklers on 15-foot spacing. A DLJ ¾"x ¾" brass flow meter w/pulse output connected to a Campbell Scientific data logger which measures all irrigation applications to the lysimeter plot. In addition, nine Texas Electronics tipping bucket rain gauges are installed flush with the turf height throughout the lysimeter plot to measure net irrigation application as well as rainfall.

DEEP PERCOLATION CALCULATIONS

Deep percolation through the lysimeters was not directly measured. Deep percolation from irrigation was calculated as the difference between applied irrigation less the increase in lysimeter weight after free drainage. During the germination period during June-July of 2010, irrigations occurred twice daily during daylight hours. This hourly data was generally excluded from the calculation of turfgrass ET. However, beginning in late July, turf water use during the drainage period was considered negligible as all irrigations were scheduled for just after sundown. Nighttime turf water use was significantly less than during daytime hours and was generally very small. As the lysimeters are free draining with sandy loam soil only 20-inches deep, any deep percolation from irrigation was assumed to be completed before sunrise. During 2010, any excessive percolate that ponded below a lysimeter was removed through a manually controlled vacuum extraction system as needed.

Deep percolation from rain was calculated similarly as for irrigation. However special considerations were required – particularly for significant daytime rain events. Deep percolation from rain was calculated as the difference between measured rainfalls less the increase in lysimeter weight (after stabilization). If the drainage period occurred during daytime hours, the data was generally excluded from the comparison to calculated ETos.

SUMMARY

Measured turfgrass water use in ac-in/ac is summarized in Table 1 for each of the 11 turfgrasses, along with ETos, for June 3rd through July 25th of 2010. The corresponding monthly Kcos crop coefficients are included in Table 2. The turfgrass ET are elevated because of twice daily watering to promote seed germination, which continued from planting in June through most of July, 2010.

Table 1. Summary of 2010 Measured Water Use from Small Turfgrass Lysimeters

	June 3-30	July 1-25	Total
	ac-in/ac	ac-in/ac	ac-in/ac
Kentucky bluegrass blend	6.13	5.90	12.03
Drought hardy Kentucky bluegrass	6.17	5.77	11.94
‘Low Grow’ mix	6.45	6.05	12.50
Perennial ryegrass blend	6.81	6.00	12.81
Texas hybrid bluegrass blend	6.17	5.86	12.03
Fine fescue blend	6.33	5.73	12.06
Reubens Canada bluegrass	6.09	5.78	11.87
Tall fescue blend	6.83	6.26	13.09
Ephraim crested wheatgrass	6.31	5.11	11.42
‘Natures Choice’ mix	6.47	5.76	12.23
Blue gramma – buffalograss mix	6.24	5.81	12.05
ETos (reference)	6.06	5.28	11.34

Table 2. Summary of 2010 Calculated Kcos Crop Coefficients for 11 Turfgrasses

	June 3-30	July 1-25	Season-partial
	Kcos	Kcos	Kcos
Kentucky bluegrass blend	1.01	1.12	1.06
Drought hardy Kentucky bluegrass	1.02	1.09	1.05
‘Low Grow’ mix	1.06	1.15	1.10
Perennial ryegrass blend	1.12	1.14	1.13
Texas hybrid bluegrass blend	1.02	1.11	1.06
Fine fescue blend	1.04	1.09	1.06
Reubens Canada bluegrass	1.00	1.09	1.05
Tall fescue blend	1.13	1.19	1.15
Ephraim crested wheatgrass	1.04	0.97	1.01
‘Natures Choice’ mix	1.07	1.09	1.08
Blue gramma – buffalograss mix	1.03	1.10	1.06

Photographs of the site location, surrounding gardens, and weather station location are provided in Figures 2-5.

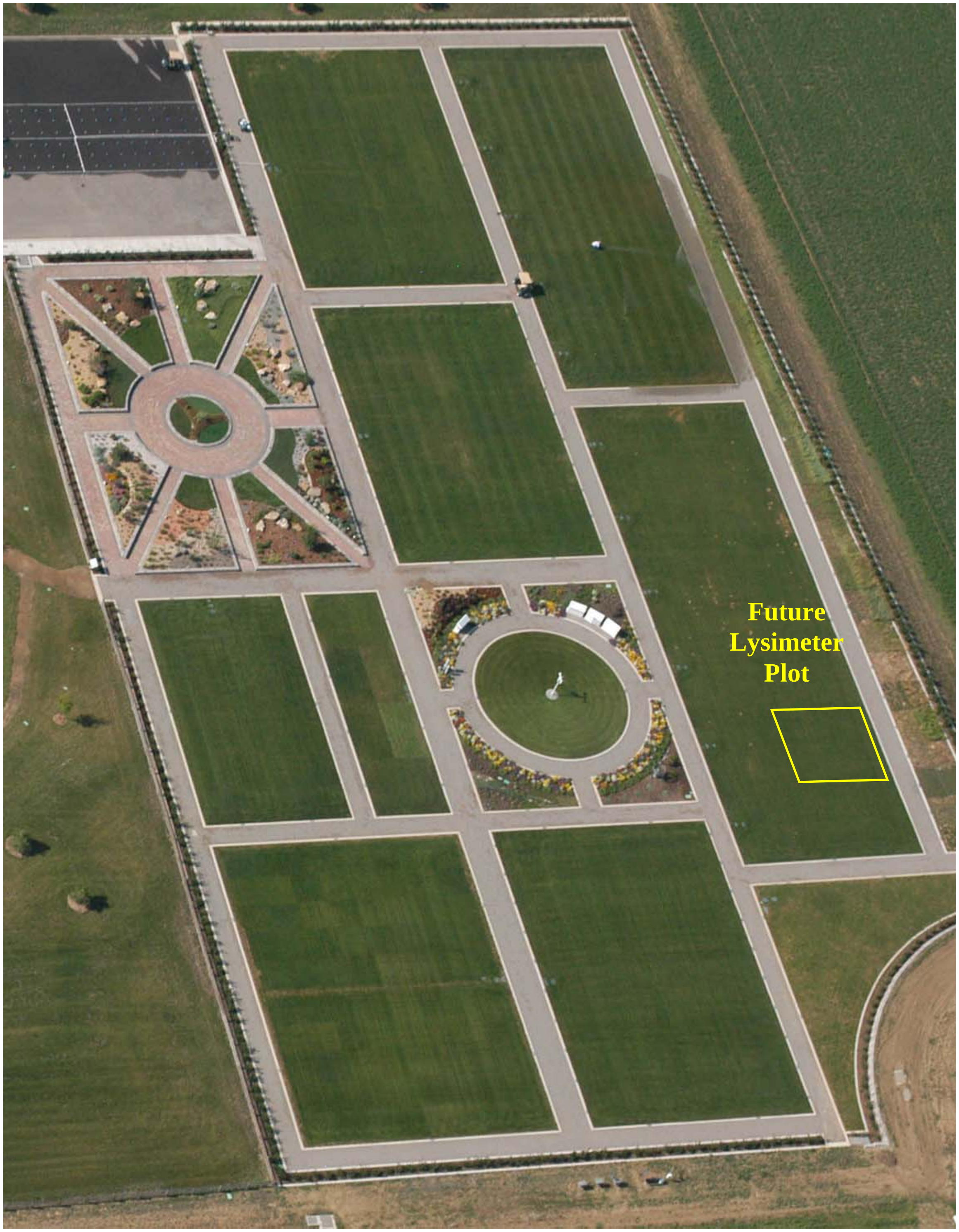

Figure 2. Aerial View of Conservation Gardens at Northern Water – before construction of lysimeter plot.

Figure 3. Conservation Gardens at Northern Water – view towards northwest.

Figure 4. Elevated View to Northwest of Weather Station and Future Lysimeter Plot.

Figure 5. View to Southeast of Weather Station and Lysimeter Plot – under construction.

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MONITORING TURF WATER STATUS WITH INFRARED THERMOMETRY

Mary J. Hattendorf[1]
Mark A. Crookston[2]

ABSTRACT

New advances in the Crop Water Stress Index (CWSI) technique pioneered by Idso et al. (1981), Jackson et al (1981), and others have reduced the data requirements and development time for detection of water stress. These new methods, sometimes called the empirical CWSI (eCWSI, O'Shaughnessy and Evett, 2009) were adapted for the Northern Water turf studies program. The adapted methods compare turf surface temperature measured with an infrared thermometer to surface temperature of a spray-pump wetted turf surface. The eCWSI of a plot of spray irrigated tall fescue was compared to the eCWSI of an adjacent plot of subsurface drip irrigated (SDI) tall fescue. Attempts were made to keep the eCWSI of each plot close in value with irrigations applied as needed to the more stressed plot. Although weather conditions in 2009 often precluded collecting data as frequently as needed, results indicated that the SDI plot was often more stressed than the spray plot. The SDI plot had less applied water than the spray-irrigated plot and soil moisture in the SDI plot also was consistently lower than in the spray plot. These results suggest that maintaining eCWSI at equal levels would increase the applied irrigation to the SDI plot. Information in 2010 will help define whether true applied irrigation differences exist between the SDI and spray-irrigated plots. The new eCWSI approach for turf is robust, simple, and has potential for technology transfer to turf managers with inexpensive, off-the-shelf instrumentation and equipment.

INTRODUCTION

Infrared thermometry to detect plant water stress was pioneered by Idso et al. (1981) and Jackson et al. (1981). Jackson et al (1981) showed that the empirical approach of Idso et al (1981) was well-grounded in theory. The CWSI represents the ratio of actual evapotranspiration (E) to potential ET (E_p) in the following way: $1\text{-}E/E_{p,}$ where 0 is non-stressed, and 1.0 indicates no transpiration. In practice, the CWSI was typically implemented using hand-held infrared thermometers and on-site humidity and air temperature data. While robust and sensitive, the technique had several drawbacks that limited its practical application on a wide-spread basis.

One major limitation was that the empirical non-stressed baseline had to be pre-developed for each crop and sometimes for each variety. The technique required a wide range of vapor pressure deficit conditions to be transportable among locations or even among years at the same location. Another drawback was that baselines had to be

[1] Water Management & Conservation Specialist, Northern Colorado Water Conservancy District, 220 Water Ave, Berthoud, CO 80513 mhattendorf@ncwcd.org
[2] Manager, Irrigation Management Department, Northern Water, 220 Water Avenue, Berthoud, CO 80513 mcrookston@ncwcd.org

developed for various canopy cover conditions. A baseline developed for full cover was not appropriate for partial canopy cover.

A recent resurgence of interest and activity in the CWSI has yielded several improvements in usability of the technique. Instead of developing baselines for each crop or variety, Jones et al (1999) used natural wet and dry reference surfaces to provide the upper and lower limits of the CWSI. The wet reference surfaces ranged from spray-wetted leaves or canopies (Möller et al, 2007) to fully-irrigated crops (Grant et al. 2007). Artificial wet reference surfaces were also used to standardize the wet reference against crop condition or spatial variability (Cohen et al., 2007; O'Shaughnessy and Evett, 2009).

Using a wet reference surface eliminates the need to pre-develop a well-watered baseline for each crop or variety. The wet reference evaporation varies with immediate weather conditions and so provides a site-specific, time-specific method for a non-stressed data point with which to compare actual crop surface temperatures. If the crop surface itself is wetted, the wetted surface then has the color, texture, and similar sunlight and shaded portions as the measurement areas of the crop. However, variability in color or density of crop surfaces can lead to problems in consistency of the wetted reference surface. Also, if a number of different crops or varieties are monitored, wetted canopy reference surfaces for each crop should be used.

The upper limit of the CWSI is theoretically the canopy minus air temperature value at any given vapor pressure deficit at which transpiration is zero. Idso et al (1981) described a method of finding an approximate upper limit. O'Shaughnessy and Evett (2009) documented an approach to the upper limit which used maximum daily air temperature plus 5 degrees C.

A method was needed to determine turf water status in comparative plots that was robust and quick. The CWSI approach of Idso et al (1981) is well-known, but not without drawbacks, chief of which was that a well-watered baseline was not available for our site and would have to be developed over time. The sources outlined in this section allowed us to develop an immediately usable technique that appears to be robust and relatively simple in its ancillary data requirements.

The 2009 test study at Northern Water compared applied water on a tall fescue spray-irrigated plot to applied water on an SDI tall fescue plot. The empirical CWSI (eCWSI) method of O'Shaughnessy and Evett (2009) was modified to monitor turf water status and independently verify that the irrigation schedules were maintaining the tall fescue at similar plant water status.

The purpose of this paper is to discuss the technique and to relate the eCWSI relationship to applied irrigation and soil moisture for spray and subsurface drip irrigated plots.

METHODS

Tall fescue was established in 2 plots in 2005. Each plot was wedge-shaped and 1400 sq ft in size. Fixed spray heads (4” pop-up sprinkler heads with 10’, 12’, and 15’ fixed spray nozzles) were installed in one plot. Subsurface drip tubing was installed in the second plot 5” below grade on 15” spacing. The dripline consisted of polyethylene pipe with internal emitters (0.26 gph) at 18” intervals. The soil type in the plots was amended silty clay. Turf was maintained at industry standards for best management practices. Each plot had a Baseline biSensor™ (soil moisture sensor) installed at the 8” depth. Flow meters measured water applied to each plot, and the spray plot had three rain gauges installed. Northern Water’s Berthoud onsite weather station independently monitored air temperature, solar radiation, wind speed, rainfall, soil temperature, and humidity.
Total rainfall from April-October 2009 was 14.4 inches. Irrigation water was applied at approximately 90% of ETo (standardized grass reference ET) for each plot. Initially soil moisture was the primary basis for irrigation occurrence.

The instrument used for measurement of crop temperature was a Scheduler Plant Stress Monitor (Standard Oil Engineered Materials Company). Although an older instrument, calibration checks indicated that it was still accurate. The Scheduler collects a variety of data and provides a variety of information. The only data used from the Scheduler was the canopy temperature value, which was manually recorded. Temperatures were converted to Celsius for calculation of the eCWSI. Time of data collection was also recorded.

A large separate plot of tall fescue, also seeded in 2005, was used for the wet reference. This plot was maintained at about 90% of ETo and monitored for its overall eCWSI status as well. The irrigation system in this plot was rotor heads at 30’ spacing.

The wet reference surface was established by spraying a 4’ by 4’ area with water from a hand-held sprayer, similar to Möller et al (2007) on grapevines. This method was chosen because it was 1) convenient and 2) in Möller et al (2007), the actual wetted plant canopy was least affected by any seasonal changes as it incorporated color and texture of the plant canopy into the wet reference temperature.

The turf wet reference temperature was obtained from each cardinal direction with the instrument held at a consistent angle and height by the user. From three to five complete data sets of the wet reference were collected. Because the data had to be collected sequentially and not simultaneously from each direction, data were collected until it was apparent that the surface was warming appreciably. It took approximately 2 minutes to complete each sequence of the cardinal directions. Care was taken to exclude shadows from the instrument or the user in the field of view.

During data analysis, the sequential wet reference datasets were scrutinized and measurements were eliminated during a short initial period during which the sprayed-on water would come into equilibrium with the grass surface. Data from the cardinal directions were averaged from the selected sequence or sequences and used as the lower limit of the eCWSI.

Three canopy temperature data points from each cardinal direction were collected in the spray and SDI plots between 1100 and 1200 MDT. Data collection was distributed throughout each plot and averaged into one canopy temperature value representative of the entire plot.

In order to calculate an eCWSI value on the same day as data collection, the National Weather Service (NWS) forecast high temperature for Berthoud, CO, obtained close to the time of data collection, was used to provide the daily maximum air temperature value required by the eCWSI calculation. Actual maximum daily air temperature at Northern Water's Berthoud weather station was obtained from the weather database on the following day and compared to the NWS forecast value.

The eCWSI is calculated by

$$eCWSI = (T_c - T_{wet})/[(T_{dry}) - T_{wet}] \quad (1)$$

$$T_{dry} = T_{max} + 5^oC \quad (2)$$

where T_c is the measured canopy temperature, T_{wet} is the measured wet reference temperature, and T_{max} is the NWS forecast or actual daily high air temperature. T_{dry} is the upper limit at which no transpiration occurs.

The eCWSI was used both as a turf water status monitor and as an irrigation trigger later in the season. Irrigations were not applied unless a plot exceeded about 0.2 eCWSI. This value is typical for keeping crops, including turf, at a well-watered state. Unfavorable weather conditions prevented data collection on many days, making it more difficult to keep turf conditions at comparable well-watered levels.

RESULTS AND DISCUSSION

Total irrigation applied to the SDI plot in 2009 was 16.1 inches, while 17.7 inches were applied to the spray plot (Figure 1).

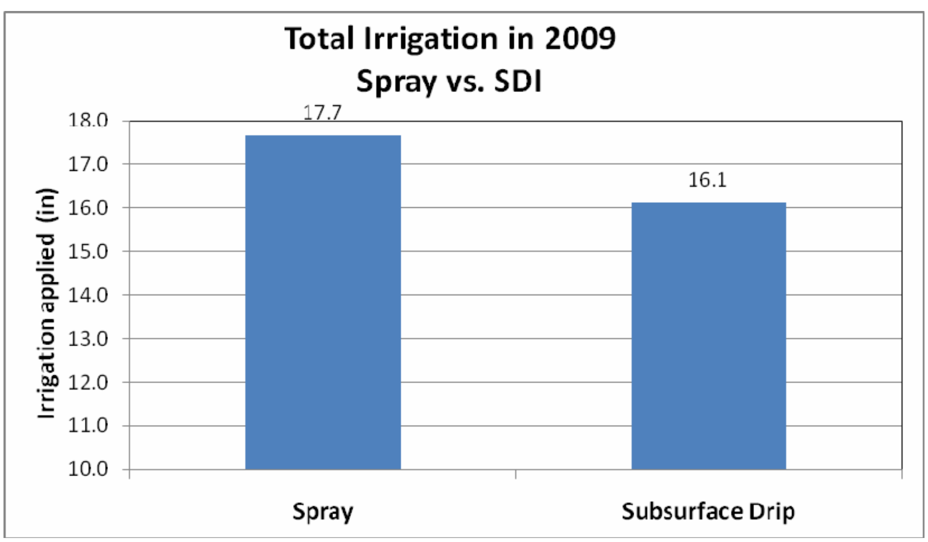

Figure 1. Total applied irrigation to tall fescue spray vs. SDI irrigated plots in 2009.

While the NWS forecast typically overestimated the actual high temperature value by a few degrees (Figure 2), the eCWSI values were accurate enough that they provided a good prediction of whether irrigation should occur (Figures 3 and 4).

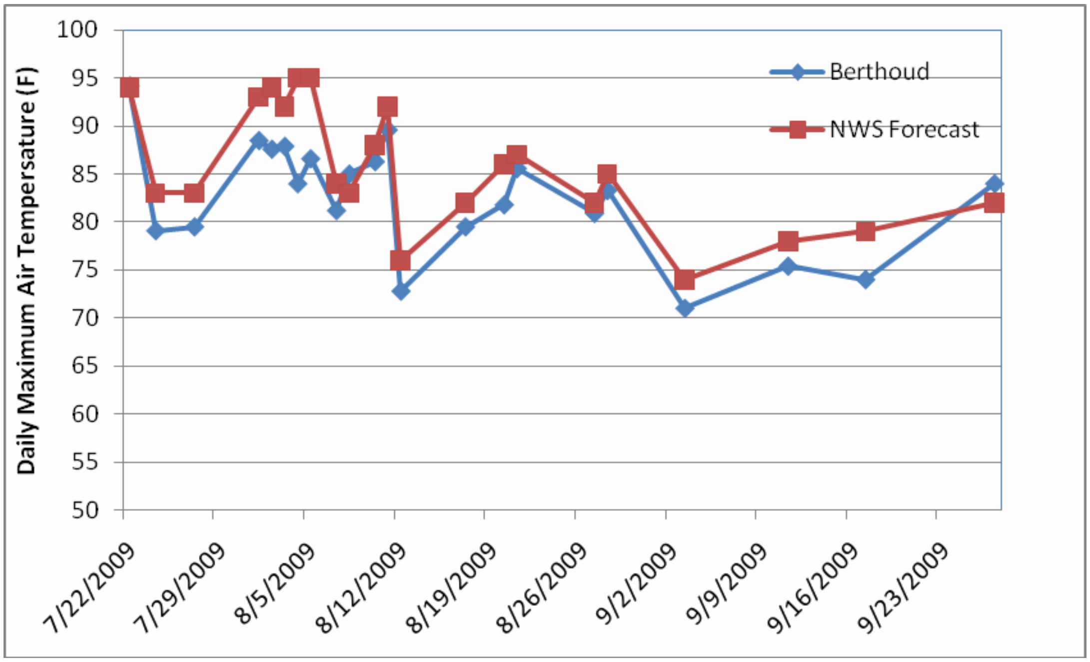

Figure 2. Comparison of NWS forecast daily high temperature and actual Berthoud daily maximum air temperature.

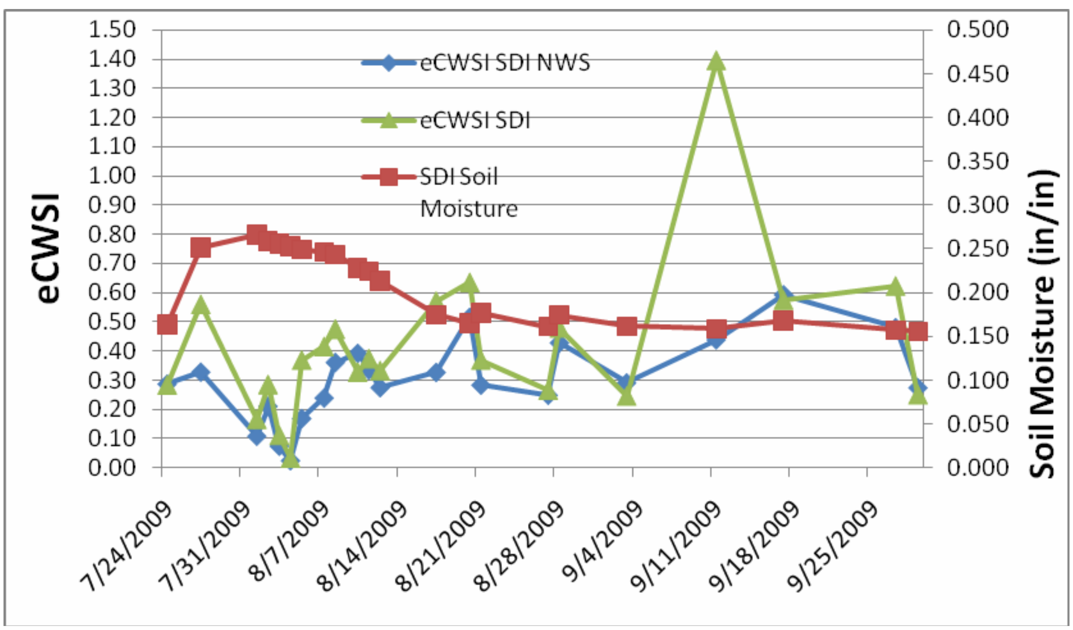

Figure 3. Comparison of eCWSI for SDI calculated with NWS forecast high and the actual Berthoud daily maximum temperature.

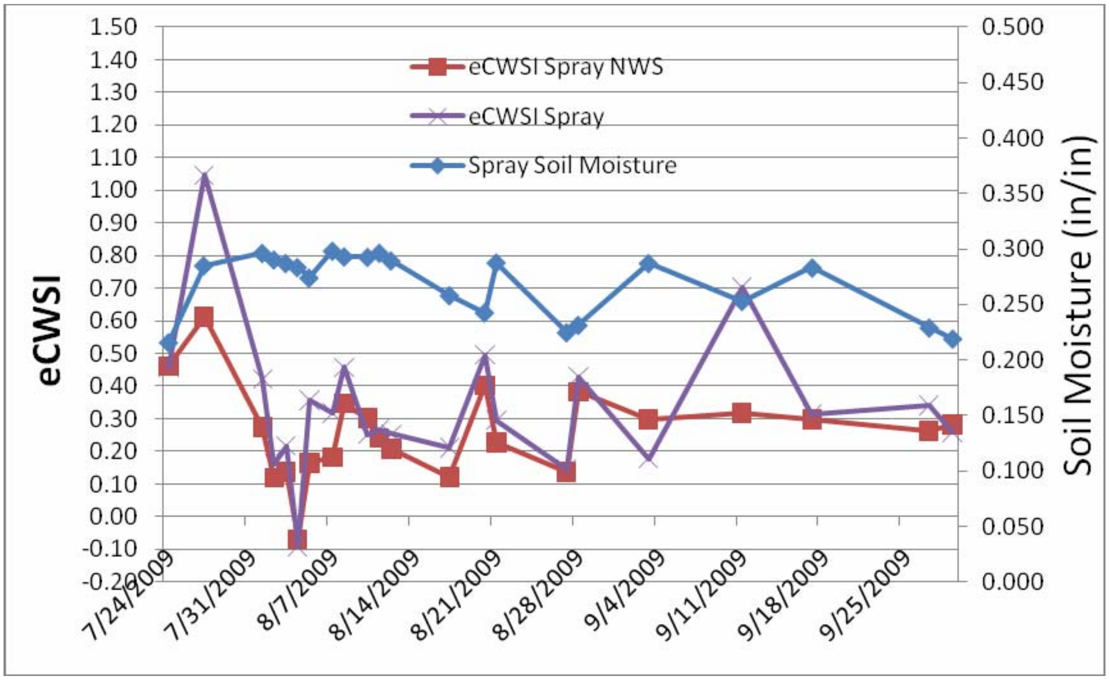

Figure 4. Comparison of eCWSI for spray irrigation calculated with NWS forecast high and the actual Berthoud daily maximum temperature.

The eCWSI values calculated with the NWS high and the Berthoud daily Tmax tracked well, with eCWSI in the SDI plot showing greater differences than the spray irrigated plot eCWSI for about a week in August. This corresponds with a larger difference between the NWS forecast and the Berthoud Tmax during the same period. On 27 July 2009 and 11 Sept 2009, there is a wide divergence of eCWSI values, with eCWSI based on the Berthoud Tmax ranging above 1.0, the zero transpiration upper limit. Because there is no concurrent change in soil moisture (Figures 3 and 4), the NWS value was considered to be the more accurate value to use in the eCWSI calculation.

Figures 3 and 4 generally validate the use of the NWS forecast high as a surrogate for an onsite daily maximum air temperature value if immediate decisions are required. Usually, the turf water status was evaluated on the same day as data collection and therefore the NWS forecast-based eCWSI value was used to make decisions and is shown in subsequent figures.

The eCWSI varied for the spray and SDI plots in 2009 (Figure 5). Well-watered conditions generally are indicated by an eCWSI of 0.2 or less. Negative values can occur during highly-variable environmental conditions during data collection, which contribute to variability in the turf surface temperature. The early data point for the SDI eCWSI reflects conditions after heavy rainfall. The SDI plot showed moderately high stress on July 24. This was likely because of saturated soils from heavy rains, which contributed to lower oxygen content in the soil. Lack of oxygen in soils can inhibit plant water uptake, leading to apparent water stress conditions. There is no data point for the spray-irrigated plot on July 24, as a storm front came in during data collection. In September, the SDI plot was not irrigated from September 15 through September 28 and became water stressed. The eCWSI on September 27 was used as a trigger for the September 28 irrigation. The amount applied was 90 percent of replacement ETo (grass reference ET) from the last irrigation date to the current date. The eCWSI value on September 29 showed that water stress on the SDI plot was relieved on that date.

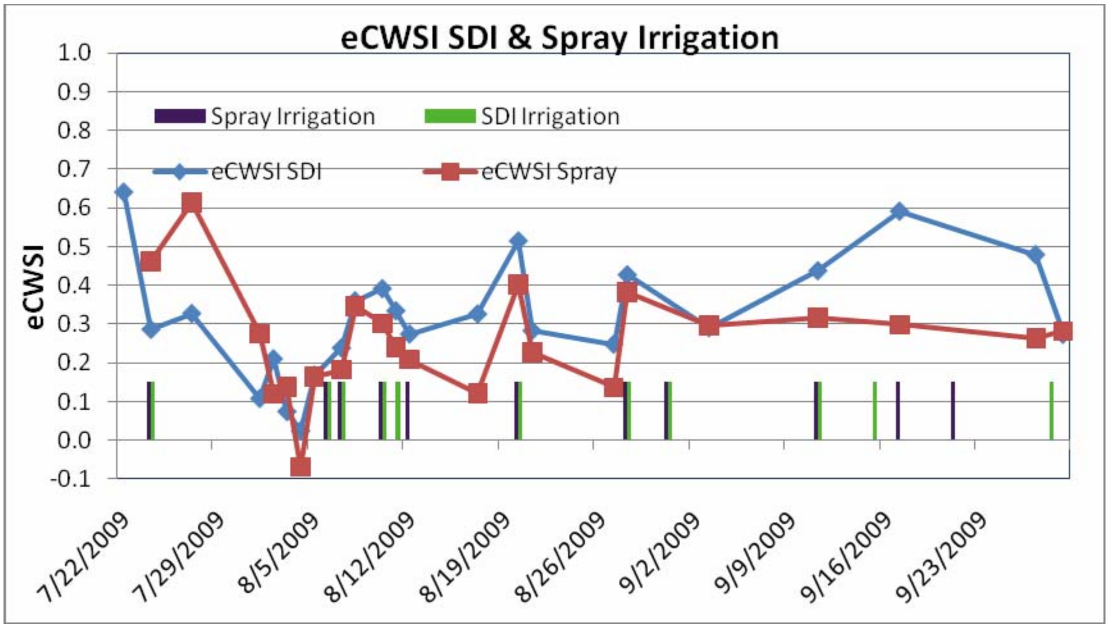

Figure 5. Spray and SDI eCWSI values for July –Sept 2009. Irrigation bars denote timing, not amount applied.

PLANS FOR 2010

Five Apogee SI 121 infrared thermometers were purchased in early 2010. These sensors will be mounted on a portable frame and connected to a datalogger. The frame will be constructed such that shadow effects are avoided and maximum field of view can be obtained. The frame-mounted sensors will be used to collect canopy temperature data in each of several studies at Northern Water. The wet reference technique will be modified to follow the technique of Möller (2007) and O'Shaughnessy and Evett (2009). Both used a wetted fabric surface floating in a shallow water reservoir as the wet reference. Changing to this technique will provide a standardized reference for several turf grasses. Time constraints and limited plant material preclude using the wetted turf itself as a wet reference for the various Northern Water turf studies.
The canopy temperature variability in the SDI vs. the spray plot will also be analysed. Some studies have shown that canopy temperature variability is an important consideration in whether a crop has become stressed.

One of the main studies that will be monitored is a Smart Controller comparison. Smart Controllers are designed to irrigate landscapes based on climatic data. The eCWSI will provide an independent measure of how well each Smart Controller performs. Another study will compare turf water status of 11 varieties irrigated with a line source irrigation system.

An commercial infrared thermometer purchased for less than $100 at a local hardware store will be tested. This instrument, while of lower accuracy than the instruments currently used, may prove to be effective in detecting turf water status and have utility in technology transfer to turf managers.

Data from 2010 will be included in the presentation.

SUMMARY

The eCWSI method was fairly easy to implement and interpret. The results are robust and provided a good method for monitoring turf water status. The on-the-spot, accessible methods considerably reduce the data requirements to produce a good eCWSI value, although with the wet reference technique used here, some user experience and discretion is necessary. Rapid and simultaneous logging of the wet reference surface temperature plus ancillary weather data may provide data for developing guidelines on selecting the best wet reference data for the eCWSI if using the wetted canopy technique.

Soil moisture changes tracked reasonably with the eCWSI, lending more confidence to the technique and its execution. Modifications and extensions of the technique will provide better turf water status information for the ongoing studies at Northern Water.

Total applied irrigation was higher for the spray plot than the SDI plot in 2009. However, the eCWSI for the SDI plot often was higher than the spray plot eCWSI, and the soil moisture values lower. More frequent data collection in 2010 and closer monitoring of the spray and SDI plots may improve the study results.

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TRAINING TOOL FOR ON-FARM WATER MANAGEMENT USING HEURISTIC SIMULATION SOFTWARE

Mohammed Z. Shaban[1]
Gary P. Merkley[2]

ABSTRACT

A modern computer-based simulation tool in the form of a game for on-farm water management has been developed for application in training events for farmers, irrigators, irrigation extension specialists, and students. This training tool can be used to analyze both strategic and operational issues related to the management of on-farm water resources, and automatic analysis of the results to provide feedback to the trainees. It utilizes an interactive framework, thereby allowing the trainee (or player) to develop scenarios and test alternatives in a convenient, risk-free environment. It employs heuristic capabilities in a simulation approach for modeling all of the important aspects of on-farm water management that are essential to effective planning.

