SCADA and Related Technologies for Irrigation District Modernization, II

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Preface

The papers included in these Proceedings were presented during the **USCID Water Management Conference**, held June 6-9, 2007, in Denver, Colorado. The theme of the Conference, sponsored by the U.S. Committee on Irrigation and Drainage, was ***SCADA and Related Technologies for Irrigation District Modernization.*** This conference was the second USCID Conference dedicated to SCADA applications.

Today's irrigation and water districts face ever-increasing challenges in their daily operations. These include demands for flexible and efficient system operation, new regulatory and reporting requirements, the need to maintain and archive historical operations data, rising costs of energy, limited water supplies and more limited and costly labor resources. A further concern is the competition for water among the many water users, i.e., municipal and industrial, environmental, endangered species and recreational. To address these management concerns, many districts are pursuing modernization projects that will improve delivery and distribution system infrastructure and enhance operational monitoring and control capabilities utilizing Internet applications and state-of-the-art **Supervisory Control and Data Acquisition Systems** (SCADA). It has become apparent that agricultural water users must use technology to remain viable in managing their water resources.

USCID's Second SCADA Conference provided a forum to discuss the many issues relating to the application of technology to water management.

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

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

Gerald A. Gibbens
Berthoud, Colorado

Conference Chairman

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SCADA INFORMATION UMBRELLAS FOR IRRIGATION DISTRICTS

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ABSTRACT

SCADA systems in irrigation districts have focused on remote monitoring and remote control. In many districts, the remote control is manual, but in others the automation of structures is enabled through the usage of distributed control for the automation of individual structures. This paper presents the concept of an expanded, "umbrella" SCADA system that will perform the standard functions of remote control and remote monitoring, and will also incorporate information flow in the field for operators. The umbrella SCADA system will mesh the equipment-equipment information into an equipment-program-personnel network.

TYPICAL IRRIGATION DISTRICT SCADA SYSTEMS

Today's SCADA systems can store and display tremendous amounts of current and historical information. The total number of monitored sites in a large district may range from 10 to 50, and the number of control sites is typically less. The SCADA systems are generally linked to a limited number of key structures in the field, such as:

- Gates at the heads of canals
- Reservoirs
- Pumps
- Spill points
- Automated check structures

SCADA systems in western US irrigation districts are quite varied, but in general they fall somewhere within four broad categories:

1. Web-based remote monitoring information. This is typical public domain information that is made available through various government organizations such as USBR, USEPA, or USGS. The information can be accessed through the web, without any special equipment or technical knowledge. Having this information has been extremely helpful for some organizations – but they are

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primarily organizations that operate on a basin-wide water management basis. Examples include:

a. Weather information from weather stations
b. Stream flows
c. Dam releases

2. Local remote monitoring and simple remote manual control. Many irrigation districts have this SCADA configuration. Often these systems have been rather haphazardly assembled, with a menagerie of dataloggers, radios, sensors, etc. from different brands. Often these systems are hybrids that are attempting to use modified dataloggers as PLCs – with very limited capabilities. Office and field software is often locally designed, with considerable pride in ownership. Newer systems are well planned out with modern control, communication, and display hardware and software. The speed of data communication on the old systems is often slow – such as once per 15 minutes. These systems give districts the ability to remotely monitor water levels and flow rates in key locations throughout the district. The ability to remotely monitor and change flows (sometimes using a remotely activated timer in the middle of the night) is a major improvement over 20 years ago.

3. Local remote monitoring combined with distributed control. Automation of key structures is accomplished with local control, but target values can be changed from the office. There is often an excellent system of alarms and data archiving and screen displays. Polling (querying) of all sites in the district takes only about a minute or less. These systems have almost always been installed using the services of professional engineers and integrators. This is by far the most common "modern" SCADA system that irrigation districts are implementing in 2007, and encompasses most of ITRC's SCADA work.

4. Options (2) or (3) including some type of mobile field operator access to the office information. This may be through cell phones, BlackBerries, or radio. The access is almost always only "read-only" or "monitoring". In general, the amount of information and the speed of information transmission to the mobile field operators have been limited. Some examples will be given later in this paper.

Other Tasks

Irrigation districts use communication systems (phones, radios, even the web) and databases to organize other types of minute-to-minute information. The information from some of these databases is sometimes used to make decisions on how to use the SCADA system with many aspects of daily operations. For example, irrigation districts have developed a variety of techniques for:

- Receiving water orders from farmers.
- Verifying when water can actually be delivered to a turnout.
- Verifying that water is actually being delivered to a turnout.
- Allowing water to be turned off at a turnout.

There are many variations to this, even in districts with some type of SCADA. A range of options includes:

1. In many districts, farmers communicate directly with local ditchriders. The ditchriders have complete power to decide when and how much water can be delivered. The main office will have no idea what happened until a week or so later. The main office only knows if a change is needed by noting excess spill (for example) or if a ditchrider calls up and asks for more or less water.
2. In other districts, farmers call the district office. Water orders are accumulated on a board, on a hand-written form, or in a database. This may be done automatically via web-based access by farmers, or through some touch-tone entry by farmers. The orders are subsequently organized by ditchrider zone. Then at a daily meeting between the ditchrider and the watermaster (the ditchrider boss), everyone decides what can be done and when. At that time, the farmers may be notified that their water order has been approved.
3. In a very few districts (Delano-Earlimart ID in the San Joaquin Valley is an example), farmers call in with a request and the order-taker in the office accesses a program that checks to see if there will be capacity in the delivery system during the request time. The order is immediately confirmed or shifted in time depending upon available capacity. ITRC developed this database for the "relatively" simple pipeline system of DEID, with about 600 turnouts.
4. One interesting variation is used by Yuma County Water Users Association. The water ordering/scheduling database is maintained at the office. It identifies future orders as well as present deliveries, by turnout. That simple database is linked to the web, and ditchriders have hardened laptops in their pickups that are always linked to the web (via cell phone, which is somewhat slow). The most interesting aspect is that either the ditchriders or the office personnel can make changes to the database at any time, and everyone sees the changes.

There are other functions that involve databases and spatial information. These include:

- Hand-held data recorders, often scanning bar codes on turnouts, are commonly used in many districts to document flows and volumes. In general, the recorders are placed in docking stations at night to download information and receive database updates.

- A few districts use Global Positioning Systems (GPS) to keep track of where employees are at all times (locations and durations of stops) during the working day. A little imagination can be used to envision how this has helped management identify work habits of ditchriders and maintenance crews.

The interesting point, however, is that all of these functions are typically separate. Different databases, hardware, people, etc. are used for the different functions – although the functions are often inter-dependent. This has similarities to districts still in the first level of SCADA, which is characterized by having hardware and software that is "cobbled together". Those districts often use several different programs to display and archive different types of SCADA information, and sometimes use several radio systems that are incompatible with each other. The newer SCADA systems have streamlined the people-to-hardware information flow, but they have yet to integrate these other co-dependent functions/databases, and the field operators lack ample access to the office information.

THE FUTURE – ICIMS

In essence, most modern SCADA systems are tremendous tools to help operate main canal networks by providing information and control at a few points. However, when people consider expanding existing SCADA systems, the thinking is generally to expand the number of sites throughout the distribution system.

With recent advances in PLCs, laptop PCs, SCADA software, the Internet, and Internet service providers, SCADA system expansion should include new means of communications and daily operations. We suggest that in the future, we will not talk about SCADA systems as much as what we term an "Irrigation Control and Information Management System" (ICIMS). Figure 1 below illustrates a fledgling "Stage 1" ICIMS.

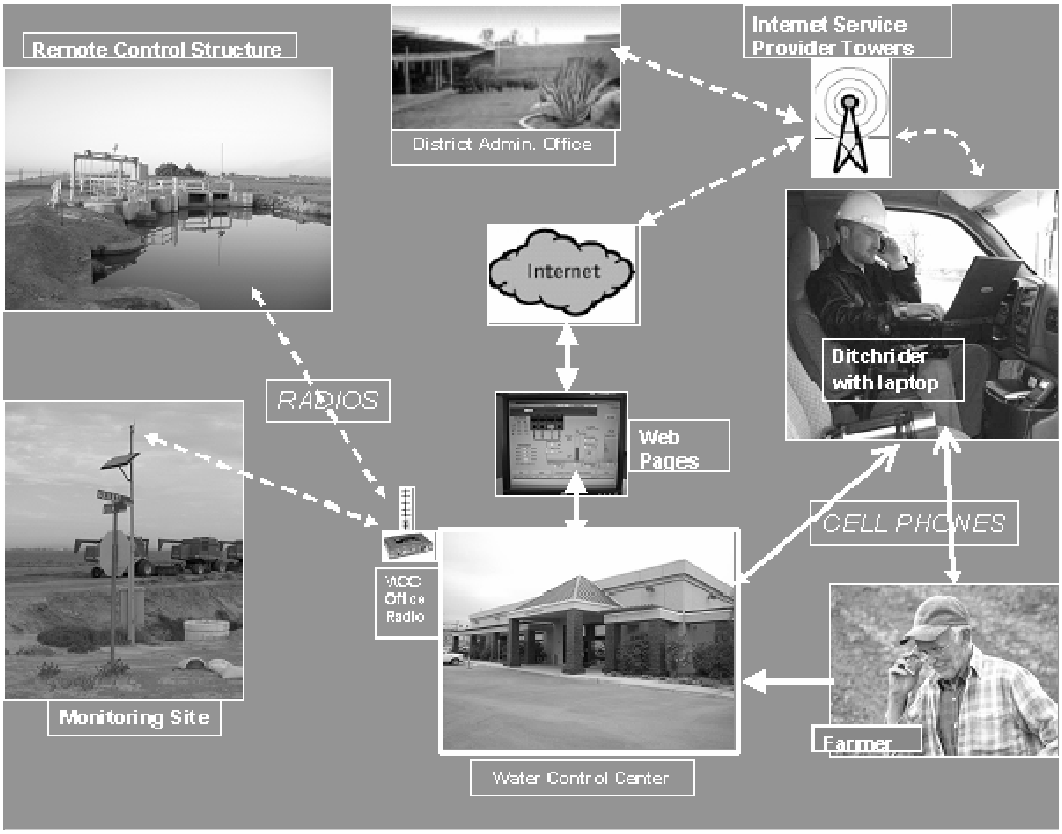

Figure 1. Envisioned organization of a Stage 1 ICIMS

Figure 1 illustrates powerful abilities to improve service. A ditchrider, for example, can know the complete status of gates, water levels, etc. within his zone of operation. Assuming the system has remote control capability, or remote changing of automation targets, there should be nothing to hinder the ditchrider from remotely making required changes throughout his zone. Obviously, there would need to be standard operating procedures for who can make changes to flows into laterals from the main canal – because that will impact more than just the ditchrider's zone. But it will be just as easy for a ditchrider to make a change as it is for an office watermaster to make a change.

A key ingredient of the ICIMS will be expanded usage of web-based information (with all of the necessary security measures). The type of SCADA that will be used in ICIMS already has several names – "Internet SCADA", "Web-based SCADA", and "IP-based SCADA". A few developments make widely expanded IP-based SCADA a real possibility for many irrigation districts today:

1. Some of the latest commercial HMI software programs, such as ClearSCADA, seamlessly translate their display screens into web pages.
2. Some rural areas now have private companies that provide local high-speed wireless Internet access. This is the same system that is used instead of cable

or satellite to provide TV access. We expect this service to expand rapidly into new areas. There are two major advantages that these Internet Service Providers (ISPs) give:

a. Communication speeds are much faster than cell phone Internet access, which means that having access to large databases (read: "typical SCADA screens") that continually update is now possible.
b. Charges are monthly, which makes them much less expensive than satellite options.
c. Strong signal strength can be achieved without needing directional antennas on mobile pickup trucks – as is generally required for satellite and radio communications. Directional antennas must be oriented properly to maximize signal strength.
d. Hardened laptops are available at reasonable prices. The hard drives function well even while being bounced around in pickups on dirt roads.

Because of the new software and the high-speed connections, the ditchrider can have real-time access to the complete set of office databases/screens, rather than just having access to very limited information on a monitoring basis. This saves both programming and training time – everyone looks at the same information (to whatever level of office data their security clearance will allow).

Once a district makes the leap to go to web-based field and office information management, many other doors immediately open up. For example:

1. Hand held data recorders can be equipped with various wireless connections to the pickup laptop – meaning instant updating of the complete database with current information on turnout flows, etc. There are other options, of course, on how to physically get the information into the common ICIMS system. AT&T, for example, unveiled a new service in the spring of 2007 that allows a BlackBerry to become a real-time wireless dispatch system that reads bar codes and also keeps track of workers in the field through its global positioning system.
2. The water ordering program/database can be integrated into the same ICIMS system – as mentioned earlier, they are now typically in a completely separate system.
3. Once the water ordering program/database is integrated into the ICIMS system, it is only a matter of time before flow scheduling/routing programs will be developed that incorporate water ordering software with canal reach capacities, lag times, etc. This will enable a quick check to be made of capacity limitations, and will also provide guidance to ditchriders as to when flows might be released or stopped at key bifurcation points – so that they arrive at turnouts at the proper time.

Implications of an ICIMS System

Suddenly, the concept of "real-time management" takes on a whole new meaning. Information is instantaneously available to everyone, and can be appropriately acted upon because the information is accompanied by control capabilities. This also requires new arrangements of power sharing, and allocation of responsibilities, among staff in the irrigation district.

Quick and appropriate responses – done manually through improved information management and remote control and distributed automation – have important consequences on a variety of engineering aspects. For example, if a ditchrider can quickly change a flow into a lateral, it can reduce spill from the end of a lateral. That in turn can reduce the size of recirculation facilities. It can also reduce the need for increasing the canal capacity at the tail ends of laterals (needed to accommodate more flexibility in shutting off turnout flow).

Embedded in this discussion is the concept that in irrigation district canal systems – which have lag time, unsteady flow, trash problems, inexact flow measurements, and sometimes unpredictable customers – we will probably generally always need some type of "open-loop" control in many areas – especially in the laterals. The fact is that ditchriders often know who will accept water early or late, if there is a temporary flow rate capacity issue in some area, if there is a high probability of strange behavior by a particular irrigator, etc. Therefore, if they have easy access to high-quality, strategic information – plus the ability to remotely control key points – they can act rapidly and efficiently.

These actions can be both anticipatory and reactionary, depending upon the circumstance. Right now, most ditchriders spend most of their time driving the canal banks with fairly unproductive time – just looking at things, driving to make a gate change, etc. The ICIMS can increase productivity while making the job a bit more relaxed and less hectic.

HERE AND NOW

Meanwhile, until the broadband private Internet service providers become commonplace, various irrigation districts are gradually working on temporary options. These will continue to vary rapidly as technology evolves, but we aren't quite there yet in most areas.

The variations that irrigation districts use to access the web, provide security, etc. are so diverse that we will not attempt to outline them in this paper. Some will be included in the conference presentation. It is our prediction, though, that this will become simpler as time goes on – not more complicated. Some of us remember how in the early days we needed to solder the wires between printers and early

PCs, and we needed to know all the pin numbers. Now it's just "plug and play" and much more powerful.

It is fairly complicated at first glance, with terminology that many have heard but don't completely understand. We thought that the vocabulary and technology primers below might be useful to the reader.

Terminology

1. General Packet Radio System (GPRS). This is a relatively newer type of mobile data service, available to users with GSM-equipped cell phones. Charges are usually accrued based on the amount of data transferred, rather than connection time (as is the case with traditional cell phones).
2. Global Positioning System (GPS). This global navigation satellite system transmits signals to GPS receivers, and identifies the receiver's location.
3. Human-Machine Interface (HMI). This is what most people think of as the "office SCADA system". A number of commercial HMI software packages are available to display information on computer screens, ask remote sites for information, store data, manage databases, send alarms, etc.
4. Internet Protocol (IP) technology. In order for your office computer to get hooked up to the web, it needs an "IP address" so the worldwide web knows where it is. The same goes for web sites – they each have an "IP address". So when you develop web pages that you want to make accessible to the web, there needs to an "IP address" associated with that information. What is relatively new is that we can now purchase devices such as PLCs, radios, cameras, dataloggers, and even sensors with their own IP addresses. As long as there is a communication link (satellite links, fiber-optic cables, radios, cell phones, or other methods), these devices can be directly accessed.
5. Internet Service Provider (ISP). This is an organization (such as Verizon, AT&T, Comcast, or many others) that offers access to the Internet and related services. Usually a monthly service fee is involved.
6. Programmable Logic Controller (PLC). This is the static "computer" out in the field that is hooked up to various sensors, outputs, a radio, etc. It is sometimes programmed to perform automation tasks.

Remote Connections to the SCADA Computer

There are a variety of ways to connect a remote PC to an office SCADA computer. Some have been used for many years. The major options used by various irrigation districts are described below.

1. PCAnywhere. This is a commercial software program that retails for about $199, but which can be purchased online for about $40. It requires that the software be installed on both the laptop and the office SCADA computer. PCAnywhere can communicate via the Internet or a phone line, and enables a

remote user to have complete access and control of the office SCADA computer – although this does not prevent the office personnel from also using the SCADA computer.

2. GoToMyPC.com. This company sells three editions of software and access, with an annual fee per PC of about $180. It allows remote access to a PC from an Internet-connected computer or wireless devices/systems such as Windows Mobile, Pocket PC, or Windows CE. You go to www.gotomypc.com, register your office computer or server, and then log in from the same site to access the office computer. It is firewall friendly, meaning it automatically determines the best method to connect. It does slow down the remote access somewhat, because the gotomypc server is an intermediate step between your remote PC and the office computer. This service provides end-to-end encryption of the communications and some other security measures.

3. Virtual Networking Computing (VNC). VNC is a graphical desktop sharing system that uses a special protocol to remotely control another computer. It was originally developed by AT&T. It works between almost any two types of operating systems (including Macs to Windows). It is similar to gotomypc.com, but it is open-source software and is free. The disadvantage is that it isn't extremely simple to set up – a user needs to understand about firewalls, networking, etc. It works by installing the software on the office computer, and then remotely accessing the office computer using the VNC Java Client software. That Client software runs in a browser (such as Internet Explorer or Netscape) over the web, and can be downloaded to the remote PC from www.realvnc.com. This is only for web access, not for phone access.

4. Windows Terminal Services (WTS). This is very fast and can be used over phone lines or the web. It utilizes software that is included with various Windows Server packages. With the WTS server software on the office server, and WTS client software on the remote PC, it allows multiple remote users to access the office server simultaneously, running any office application they have access to. It is quite fast.

Our impression is that users usually believe the first two access methods described above are fairly secure. The last two connections are less secure, but can be made quite secure by also incorporating a Virtual Private Network (VPN).

On a remote PC, it is common to have some type of special security software, called VPN, that matches similar software or hardware on the agency/company's web server. These have to be synchronized. Some people refer to this as a type of firewall, which is used to separate a private network from a public network for security (see Figure 2). In other cases, the VPN is more a security type of software designed for access through a private local network (Intranet) rather than for remote access; it is used to establish a tunnel through a department's firewall.

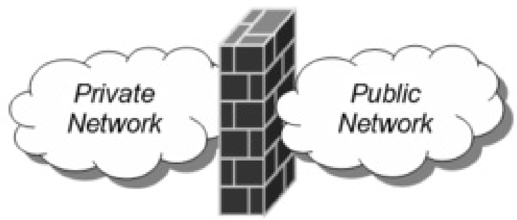

Figure 2. Illustration of a firewall
(From http://en.wikipedia.org/wiki/Firewall_%28networking%29)

The VPN, then, is some type of software or hardware set up for security purposes. It runs on two ends – at the server, and at the user's PC (the user-end could have many PCs at a time). It is typical that the server end of the VPN is set up as a VPN "box" on the inlet/outlet of a private network; the user end (or client end) runs on mobile laptops or home computers. The VPN is constructed by using public wires such as the Internet as the medium to virtually connect many computers as a private network for transporting data. It uses encryption and other security mechanisms to ensure that only authorized users can access the network and that the data cannot be intercepted.

VPN is also described as a port-forwarding, tunneling, or encapsulation technology in TCP/IP (Transmission Control Protocol/Internet Protocol), which is the basic communication language or protocol of the Internet. There are many commercial VPN products available, including a VPN from Check Point (www.checkpoint.com) and SonicWALL VPN (http://www.sonicwall.com).

DATA CONSIDERATIONS FOR SCADA PLANNING AND SETUP

Robert J. Strand[1]
Albert J. Clemmens[2]

ABSTRACT

The setup of a new SCADA system can be a daunting task. In addition to sifting through the myriad of sensors, programmable controllers, communication infrastructures, and SCADA software packages available in today's market, managers have to determine what they are going to monitor or control, what information they need to acquire from the field, what information will be sent out to field sites, the formats used to store and convey that information, and the need to archive select portions of that data for historical purposes. Even if a new implementation is done in phases, some forethought and advance preparation can simplify the process. The recommendations presented are based on experience gained from over 12 years of SCADA implementation associated with canal automation research at the U.S. Arid-Land Agricultural Research Center (ALARC) in Maricopa, AZ.

INTRODUCTION

The ALARC has been involved in canal automation research for over a decade. Beginning in 1995, the center (then known as the U.S. Water Conservation Laboratory in Phoenix, AZ) has been utilizing the WM-lateral of the Maricopa Stanfield Irrigation and Drainage District (MSIDD) in Maricopa as a platform for conducting automatic canal control research. Since 2002, the ALARC has also been assisting the Central Arizona Irrigation and Drainage District (CAIDD) of Eloy, AZ in the implementation of a supervisory control system. At present, CAIDD is able to monitor and control 121 telemetry sites on its distribution network. Recently, CAIDD has outfitted sites on three of their lateral canals with additional hardware to begin a move toward district-wide automatic control. Preliminary testing of the automatic control was conducted in the fall of 2006 and full testing will commence in the summer of 2007.

This paper is an overview of the experiences of the ALARC staff and their cooperators. It is not intended to be a SCADA implementation manual, but rather a list of considerations that may prove useful in the planning, development, and

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deployment of a flexible and functional SCADA system. It is intended that this information not be specific to any particular hardware or software manufacturer.

GENERAL CONSIDERATIONS

Bits, Bytes, Integers, and Real Numbers

Digital computers handle data using a discrete component called a "bit"; short for **bi**nary digi**t**. In our standard decimal system, each digit can be assigned one of ten values (0 to 9). Similarly, in the binary system each bit can be assigned one of two values (0 or 1). While there are digital processor functions that will allow one to manipulate a single bit of information, processors commonly access binary information in groups of 8-bits, commonly called a byte, and larger groupings in the form of 16, 32, or 64-bit "words".

In their native setting, digital processors generally use these groupings to represent integer values, i.e. 0,1,2,3, etc. and the processors are very efficient in executing integer arithmetic. In an unsigned format, the range of a binary number is from 0 to 2^n-1, where n represents the number of digits in the number. So, an unsigned byte can have a value from 0 to 255. Signed integer values are generally represented using what is called the Two's Complement format, giving a range of $-(2^{(n-1)})$ to $2^{(n-1)}-1$ (-128 to 127) for a byte.

We tend to think of numerical data in terms of a continuous spectrum of real numbers. When typing the value of 9.81 into a spreadsheet to represent the acceleration of gravity in SI units, we give little thought as to how the computer actually stores this information. The value of 9.81 is stored in word groupings using what is called a floating-point format; meaning that the decimal point (more appropriately called the radix point for systems such as binary) can float from one instance to another. The floating-point format breaks the continuous range of real numbers into a set of discrete values bounded on the positive and negative ends. Generally, this isn't a problem in our everyday use of a personal computer because responsible programmers utilize a version of the floating-point format, called 64-bit or double-precision. This version of the format has a fine discritization and the bounds allow for very large positive and negative numbers. There is also a single-precision (32-bit) version of the floating-point format which has a more coarse discritization and narrower range.

In the average personal computer, floating-point arithmetic operations are implemented in a separate math co-processor that resides on the same physical chip as the microprocessor. In older machines, such as those using Intel processors older than the Intel 80486, this processor was a separate optional chip. For these older systems, developers were forced to include floating-point emulators in their software. While these emulators were slow, they enabled program execution on machines without the processor.

Real number arithmetic can also be implemented on systems without floating-point capabilities through the fixed-point representation; so named because all instances have the same number of digits to the left and right of the radix point. In the fixed-point representation, values that would normally be floating-point are scaled by a power of two, stored as integers, manipulated using standard integer arithmetic, and then rescaled when they need to be displayed or printed.

While these numeric representations really shouldn't be a concern in the general use of a modern computer, they can be a concern in a SCADA implementation when considering the capabilities of field hardware and the communication protocols used to convey information between field devices and the central SCADA software.

The numerical capability of field hardware ranges from full double-precision floating-point to only simple integer functionality. The trade-off is one of flexibility and ease of use versus cost. The hardware that does not support floating-point is usually less expensive, but it may require some custom programming if a need arises for the field unit to use storage or calculations in a floating or fixed-point format.

Many protocols, including Modbus (with quasi-standard extensions), are compatible with varying bit-widths of the floating-point format as well as signed/unsigned integer formats. Issues can arise with communication protocols when the field unit is programmed to use custom fixed-point representations for values, such as a flow or upstream level setpoint, that need to be transmitted between the field unit and the SCADA software. Some customization may be needed in the SCADA software to be able to properly communicate information to the remote sites in the fixed-point format.

A-D Resolution

In order for a digital device such as a PLC to interact with analog devices like a pressure transducer, the PLC utilizes a process called Analog-to-Digital (A-D) conversion to convert a sensor output signal, e.g. electrical current, into a discrete digital value that can be utilized by the PLC. A-D converters are specified in varying bit-widths. One can find devices with A-D conversion on the order of 8, 10, 12, and 16-bits. Generally, 8-bit resolution is less expensive but in practice, the measurement can be too coarse. For instance, if used with a gate position sensor with a range of 4 ft, the reading of that transducer would be broken into 255 increments of approximately 0.2 inches. A finer resolution, such as 16-bit, can be a problem as well as it can result in a noisy signal. Applied to the prior example, a 16-bit A-D converter would break the gate position reading into 65535 increments each representing about 0.0007 inches. The 10 and 12-bit implementations seem to work best.

DATA CONSIDERATIONS

Physical Information

The physical dimensions and design information of various structures may be needed in a SCADA implementation. This information can be used to determine operating criteria, such as seasonal operating depths, and used in conjunction with measured data to compute useful management data such as flow rates at regulating structures. Some structures and examples of associated useful information are summarized in Table 1.

Table 1. Physical Dimensions and Design Information

Structure	Dimensions and Design Information
Sluice Gate	Gate Height Gate Width Sill Elevation
Radial Gate	Gate Radius Gate Width Trunion (Pinion) Height Sill Elevation
Weirs (Sharp Crested)	Crest Elevation Crest Length
Canal Sections	Design Flow Capacity and Water Levels Cross-Section Information
Pipe Sections	Pipe Diameter and Length

Depending on the distribution of functionality throughout the SCADA system, this information may be used in the field hardware as well as in software on the central SCADA system. If so, storing this data in a computerized database may be advantageous for a number of reasons:

(1) Many SCADA software packages are capable of reading information from standard database formats and using it to populate internal data structures.
(2) Should this information be utilized by field units for local calculations, it would be possible to use the same database with a configuration program; automatically converting to the appropriate numerical system as needed.
(3) By minimizing the number of storage locations, data entry mistakes can be minimized.

In addition to the dimensions of the physical structures, it may be advantageous to document the topology, i.e. the spatial or upstream/downstream relationship of the regulating structures, and the locations of supply and demand points in the system. With this information, it would be possible to incorporate supply/demand information into the SCADA system and provide operators with the local and downstream demands for a given structure.

Sensor Calibrations

While sensor calibrations shouldn't have to be done often (seasonally or quarterly), periodic field calibrations are necessary in order to give operators an accurate depiction of the field situation. Many sensors, including pressure transducers for water levels, potentiometers used for vertical gate position, and inclinometers used for radial gate position can be considered linear devices. The ALARC has adopted a linear calibration method that applies to each of these sensors.

$$\text{Output Value} = (\text{Sensor Output} - \text{Offset}) * \text{Slope} + \text{Bias} \qquad (1)$$

Where:

- Offset - represents the minimum output of the sensor
- Slope - represents the rate of change of the sensor reading
- Bias - represents the relation between the sensor and the real world, i.e. zeroing

It should be noted that Equation (1) can have useful physical meaning without the Bias term. The following table summarizes the use of this calibration for the cases of a pressure transducer used for measuring a water level upstream from a broad crested weir, and for a potentiometer used to measure a gate position for a rectangular sluice gate covering a circular pipe, with overlap of the pipe in the fully closed/sealed position.

Table 2. Summary of Linear Calibration

Formula Component	Pressure Transducer	Potentiometer
Offset	Output of the sensor when removed from the water	Output of the sensor when the gate is completely closed and sealed
Slope	Change in the output of the sensor for a given change in the water level above the sensor	Change in the output of the sensor for a given change in the gate position
Bias	Position of the sensor relative to the sill of the weir	The overlap - Difference between the fully closed position and where the orifice is exposed.
Equation 1 without Bias term	Actual depth of the pressure transducer	Absolute gate position with respect to fully closed position
Output Value	Water level above weir sill	Orifice opening.

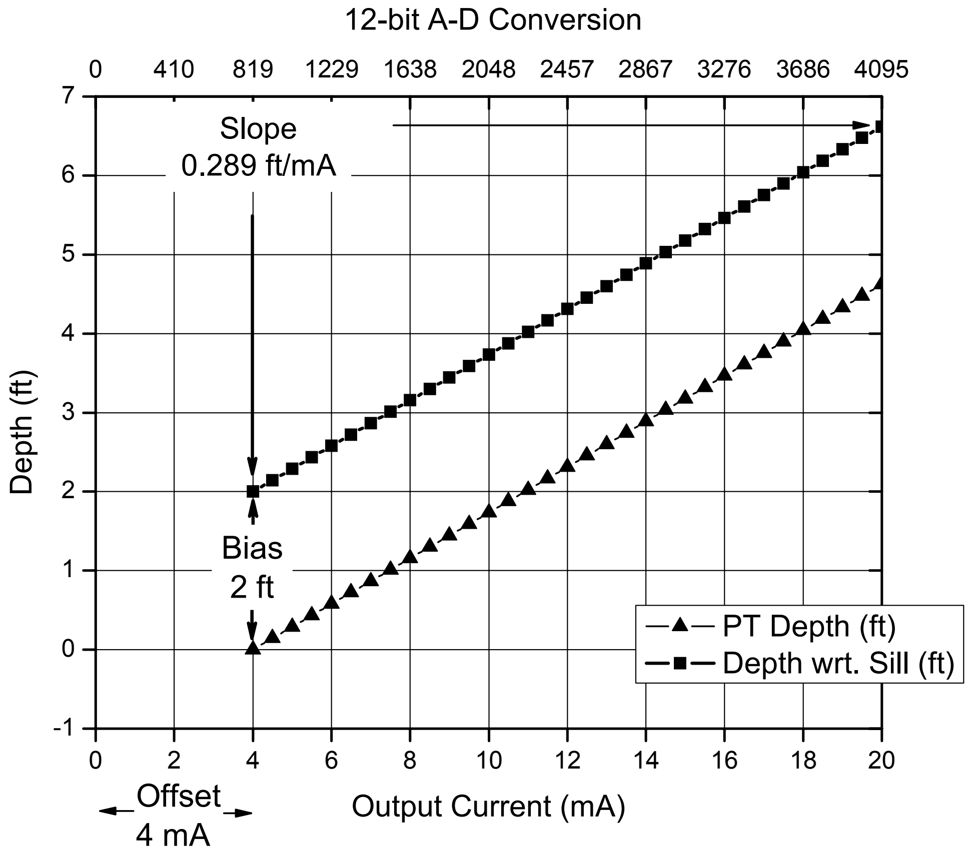

Figure 1. Example of Pressure Transducer Calibration

Figure 1 shows this calibration for a 2 psi (4.62 ft. full-scale) pressure transducer, with an output of 4-20 mA, mounted 2 ft above the invert of a canal pool. Note that the upper axis represents the sensor output from a 12-bit A-D converter.

This calibration method lends itself well to field calibration (Replogle, 1997). As shown for a pressure transducer in Figure 2, the slope can be determined by first taking a reading at the normal operating position and then taking a second reading after displacing the transducer from its operating position by some known distance. By taking measurements at additional offsets from the operating level and calculating a simple regression, the slope may be more accurate. To determine the offset, simply take the pressure transducer out of the water and take a reading. The slope and offset can be calibrated in the office or equipment crib prior to installation at a field site.

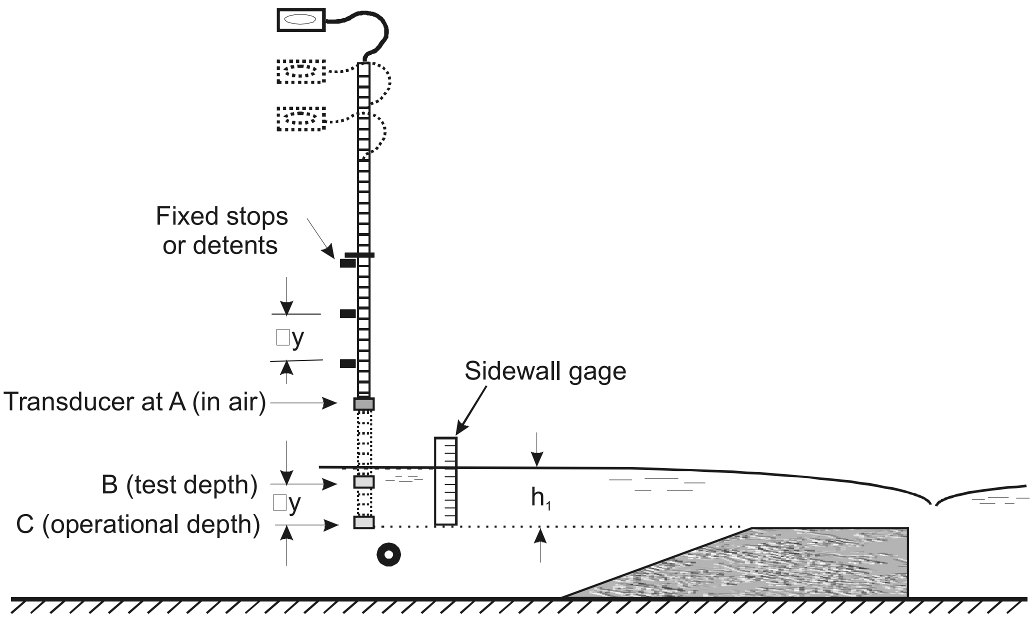

Figure 2. Pressure Transducer Calibration

Finally, to determine the bias, first determine the actual water level by comparing it to a reference point, such as the top of an overflow weir. Place the transducer in its normal operating position, take a reading, and use the slope and offset to calculate the depth of the transducer. The bias is equal to the difference between the actual depth and the transducer depth.

Note that the slope and the offset are properties of the measurement device. Nominal values for these parameters are provided by manufacturers.

Once established, these values can be entered into a SCADA configuration database for use in SCADA software and hardware configuration. It can be advantageous to keep a historic record of these calibration values in order to track seasonal variability in sensor output, to better track sensors that are having problems, and for recovery from of a SCADA computer or field hardware failure.

Operator Displays and Scan Rates

While the underlying data is the foundation of a SCADA system, it means nothing unless the operator is able to discern usable information from the user interface. To optimize computer resources, many SCADA systems rely on multiple timing loops, as shown in Figure 3, to get the information from the field to the user.

In systems designed only for remote supervisory control, i.e. no automatic controls are in place, a normal time-based rate for scanning field sites might be on the order of fifteen or twenty minutes. However, it is common to give the operator the ability to "force" a scan of a particular field unit. Consideration should be given to timing of the calculations and interface updates to insure that the operator receives timely updates when values change. In the configuration shown in Figure 3, the operator will see the change no more than 90 seconds after it has been read from the field. This timing becomes more critical when implementing centralized control from the SCADA software and automatic forced scans may be needed to provide timely values to control routines.

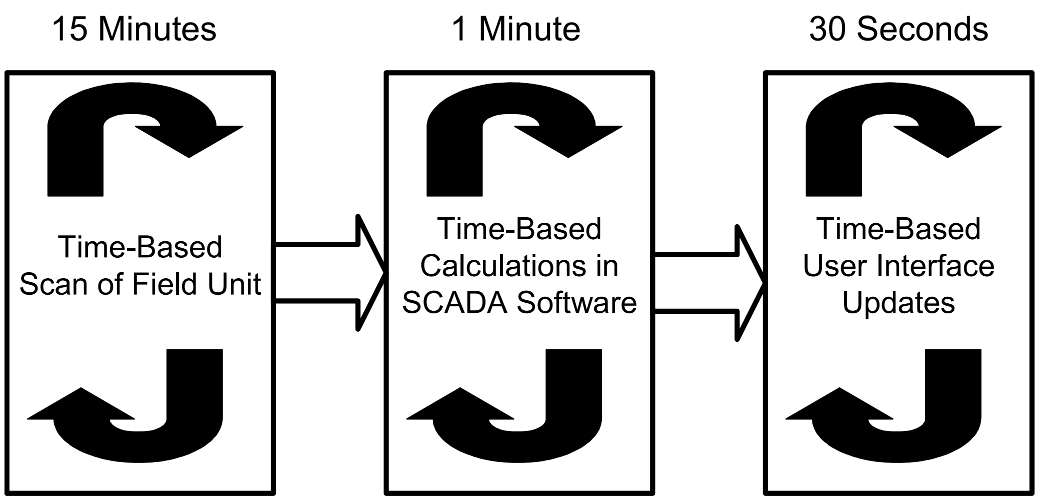

Figure 3. Time-Based Information Path

Communications Infrastructure

Many communication protocols are available for use in a SCADA environment. While formats vary, generally all specify some type of address or ID for a specific device. Additionally, some communication hardware networks, such as spread-spectrum radio networks, have unique addresses for each radio in the network. It is worthwhile to incorporate this information into a SCADA configuration database as accidentally inserting a duplicate address into either layer of the communications environment can lead to problems.