The daily soil water balance, crop phenology, root development, and a seven-day weather forecast, can be monitored by the player throughout the simulated growing season. Different crop types, water delivery methods, and irrigation methods are made available to the player. Random events (both favorable and unfavorable) and different strategic decisions are included in the game for more realism and to provide potentially more challenging game play. Scoring and recommendations are provided at the end of the game, based on the management decisions made by the player.

INTRODUCTION

An understanding of agricultural water requirements is critical for resolving water resources issues. Worldwide, agriculture consumes approximately 70 percent of available water resources, with an estimated overall efficiency of only 30-40 percent (Molle and Berkoff 2006). The growing demands on existing water resources necessitates that the agricultural sector improve water management. Much of the emphasis and resources toward dealing with the water scarcity problems in recent years have been dedicated to infrastructure and technological improvements, as well as organizational and institutional changes. These measures alone are not enough to significantly improve water management. An extensive educational program can help improve on-farm water management.

Despite the current availability of abundant information, experience indicates that an educational program is necessary to teach the actors in the field of agricultural water how to manage their water resources in a better way. Very little has been done with regard to

[1] Research Assistant, Civil and Environmental Engrg. Dept., Utah State Univ., Logan, UT. m.shaban@aggiemail.usu.edu. Fax: (435) 797-1248. Telephone: (435) 797-2793.
[2] Professor, Civil and Environmental Engrg. Dept., Utah State Univ., Logan, UT. gary.merkley@usu.edu. Fax: (435) 797-1248. Telephone: (435) 797-1139.

improved training tools that can be used to promote more complete understanding of the problems faced by farmers and irrigators, and the difficulty of the operational decisions they face with respect to irrigation water management. Simply providing handouts and other written materials to them is insufficient. It may be more effective to teach them in what is called "learning based on experience" through a schematic version of reality, and observing the effects of their management decisions.

Games as Training Tools

Simulations and games have been valuable tools and teaching aids. This includes roles in research, education, and training. Games can be considered as effective decision support tools in which players become decision makers (Ubbels and Verhallen 2000, in Lankford et al. 2004). They can provide means to direct thinking, illustrate complex inter-relationships, adapt to extreme situations, and weigh priorities (Smith 1989; Kos and Prenosilova 1999; Clarke 2004).

Clarke (2004) listed the following elements that must be contained in a game: (1) Relevance: the game must be of interest to the trainee and reflect his/her needs; (2) Simplicity: the game should be presented in a simple and clear format; (3) Realism: the program should produce realistic results and applied recommendations; (4) Interaction: rapid response , different alternatives, and good use of visual effects will attract the player's interest; (5) Flexibility: the ability of the program to modify itself in response to the user needs; (6) Excitement: to be a game, the simulation should be stimulating; and, (7) Discussion: a group de-briefing discussion is recommended once the simulation is completed.

Irrigation Management Games

Several irrigation management games have been developed by different individuals and groups over the past few decades. Although each game has its own unique features, there is some degree of overlap among them. Examples of these games are: The Green Revolution Game, a role-playing game described by Chapman (1982) in Clarke (2004); the Juba Sugar Estate Game, a role-playing game described by Carter (1989); the River Basin Game, a board game described by Lankford et al. (2004); the Wye College Irrigation Game, called "Stop the Breach," which is a mixture of role-playing and computer-based games (Smith 1989); the Irrigation Management Game (classroom version), a role-playing game initiated in 1982 and described by Burton (1994); the Irrigation Management Game, a computer version of the Irrigation Management Game (Clarke 2004); and, Irrigation Management Simulation Game (Irrigame), a computer-based game (Parrish 1982).

Heuristic Simulation Software

There is a new concept regarding heuristic software in what is called "intelligent learning systems," which is defined as an approach to learning from observations. An important goal of many intelligent systems is dynamic personalization and adaptability to the player. Adaptability provides automatic customization of software to the player's needs based on sophisticated user modeling techniques. A system may be trained to recognize the behavior of an expert or novice user, and then it may adjust its dialogue control or help the system automatically match the needs of the current player (Vivou and Jain 2008).

In their book, Vivou and Jain (2008) reported that common approaches for incorporating intelligence in user interfaces include: probabilistic reasoning through Bayesian Networks; machine-learning algorithms; neural networks; case-based reasoning; and, cognitive reasoning or decision-making theories. Ram et al. (2007) discuss three Case-Based Reasoning (CBR) approaches for adaptive games: automatic behavior adaptation for believable characters, drama management and user modeling for interactive stories, and strategic planning behavior for real-time strategy games. Kaukoranta et al. (2010) discussed the use of a pattern recognition approach in the context of computer games and its task to extract relevant information from a game, and to construct concepts to form patterns from this information.

FEATURES OF THE GAME

The methodology of this project describes the design and development of a computer-based training tool in the form of a game that can be used to analyze both strategic and operational issues related to the management of irrigation water resources. It utilizes an interactive framework, thereby allowing the user to develop scenarios and test alternatives in a user-friendly environment. It employs heuristic capabilities in a simulation approach for modeling all of the important aspects of on-farm water management that are essential to effective strategic planning.

The game was developed using the Microsoft Visual Basic .NET programming language. The game has the following target audiences: farmers, irrigators, irrigation extension specialists, and students. Two levels of the software were developed to match different trainee requirements and interests.

The software consists of three models: the technical model, which is considered the "brain" of the game; the scenario-based model, representing the user-computer interface model; and, the scoring and recommendation model which provides an overall evaluation of the decisions taken by the player at the end of a simulated situation (Fig. 1).

The technical-based module uses a database containing the input data (parameters) which are provided to the program (software) by the player in the scenario-based model. The scenario-based module mathematically analyzes the decisions and reactions made by the player, based on the different events, and automatically composes a scenario-based (heuristic) simulation. Random events are generated according to the evaluation of the player by the artificial intelligence method encoded in the program (see heuristic simulation part). Based on the tactical decisions taken as a response to the different random events, a sequence of results is obtained. Processing a comparison between the results obtained from the scenario-based module with that obtained from the technical module (the reference results) enables the scoring and recommendations module to evaluate the decisions made by the player. In terms of results scoring, the player will have a certain set of goals or objectives to meet: maximize profit or maximize on-farm water use efficiency. The scoring results will be based on the achievement of these objectives. After a simulated irrigation season, the program summarizes the overall decision implications (scoring), and makes suggestions for improvement and/or other optimal scenarios.

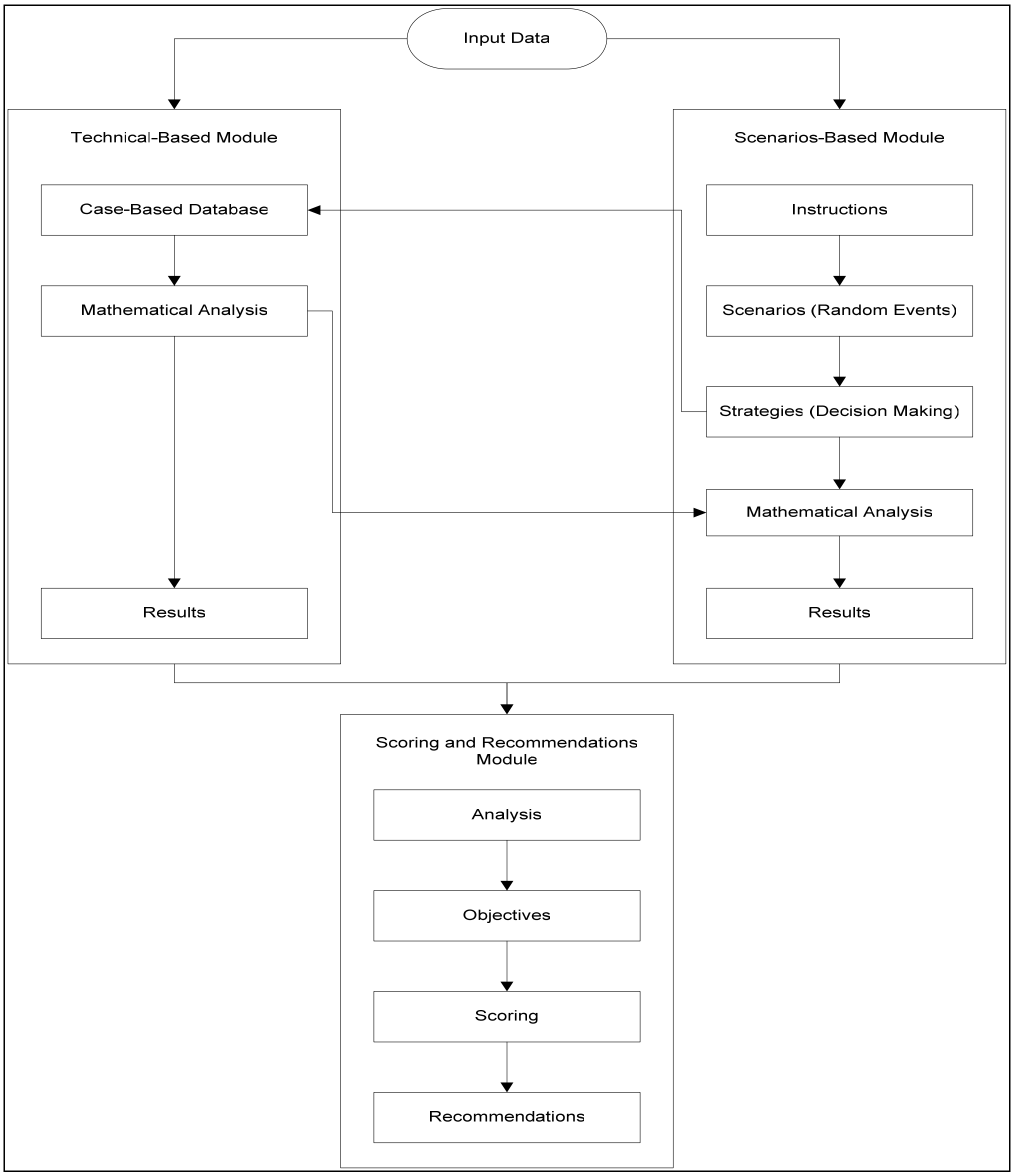

Figure 1. Schematic Diagram of the Simulation Model

Under the technical model (Fig. 2), a comprehensive sub-model has been developed which calculates soil water and salt balances in a crop root zone, and it uses a daily time step. The sub-model is described in detail in the following sections of this paper. The software includes the following options:

1. Distribution system delivery methods: fixed rotation, on-demand, and a modified demand schedule;
2. On-farm irrigation methods: surface, sprinkler, and localized (trickle); and,
3. Irrigation water quality: various salinity levels.

Random events (both favorable and unfavorable) and their effect on crop growth, phenological stage sensitivity, best management practices, and overall agricultural productivity and profitability, are also included in the software. The kinds of random events are: unexpected rain, sudden change in air temperature (weather), canal breaks/breaches, pipe bursts, pump/motor failures (water supply interruptions), unexpected increases in the available water supply (when it was previously constrained), sudden changes in agricultural market conditions (crop prices), sudden failure of the on-farm irrigation system, temporary electrical outages, labor strikes, water theft (effect on quantity and pressure), problems with water drainage, unexpected additional water requirements from non-agricultural sectors, and salinity and other water quality problems.

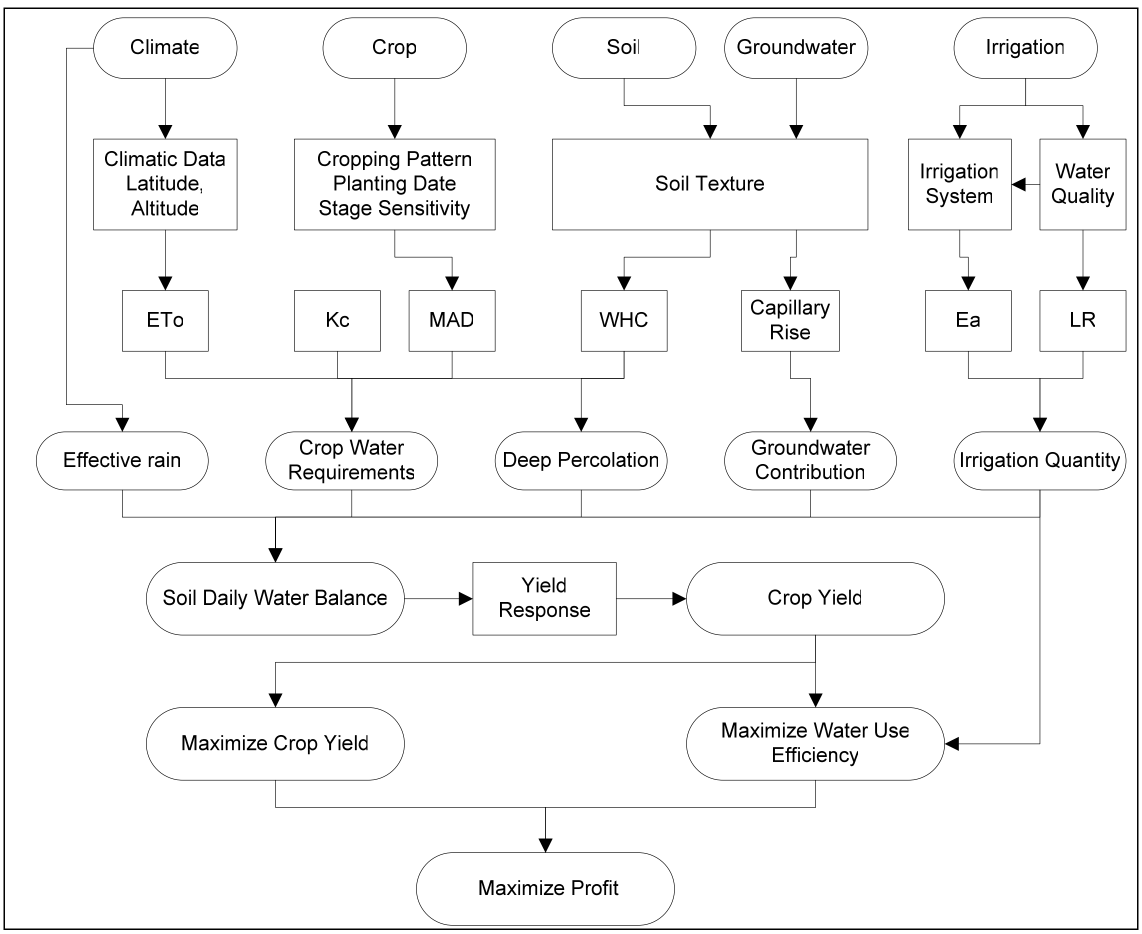

Figure 2. Schematic of the Technical Model

The game has various options for making strategic management decisions. For example, the player can choose to invest in system maintenance, water well development, a better on-farm irrigation method, or a drainage system. The software also gives the player the option to purchase additional water shares (quantity) from other water users, if available, or to sell unused water to other users.

Computer-User Interface

At the beginning of the game, the player is asked to choose one of the two proficiency levels offered by the game: beginner or professional. After this, a new window for data input appears, based on his/her choice.

In the data input window, the player is asked to select the desired climatic zone. The player has the following climatic-zone options based on Keoppen's climate classification (FAO 2010): tropical moist, wet-dry tropical, dry tropical, dry-mid latitude (steppe), Mediterranean, dry-mid latitude (grassland), and moist continental climatic zone.

The planted crop(s) can be chosen from a list of 26 different crop types as found in Doorenbos and Kassam (1979). The player can choose from five different on-farm irrigation methods: furrow, border, basin, solid-set sprinkler, and drip irrigation. The player can also choose from one of three water delivery options: on-demand, modified demand, and fixed rotation. Crop phenology, such as initial and maximum root depths, crop spacing, crop harvesting date, potential productivity (crop yield), market price of the product, and threshold soil water salinity (ECe) are fixed by the program. The cost of the irrigation method, the cost of agronomic inputs and labor, the delivery system flow rate, water table depth, and irrigation supply and groundwater salinities are also set by the program.

In the beginner level, the game allows the player to manage a 40-ha farm consisting of four different fields and a single crop type. The player is allowed to choose one on-farm irrigation method for all four fields. If the player decides to irrigate part of the farm due to water shortage or for any other reason, he/she has the option of choosing which fields are to be irrigated at each potential irrigation event. The player has the option of specifying the planting dates, but the harvest date is set by the game, as mentioned above.

In the professional level, the player will be asked to manage a 200-ha farm, with five different plots. Each plot consists of four different fields. The player has the ability to choose a different on-farm irrigation method for each plot and five different crops for the whole farm, or one crop with different planting dates. Different water sources can be used alternatively during the cropping season with the limitation of one source per irrigation. The player has the option to choose the irrigated plot and to determine the irrigated field within each plot at the beginning of each irrigation event (this option is given in the simulation window).

After completing the data input tasks, the simulation window is displayed in which the computer-player interaction starts and the artificial intelligence coding method is activated, based on the level chosen by the player. In this window, the total available water for the entire season is specified by the program, with the option of increasing/decreasing this quantity by certain random events which may or may not occur. The daily available water quantity for the remainder of the season is schematically made available to the player. A seven-day weather forecast, options for irrigation water quantity, flow rate, and different water source options (with information about the respective salinities) are made available for the player to make management decisions. Random events which are dependent upon the chosen level will appear during the simulation. Evaluation of the player's performance by the game's artificial intelligence system will occur based on the player's reactions to the random events and the management decisions he/she has made. The generation of random events is adjusted dynamically by the program to meet player capabilities. The intelligent system evaluation results in several hints to lead the player toward better management decisions in subsequent simulation events.

A dynamic sketch which shows the daily cropping conditions, based on the decisions taken by the player, is continuously presented in the simulation window. The sketch includes information about daily soil water balance, soil water excess or shortage, daily plant and root growth, plant growth conditions; whether the crop is performing well or shows symptoms of stress; whether the crop is still alive or has died; and so on.

After the end of the planting season, the game will display the final window. In this window, an economic analysis of the cropping season will be processed based on the crop yield, production cost, and on-farm water use indicators. A final score based on the overall consequences of the decisions which were made, in addition to recommendations for management improvements, are presented to the player.

Heuristic Simulation

To be an adaptive game, there are set of rules in the program which capture subtle variations of the user’s responses and behavior when face with a specific problem or decision, and these rules are used to modify the game environment. The heuristic features of the program were developed based on a combination of two artificial intelligence approaches: (1) a pattern recognition approach; and, (2) a case-based reasoning approach.

The task of pattern recognition system is to extract information from the game world (management decisions and player actions), group the information into classes of similar patterns, and forward this information to the decision-making system. The pattern recognition part of the program is responsible for developing a player module by clustering the player decisions and classifies them into a pattern class. Based on the forwarded information, the case-based reasoning system, which is the decision-making system, has the responsibility to choose the appropriate action based on the set of possible actions allowed by the game environment.

Water Balance Sub-Model

This sub-model considered the main part of the technical model of the game. It simulates the field soil water and salinity balances on a daily basis and predicts; crop growth, consumptive use, weather conditions, salinity, and relative yield response to irrigation events. Thus, the model monitors the irrigation scheduling program and its effect on crop conditions and productivity.

Various parameters that affect the daily soil and salt water balance are considered, such as: depth of applied irrigation water, depth of precipitation, groundwater contribution, evapotranspiration, deep percolation, and surface runoff.

Calculations of water balance are based on the following equation (Allen et al., 1998):

$$Dr_{EndofDay}(J) = Dr_{BeginningofDay}(J) - P_{net}(J) - I_{net}(J) - GW_{net}(J) + ET_a(J) + DP_a(J) \qquad \text{Eq.(1)}$$

where J is the day of the year; $Dr_{EndofDay}(J)$ is the depth of water depletion in the root zone at the end of day J; $Dr_{BeginningofDay}(J)$ is the depth of water depletion in the root zone at the beginning of day J; $P_{net}(J)$ is the actual amount of precipitation that enters the root zone during day J; $I_{net}(J)$ is the amount of irrigation water that infiltrates into the soil during day J; $GW_{net}(J)$ is the amount of groundwater contribution in the root zone area during day J; $ET_a(J)$ is the actual depth of crop evapotranspiration during day J; and, $DP_a(J)$ is the actual depth of water deep-percolated below the root zone during day J. All terms in Eq. (1) have units of millimeters.

Simplified assumptions were made to estimate all parameters in Eq. (1). These assumptions are as follows:

- The soil profile is homogeneous (in both texture and structure) throughout the root zone and has only one soil layer. Therefore, soil water content and salt concentration is uniform throughout the depth of the root zone for each 24-h simulation interval.
- Soil water depletion at the beginning of the planting day is assumed to be zero, and the soil water content at this time is at field capacity.
- The depth to the water table is taken to be independent of internal variables such as deep percolation or capillary rise.
- Lateral flow of soil water between adjacent fields is considered to be negligible.
- If irrigation, precipitation, and groundwater contributions all enter the crop root zone in any given day of a simulation, it is assumed that the groundwater contribution occurs first, followed by irrigation, and finally by precipitation.

- One or both of the following variables must be zero in each day of a simulation: net deep percolation from the root zone, and net groundwater contribution to the root zone.

Root depth (R_z): If there is no barrier (e.g. water table or hard pan) within the root zone, the daily root depth is calculated by assuming that the rate of daily root growth is constant and increases linearly from the date of planting. The daily root depth can be calculated using the following equation (Prajamwong et al., 1997):

$$R_z(J) = R_z(J-1) + \frac{(R_z)_{max} - R_z(J-1)}{J_{full\,cover} - J_{planting}} \quad \text{Eq.(2)}$$

where $R_z(J-1)$ is the root depth at the previous day, $(R_z)_{max}$ is the maximum root depth of the specific crop, usually reached at the end of the development growth stage; and, $J_{planting}$ is the planting day.

The sub-model will not allow the root depth to exceed the maximum reported root depth for the specific crop. Also, in calculating the root depth, the sub-model considers the groundwater table. If the bottom of the root zone is at the water table, there will be no root growth during that day. Likewise, there will not be any root growth if the water table is inside the root zone. If any portion of the root zone stays within groundwater table for more than three days, that portion will die.

The sub-model also considers whether the part of the root that atrophied due to saturated soil water conditions will grow back or not based on the crop growth stage. Also, if groundwater table is reached the ground surface for more than three days, the crop will die and there will be no need for further calculations of water and salt balance. The one exception considered herein is that of rice, which can survive fully saturated root-zone conditions.

Actual crop consumptive use (ET_a): The daily actual consumptive use is calculated based on the following equation:

$$ET_a = K_s K_e K_c ET_o \quad \text{Eq.(3)}$$

where K_s is used to account for the effect of soil water stress due to water shortage in the root zone, K_e is coefficient to reduce ET due to salinity; ET_o is the grass reference evapotranspiration (mm/day), calculated using the Penman-Monteith equation; and, K_c is the crop coefficient, a function of growth stage (Allen et al., 1998).

The climatic data to calculate ET_o are included in the software. The player must choose from one of seven climatic zones. Under each climatic zone, different sets of climatic data are included, and the software will choose one randomly. To estimate K_c on a daily basis, the following equations were used (Allen et al., 1998):

$$K_c(J) = K_{c_{prev}} + \left(K_{c_{next}} - K_{c_{prerv}}\right)\left(\frac{J_c - \sum L_{prev}}{L_{stage}}\right) \qquad \text{Eq.(4)}$$

where J_c is day number within the growing season; $K_{c_{prev}}$ is crop coefficient for the previous growth stage; $K_{c_{next}}$ is crop coefficient for the next growth stage; $\sum L_{prev}$ is sum of the length of all previous stages (days); and, L_{stage} is length of the stage under consideration (days).

The soil water and salinity stress factor, K_s, is calculated using the following equation (Allen et al., 1998):

$$K_s(J) = \left[1 - \frac{b}{100K_y}\left(EC_e(J) - EC_{threshold}\right)\right]\left[\left(\frac{TAW(J) - D_r(J)}{TAW(J) - RAW(J)}\right)\right] \qquad \text{Eq.(5)}$$

The first part of the equation represents the effect of the stress due to soil water salinity, while the second part represents the effect of the stress due to water deficit.

TAW is total available water in root zone (mm); *RAW* is readily-available water (mm); *b* is the reduction in crop yield per increase in EC_e *(%/dSm^{-1})*; $EC_{threshold}$ is the electrical conductivity of the saturation extract at the threshold when crop yield first reduces below the potential crop yield (*dS/m*); and, K_y is a yield response factor.

<u>Ground water contribution (*GW*):</u> The sub-model will check the depth of the groundwater table (*GWT*). If the water table is not inside the root zone, the groundwater contribution can affect the plant only if capillary rise from the groundwater table reaches the bottom of the root zone (Table 1). An average of the values is considered in the model for each textural classification.

Table 1. Capillary rise values for various soil types (FAO 2010).

Soil Texture	Capillary Rise (cm)
Coarse	20 to 50 cm
Medium	50 to 80 cm
Fine	more than 80 cm (up to several meters)

The groundwater contribution is the up-flux due to capillarity from the water table (m/day) and can be calculated based on Darcy's Law (Eching et al., 1994):

$$GW = -K(\theta)\frac{\partial h(\theta)}{\partial Z} = \frac{h(\theta)}{GWT} \qquad \text{Eq.(6)}$$

where $K(\theta)$ is the unsaturated hydraulic conductivity (m/day); *GWT* is the depth to the water table from the ground surface (m); and, *h* is the soil water head (m).

Unsaturated hydraulic conductivity is calculated as follows (Eching et al., 1994):

$$K(\theta) = K_{sat}\left[\frac{\theta(J)-\theta_r}{\theta_s-\theta r}\right]^{0.5}\left[1-(1-\left[\frac{\theta(J)-\theta_r}{\theta_s-\theta_r}\right]^{1/m})^m\right]^2 \qquad \text{Eq.(7)}$$

Where θ_r is residual soil water content (m^3/m^3); θ_s is saturated soil water content (m^3/m^3); K_{sat} is the saturated hydraulic conductivity (m/day); and, *m* is an empirical parameter, defined as follows:

$$m = 1 - \frac{1}{n} \qquad \text{Eq.(8)}$$

where *n* is also an empirical parameter, and is defined in Table 2; and, *h* is soil water head, and is calculated as follows (Raes 2009):

$$h(\theta) = \left(\frac{1}{\alpha}\left[\frac{\theta_s-\theta_r}{\theta(J)-\theta_r}-1\right]^{1/m}\right)^{1/n} \qquad \text{Eq.(9)}$$

Table 2. Class average values of Van Genuchten water retention parameters (Schaap et al., 1999).

Soil Type	***n***	***α*** **(m^{-1})**	**θ_s(m^3/m^3)**	**θ_r(m^3/m^3)**
Sand	3.18	0.035	0.375	0.053
Loam	1.48	0.0098	0.4	0.062
Clay	1.27	0.011	0.457	0.1

Amount of irrigation water (*Inet*): Based on the chosen on-farm irrigation method, the sub-model calculates the net amount of irrigation water that enters the soil profile. For basin irrigation, the total amount of irrigation water has the potential to enter the soil profile, with no surface runoff losses. The sub-model checks if the amount of total irrigation water is enough to saturate the soil. If it does, it means there will be some extra water, which will be stored on the soil surface as ponded water. The ponded water might take more than one day to infiltrate in the soil. The sub-model accounts for this and calculates the depth (which may be zero) of ponded water on a daily basis.

With furrow, border, sprinkler, and drip irrigation methods, no ponded water is allowed to remain on the soil surface. Also, not all of the irrigation water will infiltrate the soil even if the amount of water is less than the amount required to bring the water content to saturation. Some of the irrigation water will be lost from the field due to runoff. The amount of runoff is estimated as a fraction of the total irrigation water (p). The fraction was decided based on information from Walker (2010) and is presented in Table 3.

Table 3: Fraction of total irrigation water lost as runoff.

Soil Texture	**Irrigation Method**	**p**
Coarse	Furrow	0.1
Coarse	Border	0.1
Coarse	Drip	0.0
Coarse	Sprinkler	0.01
Medium	Furrow	0.2
Medium	Border	0.15
Medium	Drip	0.0
Medium	Sprinkler	0.02
Fine	Furrow	0.3
Fine	Border	0.2
Fine	Drip	0.0
Fine	Sprinkler	0.05

Amount of precipitation water (Pnet): The calculation of the amount of precipitation water follows the same reasoning as the calculation of the net irrigation that enters the soil profile, taking into consideration the irrigation method used. But, instead of taking the runoff quantity as a fraction (percentage) from the total precipitation, the sub-model calculates the effective precipitation by following the FAO-AGLW approach, after adapting it for daily calculations (Smith 1998):

$$P_{eff} = 0.6P_{total} - \frac{10}{30}; P_{total} \leq \frac{70}{30} mm \qquad \text{Eq.(10)}$$

$$P_{eff} = 0.8P_{total} - \frac{25}{30}; P_{total} > \frac{70}{30} mm \qquad \text{Eq.(11)}$$

where P_{eff} is the amount of effective precipitation, which is the amount of precipitation that infiltrates the soil at the surface.

Deep Percolation (*DP*): If the soil water content in the root zone is more than the field capacity there will be some amount of water deep percolated at the bottom of the root zone, and it is considered in the sub-model. The deep percolation potential (*DPp*) is the amount of water that could potentially percolate below the root zone (which includes the soil water content above field capacity and any extra water on the soil surface).

Since only a specific amount of water can percolate below the root zone, according to the soil texture, not all the deep percolation potential can leave the root zone in one day. The sub-model will define the maximum amount of water that can be deep percolated in one day. For the normal range of agricultural soil textures, it will take 1 to 4 days for the extra water (above field capacity) to drain from the root zone due to gravity (Hargreaves and Merkley 1998). The sub-model considers 3 days for heavy soils, 2 days for medium soils, and 1 day for light soil textures.

Due to actual deep percolation of soil water below the root zone, the soil moisture content will change and must be recalculated as follows:

$$\theta(J) = \theta(J) - \frac{DP_a(J)}{1000 R_z(J)} \qquad \text{Eq.(12)}$$

where R_z is in *m*.

Salt Balance Calculation

When large amount of water percolates below root zone, a change in the salt concentration in the soil profile is expected to occur. Therefore, the root-zone salt balance is calculated on a daily basis in order to determine the daily EC_e in the root-zone. The sub-model calculating root-zone salt balance is based on the following concept:

$$S_{today} = S_{yesterday} + \Delta S \qquad \text{Eq.(13)}$$

where ΔS is the change in salt mass in the root zone.

The sub-model will start with an initial value of EC_e on the day of planting. The initial value for soil water salinity, (EC_{sw}) is calculated based on the daily soil moisture content by using the following equation:

$$EC_{sw}(J) = EC_e(J)\frac{\theta_s}{\theta(J)} \qquad \text{Eq.(14)}$$

where θ_s, and $\theta(J)$ are soil water content at saturation and the actual water content, respectively, on a given day.

Accordingly, the salt content in the soil in root zone (S) can be calculated as:

$$S(J) = 0.64 EC_e(J) R_z(J) \qquad \text{Eq.(15)}$$

where S is in kg/m^2; and, EC_e is in dS/m. The constant 0.64 is a conversion factor. The calculations are performed for a day other than the planting day, and according to a salt mass balance:

$$S(J) = S(J-1) + \Delta S(J-1) \qquad \text{Eq.(16)}$$

The change in salt mass calculations occurs based on the calculation of the root-zone water balance components; net irrigation water, ground water contribution quantity, or amount of deep percolation, and the salinity of these components as follows:

$$\Delta S(J) = 6.4(10^{-4})\left[I_{net}(J)EC_i(J) + GW_{net}(J)EC_{gw}(J) - DP_a(J)EC_{dp}(J)\right] \qquad \text{Eq.(17)}$$

The constant $6.4(10^{-4})$ is used for conversion of units, and ΔS is in kg/m^2. The amount of drainage water salinity is calculated, based on the following assumption (Ayers and Westcott 1994):

$$EC_{dp}(J) = 2EC_e(J) \qquad \text{Eq.(18)}$$

Since the calculations are performed on a daily basis, root depth is potentially changing every day. Therefore, the change in root depth should be considered in the salt mass balance equation. The daily salt content is calculated as follows:

$$S(J) = \left(S(J-1) + \Delta S(J-1)\right)\frac{R_z(J)}{R_z(J-1)} \qquad \text{Eq.(19)}$$

And, the average soil saturated extract salinity will be:

$$EC_e(J) = \frac{S(J)}{0.64R_z(J)} \qquad \text{Eq.(20)}$$

<u>Yield Response (Ky):</u> Crop yield is predicted in terms of the relative value with respect to potential crop yield. The relative crop yield is estimated by the sub-model by considering possible yield reduction due to root-zone water deficit and salinity stress. The relative yield reduction can be calculated at the end of the season using the following equation (Stewart et al. 1977):

$$\frac{Y_a}{Y_m} = 1 - K_y\left(1 - \frac{ET_a}{ET_c}\right) \qquad \text{Eq.(21)}$$

where Y_a is the actual harvested yield; Y_m is the maximum potential harvested yield; K_y is a yield response factor; and, ET_c is the maximum evapotranspiration under ideal growing conditions (mm), equal to K_c. ET_o.

SUMMARY AND CONCLUSIONS

A computer-based training tool in the form of a game was developed to be used in training events for farmers and irrigators on irrigation water management. It analyzes both strategic and operational issues related to the management of irrigation water resources. It utilizes an interactive framework, thereby allowing the user to develop scenarios and test alternatives in a user-friendly environment. It employs heuristic capabilities in a simulation approach for modeling all of the important aspects of on-farm water management that are essential to effective strategic planning.

Through intelligent and heuristic simulation tools in the form of a game in which the effect of decisions can be visualized, a great deal of understanding of the parameter and variable interrelationships for a variety of situations can be attained in a much shorter time that it would take by field experience alone. This understanding can lead directly to improvements in on-farm water management.

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WATER PRODUCTION FUNCTIONS FOR HIGH PLAINS CROPS

Thomas J. Trout[1]
Walter Bausch[2]
Gerald Buchleiter[3]

ABSTRACT

Increasing demands on limited water supplies will require maximizing crop production per unit water. Field studies are being carried out near Greeley, Colorado to develop water production functions for crops grown in the Great Plains. These yield per unit water relationships can be used to determine if deficit irrigation is economically desirable and how to best manage limited water supplies. A field facility, the Limited Irrigation Research Farm, was developed specifically to carry out limited irrigation research. Irrigation water is applied through drip irrigation systems; precipitation and reference evapotranspiration (ET) is measured with a weather station; soil water content is measured with time-domain reflectometry (TDR) and neutron probes; canopy temperatures are monitored; and growth, ground cover, biomass, and yields are measured. Yields are related to irrigation applications, crop ET, and crop transpiration. Initial results with corn, sunflower, wheat, and dry beans show linear relationships between yield and crop ET and transpiration.

BACKGROUND

Past studies have shown that the reduction in yield with deficit irrigation is usually less than the reduction in irrigation water applied - for example, a 30% reduction in irrigation results in only a 10% reduction in yield. This means the marginal productivity of irrigation water applied tends to be low when water application is near full irrigation. This results either from increased efficiency of water applications (less deep percolation, runoff, and evaporation losses from irrigation and better use of precipitation) with deficit irrigation, or from a physiological response in plants that increases productivity per unit water consumed when water is limited. Economically managing limited water supplies may involve deficit irrigation rather than reducing acreage. Likewise, if water supplies can be transferred or sold for other uses and the value is higher than the value of using the water to produce maximum yields, selling the water can increase the farm income.

In Colorado, there is continuing need for additional water supplies for growing cities, groundwater augmentation, and environmental restoration. This water is usually purchased from agriculture through “buy and dry” – purchasing the water rights and fallowing the land. Limited irrigation may be an alternative way to provide for other water needs while sustaining productive agriculture. However, in fully allocated basins where one farmer’s return flows becomes water supplies for downstream users, only the

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[1] USDA-ARS Water Management Research, 2150 Centre Ave., Ft. Collins, CO 80526. Thomas.trout@ars.usda.gov
[2] USDA-ARS Water Management Research, 2150 Centre Ave., Ft. Collins, CO 80526
[3] USDA-ARS Water Management Research, 2150 Centre Ave., Ft. Collins, CO 80526

consumed portion of irrigation supplies – that lost to evapotranspiration - can be sold and the return flows must be maintained. Thus, it becomes critical to evaluate limited irrigation based on reductions in water consumptive use (CU) or equivalently, evapotranspiration (ET) rather than irrigation applications.

Improved irrigation efficiency is not likely to produce much transferable water because it results primarily in a reduction of return flows rather than a reduction in ET. If significant transferable water is to be produced by deficit irrigation, it must result from reduced ET. For deficit irrigation to provide economic benefits to growers, it must result in improved efficiency of the crop to convert ET to yield. Thus, the "maximize crop per drop" slogan must in reality be to maximize crop per consumptively used drop.

Although many limited irrigation studies have been carried out in the high plains and around the world, we feel there continues to be a need for more information on crop responses to deficit irrigation. So, in 2008, USDA-ARS began a field study of the water productivity of 4 high plains crops – corn, dry beans, wheat, and sunflower - under a wide range of irrigation levels from fully irrigated to rainfed. We are measuring ET of the crops under each of these conditions. We also strive to better understand and predict the responses of the crops to deficit irrigation so that limited irrigation water can be scheduled and managed to maximize yields.

THE LIMITED IRRIGATION RESEARCH FARM - LIRF

A 50 acre research farm northeast of Greeley, CO was developed to enable the precision water control and field measurements required to accurately measure ET of field crops. The farm, originally known as the Potato Research Farm and later as the Northern Colorado Research and Demonstration Center had been operated collaboratively by CSU and ARS for many years (in the 1980s, Harold Duke and students conducted surge irrigation trials there), but had not been in active research for over 20 years. The predominately sandy-loam soils and good groundwater well are ideal for irrigation research.

Four crops – winter wheat, field corn, sunflower (oil), and dry beans (pinto) are rotated through research fields on the farm. Crops are planted, fertilized, and managed for maximum production under fully irrigated conditions, but are irrigated at 6 levels that range from fully irrigated to only 40% of the fully irrigated amount. Deficit irrigations are timed to maximize production – usually by allowing relatively higher stress during early vegetative and late maturity stages and applying extra water to reduce stress during reproductive stages.

We apply irrigation water with drip irrigation tubes placed on the soil surface in each row. In this way we can accurately measure applications and know that the water is applied uniformly. This is essential to be able to complete the water balance. Water applied to each irrigation plot is measured with flow meters. Four crops, six irrigation levels, and 4 replications result in 96 individual plots.

A CoAgMet (Colorado Agricultural Meteorological Network) automated weather station is located on the farm near the center of a one acre grass plot. Hourly weather data from the station are used to calculate ASCE Standardized Penman-Monteith alfalfa reference evapotranspiration (ETr). Soil water content between 6 inches and 6 ft depth is measured by a neutron probe from an access tube in the center of each plot. Soil water content in the surface 6 inches is measured with a portable TDR system. Irrigations are scheduled using both predicted soil water depletions based on ETr estimations, and measured soil water depletion.

Plant measurements are taken periodically to determine crop responses to the water levels. We record plant growth stage and measure canopy cover with digital cameras. The digital cameras along with spectral radiometers and an infrared thermometer are mounted on a "high boy" mobile platform and driven through the plots weekly. Indicators of crop water stress such as stomatal conductance, canopy temperature, and leaf water potential are measured periodically. At the end of the season, seed yield and quality as well as total biomass are measured from each plot. On one field on the farm, crop ET is measured with energy balance instruments (Bowen Ratio method) for well-watered crops. These measurements allow crop coefficients to be estimated for the crops. On other fields on the farm, we are cooperating with CSU faculty to test wheat and dry bean varieties under varying irrigation levels.

An important part of the research is to extend the results beyond the climate and soils at LIRF. We are working with the ARS Agricultural Systems Research group to use this field data to improve and validate crop models. Once we have confidence in the models, we can estimate crop water use and yields over a wide range of conditions.

RESULTS

This project began in 2008. We will summarize the first two years of corn results in this article. Figure 1 shows the yield:water relationship for corn for each year. Irrigation applications (the lines on the left side in the figure) varied from about 430 mm (17") for the fully irrigated crop down to 120 mm (5"). When precipitation is added (about 230 mm (9") each growing season), deep percolation below the root zone is subtracted, and depletion of stored soil water is included, the remaining evapotranspiration for the crops varied from about 590 mm (23") down to 380 mm (15"). Of that ET, about 60 – 90 mm was evaporation from the soil surface and the remainder was transpiration through the plants. Soil evaporation would be higher with sprinkler or furrow irrigation. Irrigations were timed such that plant water stress for the deficit irrigation levels was least between tasseling and soft dough (growth stages VT to R4).

The top (red) data in the figure are total above ground biomass (dry weight) and the bottom lines (blue) are grain yields. Grain yields varied from 13 Mg/ha (200 bu/ac) at full irrigation down to 6 Mg/ha (100 bu/ac) and biomass was about double grain yields. Hail damage in 2009 resulted in about 15% lower grain yields but little difference in total biomass. Harvest index (the portion of total biomass that is grain) ranged from 50 – 60% and did not vary with irrigation level.

The water production function for grain (blue lines) based on applied irrigation water curves downward as the water application decreases, showing that the decrease in yield for each unit decrease in water applied is relatively small when the deficit is small, but the rate of yield decrease gets larger as the deficit increases. This means that the marginal value of irrigation water is relatively low near full irrigation, showing the potential benefit to the farmer of transferring water to higher-valued uses. The marginal value of water increases from about 1.3 kg/m^3 (60 bu/ac-ft) of water applied near full irrigation to 3 kg/m^3 (150 bu/ac-ft) at the lowest irrigation level.

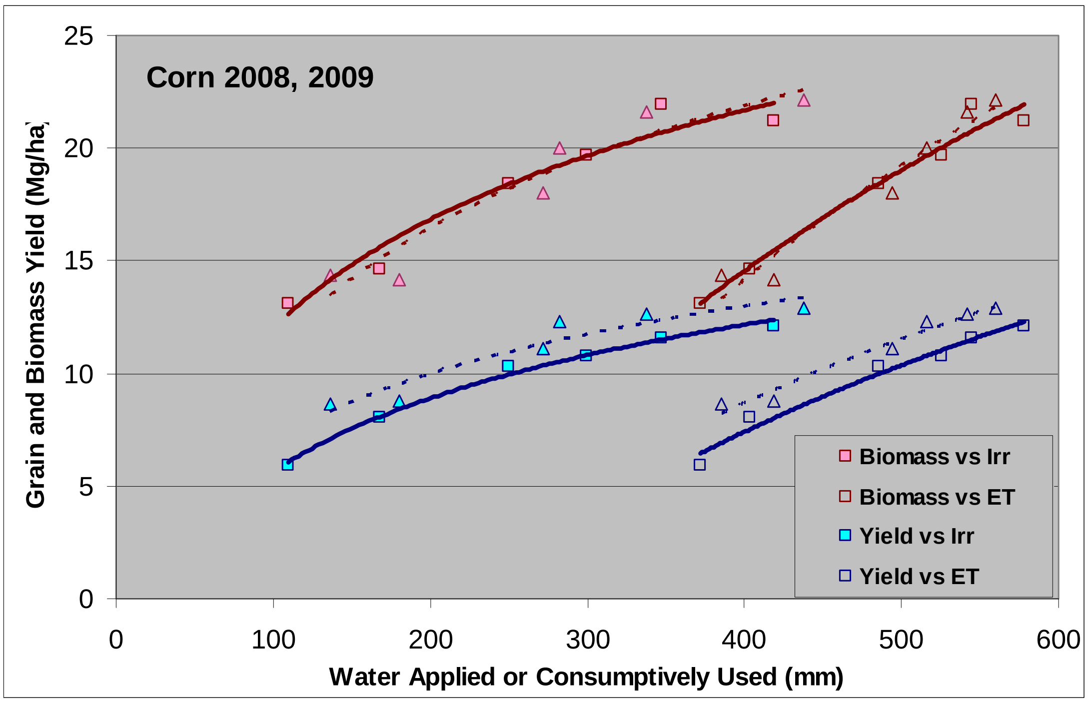

Figure 1. Water production functions for 2008 and 2009 corn. Red lines are total biomass (dry wt.). Blue lines are grain yield (15.5% moisture content). Yields are plotted relative to irrigation amount (Irr) and crop ET. Triangles and dashed lines are 2008 data. Squares and solid lines are 2009 data.

Figure 2. Comparison of corn growth condition on July 31, 2008 just before tasseling. Rows at the left and background are fully irrigated; rows at right are the lowest irrigation level.

However, the water production function for grain yield based on ET is relatively linear. This implies that the corn is equally efficient in it's use of every additional unit of water consumed and the marginal value of the consumptively used water is fairly constant over the wide range of applications – about 3 kg/m^3 (150 bu/ac-ft).

These results imply that nearly all of the increase in the marginal value of applied water with deficit irrigation results from more effective use of precipitation and increased use of stored soil water, or conversely, the lower marginal value of water near full irrigation is due to inefficient use of rainfall and irrigation water. The marginal value of applied water near full irrigation would be even smaller with less efficient irrigation systems since more of the applied water would be lost to runoff and deep percolation.

These results also imply that, based on consumptive use, there would be little or no yield benefit to deficit irrigation compared to fully irrigating only a portion of the land. In fact, fully irrigating less land would likely provide the highest economic returns due to lower production costs.

These preliminary results show the importance of developing water production functions based on the correct unit of water. If water value is based on cost of the water supply (eg. pumping costs from a well), then productivity based on applied water is important. However, for the purpose of transferring consumptive use savings, the productivity must be based on water consumed. The value of limited irrigation based on CU savings will likely be less, and if the crop is efficient at converting increased CU to yield, there may be no economic benefit to limited irrigation.

This limited irrigation study will be continued to confirm these initial results for each of the four crops.

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STORMWATER AND IRRIGATION CANALS – EMERGING ISSUES

Richard L. Belt, P.E., P.H.[1]
Kyle Abbott[2]

ABSTRACT

Acceptance and management of stormwater in irrigation ditches and canals has historically been challenging, primarily related to canal infrastructure protection and excess flow management. As is the case with many topics related to canal operations and management, new challenges are on the horizon.

Ditches and canals in urbanizing areas have been used to receive and convey stormwater, both with and without the concurrence of the canal owner. Canals can receive stormwater from a variety of sources, including direct discharge from storm drainage systems, unconcentrated flows from adjoining property, and detention/retention vessels. These flows can be altered, in both quantity and timing, from historic stormwater inflows and may render current canal operational approaches or structures inadequate. Irrigation districts or companies which have agreed to accept stormwater, intentionally or unintentionally, may have also accepted the liability for damage to adjoining properties resulting from flooding caused by this stormwater.

Irrigation districts or companies which have or may be considering accepting stormwater should understand the current (and ever-changing) regulatory environment, their liability and future obligations, and seek adequate agreements to protect their constituents. They also need to ensure that they are adequately compensated for acceptance of additional risk and liability.

INTRODUCTION AND BACKGROUND

Over the last several years, there has been an increasing focus on the transfer of land and water from agriculture to urban uses, in particular issues related to maintaining the productivity of prime agricultural lands, sustainability of rural communities, and changes of water from agriculture to urban uses and the associated issues. These issues should be broadened to include the significant infrastructure, liability, and regulatory issues that result from these transfers.

Historically, stormwater was treated a benefit to canal systems as it resulted in additional water for delivery to irrigation. It was not a panacea, due to challenges resulting from overloaded canals and additional maintenance expense and effort due to debris often carried into the canals and structures. Stormwater was often accepted from small watercourses which intersected with canals or as diffuse, surface runoff from up-gradient fields or rangelands. Canal operators were historically concerned primarily with infrastructure protection and operational issues associated with stormwater. There was

[1]Principal, Aqua Engineering, Inc., 4803 Innovation Drive, Fort Collins, CO rbelt@aquaengr.com
[2] Intern, Aqua Engineering, Inc., 4803 Innovation Drive, Fort Collins, CO

little concern for canal liability because there was typically not much high-value property at risk in agricultural areas and area residents typically directly benefitted from canal infrastructure, and the risk of property damage was worth the considerable benefit afforded by irrigation.

Agricultural canals and their associated easements are attractive assets as a convenient conveyance for stormwater in newly urbanizing areas. Some canal systems may unwittingly receive stormwater inflows from surreptitious connections or outfalls from adjoining or upstream development into natural watercourses that were historically intercepted. Sophisticated canal systems may have negotiated payments or infrastructure improvements in return for accepting stormwater. Often, in both scenarios, stormwater was accepted by canal operators with little regard for the liability or regulatory issues that they may create for themselves, resulting from both stormwater quantity and quality.

LIABILITY FROM STORMWATER-RELATED ISSUES

All canals are trans-basin diversions. In their simplest form, a canal diverts from a watercourse and conveys that water overland to areas outside, though possibly tributary to, the basin of origin (Figure 1). Further, canals are naturally distributary and decrease in capacity as they progress downstream and deliver water to irrigated lands in the service area, contrasting with the tributary nature of natural watercourses. Two legal concepts indicate that a canal owner may have liability for damage caused as a result of accepting stormwater (Akolt, 2010). First, in many western states, stormwater follows a "modified civil rule", meaning that the up-gradient land owner possesses a natural easement over the down-gradient property for the drainage of water in its natural course. Accordingly, natural drainage conditions may be altered by the up-gradient landowner provided that the altered conditions are not more injurious to the down-gradient landowner than that which occurred historically. The protection of the modified civil rule does not apply to canals which move water between basins; as a result, the canal owner is liable for water in the canal once it has been accepted. Second, state statutes regarding canal owner liability typically require canal owners to maintain their facilities in good condition and prevent water from escaping to the injury of any mining claim, road, ditch, or other property. Colorado case law has further shown that this responsibility and resulting liability applies to third-party structures that companies may have allowed to be constructed in their systems (Colo. App, 2003, East Meadows Co, LLC v. Greeley Irr. Co. 66P.3d 214).

Typically, canals include spillways at or near locations where historic stormwater run-in is heavy, at system constrictions, and at critical structures. During the initial development of canal systems, operators often lived close to their canals, learned the runoff characteristics of the contributing watersheds, and adapted their canal systems through trial-and-error. This process carried relatively few consequences, since property damage was minimal following a breach or failure.

Following urbanization, stormwater discharges can be altered in both quantity and timing relative to historic stormwater inflows, even if stormwater management principals are followed. These altered conditions, particularly the cumulative effects of wholesale upstream urbanization, may render existing canal operational approaches and structures inadequate. Canal systems, typically faced with severe aging infrastructure issues, can experience damage to already marginal or inadequate structures resulting in wider canal breaches or failures. Compounding the situation, urbanization within the irrigation service area below the canal increases the hazard associated with the embankment, through the increase in high-value property density. This cycle is particularly vicious insofar as the canal company may not have participated in the review of the adjoining improvements during the local planning and entitlement process, did not approve the development, nor specifically agreed to accept the resulting stormwater.

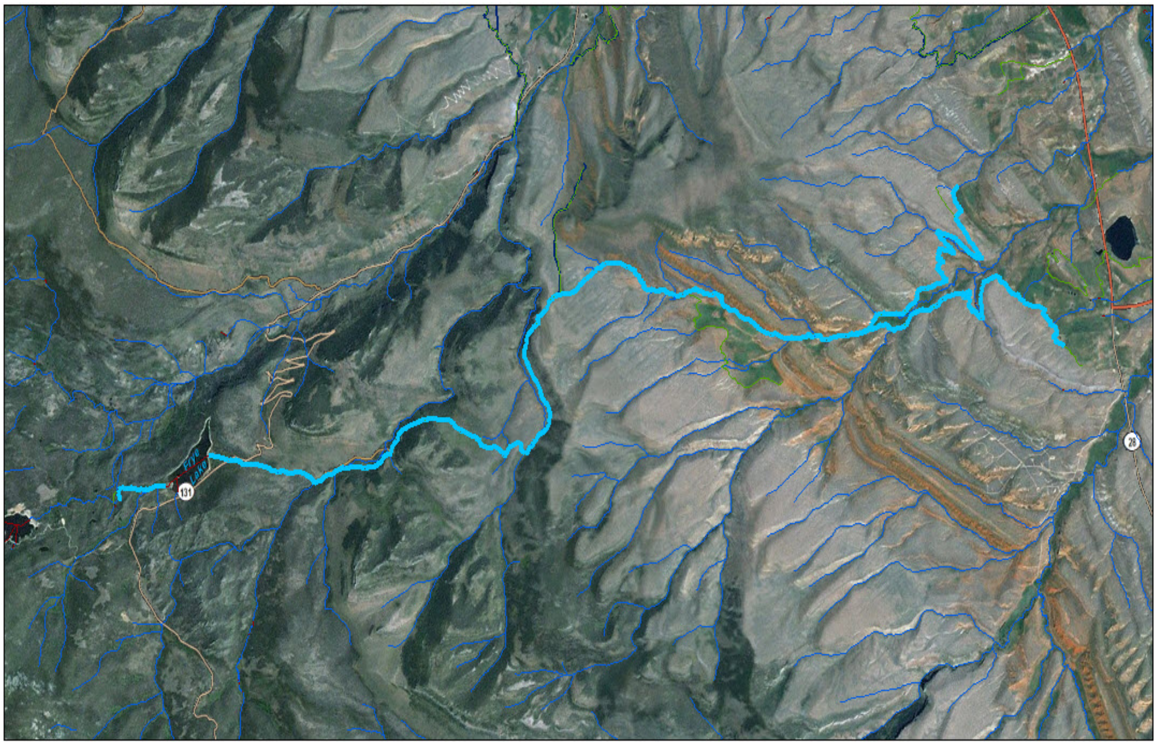

Figure 1. Enterprise Ditch near Lander, WY. Heavy blue line shows the alignment of a small ditch which intercepts drainage from a 14-square mile basin.

Further, the company did not agree to the additional liability resulting from improvements within the service area. A specific example of this type of increased burden results from improvements below reservoirs. Often, storage reservoirs or equalization basins are small structures, built without the benefit of modern construction equipment and methods. In some cases, these structures can't be certified under current safety of dams standards, but this may have been inconsequential due to low hazard classification. Urbanization downstream of the structure can suddenly result in a hazard classification revision and the resulting regulatory scrutiny, expense, and the threat of operational restriction. There is no current method to compensate dam or canal owners for the increased burden and liability.

AREAS OF CONCERN

Aqua Engineering, Inc. has undertaken a high-level review of the number of urban canal miles and acreage of potential impact for a few northern Colorado communities, focusing on large-capacity canals, canals which traverse heavily-urbanized areas, and canals with which our firm is familiar through previous work. The number of canal miles is the mileage beginning with the onset of improvements at a sub-urban density within relatively close proximity of the canal. The number of miles is totalized until the canal terminus is reached or that the development density has reduced back to agricultural levels.

The acreage of potential impact from a canal breach or structure failure is typically located directly below the canal embankment and is believed to be within relatively close proximity to the canal. "Relatively close proximity" is defined as a distance of several hundred yards, encompassing a few blocks in a heavily-urbanized area. This is an approximate distance and is used to gain an understanding of the approximate order-of-magnitude of concern. Canal mileage and potentially impacted acreage were digitized using 2009 National Agriculture Inventory Program (NAIP) imagery (Figure 2).

Three northern Colorado canal systems, located in Fort Collins, Loveland, and Greeley, respectively, have been reviewed to identify the magnitude of the potential hazard. Initial results are summarized in Table 1. Even conservative estimates of damage resulting from a significant canal breach (i.e. $500,000 per acre) result in astronomical liability, on the order of tens of millions of dollars per urban canal mile. It is apparent that this is a significant concern for these communities, but it is one that is not currently recognized by most federal, state, or local floodplain and emergency managers. Similar situations can be found in many western communities, in particular those communities which have experienced urbanization of the agricultural areas which historically surrounded those communities.

High-profile canal failures resulting in damage to urbanized areas have occurred recently in Fernley, Nevada, in Logan, Utah and in the Layton-Ogden area in Utah. The U.S. Bureau of Reclamation (USBR) is undertaking a review of their canals traversing urban or urbanizing areas to evaluate the condition and hazard of those canals during 2010 and 2011.

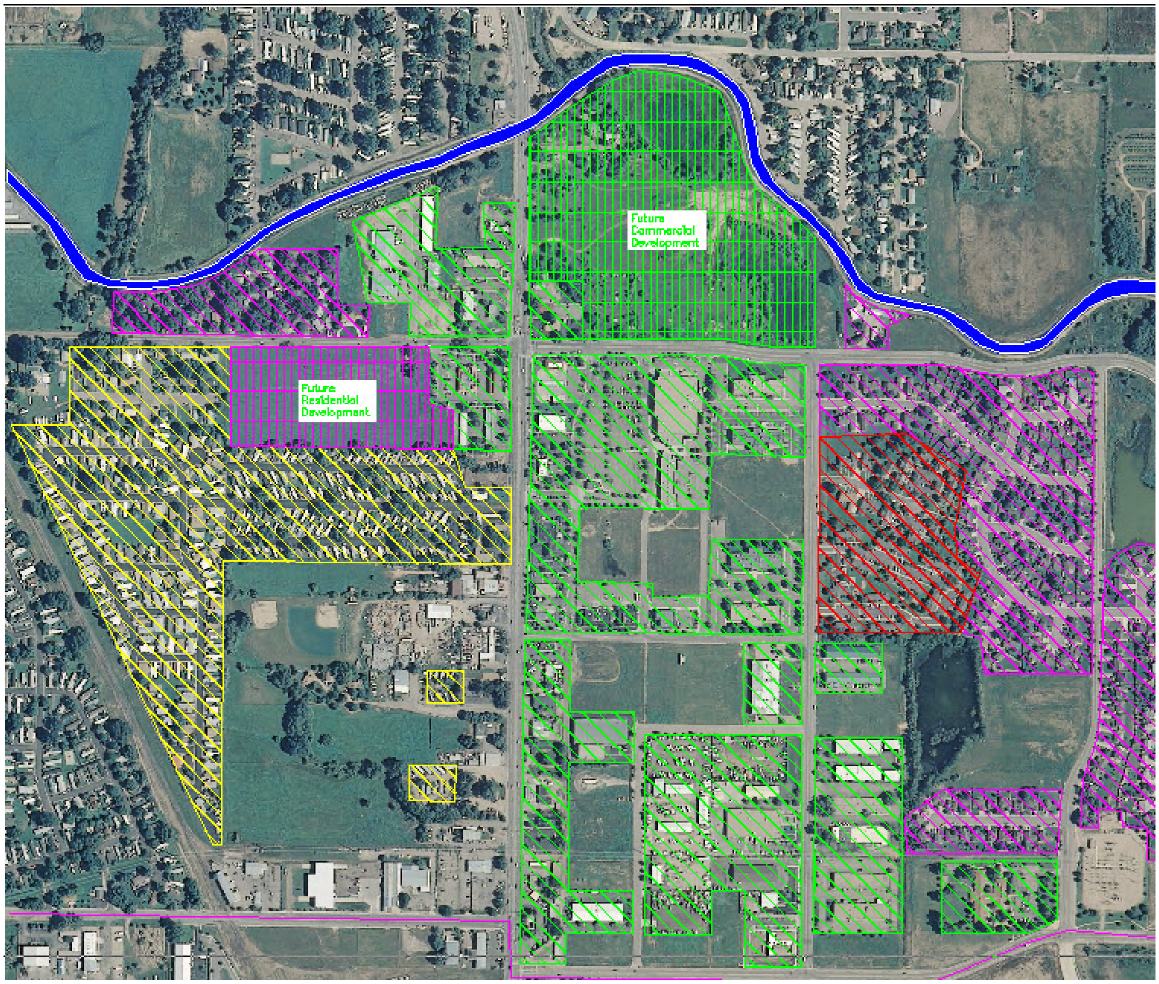

Figure 2. Larimer and Weld Canal, Fort Collins, CO. Hatched areas show different land-uses at potential risk in the event of a canal breach.

Table 1. Potential urban canal breach hazard areas

Canal	Urban Length (mi)	Mobile (ac)	Single Fam. (ac)	Multi-Fam. (ac)	Comm. (ac)	Low-density Comm. (ac)	Total (ac)	Total per mile (ac/mi)
Greeley No. 3	5.4	257	416	46	150	130	999	184
Larimer and Weld	5.1	129	721	45	114	25	1,033	204
Greeley-Loveland	7.1	0	491	84	382	0	958	135

APPROACH TO HAZARD RECOGNITION AND MITIGATION

The increasing liability to canal owners, resulting from activities or decisions that may have been made decades in the past, is inequitable, so canal operators and representative organizations must become more active in the recognizing and developing approaches to addressing this situation. A proposed approach is outline below:

1. **Engagement.** Canal companies and representative organizations should use this opportunity to engage government at all levels to educate them about these issues; in particular, the concept that this liability may have been created through no fault or action of the canal owner.

2. **Hazard Recognition.** Canal companies should identify the areas of most significant hazard within their systems and work with the affected community to identify the extent of the resulting risk. Initially, these efforts should focus on reaches with constructed embankments, large elevation differential between the canal and down-gradient suburban and urban areas, critical down-gradient infrastructure or services, canals conveying large volumes of water, reaches with a history of overtopping, reaches with significant rodent activity or potential, recently urbanized areas which drain into canals, etc. These areas can be noted as having a special hazard by the community, and community resources can be dedicated to understanding the specific issues.

3. **Research.** The US Bureau of Reclamation, as a large canal operator which has experienced significant urbanization in the vicinity of some of its projects, should undertake research related to canal overtopping failure. Of particular need is research related to flow velocity and impact force at the toe of an embankment, velocity and impact force dissipation characteristics, and embankment erosion characteristics. This research will be used to gain an understanding of the areas of most significant hazard, the conditions which contribute most significantly to the hazard, the contribution of mudflows and debris from the embankment to the downstream damage, etc.

4. **Hazard Mapping.** Armed with research findings and initial hazard recognition efforts, formal hazard mapping should be completed, possibly modeled on Federal Emergency Management Agency (FEMA) methodology used to create Flood Insurance Rate Map (FIRM) panels. Hazard mapping of canal embankment breaches would likely include two components; velocity risk zones (Zone V equivalent) adjoining and below the canal with limits to be determined based on research results; and shallow sheet flooding zones (Zone AH) for those areas at risk of inundation but not necessarily velocity or impact damage.

   Mapping of the flood hazard associated with canal embankment failure should consider both contributing and mitigating factors, both specific to the canals being mapped. Contributing factors could include many of the items listed under item 2, above. These are issues which would tend to increase the hazard to human life, the magnitude of the potential damage, or the risk to the overall community resulting from canal embankment failure.

Mitigating factors could include the location and frequency of check structures, the presence of supervisory control and data acquisition systems (SCADA) to alert canal operators to a breach and allow for automated or remote control of structures which would mitigate the severity of the resulting flooding, automated rain or stream gage structures which would alert canal operators of flooding risk, etc.

5. **Hazard Management.** Once mapped, local communities could better manage canal embankment failure risks through zoning or development requirements, a flood insurance requirement, high-risk land acquisition program, an impact fee program to support canal rehabilitation, or some combination of all of these measures. A principal difficulty with any of these approaches is that, in many communities, the hazard resulting from urbanization below canals has also existed for decades.

OPPORTUNITIES FOR CANAL COMPANIES

The principal opportunity for canal companies in understanding their risk from canal embankment failure or overtopping is in engaging with the community to develop approaches to address these conditions. Communities which require flood insurance or acquire properties in high-risk areas will facilitate a beneficial risk transfer from the canal company. Alternately, implementation of an impact fee program will generate revenues which could support canal infrastructure improvement resulting in risk reduction for the canal company. For many canal companies, the ideal solution would include elements of both approaches.

Acceptance of new stormwater by canal companies is occasionally unavoidable, depending on state law, and has been used to generate valuable revenue and canal infrastructure improvements. Until such time as a comprehensive hazard management program can be adopted, it is important for canal companies to protect themselves when considering acceptance of stormwater into their canals (after Akolt, 2010):

1. Have all studies and designs completed and sealed by the project proponent's Professional Engineer.

2. Have all project studies and designs reviewed by the company's independent Professional Engineer.

3. Have the company's Professional Engineer certify the capacity of all canal infrastructure which may be affected by the proposed project, and ensure that the proposed project includes the development of appropriate additional spillway capacity *within* the basin of origin.

4. Engage an attorney experienced in such matters and obtain an indemnification agreement from a *public entity* which clearly defines the limits of indemnity.

5. Ensure that the indemnification agreement places compliance with all present or future permitting or regulation pertaining to stormwater quantity or quality issues with the public entity.