Data Flow and Equations

Some field hardware is capable of returning absolute values that have direct meaning to a SCADA operator. For example, many flow meters are capable of returning a floating-point value of the measured flow. In other cases, a meaningful value has to be calculated either in the field hardware or in the SCADA software. Figure 4 shows the data flow for the calculation of an upstream depth based on the calibration in Equation 1.

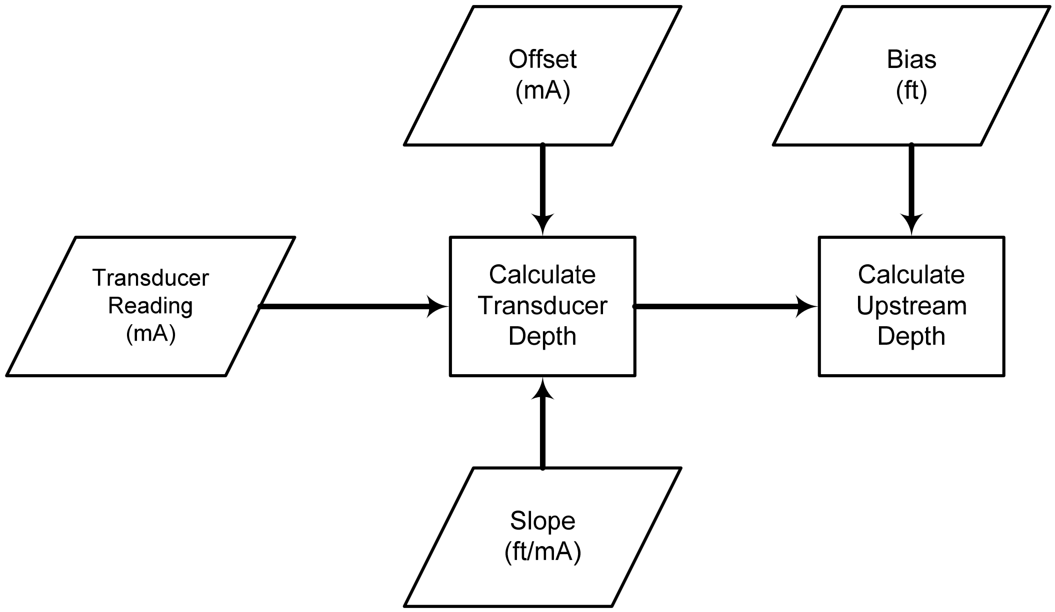

Figure 4. Data Flow for Upstream Depth Calculation

Note that if the transducer reading is returned as a binary integer, the offset and slope are calculated in terms of binary values.

SCADA software packages provide a number of methods for driving these calculations. One option is to execute a calculation on a time basis. Using the timing shown in Figure 3, the communication driver acquires data from a field site every 15 minutes and stores it in the SCADA system. The transducer reading is then checked every minute, which forces calculation of the transducer depth and then the calculation of the upstream depth. The user interface then checks these computed values every 30 seconds and displays the value.

Another option is to execute the calculation on an "exception" basis; meaning that the software executes the calculation only when the input changes. Again, using Figure 3, the communication driver polls a site every 15 minutes. Instead of simply storing the acquired value, it also checks to see if the value has changed. If the value is unchanged, no calculations are executed. If the value has changed, then the new value passed and the calculation chain is executed.

Once the fundamental measurements are calculated, they can be used in other calculations. Figure 5 shows the data flow for the calculation of the combined flow for a control structure consisting of a submerged gate and an overflow weir. Again, these calculations can be carried out in the field or in the central SCADA software. Care should be taken in selecting appropriate equations for computing elements such as weir and gate flows.

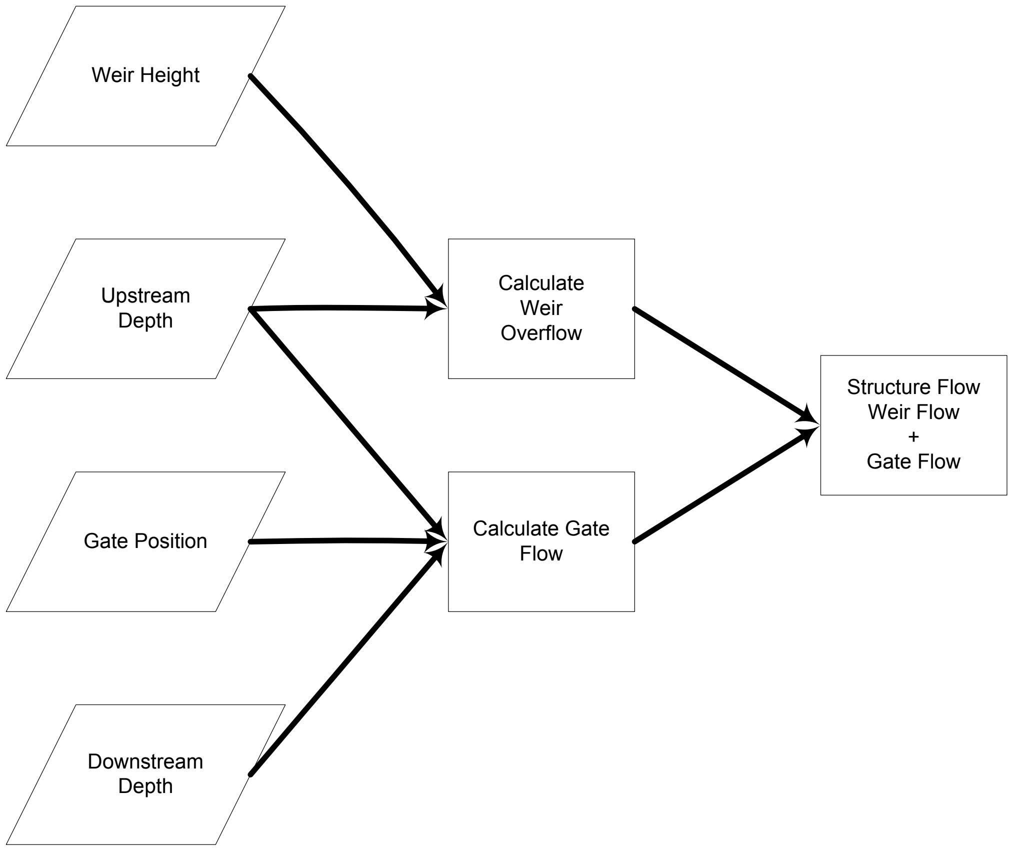

Figure 5. Data Flow Diagram for Calculating Control Structure Flow

Filtering

Filtering should be used with some caution. While it can be helpful to filter the output of a particularly noisy sensor, an improperly configured filter can induce large attenuation or delays in the signal seen by an operator.

In some SCADA software, filtering can be executed in the same manner as other calculations.

Avoid driving a filter calculation on an exception basis. Even for simple moving-average filters, consecutive identical values should be used to compute the filtered value. As a simple example, consider a 4-element data stream of [1,2,2,3]. A three-point moving average would return a value of 2.33. An exception-based three-point moving average would return an erroneous value of 2.

For time-based filtering, make sure that the filtering rate matches the rate at which data is being acquired. If the filter is sampling faster than the data is acquired, then inaccurate duplicates are included in the filter result. Again, using the timing shown in Figure 3, the filtering should be done on a 15-minute interval. If done more frequently, it will use duplicate values and will be incorrect.

Alarm Limits

An important component of any SCADA system is the capability to alert an operator to problems at field sites through some type of alarming system. A primary type of alarm is a limit alarm for semi-continuous values such as flow rate or water level. The ability to prioritize alarms is helpful. For instance, a flow rate deviation of +/- 10% from an established flow setpoint may warrant a lower priority alarm than a flow rate that exceeds the design capacity of the canal reach.

Rate-of-Change (ROC) alarms are important as well. These alarms are based on a time-rate of change in a particular value. Generally these alarms are set up to examine a particular calculation result or measurement at regular intervals. For instance, a ROC alarm could be configured to examine a water level at 20 minute intervals and signal an operator if the level changed more than 0.3 feet in that time period.

The timing and the allowable incremental change need to be appropriately scaled. For example, to protect canal linings, a district may have a policy of not allowing pool levels in large canals to change more than one foot in a 24-hour period. It wouldn't be appropriate to check for a one-foot change in the level one time each day. The time frame is too coarse. Splitting it up into a 0.014 ft limit in a 20 minute period probably won't work either. The incremental limit is too fine and the alarm will be signaled continuously. Two different ROC alarms may be advisable. One alarm would monitor long term changes and another would catch quick changes due to a stuck gate, a weed plug, or vandalism.

While it isn't necessarily inadvisable to base ROC alarms on filtered values, care should be taken to ensure that the filter doesn't attenuate the real signal to the point that the ROC alarm is overly delayed.

ADDITIONAL CONSIDERATIONS

Data Security

While some data elements such as the width of a gate or the flow capacity of a canal reach probably won't change over time, there are other items that SCADA operators will periodically need to modify. For instance, it is convenient for a central operator to be able to execute a field calibration of a pressure transducer with the assistance of someone at the field site. Using the calibration scheme previously described, the operator would need the ability to modify the offset, slope, and bias of the calibration.

As usual, when granting access to configuration data, there is potential for exploitation. For example, consider a situation where an operator is having trouble keeping a pool level within the alarm limits, is getting tired of hearing the alarm horn, and doesn't have access to modify the alarm limits. One way to silence the alarm is to modify the calibration bias and bring the computed water level within the limits. While this might alleviate the frustration of hearing an alarm horn, the computed water level is no longer accurate. This can cause problems for the subsequent shifts who probably won't know about the calibration change.

Many SCADA software packages incorporate internal security and user management systems into the software architecture. Additionally, some Windows-based SCADA packages are able to run as a Windows Service. This allows the SCADA software to continue to run while a new operator logs in to the system. In either case, the SCADA software can then tailor data access and track data changes and user actions based on the internal user information or the Windows user information.

Historical Data

In order to analyze system operation and for possible liability issues, various data elements in the SCADA system may need to be preserved in a time-based historical database. These might include water levels, flow rates, gate positions, level and flow setpoints, control actions, and the raw data from field devices that would be used to compute other values. Many SCADA software packages allow developers to specify which data elements are stored, and the frequency at which they are recorded. Some time-based historical database formats minimize the amount of storage space needed by only creating entries in the database when values change. When querying the database for historic data, a complete timeline is created from the recorded changes.

Many SCADA packages encrypt historic databases to prevent tampering. This may be an important consideration if there is a chance that an irrigation district may need to use this information in liability litigation.

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AUTOMATED SCHEDULING OF OPEN-CHANNEL DELIVERIES: POTENTIAL AND LIMITATIONS

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ABSTRACT

Irrigation and municipal water delivery systems are under ever-increasing pressure to improve operations. Supervisory Control and Data Acquisition (SCADA) technology is helping delivery organizations improve flexibility of operations, reduce costs, and overcome operational constraints, as it allows operators to remotely monitor and operate check gates to maintain desired water level and/or flow targets at control points. Computerized canal control schemes in combination with the SCADA technology, can further enhance operations by automatically handling scheduled demand changes (feedforward control) and responding to unexpected perturbations (feedback control). Significant progress has been made in recent years in the development of computerized control schemes, but adoption of such technologies is slow, partly because the potential benefits relative to existing manual operational procedures cannot be easily predicted, and partly because control schemes, ultimately, must be configured to the particular needs and constraints of the delivery system.

This paper examines the potential application of computerized scheduling on the Salt River Project's (SRP) delivery system. The objective is to evaluate the potential for improved water control compared with current manual operations. We also examine particular constraints faced by SRP operators, how they impact the development of daily operational schedules, and how that would limit the applicability of automated scheduling concepts.

BACKGROUND

The Salt River Project (SRP) is an organization consisting of the Salt River Valley Water Users Association and the Salt River Agricultural Improvement and Power District. SRP delivers water to about 250,000 acres, and power to about 2900 square miles in and around the metropolitan Phoenix area in south central Arizona. Six reservoirs with a total storage capacity of more than 2.3 million

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acre-feet store water from the 13,000 square mile watershed of the Salt and Verde Rivers north and east of the service area. Water released from these reservoirs is then routed through 1300 miles of canals and laterals to the water users. Other sources of water include 250 groundwater wells and a connection to the Central Arizona Project (CAP), which brings water from the Colorado River to farms and cities throughout central and southern Arizona.

Water delivery operations have evolved at SRP in response to the changing service demands, water control technologies, and constraints imposed on delivery operations. As part of this evolution, SRP initiated a pilot project in 1996 to develop and test a canal control algorithm on a portion of SRP's canal system (Gooch 1996; Clemmens et al 1997; Clemmens et al 2001). This project was completed in cooperation with the former United States Water Conservation Laboratory (now Arid Lands Agricultural Research Center - ALARC), U.S. Department of Agriculture, Agricultural Research Service. Simulation model results showed that the control algorithms worked well (Bautista et al 2006), and this same controller was applied successfully in the field in another district (Clemmens et al 2005).

The next step was to apply the controllers to the canal system. Operations personnel were not comfortable with applying both the feedback and feedforward control to the canal system at once. Recently, the manual canal scheduling process was complicated somewhat by changes in a related process that provided distribution schedules. It was decided to separate the feedforward and feedback controllers from each other and apply only the feedforward portion of the algorithm, which would be modified to generate a schedule to be applied manually by the canal operators, known as watermasters, thereby simplifying the scheduling procedure. The initial results of that effort are discussed in this paper.

CURRENT SRP CANAL OPERATIONS

SRP currently operates as a limited customer-driven delivery system with relatively flexible service. Typically, customers submit water orders the day prior to the desired change in delivery (new delivery, cutoff, or change in flow rate) and can specify both the flow rate and the timing of the change. These orders are subject to the limitations of canal capacity and travel times from upstream reservoirs through the distribution system. Many times large changes are not scheduled at a specific time, but rather "on the raise", meaning at the time the water being routed from the reservoirs actually arrives at the delivery point. Same-day changes, termed "red changes", can be accommodated if they can be offset by other same-day requests, or if they are small enough to be absorbed by the system. Emergency conditions, *e.g.* storms, unanticipated shutdowns by water treatment plants, and accidents, are handled by manually routing water to emergency spillways.

The control strategy aims to maintain forebay water levels close to a target value. A forebay is the channel section just upstream from cross-regulators (radial gate check structures). Offtakes located upstream from these structures are adjusted manually based on the target level and the water order. There are a few offtakes that are automatically controlled by adjusting the gate according to a downstream discharge measurement. There are also a number of offtakes that are not located near the check structures, including some of the larger delivery points to water treatment plants. Watermasters take special care to minimize changes in water levels throughout the length of the pools in which these deliveries are located. Watermasters maintain water levels primarily by adjusting gates based on a predetermined schedule and on observation of deviation of water surface measurements and flow rates from target values throughout the day. These deviations may be due to system noise, unaccounted for system losses and gains, and unknown changes in field operations.

A supervisory control and data acquisition (SCADA) system is used by watermasters to remotely monitor water surface elevations and flows throughout the canal system, and to remotely operate the check gates, some of the offtake gates, and many of the groundwater pumps that provide additional water to the canal system. The SCADA system displays current water levels at each check structure, along with the water level history for each of those levels from which trends and flow imbalances can be discerned. It also monitors flow rates at several flow measurement sites within the system.

For routine operations, a delivery schedule is compiled from user orders by an automated water accounting and tracking procedure. The watermasters group the deliveries by inspection and, using rule-of-thumb travel times, develop a schedule of flow changes at the cross-regulating check structures along the canal. These changes are entered into a spreadsheet, sorted by time of day, and then used by the watermasters during the day as a guide for their operations and as a place to record actual operations during the day.

SACMAN SCHEDULER

The SacMan-Orders program is the canal scheduling component of the Software for Automated Canal Management (SacMan) program, developed by the USDA-ARS (Clemmens et al 2005). It uses the concept of volume compensation (Bautista and Clemmens 2005) to compute the schedule of flow changes at the cross-regulators for a known schedule of water demand changes. The volume compensation method assumes a succession of steady-states: for example, in a single pool canal with inflow Q_0 and a known change in offtake demand Δq, the method calculates ΔV, the volume by which pool storage needs to increase or decrease in order to produce a new steady condition:

$$\Delta V = V(Q_0 + \Delta q) - V(Q_0) \tag{1}$$

ΔV is then used to determine the time at which the pool's upstream check structure needs to be adjusted by an amount Δq. If the demand change is requested at time t_d (day/time), then the upstream check flow needs to be adjusted at time t_1

$$t_1 = t_d - \Delta\tau \tag{2}$$

where $\Delta\tau = \Delta V / \Delta q$. This travel time estimate $\Delta\tau$ has been shown to produce reasonable water level control under a variety of pool configurations and flows (Bautista et al. 2003; Bautista and Clemmens, 2005). The SacMan program does not carry out the steady-state calculations needed to determine ΔV. Instead, it interpolates from tables of volumes computed as a function of Q, the pool's setpoint depth y_{stp}, and the Manning roughness coefficient n.

For the more general case of a canal with multiple pools subjected to multiple demand changes, a global schedule is found by superimposing the solutions calculated for individual flow changes and individual pools.

COMPARISON OF RESULTS

The example presented herein compares the January 8, 2007, schedule computed by the SRP watermasters with the schedule computed by the SacMan Scheduler for two of the six main canals in the SRP canal network, the Arizona and Grand Canals. These two canals consist of 31 pools regulated by cross-regulating check structures that use of batteries of radial (undershot) gates for control. The Grand Canal splits off from the Arizona Canal 18 miles downstream from the Arizona Canal headgates which divert water from the Salt River. The Arizona and Grand Canals deliver water to over 40 major delivery points (water treatment plants, laterals, or lateral groupings). They are supplied by SRP reservoirs, groundwater, and deliveries from the CAP, with the latter entering the system just below the Arizona Canal headgates. The Arizona Canal's capacity ranges from 1600 cfs at the head to 625 cfs at the tail, and the Grand Canal's capacity ranges from 625 cfs at the head to 450 cfs at the tail.

Water demands during January are low and, therefore, the flow conditions of the example (which are summarized in Table 1) are relatively simple. On the selected day, only ten offtakes were active, total demand barely exceeded 100 cfs, and all supplies were from SRP reservoirs. Six demand changes were requested on these canals on that day. In Table 1, the Canal column is used to identify the location of a flow structure; the Type column identifies the flow structure type; the Chainage column gives the location of the structure relative to the headgate; the Initial Flow column gives the initial cumulative check flows and offtake outflows; and the last two columns give the demand change schedule (magnitude and timing).

Table 1. Initial flows and demands for SRP's Arizona and Grand Canals
January 8, 2007

Canal*	Structure Type**	Chainage mi	Name	Initial flow cfs	Demand Change cfs	Time
AZ	CHK	0.00	1-00.0	103.275		
AZ	otk	7.77	SRPMIC-PUMP	16	8	6:00 AM
AZ	otk	7.83	SRPMIC-NSD	40	-12.5	6:00 AM
AZ	CHK	7.88	1-00.6	47.275		
AZ	otk	13.55	LAT 010-019	0.625	-0.125	12:01 AM
AZ	otk		CHAPARRAL WTP	12.375		
AZ	CHK	14.19	1-01.9	34.275		
AZ	otk	16.53	LAT 020-030	0.875		
AZ	CHK	16.76	1-03.0	33.4		
AZ	CHK	17.44	1-03.4	33.4		
AZ		18.04	GRAND Canal	15.45		
AZ	CHK	19.03	1-05.0	17.95		
AZ	otk	22.78	LAT 070-080	0.75	-0.75	3:00 AM
AZ	CHK	22.81	1-08.0	17.2		
AZ	otk	25.36	LAT 085-100	0.5	-0.5	3:15 AM
AZ	CHK	25.48	1-10.0	16.7		
AZ	CHK	27.24	1-11.0	16.7		
AZ	CHK	29.56	1-13.1	16.7		
AZ	CHK	31.14	1-14.4	16.7		
AZ	CHK	32.84	1-16.1	16.7		
AZ	otk	33.80	CHOLLA WTP	15.45		
AZ	CHK	34.28	1-17.1	1.25		
AZ	otk	35.43	LAT 174-181	1.25		
AZ	CHK	35.51	1-18.1	0		
AZ	CHK	36.94	1-19.1	0		
AZ	CHK	37.99	1-20.0	0		
GR	CHK	18.04	2-00.0	15.45		
GR	CHK	18.74	2-02.0	15.45		
GR	otk	20.65	PAPAGO WTP	15.45	-15.45	8:00 AM
GR	CHK	21.15	2-04.2	0		

* "AZ" indicates Arizona Canal; "GR" indicates Grand Canal
** "CHK" indicates check structure; "otk" indicates offtake

Figure 1 depicts the flow schedules computed by SacMan (solid lines) and the watermasters (dashed line) for the headgate (structure 1-00-0) and three other check structures. Differences between these schedules, and the implications for practical application of automated scheduling, are discussed in the following paragraphs.

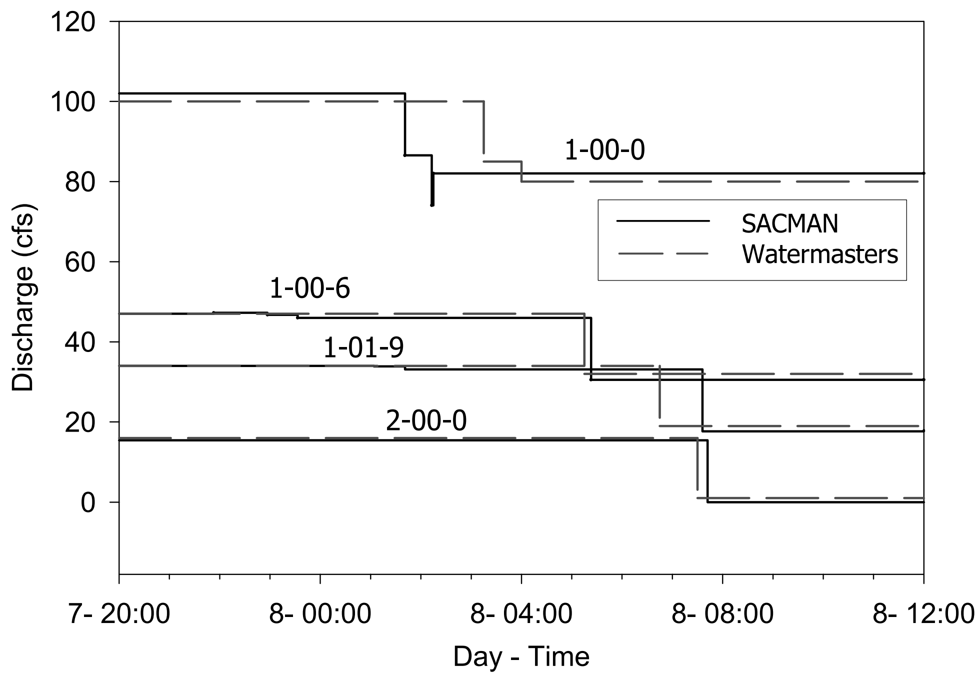

Figure 1. Flow Schedule Comparison

There are slight differences in total initial inflow (the flow at structure 1-00-0) with the SacMan calculations being slightly higher. Although the schedules are based on the same demand data, the watermasters' schedule includes an estimate for "carriage water", which accounts for system gains or losses and for volume changes needed for the day being scheduled. Watermasters charge carriage water to an entire scheduling zone (a group of pools). Estimates vary depending on the time of the year and can represent as much as 10% of the total water order (Clemmens et al. 2001). The worksheets developed by the watermasters for January 8 indicate that the watermasters deducted 3 cfs from the total order.

In SacMan, carriage water can be considered simply an additional diversion or intake point. Since SacMan accounts for volume compensation in its calculations, the difficulty is in translating the watermasters' judgments into a set of computational rules that allow the scheduling program to allocate carriage water which would account for system gains and losses only. No carriage water was used in SacMan for this example.

Total flow changes calculated by SacMan differ from the total changes computed by the watermasters. Table 2 compares the cumulative flow changes for January 8 at relevant check structures. Differences can be seen to be nearly 2 cfs at some locations. The difference is explained by rounding-off in the watermasters calculations due partly to the demand report generated by the water accounting system. The report displays the demands to the nearest 1 cfs while user requests are generally submitted in miners inches (1 cfs = 40 MI). A more important factor, however, is the fact that watermasters take into account the accuracy of flow measurements at check structures to determine reasonable flow adjustments. Small flow changes (such as the one required at the 1-08-0 structure) generally are ignored since feedback adjustments will be needed anyway to correct pool imbalances caused by incorrect gate settings. The SacMan scheduler takes into account this resolution constraint and, therefore, the user can force calculations to within the nearest user-defined flow increment (e.g, 1 cfs, 5 cfs etc.).

Table 2. Cumulative check gate flow changes for January 8, 2007 scheduling example

Check	SACMAN	Watermaster
1-00-0	-21.325	-20
1-00-6	-16.825	-15
1-01-9	-16.700	-15
1-03-0	-16.700	-15
1-03-4	-16.700	-15
1-05-0	-1.250	0
1-08-0	-0.500	0
2-00-0	-15.450	-15
2-02-0	-15.450	-15

Comparison of the schedules reveals substantial differences in the timing of the flow changes. As explained in the previous section, SacMan -calculated delays are based on the time required to supply needed pool volume changes. Watermasters use travel times based on rules-of-thumb gained from experience, which they adjust depending on the time of the year. Table 3 compares the pool travel times computed by SacMan for the demand change at Papago WTP (see Table 1) with those employed by the watermasters. In the table, the downstream check structure is used as pool identifier. The two most upstream pools in this example (1-00-6 and 1-01-9) are long and are only partially under backwater effects. Under these conditions, substantial volume changes are needed to produce a new steady-state profile for even slight flow changes. Not surprisingly, the SacMan calculated delays are much greater than the rule-of-thumb delays. Other pools are relatively short and are entirely under backwater effects; under such conditions, small changes in pool volume are needed to achieve even large changes in pool steady-state flow. Hence, for those other pools, the watermaster delays are much greater than those calculated by SacMan. Ultimately, there is nearly an 80 minute difference in total travel time, which is reflected in Figure 1.

Table 3. Travel times (in minutes) computed for flow change at offtake Papago WTP offtake

Pool	SACMAN	Watermaster
1-00-6	222	120
1-01-9	134	90
1-03-0	4	45
1-03-4	0	0
1-05-0	2	15
2-02-0	0	0
2-04-2	17	30

At the time that this paper was written, simulation results were not available to validate the computer generated schedule. However, it is possible at least to analyze the performance of the watermasters' schedule based on recorded water levels. Inspection of reports shows the watermasters schedule was applied essentially as shown in Figure 1, with the timing of the flow changes differing from the plan by just a few minutes in some cases. Results are displayed in Figure 2, for four forebays of interest to this study. In the figure, the solid line represents the measured water depths as a function of time while the dashed lines represent the corresponding setpoint depths. SRP watermasters' objective is to maintain water levels within 0.25 ft of the target. Clearly, the schedule's performance is reasonable, but a downward drift can be noted for forebays 1-05-0 and 2-00-0, while water levels in forebay 1-01-9 appears to slowly increase. For forebay 1-05-0, the water depth at the end of the day is below the setpoint minus the tolerance value and still dropping. The water level drop in the downstream forebays can be explained in part by inaccuracies in gate flow settings and other canal uncertainties, but also to a built-in mismatch in pool inflow and outflow due to the rounding of flow changes.

CONCLUSIONS AND WORK TO BE DONE

While the above results suggest some potential for improving water level control with automatic scheduling, extensive simulation and field tests are required to prove the concept in practice. Among the difficulties to overcome is that the current scheduling and operating process was developed without automation in mind. When applying an automatic scheduling system to an existing manual system, adjustments in the process are necessary in order to provide the software with sufficient information. Until recently, this has been a significant obstacle to implementing such a process at SRP. In recent years, however, many of these adjustments have already been made in the development of new water ordering, tracking and accounting procedures.

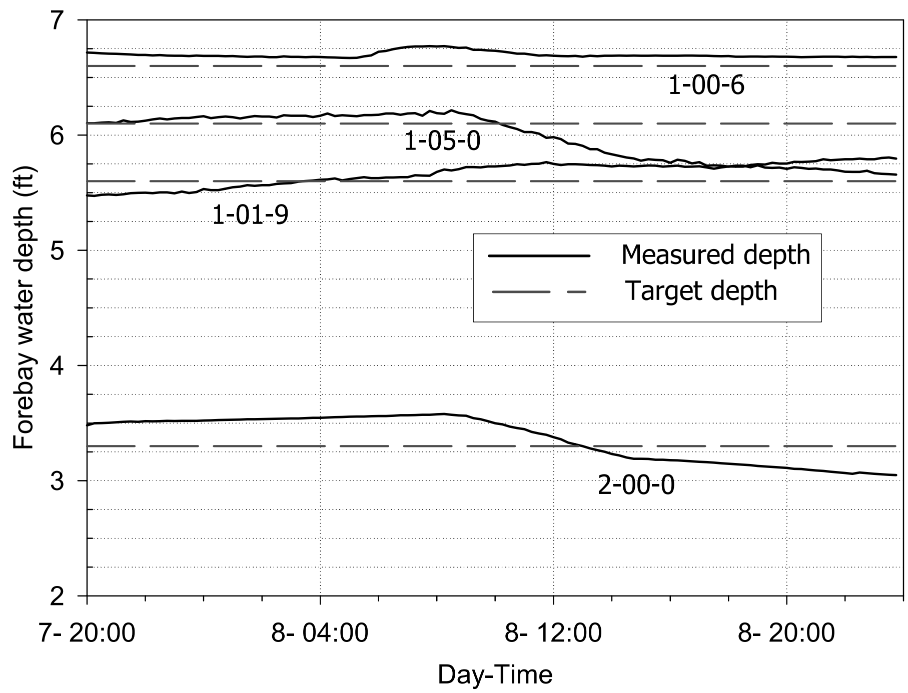

Figure 2. Variation in water depths with time at selected forebays, using the watermasters' schedule

In the simplified example used here, even with few and relatively small flow changes, there are differences in the watermaster schedule and the SacMan schedule, which can be explained by carriage water, rounding, and shortcomings in generalized rules-of-thumb. These seem to be rather minor problems to overcome. However, in a more representative demand schedule, there are still more complexities such as "red changes" and "on-the-raise" orders that may be more of a challenge to incorporate into the scheduler. Also, with a large number of demand changes, a large number of check flow changes will be required by the computer-generated schedule, which may be difficult to implement in practice. Thus, rules will have to be developed to simplifying the schedules (fewer changes, at predetermined time intervals), and the impact of such simplified schedules on system performance will have to be examined.

Although manual scheduling and canal operations procedures at SRP have produced very few instances of operational errors due to changes in deliveries, the authors believe that incorporating the scheduler in the SRP system still offers potential benefits. Manual schedules are developed based on the range of the watermasters' experiences and, thus, on natural sensemaking (Weick, 1995). Because they are based on physical principles, computerized schedules can enhance the operators' sensemaking ability, relieve of them of tedious aspects of their scheduling chores, and ultimately provide a more stable operation under typical operating conditions.

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SCADA SYSTEMS — ISLANDS OF AUTOMATION OR AN INTEGRATED PART OF THE INFORMATION TECHNOLOGY ENVIRONMENT

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ABSTRACT

Many SCADA systems are implemented as standalone projects to provide operators with an intuitive interface to view and control plant. This approach often overlooks the needs of supervisors and managers who want information for decision support and integration with other business systems.

This paper describes the approach Rubicon Systems Australia Pty Ltd has used to integrate its SCADAConnect product with a suite of other water management software applications such as water ordering, water planning and scheduling, entitlement management, usage accrual, billing and collections. The paper describes the technical architecture used to achieve this outcome, the capabilities of the integrated product suite and the facilities available for end users to analyse and extract high level system performance information.

BACKGROUND

A Google search of the History of SCADA shows that Supervisory Control and Data Acquisition Systems are recorded as being introduced in the 1960's. SCADA systems of this time were functionally simple in that the primary purpose, as is largely the case today, was to acquire and present data and provide an interface to remotely controlled equipment. These systems were characterised by specialised equipment, significant engineering design and construction effort and high costs. In many instances the display panels used to "Mimic" the plant were "hard wired" to meet individual needs. With progressive development of the digital computer, many proprietary systems were developed through the 1970's. With the wide spread penetration of the VAX and UNIX based computer systems in the 1980's, software solutions became more portable and many commercial products were produced to run on these platforms through the early 1990's. The commercial vendors migrated to the PC environment through this period and the strengthening of operating systems and graphical user interfaces make the PC the platform of choice for most commercial deployments today.

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In parallel with the end user or "host" technology transition, general advances in electronics and communications technology has seen the Remote Terminal Unit (RTU) undergo a number of significant changes. There are a plethora of RTU vendors today with many large, multinational companies offering mature and stable products. Despite the commoditisation of the RTU, the SCADA industry has made less progress with the standardisation of communications protocols than the mainstream computer industry. Interoperability of RTU's from different vendors can really only be achieved with protocols that are rudimentary by today's IT standards.

SCADA TODAY

It can be argued that implementing a SCADA system today has never been easier. There are a plethora of options for PC-based packages, RTU vendors and experienced system integrators. Many vendors also have packaged RTU software to implement local control functions based on Upstream Level, Flow or Downstream Control paradigms. The choice between the products is influenced by many factors. Some of these are:

- Functionality and technical capabilities of products
- Support availability
- Relevant experience – of vendors, implementers and authority staff
- Price and life cycle costs
- Technology and business roadmap of vendors

When making a choice regarding SCADA implementation, the superiority of a particular technology or solution must be balanced with the ability to receive timely and cost effective maintenance and support. The most important consideration is defining the objectives of SCADA technology investment and aligning the solution with these objectives.

As with any IT system implementation, a precise statement of the User or Business Requirements is the most sensible starting point. It is critical for this definition to capture the immediate needs and also articulate a strategy of how SCADA may be used in the future, including integration with other business systems like GIS, Water Ordering, Planning and Control systems, Asset and Financial Management systems. The answers to these questions have a critical bearing on the choice of technologies that are to be embedded in the overall solution for the business.

However, it is not uncommon to find SCADA systems implemented as standalone applications and indeed some customer specifications enforce physical and logical isolation of the SCADA network from the "mainstream" IT applications. In some instances this is a legitimate response to protect mainstream "critical" applications from hackers accessing insecure radio communication and SCADA protocols. In other instances this strategy is chosen to make a start and to address the integration options at a later time. It is common for the SCADA and IT departments to disagree on the best method to integrate. Defining these objectives at the outset of a SCADA project is fundamental for success.

MODERN IRRIGATION AUTHORITY OPERATING REQUIREMENTS

Many of the world's irrigation systems were constructed prior to the advent of SCADA and many of the practices used for operating these systems rely on manual human control with operators traveling around the network and adjusting manual structures to regulate flows to meet customer requirements. In many systems, water rights are shared between users using predefined and agreed rosters. On-demand systems, where customers place formal orders for water, are generally recognised as being more efficient in terms of water usage and crop production but logistically more difficult to manage. This management difficulty arises for two main reasons; the need to formally capture customer requirements as defined business transactions and to plan, schedule and operate the systems to meet varying customer requirements. Many authorities around the world still use paper-based "card" systems to lodge transactions and authority ditch riders act as go-betweens to balance customer requirements with system operating constraints. Many authorities have computerised these processes to varying degrees. Rubicon's Total Channel Control (TCC®) product completely automates the operation of large scale gravity irrigation systems by integrating water ordering, modelling, system operation and control and SCADA technologies. The remainder of this paper details the general software strategy used.

SYSTEM STRUCTURE

The operating objective of most authorities is to ensure that the flow in the system is adequate to meet customer requirements. To "supervise" this requirement it is therefore necessary to be able to compare scheduled water orders to observations from the network, and this real measurement may come from a SCADA system. If the SCADA system operates in real-time, it should also be able to identify when deviations from the schedule require human attention. In terms of SCADA system terminology two key concepts are of relevance; trending and alarming. In an architectural sense this requires the ability to incorporate the time series of demand or planned operation in the same trend as the measured or observed outcome. Thus, some form of software interface is required between the water ordering system and the SCADA system, and, if the real observations are manually collected, operators need a means for entering the observed data into the system. An ability must also be provided to define alarms based on the difference between planned and actual conditions.

Note that this is quite a different requirement from comparing measured water levels to defined control system set points, particularly for those systems being operated with an upstream control paradigm. With this control system configuration the controllers may well be meeting set-point requirements, but the underlying business objective of ensuring that supply meets demand cannot be evaluated in this way.

The approach Rubicon has taken to address this problem is to design the database schema that underpins its water management suite of products to accommodate both types of information and to build its display, alarming and reporting software to operate on this generic structure. This database has been implemented in standard relational database technology using products such as Oracle, SQL Server and Ingres to be the repository of all water system information. This approach provides significant advantages in utilising the advanced data integrity, multi-user access, scalability, backup and recovery facilities that are standard features of the mainstream database management systems.

The traditional SCADA system architecture is designed around the concepts of tags (variables from the remote sites), Remote Terminal Units (RTU's), and the business objects these entities are associated with. These tags are generally presented in an animated graphical format that resembles the Mimic panels that predate modern SCADA. A key feature of the approach Rubicon has taken with its product design is to make the business objects (that tags are associated with) network-aware. This means that the topological connection between objects is defined in the database management system and algorithms to traverse this network definition and undertake network-based computations are generically constructed. This logical arrangement is depicted graphically in Figure 1.