6. Ensure that the company is being adequately compensated for the stormwater acceptance and conveyance. In strictly administered basins in states with prior appropriations-based water laws, there may be no legal way to augment irrigation supplies with intercepted stormwater. There may be no other benefit to the company, other than direct compensation, for the acceptance of stormwater, and the resulting operational considerations, maintenance, and liability for such actions are perpetual.

CONCLUSION

It is critically important that canal companies investigate and understand existing liabilities incurred through the acceptance and delivery of stormwater outside the basin of origin. This liability may result from a company or third-party infrastructure failure which causes canal overtopping and a canal embankment failure. Aging infrastructure concerns, coupled with wholesale urbanization above and below the canal system, have exacerbated these risks. It is critically important that canal companies study their own systems to identify reaches with increasing or high risks and then engage with local communities to communicate the risk and develop risk- and community-appropriate means for mitigating the risks to both the canal company and the community. Acceptance of stormwater is a reality under most canal systems and the pressure to accept stormwater resulting from urbanization may be increasing. It is critically-important that canal companies understand their risks and liabilities, and obtain agreements and compensation which adequately addresses their needs.

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ASSESSMENT OF DISSOLVED SOLIDS CONCENTRATIONS AND LOADS IN THE SOUTH PLATTE RIVER BASIN, NORTHEASTERN COLORADO

Paul A. Haby [1]
Jim C. Loftis [2]

ABSTRACT

Historical water-quality monitoring data were utilized to perform a comprehensive assessment of dissolved solids at 13 water-quality monitoring stations located within the South Platte River Basin in northeastern Colorado. Daily dissolved solids loads were calculated and trend analysis was applied to both dissolved solids concentrations and dissolved solids loads. Significant trends in dissolved solids concentrations were detected in slightly over one-half of the 13 monitoring stations. Twice as many significant upward trends were found as downward trends. Upward trends were found in the upper part of the study area while downward trends were found in the mid- to lower-portion of the study area. In contrast, only three significant trends in annual dissolved solids loads were found. All three were downward and found at stations in the middle portion of the study area. Most of the dissolved solids loading of the mainstem of the South Platte River was determined to occur mid-basin, with significant contributions coming from the three largest tributaries. Median annual dissolved solids loads at the most downstream station were slightly lower than mid-basin loads suggesting the possibility of salt deposition in the irrigated soils of this region.

Results of this work provide the foundation for the creation of a streamflow and dissolved solids mass balance modeling tool which can be used to evaluate how proposed water diversion, exchange, and reuse projects will impact streamflow and water quality. Such projects are being driven by increased competition for scarce water resources due primarily to high population growth in the basin.

INTRODUCTION AND BACKGROUND

Similar to many river basins in the western United States, the South Platte River Basin is undergoing a transformation with regard to land and water use. Driven by an ever-increasing population in the basin, water which was historically used for agricultural purposes is being diverted in greater and greater quantities to growing urban areas in order to satisfy increasing municipal and industrial (M&I) demands. Water rights and water-quantity issues have long been at the forefront of the debate between competing water interests. However, an increasing number of agricultural-urban water exchange agreements, increased water reuse, and an increase in water conservation efforts are forcing additional attention to be given to the resulting water quality impacts of these actions.

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[1] Graduate Research Assistant, Civil and Environmental Engineering Department, Colorado State University, Fort Collins, CO, 80523; Paul.Haby@gmail.com
[2] Professor, Civil and Environmental Engineering Department, Colorado State University, Fort Collins, CO, 80523; E-mail: Jim.Loftis@ColoState.edu

Beginning in the latter half of the 19th century, the historical solution to an ever-increasing demand for water in the semi-arid plains of eastern Colorado and Colorado's populous Front Range region was to import additional water from the wetter river basins west of the Continental Divide through a series of transcontinental tunnels and reservoirs. Presently, however, due to a combination of water supply limitations, legal challenges, and economic barriers, there is little potential for additional supplementation from basins west of the Continental Divide. This has led to an increasingly competitive environment for water resources in the South Platte Basin which is already over-appropriated. It has also provided additional incentive for increased water efficiency and water reuse.

Because the economic value of water is higher for M&I uses than for agricultural uses, increasingly valuable water rights are being transferred from agricultural areas to municipalities. The commensurate decrease in irrigated acreage has the potential to change the timing, location, volume, and quality of return flows to the river. The quality of return flows is of particular concern in the lower portions of the South Platte Basin where salinization of irrigated soils has emerged as a concern. The USDA's Natural Resources Conservation Service (West Greeley Soil Conservation District, 1999) estimates that up to 25% of the irrigated land along the South Platte River may be affected by salinity.

Purpose and Scope

This study was conducted to provide a better understanding of the occurrence, temporal trends and flux of dissolved solids within the South Platte Basin. It also lays the groundwork for the development of a dissolved solids mass balance analysis which will quantify dissolved solids contributions to the river from unmeasured sources such as ground water inflows. A complete dissolved solids budget will provide the foundation for a decision support system (DSS) which will be used to evaluate potential streamflow and salinity impacts resulting from future management decisions including proposed water resource projects. This study also identifies information gaps that should be addressed in future monitoring programs.

This study utilized historical monitoring data from fixed-site monitoring stations along the mainstem of the South Platte River, as well as fixed-site monitoring stations near the mouths of larger tributaries of the South Platte River, inclusive of water years 1991 through 2004. Specific objectives were the: 1) compilation of historical streamflow and dissolved solids concentration data; 2) estimation of daily dissolved solids loads at each of the selected stations; 3) characterization of spatial patterns in dissolved solids concentrations and loads; 4) determination of temporal trends in dissolved solids concentrations and loads.

Previous efforts by Lord (1997) and the work of Hendricks et al. (Gomez-Ferrer *et al.*, 1983; Gomez-Ferrer and Hendricks, 1983; Turner and Hendricks, 1983) provided a fundamental basis for the understanding of historical salinity conditions and the flux of dissolved solids in the basin. This study updates and expands upon these previous characterization efforts.

Study Area Description

The South Platte River Basin (Figure 1) is located primarily in the north-central and north-eastern regions of Colorado. It originates in the mountains southwest of Denver along the Continental Divide and flows in a generally northerly direction through Denver until it reaches Greeley, Colorado, where it begins to flow in an easterly to northeasterly direction along a large agricultural area before reaching its confluence with the North Platte River at North Platte, Nebraska. This study focuses on the middle and lower portions of the South Platte Basin between Denver and Julesburg, Colorado.

The South Platte River drains a basin comprised of approximately 62,940 square kilometers within the states of Nebraska, Wyoming and Colorado (Gomez-Ferrer *et al.*, 1983). Between Denver and Greeley the river is joined by its three largest tributaries: the Saint Vrain River, the Big Thompson River, and the Cache la Poudre River. Because of the large volumes of water diverted below Kersey, the maximum average annual flow in the South Platte River is reached at the Kersey monitoring station near Greeley. From Kersey to North Platte, the primary alterations to flow are removal of water via irrigation diversions and addition of ground water. At several locations nearly the entire flow is diverted during the high-demand irrigation season. Below these diversions the flow in the river gradually reconstitutes due to ground water inflow and occasional surface runoff. Ground water inflow adds an estimated 5 million cubic meters per day to the river, most of which is a result of irrigation return flows (Dennehy *et al.*, 1995). Return flow also results from ground water storage and recharge projects used to help maintain legal and ecological minimum flow requirements.

Water development has caused substantial changes to the natural hydrology of the South Platte River. There are 15 inter-basin transfer projects that import water from the Colorado, Arkansas, and North Platte River basins. These projects were built to provide a reliable water supply for agricultural production in the arid eastern plains of Colorado. Today, they transport an average of 490 million cubic meters per year to the South Platte River Basin for use both by agriculture and to help satisfy the demand of the growing population centers. The basin has an extremely complex operational and legal infrastructure which provides the required regulatory framework that allows the water to be reused up to an estimated seven times for a variety of uses as it flows downstream. Due to the complexity of the water control system, the South Platte River is considered one of the most regulated rivers in the United States (Dennehy *et al.*, 1995).

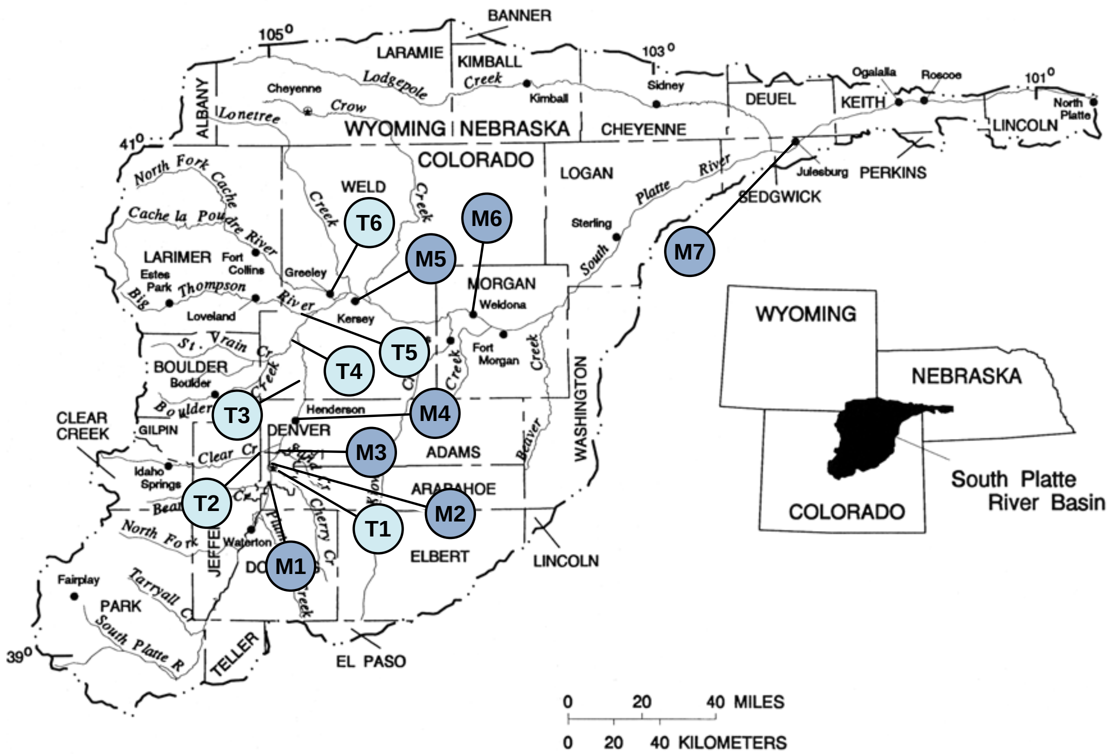

Figure 1. The South Platte River Basin (adapted from Dennehy et al. (1998))

METHODS

Data Compilation and Processing

Dissolved Solids Concentration Data Historic water-quality monitoring data were retrieved from the United States Geological Survey's (USGS) National Water Information System (NWIS) online database (U.S. Geological Survey, 2006). Electronic water-quality monitoring records for the South Platte Basin were obtained from NWIS for all surface-water monitoring stations located along the mainstem of the South Platte or near the mouths of major tributaries. From this list, stations were selected for inclusion based on length and completeness of historical monitoring record. The 13 resultant stations are listed in Table 1 and indicated on the map in Figure 1.

The NWIS database query was performed in early 2006, however records were only available through September, 2004 due to the time lag required for quality assurance checks before making data publicly available on NWIS. Based on the completeness of historical monitoring records at selected sites, the period of October, 1990 through September, 2004 (water years 1991 – 2004) was selected for analysis. The resulting database was further screened to remove duplicate observations and to remove non-routine sampling events such as flood-stage sampling.

Table 1. South Platte River Basin monitoring stations selected for this study.

USGS Station Name	Name Used in this Study	Station Location	Map ID in Figure 1	USGS Station Number
South Platte River at Union Ave at Englewood, CO	SPR nr Englewood	Mainstem	M1	6710245
Cherry Creek at Denver, CO.	Cherry Cr at Denver	Tributary	T1	6713500
South Platte River at Denver, CO.	SPR at Denver	Mainstem	M2	6714000
South Platte R at 64th Ave. Commerce City, CO.	SPR at Comm. City	Mainstem	M3	6714215
Clear Creek at Golden, CO.	Clear Cr at Golden	Tributary	T2	6719505
South Platte River at Henderson, CO.	SPR at Henderson	Mainstem	M4	6720500
Big Dry Creek at mouth near Fort Lupton, CO.	BD Cr nr Fort Lupton	Tributary	T3	6720990
St. Vrain Creek at mouth, near Platteville, CO.	SVR nr Platteville	Tributary	T4	6731000
Big Thompson River at mouth, near La Salle, CO.	BTR at La Salle	Tributary	T5	6744000
Cache La Poudre River near Greeley, CO.	CLPR nr Greeley	Tributary	T6	6752500
South Platte River near Kersey, CO.	SPR nr Kersey	Mainstem	M5	6754000
South Platte River near Weldona, CO.	SPR nr Weldona	Mainstem	M6	6758500
South Platte River at Julesburg, CO.	SPR at Julesburg	Mainstem	M7	6764000

Within the historical data, measures of salinity were often recorded using different methodologies. The most common of these was specific conductance (SC), which was measured in the field, the laboratory, or both. Total dissolved solids (TDS) was determined less frequently using a variety of measurement and calculation methods. When more than one value of either of these measures was reported for a single sampling event, the mean of the values was taken. To maximize the amount of TDS data available for load analysis, SC measurements were converted to TDS values using site-specific regression equations developed for each monitoring location using paired SC – TDS values. The resulting values were used for all analyses in the study.

Streamflow Data Daily flow values were needed for the calculation of daily loads. Daily flow values for selected stations were obtained from the Colorado Decision Support System (CDSS) Hydrobase database (Colorado Water Conservation Board and Colorado Division of Water Resources, 2007). The CDSS Hydrobase provided a more complete resource for daily flow values than the USGS's NWIS because operational control for some USGS monitoring stations within Colorado has been transferred to the Colorado Division of Water Resources (DWR). As a result, flow data for these stations are stored in the CDSS Hydrobase but not NWIS.

Load Estimation

Estimates of daily dissolved solids loads were made using the U.S. Geological Survey's Load Estimator (LOADEST) software program (Runkel *et al.*, 2004). Model calibration within LOADEST requires a minimum of 12 non-zero observations per constituent, seven of which must be uncensored. For estimation of daily loads, a minimum of one observation per day for each explanatory variable (mean daily flow) is required. Load estimation was performed for the 13 stations described above. Some stations had limited calibration data available during the study period. For these cases, the calibration period was extended to include several years prior to water year 1991 in order to provide LOADEST with sufficient calibration points. Some stations had large gaps in the water-quality monitoring records within the study period. In both of these situations, LOADEST was used to extrapolate daily loads for the periods without water-quality monitoring data. Limitations on the reliability of these results due to the use of extrapolation will be noted during the interpretation of results from these stations.

Trend Analysis

Trends in Dissolved Solids Concentrations Trend analyses were conducted on the selected monitoring stations for water years 1991 through 2004. Because dissolved solids concentrations can vary seasonally, the seasonal Kendall test (Hirsch *et al.*, 1991) was used to account for seasonality which might otherwise obscure long-term trends. Due to insufficient length of monitoring periods or inconsistent monitoring efforts, not all sites met the data requirements (Slack *et al.*, 2003) for trend analysis. For these cases, trend analysis was performed for shorter time periods if the data requirements could be met or excluded from trend analysis entirely if not.

Flow-related variability in the TDS values was removed prior to trend analysis through the computation of flow-adjusted concentrations (Schertz *et al.*, 1991). Flow-adjusted concentrations were calculated as the residuals between the observed TDS values and values predicted by fitting a locally-weighted scatterplot smoothing (LOWESS) line between concentration and flow observations. Seasonal Kendall trend analysis procedures were conducted on the resulting flow-adjusted TDS concentrations according to the guidance provided by Hirsch (1991) using the USGS-developed software package S-ESTREND (Slack *et al.*, 2003). A seasonal analysis procedure within S-ESTREND was used to assist in the determination of the optimal seasonal definition (2, 3, 4, 6 or 12 seasons per year) for each station. Following verification of minimum data requirements and selection of optimal season definitions, S-ESTREND was used to perform uncensored seasonal Kendall tests for each station.

Trends in Dissolved Solids Loads Long-term changes in dissolved solids loads are of interest for understanding the dynamics of dissolved solids flux within the basin. Trend analysis was performed on annual load values to check for evidence of significant changes to annual loads during the study period. Use of annual loads rather than seasonal, monthly, or daily loads eliminates the need for a trend test that accounts for seasonality.

The non-seasonal, parametric procedure for determination of monotonic trend is simple linear regression analysis of the variable of interest as a function of time (Hirsch *et al.*, 1991). Because streamflow values are often not normally distributed, a nonparametric variation of linear regression trend analysis was used in this study for determination of trends in annual streamflow volume. This method uses regression on the ranks of the data instead of the actual values (Loftis, 2006). This method can be used to provide a measure of significance of a trend; however regression on the original (non-ranked) values is still required to provide an estimate of trend magnitude. This modified regression trend analysis methodology was used to perform trend analysis and significance testing on cumulative annual dissolved solids load values for water years 1991 through 2004. Stations with less than 5 years of annual dissolved solids data during this period were excluded from analysis.

RESULTS AND DISCUSSION

Spatial Patterns

Dissolved Solids Concentrations   Summary statistics for TDS concentrations at the selected monitoring stations are presented in Table 2 and spatial patterns of TDS concentrations are shown in Figure 2. Figure 2 shows both mainstem and tributary stations in upstream to downstream order.

Table 2. Statistical summary of total dissolved solids concentrations at selected South Platte River water-quality monitoring stations, water years 1991 - 2004.

[N, total number of observations; mg/L, milligrams per liter]

		Total Dissolved Solids (mg/L)					
				Percentile			
Site Name	**N**	**Mean**	**Minimum**	**25th**	**50th**	**75th**	**Maximum**
SPR nr Englewood	123	411	68	291	370	521	902
Cherry Cr at Denver	248	662	72	614	672	717	1,474
SPR at Denver	126	433	95	288	436	568	817
SPR at Comm. City	125	699	124	522	672	899	1,347
Clear Cr at Golden	154	155	47	98	151	205	605
SPR at Henderson	75	541	158	484	568	625	752
BD Cr nr Fort Lupton	119	762	265	652	775	905	1,165
SVR nr Platteville	35	743	151	549	865	900	1,003
BTR at La Salle	8	1,115	430	700	1,098	1,575	1,685
CLPR nr Greeley	8	1,067	297	1,004	1,127	1,297	1,372
SPR nr Kersey	147	898	198	816	942	1,040	1,267
SPR nr Weldona	57	1,081	341	982	1,126	1,220	1,472
SPR at Julesburg	27	1,611	949	1,570	1,638	1,699	1,825

Median TDS values were found to vary substantially within the South Platte Basin. As typically observed with TDS values, concentrations generally increased in a downstream direction along the mainstem of the South Platte. Stations in the Denver metropolitan area (SPR nr Englewood, SPR at Denver) both had median TDS concentrations below 500 milligrams per liter (mg/L). The higher TDS concentrations found in Cherry Creek, which enters the mainstem between Englewood and Denver, are likely to have caused at least some of the slight increase in mainstem TDS concentrations within this reach. Between Denver and Commerce City, median TDS concentrations jumped from 440 mg/L to 670 mg/L. The station at Commerce City also had the highest amount of variability in TDS concentrations of any mainstem station. The increase in both TDS concentrations and variability might be attributable to the presence of a large diversion structure upstream from Commerce City. When in operation, this structure removes a large proportion of the total flow in the river (Dennehy *et al.*, 1998) leaving the remaining streamflow more susceptible to the influence of inflows such as ground water and point discharges that tend to have higher-TDS concentrations.

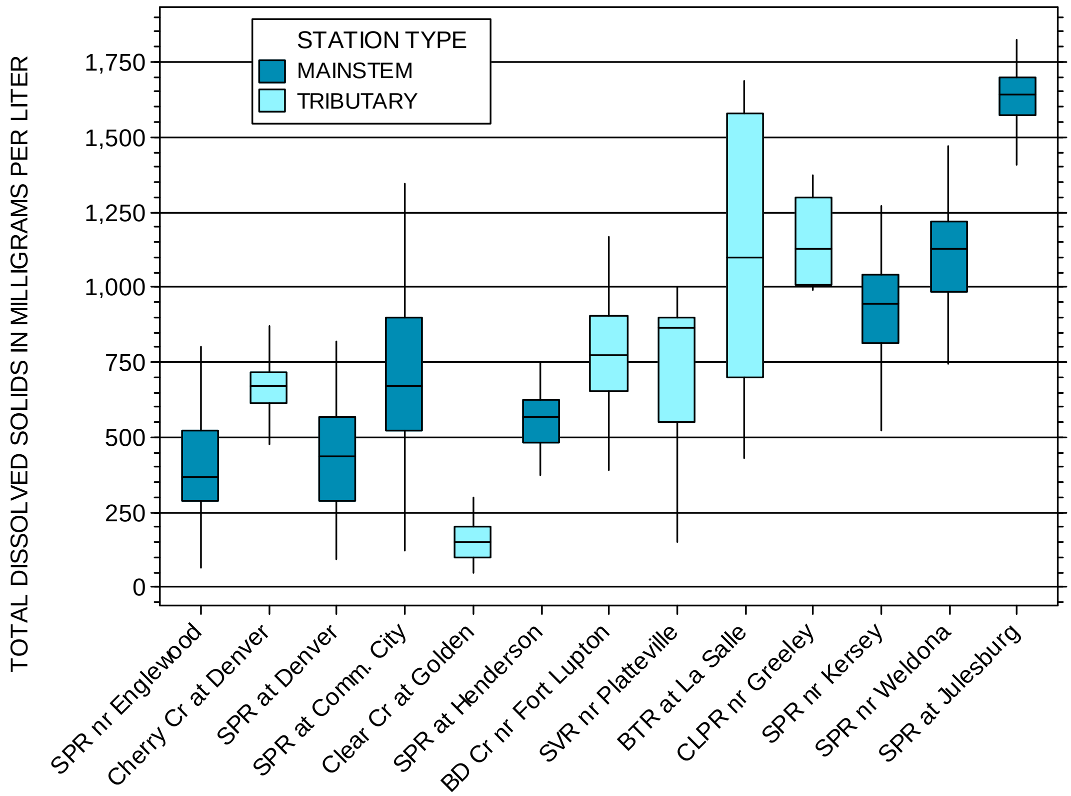

Figure 2. Boxplot of dissolved solids concentrations at selected monitoring sites within the South Platte Basin, water years 1991-2004.

Median TDS concentration decreases from 670 mg/L to 570 mg/L between Commerce City and Henderson. Two factors are likely to be responsible for this. The first is the inflow of lower TDS water from Clear Creek. The second is Denver's main wastewater treatment plant which discharges effluent into the mainstem just downstream from the monitoring station at Commerce City. At certain times of the year when the flow in the river upstream from the discharge point is low, the volume of effluent is large enough to cause the river to be comprised almost entirely of treated effluent (Dennehy *et al.*, 1995). Discharge monitoring data for this plant obtained from the U.S. Environmental Protection Agency's STORET database (U.S. Environmental Protection Agency, 2007) show the mean TDS concentration of the effluent typically ranges between 500 and 600 mg/L. It is likely that this effluent controls the TDS concentrations observed at Henderson.

Between Henderson and Kersey the mainstem is joined by Big Dry Creek as well as the three largest South Platte tributaries: the Saint Vrain, Big Thompson, and Cache la Poudre Rivers. This tends to nearly double the volume of streamflow within this reach. All four tributaries have higher median TDS concentrations than the mainstem at Henderson and, therefore, tend to raise the TDS concentrations in the mainstem along this reach. The highest TDS concentrations are seen in the Big Thompson and Cache la Poudre Rivers, both with median TDS values above 1,000 mg/L. It should be noted that these values are based on a much lower number of observations than most sites. The higher-TDS inflow from the tributaries results in a mainstem median TDS concentration of 940 mg/L at Kersey.

Beyond Kersey there are no significant tributary or point-source inputs. TDS concentrations continue to rise in a step-wise fashion due to evapoconcentration of salts as the water is used multiple times along this region. The highest TDS values of all stations on the South Platte River were found at Julesburg. This station is located downstream of all other sites and, therefore, integrates the effects of all of the natural and anthropogenic sources of dissolved solids that occur upstream as well as the effects of evapoconcentration due to consumptive use of much of the upstream streamflow.

Dissolved Solids Loads Summary statistics for annual dissolved solids loads at the selected monitoring stations are presented in Table 3. Spatial patterns of annual dissolved solids loads are shown graphically in Figure 3.

Table 3. Statistical summary of total dissolved solids loads at selected South Platte River water-quality monitoring stations, water years 1991 - 2004.

			Annual dissolved solids load (thousands of kilograms)					
					Percentile			
Site Name	Period (water years)	Number of Years	Mean	Minimum Value	25th	50th	75th	Maximum Value
SPR nr Englewood	1991 - 2004	14	38,800	12,395	28,273	31,085	45,910	84,702
Cherry Cr at Denver	1991 - 2004	14	16,980	11,531	13,373	15,292	21,793	25,198
SPR at Denver	1991 - 2004	14	96,018	61,157	80,035	86,036	110,474	143,030
SPR at Comm. City	1991 - 2004	14	58,774	22,171	30,953	48,384	80,886	121,013
Clear Cr at Golden	1991 - 2004	14	17,981	12,034	12,885	19,461	21,707	24,067
SPR at Henderson	1991 - 2004	14	192,723	138,029	166,544	184,155	215,679	264,012
BD Cr nr Fort Lupton	1993 - 2004	12	25,775	17,960	22,230	25,011	29,560	33,915
SVR nr Platteville	1991 - 2004	14	132,966	61,622	105,077	140,809	155,100	169,227
BTR at La Salle	1991 - 2004	14	62,807	28,820	43,373	70,673	75,583	87,132
CLPR nr Greeley	1991 - 2004	14	115,108	65,414	93,229	111,763	144,044	176,052
SPR nr Kersey	1991 - 2004	14	641,611	345,693	497,116	629,035	833,711	928,421
SPR nr Weldona	1991 - 2004	14	484,297	230,879	360,874	491,496	633,361	765,830
SPR at Julesburg	1991 - 2004	14	609,508	60,034	306,630	626,457	824,461	1,323,051

As with TDS values, large variation in dissolved solids loads was found among monitoring stations. Because upstream sites generally tended to have lower TDS concentrations and streamflow, upstream sites tended to have lower loads than were found at downstream sites. A large jump in median annual load from 48 million kilograms per year to 184 million kilograms per year is seen along the mainstem between Commerce City and Henderson. This increase cannot be explained by the median annual load contribution of 19 million kilograms per year from Clear Creek which enters along this reach. Much of the increase in load is likely a result of effluent discharge from the Denver metropolitan area and ground water return flow.

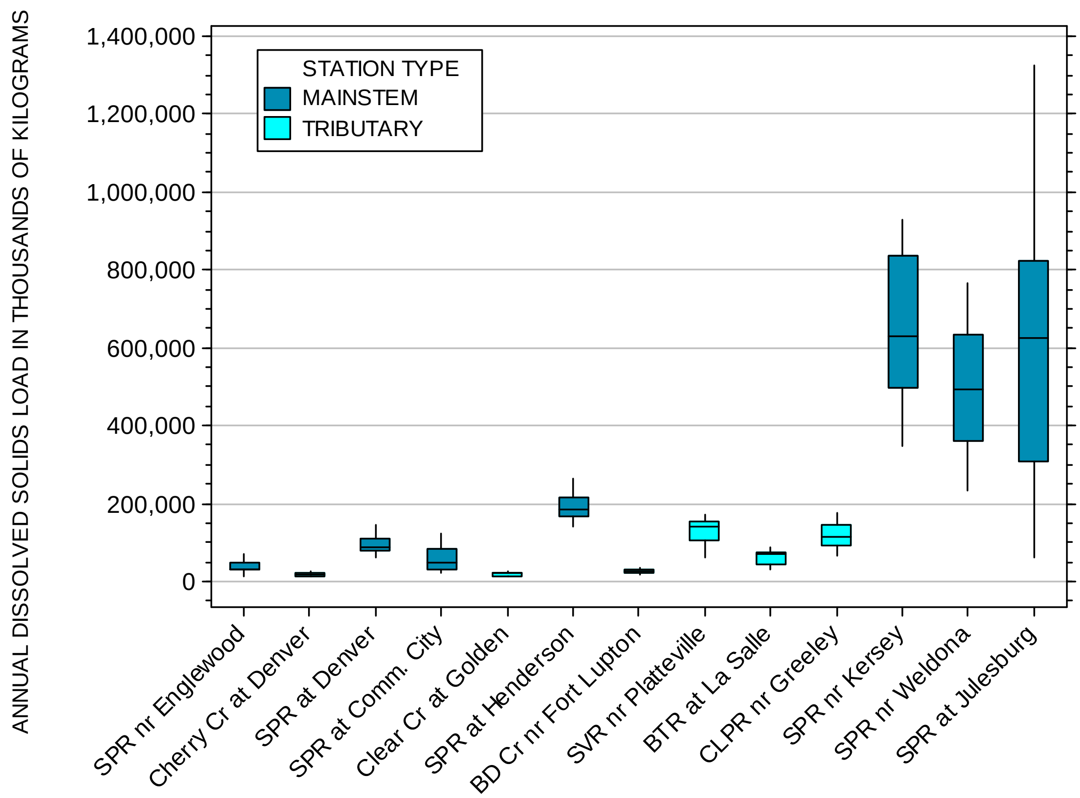

Figure 3. Boxplot of annual dissolved solids loads at selected monitoring sites within the South Platte Basin, water years 1991-2004.

The three smaller tributaries had minimal load contributions to the mainstem. However, the three larger tributaries contributed substantially to the median annual load between Henderson and Kersey. Median annual load in this reach increased from 184 million to 629 million kilograms per year. The Saint Vrain River is the largest contributor of dissolved solids load to the mainstem and the Cache la Poudre River is the second largest. As seen in Figure 3, the largest annual dissolved solids loads within the mainstem were typically found at Kersey. Annual median loads decrease at Weldona, however it is believed most of this drop is attributable to diversion of irrigation water upstream from Weldona which routes some of the dissolved solids load around the monitoring station. Most of the dissolved solids load at Kersey returns to the river by the time it flows past the Julesburg station. Although the median annual load at Julesburg is similar to that at Kersey, there is greater variation at Julesburg. The variation at Julesburg tended to be extreme, resulting in the annual load at Julesburg being alternately much higher or much lower than the annual load at Kersey. The difference between loads at Kersey and Julesburg equate to a net positive or negative salt balance in the intervening stream reach. Based on median annual values, this region has a slightly positive salt balance, meaning more salts are entering the region than are leaving it. Over the long term, a positive salt balance could result in a build-up of soil salinity levels in the irrigated soils of this region and subsequent reductions in crop yield. Future research is planned to further investigate salt flux and salt balance issues in the basin.

Trend Analysis

Trends in Dissolved Solids Concentrations   Time series plots of TDS concentrations for water years 1991 through 2004 are presented in Figure 4 and Figure 5. LOWESS smoothing lines were added to plots to aid in the visualization of the data.

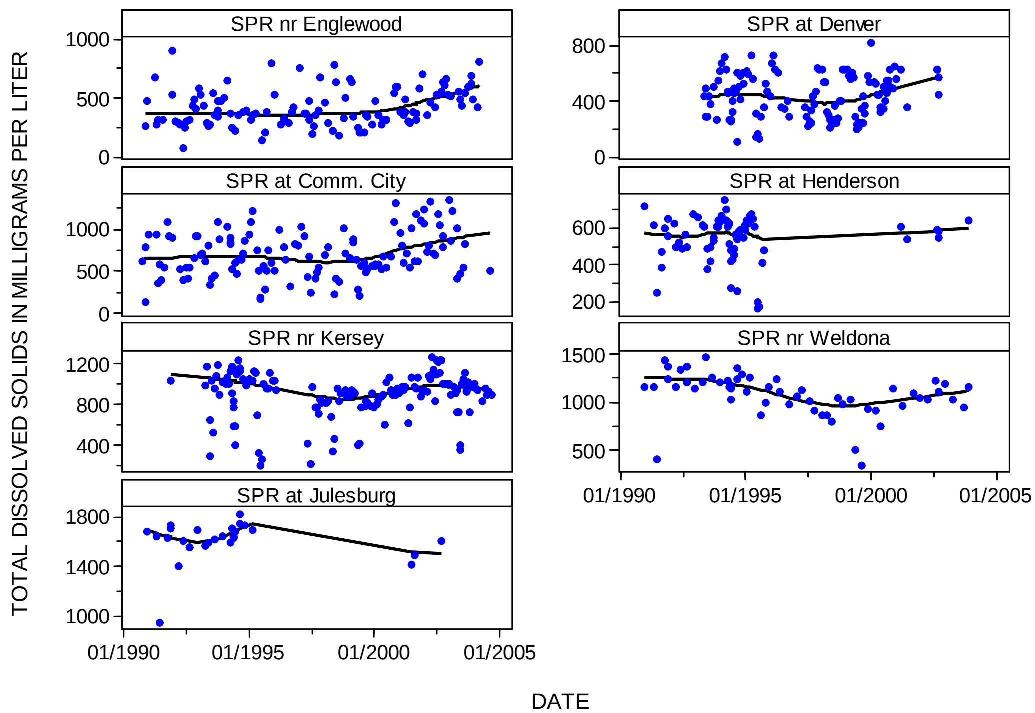

Figure 4. Time series plots of TDS concentrations with LOWESS smoothing lines at selected monitoring sites along the mainstem of the South Platte River, water years 1991-2004.