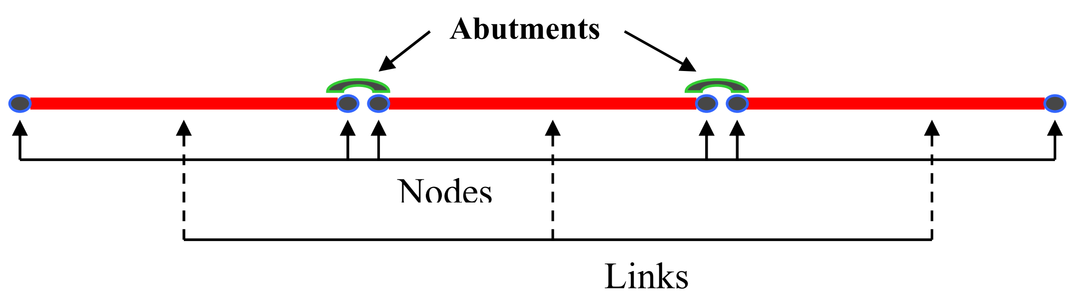

Figure 1. Topological Connections

In addition to providing a means of defining the network topology, a schematic presentation is a useful and intuitive way of visualising the underlying network. The benefits of this approach were probably first recognised with the advent of the London Underground railway system map in the 1930's. Refer to [1] for further detail.

Combining a flexible computation engine, a schematic layout of a channel system and flexible time series graphing enables operators to easily view and analyse planned and computed results. The example in Figure 2 show the schematic layout of the network with in-line channel regulators at the top left connected to the channel which is in turn connected to customer service points that are in turn connected to Service of Property entities. The SCADA Control screen or Mimic panel for the selected site is shown in the top right and a trend of flow in the bottom right. These three key functions of schematic presentation and navigation, SCADA display and trending are in this instance all presented through a single user interface. However, each function can be packaged as a standalone application for organisations that have a more departmentalised approach to operations.

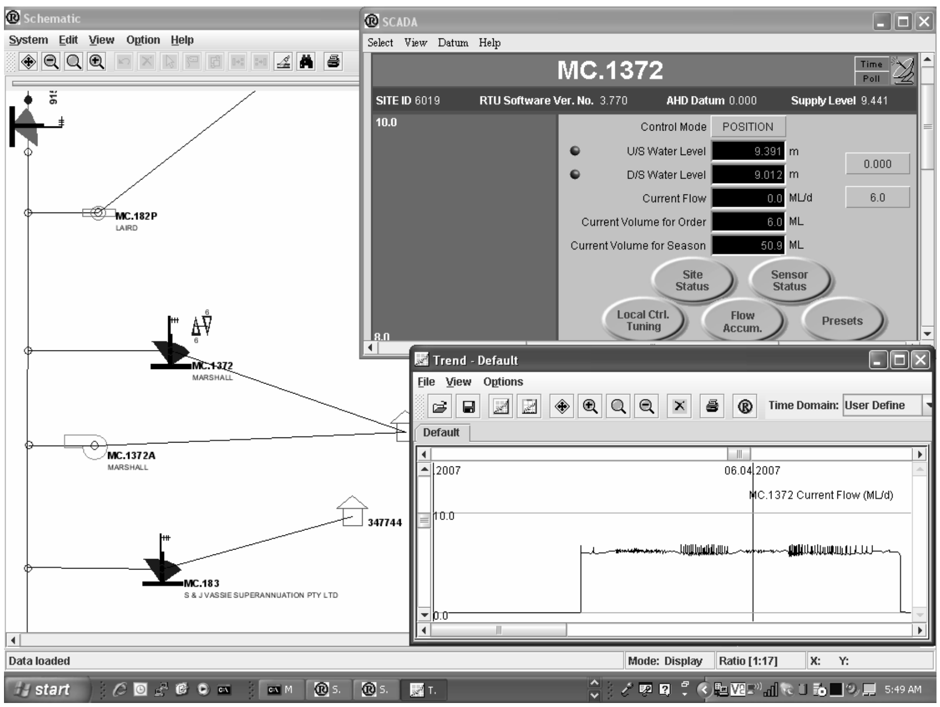

Figure 2. Integrated Schematic, Mimic Panel Screen and Trending

The example shown in Figure 3 compares the ordered flow (demand) shown by the solid black line to the measured actual flow at a single point in the network.

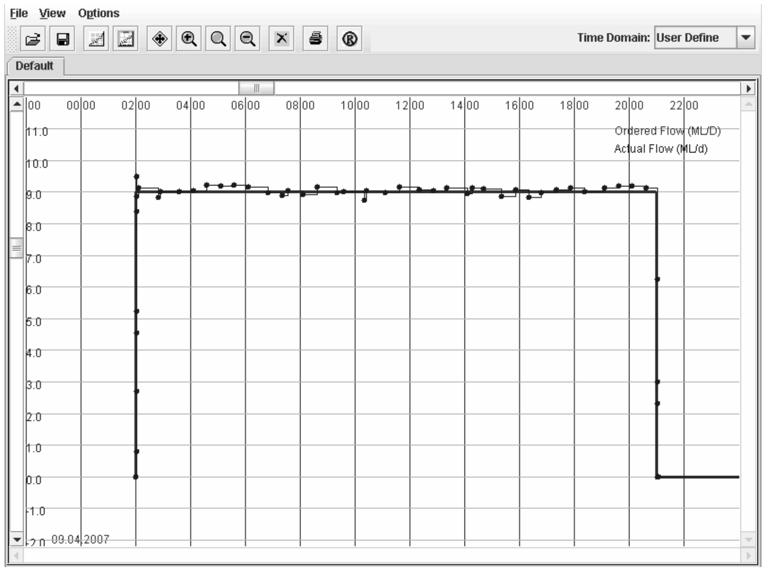

Figure 3. Time Series of Ordered and Actual measured Flow at a FlumeGate™

Figure 4 shows for many points in a network the volume of water metered and estimated from the water ordering sub-system and the total usage measured through the SCADA system and relates these two quantities to compute system delivery efficiency below each point in the network. Note that the display shown can be computed for any time throughout the season and alternatively system efficiency can be formally defined and presented as a time series trend.

From a software engineering perspective, Figure 4 has been defined as an "end user" report. The web-based management interface to the system is used to generate and present this information in HTML format.

Effective To - 06.04.2007 08:00

Regulator

Regulator	Metered Usage	Estimated Usage	Total Usage	Volume Passed	Efficiency
1053	9,906.8	96.7	10,003.5	15,754.3	63.5
1056	246.5	0.0	246.5	407.2	60.5
1060	0.0	0.0	0.0	17.6	0.0
1061	2,532.9	33.5	2,566.4	4,262.3	60.2
1086	0.0	0.0	0.0	25.5	0.0
1106	0.0	0.0	0.0	87.3	0.0
1116	0.0	0.0	0.0	58.1	0.0
1121	6,821.6	63.2	6,884.8	11,725.2	58.7
1125	29.5	9.6	39.1	54.2	72.1
1133	6,292.6	53.6	6,346.2	10,413.2	60.9
1134	159.8	0.0	159.8	201.9	79.1
1140	5,998.5	53.6	6,052.1	10,591.8	57.1
1144	5,834.0	53.6	5,887.6	9,665.6	60.9
1145	5,792.1	53.6	5,845.7	9,497.5	61.5
1146	880.6	11.0	891.6	1,450.9	61.5
1157D	0.0	0.0	0.0	31.3	0.0
1170	0.0	0.0	0.0	52.5	0.0
1172	4,911.5	42.6	4,954.1	7,673.5	64.6
1173D	226.4	5.4	231.8	287.1	80.7
1177	43.2	0.0	43.2	77.0	56.1
1181	4,513.9	37.1	4,551.0	7,281.4	62.5

Figure 4. Measured Usage compared to Volumes Passed per Regulator

This architecture can of course be further extended to enable the underlying network topology and advanced SCADA communications networks to be utilised to implement advanced control strategies, and this is the approach taken with development of the TCC technology. From a software engineering perspective, the additional functionality to support this advanced control capability is implemented using a combination of background "service" programs and distributed RTU code.

Other functional modules to support customer billing and licensing are integrated by incorporating additional database tables. These tables are related at an SQL level to the core network objects, people and water-use facilities that are embedded in the core system design. The programs to operate on these additional database tables can be integrated at the user interface level or delivered as standalone self-contained interfaces to meet organisational needs. To facilitate integration with other systems, the strategy is to do this at the database level by building "gateway" software on top of industry standard data transfer utilities or to build dedicated software interfaces that operate either in real time or “batch” modes.

CONCLUSIONS

There are a bewildering range of SCADA products available to support irrigation system modernisation programs. Making the choice between different products and architectures is not straightforward. This paper has detailed the approach Rubicon has taken to the design of its products with the key focus being on generic database design concepts with a suite of functionally rich integrated software applications founded on this architecture. This approach enables organisations to implement standalone SCADA or water ordering applications that have well developed options to interface with other IT systems like finance, billing and GIS. This approach also offers a pathway to advanced control and management systems.

The ultimate choice of the best SCADA solution is dependent on the initial and ultimate requirements of the organisation and the implementation support and training available to ensure the application is an ongoing business success.

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SCADA APPLICATION IN CENTRAL ASIA

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ABSTRACT

This paper presents an application of Supervisory Control and Data Acquisition (SCADA) in three countries of Central Asia: Uzbekistan, Kyrgyzstan and Tajikistan. The project is financed by the Swiss Development Agency for Cooperation (SDC). The objectives of this project are to stabilize the flows diverted for irrigation downstream from large hydro-power plants and to monitor the equity and reliability of water diverted to secondary canals. This application provides an example of a promising success story in irrigation modernization in developing countries. Three factors may contribute to this success: i) the existence of a regional automation company, ii) the use of factory-made control equipment and iii) the rapid intervention of the local industry when repairs or corrections to control equipment are needed. The project also demonstrates that modernization of irrigation systems can be completed at a reasonable cost. The paper presents the results of the first series of tests of the SCADA system and highlights some of the differences in the design of SCADA projects between developed and developing countries.

INTRODUCTION

Over 7 million hectares are irrigated in the five countries of Central Asia, mostly through diversion of the large Amu Darya and Syr Darya rivers flowing into the Aral Sea. Since independence from the Soviet Union in 1991, these countries are now responsible for the management of large irrigation systems that are aging and would need considerable investments in massive rehabilitation works and adaptation of the on-farm works to the on-going policy of privatization of lands.

The Swiss Agency for Development and Cooperation (SDC) is not the major lending agency in Central Asia. However it has developed an original strategy to optimize the technical assistance and limited financial assistance provided to these countries for the agriculture sector. This strategy is based on the evidence that chaos is inherent to all large-scale delivery systems (Clemmens Lecture at ICID Congress, Beijing, 2005). Chaos was defined by Clemmens as the fact that a small

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deviation in the upstream part of a canal system from a target delivery flow would result in large variations in water delivery further down. Clemmens rightly argued that neither improved management nor water measurement was the answer to that chaos: "*Improved management alone may result in small increments in the productivity of systems, but not in substantial gains. Water management is a key component of water, but it is not sufficient for significantly improving productivity by itself.*"

In 2001, SDC signed a protocol with the Scientific Information Center (SIC) of the Inter-State Commission for Water Coordination (ICWC), an international Organization of the five central Asia countries, to assist in the modernization of irrigated agriculture in the Fergana valley. The Protocol includes assistance for: i) integrated water resources management (IWRM) in the valley to contribute to the reform of irrigated agriculture through the creation and strengthening of water associations and ii) Canal automation and monitoring. This paper describes the SCADA and automation projects installed in the Fergana Valley under SDC assistance. A first project installed at a large diversion dam on the Naryn River in 2002 is now operational. A second on-going SCADA project, initiated in 2003, included a number of discrete structures on the large conveyance canal systems and three pilot irrigation canals.

Geographic Background and Irrigation Development

The Fergana Valley is a large inter-mountain plain, about 300 km long, encircled between the Tian Shan Mountains in the north and an extension of the Karakoram Mountains in the South. The plain has been irrigated since time immemorial. The URSS government built a large scale irrigation system beginning in the late 1940s that transformed the Fergana Valley into one of the most populated valleys in central Asia. The total irrigated area is now estimated at about 1,375,000 ha, with 911,300 ha in Uzbekistan, 330,700 ha in Kyrgyzstan and 133,900 ha in Tajikistan. The central plains of the valley are in Uzbekistan, and the surrounding piedmonts and mountainous areas are in Kyrgyzstan. The western part of the valley opening on the arid steppe of Central Asia belongs to Tajikistan.

Agriculture in the Fergana valley is heavily dependent on diversion of water from the Syr Darya River and its tributaries. Agriculture accounts for 92 percent of water use. Water use efficiency is very low since about 70 percent of water diverted is wasted due to aging of infrastructure and mismanagement. Most of the valley has very favorable soil conditions compared to downstream areas in the Aral Sea Basin which are largely affected by salinization and waterlogging. Nearly 85 percent of the lands in the valley are non-saline or weakly saline with only 15 percent of the lands unfavorable to irrigation due to high groundwater table or salinity.

The Fergana Valley is drained by the Syr Darya River formed by two main branch rivers draining the high mountain areas: the Naryn River and the Kara Darya River. The annual total volume of water available in the valley is estimated at about 14 billion m^3. The large hydropower potential of the Naryn River was developed through the construction of the 170-m high Toktogul dam creating a reservoir of 11 billion m^3 and a cascade of five medium and low head hydropower plants, all located in Kyrgyzstan.

The Naryn-Karadarya irrigation system is divided into a number of interconnected canals originating from the Naryn River and its two main tributaries.

Figure 1

The first structure (1) on the Naryn River in Uzbekistan just downstream from the border is the Big Fergana Headwork (submerged weir and side intake) which diverts water to the Big Fergana Canal (BFC) with a design capacity of 300 m^3/s. A few kilometers downstream (A), there is the Uchkurgan diversion dam which supplies water to the North Fergana Canal (NFC) with a capacity of 70 m^3/s and to the Feeder Canal (150 m^3/s). BFC flows are supplemented by the Feeder Canal. Two structures(2 and 3) exist on the BFC at 2.5 and 6 km from Uchkurgan dam to supply Hakulabad and the Big Andijan canal (BAC). The BFC then conveys Naryn water to the Kara Darya River just upstream of the Kuyganyar diversion dam (B). The 105-meter high Andijan dam creating a reservoir of 1.7 billion m^3 was built on the Kara Darya River. This reservoir supplies three irrigation canals including the Sharhikanzai canal, which in turn supplies the South Fergana Canal (SFC).

Earlier Automation Projects

The first SCADA project at Kuyganyar diversion dam (A) on Kara Darya River was implemented with USAID assistance in 2001. A second project under SDC assistance was implemented at Uchkurgan diversion dam (B) at a cost of US$187,000 in 2002. The objective of these two projects was to stabilize the discharges into the irrigation canals despite the large and not always scheduled variations of the flows released from the power plants located in Kyrgyzstan. These two projects were implemented by SIGMA, an integrator company specializing in automation.

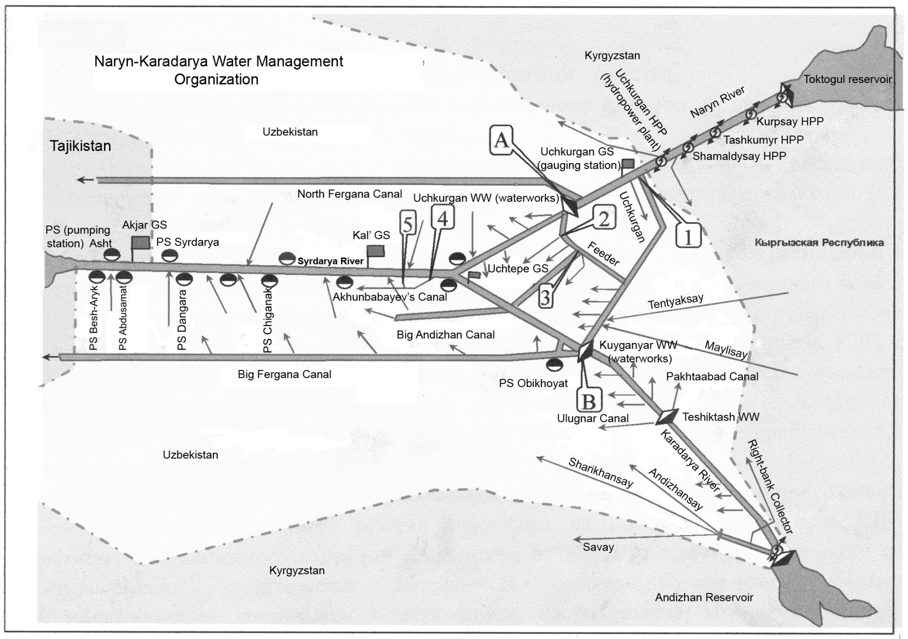

Figure 2
(A) Uchkurgan Waterworks on Naryn River.-(B) Kuyganyar Waterworks on Karadarya River.- (1) Big Fergana Canal Headwork on Naryn River.-(2) Khakulabad Divider at DP 15 of BFC Feeder-(3) Waterworks at DP66 of Feeder (Big Andizhan Canal Headwork)-(4) Headwork on Akhunbabayev Canal-(5) Spillway on Akhunbabayev Canal.

The Uchkurgan SCADA project was designed to provide target flow releases into the NFC and BFC canals and to control as much as possible the water level upstream of Uchkurgan dam, despite the variations of flows released from the upstream power plants on the Naryn River located in Kyrgyzstan. Flow data at Uchkurgan are collected and stored every 10 minutes. Data are processed to calculate hourly, daily, 10-day and monthly average flows and can be presented in graphic form.

Monitoring of the water discharges into the NFC and BFC canals during the period April 2004-April 2005 indicated that the intakes of the NFC and BFC were working under automatic control regime about 270 days during that one-year period. The average deviations between the actual flows and the target flows in automatic control regime for the entire irrigation season did not exceed 2 percent (1.61% and 1.69% for NFC and Feeder canal respectively). However the maximum deviations between actual daily flows and set flows were 6.17 m^3/s (or 11.22%) for the NFC and 11.01 m^3/s (or 1.77%) for the Feeder canal. Although these variations are still substantial, the SCADA system has considerably improved the stability of the flows released into these two canals. The Uchkurgan project has successfully proved that a considerable impact can be achieved in improving system operations with a small investment and within a limited time frame.

ONGOING FERGANA VALLEY CANAL AUTOMATION PROJECT

The objective of the ongoing SCADA project, initiated in 2003, is to introduce local automated control and remote automatic monitoring to ensure optimal allocation of water. The project includes i) four discrete structures on major conveyance canals under the responsibility of the Syr Darya Basin Organization (BVO) and ii) three irrigation pilot canals under the responsibility of local agencies: the South Fergana Canal (SFC) in Andijan and Fergana Provinces of Uzbekistan, the Aravan-Akbura Canal (AABC) in Osh Province of Kyrgyzstan and the Gulya-Kandoz canal in Soghd province of Tajikistan.

BVO Structures

The ongoing SDC canal automation project is the continuation of the previous automation project of Kuyganyar and Uchkurgan diversion dam. It includes automation of four main structures in the Naryn/Karadarya system: the intake of the BFC (1 on figure 2), two structures on the Feeder Canal (2 and 3 on figure 2), and the intake of Akhunbabayev canal on the Syr Darya River (4 and 5 on figure 2).

All BVO inter-link canals, as irrigation canals, are operated under upstream control. The first two reaches of the Feeder Canal are short and with gentle slope. Thus flow measurements by gauging stations are not reliable. Therefore canal operation was converted from upstream to downstream control during SCADA implementation. Downstream control will ease operation of the first two reaches.

Gates: There are 46 sluice gates already equipped with electric motors. These electro- mechanical devices have been checked, repaired or replaced and equipped with end switches and gate opening sensors. Electric supply and standby generators are available at the 4 locations, except at Akhunbabayev where a standby generator is planned to be installed soon.

Water level measurement: Nineteen ultrasonic level sensors have been installed upstream and downstream from each cross regulator or automated outlet**.** In some cases, hydro posts (flow gauging stations) have also been equipped with water level sensors.

Type of control: All structures are composed of a cross-regulator with upstream or downstream water level control and outlets supplying inter-link canals equipped for flow control. All gates can be operated either by automatic control or manually by the operators.

Electronic equipment**:** gates are controlled by programmable local controllers (PLC) (one PLC for 4 gates) with separate I/O modules and interfaces (analog and digital input, digital output). The PLCs are programmed to send the following 6 alarms to the supervisory software:

- Torque overload (closure or current relay in control panel)
- Error or no reading from gate position sensor
- Reading of erroneous value from gate position sensor (e.g. off-limits values, such as height greater than gate dimensions)
- Gate movement opposite to the requested movement, mostly in the early testing phases in case of inversion of cables.
- Commands that cannot be executed by the gate. This can have several origins, including electrical and mechanical problems.

One PLC is dedicated to control the other PLCs and is connected with the operator PC where all data are displayed and set points are input. PLCs are of model DECONIT 182 and are installed in tight cabinets close to the gates or in the control room. PLCs are also connected to the telecommunication system.

Telecommunication: A General Packet Radio Service (GPRS) system has been selected for the communication between new automated control structures (except between Kuyganyar and Uchkurgan dispatchers, where conventional radio was already installed and operated). This choice has some advantages:

- the maintenance of the communication network will be performed by a specialized communication company
- no authorization to use frequencies needs to be obtained from the authorities (such authorization is difficult to obtain in Uzbekistan)
- allows future expansion (e.g. link to Tashkent is possible with no additional hardware).

However, the quality of communication relies on the service provider (MTC) who has just completed installing the GSM+GPRS network in the Fergana valley (a GPRS network is already operating in the Tashkent region) and some problems were observed during the preliminary tests. Fortunately, these problems did not affect automatic control (there is only local automatism), but only the data transfer.

Software: Use of a commercially available supervisory and control software package is desirable to allow easier customization and maintenance and avoid site specific and lengthy development. SIGMA has chosen an intermediate solution between a readily available program and a totally custom-made application. The supervisory and control software was built using libraries (existing application for operator interface, archives, PLCs, …etc.) supplied by the provider of the PLCs and specific programs developed for BVO, such as flow computation using hydraulic laws of existing hydro posts.

Preliminary tests: Tests were performed on the four new automated structures in October 2006. Some problems were observed related to calibration of water level measurements, and some gates were randomly faulty and could not be operated. These problems did not affect the performance of the control that was found accurate and stable. Since October, all gates have been checked and repaired when necessary and level sensors have been adjusted and tuned.

Figure 3 presents the measurement of discharge and the openings of the five gates recorded by the SCADA system at Akhunbabayev headwork. The discrepancy between set point and controlled flow is less than 1.5%, 30 minutes after starting the control. Stability of flow is excellent.

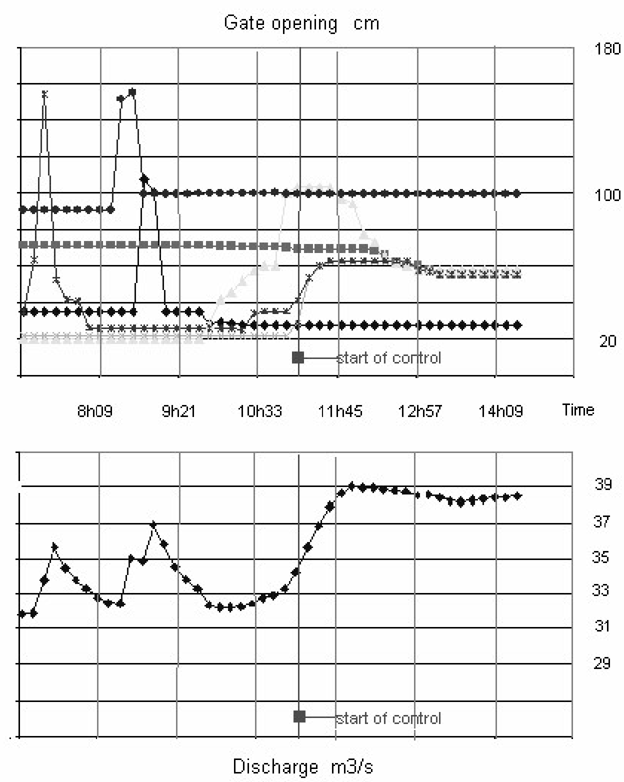

Figure 3

Pilot Irrigation Canals

a. The 120 km long South Fergana Canal with a design capacity of 100 m^3/s constructed in 1935 irrigates about 87,000 ha in the provinces of Andijan and Fergana in Uzbekistan and 2500 ha in Kyrgyzstan. This canal receives uncontrolled receives uncontrolled waters from a number of tributary rivers. At about half its length, a branch canal enables the diversion of excess water into the Karkidon compensation reservoir, which is a very favorable layout for canal operation. Design of this automation and monitoring project is not yet completed but will be very similar to the BVO automation project

b. The 21-km long Aravan Akbura canal diverts water from Akbura River about 7 km downstream of the Papan storage dam. AAB canal supplies irrigation water to about 9,000 ha in Kyrgyzstan. Design of this automation project has been completed and gate repairs and motorization are finished. The main characteristics are:

- 3 control structures with 17 gates will be automated and monitored;
- 2 remote balancing stations will be equipped with automatic level measurement;
- Equipment will be very similar to BVO project;
- Data transmission system will use VHF radio (2 frequencies are required);
- One additional VHF frequency will be used for voice communication.

c. The Gulya-Kandoz Canal diverts water from the unregulated Khokabirgan River to irrigate about 8100 ha in Tajikistan. Design has just started.

Present operation

The three pilot irrigation canals are presently operated under upstream control with a minimum number of check structures. Some of the bays found at check structures are not equipped with gates, making impossible precise control of water level. The three canals have a steep longitudinal slope on average. Several chutes and drops are found on the SFC. A unique feature common to these three canals is the very high number of direct outlets supplying small tertiary canals providing water to former collective farms. For example, over 135 gravity outlets and 68 small pumping units are found on the SFC and 80 outlets on the Khojabakirgan canal. Some sections of the canals are lined. However lining is in poor condition.

Hydro posts (gauging stations) exist along the three canals at about 10 km intervals to determine the flows through stage-discharge curves at regular intervals. The volumes of water diverted between measuring stations, known as balancing sites (i.e. water accounting sites) are then analyzed to determine the equity of water distribution among balancing sites and the gap between planned, requested and actual volumes of water delivered. Several field teams for each balancing site are responsible for monitoring and adjusting, if needed, the openings of the numerous individual outlets diverting water from the main canals three times a day to meet the agreed target flows.

In spite of efforts made by the field teams, sharing of water remains rather inequitable as shown in figures 4 and 5 (water distribution along the South Fergana canal and inside one balancing section). The SCADA project is designed to improve the equity of water distribution between balancing sites and between outlets within a site.

Figure 4

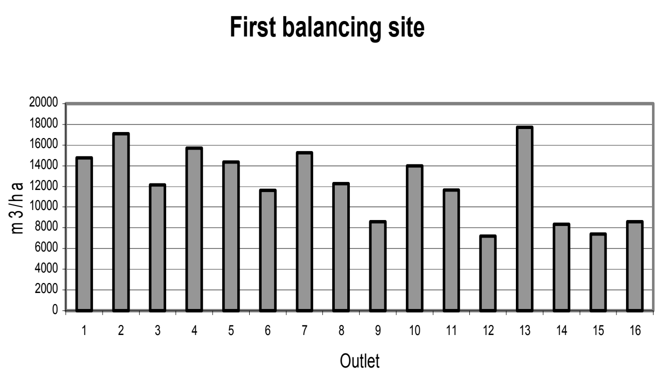

Figure 5

Costs of Automation

The total amount of automation contracts is about \$1.3 million (US), divided as follows:

- BVO works: \$ 305,000
- South Fergana canal: \$ 667,000
- Aravan-Akbura canal: \$ 337,000
- Khojabakirgan canal: \$ 104,000

The unit cost for the pilot canals range from about US\$ 6/ha for the SFC canal to US\$ 30/ha for the Aravan-Akbura Canal, which is very low compared to other rehabilitation cost. This is another example of the fact that modernization itself is not necessarily as expensive as often argued. The cost of rehabilitation of many irrigation projects could reach a few thousand US dollars for the reconstruction of dilapidated infrastructure and lining of canals. A number of these rehabilitation projects do not give appropriate attention to the modernization of the irrigation delivery service. The canal automation project in the Fergana valley demonstrates that considerable improvement can be achieved with a small investment.

CONCLUSIONS

In developed countries, the main objectives of irrigation modernization are; i) to improve the flexibility of canal in order to meet the variation of water demand (on demand or pre-arranged demand), ii) to increase the accuracy and the reliability of irrigation water service to users, iii) to reduce management costs and labor costs, and iv) to alleviate negative effects of irrigation on environment, in some cases.

The main objectives of the SCADA project in the Fergana valley are to reduce the negative impact of the operation of the power plants and to improve and control the equity of irrigation water allocation. Labor cost in Central Asia is so low that reduction of staff is not yet a consideration in modernization of irrigation projects.

There is still limited confidence in local automatic control and telecommunications. Consequently each local control station is equipped with a computer for local intervention and staffed 24 hours per day. In case of failure, instructions and reporting can still be done through telephone lines and operation of gates can still be manually done.

The factors that have contributed to the success of the earlier SCADA projects in the Fergana valley are: a) the existence of a regional automation company, ii) the use of factory-made control equipment produced in Kyrgyzstan or European countries and iii) the rapid intervention of the above company when repairs or corrections to the control equipment are needed. These conditions are not yet found in the poorest developing countries. However there are a number of emerging market countries that have developed computer and telecommunications industry to a level sufficient to provide the technical assistance for the maintenance of SCADA equipment in large irrigation districts. These countries should take advantage of the present available modern technologies to improve the performance of their irrigated agriculture.

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REQUIREMENTS FOR OPEN WATER AND IRRIGATION SYSTEM SCADA SOFTWARE

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ABSTRACT

A successful modern SCADA system will generally require some form of software to drive communications, control processing, and store data. This must not only operate as required on the first day of operation, but it has to be easily modified by the users to reflect changes that occur every day. These changes include expansion of the system as well as calibration changes and other SCADA changes to reflect changes in the network and variable field conditions. There are a multitude of SCADA software packages that exist today, generally developed for manufacturing, utility, or scientific applications. However, irrigation canals have some unusual and unique requirements which must be met. Any successful implementation of a SCADA system must address those specific considerations. We list and discuss these requirements and detail the adaptation of a standard SCADA system, Vsystem.

INTRODUCTION

Unique Needs

SCADA software for irrigation and river systems must perform a task fundamentally similar to process control software used in science, industry, and manufacturing. Many of the requirements are shared with other interests. However, there are some particular requirements of irrigation and river systems which must also be met. These requirements may be broadly classified as technical, regulatory, and financial.

Technical requirements are commonly given the most consideration. These requirements are the simple "nuts and bolts" of the software, including such things as scan rates, hardware scanners, data storage, graphical interfaces, development flexibility, and the all important consideration of reliability.

Regulatory considerations may be less obvious. Irrigation and river systems often cross political boundaries and may have extensive involvement with

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government(s). An irrigation project could violate local, state, federal, or even international laws and agreements as a result of operational problems. Also, some data must be shared with other agencies and jurisdictions, and thus flexibility to communicate data in differing formats is a necessity. Finally, reliability looms large as many people are dependant on the proper monitoring and control of irrigation and river systems. Failure could potentially pose public health and safety issues, up to and including loss of life.

Financial requirements generally receive a lot of consideration. Unfortunately, it is common to consider only the immediate bottom line, overlooking long term costs. The operation of many irrigation and river systems operations are completely or in part publicly funded. Long-term commitment of public funding may be uncertain. An up-front expenditure for software may be clearly defined, but long-term funding for future maintenance and development may not be possible, so it becomes a requirement that, by and large, they are capable of being maintained and operated by project staff: adding simplicity and ease-of maintenance to the requirements.

Vsystem

Vsystem was originally developed internally at Los Alamos National Laboratory and then commercialized by Vista Control Systems some 17 years ago. It has found applications in many industries from water and waste water to steel and aluminum production to petrochemical plant monitoring to test cells for truck transmission and aircraft engine development and testing. In addition Vsystem is used in rocket and satellite control rooms as well as for research machines very like the machine that was the origin of the software.

MRGCD

The Middle Rio Grande Conservancy District (MRGCD) delivers irrigation water to approximately 73,000 acres of farmland in central New Mexico. Water is diverted from the Rio Grande at 3 low-head dams and the outlet works of a USACE flood control reservoir. The MRGCD encompasses a 150 mile reach of the Rio Grande, 800 miles of canals, and 400 miles of drains. The system is entirely gravity-fed and was constructed locally (non-federal project) between 1928 and 1935. It was not built from a clean sheet of paper, but combined the works of 79 independent Acequia associations, most of which date to the 17th and 18th century.

During construction in the 1930's a large number of hydraulic and mechanical automatic control structures were incorporated. Unfortunately these fell into disuse and disrepair over the years. In 1996, under the all-too-common demands of endangered species, encroaching urbanization, and competing water users, MRGCD water efficiency received close examination. In response, MRGCD embarked upon a course of modernization involving measurement and automation. Eventually, the need became clear for a comprehensive software (SCADA) system capable of bringing data, hardware, and operators together.

Collaboration

MRGCD had experimented with, and investigated a number of commonly available software packages. Some of these were generic process automation and control software packages, and some were specifically tailored for surface water applications. However, none met all their requirements. At the same time, we (Vista Control Systems) learnt of some of the SCADA requirements for open water SCADA systems that were not being met with the other popular commercial packages. In response to an RFP from MRGCD we decided to make additions to Vsystem that would meet these requirements. With the help of David Gensler of the MRGCD in Albuquerque, we refined these and installed the first system there.

REQUIREMENTS AND SOLUTIONS

As previously suggested, the unique requirements of SCADA for irrigation and river systems can be broken down into the broad categories of flexibility, simplicity, and reliability.

Flexibility

The term SCADA means different things to different users, so when evaluating software, careful thought should be given to exactly what the software must accomplish.

Software for a SCADA system should be flexible. In fact, most software for these types of applications is really along the lines of a do-it-yourself kit. The differences are how much of the kit has been pre-assembled. Some packages are blank sheets of paper, just collections of tools that the user may use to construct a system. Others have large parts, or even the entire system pre-designed. In general, the more that is pre-built, the easier the system will be to install and configure, but the less flexible it will be through its life. On the other hand, a blank sheet of paper, with the right collection of tools, can be used to build a very comprehensive and effective system. There is a balance that must be struck for each user, and defining this balance is the key to success.

Communication protocol: What sort of hardware can be supported? All SCADA systems must somehow acquire information. In general, this implies that SCADA software must be capable of communicating with gadgets in the field. This may be one specific type of device, or it could be multiple types, with differing communication protocols. Information could also be sourced from digital sources, either local or remote databases, which also may require specific communication protocol. One of the first steps in planning the implementation of a SCADA system is to list the various types of devices or data which must be supported.

In the case of MRGCD, all hardware uses the Modbus protocol. MRGCD uses a proprietary feature of its RTU's to retrieve weather station data from Campbell Scientific data loggers, but, since this feature is still accessed through standard MODBUS commands, it is accommodated by Vsystem.

Output: Many SCADA systems will, at some point, receive data from, or provide data to, others. The "others" may be separate organizations, or perhaps different software clients within the organization. All of these possible exchanges should be listed, and the SCADA software should be evaluated to determine what format(s) are appropriate.

In the case of MRGCD, data is received from U.S. Geological Survey (USGS) and United States Army Corps of Engineers (USACE), and exported to the United States Bureau Of Reclamation (USBOR). This data exchange is accomplished via the SHEF text format, an old but familiar format used by the National Weather Service. Also, data is exported from Vsystem to a MS SQL database, both for permanent archiving, and to allow future data review and reporting flexibility.

Data Rate: A primary consideration of most systems is the rate at which data is collected. The Vsystem Modbus scanner as used in other applications typically functions at frequencies of 1-100 Hz. Water systems are unique in that inputs generally change much more slowly than in other industries, thus scan rates in the range of 0.001-0.0005Hz (every 15-30 minutes) are more typical. Although on the face of it, a relatively slow data rate should simplify the application, new challenges may be introduced. As an example, in other applications, much faster scan rates are required both to capture data to reflect the speed of the process under control and to give immediate feedback to the operator when changes are made. For this application, the speed of response to operator commands is very much faster than changes in flow and level when no changes are being commanded. The choice is either to have as fast a scan rate as the communication channel will allow to give occasionally required fast feedback (in larger systems, the time of a complete scan will not allow very fast feedback) or implement an entirely new mechanism solely for the immediate feedback.

In the case of MRGCD, data was to be collected from sites at regular, user defined, time intervals. Due to varying types of data, multiple intervals or polling groups, are specifiable. Also incorporated is the option to control the timestamp for a piece of data either as the actual instant it is recorded or the time at which the polling group is initiated. The Modbus scanner was modified to allow a set delay after start-up and initialization before the first scan. This added set delay to the first scan allows the scanner to be started at any time and the scans to be, for example, on the hour and half-hour. The user only has to define the time of the first scan and the appropriate scan interval to use this feature.

Data Type: Another consideration regarding data rate is whether data collection is time driven or event driven. Irrigation and surface water systems are typically time driven, so that the condition of the system is observed and recorded at regular intervals. However, event-driven data collection may be an important part of such a system too, particularly when automation is employed, so that alarm or other pre-identified extreme conditions are recorded accurately.

Operator Outputs: Some SCADA systems only collect and display or store data. But increasingly SCADA systems are living up to the “Control" in the acronym, and outputs to physical devices are part of the process. The type and timing of these outputs must be considered. Each case is likely to be unique.