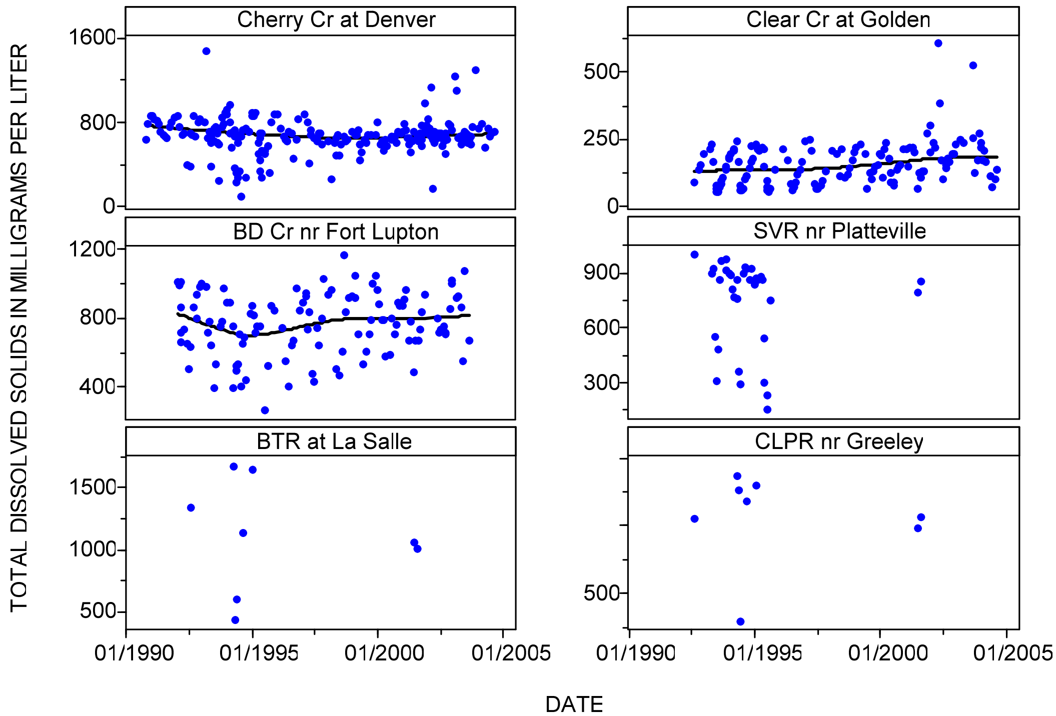

Figure 5. Time series plots of TDS concentrations with LOWESS smoothing lines at selected monitoring sites along tributaries of the South Platte River, water years 1991-2004.

Results of seasonal Kendall trend analysis of flow-adjusted TDS concentrations are presented in Table 4. Five sites did not meet the minimum data requirements for seasonal Kendall trend analysis and are denoted with an asterisk in the "Period" column. For this study, a *p*-value equal to or less than 0.10 was deemed sufficient evidence for rejection of the null hypothesis of no trend. Trends determined to be significant are shown as percent change per year.

A total of six significant trends in TDS concentrations were detected: four upward and two downward. The upward trends were all found in the upper portion of the study area. Two upward trends were found at mainstem sites and two were found at tributary sites. Both upward trends at mainstem sites were found at stations within the Denver urban area. Upward trends at tributary sites were found for streams originating both in the mountainous portion of the basin (Clear Creek) and for streams originating in the plains along the Colorado Front Range region (Big Dry Creek).

Table 4. Historical trends in total dissolved solids at selected sites in the South Platte River Basin, water years 1991 to 2004.

[obs, observations; TDS, total dissolved solids; mg, milligrams; L, liters; yr, year; %, percent;]

Site name	Period	Years	Seasons	Obs	Slope (mg/L/yr)	*p*-Value	Trend (%/yr) **
SPR nr Englewood	1990-2004	14	12	123	7.59	0.00	2.06
Cherry Cr at Denver	1990-2004	14	12	248	-1.17	0.31	
SPR at Denver	1993-2002	9	12	126	2.93	0.20	
SPR at Comm. City	1990-2004	14	12	125	9.02	0.01	1.34
Clear Cr at Golden	1992-2004	12	12	154	3.90	0.00	2.45
SPR at Henderson	*						
BD Cr nr Fort Lupton	1992-2003	11	12	119	6.21	0.06	0.79
SVR nr Platteville	*						
BTR at La Salle	*						
CLPR nr Greeley	*						
SPR nr Kersey	1993-2004	11	12	146	-12.26	0.00	-1.31
SPR nr Weldona	1990-2003	13	4	57	-21.24	0.00	-1.91
SPR at Julesburg	*						

*** Station did not meet the minimum data requirements for trend analysis during this period**
**** Trends shown only for sites with a significance level of 90% or higher**

Downward trends were detected at two sites, both of which are located on the mainstem of the river in the downstream portion of the study area. The South Platte River at Kersey and South Platte River at Weldona had significant decreasing trends in TDS concentrations equivalent to a decrease of 1.3 and 1.9 percent per year, respectively. Unfortunately, historical monitoring programs were inadequate to perform trend analysis on the nearest upstream and downstream mainstem stations at Henderson and Julesburg. These data would have provided greater insight into the area trends. Insufficient monitoring data also precluded trend analysis for tributary stations on the Saint Vrain River, Big Thompson River, and Cache la Poudre River. As the three largest tributaries to the South Platte River, trend analysis of these stations would help to explain the factors contributing to the significant decreasing trend in TDS concentrations at Kersey.

Trends in Dissolved Solids Loads Time series plots of annual dissolved solids loads for water years 1991 through 2004 are presented in Figure 6 and Figure 7. Linear regression lines were added to the plots to aid in the visualization of the general trends in the data.

Results of non-parametric, regression-based trend analysis of annual dissolved solids loads are presented in Table 5. A *p*-value equal to or less than 0.10 was used to judge significance. Trends judged to be significant are shown as percent change per year.

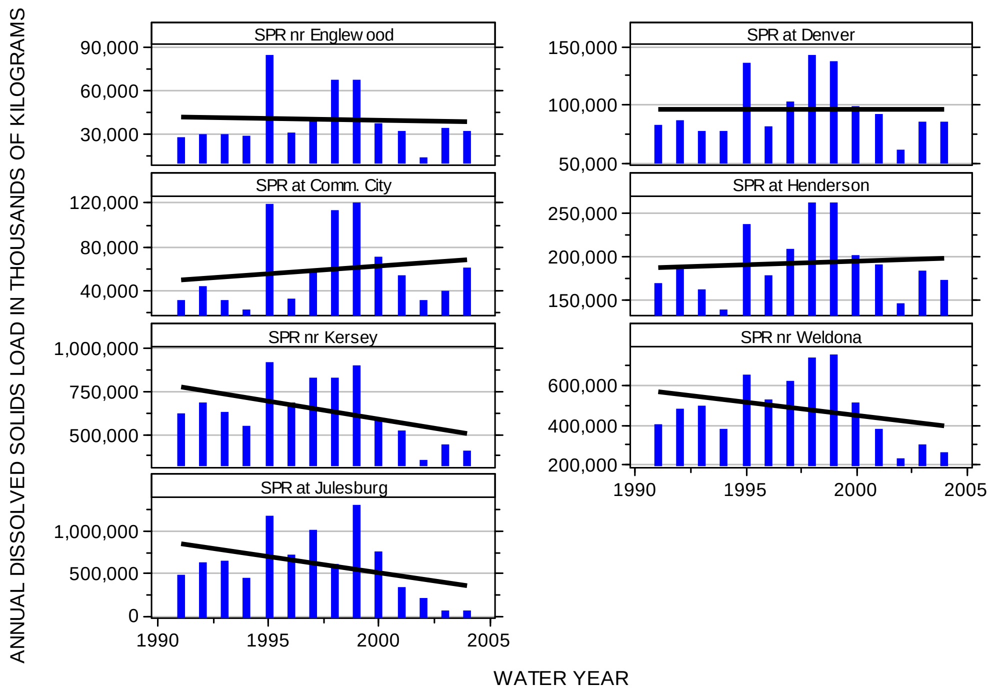

Figure 6. Time series plots of annual dissolved solids loads with linear regression line at selected monitoring sites along the mainstem of the South Platte River, water years 1991-2004.

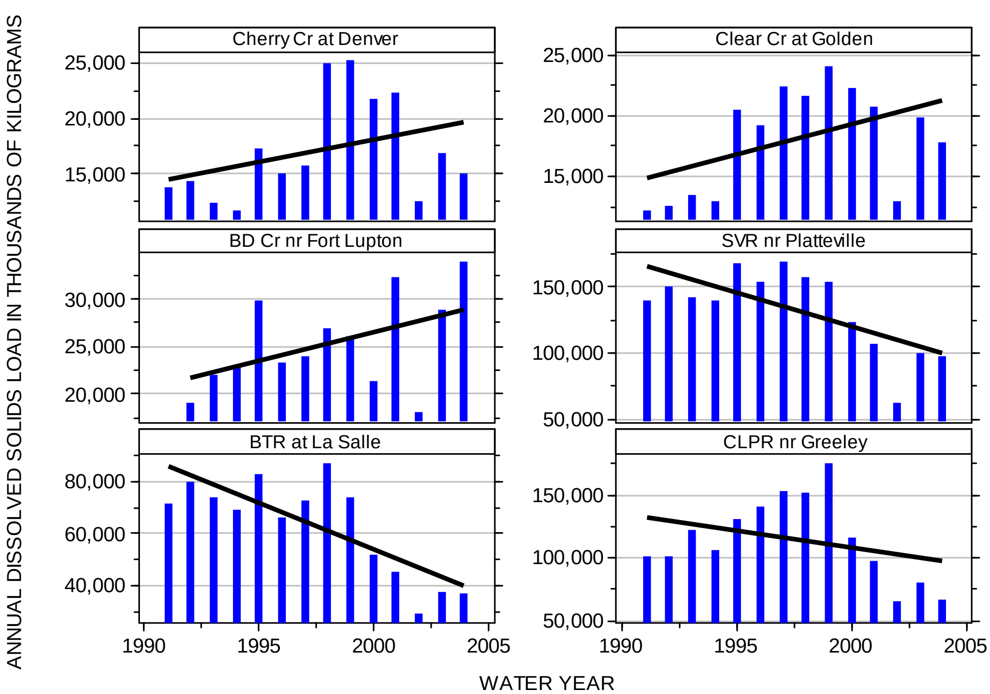

Figure 7. Time series plots of annual dissolved solids loads with linear regression line at selected monitoring sites along tributaries of the South Platte River, water years 1991-2004.

Table 5. Historical trends in total dissolved solids loads at selected sites in the South Platte River Basin, water years 1991 to 2004.

[kg, kilograms; yr, year; %, percent]

Site Name	Period (water years)	Number of Years	Slope (1000 kg/yr)	*p*-Value	Trend (%/yr) *
SPR nr Englewood	1991 - 2004	14	-257	0.358	
Cherry Cr at Denver	1991 - 2004	14	402	0.110	
SPR at Denver	1991 - 2004	14	14	0.681	
SPR at Comm. City	1991 - 2004	14	1,390	0.267	
Clear Cr at Golden	1991 - 2004	14	497	0.140	
SPR at Henderson	1991 - 2004	14	878	0.626	
BD Cr nr Fort Lupton	1993 - 2004	12	604	0.144	
SVR nr Platteville	1991 - 2004	14	-5,059	0.039	-3.8
BTR at La Salle	1991 - 2004	14	-3,561	0.011	-5.7
CLPR nr Greeley	1991 - 2004	14	-2,706	0.197	
SPR nr Kersey	1991 - 2004	14	-20,892	0.064	-3.3
SPR nr Weldona	1991 - 2004	14	-13,657	0.197	
SPR at Julesburg	1991 - 2004	14	-38,152	0.126	

*** Trends shown only for sites with a significance level of 90% or higher**

Only three significant trends in annual dissolved solids loads were detected during the period of study. All three trends were downward and occurred in the middle portion of the study area. Two downward trends in loads were found at the mouths of tributaries. A downward trend of 3.8 percent per year was found for the Saint Vrain River and a downward trend of 5.7 percent per year was found for the Big Thompson River. Only one significant trend was found on mainstem sites. A downward trend of 3.3 percent per year was detected along the South Platte River at Kersey, which is located downstream from the confluence of all three of the largest tributaries including the two with significant downward trends in dissolved solids loads.

SUMMARY AND CONCLUSIONS

Dissolved solids concentrations were found to vary substantially throughout the basin. In general, lower concentrations were found in the upper portion of the study area. Concentrations in the mainstem typically increased in a downstream direction along the river due to evaporative concentration and contributions from higher-concentration tributaries and return flows. Trend analysis of dissolved solids concentrations revealed evidence of increasing trends in concentration at four stations in the upstream urban-dominated portion of the study area and evidence of decreasing trends was found at two locations in the middle and lower regions.

Due to the inflow of the three largest tributaries, most of the dissolved solids load contribution to the river occurs in the middle portion of the basin in the region between Denver and Kersey. Most of the dissolved solids are thought to result from geologic formations in the Front Range area. Even with the large dissolved solids load found at Kersey, dissolved solids concentrations are kept low by the large amount of streamflow in the river. As the river flows through the irrigated agricultural region from Kersey to Julesburg, the dissolved solids load actually decreases slightly. This suggests that instead of contributing additional salts to the river, soils in this region are actually accumulating some of the salts leached from upstream sources. Much of the water volume in the river is lost to consumptive uses. The salts that are left behind cause dissolved solids concentrations in the river to increase sharply to levels that have the potential for deleterious effects on some crop species.

Upcoming changes in water use and river management within the basin are likely to result in reduced mid-basin streamflow and diminished return flows to the river. Due to the high dissolved solids load already in the river in this region, a reduction of lower-TDS water could result in an increase in the magnitude and geographic distribution of elevated TDS concentrations downstream. Because of this potential, it is important for policymakers to consider to what extent a proposed project might impact downstream senior water rights holders before allowing a project to proceed or when placing operational constraints on projects. The complexity of the decision making process increases when the combined downstream impacts of multiple projects are considered simultaneously and indeed might even result in different outcomes. Future research by the authors will explore these issues and attempt to develop a modeling tool to help evaluate impacts of multiple water resource projects on downstream dissolved solids concentrations.

ACKNOWLEDGEMENTS

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AUTOMATIC CONTROL OF CANAL FLOW DISTURBANCES

Albert J. Clemmens[1]

ABSTRACT

Automatic downstream water-level control methods adjust canal flows to correct water level errors. These controllers assume that the rate of change of water level in the pool is related to a mismatch between inflow and outflow. They do not take into account additional outflow changes that result from the water level error. A good example is a canal spill, which is typically not accounted for in the water level control adjustments. In this paper, a new control method is introduced that accounts for both water level errors and flow errors. Control drives the water levels to their set point and flow errors to zero. In the example presented, the disturbance controller reduced canal spills by 30%, over downstream water-level control alone. It is also proposed as a safety precaution for protection of canal linings when downstream water level control is implemented.

INTRODUCTION

Water is released into canals based on user demand. Actual demand by water users on the canal may differ from the rate of flow supplied, for a variety of reasons. This difference in supply and demand is referred to as a flow mismatch. Most canals are not monitored around the clock. If the flow mismatch is observed while operators are on duty, a change in the canal inflow can be made. Canal operators do this routinely. If the flow mismatch is not observed, the mismatch will result in an incorrect amount of water supplied to users or canal spills.

With downstream water level control, it is assumed that if the water level at a canal turnout is at a prescribed level, then the flow rate through the turnout is at the desired rate. By adjusting gates to bring water levels to their set points, a downstream water-level controller eventually adjusts the canal inflow to match the sum of outflows (i.e., user demands). When changes in water orders occur, operators route the flow through the canal starting at the canal head gate. This effectively changes the canal pool volume associated with the new canal flow. When a downstream water level controller reacts to an incorrect downstream flow, it must initially overcorrect the flow change to provide a change in volume.

Downstream water-level controllers are tuned according to either observed or simulated water level response to an upstream flow change. The water level response at the downstream end of a canal pool depends on the hydraulic structures at that location (Strelkoff, et al 1988). Thus, changes in the conditions of downstream gates and structures will change the water level response, as well as the needed control actions. To avoid some of this difficulty, the Integrator-Delay (ID) Model (Schuurmans et al 1999), often used in control design, assumes that the check gate at the downstream end is

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[1] Center Director, U.S. Arid Land Agricultural Research Center, USDA/ARS, 21881 N. Cardon Lane, Maricopa, AZ 85138 bert.clemmens@ars.usda.gov

adjusted to keep the flow constant, thus removing the complexities of the gate structure from the design of water level controllers. However, this method does not consider changes in turnout flow resulting from water level deviations, nor canal spills (e.g., undesired or unregulated flow at the end of the canal). Experience suggests that it takes longer to control the water level in a pool with downstream water-level control when a turnout gate is open than when it is closed. The rationale is that the controller does not consider the change in turnout flow resulting from a change in water level.

In this paper, a new feedback control method is developed that specifically deals with flow errors or flow disturbances that occur. The methods uses the same mathematical procedures as used for water-level-controller design by Clemmens and Schuurmans (2004); namely, Linear Quadratic Regulator (LQR).

THEORY

Water-level Control. The LQR method of Clemmens and Schuurmans (2004) uses state-feedback control with a control law of the form

$$\boldsymbol{u}(k) = -\boldsymbol{K}\,\mathbf{x}(k) \tag{1}$$

where $\boldsymbol{u}(k)$ is the vector of control actions at time k (one element of the vector for each control structure or gate), $\boldsymbol{K}$ is the controller gain matrix, and $\mathbf{x}(k)$ is the vector of states at time k. Here the control actions, $\boldsymbol{u}(k)$, are changes in gate flow rates, i.e., $\Delta Q_j(k)$ for pool j. A separate flow controller is used to adjust the gate position to provide the correct flow rate, which provides a master-slave control scenario.

A linear model is used to describe the change in downstream water level (controlled variable) as a function of a change in the flow rate at the upstream or downstream check structure (control action). The Integrator-Delay (ID) model was chosen as the linear process model (Schuurmans et al 1999). The ID model can be expressed as:

$$\begin{aligned} y_j(t) &= y_j(0) - \frac{t\Delta Q_j}{A_j} && t \le \tau_j \\ y_j(t) &= y_j(0) + \frac{(t-\tau_j)\Delta Q_{j-1}}{A_j} - \frac{t\Delta Q_j}{A_j} && t > \tau_j \end{aligned} \tag{2}$$

where y_j is the downstream water level for pool j, ΔQ_{j-1} is the change in inflow at the upstream end of pool j, ΔQ_j is the change of outflow at the downstream end of pool j, A_j is the backwater surface area for pool j, τ_j is the delay time for pool j, and t is time. Pool parameters A_j and τ_j can be obtained with a step test where the inflow rate at the upstream end of the canal pool is increased suddenly and the water level at the downstream end is observed, with the flow rate at the downstream end held constant. In this model, ΔQ_{j-1} and ΔQ_j are the controlled flow rate changes at the check gates. In the LQR design, this model is essentially inverted, where the observed change in water levels determines a control action, which is a recommended change in flow rate. Thus, this model does not explicitly take into account flow errors.

Values of the gain matrix, $\boldsymbol{K}$, are determined by minimizing the penalty function, J.

$$J = \sum_{k=0}^{\infty} \mathbf{e}(k)^T S\mathbf{e}(k) + \mathbf{u}(k)^T \mathbf{R}\mathbf{u}(k) \quad (3)$$

where $\mathbf{e}(k)$ is the vector of water level errors at time k, **S** is the penalty function for water level errors (usually an identity matrix), and **R** is the penalty function for control actions (only main diagonal elements are non zero). The solution of ***K*** is subject to the dynamic characteristics of the physical system, as described by the state-transition equations which are developed from application of Eq.(2) to each pool, where for each pool j, $e_i(\mathrm{k}) = y_i(k) - y_{\mathrm{spi}}$, and y_{spi} is the water level set point. Note that for discrete incremental form, the state vector, $\mathbf{x}(\mathrm{k})$, includes changes in water level errors $\Delta \boldsymbol{e}(\mathrm{k}) = \boldsymbol{e}(k) - \boldsymbol{e}(k\text{-}1)$, prior water level errors $\boldsymbol{e}(k\text{-}1)$, and some prior control actions $\Delta \boldsymbol{Q}(k\text{-}1)$, $\Delta \boldsymbol{Q}(k\text{-}2)$, etc. to account for the time delay in each pool. See Clemmens and Schuurmans (2004) for further details.

If **S** is an identity matrix, water level deviations in each pool are equally weighted. In this case, equation 3 attempts to minimize the sum of the squares of all water level deviations. The matrix **R** represents the penalty for control actions or changes in check gate flow set points. The intent of **R** is not necessarily to minimize gate movements, but rather to provide more stable control. Following Clemmens and Schuurmans, the diagonal elements in **R** are based on the canal capacity in the pool immediately downstream. Capacities generally decrease in the downstream direction such that **R** values increase. For example, a flow change of 10% capacity in the most upstream gate would have the same influence on the penalty in Eq. (3) as a flow change of 10% of capacity at the furthest downstream gate, even though these flow changes might be quite different.

Standard control engineering solutions are available for computing the gain matrix ***K*** that minimizes ***J***, subject to the state transition equations (Schuurmans 1997). The result is a multiple-input multiple-output (MIMO) Proportional-Integral (PI) controller where all water level errors (and some prior changes in structure flow rates) influence the recommended changes to all structure flow rates, $\mathbf{u}(k)$.

Flow-Disturbance Control. In calibration of the ID model, it is assumed that flow at the downstream end is held constant. However, if a gravity turnout is open, the flow through this turnout will change in response to the pool water level. This flow error is not considered in the LQR controller for water level deviations. Also, many canals have an emergency spill toward the downstream end, so that excess flow will not cause the canal to overtop and breach. If the water level rises high enough to cause a spill, a potentially large rate of outflow could occur. This flow is not currently considered by downstream water level controllers.

It would be desirable to add the flow-disturbance impact to the control in Eq. 1. There are several approaches. First, one could add the flow disturbance to the state vector, $\mathbf{x}(\mathrm{k})$. This creates a technical problem for controller design. Consider the furthest downstream pool. There is both a water level error and a flow disturbance error. Yet there is only one control action; a change in upstream inflow. No controller can move both errors to zero with a single control action. Clearly, in our situation, the flow rate error is related to the water level error. It makes more sense to relate the flow rate error to the water level error. This is problematic in that the water level errors represent the accumulation (integration) of flow rate errors. One could postulate a correction to the water level error based on the flow error, but this would be somewhat arbitrary. For weir spills, this is more problematic. When a spill occurs, the excess volume leaves the canal. If the spill is converted to an equivalent water level error by integrating the spill volume, the water level error would remain high even when the spill stops. Any other method of converting the flow error to a water level error is somewhat arbitrary. An alternative solution, presented below, is to develop a separate controller for flow disturbances, and to couple this controller with the controller for water level error.

A simple linear process model of a flow disturbance is

$$\begin{aligned} q_j(t) &= q_j(0) - \Delta Q_j & t \le \tau_j \\ q_j(t) &= q_j(0) + \Delta Q_{j-1} - \Delta Q_j & t > \tau_j \end{aligned} \tag{4}$$

where $q_j(t)$ is the disturbance flow rate in pool j to be eliminated

A new state vector, $\mathbf{x}_q$ is required, where $\mathbf{q}(k)$ also replaces $\mathbf{e}(k)$. A new gain matrix is determined with the same analytical procedures, producing a new gain matrix $\mathbf{K}_q$.

$$\mathbf{u_q}(k) = - \mathbf{K_q} \, \mathbf{x_q}(k) \tag{5}$$

The same form of penalty function can be used (Eq. 3) where $\mathbf{q}(k)$ replaces $\boldsymbol{e}(k)$.

$$J = \sum_{k=0}^{\infty} q(k)^T S_q q(k) + u_q(k)^T \mathbf{R}_q u_q(k) \tag{6}$$

In implementation, the two solutions $\mathbf{u}(k)$ and $\mathbf{u}_q(k)$ (from Eq. (1) and (5)) are superimposed. This superimposition is particularly important in the case of weir spills because $\mathbf{Q}_q(k)$ is one sided. For notation purposes we call the water level controller LQR_y and the flow disturbance controller LQR_q.

Tuning. For these controllers, setting values for **S**, **R**, $\mathbf{S}_q$ and $\mathbf{R}_q$ determines the controllers' performance, which essentially tunes the controllers. Clemmens and Wahlin (2004) set **S** as an identity matrix, which essentially says that water level deviations in all pools are of equal value, and determined **R** through trial and error. Of importance here is how to tune $\mathbf{S}_q$ and $\mathbf{R}_q$ such that the LQR_q controller will work in harmony with the LQR_y controller. If $\mathbf{S}_q$ is an identity matrix, then flow rate disturbances in all pools are of equal value, which is reasonable and will be used here. Of concern for combining these two controllers is that both adjust check structure flow rates and both use prior check structure flow rate adjustments within the state vector. If the two controllers respond differently to prior control action, then likely they are tuned very differently. The strategy used here was to tune the LQR_q controller until the coefficients in K for the prior control actions approximately matched the corresponding coefficients in the LQR_y controller. This at least gives a first guess at what might be reasonable. In addition, this might allow the two controllers to be integrated as one controller, which won't be discussed further here.

EXAMPLES

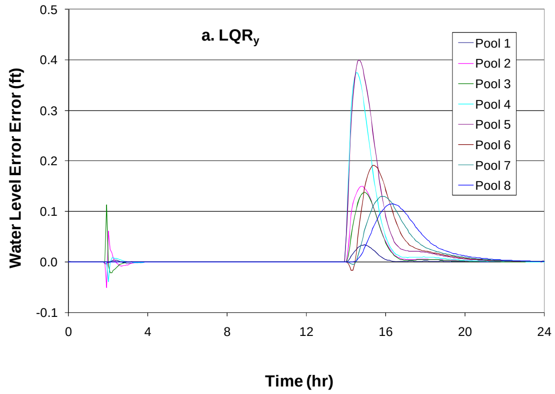
Test Case 1-1 from the ASCE task committee on Canal Automation Algorithms (Clemmens et al 1998) is used to demonstrate the implementation of a flow-disturbance controller. The details of the case are found in Clemmens et al (1998). Details of applying this test are found in Clemmens and Wahlin (2004), along with response for the LQR_y (water level) controller. The feedback controller time step was 5 minutes. They used a value of $R_1 = 20$, where R_1 is the first element in **R** and the rest are determined based on relative capacity. An identity matrix was used for **S** and $\mathbf{S}_q$. $\mathbf{R}_q$ was determined by designing controllers with different $\mathbf{R}_q$ until the controller gains for prior control actions in LQR_q matched those found for LQR_y with $R_1 = 20$. This was achieved at $R_{1q} = 120$.

Clemmens and Wahlin (2004) used the unsteady canal flow model CanalCad (Holly and Parrish, 1992), while here we test with Sobek (2000). The test cases used the following criteria to compare controllers; Maximum Absolute Error (MAE), Integral of Absolute Magnitude of Error (IAE), Steady State Error (StE for last 2 hours of test period) and Integrated Absolute Discharge Change (IAQ in m^3/s). Values were to be provided for two test periods; 0-12 hours in which turnout changes were scheduled and 12-24 hours in which turnout changes were not scheduled and not known by the controller. Also, maximum value for all pools and average values for each criteria are requested (see Clemmens et al 1998 for details). This test was run with LQR_y alone and with LQR_y and LQR_q combined. Here the flow errors at turnouts were determined from the turnout flow equation specified for the test case and the observed water levels.

To test the ability of the flow-disturbance controller to deal with weir flow, Test Canal 1 was modified to include a weir (6.5 ft, 2 m wide) and an additional pump outlet in pool 7. The initial conditions for Test 1-1 were used, except that the flow to the turnout in pool 8 was instead pumped out in pool 7, so that there was no flow in this downstream pool (7-pool example). Thus, the flows from the head gate down to check gate 6 were identical to Test 1-1. To create a flow change, the pump outlet (3.5 cfs, 0.1 m^3/s) in pool 7 was simply turned off. This creates excess flow in pool 7. This scenario was tested without the weir with LQR_y alone and with LQR_y and LQR_q combined. Then, the same tests were made with the weir in place. LQR_q was tested with two different scenarios. First, the weir flow was ignored so that only changes in turnout flows were considered. Then, both the weir and turnout flow errors were considered. Finally, a set of tests were included for a wider (13 ft, 4 m wide) weir to demonstrate the impact of this factor.

Table 1. Test Case 1-1: Control results for LQR_y only and for LQR_y & LQR_q control.

		MAE12	MAE24	IAE12	IAE24	StE12	StE24	IAQ12	IAQ24
		%	%	%	%	%	%	(cfs)	(cfs)
LQRy	Maximum	4.3	13.5	0.1	1.8	0.0	0.1	2.4	3.5
	Average	1.0	6.8	0.0	1.0	0.0	0.0	0.7	2.5
LQRy & LQRq	Maximum	4.3	13.6	0.1	1.8	0.0	0.1	2.6	3.6
	Average	1.0	6.7	0.0	1.0	0.0	0.0	0.7	2.6



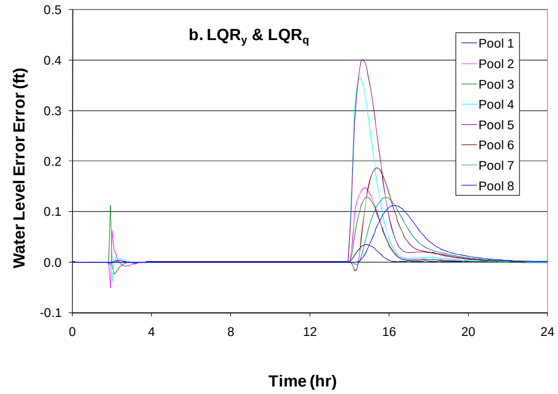


Figure 1. Water level errors for ASCE Test Case 1-1

RESULTS

The water level responses for LQR_y and for LQR_y and LQR_q combined are shown in Figure 1a and b, respectively. The tabulated performance results are given in Table 1. The LQR_y results are very close to the results presented in Clemmens and Wahlin (2004). They should be the same, but since different models were used some small differences are expected. Here we are interested in the change in results caused by the addition of the LQR_q controller. The main differences in performance indicators were for MAE. The LQR_q controller caused a slightly higher maximum value of Maximum Absolute Error (last half of test), and a smaller average value of Maximum Absolute Error (last half of test). In six of the eight pools the MAE value was smaller with the addition of the LQR_q controller. This difference can be seen by greater differences in the two highest peaks in Figures 1a and 1b. The differences are not very significant and are on the order of difference we would see with slightly different tuning of the LQR_y controller. In this situation, the turnout flow errors are very small relative to actual turnout flows; thus, addition of the LQR_q controller seems of little benefit for this situation (i.e., minor turnout flow errors).

Figure 2 shows the water level response resulting from turning off the pump in pool 7, without the weir in place, both with and without the disturbance controller (LQR_q). The sudden decrease in turnout flow results in a very large change in water level. Figure 3 shows the resulting change in check structure flows. Note that the flow rate decreased by more than the 3.5 cfs (0.1 m^3/s) turnout change, essentially to compensate for the extra volume. If the flow change had been scheduled, the head gate flow change would have occurred at least an hour before the turnout was closed. Note that the addition of the LQR_q controller slightly reduced the maximum water level deviation and brought the water levels back to the respective set points slightly faster. This is because the flow decrease was larger and occurred sooner (Figure 3b). Again, these differences are relatively small.

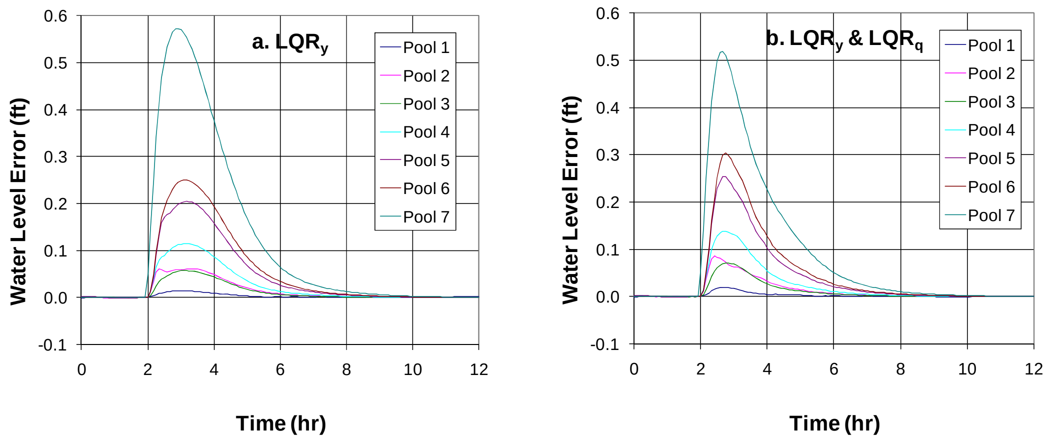


Figure 2. Water level errors for a 7-pool example with no weir.

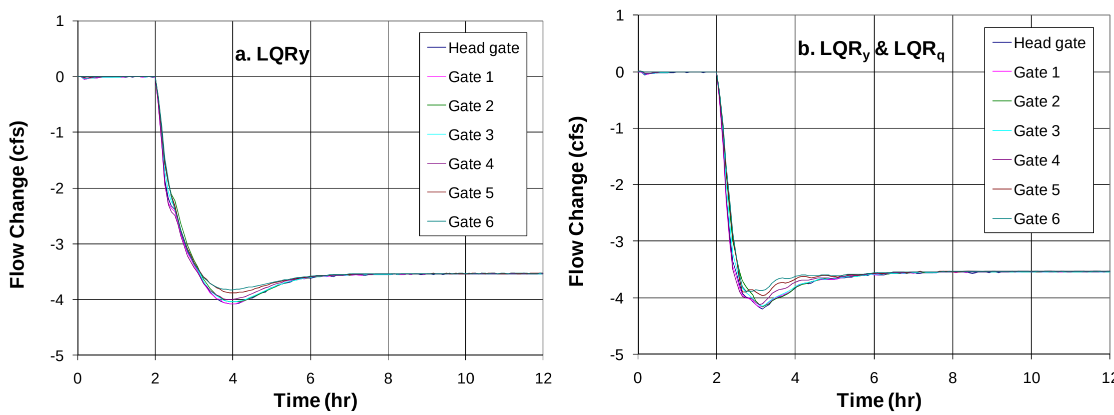


Figure 3. Flow rate response for a 7-pool example with no weir.

Adding the overflow weir in pool 7 delays the response of the downstream water level controller. First, the water level deviation is smaller since water spills over the weir rather than adding to the observed water depth. Then, the controller makes insufficient changes in canal inflow because it does not take the weir flow into account. Figure 4a shows the water level response for a downstream water level controller (LQR_y) with the weir in place. Compared to Figure 2, without the weir, the deviation is much smaller, but occurs for a longer period of time. The weir crest is 0.16 ft (0.05 m) above the water level set point, and one can see how the water level response speeds up when the water level has dropped below the weir crest. Adding a disturbance controller (LQR_q) that only considers the error in turnout (or offtake) flow due to the water level deviation ($LQR_{q\text{-}off}$) makes only a small improvement (Fig. 4c). Adding the weir flow as a disturbance (LQR_q) speeds up the response, as shown in Figure 4e. One sees small oscillations in the water level response. These do not appear to increase in magnitude, so they are not a major concern.

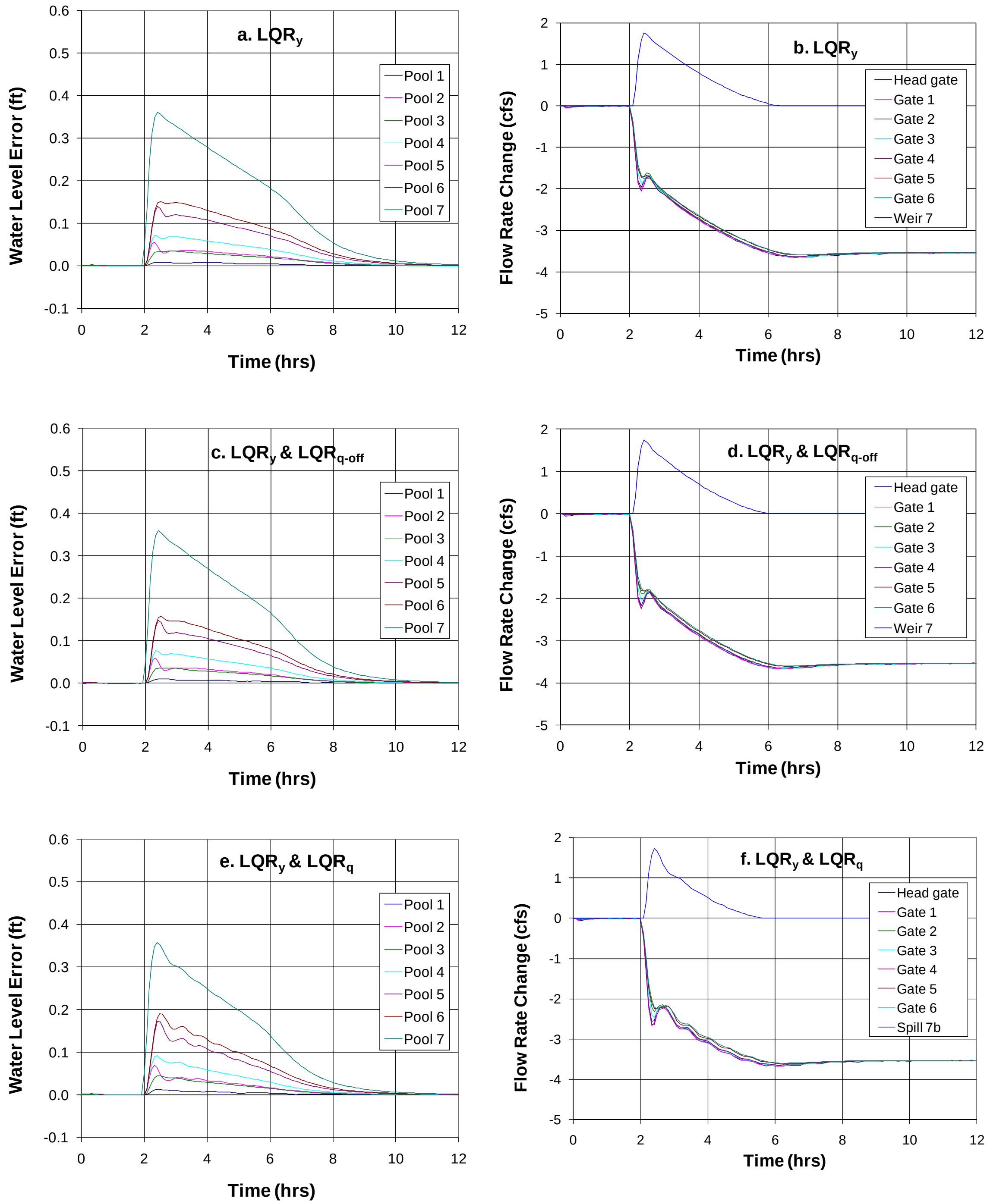


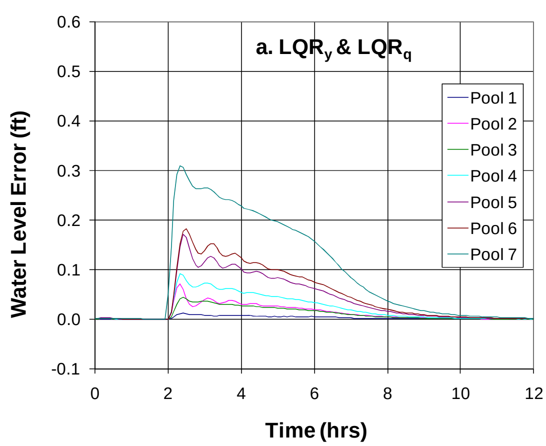
Figure 4. Water level errors and upstream flow rate changes for a 7-pool example with a 6.5 ft (2 m) wide weir. LQR_y, LQR_y & $LQR_{q\text{-}off}$ (turnouts only), and LQR_y & LQR_q (turnouts and spill) controllers.

Also shown in Figure 4 are the flow rate changes from the initial conditions. The weir flow is shown at the top of the graph. In Figure 3, the flow rates without the weir are shown. As discussed above, the flow decreases have to exceed the amount of the turnout flow decrease. In Figure 4, this does not occur because the excess water spills over the weir. Note that the area under the weir flow curve (volume) closely approximates the excess structure flow that occurs after the pump outlet is shut off (i.e., area between curves and -3.5 cfs{0.10 m^3/s}, after 2 hours). When the turnout flow changes are taken into account (Fig 4d), the weir flow stops a little earlier and the structure flows drop more quickly, but not by a lot. However, when the weir flow is included in the disturbance controller (Fig 4f), the structure flow drops much more quickly. The flow change rebounds somewhat because the water levels drop very rapidly, but there is a significant reduction in spill volume, as shown in Table 2. With only water level control, the spill volume is 0.25 ac-ft (312 m^3). When the weir flow rate (spill) is included in the LQR_q controller, the spill volume drops to 0.18 ac-ft (227 m^3), about a 30% drop for this example (Table 2). The spill volume when considering only the turnout flow errors is in between (0.23 ac-ft or 283 m^3).

Table 2. Spill volume for various controllers for the 7-pool example.

	Volume Spilled	
Controllers	6.5 ft (2 m) weir	13 ft (4 m) weir
	(ac-ft)	(ac-ft)
LQR_y	0.25	0.34
LQR_y & $LQR_{q\text{-}off}$ (offtake only)	0.23	0.31
LQR_y & LQR_q (offtake and spill)	0.18	0.23

More of the spill volume could be recovered by using more aggressive controllers (i.e., tuned with a larger value of R_1). While R_1 = 20 was used in this example, R_1 = 10 gives better results for test case 1-1. The higher value was chosen to provide more stable control as canal conditions change over time. Similarly, more of the spill could be captured with a lower value of R_{1q}. The small oscillations shown in Fig 4c might suggest that a lower value of R_{1q} is not advisable. If removing the spill is a high priority, one could experiment with lower values and decide whether or not the increased oscillations are a concern.



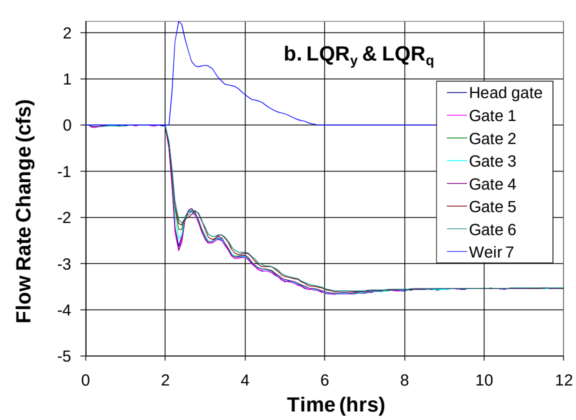


Figure 5. Water level errors and upstream flow rate changes for a 7-pool example with 13 ft (4 m) wide weir. LQR_y & LQR_q (turnouts and spill) controllers.

Also shown in Table 2 are the spill volumes for a 13 ft (4-m) wide weir. As one would expect, the spill volumes are larger. The water level doesn't need to get as high to spill the rejected delivery (Figure 5). However, the water level doesn't have to drop as far to drop below the weir crest, so for example, the amount of spill isn't doubled. The addition of the disturbance controller reduced the spill by more than 30%, where for the narrow weir it was less than 30%. Because of the larger spill flows, water levels and flows oscillate a bit more than for the 6.5 ft (2-m) wide weir, again suggesting that reducing R_{1q} may not be a good idea.

DISCUSSION

The initial motivation for the disturbance control was not spills, but providing protection for canals operated under downstream-level control. Large disturbances cannot be handled by downstream water-level controllers. If a large flow change occurs a long distance from the head gate, a large water-level deviation will occur because there is insufficient time for the flow change to arrive from upstream. In the implementation of the downstream water level control proposed by Clemmens and Schuurmans (2004) and implemented by Clemmens and Strand (2010a), each check gate is under flow control so that each gate will control the flow rate passing downstream. The downstream controller simply determines the flow rate. With a large unanticipated flow change in a pool and a flow rate control for the check gate, the water level can quickly exceed the allowable range (e.g., a minimum level for operation of turnouts and a maximum level to avoid canal overtopping, or for large canals a maximum rate of water level change).

The solution was to consider the water level to be "out-of-bounds" when the water level exceeds the allowable levels. Under "out-of-bounds" conditions, control of the check gate is changed from flow-rate to upstream-level control. This protects the canal where the disturbance occurs. The difference between the flow rate set point determined by the water level controller and the actual flow through the structure as the result of upstream water level control is the flow disturbance error, which is passed downstream. The disturbance controller was intended to account for this flow disturbance error by sending a signal upstream to change the canal flow to correct for the large disturbance. Then, when the flow through the upstream controlled gate returns to the flow set point, control of that gate reverts back to flow rate control. To date, the disturbance controller has only been tested on a real canal with a simple integral (I) controller with an untuned gain. This was used by Clemmens and Strand (2010a) just to have something operational prior to development of the disturbance controller.

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ASSESSMENT OF ECONOMIC AND HYDROLOGIC IMPACTS OF REDUCED SURFACE WATER SUPPLY FOR IRRIGATION VIA REMOTE SENSING

Duncan MacEwan[1]
Bryan Thoreson[2]
Josue Medellin-Azuara[1]
Byron Clark[2]
Richard Howitt[1]
Grant Davids[2]

ABSTRACT

Reduced surface water supplies in the Southern San Joaquin Valley of California in recent years have forced growers to make difficult decisions regarding cropping, irrigation practices, and groundwater use. There is interest in objectively quantifying economic and hydrologic impacts of these reductions at levels ranging from locally-affected communities to the State and Federal governments. However, the ability to analyze impacts is limited by the unavailability of timely disaggregated data. This paper explores the opportunity to apply satellite remote sensing of crop evapotranspiration and biomass production to increase information available and perform objective analysis of the actual economic and hydrologic impacts incurred.

INTRODUCTION

According to the California Department of Water Resources Water Plan Update 2009[3], of the 82 million acre-feet (maf) of water used (applied water) in California in 2005, 8.9 maf went to urban uses, 32 maf went to agriculture, and 41.1 maf went to other (including environmental) uses. Put into percentage terms, urban uses, agriculture, and the environment account for 11, 39, and 50 percent, respectively, with agriculture representing 78 percent of non-environmental usage. The future balance between uses will be largely shaped by urban growth and climate change (Howitt, Medellin-Azuara and MacEwan 2009), water quality (Howitt et al. 2009), environmental needs (Lund et al. 2010), and the policies that California adopts in response. These factors, combined with the stochastic nature of precipitation, have generated a growing demand for efficient and timely agricultural policy analysis. Satellite remote sensing offers real-time spatial data which can be instrumental for formulating effective policy. We explore the value of this data for defining spatial agricultural production and water use, cropped area, and economic value of precise information measures using a case study region of the San Joaquin Valley of California.

The San Joaquin Valley of California is in the Southern Central Valley bordered by the Sacramento-San Joaquin Delta to the North and the Tehachapi Mountains to the South, as seen below in Figure 1. The economy in the region is driven by agriculture, representing

[1] University of California at Davis, One Shields Ave., Davis, CA, 95616; djmacewan@ucdavis.edu
[2] SEBAL North America, Inc., 1772 Picasso Ave., Suite E, Davis, CA, 95618; byron@sebal.us
[3] http://www.waterplan.water.ca.gov/docs/cwpu2009/0310final/highlights_cwp2009_spread.pdf

Figure 1. Map of the San Joaquin Valley.

approximately 24 percent of statewide gross agricultural revenues and 16 percent of statewide agricultural acres[4] in 2005. The most prevalent crops in terms of total acres planted in 2005 include (excluding pasture/rangeland) alfalfa, almonds, pistachios, grapes, cotton, and processing tomatoes. Table 1 (a, b, and c) summarizes these crops in terms of total acres, total harvested production, and total gross revenues between the state and the San Joaquin Valley in 2005. As the data show, this region produces a large proportion of production across the state, including high-value fruit and nut crops.

Table 1a. Total Harvested Acres

Select Crops	Harvested Acres in CA	Harvested Acres in San Joaquin	Percent of State Acres
Alfalfa Hay	2,189,558	557,060	25.4%
Almonds	1,223,446	483,856	39.5%
Pistachios	230,698	102,210	44.3%
Grapes (All)	1,667,288	538,117	32.3%
Cotton	1,445,256	465,535	32.2%
Processing Tomatoes	612,930	187,413	30.6%

[4] Source: 2005 County Agricultural Commissioners' Reports

Table 1b. Total Production (Yield)

Select Crops	Production in CA	Production in San Joaquin	Percent of State Production
Alfalfa Hay	15,743,316	4,408,928	28.0%
Almonds	1,008,560	405,697	40.2%
Pistachios	336,134	148,341	44.1%
Grapes (All)	13,423,848	5,047,386	37.6%
Cotton	934,126	291,447	31.2%
Processing Tomatoes	23,176,516	7,239,241	31.2%

Table 1c. Total Gross Revenues ($M)

Select Crops	Gross Revenues in CA	Gross Revenues in San Joaquin	Percent of State Gross Revenues
Alfalfa Hay	2,100	616	29.3%
Almonds	5,738	2,309	40.2%
Pistachios	1,434	625	43.6%
Grapes (All)	8,292	2,076	25.0%
Cotton	1,464	494	33.7%
Processing Tomatoes	1,177	371	31.5%

The climate of the San Joaquin Valley is semi-arid, consisting of cold and damp winters and hot and dry summers. With summer representing the main growing season there is a heavy dependence on irrigation water from both groundwater and surface water supplies. Surface water supplies come from three main sources, including local agency supplies, the State Water Project (SWP), and the Central Valley Project (CVP). The CVP and SWP were developed in order to provide water for the southern part of the state because 70 percent of yearly runoff occurs north of the San Joaquin Valley. SWP and CVP supplies are pumped from the northern border of the San Joaquin Valley, the Sacramento-San Joaquin Delta utilizing the Delta as a central hub for conveying California's water.

There is significant heterogeneity in water availability within the San Joaquin Valley. On the eastern side of the valley, runoff from the Sierra Nevada Mountains is captured in reservoirs and used to supply irrigation water for agriculture on the valley floor. In the west, limited runoff from the Coastal Range is available leading to a higher dependence on state and federal conveyance projects. Additionally, there are significant differences in groundwater quality due to the presence of shallow groundwater salinity. Salinity problems are concentrated on the west side of the San Joaquin Valley and have significant effects on profitability through reduced crop yields and increased costs of abatement (Howitt et al. 2008b). To highlight the differences between the east and west sides of the San Joaquin Valley, Table 2 summarizes water supply availability (in thousands of acre feet) from six main sources in 2005. Sources include CVP, SWP, groundwater, local agency water, settlement and exchange contractor water (part of CVP with different water rights), and Friant Kern (also part of CVP). According to the California Department of Water Resources (DWR) classification by the composite river index for the San Joaquin Valley, 2005 represents a "wet" water year type[5]. As such, Table 2 shows above average deliveries of CVP and SWP water. East- and west-side regions are classified according to Statewide Agricultural Production Model (SWAP[6])

[5] http://cdec.water.ca.gov/cgi-progs/iodir/wsihist
[6] swap.ucdavis.edu

regions which represent homogenous agriculture sub-regions within the Central Valley of California.

Table 2. San Joaquin Water Availability for 2005

Water Source	West San Joaquin (kaf)	East San Joaquin (kaf)
CVP	1,533	1,239
Settlement and Exchange (CVP)	768	0
Friant	41	256
SWP	1,376	1
Local	1,196	4,061
Groundwater	1,874	2,267

As Table 2 indicates, there is significant variability in water deliveries within the San Joaquin Valley. East-side regions see nearly four times the surface water availability from local agencies than the west side, in addition to 20 percent more groundwater availability. Consequently, west-side regions have higher reliance on CVP and SWP deliveries relative to the east side. Water availability for west-side San Joaquin Valley regions and, in turn, agricultural production, hinges critically on the ability of the Sacramento-San Joaquin Delta to convey water from the northern part of the state. During periods of dry water years this places significant strain on the Delta ecosystem. In addition to being a hub for water conveyance, the Delta is the largest estuary in the Western U.S. and home to a wide variety of unique wildlife. The related issues are consistently at the forefront of environmental policy debate in California.

In response to increasing environmental awareness regarding the Delta ecosystem and concerns over environmental protection for Delta Smelt, Judge Oliver Wanger issued an Interim Remedial Order Following Summary Judgment and Evidentiary Hearing (2007) on December 14, 2007. The Interim Order effectively restricted Delta exports to users south of the Sacramento-San Joaquin Delta. Initial analysis found that expected economic impacts to San Joaquin Valley agriculture in 2008 were over $1 million in lost profits due to expected export restrictions for Delta Smelt with 800 direct agricultural job losses (Sunding et al. 2008). Subsequent analysis based on realized export restrictions estimated losses in gross revenues in 2009 of $586 million with 4,800 direct agricultural job losses due to pumping restrictions (Howitt, Medellin-Azuara and MacEwan 2009). Due to the heavy reliance on state and federal project deliveries, these impacts are largely concentrated along the west side of the San Joaquin Valley.

A limitation of studies like those cited above is the ability to capture spatial variation in agricultural production and water use and measure these changes in real time. To the extent that export restrictions affect localized regions differently there is some error in the analysis based on aggregate data. For example, Westlands Water District on the west side of the San Joaquin Valley is heavily dependent on CVP deliveries due to a lack of local surface water availability and limited access to good-quality groundwater. The region produces high value agriculture including fruit and nut orchards which require a continuous supply of water. As such, interruptions in deliveries due to export restrictions have relatively larger effects in regions such as Westlands relative to east-side regions with more access to groundwater and local surface supplies. Remote-sensing data offers the ability to accurately quantify these spatial differences and properly determine localized effects. Furthermore, these data are collected in real time, thus eliminating the need for forecasts of expected effects.

In addition to facilitating accurate analysis of localized effects remote-sensing data offer insights into spatial variation in production and water use across fields. To the extent that there are differences in human and physical capital across fields within an otherwise homogenous agricultural region there are likely differences in production and water use. Policies based on aggregate (county level) data omit these potentially important differences which can lead to extra costs incurred by government.

SEBAL ANALYSIS OF CHANGES IN CONSUMPTIVE USE AND BIOMASS PRODUCTION

Available datasets developed using the Surface Energy Balance Algorithm for Land (SEBAL®) were analyzed in order to explore the ability of remote sensing to evaluate spatial variability in agricultural production and water use. Additional information describing SEBAL and its validation are available from Bastiaanssen et. al (2005) and Bastiaanssen and Ali (2003). Specifically, cumulative crop consumptive use and total dry biomass production were extracted for selected water districts within the southern San Joaquin Valley for a base year (2005) and for 2008. Within each area, total consumptive use of water and biomass production were quantified. These results are compared with relative estimates of water supply across years to explore relationships between available surface water supplies and agricultural water use and resulting crop production and economic returns.

Selection of Analysis Areas

Areas were selected for analysis from a geographic coverage of water district boundaries provided by the DWR through the California Spatial Information Library (CaSIL). Coverage is provided for federal, state, and private water districts. Within the satellite image coverage area, the 10 largest water districts were selected for analysis, based on gross acreage from the geographic coverage. The 10 selected districts are listed in Table 3. The district boundaries and satellite image coverage area are shown in Figure 2.

Designation of Agricultural Areas and Extraction of Consumptive Use and Biomass Production Results

SEBAL estimates of crop evapotranspiration and biomass production were extracted for individual fields within the analysis areas. A geographic coverage of field polygons was developed by combining land-use shape files developed by the DWR for individual counties within the satellite coverage area. These shape files include polygons for agricultural, urban, and other land uses.

Table 3. Selected Water Districts.

Area	Water Supply	Gross Acres
Westlands Water District	CVP, groundwater	605,894
Kaweah Delta Water Conservation District	Local runoff, groundwater, limited CVP (Friant)	337,979
Fresno Irrigation District	Local runoff, groundwater, CVP (Friant)	247,774
Semitropic Water Storage District	SWP, groundwater	223,602
Tulare Lake Basin Water Storage District	SWP, groundwater	190,151
Consolidated Irrigation District	Local runoff, groundwater	160,704
Kings County Water District	SWP, groundwater	143,461
Alta Irrigation District	Local runoff, groundwater	134,356
Lower Tule River Irrigation District	Local runoff, CVP (Friant), groundwater	103,104
Belridge Water Storage District	SWP, groundwater	98,301
TOTALS		2,245,325

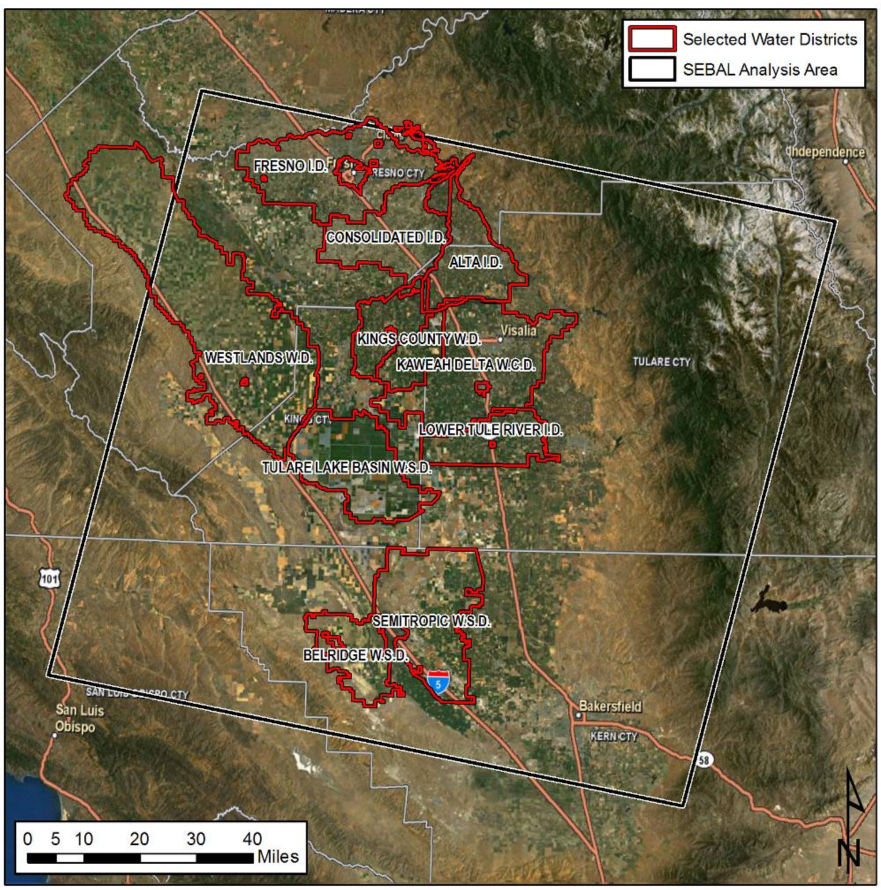

Figure 2. Selected Water Districts in the San Joaquin Valley

To isolate agricultural areas, the DWR land use polygons were overlain with a state-wide raster coverage of land use developed by the USDA NRCS for 2007. The majority land use type within each polygon was assumed to be representative of the polygon as a whole. Polygons with the majority land use classified as an agricultural crop were selected for extraction of the SEBAL results.

Prior to extracting the SEBAL results, the polygons were buffered inward by 60 meters to reduce or eliminate edge effects that could result from satellite pixels overlapping the field boundaries, or from slight mismatches between the field boundaries and satellite imagery. Polygons less than eight acres in size following buffering were excluded from the analysis to provide a sufficient number of pixels within each field to develop a representative estimate of mean actual ET and biomass production.

Mean actual evapotranspiration and biomass production were calculated for each polygon on an approximately monthly basis for the period from May to September for the years 2005 and 2008. Values for each field were stored in an MS Access database for further analysis.

Cumulative Consumptive Use and Biomass Production Estimates for Selected Areas

Cumulative consumptive use estimates for the study areas for the growing seasons of 2005 and 2008 are summarized in Table 4. Additionally, the percent difference in consumptive use of water from 2005 to 2008 is provided.

A reduction in consumptive use occurred between 2005 and 2008 for 8 of the 10 selected water use areas, with an overall reduction of approximately 6 percent. The change in consumptive use among areas ranged from a reduction of 21 percent for the Tulare Lake Basin Water Storage District to an increase of 15 percent for the Belridge Water Storage District.

Cumulative biomass production estimates for the study areas for the growing seasons of 2005 and 2008 are summarized in Table 5. Additionally, the percent difference in biomass production from 2005 to 2008 is provided.

A reduction in biomass production occurred between 2005 and 2008 for 5 of the 10 selected water use areas, with an overall reduction of approximately 3 percent. The change in biomass production among areas ranged from a reduction of 23 percent for the Tulare Lake Basin Water Storage District to an increase of 20 percent for the Belridge Water Storage District.

WATER SUPPLY ASSESSMENT FOR 2005 AND 2008

Federal, state and private water districts have different primary water sources. Private water districts' main supply source is private water rights on local streams. Some of these private water districts have built storage reservoirs. The Central Valley Project (CVP) and the State Water Project (SWP) are the main supply sources for federal and

Table 4. Estimates of Growing Season Actual Evapotranspiration for Selected Areas for 2005 and 2008

				May-September Actual Evapotranspiration				
			Acres	2005		2008		%
Area	Water Supply	Gross Acres	Sampled	ac-ft	ac-ft/ac	ac-ft	ac-ft/ac	change
Westlands Water District	CVP, groundwater	605,894	316,449	438,876	1.4	435,629	1.4	-1%
Kaweah Delta Water Conservation District	Local runoff, groundwater, limited CVP (Friant)	337,979	126,349	417,367	3.3	400,019	3.2	-4%
Fresno Irrigation District	Local runoff, groundwater, CVP (Friant)	247,774	70,873	128,616	1.8	127,667	1.8	-1%
Semitropic Water Storage District	SWP, groundwater	223,602	116,609	231,266	2.0	209,524	1.8	-9%
Tulare Lake Basin Water Storage District	SWP, groundwater	190,151	161,436	298,616	1.8	235,799	1.5	-21%
Consolidated Irrigation District	Local runoff, groundwater	160,704	65,085	114,257	1.8	102,719	1.6	-10%
Kings County Water District	SWP, groundwater	143,461	89,333	194,794	2.2	188,217	2.1	-3%
Alta Irrigation District	Local runoff, groundwater	134,356	50,074	114,049	2.3	117,090	2.3	3%
Lower Tule River Irrigation District	Local runoff, CVP (Friant), groundwater	103,104	55,884	126,586	2.3	116,254	2.1	-8%
Belridge Water Storage District	SWP, groundwater	98,301	39,915	63,871	1.6	73,605	1.8	15%
TOTALS		2,245,325	1,092,008	2,128,297	1.9	2,006,524	1.8	-6%

Table 5. Estimates of Growing Season Biomass Production for Selected Areas for 2005 and 2008

				May-September Biomass Production				
			Acres	2005		2008		%
Area	Water Supply	Gross Acres	Sampled	tons	t/ac	tons	t/ac	change
Westlands Water District	CVP, groundwater	605,894	316,449	1,268,084	4.0	1,274,182	4.0	0%
Kaweah Delta Water Conservation District	Local runoff, groundwater, limited CVP (Friant)	337,979	126,349	1,233,601	9.8	1,262,685	10.0	2%
Fresno Irrigation District	Local runoff, groundwater, CVP (Friant)	247,774	70,873	398,524	5.6	394,149	5.6	-1%
Semitropic Water Storage District	SWP, groundwater	223,602	116,609	719,010	6.2	657,347	5.6	-9%
Tulare Lake Basin Water Storage District	SWP, groundwater	190,151	161,436	828,058	5.1	639,944	4.0	-23%
Consolidated Irrigation District	Local runoff, groundwater	160,704	65,085	365,943	5.6	338,079	5.2	-8%
Kings County Water District	SWP, groundwater	143,461	89,333	591,101	6.6	590,619	6.6	0%
Alta Irrigation District	Local runoff, groundwater	134,356	50,074	342,938	6.8	363,602	7.3	6%
Lower Tule River Irrigation District	Local runoff, CVP (Friant), groundwater	103,104	55,884	391,057	7.0	373,398	6.7	-5%
Belridge Water Storage District	SWP, groundwater	98,301	39,915	196,972	4.9	235,416	5.9	20%
TOTALS		2,245,325	1,092,008	6,335,289	5.8	6,129,420	5.6	-3%

state water districts, respectively. Additionally, all of these districts supplement their main source of supply with groundwater and water transferred from users in other areas of the state.