In the case of MRGCD, extensive local automatic control of structures is performed. Setpoints can be supplied either remotely or from an operator on site. When done remotely, Vsystem is used to write setpoints and operating parameters via radio link to control gates. A series of control screens was created, using Vdraw, to display sites and parameters. When an Operator makes a change in any displayed parameter, the new value is written out to the RTU register over the radio link as soon as possible, only waiting for any other transaction to complete. So that the operator can see the response to the change, a button was added to the control screen to allow the operator to trigger a manual scan, putting a command into the Modbus scanner command channel. This scan command includes the unit number of the RTU so that all the registers of the RTU are scanned out of sequence. This was the most efficient way to implement this feature.

Data Conversion: A SCADA system requires some form of data conversion or processing. The simplest form is linear, such as scale and offset to convert raw electronic values to engineering units. This is an area where many SCADA packages provide pre-packaged routines. When considering SCADA software, the types of data conversion should be considered just as carefully as hardware interfaces. Just like proprietary communication protocol, inflexible conversion routines can severely limit success of the project.

A simple example of such a conversion is the calculation of stage and discharge from the measured data. An example equation is:

$$\text{Stage} = ((\text{raw measurement}*0.001408)+0.77)$$

While linear data conversion of the reading from the RTU to engineering units is included in Vsystem and the coefficients are easily modified, other conversion algorithms in the past have required a subroutine to be written to implement the algorithm. This subroutine would take its conversion coefficients from the channel so that while the coefficients are easy to change, an algorithm change requires code to be modified or new code written. Clearly, this is neither flexible nor desirable for open-water SCADA applications. We have added a third option for conversion definition, the capability to define the conversion equation as a typed equation. The above conversion would be typed in as:

invalue*0.001408+0.77

The equation can include values from any other channel and values of any field of any channel. More complicated statements can include conditional statements and logical tests. This could occur with an overshot gate, where discharge is calculated with one equation when the gate is raised, and acts as a sharp crested weir, and with a different equation when the gate is lowered and starts to behave as a broad-crested weir. An example is:

vsq {if (cenww.gatep > 1.5) outvalue = (((abs(cenww.stage + 0.001)) ^ 1.5) * 26.13) else outvalue = (((abs(cenww.stage + 0.001)) ^ 1.75) * 15.5) end}

Higher Level Conversions: Meaningful engineering data is often derived from more than one input, although from a water engineer's standpoint, these conversions would be just another equation. From the software developer's point of view, these are a completely different type of animal. It is one thing to perform a calculation on a piece of information as it arrives, it is an entirely separate process to gather various pieces of information, process them, and generate a new data value. Due to timing and scan rates, many packages do not have this ability. If this feature will be needed in a SCADA application, the flexibility of the package should be carefully evaluated. As an example of a higher level conversion, discharge from a processed stage value, is:

cenww.disch = (((cenww.poolh - cenww.gatep)^1.5)* 33.76)

"Pseudo RTU's": Another feature, commonly desirable in the irrigation and water business is what we have termed a "pseudo-RTU". This is data describing the system that is not immediately derived from hardware registers but is either from another data source or is higher-level data that is the result of calculations using data from one or more RTUs. It is convenient if this data could appear to come from a non-existent RTU. We have added the capability to define this RTU and its data exactly as a real RTU is defined except only for a flag to indicate to the Modbus scanner that this RTU does not actually exist. Thus the registers of this pseudo RTU provide higher-level data that is actually data calculated from other, real, RTU measurements and other sources. This higher-level data can also be used in other calculations. An example, from MRGCD's application is the calculation of a Diversion rate from 3 separate input values:

ANGDV.Q = ((ALBCN.Q + ATFCN.Q) - ALGDR.Q)

The generation of the Angostura dam diversion rate originates as the raw A-D output from RTU's on 2 canals and a drain. These outputs are first resolved individually to stage, then to discharge, and finally combined to arrive at the diversion value. ANGDV.Q then becomes a variable in other equations and could be implemented as a control output. The use of a pseudo-RTU is not a requirement for an implementation, rather a convenience to users. The same result could be obtained with channels unassociated with any RTU.

User Interface: Standard Vdraw, the Vsystem GUI development tool, was used by MRGCD to develop the screens required for the operation of the system. Two examples from the application are shown in Figure 1 below.

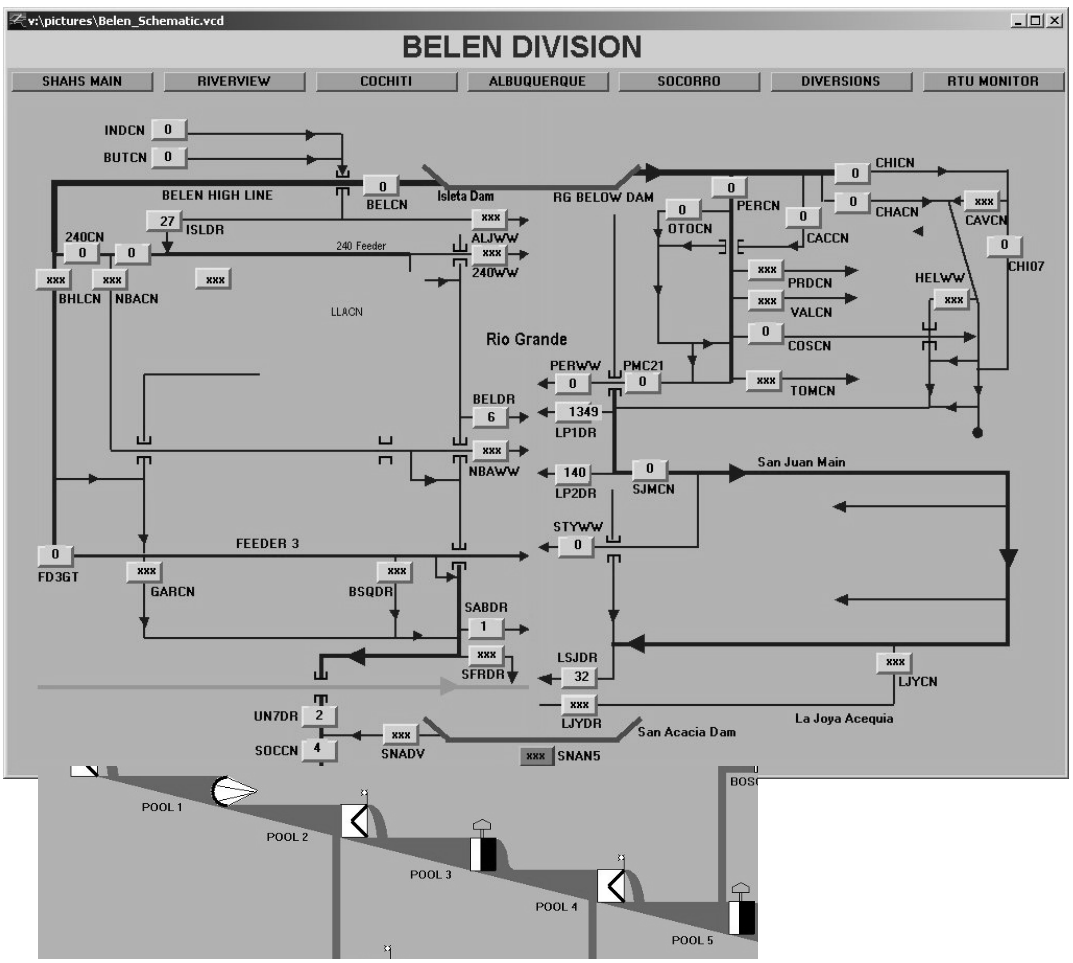

Figure 1. Two example operator screens form the MRGCD SCADA system.

Data Storage: For long-term analysis and reporting requirements (the regulatory environment), operational data should be stored to a permanent database. This may be a proprietary part of a SCADA package, or external to the software. Maximum flexibility, particularly with regards to data exchange, is more likely to be achieved with a common external database. In the case of MRGCD, there are 2 essentially identical but separate databases. Vsystem contains its own proprietary database (Vlogger). Within Vlogger is a permanent record of every piece of information generated by the SCADA system. External to Vsystem is a database built around Microsoft SQL. The operational data is first recorded to the Vsystem historian, Vlogger, and then, periodically, the data is written to records in Microsoft SQL-Server using the SQL interfaces, one SQL interface to Vlogger data and one to Microsoft SQL-Server. This Microsoft SQL-Server update utility operates on a user-defined schedule and automatically updates the Microsoft SQL-Server database with all the new data in the Vlogger archive.

The Microsoft SQL database tables are created automatically from the information in the Vsystem database. Data from each RTU is stored in a separate table. The columns are timestamp and each channel that was logged. Each time entry read from the Vlog archive file becomes a new row. Multiple Vlog archive files can be combined into a single Microsoft SQL database. If any RTU's or channels have been added to the Vsystem database, then new tables and columns are automatically added to the Microsoft SQL database.

Other Applications: It may be the case that a SCADA system will operate and interact with other software (ie: GIS) applications. As with hardware, all possible interactions should be considered, and compatibility evaluated. In the case of MRGCD, Vsystem will interact with a DSS model developed by Colorado State University to predict irrigation demand. Vsystem will provide inputs, and accept outputs from the DSS model so that it may be run from the Vsystem control screen, and projected canal flows from the DSS displayed alongside actual flows from Vsystem. Vsystem was designed from the beginning to easily incorporate computer models of the system being monitored and controlled.

Simplicity

Setup: When considering SCADA software, the user should consider the requirements for configuring the package. In large measure, these requirements will be a reflection of the background of the personnel using the product. Once again, irrigation and river systems seem unique. A large industrial setting, an oil refinery for example, may have dozens of trained computer personnel on staff, and thus building the SCADA package need not be particularly user friendly. An irrigation project may have only a few engineers (not computer specialists), and putting together the SCADA system will likely be only one of many unrelated tasks they must perform. So, the SCADA system must have a relatively straightforward and logical approach to configuration, which does not require intensive training. When planning SCADA software, one should consider carefully setup interface that is required without sacrificing necessary flexibility.

In the case of MRGCD a configuration interface, Vriver, was developed for Vsystem. Vriver is a wizard that interacts with the user in a way that is focused on the setting up of the software for the hardware configuration, polling groups/times, data processing, and data storage. Vriver was designed to be similar to the RTU configuration utility supplied by the RTU manufacturer, with which MRGCD was already familiar. The output of a set-up session is a set of files that then starts up and configures Vsystem to scan and record the data from the RTUs and when necessary write out new settings to RTUs. The capability still exists to write or edit setup files directly, without using the Vriver interface, so that a full range of flexibility is preserved.

The following screen shots in Figure 2 show the stages of setting up and editing the RTU configuration for Vsystem.

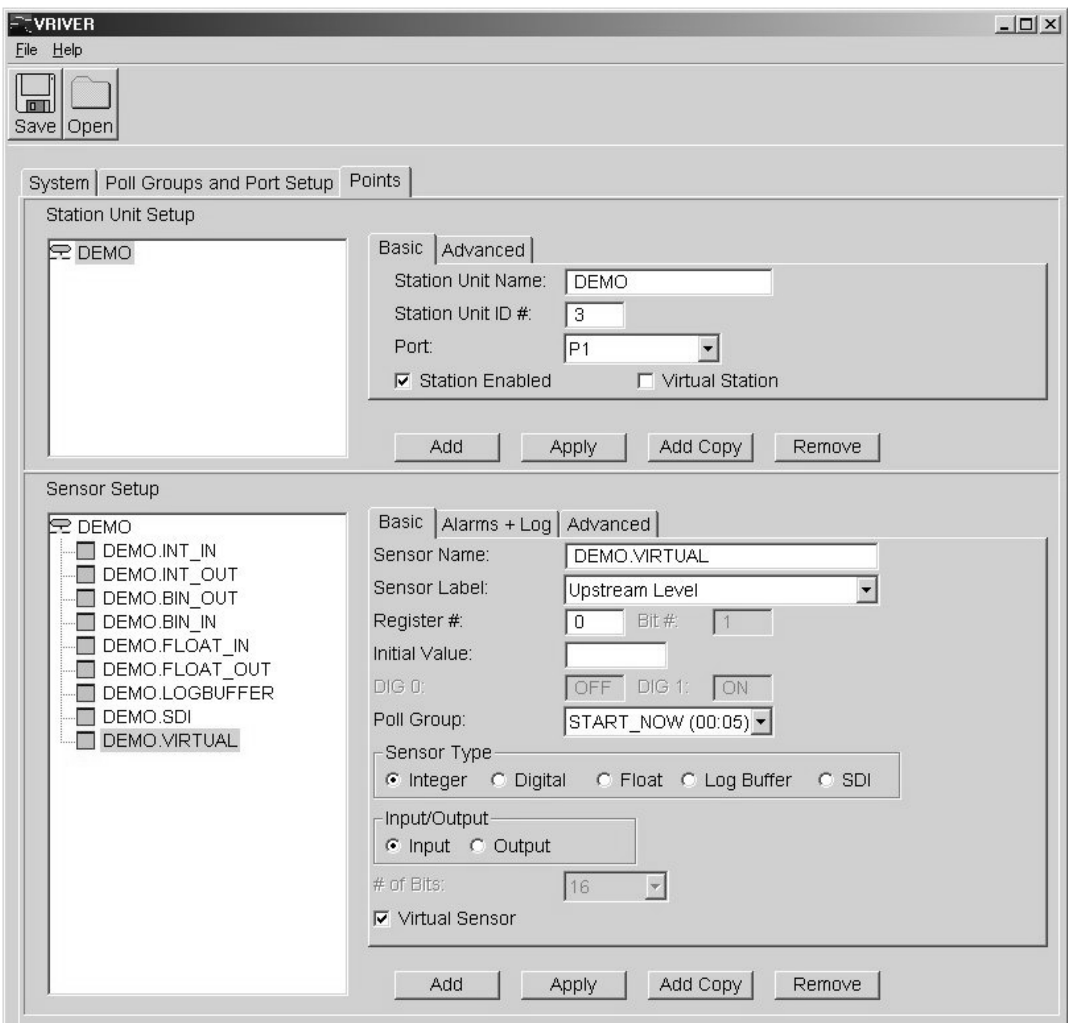

Figure 2. Screen showing some of the Vriver set-up functions.

Reliability

Vsystem in developed using traditional, proven, programming techniques and, being developed for several operating systems, it uses system services and graphics services at the lower and more dependable levels. Thus, Vsystem applications have been proven robust over years of operation. Data integrity is ensured by having two separate historian files maintained, Vlogger and MS SQL Server.

Radio communications are less reliable than solid, copper connections if only because of interference from other radio systems and changing atmospheric conditions. To monitor and improve radio reliability, it is important to keep track of the successful scans for each RTU and so the facility has been added to the Modbus scanner to count the number of successful scans as well as the total number of scans and maintain a channel for each RTU with the percentage of successful scans for that RTU.

CONCLUSION

A modern SCADA system requires software. A variety of products exist, though many are of a generic form and are designed for industrial and manufacturing environments. The needs of irrigation and rivers systems are unique, and these products may be adapted, with varying degrees of success.

When planning the implementation of SCADA software from any source, the specific needs of irrigation and river systems should be carefully considered. Flexibility is a highly valued feature, though it may come at the cost of some simplicity and ease of implementation. Conversely, effort expended upfront to build a good system will likely result in a much smaller burden for long term operation and maintenance costs. A system that is not flexible, regardless of how simple it is to implement, will probably turn out to be of dubious value. A high degree of reliability is also required.

Vista Controls has modified an existing SCADA product to meet the specific management needs of the Middle Rio Grande Conservancy District. The result has been a system which the MRGCD believes is a contributor to its water saving program. We have described the specifics of that application as an example of the unique needs of SCADA software for irrigation monitoring and control.

ACKNOWLEDGEMENTS

We very gratefully acknowledge the guidance and advice of David Gensler of the MRGCD for his technical help right through this project.

DESCRIPTION AND MEASUREMENT OF UNCERTAINTY FOR STATE-SPACE MODEL OF LARGE CASCADE CANAL SYSTEM

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ABSTRACT

Automatic control of canal network is a key solution for modern water-saving irrigation, and it is also a vital technique puzzle of the Middle Routine of the South-to-North water transfer project of China. The design of the controller is based on a liner mathematical model deduced from Saint-Venant Equation system, but the S-V Equations are a system of first order partial differential equations. A state-space model of a cascaded canal system is used in this paper to analyze the uncertainty including the uncertainty of the system itself and the uncertainty introduced in the procedure of mode-building. This uncertainty will be a precondition for the design of a robust controller. Using the liner model as the nominal case, the uncertainty is measured by the largest singular value of the distance matrix of the models. At last a simulation case of six canals is given together with quantificational describe of uncertainty.

INTRODUCTION

A canal system is a complicated system built with water flow, controlling gates and corresponding measuring equipments. The signal is mainly carried by water wave. The main equation system that describes the dynamic procedure of open canal flow is the S-V Equation system, which is a first order partial differential equation system. Ordinarily this equation system could not be solved directly. The water wave in open canal is a gravity wave, and the wave velocity is proportional to the square root proportion of the equivalent water depth. So it is usually not large. So the system has a large time-lag and is highly nonlinear. Additionally, there are strong coupling effects among the reaches, and adding with the uncertainty disturbance such as wind wave and unscheduled water withdraw, this system may be very complicated.

The design of the controller is based on the state-space linear mathematical model. One key limit of modern control theory is that the mathematical model must

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describe the real system accurately. In another words, the design of the controller relies on the accuracy of the mathematical model. The linear state-space model of the canal system is built by truncating the Taylor series and taking the first order term. The ignored higher order items will bring uncertainty. How to account for this uncertainty and introduce it into the controller design procedure so that the system can tolerant this difference is the main task of robust control. The final robust controller can limit the influence of this uncertainty within limits, so the model uncertainty measurement is very important.

THEORY BACKGROUND

An effective canal automatic control system must choose an appropriate operation method according to hydraulic characteristic and function of its own. The method of operation directly affects the canal regulation volume of water and has a great influence to the canal operation, stability. The basic methods of operation are constant downstream depth, constant upstream depth, constant volume and controlled volume operation method. The main idea of the constant volume method is to keep the water volume in the canal pool constant by keeping the middle point of the water surface constant. In this way, the water volume of neighboring canal reaches can feed each other. The canal system can meet the water volume demand by itself, so it has a faster respone. The following model is based on this idea.

Much work has been carried out for the canal network modeling and many models have been developed. But these models may not make good balance on the accuracy and the simplicity. Usually the S-V equations are solved by characteristic method or explicit difference method. According to our experience, the characteristic method has larger error when discharge is large; its calculation will lead to a flow imbalance. The explicit difference method is easier to program but inaccurate. In this paper, the Preismann implicit scheme is used because it has high accuracy and can reach unconditioned convergence.

MATHEMATICAL MODEL

The continuity equation and the momentum equation of S-V Equations can be discretized by Preissmann implicit scheme, and expanded at the target operating point with Taylor series into the following two matrixes:

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \end{bmatrix} \cdot \begin{bmatrix} \delta Q^{+}{}_{i} \\ \delta z^{+}{}_{i} \\ \delta Q^{+}{}_{j} \\ \delta z^{+}{}_{j} \end{bmatrix} = \begin{bmatrix} B_{11} & B_{12} & B_{13} & B_{14} \\ B_{21} & B_{22} & B_{23} & B_{24} \end{bmatrix} \cdot \begin{bmatrix} \delta Q_{i} \\ \delta z_{i} \\ \delta Q_{j} \\ \delta z_{j} \end{bmatrix} \tag{1}$$

The coefficients and the calculation procedure can be found in reference [1].

The change of discharge is reflected by the change of water level, so accuracy of the discharge calculation is vital to the accuracy of discharge adjustment. Actually, the gates are vary in type, shapes and dimension, so there may be no unique discharge calculation formula. The most popular one is the discharge formula of large orifice outflow. But in this formula the discharge coefficient varies with the change of flow rate so it is hard to fix. In experimental study, Henry's (1950) method for the calculation of discharge coefficient for free outflow and submerged outflow is widely accepted. So in this paper, Henry's formula is used to calculate the gate discharge. The control matrix for gate node is:

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} & \\ A_{21} & A_{22} & A_{23} & A_{24} & \\ & -(\frac{\partial f}{\partial z_j})_e & 1 & -(\frac{\partial f}{\partial z_k})_e & \end{bmatrix} . \begin{bmatrix} \delta Q^+{}_i \\ \delta z^+{}_i \\ \delta z^+{}_j \\ \delta Q^+{}_k \\ \delta z^+{}_k \end{bmatrix} = \begin{bmatrix} B_{11} & B_{12} & B_{13} & B_{14} & \\ B_{21} & B_{22} & B_{23} & B_{24} & \\ & -(\frac{\partial f}{\partial z_j})_e & 1 & -(\frac{\partial f}{\partial z_k})_e & \end{bmatrix} . \begin{bmatrix} \delta Q_i \\ \delta z_i \\ \delta z_j \\ \delta Q_k \\ \delta z_k \end{bmatrix} . + \begin{bmatrix} 0 \\ 0 \\ (\frac{\partial f}{\partial u})_e \end{bmatrix} . \Delta \delta u$$

(2)

Here the function f(x) is the conducted form Henry's equations [1].

Generally, water intake in canal network is in the vertical direction to flow. With the scheduled increase or decrease of discharge, the water level at the intake point will rise or drop. This is called lateral flow. For canals at the size of the South-to-North water transfer project (China), while the water intake flow is 20 or $50m^3/s$, the intake point will have a drop of 1mm and 3mm separately. Because this drop is relatively small, we ignore it in modeling. So the water level relationship at intake node is continuous.

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \end{bmatrix} . \begin{bmatrix} \delta Q^+{}_j \\ \delta z^+{}_j \\ \delta Q^+{}_l \\ \delta z^+{}_l \end{bmatrix} = \begin{bmatrix} B_{11} & B_{12} & B_{13} & B_{14} \\ B_{21} & B_{22} & B_{23} & B_{24} \end{bmatrix} . \begin{bmatrix} \delta Q_j \\ \delta z_j \\ \delta Q_l \\ \delta z_l \end{bmatrix} . + \begin{bmatrix} A_{11} & -B_{11} \\ A_{21} & -B_{21} \end{bmatrix} . \begin{bmatrix} \delta Q_p \\ \delta Q^+{}_p \end{bmatrix}$$

(3)

To simplify the model, in the control of multiple-canals, we assume that upstream and downstream ends of the canal system are large reservoirs which insure that the first and last node can remain constant. Because the state variable that we take is the deviations value of water depth and flow rate from the operating point, the water depth variables at the up and down border point equal zero.

Putting the coefficients about the δz and δQ at ordinary node, the gate node and the water intake point node together into the corresponding position at the A_L *and* A_R matrixes, the coefficient of δu into the matrix B and coefficient of δq into matrix C, we can get:

$$A_L \delta x(t+1) = A_R \delta x(t+1) + B\delta u(t) + C\Delta \delta q(t) \tag{4}$$

Multiply both sides with $(A_L)^{-1}$, then

$$\delta x(t+1) = \Phi \delta x(t) + \Gamma \delta u(t) + \Psi \delta q(t) \tag{5}$$

Here $\Phi = (A_L)^{-1} * A_R$, it is the feedback matrix of the system, $\Gamma = (A_L)^{-1} * B$, the control matrix, $\Psi = (A_L)^{-1} * C$, the system disturbance matrix. $\delta x(t)$ is the state vector, $\delta u(t)$ is control vector and $\delta q(t)$ is disturbance vector.

We define the output equation as $\delta y(t) = H\delta x(t)$, where H is the output matrix.

MODEL UNCERTAINTY

Because the nonlinear model is "waving" around the linear nominal model, we can use corresponding "amplitude" to describe this range. If we can calculate the maximum value of difference inform the target, it can serve as a measurement of this uncertainty. Robust controller designed from this maximum uncertainty can stabilize the system in this series of uncertainty.

There are many ways to describe uncertainty: multiplication uncertainty, addition uncertainty, and coprime factor uncertainty, among these the first two ones are more popular.

(1) multiplication uncertainty

$$\widetilde{p}(s) = p(s)(1 + W(s)\Delta p), \ \|\Delta p\|_\infty < 1 \tag{6}$$

Here p(s) is the nominal model, Δp is the unknown disturbance, W(s) is the border function of Δp, it is also called weight function.

(2) addition uncertainty

$$\widetilde{p}(s) = p(s) + W(s)\Delta p, \quad \|\Delta p\|_\infty < 1 \tag{7}$$

Ordinarily, most uncertainty measurement of robust control uses multiplication uncertainty, because it is easier to deal in math. Using multiplication uncertainty, the relations between nominal model and original model can be described as:

$$G(j\omega) = [I + L(j\omega)]G_A(j\omega) \tag{8}$$

The matrix $L(j\omega)$ bounds G around G_A, it describes the uncertainty in the form of multiplication.

When G and G_A are known, we can get $L(j\omega)$ from equation (8), usually largest singular value $\bar{\sigma}[L(j\omega)]$ is taken as the norm of $L(j\omega)$.

UNCERTAINTY SOURCES

In the modeling procedure of this paper, the non-structural uncertainty comes from two aspects. First the physical model is a dynamic model, the geometry parameter has errors and operating point varies with time. The second kind of uncertainty comes from the model-building procedure, the discrete and liberalizing all can introduce uncertainty.

The uncertainty of the physical model itself

(1) Uncertainty introduced in construction

Geometry parameters include length of canal, bottom width, side slope, vertical slope, canal depth and so on. Ordinarily, when a project is designed and constructed, the canal geometry parameters fit some Chinese design and construction codes or standards. According to these codes and standards, the construction dimension error must not exceed 10mm. In such condition, the construction error is limited in 0.5%. For the canal length, we always get this data by measuring after construction, and the measuring error is also within 0.5%. So for large canal system like in the South-to North water transfer project of China, the geometry parameter error is small.

(2) Outside disturbance in operating

Real canal systems operate in natural conditions, so there are many natural and man-made disturbances in its operation process.

First we discuss the natural disturbance. One main natural disturbance is wind waves. Here we take a wave as a kind of stochastic disturbance like white noise. It is described by a sine function of time (t):

$$\Delta h_{dis} = A \sin Kt \tag{9}$$

Here A is the amplitude, K is the wave frequency. We will do simulations to demonstrate its influence later.

Man-made disturbance is mainly caused by unscheduled water inflows, and unexpected offtakes downstream. It generally leads to the change of flow rate in canals, and departure from designed operating point. So the next section focuses on the uncertainty caused by the unscheduled water intake and the change of operating point.

The uncertainty introduced in the modeling procedure

The gap between the nonlinear model and the linear model is the truncation error of Taylor series. It is an extreme-value problem and in real operating practices the independent variables alter in a very limited zone. If we seek for the extreme value without any precondition, the result model uncertainty will be much larger than necessary and it is almost impossible to design a controller which can 'endure' such a large uncertainty. So we linearize the nonlinear system at many operating points, measure the difference between these models and the original one, and take this as a measure of the truncation error of Taylor series. Of course, this method is quite conservative, but it can reach acceptable result for the desired limited changes. So the uncertainty problem becomes:

$$\overline{\sigma}\left[L(j\omega)\right]=\max_{i}\overline{\sigma}\left[G_i(j\omega)G_A^{-1}(j\omega)-I\right] \tag{10}$$

CASE STUDY

In order to study the uncertainty of the canal system model in quantity, we are to build model of a given case. It is a multi-reach canal system made of six reaches, the geometric parameters come from the design material of South-to North water transfer project, as shown in Figure 1 and the canal dimensions can be found in Table1.

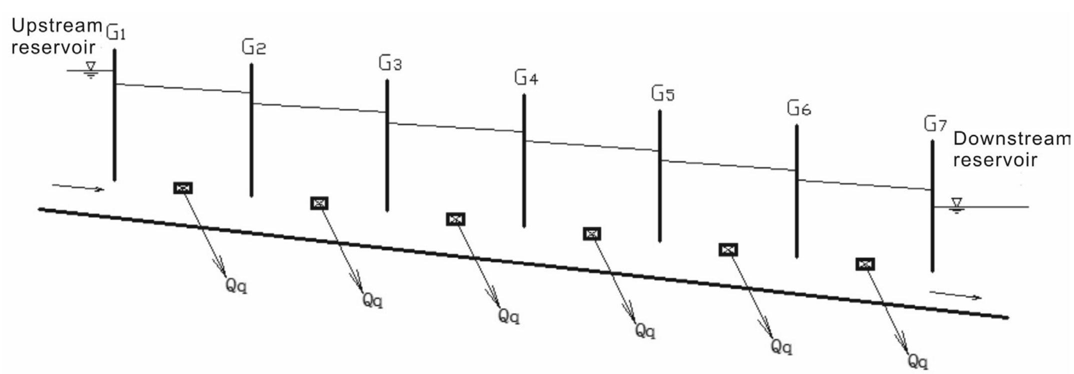

Figure 1. Profile of test case

Table 1.Canal parameters

parameter \ Canal number		1	2	3	4	5	6
Bottom height(m)	upstream	4.8	4.0	3.2	2.4	1.6	0.8
	downstream	4.0	3.2	2.4	1.6	0.8	0.0
length (m)		2000	2000	2000	2000	2000	2000
Initial downstream water level (m)		4.0	3.8	3.6	3.4	3.2	3.0
Roughness		0.015	0.015	0.015	0.015	0.015	0.015
Bottom width (m)		15	15	15	15	15	15
Side slope		2.0	2.0	2.0	2.0	2.0	2.0
Bottom slope i		0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
Width of control gate(m)		15	15	15	15	15	15
Initial discharge(m^3/s)		60	55	50	45	40	35

The whole system is made up of six reaches, and 32 nodes. The size of the state-space equation: A_L is a matrix of 55×55, A_R is 55×55, B is 55×7, C is 55×12. The parameter matrix Φ is 55×55, Γ is 55×4, disturbance matrix Ψ is 55×12.

(1) Influence of geometric parameter uncertainty

Construction error is within 10mm, the length error of reaches is within 5%, so here we give the variability of canal geometric parameters in Table 2.

Table 2. Variability in canal geometric parameters

	Length of reach (m)	Bottom width(m)	Width of control gates(m)
Nominal system	2000	15	15
Case1	2010	15.01	15.01
Case2	1990	14.99	14.99

Now we get three groups of linear system models. If we measure the uncertainty of case1 and case2 from the nominal one by method above, we can get the result of Table 3.

Table 3. Measurement for uncertainty form turbulence in canal geometric parameter

	Uncertainty for matrix Φ (%)	Uncertainty for matrix Γ (%)
Case1	0.088	0.28
Case2	0.09	0.27

From the above results we can see that the influence of variability in canal geometric parameters is making Φ matrix has ±0.1% uncertainty, and Γ matrix has ±0.3% uncertainty.

(2) Wave disturbance analysis

We simulate two kinds of operating condition. First we assume A=0.15 and K=$\pi/40$ (it is inverse solution of a cycle of 80s), the gate discharge line is in Fig. 2.

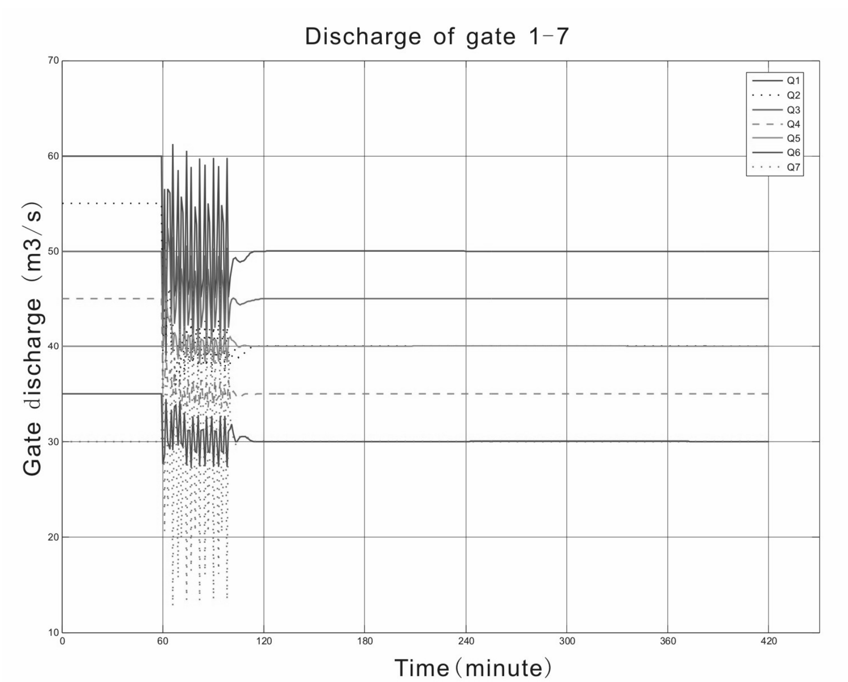

Figure 2. Gate discharge in waving disturbance (K = $\pi/40$)

The second condition, A=0.15 and K=$\pi/30$ (a cycle of 60s), the gate discharge line is in Fig 3.

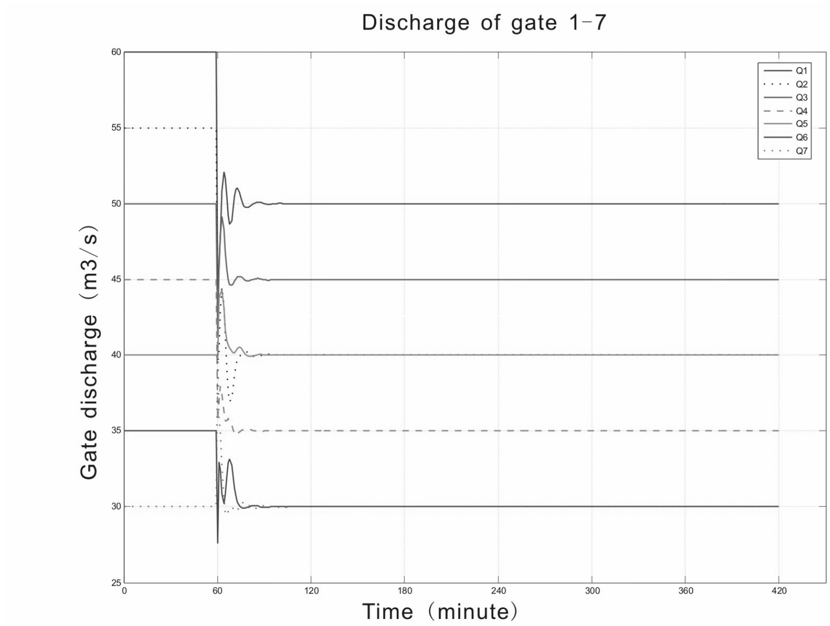

Figure 3. Gate discharge in waving disturbance (K = $\pi/30$)

Comparisons and analyzes of the two simulation results show that, $K = \pi/40$ is the worst condition. If the wave cycle is not an integer multiple of the system time step, the wave influence is quite limited. If $K = \pi/30$, the discharge can have very good dynamic performance, the wave only influences the water level error visibly. If amplitude was made 2 times of original, the system also has acceptable dynamic performance, which will not be listed here.

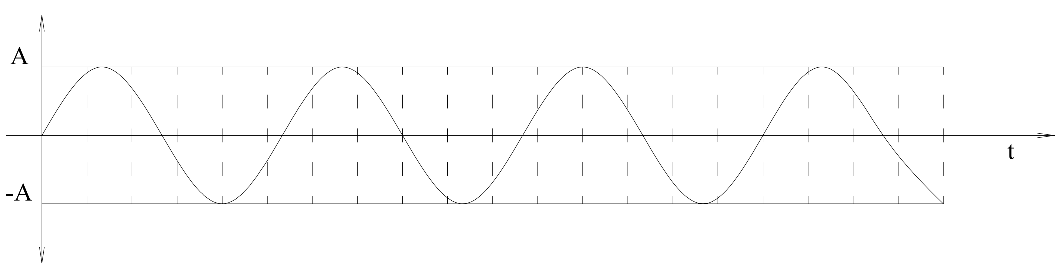

Figure 4. Illustration of wave cycle and system time step

Figure 4 illustrates the wave height when the wave cycle differs from the system time step, the real sinusoid line is the water level wave near the gate, and the dash line is the system time step. The cross point is the water level height at measure time. We can read from the plot that this height reaches only one max in one cycle. Mostly it is far smaller than amplitude A, so the influence of wave is cut down greatly.

This means that while considering the influence of wave, the cycle is the key factor. To stabilize the canal system in some range of frequency, the discrete time step should be chosen carefully. Since, the S-V equation is solved in the mathematical model using the Preissmann implicit scheme, the choosing of time step can ignore the restriction of the so-called Courant-Friederichs-Levy condition. In reality, a natural wave is not just simple sinusoid, so the cycle is a series of cycles ranging in a certain field instead of a fixed one, so the choice of time step should go beyond this field.

(3) Uncertainty of operating point change

In the test cases of this paper, the change of operating point can be realized by changing the flow rate of each water intakes. Since there are six water intakes. If we increase and decrease each water intake's flow rate by 50% separately, and assume this to be the ranging filed of possible operating point change, we can get Table 4.

Table 4. Operating point change

Gate discharge		QG1	QG2	QG3	QG4	QG5	QG6	QG7
Nominal point		60	55	50	45	40	35	30
Flow rate increase 50%	case1	60	52.5	47.5	42.5	37.5	32.5	27.5
	case2	60	55	47.5	42.5	37.5	32.5	27.5
	case3	60	55	50	42.5	37.5	32.5	27.5
	case4	60	55	50	45	37.5	32.5	27.5
	case5	60	55	50	45	40	32.5	27.5
	case6	60	55	50	45	40	35	27.5
Flow rate decrease 50%	case7	60	57.5	52.5	47.5	42.5	37.5	32.5
	case8	60	55	52.5	47.5	42.5	37.5	32.5
	case9	60	55	50	47.5	42.5	37.5	32.5
	case10	60	55	50	45	42.5	37.5	32.5
	case11	60	55	50	45	40	37.5	32.5
	case12	60	55	50	45	40	35	32.5
No water intake	case13	60	60	60	60	60	60	60

From calculating we get 13 groups of linear model. Measuring the uncertainty of all cases by the method above separately, the result is in Table 5.

Table 5. Measurement for operating point change

		Uncertainty for matrix Φ (%)	Uncertainty for matrix Γ (%)
Flow rate increase 50%	case1	2.04	2.33
	case2	6.51	6.23
	case3	6.72	6.48
	case4	6.75	6.72
	case5	6.75	6.96
	case6	6.75	7.19
Flow rate decrease 50%	case7	1.94	2.22
	case8	5.91	5.64
	case9	6.07	5.82
	case10	6.08	5.98
	case11	6.08	5.90
	case12	6.08	6.26
No water intake	case13	298.45	327.49

From the above results we can see, the uncertainty brought by the changing of operating point is within 8%. We then calculate a extreme condition for shutting down all water intake, giving ±300% of uncertainty. So if the change of discharge is bounded in a certain range, it will introduce little uncertainty, larger flow rate change will lead to larger uncertainty. So if the change is in a small field, we can use a single mathematic model and the controller will stabilize the system. If the change is large, it should be broken down into n sub-procedures, modeling should be done in n steps, and controller should be solved separately to cut down the oscillation.

SUMMARY

The uncertainty of the system model impacts the design of a controller. The flaw of modern control theory is it relies too much on the accuracy of model. As a highly nonlinear system, the canal control system will loose high-order terms through linearization, leading to an inaccurate mathematic model. In this paper, we try to discuss this uncertainty introduced in modeling and the uncertainty of the physical model. The multiple uncertainty (2 norm) is used to describe this. If we consider this uncertainty in the design of a robust controller, we will be able to stabilize the system while it switches in a certain field. At last a test case is simulated and the results show that the ignored high-order items bring the main uncertainty.

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USE OF SOPHISTICATED STATE-OF-ART SCADA SYSTEM FOR VERY EFFICIENT AUTOMATED IRRIGATION OPERATIONS ON 22,070 ACRES OF AGROFORESTRY

Nabil Mohamed[1]

ABSTRACT

Along the mighty Columbia River in Eastern Oregon, U.S.A, in an area with less than 8 inches of total annual precipitation, exists the world's largest contiguous drip irrigated tree farm project. This Potlatch Corporation **W**estern **W**hite **P**oplar **P**roject (WWPP) uses high level automated technology to produce solid wood on a national and international certified sustainable rate.

The project's 6,000,000 fast-growing desert hardwood trees (*Western White Poplar)* on 17,300 acres are irrigated by a massive and very complex automated water distribution system. Additionally the irrigation system also supplies water to other crops on 4,770 acres under pivot irrigation.

Irrigation pumping energy costs are the major operational cost of tree production on this project; so a very determined effort is made to operate the irrigation system in an efficient and cost effective manner. The **only economical and efficient** way to irrigate this very large and complex project is by the use of an advanced customized **S**upervisory **C**ontrol and **D**ata **A**cquisition (SCADA) system. This State-of-Art SCADA system controls and monitors all pumps, individual fields, sensors and center pivots. This SCADA system makes the WWPP one of the most advanced automated large-scale drip irrigation farm projects in U.S.A., if not in the world. Additionally for the past decade, it has sustained its position as the world leader in large scale drip irrigation efficiency.

INTRODUCTION

In early 1990's near the town of Boardman, Oregon, Potlatch Corporation's "Fiber for the Future" project acquired two very large center pivot-irrigated farms, with a combined total acreage of 22,070 acres, for intensive farming of fast growing Poplar trees (*Western White Poplar)*.

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The “Fiber for the Future” project was developed on farmland previously irrigated with center pivots. Gradually over six years, 2,000 to 4,000 acres were converted each year from center pivot to drip irrigation (Figure 1). The converted circular pivot fields were “squared” up to utilize all of the land. At each previous pivot point, a distribution manifold (field) was constructed with valving and automation to serve four, 40 acre or 70 acre blocks. The existing pumping plants and buried pipeline network were also modified to maximize water delivery and operational efficiency. The pivot to drip conversion was discontinued after 17,300 acres and the rest of the pivot acreage was sold.

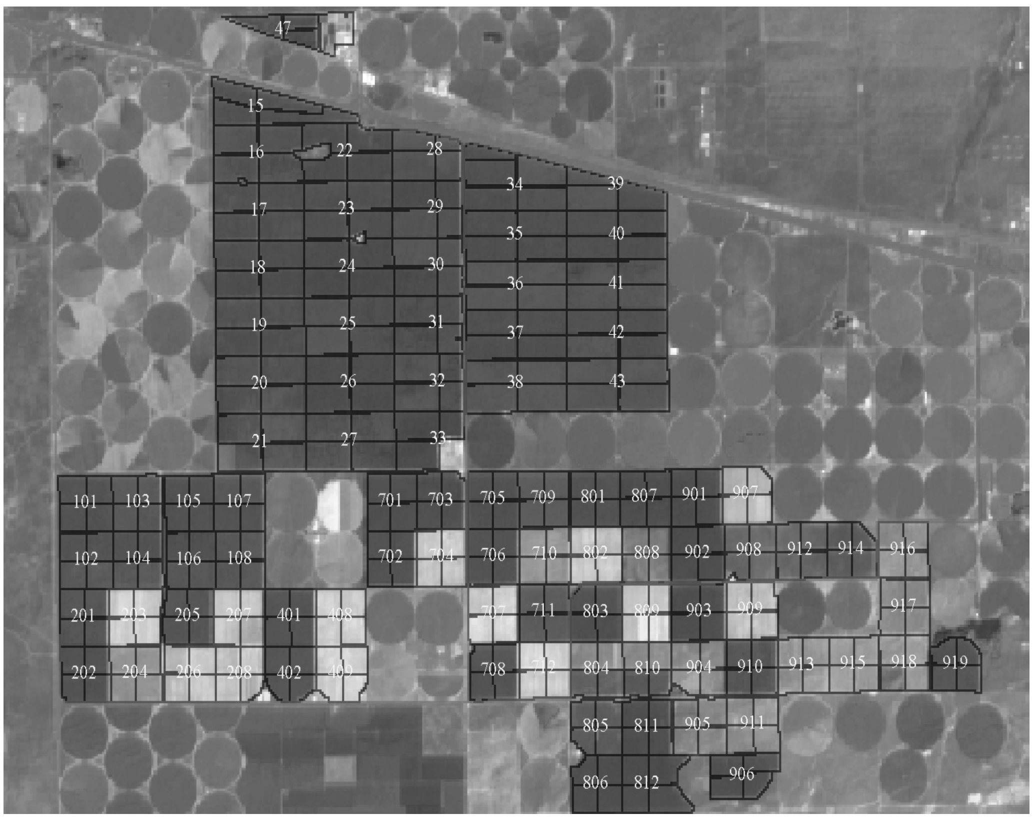

Figure 1: Satellite image of Western White Poplar Project (WWPP) showing both the drip and pivot irrigated lands.

This “Fiber for the Future” farm project was originally designed to provide approximately 25% to 30% of the total chip fiber requirement for the massive Potlatch Pulp & Paperboard operations located at Lewiston, Idaho. By the late 1990’s, opportunities for using the fiber in higher value solid wood products was identified. The project’s management was then moved from pulp-based to saw log management by thinning and pruning younger trees, changing tree clones and spacing, and extending the tree rotation from 7 to 11 years.

The project's 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 clonal material and the continuous monitoring of crop vigor and health, the project aims to become the lowest cost producer of high quality sustainable saw logs and wood products.

PROJECT FACTS

At its present size of 17,300 acres the project is the world's largest irrigated fiber farm and one of the largest contiguous drip irrigated farms in the world. It is also a world leader in large-scale drip irrigation efficiency.

On this fiber farm, approximately 6,000,000 trees grow on an eleven-year rotation. For disease and other reasons, multiple clones of Poplar trees are used to add genetic diversity. Each clone has it own characteristic needs for water and fertilizer and unique production quality and quantity. These special Poplar trees are known to grow nearly two inches a day during peak growth and have growth rings more than 1.5 inches wide. The trees are harvested at an average sustainable rate of one tree every 16 seconds.

The project's irrigation system has a pumping capacity that exceeds 257,000,000 gallons per day, making its irrigation system among one of the largest in the State of Oregon. At peak flow, nearly 180,000 **g**allons **p**er **m**inute (gpm) are flowing through an irrigation system consisting of 68 major pumps at 13 different pumping stations. Total Horsepower exceeds 30,000 **H**orse**p**ower (Hp) with pump motors ranging in size from 30 Hp to 1,000 Hp. Single pump capacities range from 500 to 32,000 gpm. The pipe network consists of nearly 500 miles of buried pipe ranging in size from 1½ to 72 inches diameter. The drip tube's total length is an astounding 14,300 miles! Finally this large amount of water is fed to the trees through nearly 20,000,000 emitters.

SUPERVISORY CONTROL AND DATA ACQUISTION (SCADA) SYSTEM

This WWPP is so large and complex that it requires a very sophisticated control and monitoring system. The WWPP **S**upervisory **C**ontrol and **D**ata **A**cquisition (SCADA) system controls and monitors all 68 irrigation pumps (Figure 2), 93 manifolds and 46 center pivots. The project's SCADA system consists of two processors and a single computer installed with the latest in **H**uman **M**achine **I**nterface (HMI) software, interacting together with the 153 field processors. All communication to the field processors is done by State-of-Art Spread Spectrum radio telemetry. This SCADA system is designed with the ability to control valve(s) or pump(s) from the SCADA **O**perator **I**nterface **T**erminal (OIT) at the office and at distances greater than 15 miles. All SCADA actions occur within 2 seconds of operator command, with full control acknowledgement within 5 seconds of command initialization from the OIT.

Figure 2: SCADA system on Western White Poplar Project irrigation canal pump station.

<u>"Stand Alone" SCADA system</u>

Through an elaborate process of decision making and implementation via the SCADA system, the project has attained the level where it can provide a different irrigation regime to each of the 370 blocks and at the same time also apply different irrigation regimes multiple times a day to the individual block. The process manages to do all this complex combination of irrigation regimes while maintaining a hydraulic balance on a huge and very complex irrigation system. No pump changes occur during the duration of an irrigation schedule! This fine-tuning of the hydraulic balance in the irrigation schedule ensures that the system "hums" along with very little human intervention day and night. The only time pump change occurs is when pivot operators' demand it or when the next irrigation schedule changes. The smooth hydraulic balance also enables the project to operate a massive irrigation system without the need of complex and expensive pump automation programs. This "smooth" operation of the irrigation system is "easy' on the hardware of the system and lessens the burden to the irrigation team members who then only have to interact with the SCADA system when the SCADA system remotely alarms them. This hydraulically smooth operation is what enables the WWPP SCADA system to become a "stand alone" system.

SCADA Answer to the Irrigation Challenges

Survival of these trees on the WWPP is largely dependant 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 just as important as the irrigation amount. Growing these trees under these conditions and in sandy soils will cause a detrimental reduction in yields or even death of trees, if there is any cessation of irrigation for more than 15 hours! With all these tough environmental and tree demands, it has forced the project to implement very sophisticated and reliable water management practices. With more than 370 individual blocks, that cycle irrigation as much as four times a day, irrigation scheduling is also a hydraulic nightmare. With the use of a State-of-Art SCADA system, extensive soil moisture monitoring, weather data, crop curves and the use of complex customized and in-house software, has enabled the project to not only adequately irrigate its trees, but do it in such a high level of efficiency that it has made this project a world leader in large scale drip irrigation efficiency. One of the success stories of the project's excellent water management practices is the demonstrated ability to irrigate with such precision that the central 2-foot wide strip between the 10-foot tree rows always remains dry. This level of water application efficiency is unparallel in such a grand scale anywhere in this world!

There are basically three major irrigation challenges facing this project and its SCADA system:

1) Water deliverance from the source to the trees.

Every irrigation project has its challenges and the challenges faced by this project, especially in water deliverance are not unique except for its very large scale of operation. The projects meet 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 SCADA system was installed to control and monitor the whole of the irrigation system. This SCADA system provides the ability to "spoon feed" the trees with specific amounts of water and fertilizer.

2) Water management and irrigation scheduling.

In water management and irrigation scheduling, the challenges on this project are huge, ongoing and very complex and require unique solutions that involve collectively the SCADA system and the use of multiple customized and in-house software. These challenges are demanding as they affect the whole economics of operation.

The complexity of water management and irrigation scheduling on this project is a daunting task as the variables are enormous and constraints are extremely restricting. This is where the strength of sophisticated control and monitoring by the SCADA system, allows the very complex operations of irrigation scheduling on each of the individual 370 irrigation blocks.

The SCADA system tackles these daunting tasks of water management and irrigation scheduling by working together with sophisticated and customized **A**dvanced **H**ydraulic **B**alanced **I**rrigation **S**cheduling (AHBIS) software that generates weekly a SCADA operational binary code file with nearly 9,000 individual block irrigation schedules that are hydraulically balanced. This SCADA /AHBIS interaction allows the project to micromanage irrigation scheduling at the individual 40 to 70 acres block level.

3) Water quality.

Maintaining irrigation water quality to avoid plugging 20 million emitters requires the use of both primary and secondary filters, extensive chemical injections and a very closely monitored water quality program utilizing sensors such as automated turbidity meters, pH and chlorine residues sensors. This is where the monitoring and control strength of SCADA system comes into play. Additionally the SCADA system is programmed to do block flushes, flush fills, desilts etc., that mitigates the effect of any silt loading of the drip line and thereby avoid emitter plugging.

SCADA and Pump Energy Efficiencies

With seasonal pumping energy costs in excess of two million dollars, economics dictates that the project maximizes the efficiency of operating its multitude of pumps. The pump motors and pump stations are installed with "near-utility grade" power monitors for monitoring, via SCADA OIT, the "wire to water" efficiency during pump selections and operations. The SCADA system also allows the project to conduct individual or group pump tests in Real-Time for evaluation of present and also predict future pump/motor efficiencies and the corresponding cost of pumping.

SCADA SUMMARY

Potlatch Corporation Western White Poplar Project (WWPP)
Supervisory Control and Data Acquisition (SCADA) System

This "Stand Alone" WWPP SCADA system controls and monitors:

An irrigation distribution system that consists of 500 miles of buried pipe and 14,300 miles of drip tube with 20,000,000 emitters, capable of carrying a peak water flow of 182,000 gallons per minute generated from 13 different pumping stations located on two independent farm water supply distributions.

WWPP SCADA system control and monitoring area encompasses:

- 17,300 acres of drip irrigated land under Poplar trees.
- 4,770 acres pivot irrigated land under various crops.

Overall the WWPP SCADA system remotely controls and monitors by Radio Telemetry:

- 129 field processors.
- 68 irrigation pumps with a total of 30,000 Hp.
- 93 manifolds with 369 individual irrigated blocks of 40 / 70 acres.
- 110 flow meters.
- 349 pressure transducers.
- 1254 automatic valves.
- 147 fertilizer/chlorine pumps.
- 288 soil moisture sensors.
- 38 electrical power monitoring sensors.
- 113 timers.
- 11 water quality sensors.
- 38 flush counters.
- 101 primary and secondary screen filters.
- 46 center pivots.

These massive Irrigation and SCADA systems are operated and maintained 24/7 by less than 6 full time staff!!

SCADA has allowed enormous irrigation efficiency improvements on the WWPP namely:

1. SCADA allows the sophisticated implementation of the AHBIS program, which optimizes individual block irrigation schedule regimes. This optimization leads to a smooth and steady hydraulic pump station

operation. Therefore no pump changes occur during a particular irrigation schedule regime, eliminating the need of expensive and very complex pump automation programs. It also leads to a steady irrigation canal flow withdrawal rates that assist the irrigation district to run an efficient irrigation canal operation. This overall enhances pumping energy efficiency, decreases irrigation system wear, greatly improves human resource allocations and reduce operational costs.

2. SCADA control and monitoring of **V**ariable **F**requency **D**rive (VFD) motors together with Real-Time data of energy usage per unit water pumped, combined with on-line pump testing; all collectively help improve irrigation pumping energy efficiencies.

3. SCADA's ability to monitor extensive Real-Time flow and pressures of pump station and individual blocks enables high irrigation uniformity efficiencies.

4. SCADA's use of sophisticated auto-pump shut-off programs for maintaining system integrity when irrigation system fails. This is combined together with extensive SCADA Real-Time alarm/pager system to remotely alert operators of an irrigation situation that would adversely affect irrigation performance or efficiency.

5. SCADA planned interaction in Real-Time with a **H**ydraulic **M**odel **S**imulation (HMS), will enable irrigation operation at operational minimum pressures, leading to an even better pumping energy savings.

CONCLUSION

Potlatch Corporation Western White Poplar Project efforts to mass-produce a tree that has a high evapotranspiration requirements and is sensitive to soil moisture stress, is a challenge in itself. To grow these trees in a desert like environment, in soils with low soil moisture-holding capacity brings additional challenges. All of these irrigation challenges and others were met by the use of latest technology in SCADA and other resources which allowed the project to demonstrate its ability of not only operating the largest drip irrigated project in the world but do it very efficiently and economically.

Using the best available State-of-Art SCADA automation technologies has allowed WWPP to maintain a very high level of efficiency, in its endowers to produce the most efficient and cost competitive high quality “green” wood products with minimum of staff and in a sustainable, safe and environmentally conscientious manner. Additionally this SCADA system has allowed the project to sustain its position as the world leader in large scale drip irrigation efficiency for the past decade.

The WWPP was the first plantation in North America to achieve Forest Stewardship Council Certification and has been recognized as a fully sustainable wood supplier and a well managed plantation.

As a final conclusion, SCADA has enabled the WWPP to utilize efficiently the scarce water and energy resource to grow short rotation Poplar trees at a sustainable rate. These Poplar trees yield more than 18 times the fiber yield of a natural forest; can produce per acre two to three times more ethanol than corn and produce white wood chips that save on strong chemical use in paper production. Additionally these Poplar trees improve habitat and recreational activities, increase plant and animal species and are a superior "carbon sink," with huge capacity to suck up harmful carbon dioxide, a greenhouse gas. Irrigated Agroforestry generates an astonishing local area land surface cooling; by as much as 54 degrees Fahrenheit! It is hoped that this “Green” Agroforestry, a eco-friendly practice, will in an age of federal timber restrictions eventually supply much of the nation's wood and fiber needs and at the same time offer up its numerous other benefits.

ACKNOWLEDGEMENT

Appreciation is extended to the Potlatch Corporation and its Western White Poplar Project Team, whose members devote tireless efforts in seeking higher levels of efficiency in producing a low cost “Desert Wood”.

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MODERNIZATION PROJECT AND SCIENTIFIC PLATFORM ON THE GIGNAC CANAL

Pierre Yves Vion[1]
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ABSTRACT

Theoretical progress in the domain of open channel automatic control has been achieved in the last decades. Controllers are generally designed with the help of mathematical software and tested on computer simulation models. Nevertheless, a phase of real-time testing appears to be necessary before the full validation allowing wide spread implementations of given automatic controllers. This helps taking into account and solving problems linked to the physical limits of sensors or actuators or to usually neglected phenomenon such as communication delays, faults and model errors.

The Gignac canal project aims at addressing this issue and sharing a research platform with diverse industrial and academic partners. It involves mainly the equipment of the canal with sensors and actuators, and an opened SCADA system. It has been designed to make possible the test of a wide range of control architectures and algorithms.

The equipment also helps the canal manager facing strengthening management constraints. They appear with the strict application of new legislations which lead to diminish intake withdrawals and to modernize parts of the secondary network. The project associates in a scientific committee: the canal manager, research teams, engineering companies, Universities and Colleges. It helps transferring academic knowledge and focusing the experiments on problem solving and end-users' requirements. Universities and Colleges take benefit from the facilities for practical work for teaching programmes in hydraulics and automatics.

INTRODUCTION

The project of scientific platform on the Gignac canal was initiated by the TRANSCAN team of Cemagref, which studies hydraulic modelling and automation for open channels. After several years of theoretical research in

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automatic control applied to wide hydraulic systems and particularly to irrigation channels, an experimental laboratory appeared more and more necessary. Indeed, with the exception of a few experimental channels of small dimension (of the range of tens of meters) existing in France, Mexico, Portugal or the USA, such facilities, aiming at this kind of specific testing, did not exist to our knowledge. The existence of an open channel not far from Montpellier (see **Figure 1**) and financial opportunities enabled us to materialize this idea.

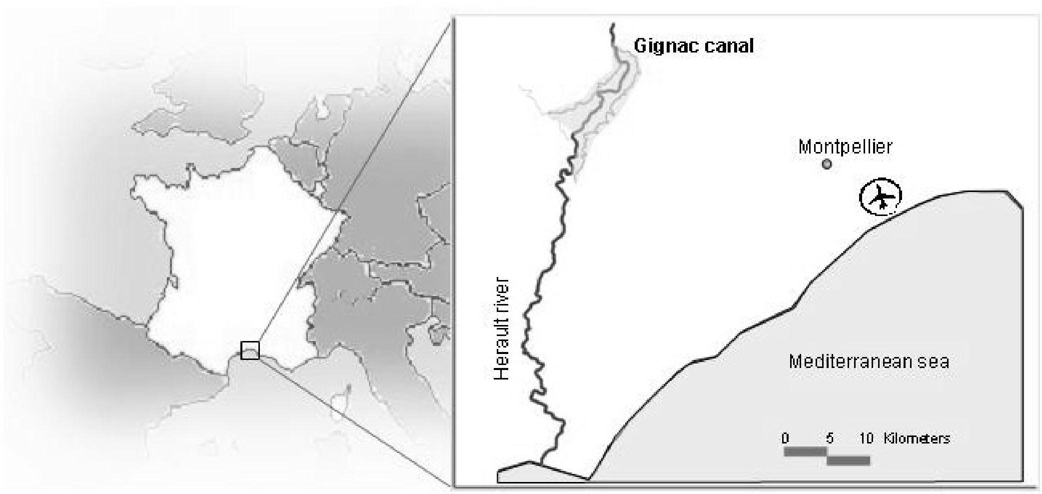


Figure 1. The Gignac Canal - Location Map

Stakes and Scientific Objectives

Stakes: In most regions of the world, diminishing available water and limited investment capacities of stakeholders and funding agencies lead to favour water savings through improved infrastructure and operations rather than investments for the development of alternative water resources. Those questions are particularly acute in southern France and, more generally, in the Mediterranean countries.

In France, growing conflicts around the use of water and the progressive introduction of contractual management of water resources at the basin level make this question essential for the agricultural sector and for emerging water uses in suburban areas.

Beside demand management, modernisation of irrigated schemes through an improvement of transport and delivery channel management appears to be the main way to achieve water savings. Indeed, manually operated open channels are characterised by a low efficiency (30 % in some cases), which can reach 70 % or more on fully automated systems.

The creation of an experimental laboratory follows this logic and aims at:

- demonstrating that modernization can lead to water savings,
- setting facilities enabling researchers to develop, test and evaluate new control methods and algorithms, and,
- promoting new techniques among engineering companies, canal managers and educational establishments.

Scientific Objectives: From a scientific point of view, the control of irrigation open channels is complex. This complexity is due to multiple factors like: delayed and non linear dynamics, complex topology of networks, interactions between control devices, unpredicted perturbations.

Like the Gignac canal, many systems in France and around the world are still manually operated, with upstream regulation, and a low on-line storage capacity. Those systems are particularly difficult to manage and modernize.
Improved hydraulic management can lay on two groups of control methods of growing complexity:

- local monovariable automatic control, sometimes associated with manual operational rules at some devices,
- multivariable control, generally centralised, and associated with robustness analysis.

Those methods can be tested on hydraulic models but they need a real-size validation before being industrialized. In this aim, the Gignac canal laboratory has a double interest:

- for the evaluation of the first group of methods, which could be of particular importance in developing countries,
- for the development and the *in situ* tests of the second group of methods.

Why the Gignac Canal?

Numerous reasons lead to the choice of the Gignac canal for becoming an experimental laboratory. On the one hand, its size is comparable to many irrigation channels, in France or abroad, and it is sufficient for achieving representative experiments. On the other hand, a modernisation programme initiated by the canal manager and the possibility to lead experiments in the fall-winter time when the canal is not in function are interesting opportunities. The improvement of the hydraulic management and efficiency of the canal itself has a particular importance because of the scarcity of the water resource in the basin. Lastly, this canal is located close to Montpellier, where Agropolis Research Complex hosts several research institutes dealing with water issues, attracting several national and international events (2003 54th Executive Council of ICID and 20th European Regional ICID Conference, 2008 XIIIth World Water Congress) and many delegations from all over the world interested in thematic visits.

PRESENTATION OF THE PROJECT

The Gignac Canal

Description and Main Figures: The Gignac canal is the main work of an irrigated area managed by the "ASA[4] du canal de Gignac", and was built in 1890. It is located about 35 km west from Montpellier (south of France). The resource comes from an intake in the Hérault River, which has a very pronounced Mediterranean regime, with severe lows in summer. The main canal is 50 km long, with a common trunk (8 km) and two branches on the left and right banks of the river (resp. 27 and 15 km). The nominal flow of the common trunk is 3.5 m^3/s. The dominated area is about 3,500 ha wide, out of which 2,800 ha are irrigable.

Water Delivery: For a bit less than 90 % of the surface, the water delivery is done through the open channel secondary network with a fixed rotational schedule, allocating 35 l/s during 5 hours per week per ha, which represents 63 mm/week. The remaining 10 – 12 %, essentially in suburban zones, receives water through pipe networks, with or without additional pumping.

Crops and Irrigation Techniques: Vine is the dominant crop with about 58 % of the surface. Other crops are cereals, orchards, and market and private gardens with respectively 6.3, 4.7 and 7.3 %. Non irrigated surfaces (waste land, gravel extraction, forests) accounts for about 24 %.

Traditional furrow irrigation is the most used technique in the area, especially in vineyards. Market gardens and orchards are mostly irrigated with drip and spray irrigation respectively, even if the water is delivered through open channels to the plots. In these cases, farmers have their own pressure devices.

Urban gardens are mainly supplied through low - or high- pressure networks and use spray irrigation.

Equipment

The project consisted mainly in installing sensors and actuators, and building an opened SCADA system for the canal, enabling supervision and local or remote automatic control. It has been designed to make possible the test of a wide range of control architectures and algorithms. Level, gate position and flow velocity sensors have been installed on the whole main canal at strategic locations.

Equipment Rationale: Transforming the canal into a laboratory consisted in permitting the centralisation of the measurements and the commands. More

[4] ASA : Association Syndicale Autorisée = association of landowners, under public administration control

precisely, it has been build around a supervisory system, located in the ASA's head office, and distant devices like sensors and motorised gates.
Because of the high cost of the equipment, choices had to be made. They were done according to the following constraints:

- command and measure discharges upstream of the 3 main branches,
- command outlets for security reasons and for enabling perturbation simulation,
- command four reaches in a row, in order to take interactions into account,
- get measurements on a "sufficient" number of points,
- guarantee a collection time of the variables compatible with the dynamic of the system, and,
- have at disposal a SCADA system enabling the integration of any control modules.

The choices also took into account various constraints linked to the topography, the possibility to reject important discharges, to the proximity of the power supply network, etc.

Equipment Description: Those criteria led to retain the following equipments (see Figure 2):

- measures and commands on some points of the common trunk and of the right branch,
- measures only, on the left branch.

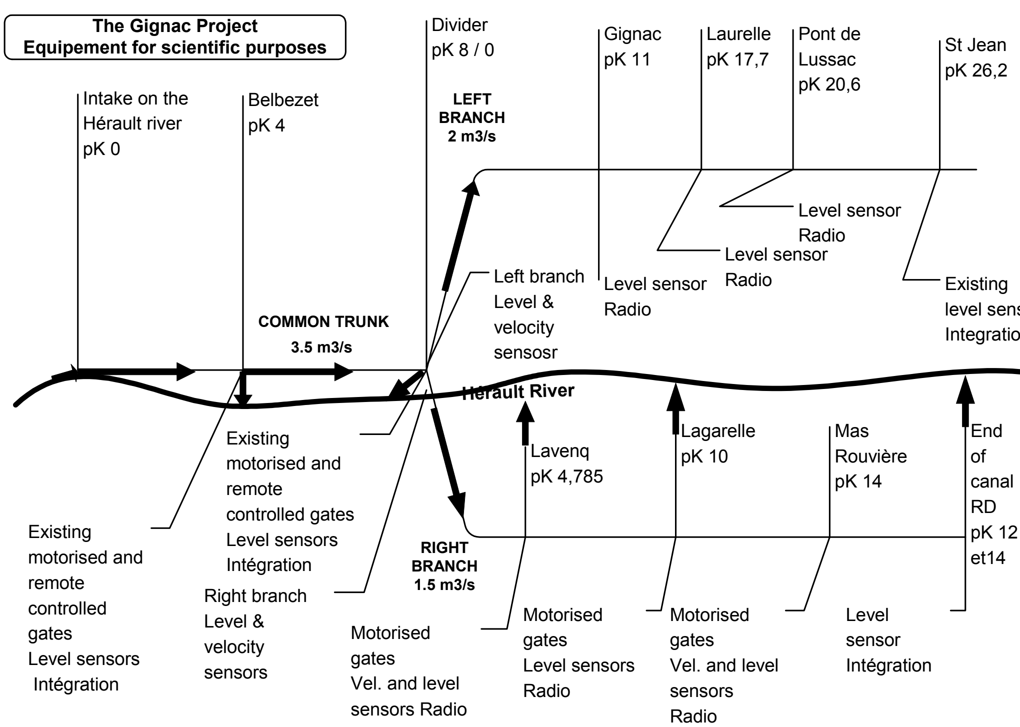


Figure 2. Installed Equipment on the Gignac Canal

Variables and Types of Sensors: Measured variables are:
- water levels, with piezoresistive sensors,
- discharges, with ultrasonic velocity sensors, and,
- gate openings.

Discharges can also be evaluated with indirect methods, with the measurement of water levels over freeflow weirs, the measurements of water levels upstream and downstream in addition to the gate openings at cross devices, or the establishment of discharge rating curves on some interesting locations. Three rain gauges give additional information on the meteorological situation.

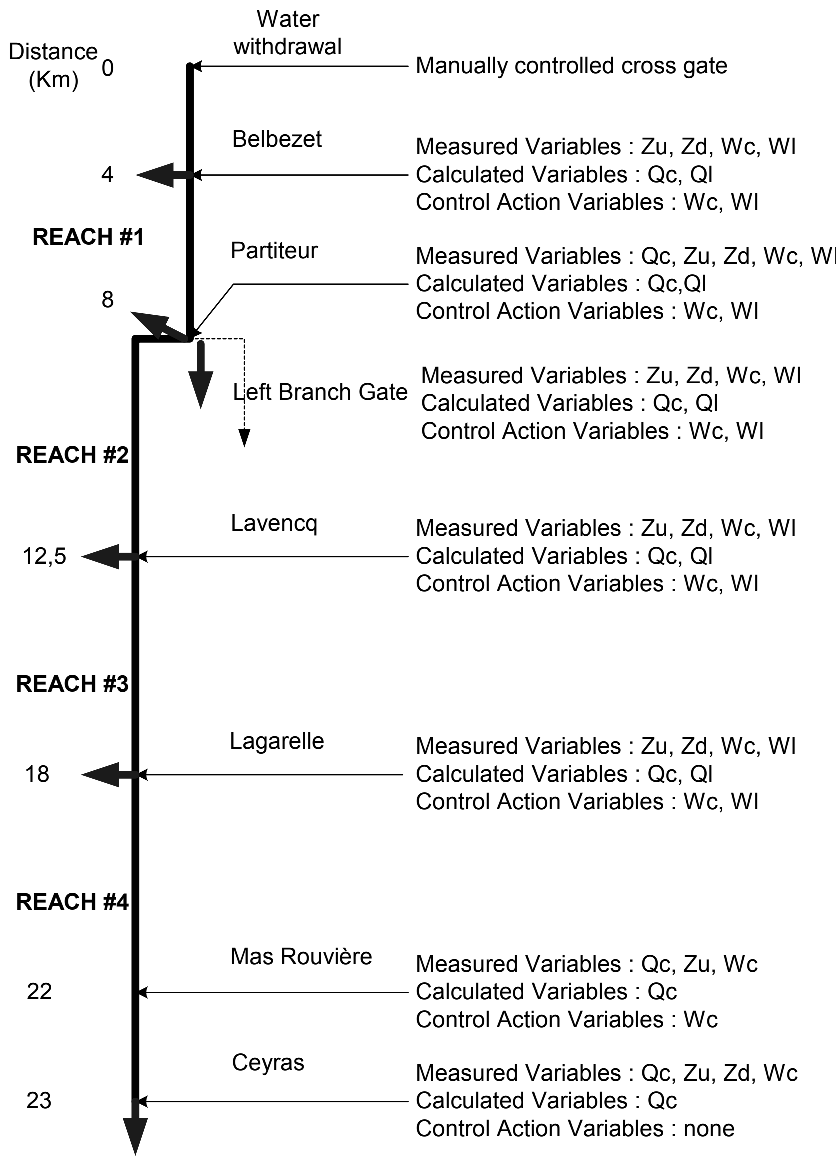
Control Action Variables: Control action variables are the gates openings, which can be cross gates, for level or transient discharge control, or lateral gates for perturbations generation and security outlets discharges.

Communications: Some sites were already equipped with remote measurements and control through the landline telephone network. This transmission method presents the disadvantage of being slow and expensive. The time for the scanning of eleven remote sites would have been of about ten minutes, which appeared too long regarding the dynamic of the system, and especially near the gates.

Hence, a 470 MHz radio system has been chosen, even if some location could not be equipped due to the topography. They were equipped with the telephone, and the central had to be designed to be able to communicate through both media.

SCADA and Control Modules: One of the main constraints in the conception of the supervisory devices was to enable the operator to link any control module to the SCADA system. The solution adopted is presented in a separate paper (mala et al., 2007).

GIS: A Geographical Information System has been added to the equipment. It includes the existing database of the ASA and various layers of data (primary and secondary network, land ownership, land occupation, soil reserve, etc.). The GIS is useful to the ASA for its day-to-day management and to the scientific teams for diverse studies.



NOTATIONS :

Z = water leval
Zu = upstream water level (gate or weir)
Zd = downstream water level (gate or weir)
Qc = discharge in the channel
Qd = lateral discharge (outlet)
Wc = cross gate opening
Wl = lateral gate opening

Figure 3. The Gignac Canal (Common Trunk + Right Branch): Measured, Calculated and Control Action Variables

Finance and Partnership

Financial Aspects: The total cost of the programme reaches 900 k€ (1170 k$), including about 510 k€ (660 k$) of investments. Local institutions (*Conseil Général de l'Hérault* and *Conseil Régional du Languedoc-Roussillon*) and the Water Basin Agency (*Agence de l'Eau Rhône-Méditerranée et Corse*) funded the project, partly because the investments were also a means to help modernizing the canal.

Partnership: The partnership includes the canal managing institution (ASA du canal de Gignac), 3 scientific laboratories, 3 engineering companies and 3 engineering Colleges. It is settled with a main M.O.U., the *Scientific Interest Group*, which includes all partners, and 2 M.O.U.s between the scientific leading institution (Cemagref) and the canal manager, which regulate the use of the canal for scientific purposes.

ACHIEVEMENTS AND RESULTS

Experiments

The experiments are conducted mainly before and after the exploitation period of the canal, which starts generally at the beginning of March and ends in mid-October. During those two periods, the canal can be completely dedicated to measurements and experiments.

Some tests may also be achieved during the exploitation period, as soon as they do not disturb the water delivery.

Research Topics

The various topics studied with the canal can be represented in the perspective of their automation (see Figure 4).

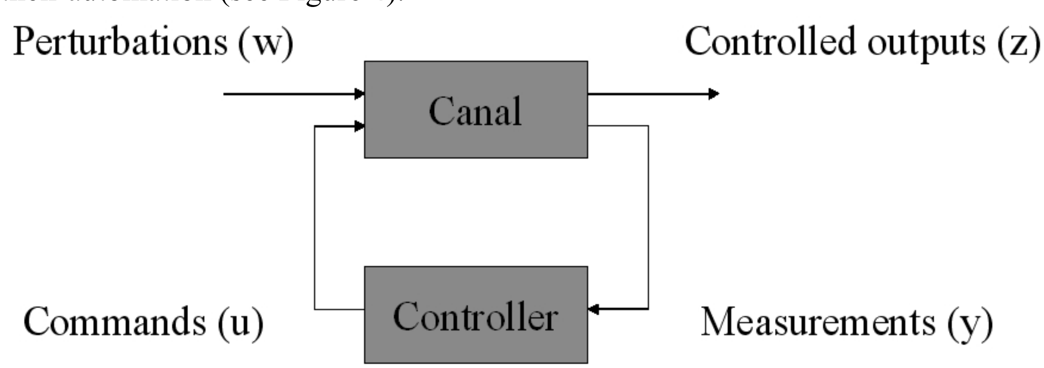


Figure 4. Automatic Control of a Canal - Studied Topics

Canal Model

A hydraulic model of the primary canals has been build with the SIC software, which allows simulation of one-dimensional steady and transient flows. The large amount of precise data enabled us to have a fine appreciation of the precision of the model. It is used for testing scenarios and control modules before their implementation on the real system.

Perturbations

Demand Study: Due to the inherent time delays of the system it is interesting to make a prediction of the water demands and to use it in a feedforward controller added to feedback controllers.

Evolutions in the Perimeter: Some former lands are converted to urban areas where the new inhabitants keep the ancient water right associated with the land. A low pressure piped network is then constructed providing raw water for gardening, swimming pools and some domestic uses. This change, although still limited, has an impact on the water demand and therefore on the canal operations that is currently studied.

Observation : Measurements and Controlled Outputs

Canal Supervision: As soon as real time measurements are used for real time control the issue of data validation, data reconciliation and fault detection is raised. Several studies have been conducted on this aspect leading to scientific publication, a PhD thesis and software tools.