The goal of all these districts is a constant, reliable water supply for agriculture. In general, the water supply varies depending upon the amount of snow received in the winter and the amount of water available through the CVP and SWP (dependent on winter rain and snow in northern California). Generally, in even the wettest years, there is some volume of groundwater included in the supply. In years with limited surface water supplies, groundwater pumping is increased to supplement the surface supply. In these low surface supply years, efforts to purchase water from users in other areas also increase.

In 2007, the Wanger decision restricted pumping from the Delta by the CVP and SWP, adding an additional water supply constraint on the federal and state districts. In the short-term, it is likely that this reduced supply will be replaced with additional groundwater pumping. However, in the long term, this may not be sustainable.

Water supplies can be assessed for the federal and state districts by comparing the CVP and SWP allocations for 2005 and 2008. As general indicators of local surface water supply availability, the DWR defines San Joaquin River Basin water years types based on the measured unimpaired runoff of four rivers. The four rivers are: (1) Stanislaus River inflow to New Melones, (2) Tuolumne River inflow to New Don Pedro, (3) Merced River inflow to New Exchequer, and (4) San Joaquin River inflow to Millerton. For local districts, this index provides a convenient metric to assess the availability of water from the local streams.

The federal and state districts had 2008 allocations of 40 and 35 percent compared to 2005 allocations of 85 and 90 percent relative to their contract entitlements, respectively (Table 6). The private districts also had a significantly reduced supply with 2008 being a critical water year compared to a wet year in 2005 based on the San Joaquin Valley Water Year Index developed by the DWR[7].

Table 6. Relative Surface Water Supplies in 2005 and 2008

District Type	2005	2008
Federal	85%	40%
State	90%	35%
Private	Wet	Critical

These are significant reductions in the district's main water supplies; however, districts have differing abilities to supplement these supplies with groundwater and additional supplies obtained through water transfers. In any given year, some districts may be able replace these reduced supplies through the two-pronged approach of increased groundwater use and increased water transfers. Additionally, when water supplies are scarce growers can maximize returns to water by applying the reduced supplies on their most fertile land.

ESTIMATION OF THE ECONOMIC VALUE OF EVAPOTRANSPIRATION

The economic value of water is by definition the shadow (scarcity) value of an additional unit of water. A farmer operating under a water constraint is willing to pay an amount in order to secure an additional unit of water, thereby relaxing the water constraint and

[7] http://cdec.water.ca.gov/cgi-progs/iodir/wsihist

allowing for additional crops to be grown, and this value is called the shadow value of water. In general, this value depends on the types of crops being grown, production practices, and degree of water scarcity. For example, a farmer growing almonds will be willing to pay more than the same farmer growing alfalfa when facing an identical water shortage, all else being constant. This reflects the fact that stress irrigation is more feasible with alfalfa, and almonds are of relatively higher value. The economic value of water varies significantly between regions in the San Joaquin Valley with west-side regions seeing higher values than those on the east side in response to water availability.

To determine the economic value of evapotranspiration (ET) we use the Statewide Agricultural Production Model (SWAP) to quantify farmers' growing decisions and to determine the marginal value of an additional acre-foot of water. SWAP was developed by Howitt and collaborators (2001) for the original use of providing the economic scarcity cost of water for agriculture to CALVIN (Jenkins et al. 2001), a statewide economic engineering optimization model for water management in California.[8] More recently, SWAP has been used to estimate economic losses due to salinity in the Central Valley (Howitt et al. 2008a), economic losses to agriculture in the San Joaquin Delta (Appendix to Lund et al. 2007), economic losses for agriculture and confined animal operations in California's Central Valley (Appendix to Lund et al. 2008), and economic losses due to Delta export restrictions (Howitt et al. 2009).

SWAP, at its root, is a mathematical programming model for major crops and regions in California and uses Positive Mathematical Programming (PMP) (Howitt 1995). PMP is a deductive approach to evaluating the effects of policy changes on cropping patterns at the extensive and intensive margins. SWAP is a three-step, self-calibrating model that assumes that farmers behave in a profit-maximizing fashion. In the first step, a linear program for profit maximization is solved. In addition to the traditional resource and non-negativity constraints, a set of calibration constraints is added to restrict land use to observed values. In the second step, the optimization first-order conditions are used to derive the parameters for an exponential cost function and a non-linear Constant Elasticity of Substitution (CES) production function. The third and last step incorporates the parameterized functions from step two into a non-linear profit maximization program, with constraints on resource use.

SWAP is calibrated to agricultural data from 2005, representing the most recent comprehensive set of agricultural production data available for the state. Three scenarios are considered in order to generate a range of shadow values of water, a base case with no shortage, a case with a 10 percent reduction in total available irrigation water, and a case with a 20 percent reduction in total available irrigation water. Since SWAP is an economic model and production decisions are based on applied water, the model results generate the marginal value of an additional acre-foot of applied water. We used DWR regional water use efficiency estimates to generate the marginal value of an acre-foot of ET. Within each SWAP region there is a value of ET associated with each individual crop grown, based on this efficiency measure. We aggregated by weighted average over

[8] http://cee.engr.ucdavis.edu/CALVIN.

all crops in the region to generate a region specific shadow value of ET. Results are summarized in Table 7 below for the 10 selected geographic regions.

Table 7. Economic Value per acre-foot of ET

Area	BASE $ET	10% Shortage $ET	20% Shortage $ET
Westlands WD	$246.99	$402.97	$938.17
Kaweah Delta Water CD	$159.71	$279.69	$318.66
Fresno ID	$193.80	$461.39	$764.88
Semitropic Water SD	$142.87	$275.11	$351.63
Tulare Lake Basin Water SD	$176.87	$282.28	$338.55
Consolidated ID	$168.30	$324.93	$859.59
Kings County WD	$176.87	$282.28	$338.55
Alta ID	$168.30	$324.93	$859.59
Lower Tule River ID	$341.61	$568.22	$869.25
Belridge Water SD	$306.15	$765.48	$915.02

As discussed previously, the shadow value of ET is based on the crop mix in the specific region as well as the level of the water shortage. Under no shortage, the average value of an acre-foot of ET ranges between $140 and $340 depending on the region. With severe drought equal to twenty percent of all available supplies, the marginal value of ET increases to a range of $340 to $930, with Westlands Water District representing the highest marginal value. There is a significant economic gradient for the value of water that could be exploited under functioning water markets, a situation that can be explored using remotely sensed data.

COMPARISON OF CHANGE IN EVAPOTRANSPIRATION AND BIOMASS PRODUCTION TO THE ECONOMIC VALUE OF EVAPOTRANSPIRATION

The economic value of ET corresponding to a 10 percent reduction in total water supply from SWAP is assumed to be reasonably representative of 2008. Analysis of percent reduction in consumptive use of water and biomass production by district and the corresponding economic value of ET provide insight into the response of growers to reductions in surface water supply. Differences in physical characteristics, management practices, and economic gradients across regions between 2005 and 2008 determine the relationship between economic value of water and changes in biomass production and consumptive use.

Table 8 summarizes the economic value of ET, percent change in biomass production, and percent change in consumptive use for selected regions between 2005 and 2008. There is significant variation in both changes in production and water use and the economic value of water across regions. Furthermore, taken individually, there is some correlation between the economic value of water and consumptive use and biomass. In general this correlation suggests regions with higher economic value of water see increases (or relatively lesser decreases) in consumptive use and biomass production between 2005 and 2008. Conversely, regions with low economic value of water realize relatively higher reductions in biomass production and consumptive use. For example, under a 10 percent shortage scenario, Belridge Storage District has an estimated economic value of water of $765 per af and realizes an increase of 20 and 15 percent in biomass production and ET, respectively, whereas Tulare Lake Storage District has a value of $282 per af and realizes a decrease of 23 and 21 percent in biomass and ET, respectively. We caution that this relationship is not causal as there are likely several factors acting simultaneously to determine changes in production and water use relative to the economic value of water; and we discuss these below.

Table 8. Summary of Economic Value of Water and Change in Biomass and ET

Area	Shadow Value of Water ($)	Pct Chg in Biomass	Pct Chg in ET
Westlands WD	403	0	-1
Kaweah Delta Water CD	280	2	-4
Fresno ID	461	-1	-1
Semitropic Water SD	275	-9	-9
Tulare Lake Basin Water SD	282	-23	-21
Consolidated ID	325	-8	-10
Kings County WE	282	0	-3
Alta ID	325	6	3
Lower Tule River ID	568	-5	-8
Belridge Water SD	765	20	15

Several factors are acting simultaneously to determine relative changes in water use and production across regions including, availability or unavailability of sufficient groundwater supplies or external transfers to offset reductions in surface water supply, changes in cropping due to market or other factors, and/or changes in water management practices across years. Additionally, changes in weather induce changes in evaporative demand and/or solar radiation to drive photosynthesis which have differential effects on consumptive use and biomass production, respectively, across regions.

In addition to variation in physical characteristics and weather across regions between 2005 and 2008 there are other potential differences between regions. We discuss two potential differences. Relative to regions with low economic value of water, regions with high value likely may grow a higher value crop mix and face an initial water constraint that is more restrictive. These two factors lead to opposite expected effects of water shortage, which we consider in turn. First, a higher value crop leads to a higher willingness to pay for additional water, thereby creating an economic gradient to transfer water from lower value uses in other regions into regions and fields with higher value crops. To the extent that water markets are available, this effect would cause regions with higher economic value of water (buyers of water) to import more water during critical years resulting in lower reductions (or increases) in production and water use relative to regions with low economic value of water (sellers of water)[9]. Working opposite this effect, a more restrictive initial water constraint in regions with high economic value of water would likely cause relatively larger reductions in production and consumptive use. The mechanics of this effect are intuitive; regions with tight initial water supplies are more likely to have to resort to fallowing in response to shortage. The net effect of water shortage on production and water use compared to the economic value of water depends on the balance of these forces and groundwater, water management, and other physical characteristics.

CASE STUDY: ECONOMIC VALUE OF PRECISE SPATIAL DATA

The value of precise spatial measurement of crop production and water use is directly tied to the ability of policy makers to use the information in real time. Spatial variability in land and water use indicates that there is spatial variability in the value of individual fields which translates into differences in the marginal value product of water. Currently, modeling the response of California crop production and water use to changes in policies, prices, and resources is restricted by the current dearth of disaggregated data. In practice, policies need to reflect the marginal adjustments by farmers and changes in the spatial distribution of agricultural production and water use. Spatial variation due to differences in physical and human capital of farmers is manifested through differences in water use and crop yields across fields. Understanding potential micro-level adjustments in response to these differences is fundamental to effective agricultural policies. In order to focus ideas, we quantify the potential economic value of this information by way of a case study and the example presented in this section.

We combine biomass, ET, and crop production geo-referenced data for Kern County, in the area of the Semi-tropic Water Storage District, in 2002. Kern County has an urban population of about 800,000 and is located in the southern part of the San Joaquin Valley of California. It represents a diverse region in terms of agricultural production with over forty unique crops produced in a given year. Since Kern is a large county, we controlled for heterogeneity by focusing on the Semi-tropic Water Storage District, which corresponds to SWAP model region 19b.

As an agricultural policy example we considered a policy designed to reduce agricultural water use by 20 percent in any given year. Specifically, consider a fallowing program whereby the government pays farmers to fallow certain crops, with the target of reducing water use by 20 percent. We consider a policy that specifically targets alfalfa for a 20 percent reduction in water use. We make this simplification in order to avoid the computational complexities of a variety of crop types, in essence allowing us to forgo the use of a full economic production model. Another reason for this simplification is that we can hypothesize a linear relationship between SEBAL biomass and crop yield in order to generate field-specific yield estimates. Specifically, we assume a linear relationship where the mean total dry biomass production from SEBAL is estimated at 11.4 tons per acre, whereas the average yield from the county estimates is 7.8 tons of dry alfalfa hay per acre. As such, each biomass estimate is scaled by 0.68 such that the mean total dry

[9]See http://swap.ucdavis.edu for preliminary analysis of water transfers in the Central Valley

biomass production and mean dry yields coincide. We take these to represent estimates of alfalfa yield by field and assume uniform yield over all acres in a given field. We note that the qualitative results we derive from this analysis generalize to any other crop and across all other regions in California; however, the magnitude of the effect will differ due to regional differences and market effects.

An ideal land retirement policy targets acres with low marginal value product, thereby receiving the highest return per dollar of water saved. The extent of the variability in the distribution of production and water use across fields is an indicator of the degree of importance of precise spatial information. To highlight this fact and provide a basis for the following analysis we calculate the gross revenue per acre as the price of alfalfa in 2002, $113 per ton, multiplied by the yield per acre as calculated above, and divide by actual ET per acre in feet. The result is an estimate of gross revenue per foot of ET, and the distribution is shown in Figure 3. For comparison purposes, using county average survey data from 2002, crop yield is estimated at 7.74 tons per acre with 3.77 feet ET, implying $232 gross revenue per foot of ET.

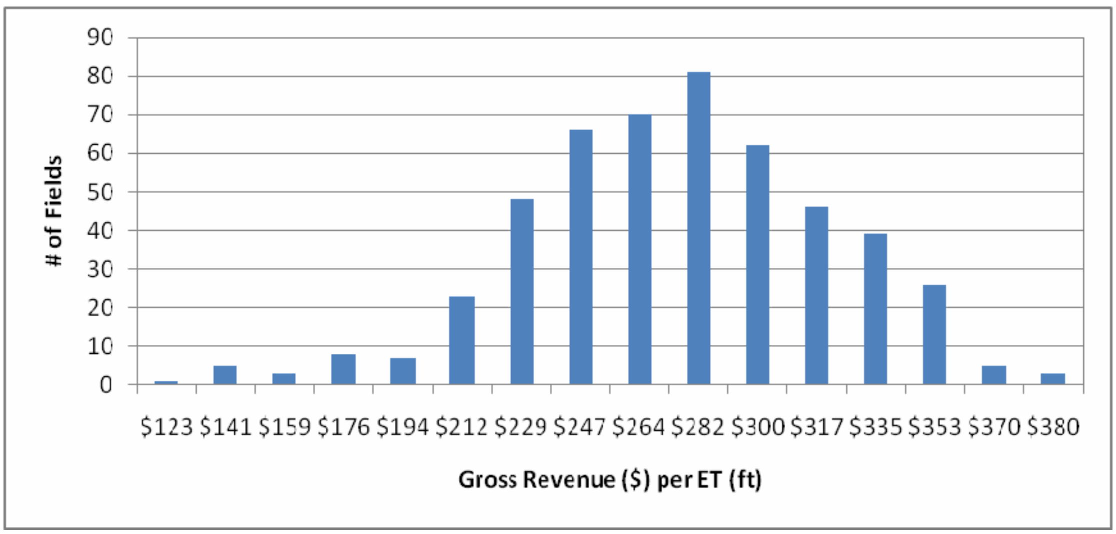

Figure 3. Distribution of Alfalfa Gross Revenue per ET by Field

As shown in Figure 3, there is significant variability in the gross revenue per foot ET across alfalfa fields in Kern County. This information is valuable to policymakers and has not, as of yet, been explicitly incorporated into policy analysis. Consider the hypothesized 20-percent alfalfa fallowing program. For simplicity we assume that costs are constant across all acres, thus gross revenue per acre is an exact proxy for total value per acre. Two situations are considered to illustrate the value of more precise information. First, consider a naïve case where the policy maker has no knowledge of the exact distribution and is only able to offer a constant price per acre. The second case allows for perfect information (in the economic sense) where the distribution is known by the policy maker with certainty and the policy maker is able to offer different prices between acres. In reality the policymaker likely has some knowledge of the distribution and might design a bidding mechanism for land retirement. We discuss this possibility as well, highlight some of the difficulties with implementation, and show potential value of remotely-sensed data in this setting. Figure 4 shows the cumulative acres over the lowest value 23,000 acres (total acres are 35,000) graphed against the county average.

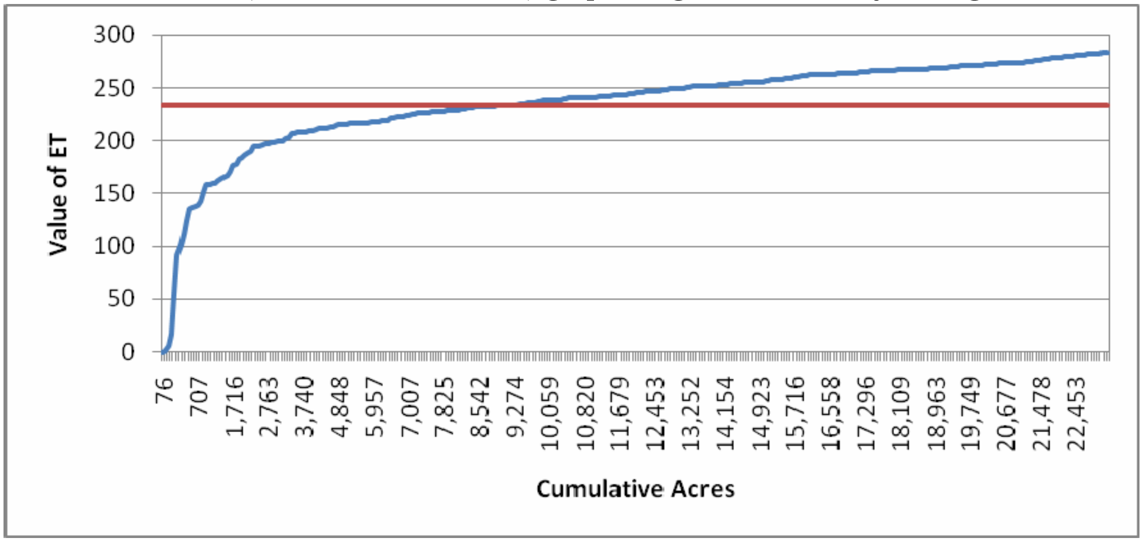

Figure 4. Observed and Average Gross Revenue of Alfalfa per foot ET: Cumulative Acres (County Average in Red)

First consider the naïve case where the government can only offer a constant price per acre for alfalfa land and has no knowledge of this distribution. The policy is designed based on the average measurements, namely 7.74 tons yield per acre at a value of $113 per ton and 3.77 feet of ET per acre. The county average data translates into value of $232 per acre and with 35,000 total acres of alfalfa, the program wants to buy back 7,000 acres (20 percent). Since the value per field is also the willingness of each farmer to accept this price, farmers are willing to retire land up to a maximum of 8,992 acres. This is shown by the intersection of the average and actual gross revenue curves in Figure 4 which reflects the fact that farmers have knowledge of their own land value and will only offer marginal land for the program. For simplicity, assume that the lowest value 7,000 acres are those that are actually fallowed, although in principal any of the 8,992 acres could be sold into the program. With this assumption 7,000 acres are fallowed at $232 per acre for a total cost of $1.63 million. Given the true distribution of value across acres the value per acre on the 7,000th acre is actually $220, as seen in Figure 4. Thus, the government could have offered $220 and fallowed the same 7,000 acres which translates into a saving of $84,000, representing a 5 percent reduction in total cost of the program due to having more precise information

As a second example, consider the case at the opposite extreme where the policy maker knows the exact distribution of gross revenues (value) across all acres. In this case the optimal policy is perfect price discrimination where the lowest value 7,000 acres are fallowed at an individualized price exactly equal to the value per acre. In this situation excess payments are exactly zero since each acre is paid its exact value and, furthermore, the lowest value acres are fallowed. Relative to the case where farmers are offered a constant price of $232 per acre, this program reduces the fallowing payments by $298,000, the difference between price paid and actual value on each of the 7,000 acres. This translates into an 18 percent reduction in fallowing expenditures and represents a significant value of the precise information. Note that $298,000 is an upper bound on the potential savings from knowledge of the value distribution. In practice, the ability of the policy maker to extract some of this excess value depends on the pricing design. For example, second degree price discrimination would allow the policy maker to extract some portion of the $298,000 potential savings.

A more realistic situation is that policy makers are aware of the existence of a distribution of value across acres but are unsure of its exact nature. One option is to accept bids from farmers of their willingness to accept to sell into the program. In theory, a properly designed bidding mechanism would encourage each farmer to bid the true value per field. However, there is often significant collusion among farmers in bidding the value of land, as was the case in the Conservation Reserve Program. Ferraro (2007) reviews some of the literature related to this result and summarizes the significant potential for collusion among farmers to fix bid prices for land fallowing. Knowledge of the actual distribution circumvents the need for auctions, and consequently eliminates the possibility of bidding collusion. In addition to savings from reduced overpayment per field there is an additional savings of administrative costs. This same idea extends to a variety of possible land fallowing program designs. In each case the value of remotely-sensed data is the difference between what is paid and the actual value per field, plus any costs associated with program implementation (auctions, etc). The two bounding cases are summarized in Table 9.

Table 9. Value of Precise Data

Policy	Cost with County Average Data	Cost with SEBAL Data	Cost Savings
Point Information	$1,624,000	$1,540,000	$84,000
Perfect Discrimination	$1,624,000	$1,325,254	$298,746

Spatial variability in crop water use and production has significant policy implications. In the context of Delta pumping restrictions, the lack of spatial data makes it unlikely that policymakers are accurately evaluating the highly localized effects of pumping restrictions. There is an economic incentive to transfer water from areas with a relatively low marginal value of water to areas with a relatively high marginal value of water. In essence accurate spatial data allows for structuring real time water markets that allow for transfers of available water supplies to those areas with the greatest marginal values of water.

CONCLUSION

The future balance of urban, environmental, and agricultural water use in California hinges critically on the decisions of policymakers which, in turn, depend on availability of accurate water use and agricultural production data. Recent rulings together with a series of critically dry water years have significantly reduced water availability in regions with heavy reliance on State and Federal project deliveries. In general, these regions are concentrated along the West-side of the San Joaquin Valley. Analysis of SEBAL data for selected regions found changes in biomass and consumptive use ranging from reductions of 23 percent to increases 20 percent. Comparing changes in biomass and water use to the economic value of water by region provides evidence that the most significant changes in biomass and water use are concentrated in regions with high/low economic value of water; however, water transfers and a shifting crop mix in regions across the entire Valley make a causal link between economic value of water and production and water use unlikely. The concluding case study highlights the importance of detailed spatial information for providing policymakers with an accurate representation of the localized effects of water shortage in real time. Future research should be focused on integrating remote sensing data directly into policy models, developing economic models that explicitly account for this detailed spatial variation, and developing policies that maximize benefits of this information.

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DEVELOPING CORN REGIONAL CROP COEFFICIENTS USING A SATELLITE–BASED ENERGY BALANCE MODEL (RESET) IN THE SOUTH PLATTE RIVER AREA OF COLORADO

Aymn Elhaddad [1]
Luis A. Garcia[2]
Jon Altenhofen, P.E.[3]
Mary Hattendorf[4]

ABSTRACT

Accurate estimates of evapotranspiration for agricultural crops are essential for water resources management and for crop production. Traditional methods for estimating crop evapotranspiration are based on weather based reference evapotranspiration estimates multiplied by a crop coefficient (Kc). The crop coefficient varies based on crop type and growth stage and optimum growing conditions are assumed in this approach. Satellite based energy balance models can directly measure actual ET in fields and these measurements can be used to develop crop coefficients for different crops for a particular region. In this study a surface energy balance model (ReSET) is used to measure actual ET for corn fields in the South Plate River Basin of Colorado. The study covers four growing seasons (2001, 2004, 2005 and 2006). A total of 79 Landsat 5 and 7 images were used for the four years using two satellite paths 33/32 and 32/32.

INTRODUCTION

Remote sensing algorithms that use satellite imagery have been widely used to estimate evapotranspiration (ET). These algorithms are called surface energy balance models and most of them were developed in the last decade (Kustas and Norman 1996; Bastiaanssen et al. 1998a,b; Timmermans et al. 2004; Nagler et al. 2005; Allen et al. 2007a,b). These models use satellite imagery such as Landsat, AVHRR, ASTER, and MODIS to estimate ET (Nishida et al. 2003). The models estimate the actual ET occurring in the fields, which takes into account the cumulative impact on ET of all ground factors such as water stress, soil salinity, pest infestations, hail damage, agronomic practices, etc. The models cannot determine the impact of each factor but the combined impact of all ground factors. Remote sensing of ET provides an "actual" estimate of ET versus more traditional ET methods which calculate a reference crop ET and then apply crop coefficients to estimate the ET for different crops under optimum conditions. Of the traditional approaches for calculating crop ET, weather based reference ET is the most commonly used along with

[1] Research Scientist, Integrated Decision Support Group, Dept. of Civil and Environmental Engineering (1372), Colorado State Univ., Fort Collins, CO. 80523
[2] Director, Integrated Decision Support Group and Prof., Dept. of Civil and Environmental Engineering (1372), Colorado State Univ., Fort Collins, CO. 80523
[3] Supervisory Water Resource Engineer, Northern Colorado Water Conservancy District, 220 Water Ave, Berthoud, CO 80513.
[4] Water Management & Conservation Specialist, Northern Colorado Water Conservancy District, 220 Water Ave, Berthoud, CO 80513.

crop coefficient (Kc) curves to estimate water demand for different crops. Crop coefficient curves presented in the literature by Doorenbos and Pruitt (1977), Wright (1981, 1982 and 1995) and Allen et al. (1998) are based on point measurements and assume optimum cultivating conditions (management, irrigation, etc). Such assumptions do not apply for many fields since irrigation type and adequacy differs from field to field as well as soil type. Presence of soil salinity and fertilizers application can also vary significantly between fields that have the same crop. A regional based crop coefficient approach is proposed in this research that takes into account the spatial and temporal variability in crop conditions in an area, which can be accomplished using surface energy balance models using satellite imagery. Surface energy balance models measure actual ET in the fields which aggregates all temporal and spatial variability. This actual measured ET is then used with weather based reference ET to develop crop coefficient curves that are tailored to each crop type and to each region. These regional crop coefficient curves can be used to determine crop water requirements for a particular region. The ReSET (Elhaddad et al., 2008) surface energy balance model is used in this research to determine the “actual” ET.

METHODOLOGY

The study area is an agricultural area covering a portion of the South Platte river basin in northwest Colorado. This region has a semi-arid climate with irrigation water resources in the area mainly from the South Platte River or from ground water. The main crops cultivated in the area are corn, alfalfa, small grains, dry beans and sugar beets. The study area falls on two Landsat paths 32/32 and 33/32. In this study crop coefficients for grain corn were developed; the study area starts on the west at the town of Wiggins and extends north east to the town of Ovid as shown in Figure 1.

The data used in the ReSET model includes a digital elevation map for the area, hourly and daily reference ET grids from five weather stations in the area (Crook, Ovid, Sterling, Brush and Wiggins) and finally Landsat 5 and 7 images collected at 11:20 am (during the growing season – daylight savings time). The study covered the growing season for corn (May to October) for four years (2001, 2004, 2005 and 2006) for Landsat paths 32/32 and 33/32. Landsat images are available every 16 days for each path which makes it possible to collect almost 4 images from the two satellites (Landsat 5 and 7) per month. However, the number of usable images per month is less than four since the ReSET model can only use cloud free images, therefore the number of usable images varies depending on the cloud cover. The Landsat 7 imagery for the 2001 year was useable since it did not have the stripping problem of blank strips with no data that started in 2003. The Landsat 7 images from years 2004, 2005 and 2006 had the stripping problem and the areas covered by the strips were masked with values of no data, which allowed the remainder of the image to be use in the Kc calculations.

A total number of seventy nine Landsat images were used to develop the corn Kc curve with an average of four images per month and twenty images per growing season. An initial set of corn fields were identified based on a crop classification map developed by the Northern Colorado Water Conservancy District (NCWCD) for each growing season. Those sets of fields had to be filtered to eliminate fields that might have been misclassified, partially cultivated, fields that were abandoned during the growing season and/or fields that were harvest for silage (since they are harvest earlier than grain corn). The objective of the filtering procedure is not to select ideal grain corn fields but to select grain corn fields growing under typical and variable conditions for an entire corn grain season.

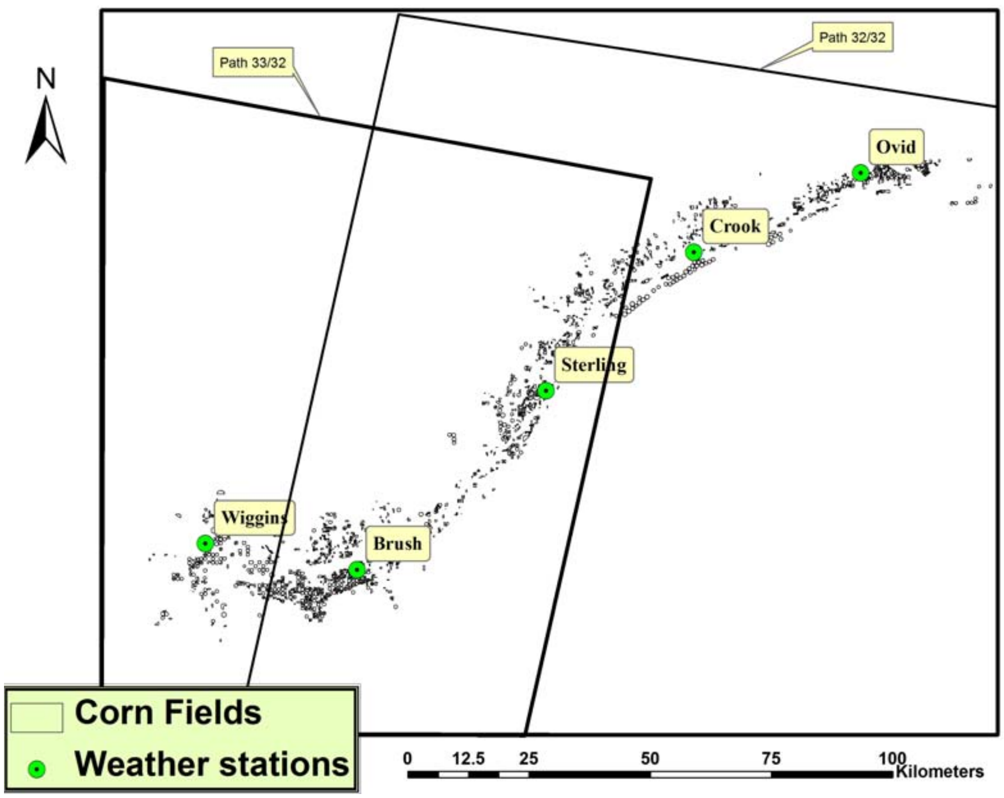

Figure 1. Study Area

Filtering Procedure for Fields

1. ***Using Consecutive Values of NDVI:*** Knowing the mean Normalized Difference Vegetation Index (NDVI) value for each field for several consecutive dates (this value is expected to increase throughout the season), if a different behavior is detected (NDVI decreases during the middle of the season) this indicates that the crop is either not corn, silage corn, or corn that was grown under abnormal growing conditions (drought, hail damage, pests) and therefore these fields were removed from the dataset. An example is shown in Figure 2, which is a false color infrared image where red represents actively growing crops and fields classified as corn by NCWCD are shown with an outline. The left image was taken in July 14, 2006 and clearly shows an actively growing crop in the two center pivots inside the black circle in the middle of the image. The right image was taken on July 30, 2006 and shows the same fields but with very light color that indicates a drop in vegetation density.