Flow measurement: several options are available to measure flows in a canal, such as calibrated rating curves, ADCP techniques, and device equations. The quantity of data that are measured and saved in the database allowed us to evaluate and compare several alternatives for these measurements.

Commands

Several control action variables are possible as outputs of a controller. The main classical ones are the discharge Q or the gate position W. These alternatives could be further tested and compared on the real system. This work was presented in scientific publications and is still under investigation.

Controllers

Several SISO and MIMO controllers have been studied in the frame of several research projects leading to scientific publications and PhDs. Some of these controllers are presented in a separate paper (litrico et al., 2007).

CONCLUSION

The first phase (2002-2007) of the scientific project of the Gignac canal will be achieved in 2007.

For the scientific teams involved, it has been an essential element for the validation of various control algorithms and supervision methods. It enabled the teams to publish several articles and two PhDs, which include real-size test results.

Those results are now available for engineering companies, which also take benefits of the know-how gained during the installation phase of supervision and command system.

Several Colleges organized visits and conferences around the Gignac canal, practical works in hydraulic simulation and automation have been backed on data taken from it and about ten students worked on Gignac during training periods.

The canal manager has also improved its knowledge and comprehension of the system behaviour through the modelling and the various experiments and studies conducted on the canal. As it is now facing new environmental constraints, this knowledge will help making decisions on a modernizing plan.

Lastly, a second phase of experiments and testing has to be discussed in 2007 between the scientific teams potentially involved in the field of canal automation.

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SCADA INTERFACE OF THE SIC SOFTWARE FOR EASY REAL TIME APPLICATION OF ADVANCED REGULATION ALGORITHMS

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Christophe Chateau[2]

ABSTRACT

An increasing number of irrigation canals are following modernization projects to improve their hydraulic efficiency, their quality of service to users and to face new operational constraints. The Gignac Canal has been specifically modernized in order to be used during certain periods of the year as an experimental platform for several partners. A SCADA system has been installed with display screens at the manager's office and a SCADA interface has been developed into the SIC hydrodynamic software allowing testing of any type of control algorithm. This testing can be done first on the SIC hydraulic simulation model, and then switched onto the real canal without any code rewriting or parameters change. This SIC SCADA interface is communicating with the SCADA system developed by DSA Company exchanging data forth and back through simple ASCII files. The features of this approach are described in this paper. This SCADA module is now included into the standard library of the SIC software. This tool has been intensively tested on the Gignac canal that will be used for illustration.

INTRODUCTION

Context

The project of scientific platform on the Gignac canal was initiated by the Transcan Research Team of Cemagref in 2000. Funds have been obtained for the period 2000-2006 from different partners including the State (Federal funds and Cemagref), the Region (Languedoc-Roussillon), the Department (Hérault) and the Water Agency (Rhône Méditerranée Corse). The rational of this project is described in a separate paper (Vion et al., 2007). Some important equipment have been installed on the canal including sensors, hydraulic devices, actuators, and a SCADA system allowing to observe and control remotely the main canals from the manager's office. The innovative aspect of this project was, in addition to modernizing the canal for its traditional irrigation objectives, to make this real irrigation system a scientific platform that can be used by several partners for scientific purposes. The 12 partners of this project are gathered in a "Groupement d'Intérêt Scientifique" (Scientific Interest Group). It includes 3 consultant

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companies, 4 automatic control laboratories, 3 engineering schools and Universities, the Canal Manager and Cemagref.

Terms of References of the SCADA System

- The first objective of the SCADA system was the classical one, i.e. collecting real-time data, storing them into a structured database, displaying then in user friendly standards, managing the defaults and alarms, and allowing remote control of some devices.
- The second objective of the SCADA system, less classical, was to allow testing of any automatic control algorithm, from simple ones such as SISO PID controllers, to very advanced ones such as multivariable LQG, H_{inf}, l_1 controllers.
- Due to the complexity of some of these controllers, the third objective was that this testing could be done with as limited sources of errors and as little efforts as possible.

It was decided that the second objective would be attained if all the controllers already programmed into the SIC regulation module library including those than can be written using the open Fortran, MatLab or Scilab interfaces, could be tested as it.

It was decided that the third objective would be attained if any given controller could be tested first on the SIC hydraulic numerical model (offline), and then on the real canal (online) without any code rewriting or parameter editing.

The experiments protocol imposed within the partners of the project was then to test first the studied controller onto the SIC simulation model using the Gignac data files provided by Cemagref, and then, when validated by the canal manager and Cemagref on the selected scenarios, to run the experiment on the real canal, on line.

The two next chapters describe, first the general features of the SCADA software developed by DSA Company, and second the SIC-SCADA interface principles allowing fulfilling the above terms of references. A last chapter gives an illustration of use of this interface.

SCADA SOFTWARE PRINCIPLES

The SCADA software installed on the Gignac Canal is proprietary software developed by DSA Company. It is nevertheless based on standard software solutions such as SQL database, PCView for the graphical displays and Java components for the management of the data and the communication devices. A web interface is available for users in order to monitor and control the plant using a secure Internet access.

Different users' profiles are defined into the SCADA software allowing different functionalities to different users. The canal manager has the full access to all options including visualizing the canal hydraulic state, the alarms, acknowledging the alarms status, changing RTU parameters, activating some local controllers, sending manual gate movements or operational objectives in terms of discharges or water levels, etc. The research-student login allows visualizing the canal state and to operate one or several gates as authorized by the canal manager.

After the login procedure, a general display screen (Figure 1) allows visualizing general information on the canal at 13 different local field stations: the main canal intake on the Hérault River, the partition between the right bank and the left bank, 4 stations along the right bank main canal and 4 stations along the left bank main canal corresponding to 8 cross devices, the radio communication station and a moveable station that can be used to monitor any location depending on the experiment. This moveable station is based on a small trailer with safety protections and includes data logger, sensors, and a radio communication system. This screen displays information on the alarm status for each station, on the communication status and most of the hydraulic and device position data.

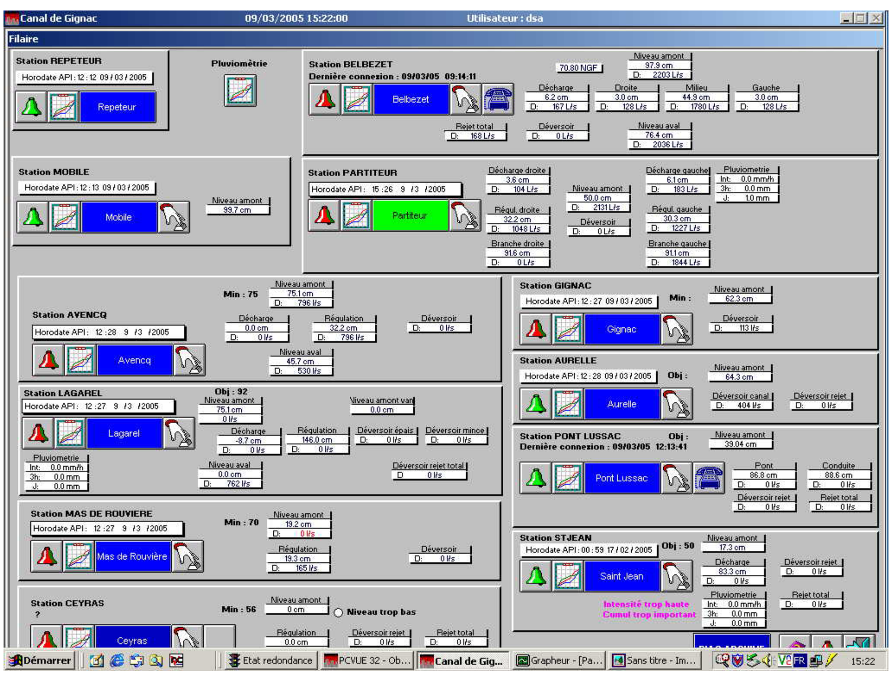

Figure 1. General Display of the Field Stations

More detailed information and a synoptic drawing is displayed if a given station is selected (Figure 2).

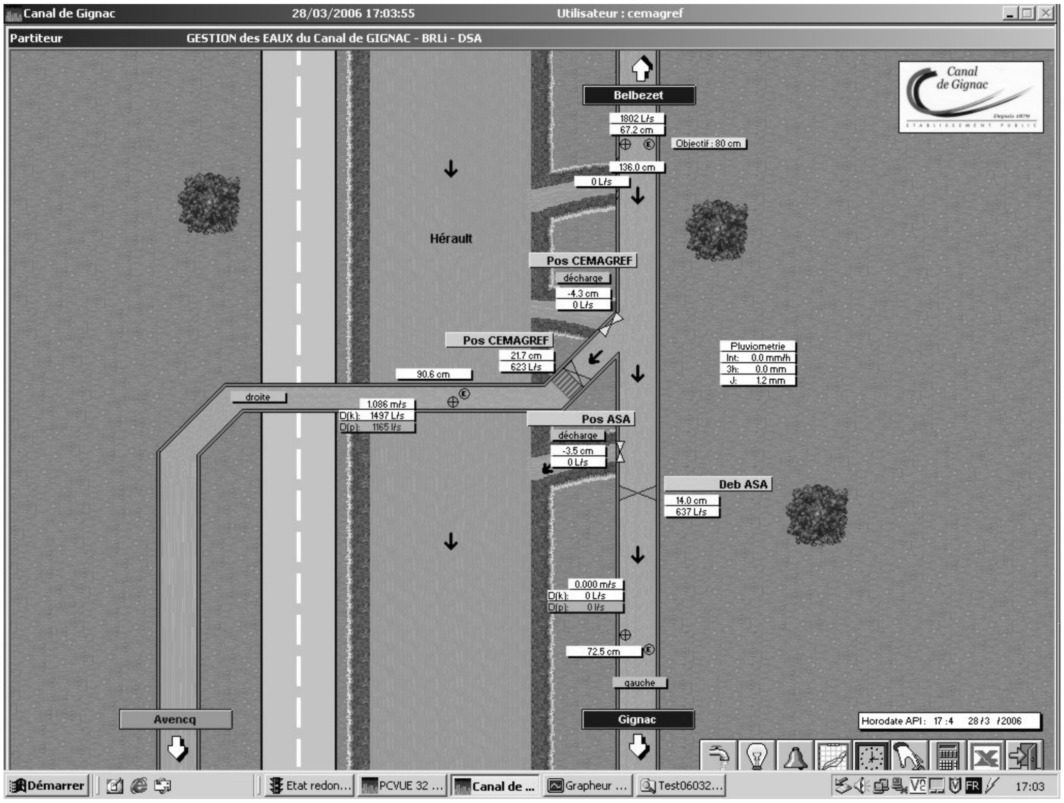

Figure 2. Detailed Display of a Station (Partiteur)

Each hydraulic device (cross regulator or lateral offtake gate) can be switched into 4 different modes:

- "position Cemagref": a user logged under the Cemagref login for field experiments can change the position of the device.
- "discharge Cemagref": a user logged under the Cemagref login for field experiments can change the discharge target at the device and a local slave controller (programmed into the local RTU) will calculate the position of the device to get this discharge.
- "position ASA": only the manager can change the position of this device.
- "discharge ASA": only the manager can change the discharge target at this device and a local slave controller exists as above (with possibly different parameters).

The management of these 4 modes was imposed in the terms of the reference of the SCADA system in order, during the field experiments, to limit the operation at the selected devices and to prevent unwanted operations at other devices.

SIC-SCADA INTERFACE

Except a specific management of several modes for the operations at the cross or lateral structures as described in the previous chapter, the SCADA system in itself is following a standard framework. DSA Company has an extensive experience of similar applications in several industrial domains going from the supervision of a shampoo plant to an integrated flood alert system. The most innovative aspect, as imposed by the terms of references, was to have an opened software structure allowing, as easily as possible, the test of any simple or advanced automatic control algorithm on any hydraulic device. Several options where possible for this software component.

Several possible options

The first option is to program the algorithms to be tested directly into the SCADA software when it allows such option (ex.: in proprietary, in Java or in c programming language). The advantage of this method is that being incorporated into the SCADA software the computational speed is optimized and no interaction is necessary with any third party software. The drawbacks of this method are:

- only PID and predictive controller are sometimes present in the commercial SCADA packages,
- programming of other algorithms needs lots of efforts, in languages offering few specialized libraries,
- if the algorithm has to be tested first on the SIC simulation model the programming has probably to be done twice: in the SCADA software and in the SIC software,
- since different partners can propose algorithms, the management of the SCADA source and executable version (existing on several computers) has to be managed carefully.

The second option is to program a specific software interfaced with the given SCADA interacting through files (ex.: ASCII files) or in memory (ex.: DDE link). Compared to the previous method the advantage of such approach is to have more flexibility in the choice of the programming language and therefore to be able to use specific mathematical or control libraries or links with specialized software such as MatLab or Scilab. It would have been also possible to reuse some existing Fortran code of the SIC Regulation Module Toolbox. The drawbacks of this approach are the same as the 2 latest of the previous option: redundant programming and management of the source files as a new project with several programmers.

Transcan research team of Cemagref used a third option consisting in developing a SCADA interface into its SIC hydrodynamic software. This SIC SCADA interface is communicating with the SCADA software developed by DSA exchanging data forth and back through simple ASCII files. The great advantage of this approach is manifold:

- All control algorithms available into the SIC software library can be used on the real canal (simple PID controllers, auto tuned robust PID, any State

Space controller such as LQG, H_{inf}, l_1, Open Loop controller, user's defined controller through the simple Fortran interface or through the DDE link with MatLab or Scilab).

- It is possible to test first the controllers on the SIC simulation model, and then just by switching on the SCADA option to use exactly the same controllers and parameters on the real canal.
- The SIC unsteady flow program can be automatically synchronized with the real time data allowing checking the calibration of the model, by comparing the simulated data with the real-time measured data.
- This SIC SCADA interface allows using SIC interfaces for example to check the operation of the gates, to compute performance indicators, etc.
- If an advanced controller needs some unmeasured hydraulic data, these data are available into the hydraulic model (for example for an advanced conversion between the gate discharge and opening).

Description of the SIC-SCADA Interface Principles

The "Digesteur" is the name given by DSA to the SCADA module managing the communication between the database located in the 2 frontals (in redundancy) and the Cemagref tools described hereafter allowing testing control algorithms in real-time on the Gignac canal. The SCADA module of the SIC software named "Scada_Sic" hereafter is the name given by Cemagref to the software component managing the communication between the files of the Digesteur detailed hereafter (csg.txt, data.txt and the parameters file) and the unsteady flow calculation module of SIC, including the standard regulation module library.

The Scada_Sic module is in fact a regulation module of SIC with a similar structure of the classical ones. It has been programmed by Cemagref but using the open Fortran interface of SIC it could have been programmed by any SIC user. Before describing the principle of the Scada_Sic module, let us first recall the principle of the SIC regulation modules.

A regulation module as defined in the SIC software is composed of several elements:

- a selection of the measured variables,
- a selection of the controlled variables,
- a selection of the control action variable,
- a control algorithm,
- parameters for the algorithm.

The first 3 type of variables are selected using a user's friendly editor among a large type of variables at all possible locations along the canal. The control algorithm can either be selected among a list of pre-programmed algorithms such as PID, state space feedback controllers, open loop controllers or can be

programmed in Fortran, MatLab or Scilab programming language. The parameters of the controllers depend of course on the selected algorithm. These data are saved into a .reg file.
During an unsteady flow simulation the corresponding module of the SIC software is then collecting the measured and the controlled variables, provides these values to the control algorithm, gets the output of the algorithm and apply the values to the control action variables.

The general principle of the Scada_Sic regulation module is the same. It has 3 parameters:

- Name of the algorithm to be used (among the list of the regulation modules, including the MatLab, Scilab and the Fortran ones).
- Flag indicating that the measured and controlled variables must be taken from the data.txt file (i.e. from the field real-time values) instead of the unsteady flow calculation.
- Flag indicating that the control action variable calculated by the algorithm must be written into the csg.txt file (i.e. to be applied to the field in real-time) or/and applied to the variables in the unsteady flow calculation.

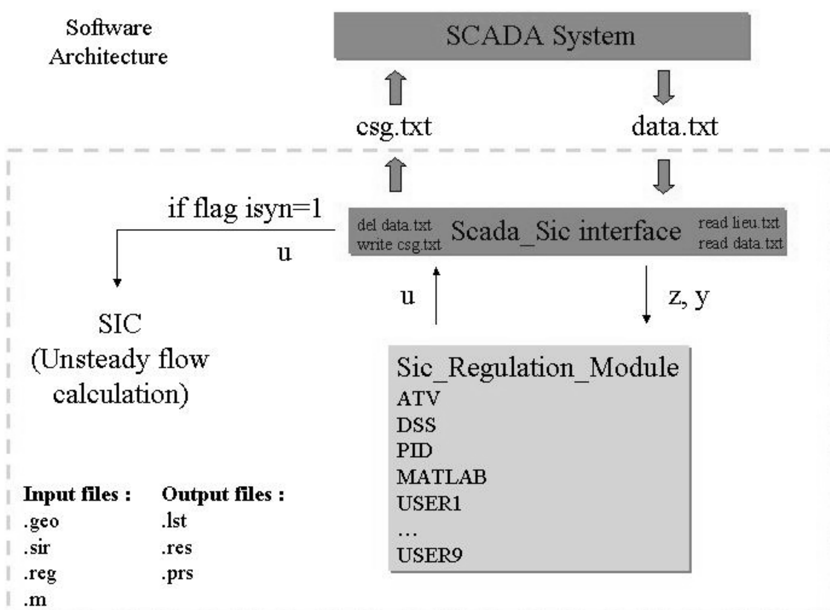

Figure 3. Software Architecture of the SIC SCADA Interface

Variables managed by the Digesteur and the Scada_SIC module

The SQL database of the SCADA system for the Gignac canal contains several hundreds of variables. Each of them is described using several fields. One of them is named "ItemRegulateur". If this field is nil the corresponding variable will not be considered by the Digesteur. If a name is given in this field, this variable will be managed by the Digesteur. When the name starts by "data", then the variable will be written in the data.txt ASCII file at a regular time step. When the name starts by "csg", then the variable will be looked for in the csg.txt ASCII file at a regular time step and, if found, applied on the field in real-time. The names given in the "ItemRegulateur" field can be for example: Data.Avencq.DebitAmont for the discharge upstream of the Avencq station, or Csg.Avencq.PosVanneReg for the gate position at the Avencq cross device.

Data Sub-Directory

A sub directory named Data contains the data.txt files generated periodically by the Digesteur at a given time step indicated in a config.txt file. These data.txt files will be read by the Scada_Sic module and then deleted, to leave room for the next iteration.

A data.txt file contains several sections including a header with the time of the creation of the file, an index that is incremented during the simulation for each new file and then the data with their name, date and time of latest field collection and value. The units and offsets are specified in the database.

Exemple of Part of a Data.txt File

```
[Header]
Horodate=26/10/2004 17:03:02
Index=01
[Data]
DATA.AURELLE.DEFPIEZZO;   20/03/2004 10:31:16;  0.0000000000E000
DATA.AURELLE.DEFSURVERSE; 20/03/2004 10:31:16;  0.0000000000E000
DATA.AURELLE.NIVPIEZZO;   26/03/2004 15:51:07;  7.0000000000E001
DATA.AVENCQ.DEBITAMONT;   26/03/2004 15:51:27;  5.3100000000E002
DATA.AVENCQ.DEBITAVAL;    26/03/2004 15:51:27;  5.3100000000E002
...
[End]
```

ILLUSTRATION OF SOME USES

Several experiments of control algorithms have been carried out on the Gignac Canal by several partners of the project. We present hereafter some results obtained testing an auto-tuned PID algorithm using an improved ATV method. This experiment is further detailed in a journal paper (Litrico et al., 2007). Figure 4 displays the screen interface of the SIC SCADA module during the experiment. We can check the parameters of the module and all input data (measured and controlled variables obtained from the field stations via the data.txt files) and output data (control action variables as calculated by the tested algorithm as written on the csg.txt file before being sent to the field stations).

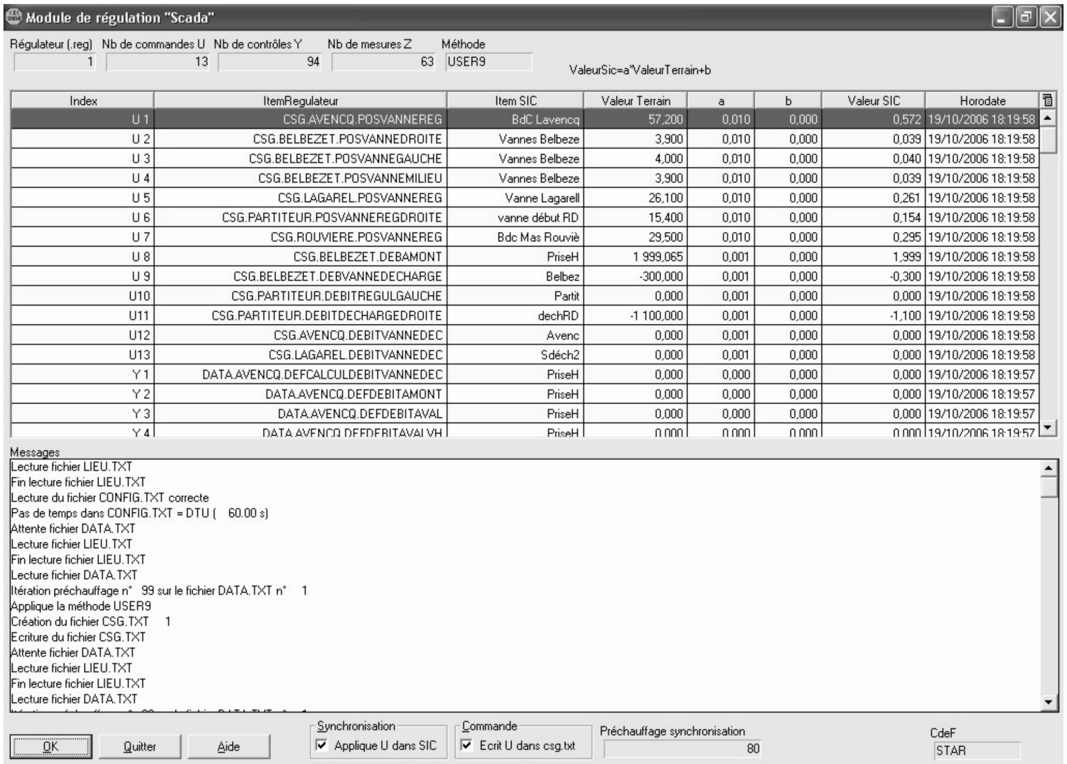

Figure 4. SIC SCADA Display During the Experiment

Figure 5 shows a real-time field experiment using the standard ATVPID regulation module of the SIC software and the SIC SCADA interface. We can see a first phase during which a relay experiment is carried on. Then using the result of this experiment as described in (Litrico and Malaterre, 2007) the PID parameters are automatically calculated and the PID is activated. We can see that the tracking of a new target is followed very quickly. All this is done without any human input during the experiment. It can be used and was tested for any local upstream, local downstream and distant downstream PID controllers.

CONCLUSION

The SCADA software installed for the supervision and control of the Gignac canal followed terms of references including classical features for a SCADA systems plus specific features in order to allow extensive tests of all types of automatic controllers from simple ones to the most advanced we could imagine. This should also be done reducing the time taken by the users to do these tests and to limit the risks of problems occurring including operations at wrong locations or operations damaging the system.

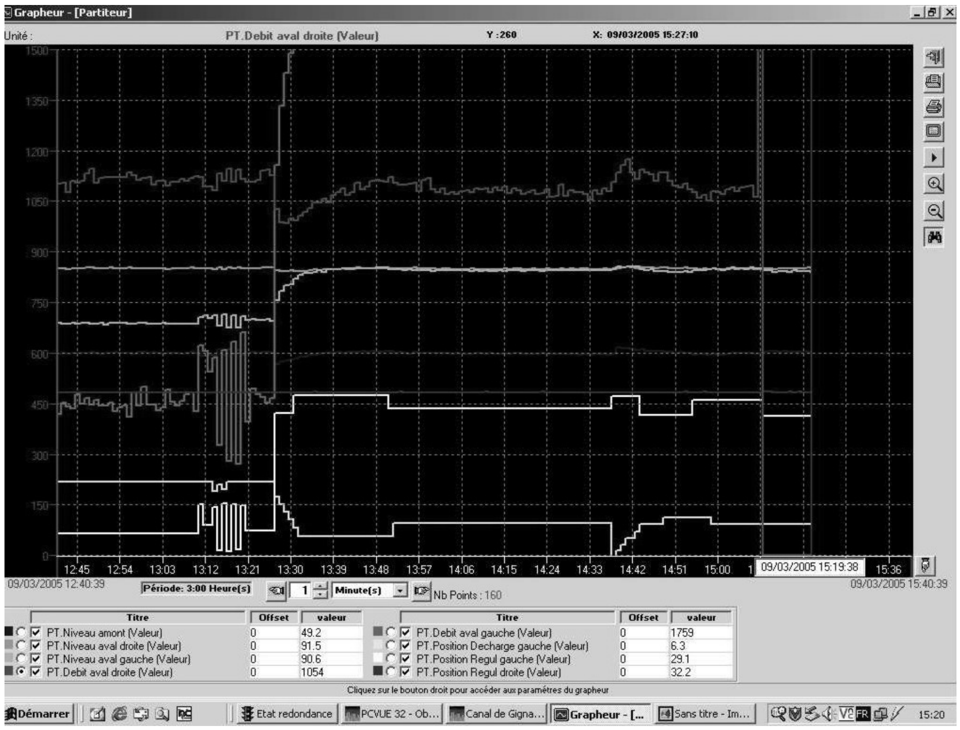

Figure 5. SCADA Display Showing an Autotuned ATV-PID Experiment

The SIC SCADA module has been used routinely for many experiments for 3 years now. It proved to be very powerful and flexible.

The fact that the controller can be tested first in simulation mode using the classical SIC software offline, and then switched in real-time onto the real canal without any code rewriting or parameter re-entering is a very simple, fast and safe procedure. The fact that the SIC SCADA module is a regulation module incorporated into the SIC program is also very powerful since it is possible, if needed, to use the unsteady flow calculation for some advanced control algorithms or to check if the field data are matching the simulated data. Using this feature it is also possible to test auto calibration algorithms for example to calibrate friction coefficients or gate coefficients using real-time measurements without manual data entry on extended period.

The fact that this SIC SCADA module is incorporated into SIC also enables it to benefit directly from all the SIC improvements such as new interfaces, new installation procedures, new regulation modules, etc.

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TEST OF AUTO-TUNED AUTOMATIC DOWNSTREAM CONTROLLERS ON GIGNAC CANAL

Xavier Litrico[1]
Pierre-Olivier Malaterre[2]

ABSTRACT

The paper extends the automatic tuning method proposed by the authors for the case of a single pool to the case of multiple-pool canal. The relay experiment is used to automatically compute the decouplers, and the controller is automatically switched on after the relay test, leading to a set of decentralized distant downstream PI controllers with decouplers. The method is evaluated in simulation and in reality on a large scale irrigation canal pool located in the South of France.

INTRODUCTION

The modernization of irrigation canals requires to easily implement and tune downstream controllers. Even for simple controllers such as PI controllers, the tuning process is usually done by trial and error, which is time consuming, and not a straightforward procedure. It would be desirable to have a straightforward method to tune such simple controllers for an irrigation canal. Litrico et al. (2007) proposed to use the Auto Tune Variation (ATV) method initially developed by Astrom and Hagglung (1984), to tune PID controllers for an irrigation canal pool. This method enables to identify important characteristics of the frequency response of the canal pool by using a simple relay experiment.

The objective of the paper is to extend this automatic tuning method to the case of multiple pools irrigation canals, by automatically computing the decoupler value. The relay experiment is used to automatically compute the decouplers, and the controller is automatically switched on after the relay test, leading to a set of decentralized distant downstream PI controllers with decouplers. The method is evaluated in simulation and in reality on a large scale irrigation canal pool located in the South of France.

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PROBLEM DESCRIPTION

Notations

For pool i we denote u_i the control variable at the upstream end, u_{i+1} the control variable at the downstream end, y_i the controlled variable (water depth at the downstream of pool i).

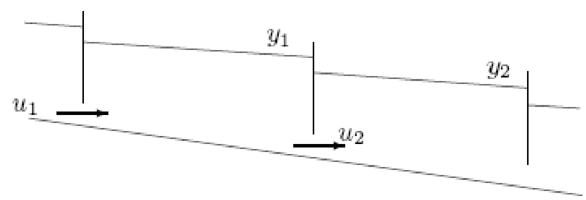

Figure 1. Schematic longitudinal view of an irrigation canal with two pools

The linearized Saint-Venant equations lead to the following frequency domain representation for one canal pool:

$$y_i(s) = G_i(s)u_i(s) + \widetilde{G}_i(s)u_{i+1}(s) \tag{1.}$$

A simple approximation of transfer functions $G_i(s)$ and $\widetilde{G}_i(s)$ is given by the Integrator Delay model, leading to:

$$G_i(s) = \frac{e^{-\tau_i s}}{A_i s} \tag{2.}$$

$$\widetilde{G}_i(s) = -\frac{1}{A_i s} \tag{3.}$$

with τ_i the time-delay for downstream propagation and A_i the equivalent backwater area. The delay τ_i and the integrator gain can be obtained analytically from the hydraulic parameters of the pool (see Schuurmans et al., 1999, Litrico and Fromion, 2004).

Description of ATV Tuning Method

The relay feedback auto-tuning proposed by Astrom and Hagglung (1984) was one of the first to be commercialized for tuning of PID controller in industry. It has since remained attractive owing to its simplicity and robustness. In this method, the process to control is connected in a feedback loop with a relay, as shown in Figure 2.

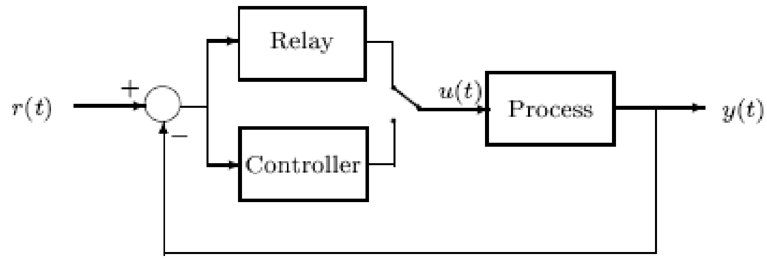

Figure 2. Relay feedback system

The objective of the method is to determine from a single experiment the critical point, i.e. the process frequency response at the phase lag of *-180°*. It can be shown that under relay control as in Fig. 2, the process will oscillate with the period T_u and that the critical gain k_u is approximately given by:

$$k_u = \frac{4d}{\pi a} \tag{4.}$$

where *d* is the relay amplitude and *a* is the amplitude of the process output (Astrom and Hagglung, 1984).

Typical responses are as in Fig. 3. The relay is a simple nonlinear element that changes the input to *-d* when the output error becomes negative, and to *d* when the error becomes positive. It is therefore very easy to implement on a real canal, since the gate opening has to be opened or closed according to a measured water level.

The relay amplitude *d* is positive when dealing with downstream control and it is negative when dealing with upstream control.

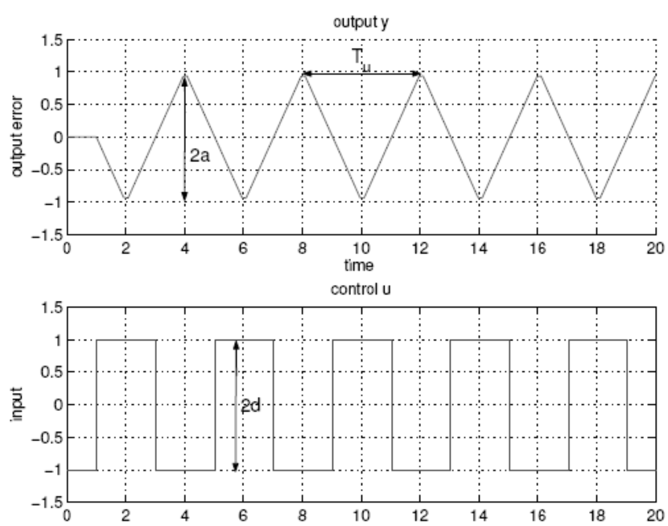

Figure 3. Simulation of a relay experiment on a dimensionless Integrator Delay system.

In the following, since we deal with multiple pools, we will denote by a superscript $^{(i)}$ the parameters corresponding to pool i of the considered canal.

AUTOMATIC TUNING OF DOWNSTREAM CONTROLLERS

Case of a Single Pool

The canal pool approximated by an Integrator Delay model is then represented by:

$$y_i(s) = \frac{e^{-\tau_i s}}{A_i s} u_i(s) \tag{5.}$$

In this case, one may show that the relay experiment leads to the following values (see Litrico et al., 2007 for details):

$$k_u^{(i)} = \frac{4A_i}{\pi\tau_i} \tag{6.}$$

$$T_u^{(i)} = 4\tau_i \tag{7.}$$

Therefore the relay experiment enables to identify the ID model parameters A_i and τ_i.

Case of Multiple Pools

In the case of multiple pools controlled with distant downstream PI controllers, one may use a relay experiment to tune successively each pool. This will lead to decentralized PI controllers for the canal pool. However, it is well-known that pool interactions decrease the overall performance of decentralized controllers for an irrigation canal (Schuurmans, 1997). This is why it is interesting to find a way to compute the value of decouplers from a relay experiment. The decoupler is a constant coefficient $D^{(i)}$ that is used to compute the modification in the upstream control variable u_i of pool i to compensate for the effect of the downstream control variable u_{i+1} over the controlled variable (the downstream level y_i). The coefficient can be determined from two relay experiments:

- one relay experiment for local upstream control between u_{i+1} and y_i, leading to ultimate parameters denoted by $\tilde{k}_u^{(i)}$ and $\tilde{T}_u^{(i)}$, and
- one relay experiment for distant downstream control between u_i and y_i, leading to ultimate cycle parameters denoted by $k_u^{(i)}$ and $T_u^{(i)}$.

Then the decoupler for pool i is given by (see Appendix for details):

$$D^{(i)} = -\frac{k_u^{(i)} T_u^{(i)}}{\tilde{k}_u^{(i)} \tilde{T}_u^{(i)}} \tag{8.}$$

Furthermore, if the controllers are tuned from the downstream end of the canal towards the upstream end of the canal, it is not necessary to perform the relay experiment specifically for local upstream control. Indeed, if one denotes $\tilde{a}_i$ the amplitude of level y_i during the distant downstream experiment for pool $i+1$, then the ultimate parameters for local upstream control of pool i are given by:

$$\tilde{k}_u^{(i)} = \frac{4d_{i+1}T_u^{(i+1)}}{\pi\tilde{a}_i T_s} \qquad (9.)$$

and

$$\tilde{T}_u^{(i)} = 2T_s \qquad (10.)$$

with T_s the sampling time period.

APPLICATIONS OF ATV METHOD

Description of Gignac Canal

The experiments are performed on the Gignac canal, located 40 km north-west of Montpellier, south of France. The main canal is 50 km long, with a common feeder (8 km long) and two branches on the left and right banks of the river (resp. 27 and 15 km long). The canal is concrete lined, with a rectangular cross section on the feeder and a trapezoidal one on the branches, with average slopes of respectively, 0.35 and 0.50 m/km. The design flow of the canal is 3.5 m^3/s.
The canal has been equipped with sensors, actuators and a SCADA system interfaced with the SIC-SCADA real-time module of the SIC software, which enables the monitoring and control of the cross-regulators of the right bank main canal.

Experimental Results

The proposed method is applied on three pools of Gignac canal, between corss-regulators Partiteur, Avencq, Lagarel and Mas Rouvière. The location of these cross-regulators is depicted in Figure 4.

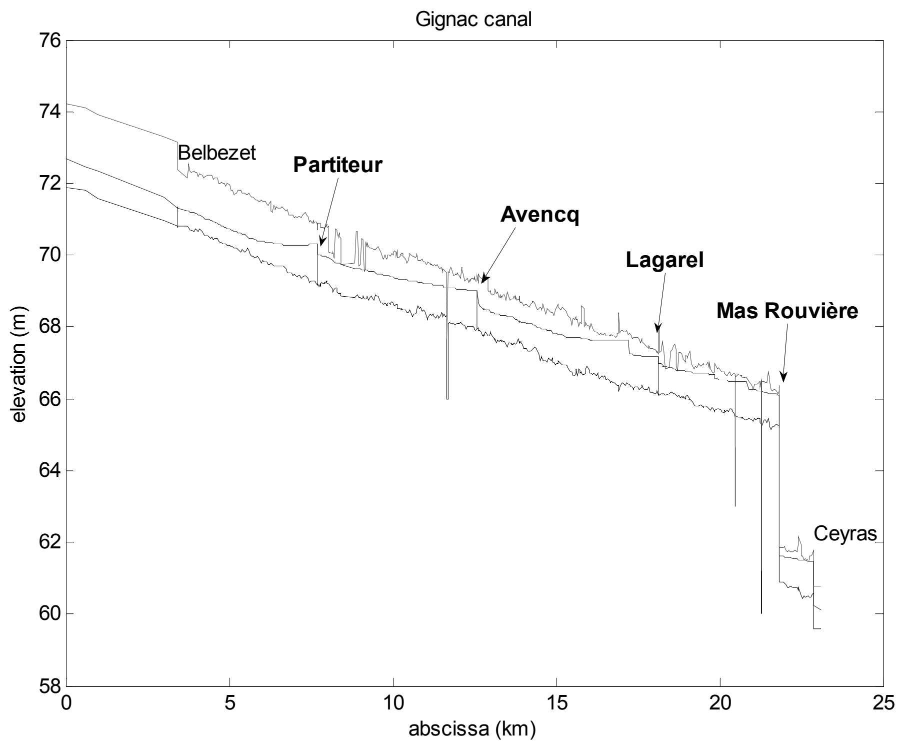

Figure 4. Longitudinal profile of Gignac Canal

The corresponding variables are denoted as follows:

- u_1 is the gate opening at Partiteur, y_1 is the water level upstream Avencq
- u_2 is the gate opening at Avencq, y_2 is the water level upstream Lagarel
- u_3 is the gate opening at Lagarel, y_3 is the water level upstream Mas Rouvière

The sampling period is chosen equal to 5 min. The controllers are tuned sequentially from downstream to upstream. After the relay experiment, the PI controllers coefficients are computed using the method proposed by Litrico and Fromion (2006), so as to ensure a gain margin of 10 dB and a phase margin of 45 degrees. The decouplers are computed using Eq. (8) of this paper, and are used to compute the gate openings at regulators Avencq and Partiteur.

The corresponding setpoints are :

- $y_c=84$ cm for the water level upstream of Mas Rouvière
- $y_c=95$ cm for the water level upstream of Lagarel
- $y_c=79$ cm for the water level upstream of Avencq

The chosen gate deviations for the relay experiment are:

- $d=5$ cm for the gate opening at Lagarel

- *d=10* cm for the gate opening at Avencq
- *d=6* cm for the gate opening at Partiteur

Once a controller is switched on, it is tested during a few hours to check its stability and performance. After this time period, the next relay experiment is done to tune the next controller and the corresponding decoupler.

The results are displayed in Figure 5 . It appears clearly that during a relay experiment, the controlled water level downstream of the pool oscillates due the relay, but so does the water level located just upstream of the gate! Therefore, one can measure the amplitude of these oscillations in order to determine the decoupler value. This is what is proposed in this paper.

As shown by the experimental results, the controllers perform correctly during the whole experiment, and lead to a good performance.

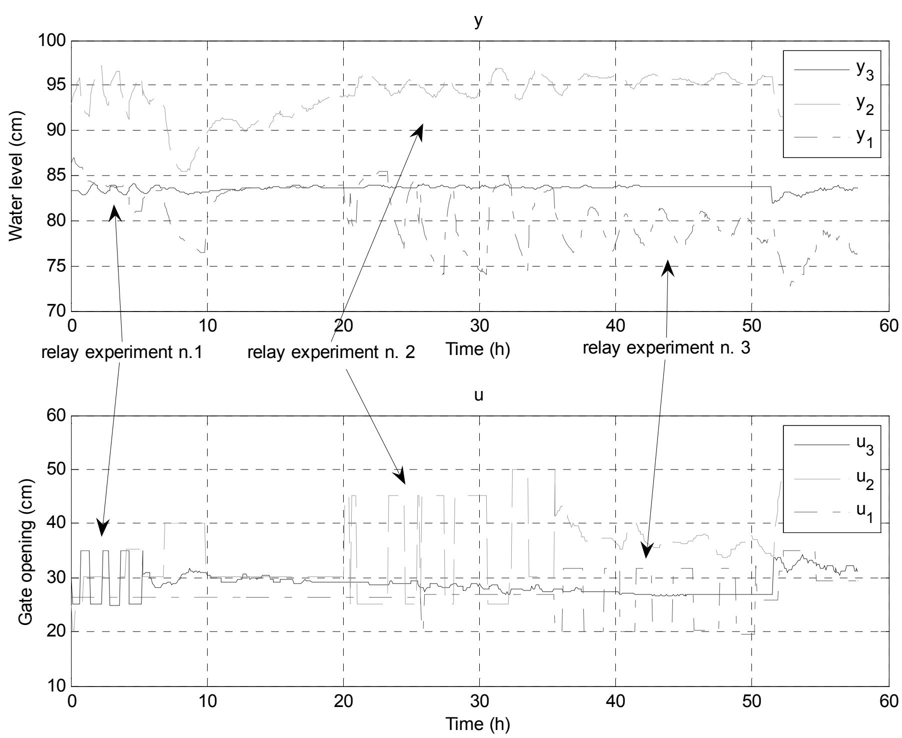

Figure 5. Relay experiments

CONCLUSION

We extended in this paper the ATV method proposed for one canal pool to automatically tune PID controllers for a multiple pools canal. The proposed method allows to automatically compute the decouplers for distant downstream control of a multiple pools canal.

The proposed method has been evaluated on three successive pools of the Gignac canal. The experimental results show the effectiveness of the approach.

ACKNOWLEDGEMENTS

The authors acknowledge the financial help of Région Languedoc-Roussillon, Conseil Général de l'Hérault, Agence de l'Eau Rhône-Méditerranée-Corse and Cemagref through the "Plateforme expérimentale du canal de Gignac".
We thank Vincent Kulesza, head of the ASA de Gignac, for his collaboration concerning the experiments.

APPENDIX

Ultimate Cycle Parameters Obtained via a Relay Experiment for an Integrator Delay Model

We compute in this section the ultimate cycle parameters obtained via a relay experiment for an ID model given by equation (1). Let us examine the system behaviour in steady state with persistent limit cycle. We suppose without loss of generality that the error becomes negative at $t=0$. Due to the integrator and since this output error comes from an input negative step of amplitude d_i, the error is decreasing as a negative ramp of slope $-d_i/A_i$. Then, at $t=0$ the relay leads to a input positive step of amplitude d. At $t=\tau_i$, this positive step influences the output, which has reached the value $-d_i\ \tau_i/A_i$. Then the output increases as a positive ramp of slope d_i/A_i, during a time equal to $2\tau_i$. This is depicted in Figure 6.

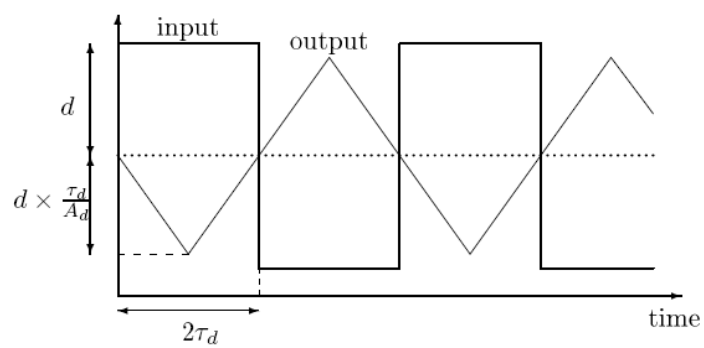

Figure 6: Relay experiment for an ID model

Therefore, the amplitude of the output is equal to:

$$a_i = d_i \frac{\tau_i}{A_i} \tag{11.}$$

and using equation (6), the ultimate parameters are given by:

$$k_u^{(i)} = \frac{4a_i}{\pi\tau_i} \tag{12.}$$

and

$$T_u^{(i)} = 4\tau_i\,. \tag{13.}$$

Computation of the Distant Downstream Decoupler Coefficient from the Ultimate Cycle Parameters

If the control action variable is a discharge, then the decoupler should be equal to 1. However, in many cases one may not use the discharge as a control action variable, but the gate opening. In this case, if the upstream water level is controlled, the outgoing discharge is roughly proportional to the gate opening. Let us denote k_i this proportional coefficient for gate i (upstream gate of pool i). Then, the decoupler for distant downstream control of pool i should be equal to

$$D^{(i)} = \frac{k_{i+1}}{k_i} \tag{14.}$$

In this case, each pool controlled with the gate opening is represented by an ID model where the integrator inverse coefficient A_i is equal to

$$A_i = \frac{A_{di}}{k_i} \tag{15.}$$

where A_{di} is the backwater area. For local upstream control, the integrator coefficient $\widetilde{A}_i$ is equal to

$$\widetilde{A}_i = \frac{A_{di}}{k_{i+1}} \tag{16.}$$

Using results from Appendix I, each relay experiment enables to identify parameters of the ID model. For distant downstream control, one gets from Eqs. (12-13):

$$A_i = \frac{\pi}{16} k_u^{(i)} T_u^{(i)} \tag{17.}$$

Using Eq. (15), this leads to:

$$k_i = \frac{16 A_{di}}{\pi} \frac{1}{k_u^{(i)} T_u^{(i)}} \tag{18.}$$

For local upstream control, one gets:

$$\widetilde{A}_i = -\frac{\pi}{16} \widetilde{k}_u^{(i)} \widetilde{T}_u^{(i)} \tag{19.}$$

(note that $\widetilde{k}_u^{(i)} < 0$), and

$$k_{i+1} = -\frac{16 A_{di}}{\pi} \frac{1}{\widetilde{k}_u^{(i)} \widetilde{T}_u^{(i)}} \tag{20.}$$

Then, collecting Eqs. (14), (18) and (20) leads to :

$$D^{(i)} = \frac{k_{i+1}}{k_i} = -\frac{k_u^{(i)} T_u^{(i)}}{\widetilde{k}_u^{(i)} \widetilde{T}_u^{(i)}} \tag{21.}$$

Let us assume that the model of pool i is described by the following equation:

$$\widetilde{G}_i(s) = -\frac{e^{-\frac{T_s}{2}s}}{A_i s} \tag{22.}$$

i.e. an integrator delay model with a delay equal to half the sampling period. This is true if the measurement point is close enough to the gate.
Then, according to equation (6), we have:

$$\widetilde{k}_u^{(i)} = \frac{8\widetilde{A}_i}{\pi T_s} \widetilde{T}_u^{(i)} \tag{23.}$$

Parameter $\widetilde{A}_i$ can be estimated either by using a relay test for local upstream control, or by using the measurements done during the distant downstream relay test between u_{i+1} and y_{i+1}. Indeed, assuming the ID model (5), the amplitude $\widetilde{a}_i$ of y_i due to step variations of the control action variable u_{i+1} with period $T_u^{(i+1)}$ and amplitude $2d_{i+1}$ is given by:

$$\widetilde{a}_i = \frac{d_{i+1} T_u^{(i+1)}}{2\widetilde{A}_i} \tag{24.}$$

Therefore, using Eq. (23) the ultimate parameters for upstream control of pool i are given by:

$$\widetilde{k}_u^{(i)} = \frac{4 d_{i+1} T_u^{(i+1)}}{\pi \widetilde{a}_i T_s} \tag{25.}$$

and

$$\widetilde{T}_u^{(i)} = 2T_s\,. \tag{26.}$$

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REAL-TIME FLOW MEASUREMENT IN CACHE VALLEY IRRIGATION CANALS

Evan Thompson[1]
Gary Merkley[2]

ABSTRACT

Increased stress on water resources in Cache Valley, Utah has caused a need for improved water management on the irrigation canals throughout the valley. Through a joint project with the Utah Division of Water Rights (UDWR), the Utah Water Research Laboratory (UWRL), various canal companies, and Utah State University (USU), a data acquisition and telemetry system was expanded to include several irrigation canals which take water from the Logan River. With the cooperation of the Logan River Commissioner and several canal companies, new stations were set up to monitor the flow rate on seven irrigation supply canals. Through the use of digital shaft encoders and a radio telemetry system, real-time flow data are now publicly available on the UDWR website. The installation of this system is expected to help improve water regulation throughout the valley. The readily available flow monitoring data has made water managers' jobs easier, as well as providing water users with a more efficient way of monitoring water levels in order to conserve water throughout the irrigation season.

INTRODUCTION

Background

Historically, due to water abundance, there has been no need to actively regulate water withdrawals from the Lower Bear River. However, recent years of drought have caused increased stress on the water resources of the lower Bear River in Cache Valley, Utah. As water grew scarce in a recent summer, some water users continued to pump more than their given allocation from the Bear River. It takes about five days for the river commissioner to physically visit each of the pump stations along the river, allowing water users to run their pumps for several days before being noticed, or simply stop pumping when they knew the river commissioner would be passing by.

In order to solve this problem, the UDWR implemented a data acquisition and telemetry system to provide better and more frequent information for the monitoring and documentation of withdrawals from the river. Since the spring of

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2005, some 120 stations have been set up at pump sites and open-channel measurement flumes along the lower Bear River in northern Utah. Each station transmits water depth or flow data to the UDWR base station in Logan via radio signal. The data are then sent to the UDWR server in Salt Lake City, are processed using calibration and other algorithms, and are made available to the public on the UDWR website.

In the spring of 2006, the Logan River Commissioner contacted the Biological and Irrigation Engineering Department at USU to request help with irrigation water management on the canals which take water from the Logan River, a tributary of the Bear River. The UWRL, through USU, provided funding for the design and implementation of a data acquisition system at sites in seven of the canals. The list of sites was provided by the Logan River Commissioner, Ms. Colleen Gnehm, after a review of the condition of extant mechanical water level recorders. Some of the required SCADA equipment was purchased by the UWRL, and the rest was supplied by the UDWR, but both collaborated on the installation at the various canal sites. Canal company personnel also assisted in the installations, providing some tools and labor to complete the process.

METHODS AND DESIGN

Project Overview

The design consisted of a data acquisition and telemetry system, along with a power supply, at seven existing Parshall flumes and broad-crested weirs, all of which operate exclusively under free-flow conditions. Thus, a single water level measurement was sufficient to determine the flow rate at each measurement structure. In locations where the radio signal was unavailable or too weak due to obstructions from trees or buildings, a data logger was used in place of the telemetry system to record, rather than transmit, flow measurement data. This was the case at two of the seven sites. A summary of the project components and their respective uses is given in Table 1.

A small shelter houses the data acquisition system at each site, protecting it from the weather and vandalism. The shelter rests over a stilling well, and the depth of water in the well corresponds to the depth of the water in the canal on the upstream side of a measurement flume or broad-crested weir. The stilling wells were connected to the measurement structures through a standard tap, according to their design. The digital shaft encoder was installed in the shelter on a wooden board over the stilling well. The new encoders and float assemblies replaced the existing and dilapidated Steven’s recorders, which were removed. The encoder was connected to a pulley with a float and counterweight which was placed inside the stilling well.

Table 1. Summary of Project Equipment.

Equipment	Use
Telemetry System	
Repeater Antenna	Relay radio signal to base station at UDWR
Transmitter and Antenna	Send flow measurements to repeater antenna
Signal Converter	Convert SDI-12 from encoder to RS-232 for radio transmission
Data Acquisition	
Digital Shaft Encoder	Measure depth of flow in canal and transmits via SDI-12 signal
Data Logger*	Record depth from encoder and convert to flow rate
Power Supply	
Solar Panel	Collect sunlight and convert to power
Solar Controller	Prevent solar panel from overcharging the battery
Battery	Provide power to the system

*only used on sites where radio reception was unavailable

In order to transmit flow data from various locations around Cache Valley to the UDWR base station, a network of repeater towers was necessary, providing line-of-sight coverage. One such repeater tower was placed on the roof of the Engineering Building at USU (Figure 1). To establish signal connection with the repeater antenna, a radio antenna and transmitter were mounted on a steel pole that was cemented into the ground next to each shelter (Figure 2). Water level data are then transferred from the UDWR base station in Logan to the server in Salt Lake City for display on their web page (http://waterrights.utah.gov/cgi-bin/dvrtview.exe?Modinfo=Collection_Sysview&COLLECTION_SYSTEM=LBEAR).

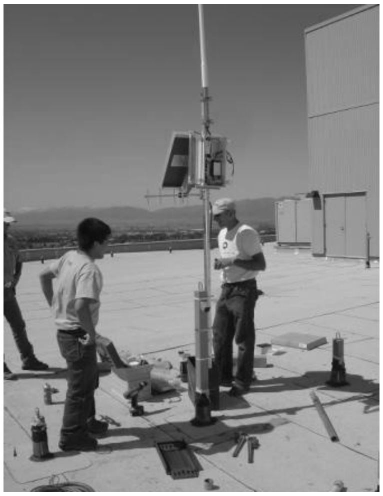

Figure 1. Installation of the Repeater Antenna on the USU Engineering

Figure 2. Installing a radio antenna and solar panel next to a shelter at a Parshall flume.

Component Details

The radio signal used in this project is a license-free, low power, 100-mW frequency. The antennas are 900 MHz, spread-spectrum, 9dBi Yagi antennas, manufactured by HyperLink Technologies. They were coupled with an XStream-PKG-R RS-232/485 RF modem manufactured by MaxStream. The modem, or transmitter, has a range of up to 20 miles with a high-gain antenna. The transmitter uses an RS-232 serial port to receive data from the encoder, thus it was used in conjunction with a RS-232 to SDI-12 host interface manufactured by Water Log Series to allow communication with the encoder (Clayton and Hunt 2007). The digital shaft encoders used were Enviro-Systems SDI-12, model SE105S. A Water Log Series model H-500XL data collection platform was used where adequate radio signal strength was unavailable. The data logger has an SDI-12 input and three RS-232 serial ports for interaction with a PC that allows data to be downloaded directly to a portable computer. This eliminated the need for installation of a SDI-12 to RS-232 signal converter. In addition, the logger has a built-in key pad and display for programming in the field. It also has a PC card slot that can be combined with a compact flash card for data download, eliminating the need to take a laptop computer to the field. The logger also has extra ports for additional data logging capabilities, which allows expansion for future water management developments.

Each station was powered by a 16 x 19 in., 20-watt solar panel connected to a 4.5-amp solar controller which prevents the batteries from being overcharged. Sealed, lead-acid 12-volt, 24 amp-hour batteries were used at each site.

Installation

Installation procedures of the encoders and telemetry system varied at each location, as the conditions at each flume or weir were quite different. In many cases, overgrown vegetation had to be trimmed back in order to gain access to the stilling-well enclosure. In some cases, the board covering the stilling well had to be replaced, as shown in Figure 3. In other cases, existing base boards and cable holes from the old Steven's Recorders were used (Figure 4).

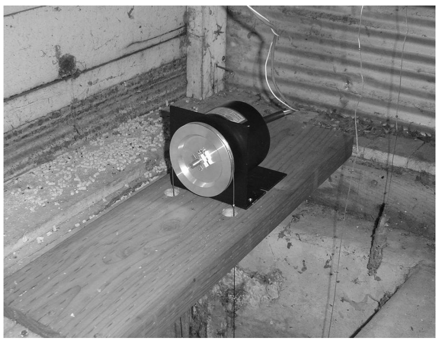

Figure 3. New Digital Shaft Encoder

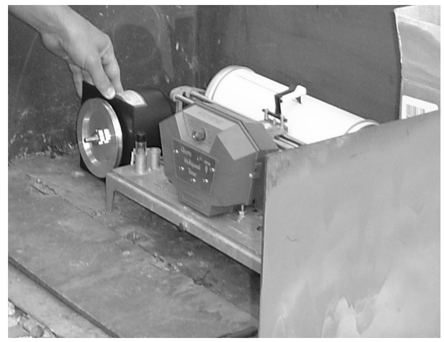

Figure 4. A New Encoder Next to an Old Steven's Recorder

The radio antenna and transmitter, along with the solar panel and controller were mounted on a steel pole that was cemented into the ground next to the shelter. In one case, the antenna and power supply was installed on the roof of a neighboring business building to provide adequate radio reception to the site.

Data loggers were programmed to record date, time, battery voltage, water depth, and flow rate. To determine the flow rate, the free-flow equation was programmed into the data logger using coefficients and exponents that were obtained from calibration measurements of the specific flume or weir of the site. Records and observations show that the flumes at these two locations have a downstream drop in canal bed elevation and never operate under submerged-flow conditions.

The five new stations with radio reception that were set up on the Logan River canals were assigned a unique address for identification in the existing system. Each station in the system is assigned a specific address, or numeric code, for identification by the UDWR server. To gather data, the system sends out each address sequentially. Each station responds by sending back its address, voltage, and flow rate. If the address is correct and the values look reasonable, then the data is recorded. If the station does not respond, the system goes through a certain number of "retries" in order to gather data before passing on to the next station on the system. This number is defined by the administrator and is partially based on the signal strength at each station (stations with weak signal strength tend to require more retries).

Once the system has called (or attempted to call) every station, it automatically starts over. If the system runs through a complete cycle of all stations in under five minutes, a sleep mode is invoked until the five-minute period is reached, at which point the call cycle begins again. However, the cycle has never been completed in less than five minutes in this system, especially with the recent addition of several new stations.

The two stations without radio reception are manually integrated into the system as the River Commissioner gathers the data during the normal weekly route of checking pumps, flumes, and measurement weirs. The data can either be downloaded by the use of a data card that inserts directly into the data logger or by hooking the data logger up to a PC for direct download. A manual was written for the River Commissioner on how to utilize the data loggers.

RESULTS AND DISCUSSION

As this project was only recently completed, direct impacts of the system on water management have not yet been determined. However, as other projects of similar nature have shown, the beneficial effects will be felt by both water managers and users alike. Administrators of the lower Bear River project have stated that the publicly available data has solved a number of water disputes between farmers. Similar results were seen in the Sevier River Basin, where a large-scale SCADA system has improved water conservation and provided easier decision making for water managers (Berger et al. 2006). Dr. Mac McKee, director of the UWRL, commented on how the system has improved management during years of drought and reduced water disputes (McKee and Khalil 2006). It is expected that the addition of data from the Logan River to the system already in place on the lower Bear River will have similar effects.

This project has shown how major organizations can successfully cooperate to improve water management and conservation. The UDWR provided the technology and design of the telemetry system, and the UWRL provided funds to complete the project. The expertise and effort of USU faculty and students were a valuable resource for both labor and problem solving. Last, but not least, local canal companies provided labor and tools to assist with the equipment installation. As a result, all organizations involved have gained valuable experience in cooperating to improve circumstances for both water managers and water users.

SUMMARY

Through the combined effort of the UDWR, UWRL, USU, and various canal companies, the lower Bear River SCADA system was expanded to include the canals of the Logan River, a major tributary of the Bear River. Digital shaft encoders, radio transmitters, and data loggers were installed to bring accurate and timely data to water managers and water users through the UDWR webpage. The implementation of this project is expected to improve water regulation throughout Cache Valley, which will help make a positive impact on the local water supply and water conservation in general. The cooperation of state and local organizations serves as an excellent example of how to use all available resources collaboratively in order to enhance water management.

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SCADA APPLICATION ON A DIVERSION DAM

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Eliseo Villagrana[3] Valentín Bernabe[3]
Ernesto Romero[3] Javier Ramirez[1]

ABSTRACT

This paper describes a flow control regulator application in a diversion dam at the Irrigation District 097, "Lázaro Cardenas", Michoacan, Mexico. A Hydropower Company has started to produce electricity during high demand peak hours releasing the daily volume for irrigation in few hours. Downstream of the storage dam, a Diversion dam stores the water released for power and delivers the water as the irrigation district requires under controlled conditions. Because of these changes in operations at the diversion dam a SCADA systems was installed. The measurement and operation equipment integrated for this application consisted in a SCADAPack, the Probe ultrasonic level sensor, gate position sensor and Horizontal Doppler Current Profiler Channel Master as flow meter. The SCADAPacks at the flow meter and diversion dam were connected by low cost radios called Maxstream. To improve the reliability of the systems redundant equipment was installed on gate position, upstream level sensor. For flow measurement reliability the gate equation, calibrated with the H-ADCP data, was used. As a first step a set of rules were introduced to adjust the gate opening to keep the flow at the head of the main canal constant as the level on the diversion dam change. Since the end of 2006 the system is being transferred from a manual system to an automated system.

INTRODUCTION

The Mexican water law promotes the "Integral use of Water". A water source can be used for different water users while its profit does not affect the rights of the other users. Since Federal Company of Electricity, "Comisión Federal del Electricidad" (CFE) is not interested to produce electricity at small storage dams, small Hydropower companies have started to install hydropower facilities because they have smaller operation costs. The main constraint for the Hydropower companies is that they can only use the volume used for irrigation each day.

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With different water requirement in time and flow the Hydropower Company (HC) and the irrigation district required to modify the operation of the hydraulic infrastructure on their operation boundaries to make compatible their water requirement. The HC request large flow rates during the peak hours of electricity every night, taking all the volume for irrigation in some hours while irrigation district needs a constant flow rate all day. In the case of the “Chilatan” storage dam at the Irrigation District 097 “Lazaro Cardenas” in the state of Michoacan the only hydraulic infrastructure to make possible the profit of water for both water users is the “Piedras Blancas” diversion dam. The diversion dam stores the water used to release for power at storage dam and release it as the irrigation district request under controlled conditions. In front of these new operation conditions some modifications were made, the storage capacity of the diversion dam was increased and the gates and its actuators at the head control structure of the Left Bank Main Canal (LBMC) were rehabilitated. For the control system for the diversion dam operation the HC contacted Dr. C. Burt. Dr. Burt suggested that the Mexican Institute of Water Technology (IMTA) could make the project. Finally the “Comisión Nacional del Agua” (CONAGUA), Federal Agency in charge of water reclamations in México, responsible of diversion dam management, requested to IMTA a turn key solution for the control of the diversion dam (Fig. 1).

This paper describes the solution proposed for the operation of the Diversion Dam, the equipment used for it implementation, the typical manual operation made at the Diversion Dam and some simulation obtained with the control algorithms and the future works to finish the control project.

Figure 1. Piedras Blancas Diversion Dam

CONTROL PROBLEM DESCRIPTION

CONAGUA and HC reviewed the operation of the diversion dam considering the water users requirements. The storage capacity of diversion dam was increased, the spillway was raised 1.5 m. The seal of the emergency gates of the Diversion Dam were rehabilitated and motor actuators were installed. At the control structure of the LBMC on the Diversion Dam the seal of the gates were changed and motor actuators were installed.

For the gates at the head of the LBMC a flow control systems was requested to keep the flow constant for the irrigation requirements when the level on the diversion dam change. The control structure at the diversion dam has three radial gates three meter tall and four wide. In all the gates measurement and control equipment were installed for flow control. The original control project considered that the flow at the head of the canal could be measured with a Replogle flume. The hydraulic conditions presented in the canal and the diversion dam made impossible to install a flume without and important reduction of the storage capacity at the diversion dam. To avoid this problem and Horizontal Acoustic Doppler Current Profiler (Channel Master RD Instruments, H-ADCP) was installed. With the change on flow measurement device, the flow measurement problem became more complicated. The canal dynamics, volume changes and wave propagation were added to the flow measurement problem.

For reliability of the flow control system to design, the redundancy of all the sensors, level, gate opening and flow was considered

IMPLEMENTATION EQUIPMENT

For the operation of the Diversion Dam a SCADAPack RTU was used. For level sensors the ultrasonic sensor “The Probe” from Milltronics Siemens were installed upstream and downstream. The gate position was measured with a potentiometer connected to the gear box of the gate actuators. Transpack T752 transducers were used to transform the resistance of the potentiometer on a 4-20 current loop. For the operation of the three gates an electric circuit of electromagnetic relay was made. This circuit advice the RTU when the gate in on manual operation or RTU operation and activate the gate actuator function of the digital outputs signals of the RTU. The circuit panel used for manual operation was not modified. On RTU the procedures for gate operation was programmed on Leader Logic and the procedures for sensor calibration, level and gate opening, on “C” lenguage.

To measure the flow a Channel Master was installed. The Channel Master was calibrated considering four different flow conditions that cover the flow operation range in the LBMC. During the calibration procedure the flow was measured using the mobile ADCP Steam Pro. From the calibration procedure, velocity index equation obtained had only one coefficient. The H-ADCP was configured to send every five minutes the average data collected of flow, volume, velocity, Pitch, Roll, Temperature, to a SCADAPack RTU. The SCADAPack using a “C” program reads the ASCII code sent by the H-ADCP.

Low cost radios from Maxstream allowed the data exchange between the RTUs on the H-ADCP and the Diversion Dam.

Redundant sensors were considered on all the collected data, for upstream level and gate position two sensors were installed at the diversion dam and on each gate. For flow measurement the H-ADCP data will be compared with the gate equation, actually under development. For downstream level sensor the level was measured by an ultrasonic level sensor and the ultrasonic level sensor of the H-ADCP.

For security on the operation, difference of two centimeters was allowed on the gate opening and upstream level sensor. If the difference was grater than the tolerance the leader logic program stop the operation of the gate and turn on an alarm. The alarm is reseted when the difference was eliminated and the reset alarm switch is activated.

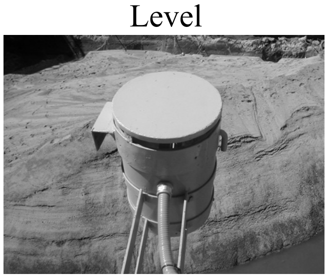
For this simple application of a control structure, the master station was integrated using a PC and Lookout as Man Machine Interface. The RTU of the diversion dam and the master station were in the same office and were connected by wire.

H-ADCP

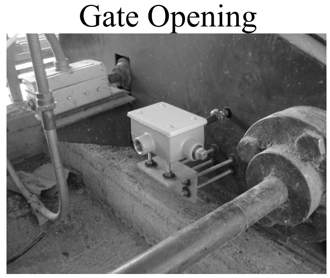
Diversion Dam

Figure 2. RTU at the H-ADCP and Diversion Dam

Level



Gate Opening



Channel Master H-ADCP

Figure 3. Level and Gate Position Sensors

In the integration of the systems the protocol used was MODBUS. The RTU installed has the possibility to change to DNP3 when more measurement and operation points will be added to the SCADA system.

MANUAL OPERATION

Until now the operation of the Diversion Dam were made manually. The level on the diversion dam rises as the water coming from the Storage Dam arrives and decreases as the flow from the storage dam stop. As it can be seen on Fig. 4 the gate adjustments were made mainly between 7 am to 3 pm when the diversion dam is draining and the head on the control structures decrease and between 7 pm to 11 pm when the water used during the peak demand hours of electricity production 6 pm to 10 pm arrives. After review some weeks of operation, the results show that the operation made by the ditchrider was not the same all the days of the week. On Friday and Saturday the quality of the irrigation service decreased. On Sunday the peak hours of electricity generation decreased. In general with manual operation more water than requested was given to the user association in charge of the LBMC management.

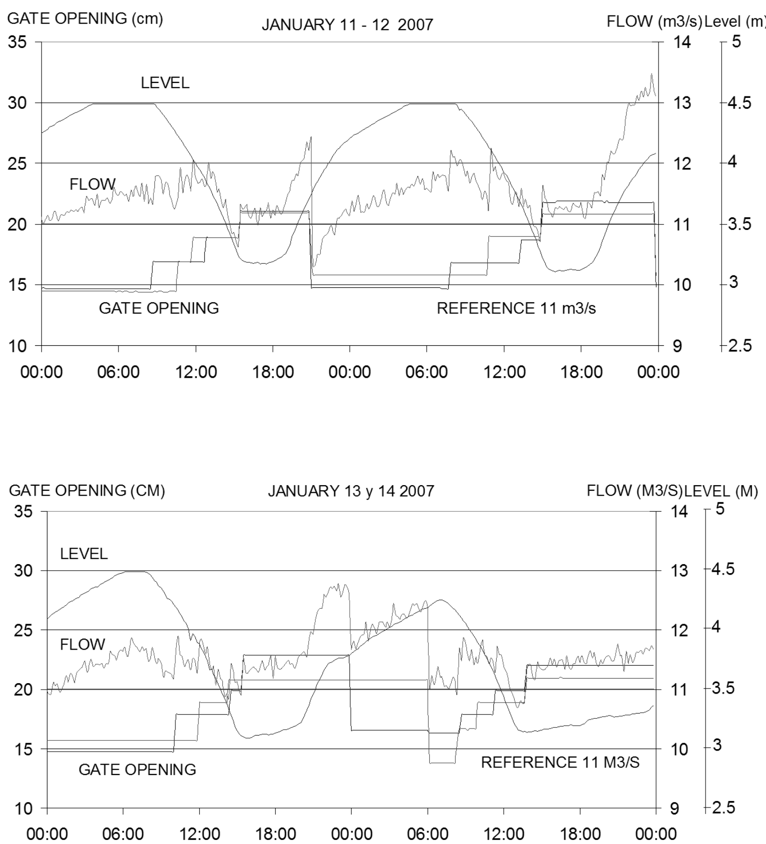


Figure 4. Performance of the Diversion Dam on Manual Operation.

CONTROL ALGORITHM

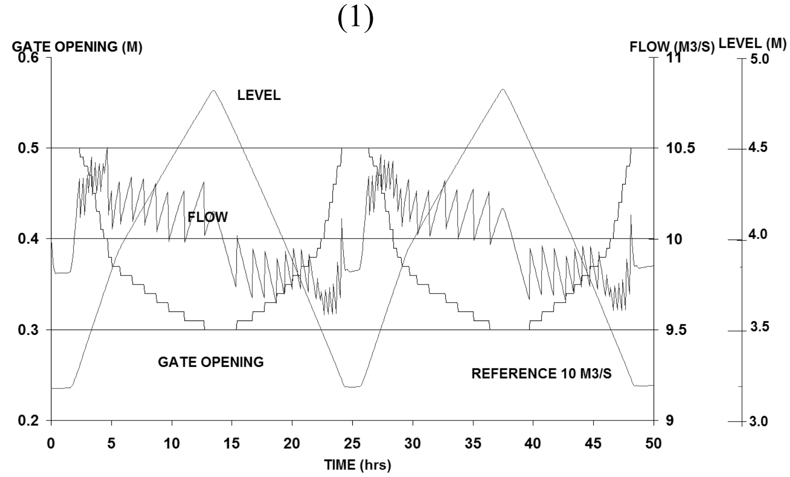
Dr. C. Burt showed the data collect by the system on its first months of manual operation and suggested that we use simple rules to drive the canal rather than a Proportional Integral Regulator (PI). In general PI regulator presents overshoots not recommended for flow control. Dr. Burt suggested some simple rules to drive the canal:

IF your flow error is greater that the tolerance :
  If flow is grater than the reference: (1)
    Close the gate 90% of the error/reference
  If flow is smaller than the reference:
    Open the gate 110% of the error/reference

make control decision every 30 minutes.

The rule proposed by Dr. Burt was tested on simulation using the SIC canal model simulator developed by the CEMAGREF. The SIC model was configured to approximate the data collected on the field. On Fig. 5 the performance of the rules were tested on two days of operation. Two cases are presented in the first one the percentage factors (1) were the proposed by Dr. Burt on the second one the factors are 120 and 150 respectively. With a higher percentage a better response was obtained since not only the present error was considered in the correction, also the future evolution on the dam's level was considered. The higher percentage reduced the number of movement in the gate. In this simulation the regulator dead zone was 0.25 m3/s and the sampling time was 20 minutes. Fig. 6 show the results when the regulator dead zone changed from 0.25 to 0.4 m3/s and the percentages of correction were the original ones (1) and 150 and 200 respectively. As seen in the above simulation results as the regulator dead zone increase and the percentage factor increase the maximum operation error in the flow was higher and the number of gate movements was reduced.

(1)



(2)

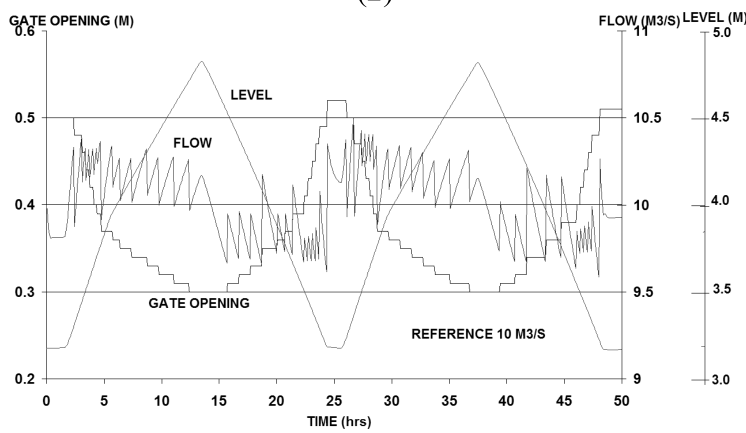
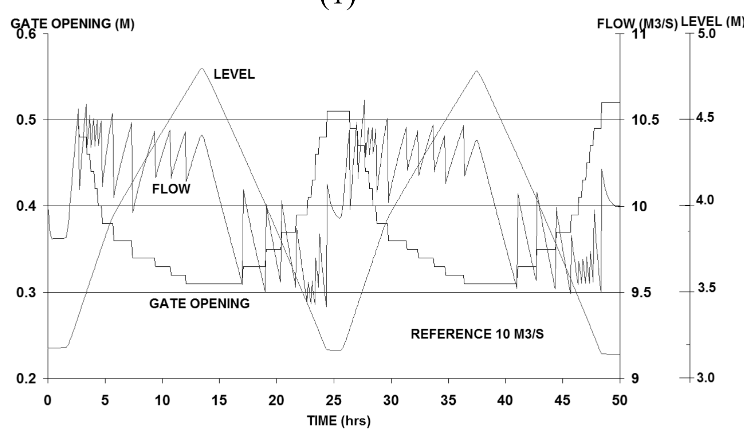


Figure 5. Evolution of the Diversion Dam with Different Control Rules
(1) Percentage 90 and 110, (2) Percentage 120 and 150

(1)



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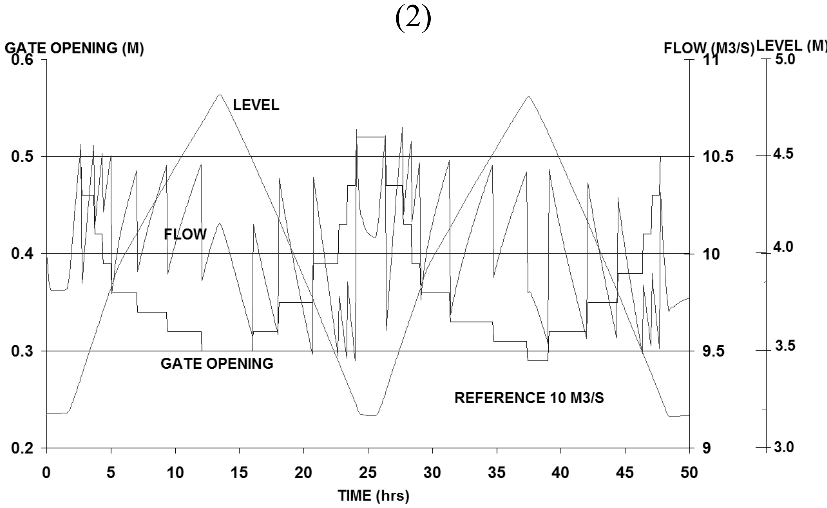

Figure 6. Evolution of the Diversion Dam with a Dead Zone of 0.4 m3/s
(1) Percentage 90 and 110, (2) Percentage 150 and 2000

Finally, a one day SIC- simulation was done, looking for the control action that produced the smallest flow error in front of the level variation present on the diversion dam (Fig. 7). As in the other simulation the control decision were made every 20 minutes. On the simulation result (Fig. 7) almost every 20 minutes a gate movement of 1 cm was done, the number of gate movements increased. To reduce the flow difference to the reference flow the perturbation introduced by the fill and empty of the dam needed to be included on the control algorithm. The rules only consider the past, the effect on the flow at the head of the LBMC, feedback, and it should include the future that it is more or less known, volume change on de diversion dam, Feedforward.