These fields were excluded because they were probably not corn or corn that was harvest very early as silage corn.

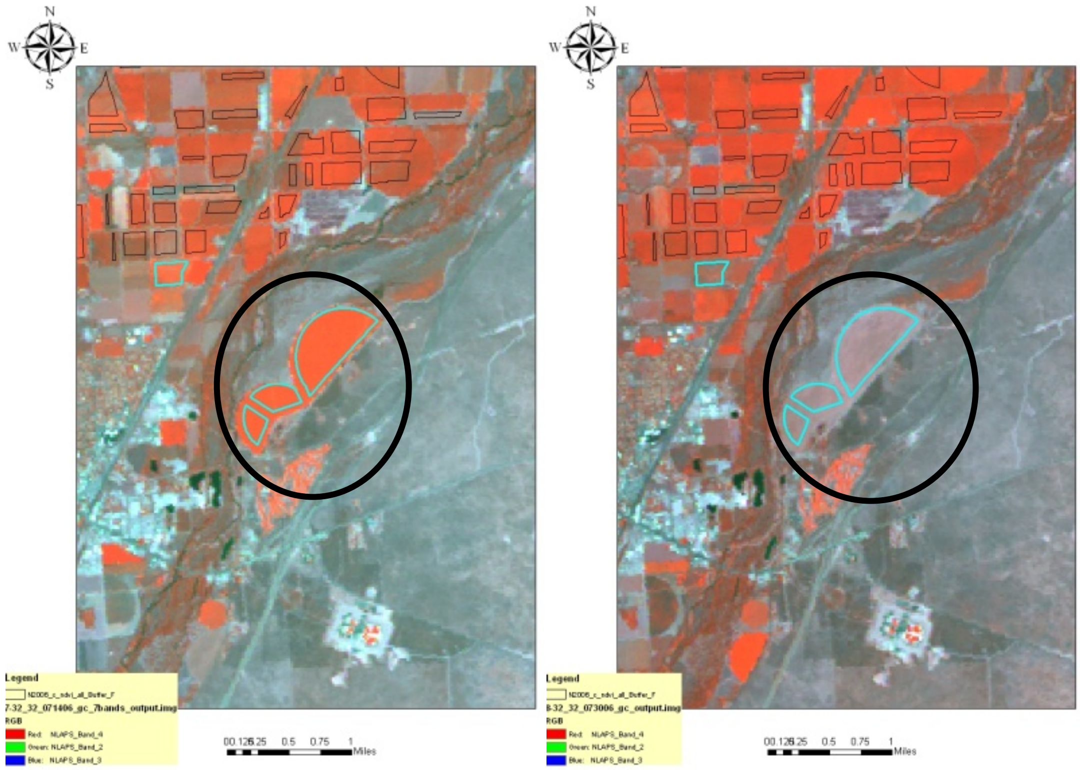

Figure 2. Fields probably misclassified as corn. Left image was taken on 7/14/06 and right image was taken on 7/30/06.

2. ***High NDVI Standard Deviation:*** Fields with high NDVI standard deviation indicate a large spatial variation in the field which could be because the field is partially cultivated as seen in Figure 3 or the field has areas with high salinity, partially irrigated, pests, etc. These are not good fields for use in generating Kc values for corn since they will cause an underestimation of the Kc values. Fields with high NDVI standard deviation (higher than 0.1) were removed from the analysis.

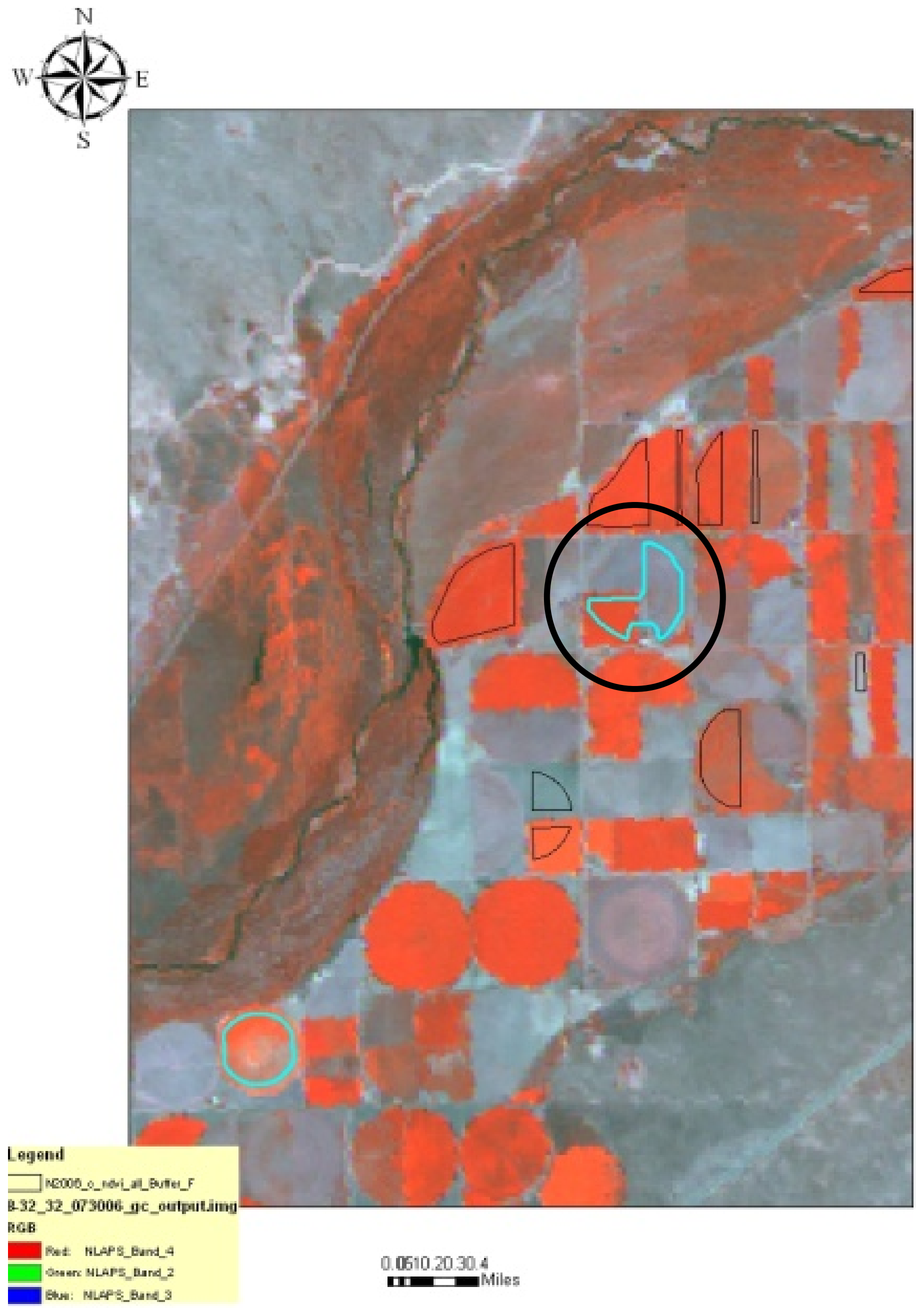

Figure 3. Fields classified as corn but partially cultivated.

3. ***Using NDVI Values to Single Out Non-corn Fields***: The last check to ensure that the selected fields are all corn fields is a NDVI value check at early, mid and late season. Corn fields should have low NDVI values during the early part of the growing season (May-June) since they should have little vegetation at that time and therefore a low NDVI value (0.1 to 0.5). Fields with high NDVI values during the early part of the season such as those shown in Figure 4 from a satellite image taken on 4/16/2006 should be excluded. Those fields are either not corn, corn that was planted very early,

or another crop and therefore would introduce some error when calculating Kc for the majority of corn fields, a mid season check on the NDVI values around late July is done to exclude fields with low NDVI values (less than 0.7) in July since fields with corn in good conditions should have NDVI values from 0.7 to 0.8. Any fields with low NDVI during this time should be excluded. For the late season NDVI values should not exceed 0.5 for corn fields, fields with higher values should be excluded.

Figure 4. Non corn fields or fields with corn planted very early since it is actively growing on 4/16/2006.

4. ***Cloud Masking***: Creating a subset of the fields that are cloud free on ALL dates may reduce the number of fields too much. Therefore, sets of fields for each image date are created so that the maximum number of fields is used for each image date. To do this the shapefile containing the corn fields with the correct range of NDVI values and NDVI standard deviation values are used as the starting set. This set stays the same on dates with no clouds; for dates with cloud cover a shapefile excluding the fields under cloudy areas is created.

Fields that passed all these filtering procedures are considered representative full season grain corn fields for the range of growing conditions and can be used to calculate Kc for grain corn. Before the application of the filtering procedure, all fields were buffered with a 60 m inward buffer to minimize the thermal pixel contamination at the borders of the fields caused by the areas surrounding the fields. After the buffer is applied, the fields with areas less than 28,328 m^2 (7 acres) were excluded from the set for being too small compared to the thermal pixel size. The maximum pixel size (thermal pixels) in the imagery used (Landsat 5) is 120 m by 120 m which represents an area of 14,400 m^2, to ensure that the smallest field used contains at least two thermal pixels, the area of 28,800 m^2 was used. The mean value of the hourly ET estimated by the ReSET model from all pixels within the boundary of each field is assigned as a single value for each field. This value is divided by the spatially corresponding gridded weather station hourly reference ET to develop a Kc value for that field. A mean value of the Kc for all fields is then used to represent the corn Kc for that date. The Kc developed from each date was then combined to create a corn Kc curve for the whole growing season for each year. A final cumulative Kc curve for the four years (2001, 2004, 2005 and 2006) for the study area was developed.

The interpolated spatial grid of hourly weather station reference ET from all five weather stations was generated for each of the Landsat image dates. The reference ET for each field was extracted from these grids based on the location of each field. This process allocates reference ET based on the spatial location of each field rather than using a point value from one or more weather stations for all fields which could cause either an overestimation or underestimation of the reference ET because of spatial variability in weather conditions.

RESULTS AND DISCUSSION

The ResET model was used to estimate hourly ET (Fig 5b) from Landsat 5, 7 images (Fig 5a), a shapefile of corn fields (Fig 6) was buffered and fields smaller than 28,328 m^2 (7 acres) were excluded (Fig 7) to avoid thermal pixel contamination.

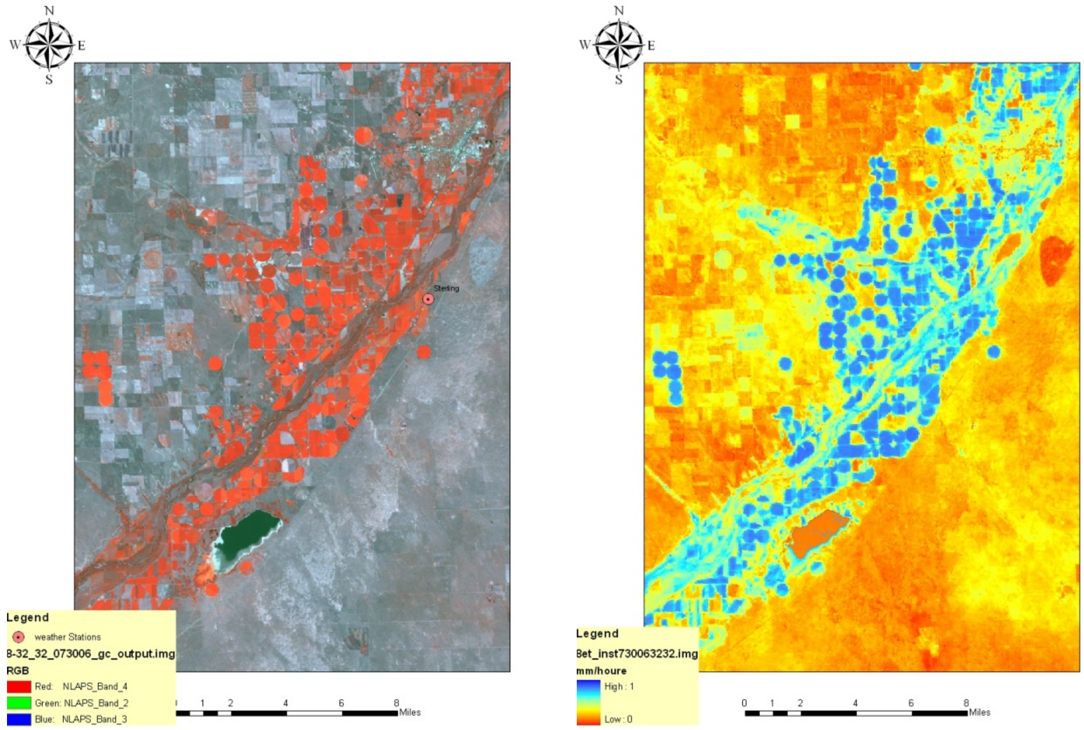

Figure 5. a) Landsat image on 7/30/2006 b) Hourly ReSET ET 7/30/2006

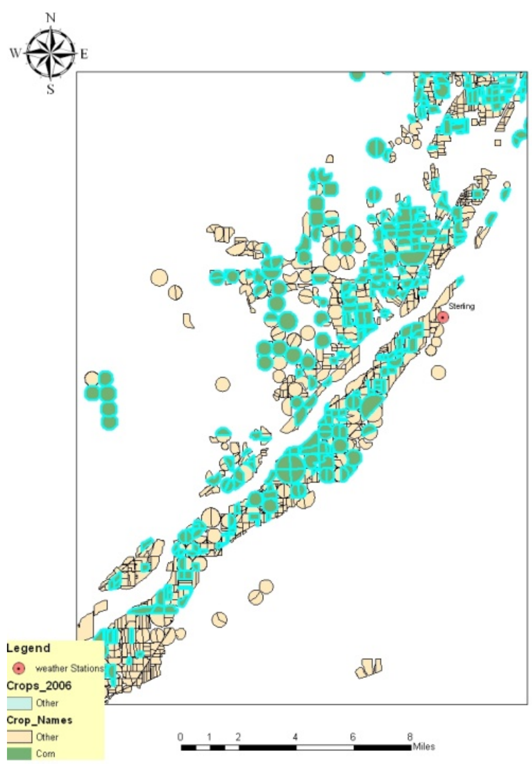

Figure 6. Corn fields

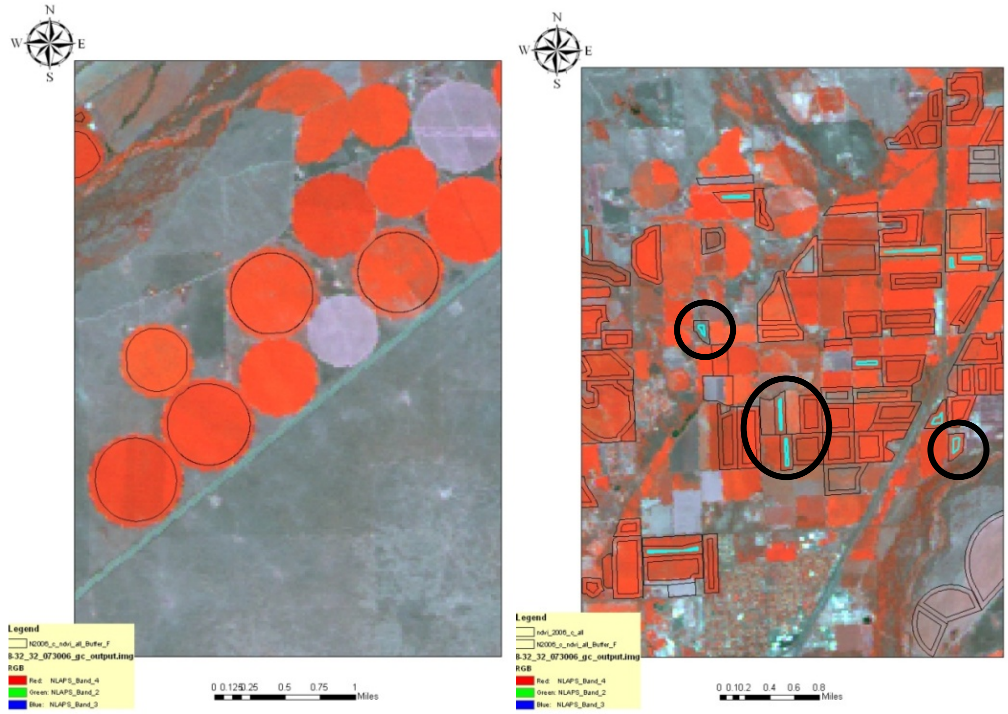

Figure 7. a) Buffered corn fields b) Smaller fields selected and excluded

Within each polygon (field) using the zonal statistics function in ArcGIS a set of values are calculated:

- ReSET estimated hourly ET (mean values).
- NDVI (mean, standard deviation).
- Reference hourly ET from weather stations grid (mean values).
- Corn Kc for each image date is calculated by dividing the mean value of the hourly ET from the ReSET model by the weather station reference hourly ET corresponding value.

Mean corn Kc values for each date are obtained from the attribute table of the final shapefile Fig (8).

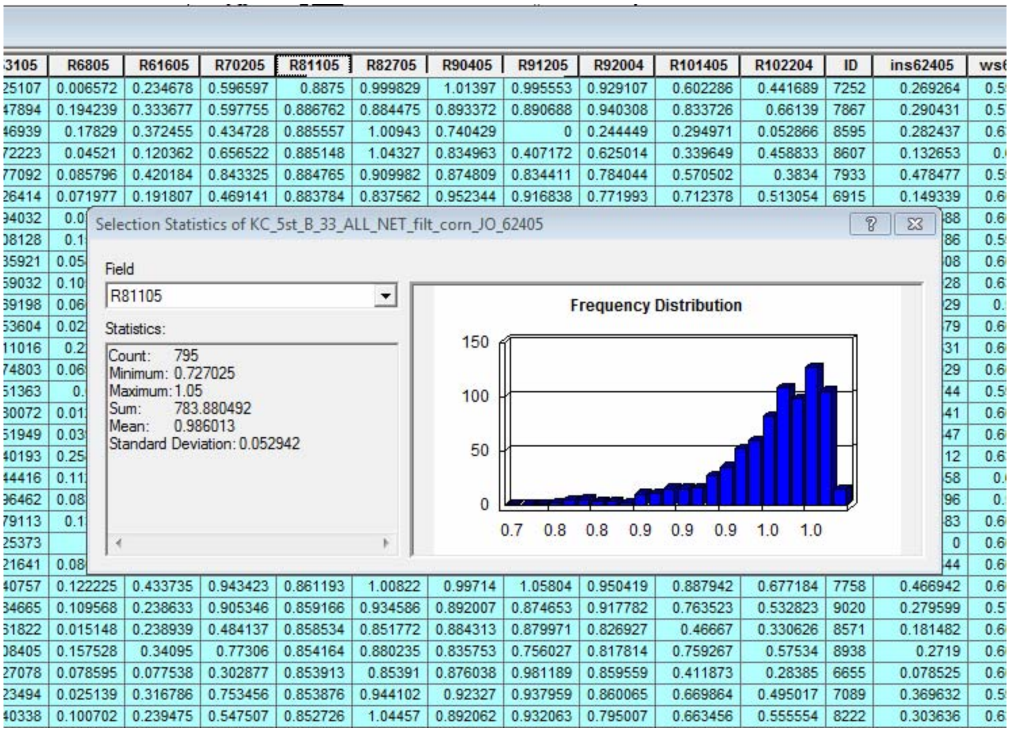

Figure 8. Corn Kc values for each date.

For the year 2001, twenty two Landsat images were used to develop corn Kc for that year, ten of them are Landsat 7 and 12 are Landsat 5. Of these images thirteen fall on path 33/32 and nine images fall on path 32/32. A maximum number of 1,295 corn fields were used from path 32/32 and a maximum number of 1,701 were used from path 33/32. Figure 9 shows the 2001 Kc for corn developed using ReSET plotted against growing degree days and Figure 10 shows the 2001 Kc for corn plotted against dates. The regression curves shown in each image have an R^2 value of 0.97 and 0.96 respectively. For 2004 twenty one Landsat images were used to develop corn Kc values which resulted in an R^2 value of 0.90 and 0.95 for growing degree days and dates respectively. For 2005 only thirteen Landsat images were used to develop Kc due to high cloud cover which resulted in an R^2 value of 0.93 and 0.94 for growing degree days and dates respectively. For 2006 twenty three Landsat images were used to develop corn Kc which resulted in an R^2 value of 0.96 and 0.94 respectively. Figure 11 and 12 show a combined graph for all years (2001 to 2006) of the corn Kc plotted against growing degree days (Figure 11) and against day of the year (Figure 12). Each year is treated as a separate data series, years 2004 and 2005 show lower corn Kc values at the beginning of the season compared to years 2001 and 2006. The R^2 value of a polynomial fitted through the data for all the years is 0.89 and 0.91 respectively for growing degree days and day of the year. The intent of using growing degree days as a scale for Kc values is to reduce the variability due to temperature differences between years.

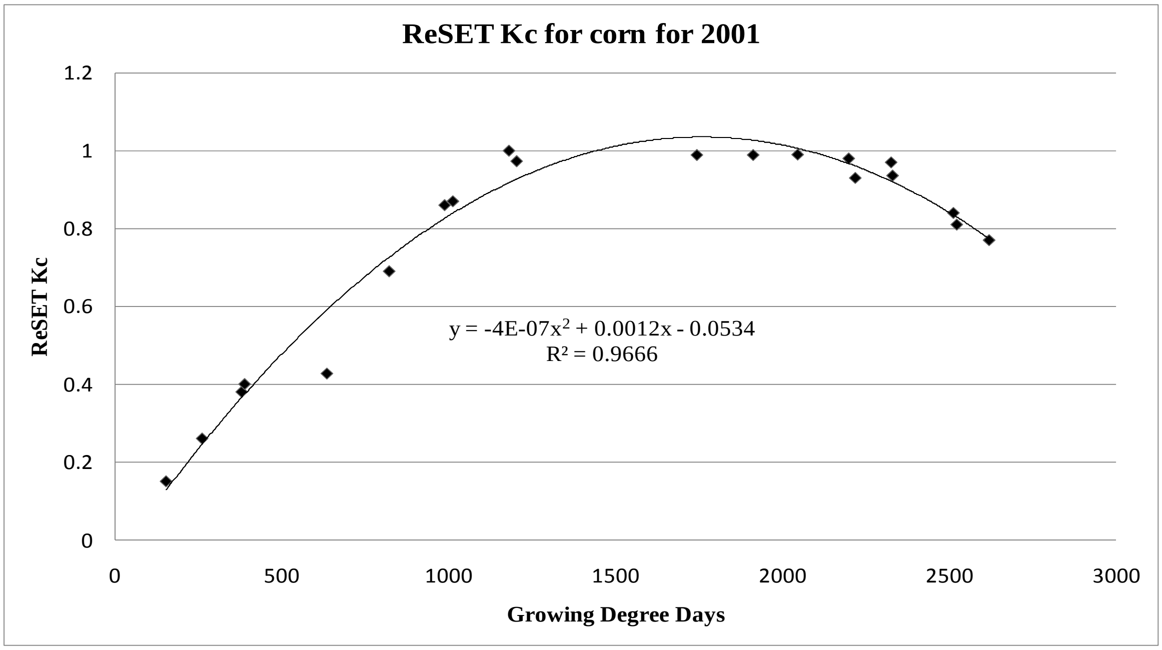

Figure 9. ReSET growing degree day corn Kc curve developed using 2001 data.

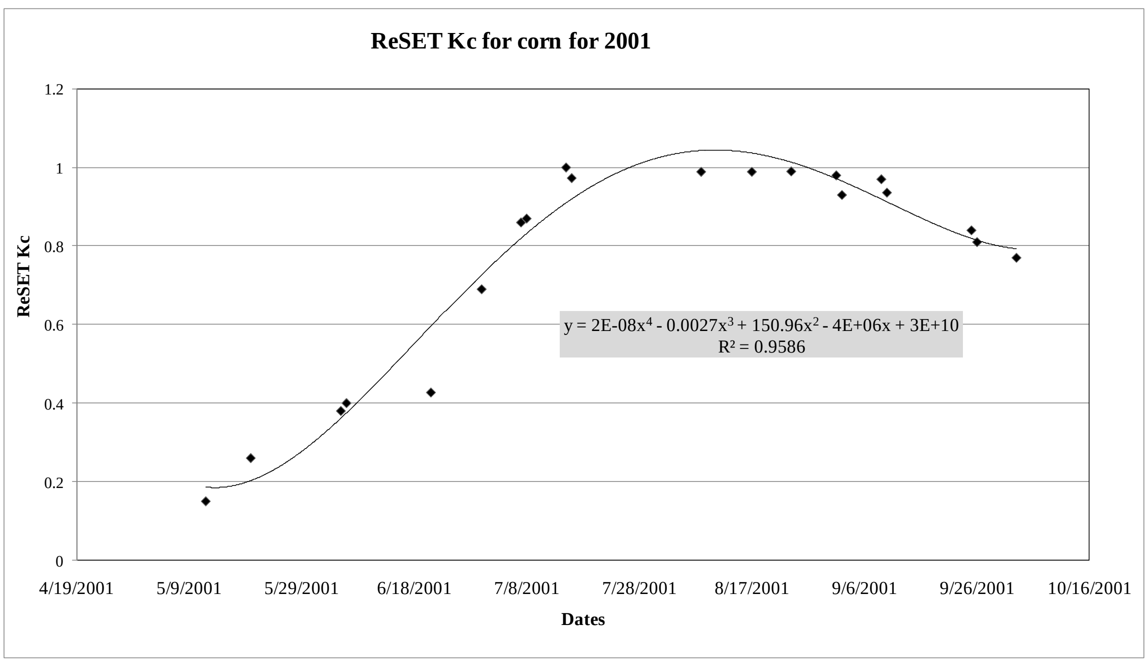

Figure 10. ReSET corn Kc curve developed using 2001 data.

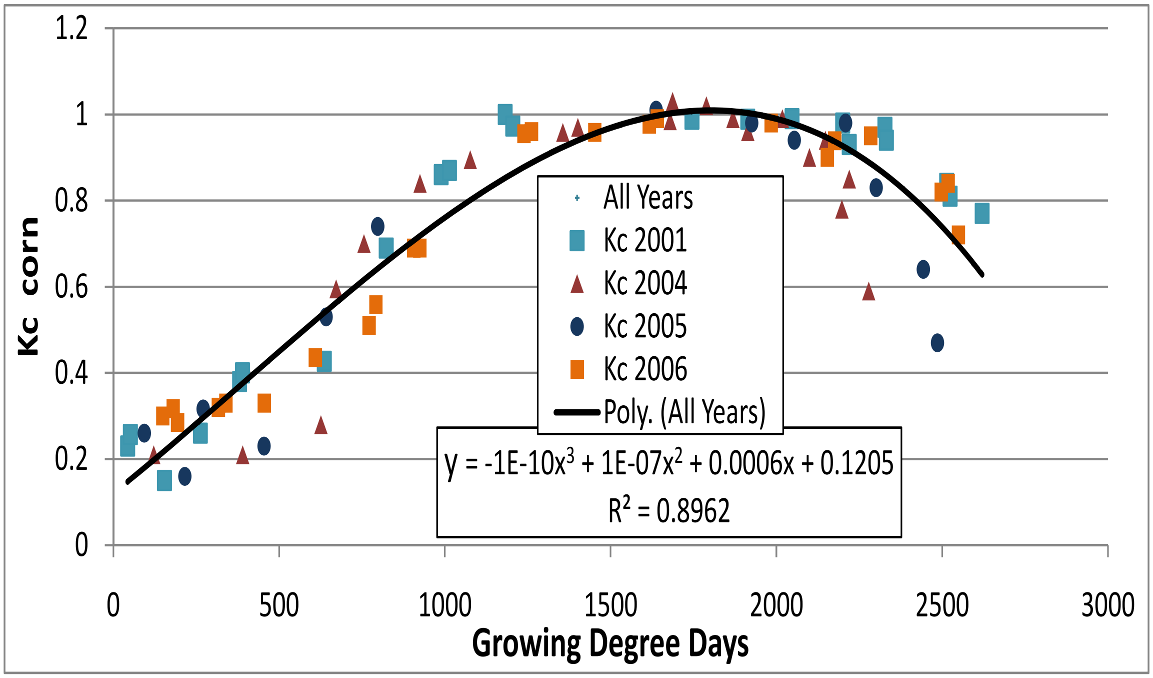

Figure 11. ReSET corn Kc values developed using 2001, 2004, 2005 and 2006 data.

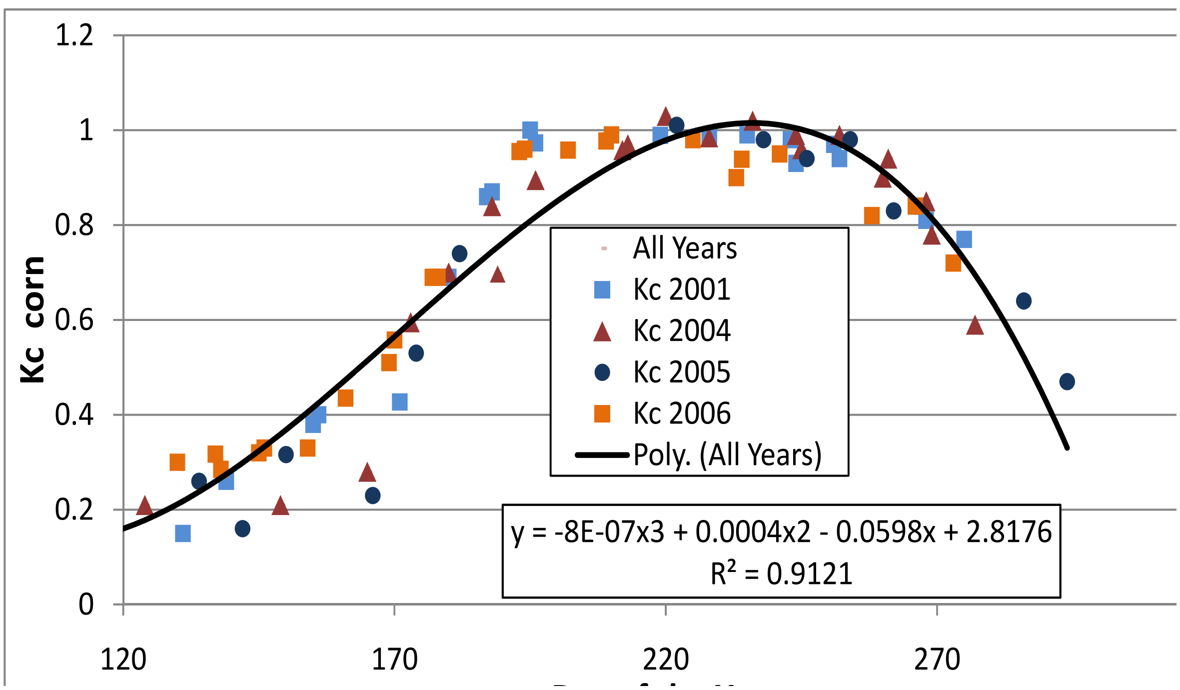

Figure 12. ReSET corn Kc values developed using 2001, 2004, 2005 and 2006 data.

As seen in all the years of the study the variability in the model calculated corn Kc is large at the start and the end of the corn growing season while it is smaller during the middle of the season. This is probably due to the temporal variability in planting and irrigation dates as the model is sensitive to surface temperature of irrigated fields which are likely to have more transpiration from bare soil early in the season which would result in higher values for Kc. The variation in Kc at the end of the season is most likely caused by senescence of the crop; crop harvesting or because of variable drying of the field at the end of the season. Since all these events are field dependent they all contribute to the larger variation in Kc at the end of the season. Corn Kc during the middle of the season (mid July to end of August) has much less variation because of the similarity in crop conditions in most of the fields and because of the high crop coverage which minimizes the impacting of wet soil.

SUMMARY AND CONCLUSIONS

The results of this study show that surface energy balance models such as the ReSET model can be used to develop regional Kc values for agricultural crops. The Kc developed for grain corn fields in the South Platte of Colorado used data for a period of four years, with a total of 79 Landsat images using over 1,000 corn fields during the growing season which extends from May to October. The Kc for each of the years (Figures 11 and 12) matched well which supports the approach for using models such as ReSET in developing Kc for agricultural crops. This approach provides a convenient and practical way of estimating a regional crop Kc. These Kc values can be compared to others developed for other regions to determine if there are local conditions that are reflected in the regional Kc values.

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