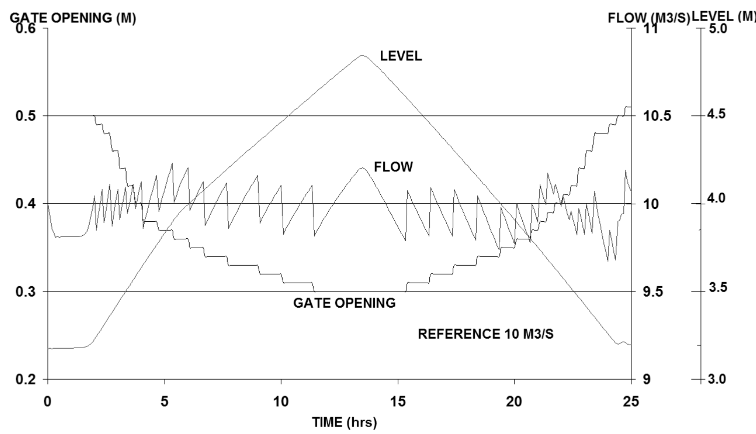

Figure 7. Evolution of the Diversion Dam Under Manual Operation Considering the Evolution of the Level on the Diversion Dam

WORK ON DEVELOPMENT

To complete the control system two aspects are needed to be done: a simple flow gate equation for the canal control structure on the diversion dam and the integration of the known perturbation on the control algorithm.

The main control problem on the Diversion Dam operation is the rejection of the perturbation, level variation, which is known. In this condition it is necessary to use a control algorithm that includes the information of the known perturbation in the operation of the Dam. Predictive control is a strategy that will be evaluated to incorporate the known perturbation as a feedforward component.

The data collected from levels, gate opening and flow will be used to obtain the flow equation of the gate. As a first step all the scales, level and gate openings, must be checked in both dam and canal. With data verified the equation will be determined and used to improve the reliability of the flow measurement.

CONCLUSIONS

The use of SCADA system for the flow control at the Piedras Blancas diversion dam is the only feasible solution to attain a reliable irrigation service at the head of the LBMC, since with Manual operation it is impossible to obtain the desired service. With Manual operations more water than requested is supplied to the Water Users Association.

With the automated control system on the diversion dam the safety on the canal will also be improved. This is the result of less water level fluctuations which damage structures and canal lining.

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ANALYSIS OF DISCHARGE MEASUREMENTS ON KING ABDULLAH CANAL

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Bruno Grawitz[2]
Thomas Dubreuil[3]
Jacques Sau[4]

ABSTRACT

In Jordan, water requirements are growing sharply, due to population growths, associated to the industrialization and the development of the country. Moreover, water resources are limited and subject to competitive use with neighboring countries.

The King Abdullah Canal (KAC) takes mainly the water in the Yarmouk and Zarqa Rivers, supplies the irrigation of 30000 ha and transfers water to Amman for domestic and industrial needs.

The KAC main structures are monitored and remotely controlled from a General Control Center through a SCADA system which includes a regulation module providing automatic and permanent control of canal flows as well as safety systems.

In canal systems, discharge measurements are fundamental. However, measurement network on hydraulic systems include many sensors spread over a large area, and subject to failure or deviation. In addition discharge and volume measurements in open channel are characterized by large uncertainties.

The KAC SCADA system is operational since 7 years, and a large database of measurements on the canal system is available. A review of flow measurements is made, with an analysis of the uncertainties coming from the use of gate laws. The analysis includes a comparison of the results given by different algorithms:

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Cemagref algorithm implemented in SIC software, USBR gate law, classical free flow and submerged flow orifice law. In the analysis, one of the KAC check gate appears to behave abnormally, with a systematic overestimation of the discharge. Analysis of flow measurements on field have been undertaken, as well as flow estimation based on open channel simulations using SIC software. This complete analysis provides relevant conclusions on the coherence of flow measurements.

INTRODUCTION

Radial gates are widely used as water control structures. They also offer the ability to discharge measurements. However, it must be understood that these two functionalities have not exactly the same specifications and constraints. In automatic control, one is mainly interested by the control of hydraulic variables (levels for example) and the feedback loop is expected to do the job. A gate equation is used for the design of the control, but a high accuracy is not really needed. On the other hand, if accurate water deliveries are needed, calibration of radial gates become a challenging task, since they offer the opportunity to perform discharge measurements. The equations for free flow mode are usually simple, accurate enough and easy to use. However this working mode is not always possible for radial gates. On KAC North Branch, which is the subject of this analysis, the cross structures are most of the time in submerged mode.

The KAC SCADA system is operational for 7 years, and a large database of measurements on the canal system is available. A review of flow measurements can then be performed. The gate equation used is the Cemagref algorithm implemented in SIC software (Baume 1997). The aim of this work is the analysis of discharge measurements given by gate equations on cross structures. This analysis will use also the discharge values given by flow meters on the KAC offtakes. In the analysis, one gate appears to behave abnormally, with a systematic overestimation of the discharge. We shall then investigate the role of gate equation used in submerged mode;

This work concerns the North part of the KAC which will be briefly described in the next section. An analysis of the measured discharges, based on a volume balance method, will be undertaken in the third section. The fourth section will be devoted to examination of gate equations in the case of KAC hydraulic working conditions.

THE KAC NORTH BRANCH

The King Abdullah Canal is located in the East of Jordan. It mainly supplies water to 22,800 ha of farmland, and to the town of Amman. It is 110 km long, with a maximum head flow of 17 m^3/s. It includes 37 gates not all motor-driven and remotely controlled. Most of the irrigation networks are pipe pressurized networks.

The KAC is divided in two distinct sections: the North section and the South section. The North section includes 24 gates, of which 17 controlled. The North section feeds the south section through a downstream gate (check gate 25) discharging into a siphon followed by the calibrated weir of Abu Zeghan

The North branch is supplied mainly by the Yarmouk river, the Mukheibeh underground water and the KAC conveyor which can take water from Tiberiade Lake.

The Ammam offtake is located on the last reach of the North branch, downstream of check gate 24.

Most of the time, gate 25 is closed. The two branches really communicate from time to time when transfer of large amount of water from North to South is needed.

DISCHARGE MEASUREMENT ANALYSIS

Different type of measurements are performed by sensors all along the KAC. Level measurements are performed upstream and downstream levels on cross structures. Intermediate level measurements on interesting points are also performed. These measurements are used for flow calculation and reach volume estimation. They are stored in real time and archived on a quarter an hour period.

Starting from the data recorded in the SCADA database, an analysis of discharge measurements has been undertaken. The aim of this study is to bring to the fore possible inconsistencies in discharge measurements. It will lead to review of gate laws for flow measurements and their ability to accurately measure discharge at water control structures. It will lead also to a better knowledge of the on-field operations and maintenance actions.

Analysis of Transiting Discharge

Volume balance method: In the selected periods, gate 25, downstream of the North Branch of the KAC, is most of time closed. On the other hand, the offtakes on this branch are equipped with electromagnetic flowmeters, which provide high confidence on offtake flow measurements. In order to validate discharge measurements by a given gate, daily volume balance can then be performed in the following way: For a given gate i, the branch part between this gate and gate 25, downstream of the branch is selected. Let us then call:

- V_i the total volume leaving this part during a day
- V_{B0} and V_{BT}, respectively the volumes of water at the beginning and at the end of the day. These volumes can be estimated by a now well established procedure in use at Societé de Canal de Provence for a long time (Rogier 1987, Viala 2003).

In fact these volumes could be neglected, since they are of an order of magnitude smaller than the transiting volume V_i,

The average discharge transiting through gate i, is given by the relation:

$$Q_{Mi} = \frac{V_i + V_T - V_0}{T}$$

This value can be compared to the corresponding one, Q_{Gi}, given by flow measurements from gate law.

Application on Normal period: We have performed this analysis on a normal period, corresponding to the usual working conditions of the Canal (95 % of the time). As typical illustrative example, we present here the analysis on April 2006 and for gates 18, 21 and 24. The average daily discharges Q_{Gi}, together with the deviation $Q_{Gi} - Q_{Mi}$ are depicted figure 1. Table 1 gives quantitatively the average relative difference value for the period.

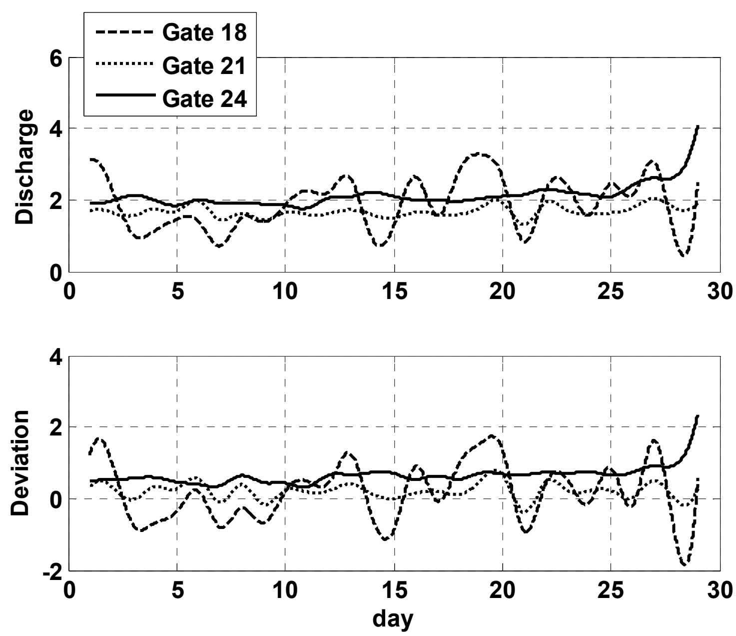

Figure 1. Gate discharges and discharge deviations

Table 1. Relative deviation

Gate	Average Deviation %
18	11
21	13
24	31

The gates are working on submerged flow conditions. One can observe that the mean over all variation of the deviation follows the discharge variation. For gate 18 and 21, and it is also the case for gates 19 and 22, the deviation is consistent with the expected uncertainties of gate laws. However gate 24 shows a too large deviation and always positive $Q_{Gi} - Q_{Mi}$. This point will be investigated more particularly in the following section.

Application on a peak transiting discharge case: We select now a period with a transiting peak discharge. Figure 2 shows the average daily discharges Q_{Mi} and Q_{Gi}, and the deviation $Q_{Mi} - Q_{Gi}$ on February 2006. Table 2 gives quantitatively the mean relative difference value for this period.

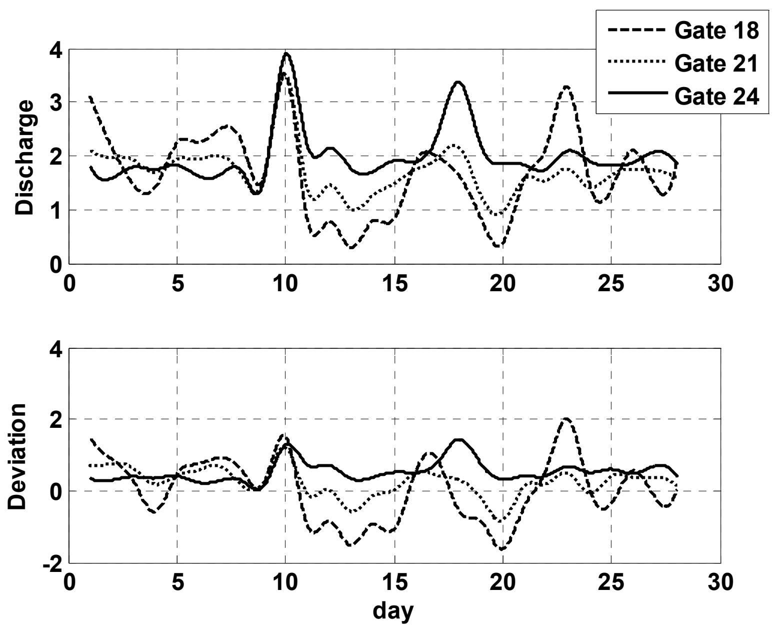

Figure 2:Gate discharges and discharge deviations

Table 2: Relative deviation

Gate	Average Deviation %
18	-2 %
21	17 %
24	29 %

Same conclusion as in the previous paragraph arises: the gate 24 too large overestimation of discharge appears clearly. In order to examine more precisely the peak event, figure 3 shows more particularly what happens on February 9-11. One can observe on the graph the three hours transiting time between gate 18 and gate 24. In the same graph is also drawn the sum of Amman offtake and Abou Zeghan weir values. Gate 24 discharge is then expected to be close to this value, which is not the case, although the variations are consistent.

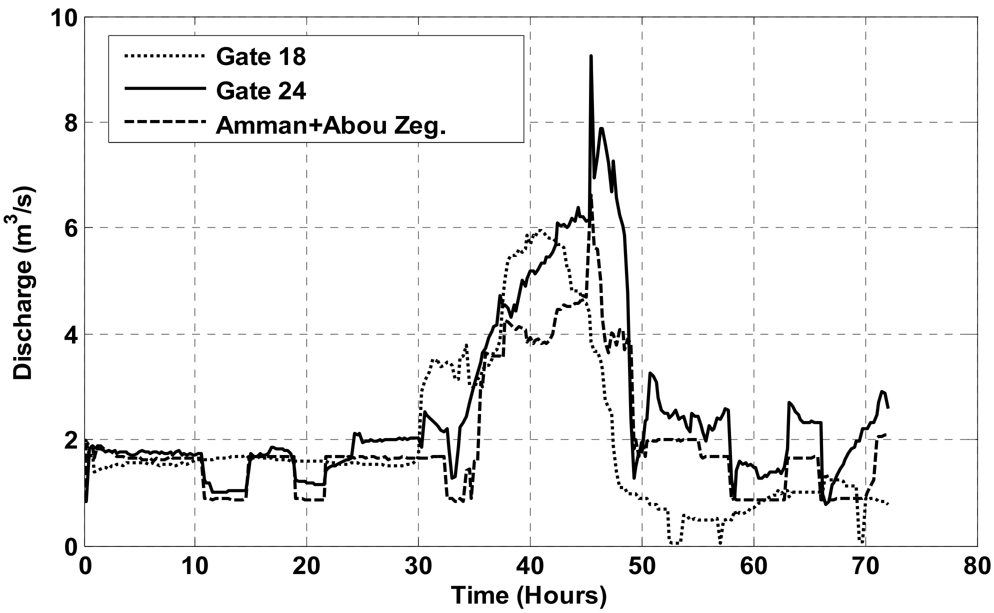

Figure 3. The peak discharge on February 9-11 2006

Dynamical Reconstruction of Gate 24 Discharge: The KAC has been modelled with SIC software. We have then at our disposal, the model of the last reach, downstream gate 24. On the other hand, in the data base the history of the downstream level of the reach, and the offtake discharge values are recorded. We have then designed a tracking control of the known downstream level, with command variable the upstream discharge. This command has been implemented in SIC. The obtained discharge command represents then the needed discharge in order to get the downstream level history, in the physical conditions close to the real ones. The aim of this study in transient hydraulic conditions, is to confirm the daily volume balance analysis. Figure 4 shows a typical result, concerning a period with an important Amman water demand.

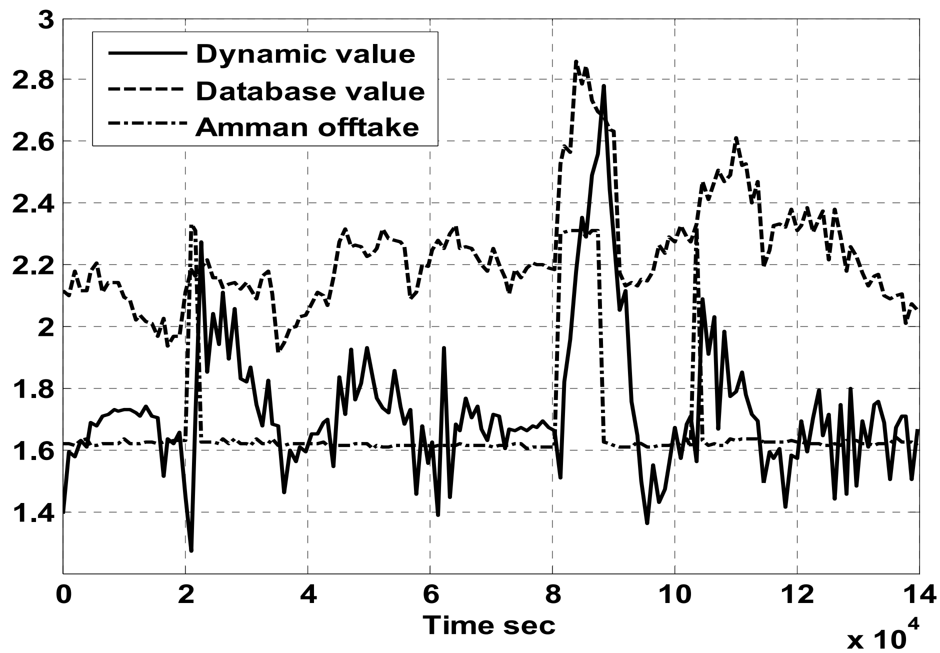

Figure 4. Comparison between database value and dynamically reconstructed discharge

This transient analysis confirms the daily volume balance study. The overestimation of the discharge by gate 24 appears clearly. However the relative variations are well reproduced. A correct treatment of this problem would have been a design of a non linear observer. This work is currently in progress.

GATE LAWS ANALYSIS

The disagreement in discharge balance observed for gate 24, leads us to take interest in the gate equations. The gate equation implemented in the KAC SCADA system is the CEMAGREF gate equation (Baume 1997). This equation has the advantage to provide continuous transition between different flow regimes: open channel (upstream level lower than gate opening) - free flow - submerged flow-over flow conditions. The analysis we present in this work is the comparison between this equation and the simple usual orifice equation in the free flow and submerged flow regimes. We also have performed the comparison with the USBR proposition(Buyaski 1983) to these same hydraulic conditions. Recently a so called E-M procedure has been proposed (Clemmens 2003) for submerged radial gate. It is our project to extend our study with these new algorithms and including other on field data.

Gate equations

The detailed Cemagref equation can be found in (Baume 1997). The basic principle is to deduce the gate discharge from two weir discharge difference. The various coefficients which appear in the formulae are adjusted in order to provide continuity between the different flow regimes. Consequently the user can adjust only one global effective discharge coefficient, taken usually around 0.6.

The USBR gate equation can be found in (Buyaski 1983). The equation is obtained from a-dimensional analysis based on the geometrical characteristics of the radial gate. A series of 2647 tests conducted at the USBR Water Resources Laboratory with different geometries, seal type and gate opening permitted to fix the parameters of the algorithm. Although the KAC gates are not strictly in the specified validity domain, we use the sharp-edge equation since we are mainly interested in the general variation trend.

The classical (Lefebre 1986, Lencastre 1986) orifice formulae are written:

$$Q = C_D L w \sqrt{2gH}$$

Where L is the gate width, w the gate opening, C_D the discharge coefficient and

$$H = h_1 - w/2$$

In free flow mode and

$$H = h_1 - h_2$$

In submerged flow mode, h_1 et h_2 being respectively the upstream and downstream water levels.

Discharge calculations

The calculated discharge given by these three equations can be compared. We use here the gate 21 characteristics. In a typical free flow mode, see figure 5, the response discharges are almost identical.

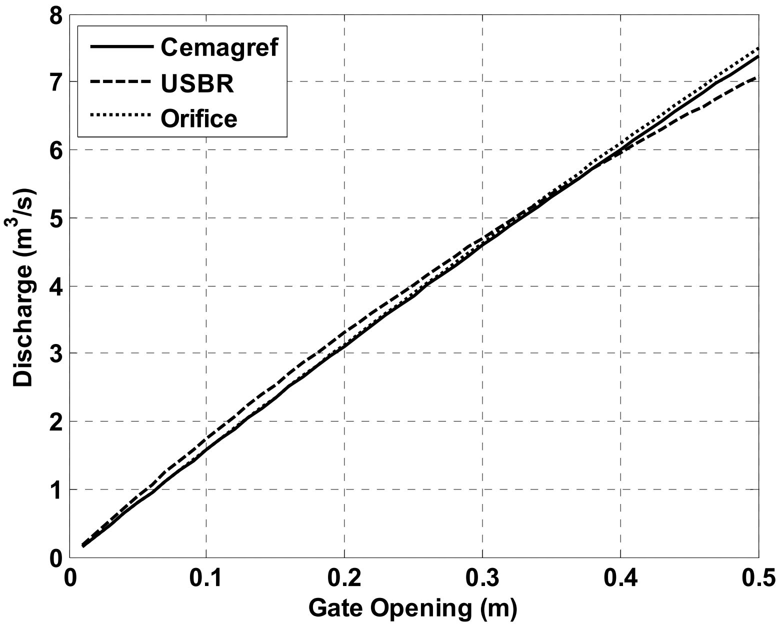

Figure 5.

In submerged flow mode, Figure 6, the responses agree but for the orifice law, the discharge coefficient must vary from 0.6 to 0.8 in order to give consistent results with the two other equations.

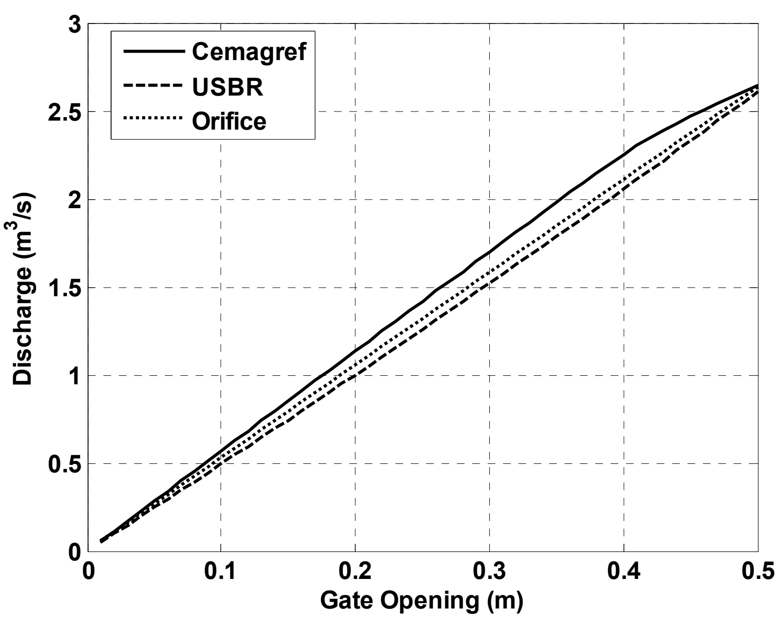

Figure 6.

We have also proceeded to a scan of the modes, discharge versus opening for different (h_1, h_2) values. Figure 7 presents an illustrative case. Only Cemagref equation is able to propose continuity from free flow to submerged flow regime. It is also the only equation which is able to continuously make the transition to open channel mode, which also prevents the divergences at large gate openings which are seen on the other equations. Nevertheless a non physical decrease of the discharge appears near the open channel transition. However one may think that such extreme modes occur rather scarcely.

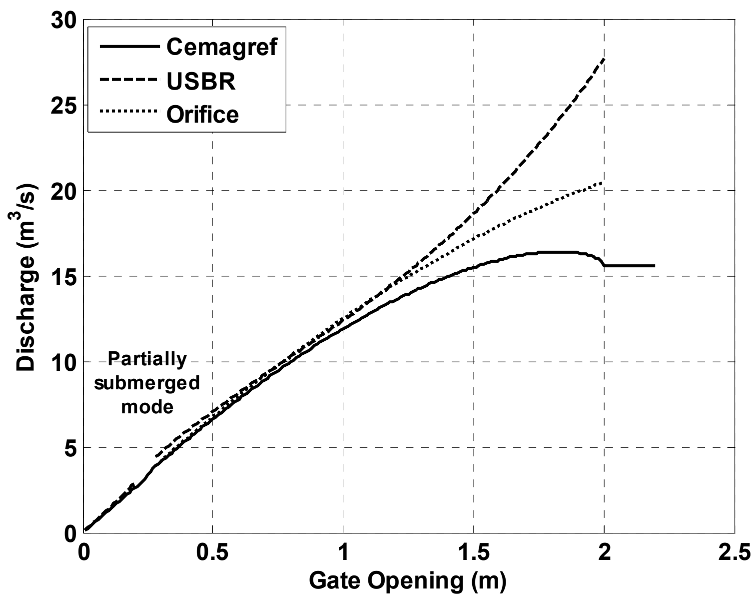

Figure 7.

We have finally performed a statistical uncertainty analysis. The problem is stated as follows: let us assume that the gate equation is right, what is then the uncertainty on the calculated discharge caused by the uncertainties of the sensors. Level and opening values are supposed to be random normal variables. Since the relation giving the discharge is non linear, this last variable is not normal, but Monte-Carlo method gives a numerical way to reach the uncertainty of the discharge. The results are shown table 3, for the gate 21 on same hydraulic conditions for all equations.

Table 3.

		Cemagref	USBR	Orifice
Free flow	Discharge (m^3/s)	4,12	4,65	4,16
	Uncertainty	(+/-) 3,0 %	(+/-) 2,7 %	(+/-) 3,1 %
Submerged flow	Discharge (m^3/s)	2,65	2,60	2,64
	Uncertainty	(+/-) 11,3 %	(+/-) 15,0 %	(+/-) 14,7 %

As expected, the three algorithms give almost the same good result at free flow mode. These results deteriorate at submerged flow, although the Cemagref equation behaves a little better.

The general conclusion of this analysis is that the gate equations give similar results for the usual working conditions of the North Branch of the KAC. The abnormal over estimation of the discharge for gate 24 cannot be explained by the equation.

The abnormal behavior of Cemagref equation at large gate opening has been noticed above. On some period, for example on flooding period, a large quantity of water is transferred from the North Branch to the South one. Downstream gate 24, there is a good calibrated weir between the North and South parts, and the flowmeter of the Amman offtake. Therefore the discharge transiting beneath gate 24 can be rebuilt and compared to the one given by the Cemagref gate equation. During this event, gate 24 works at large gate opening. The consequence of the abnormal behavior of Cemagref equation is that, at the time of this event, gate 24 underestimates strongly the discharge. Figure 8 shows the comparison of gate 24 and Amman offtake plus Abu Zeghan weir discharges during March 2005 when a flood event took place.

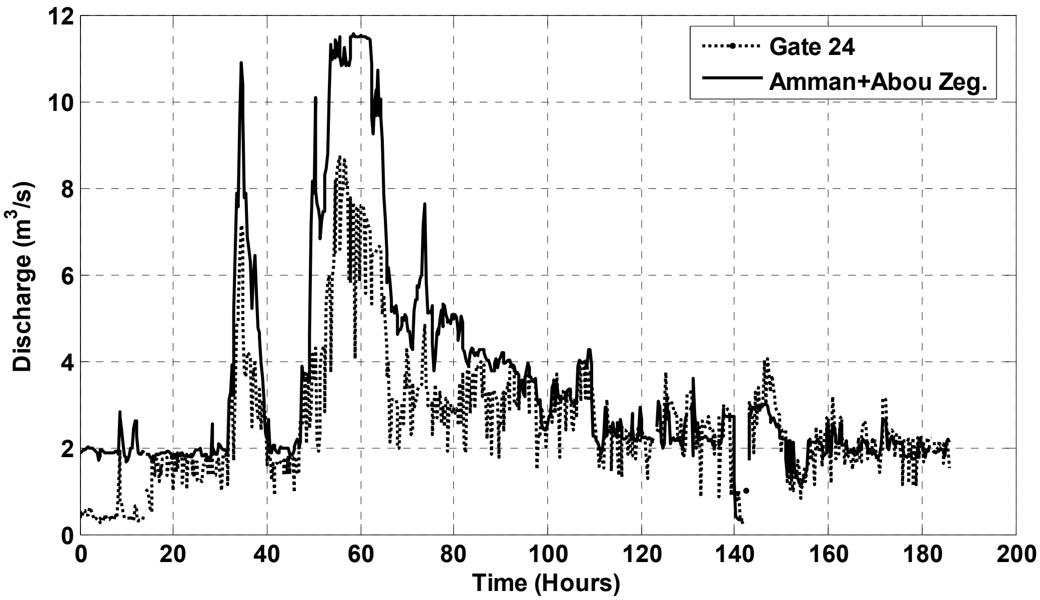

Figure 8. Flood event

SUMMARY

A good knowledge of the canal geometry and physics represents one of the means to improve the efficiency of a canal system. In this spirit, a complete analysis of discharge measurements has been performed, starting from the data recorded in the SCADA of the KAC. This study is also important, because it leads to a better knowledge of the on-field operations and maintenance actions. Moreover, the concluding results can be confirmed by fore coming on field observations. On the whole, the results are correct, except for one gate. Investigations for the reason of this failure, which seems not to be due to the used gate law, are in progress,

Since radial gates are widely used for flow measurements, gate law able to work continuously with reasonable accuracy on all the working modes of the gate are then needed. We think that the problem is still open. Our project is to continue this work, taking into account new gate equations and also new data sets. Besides, starting from the measurements recorded in the database, we are interested to perform a dynamical re-estimation of the discharges on the canal, in transient mode, with the design of a non linear observer.

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IRRIGATION FLOW MONITORING EQUIPMENT DEMONSTRATION AND COMPARISON

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Alan A. Halley[2]
June R. Caves[3]

ABSTRACT

Northern Water (Northern Colorado Water Conservancy District) conducted field demonstrations and comparisons of flow monitoring equipment at 18 canal and ditch sites in the lower South Platter River Basin during the 2006 irrigation season. Equipment included data loggers from 8 different manufacturers, 16 different models of water level sensors from 12 manufacturers, and 4 different types of telemetry from 7 manufacturers.

The data loggers that were demonstrated included four models of single-sensor with integrated data logger, four models of programmable multi-sensor data logger, and one model of basic, low-cost data logger without telemetry. Relative equipment costs for each data logger system are summarized in Table 6.

The water level sensors tested included submersible pressure transducers, optical shaft encoders, ultrasonic distance sensors, bubbler level sensor, float and pulley with potentiometer, buoyancy sensor, and a laser distance sensor. Bench checks of sensor calibrations were accomplished by Northern Water staff before field installation, and again at the end of the irrigation season. Observed sensor accuracy was compared to that expected from manufacturer specifications.

The telemetry systems tested in the field included license-free spread-spectrum radios from four manufacturers, licensed radio modems in the 450 MHz range, satellite radio modems to a web server, and cdma modems with static IP addresses. Increased mast height and high gain directional antenna improved radio telemetry as expected. Additionally, operational files were utilized to document telemetry performance when available.

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The purpose and intent of the equipment demonstration and comparison was not to identify a single best data logger, sensor, and/or telemetry system. Each has different features and strengths, as well as varying costs. For each specific flow monitoring application, different equipment may be preferred or better suited than other equipment. However, the 2006 demonstration and comparison should provide a reference point for those seeking to become more knowledgeable in equipment selection while avoiding unpleasant surprises.

INTRODUCTION

Background

In 2006 the Colorado Division of Water Resources, Division 1 – South Platte River, Districts 1 and 64 provided stimulus for irrigation companies to transition from paper chart recorders to electronic flow monitoring devices at their water measurement structures. In conjunction with this process and in response to the water users' interest regarding available equipment for such purposes, the Irrigation Management Department of Northern Water proposed and implemented field demonstrations of various data loggers and sensors utilizing ditch companies' existing, serviceable flow measurement structures. Additionally, the demonstration project was installed and operated partially to assist in meeting the needs of the State of Colorado to monitor flows at key river diversions within the lower South Platte River.

Terminology

Data processing and control is generally accomplished at a central location for *Remote Terminal Units* (RTU) which often do not include any onsite capabilities for data processing and logging to memory. They are essentially the non-programmable interface needed for a central site to access remote sensors and equipment. If communication to the remote stations is lost, data collection/processing and equipment control is typically suspended until telemetry operations are restored. However with *Programmable Logic Controllers* (PLC) the processing and control functions are disbursed to the remote sites and can continue without interruption even when communications with the central location go down. Sensors continue to be sampled and the data stored to memory. Gate control will continue according to pre-programmed algorithms in response to sensor information and stipulated constraints. In further contrast, *Data Loggers* will always include onsite data collection and storage, but may or may not incorporate data processing, telemetry and/or capabilities to control appurtenant equipment such as gates. However it is increasingly common for many data loggers to include telemetry capabilities and control functions, becoming interchangeable with PLCs. This paper will use the term data loggers as all referenced equipment included this functionality and no effort was attempted during 2006 to utilize available controller capabilities.

DATA LOGGER COMPARISONS

Data Logger Capabilities

Data logger capabilities can be quite extensive and this paper will not attempt to replicate manufacturer's specification sheets. However, the advantages of several features will be highlighted and Table 1 provides a brief summary.

Table 1. Data Logger Capabilities

	Telemetry utilized	Integrated sensor	Sensor input channels
Sutron SDR (stage discharge recorder)	AirLink Raven cdma modem	Shaft encoder	n/a
Hach/OTT Thalimedes	AirLink Raven cdma modem	Shaft encoder	n/a
INW PT2X Smart Sensor	AirLink Raven cdma modem	Submersible pressure transducer w/ temperature	n/a
Hach/OTT Nimbus	AirLink Raven cdma modem	Bubbler	n/a
Automata MINI-SAT Field Station	Satellite modem to web server	n/a	3 – analog 2 – pulse count
Campbell Scientific CR200	AirLink Raven cdma modem & spread-spectrum radios 100-mW & 1-W	n/a	5 – analog 2 – pulse count 1 – SDI-12
IC Tech C44P	Licensed 450 MHz radio-modem 5-W	n/a	6 – analog
Control MicroSystems SCADAPack100	Cirronet HN-291 spread spectrum radio 500-mW	n/a	3 – analog 1 – pulse count
HOBO H8 w/ Stevens Type F	Not available	Temperature	1 – analog

Data loggers are expected to operate reliably over wide temperature extremes. For deployment in remote locations they will typically utilize 12-VDC rechargeable batteries, photovoltaic panels, and a charge regulator to provide needed electrical power. They will typically record or log sensor values to memory on a schedule that is user selectable and which should preferably include the corresponding date/time stamp and site identifier. An internal backup battery should maintain accuracy of the onboard clock, even when external power is lost for brief periods.

Historically, most flow data records were constrained to end-of-period readings because of equipment and/or personnel limitations. This end-of-period data logging has been typical of RTU type systems. Whether the selected period was 15-minutes, hourly or even daily, the end-of-period reading was assumed to be representative of the entire time period. Modern data loggers make feasible the more rapid collection of water level data with their associated flow calculations. However, it is preferable that rapid or frequent readings be processed (averaged, totaled, etc.) by the data logger so the amount of data stored in memory and/or transmitted to a central site is reduced to manageable levels. Flow rates and volumes calculated on a higher frequency are mathematically more representative of the actual flows than those derived based on a more reduced or limited number of level readings, particularly if water levels fluctuate significantly over time.

When utilizing submersible pressure transducers, ultrasonic sensors and/or buoyancy sensors it is advantageous to utilize a data logger capable of onboard processing. The minor fluctuations in readings typical of these sensors can often be readily smoothed with short-term data averaging. Typically sensors might be sampled every 3 seconds, with 20 such values averaged every minute. This one-minute value could then be utilized by the onsite LCD display, if available. If it is desirable that an end of period reading be stored in memory (along with or in place of the average value for the given time period), then the most recent one-minute average value would be the reading logged to memory by the data logger.

To facilitate periodic site checks and verification of sensor readings, an LCD display at each remote station is generally desirable. The display may be built-in to the data logger (or sensor), be an optional feature mounted in the enclosure door, be a plug-in accessory portable from site to site, or even be a pocket PC device. Operators can quickly compare an on-site manual staff gauge reading to the water level reading by the data logger as viewed via the display. Appropriate corrections or adjustments can then be made expeditiously. In practice, the use of a pocket PC device is often more economical than a permanently installed LCD display as its cost is distributed over multiple sites. It may also provide an increased level of security over a built-in keypad used to configure the data logger.

Telemetry equipment provides a connection between the central site and the data logger at the remote location. Typically a data logger must be compatible with the Modbus protocol in order to utilize radio telemetry. Otherwise telemetry will be limited to direct wire connections, dial-up telephone modems, and cdma modems. Other data logger capabilities often found to be desirable are the ability to power down sensors and telemetry to conserve power, the ability to generate alarm calls for emergency conditions, and the ability to control gates, heaters, security cameras, etc. The data logger clock should continue to keep accurate time even when external power is lost to the data logger. Thus when power is restored and data logger functions resume, correct date/time stamps are recorded. Additionally, loss of external power should not result in loss of stored data at the remote site.

Data Logger and Sensor Compatibility

Sensor selection is often constrained by site conditions. If there is no existing stilling well it may be more economical to select an ultrasonic ‘down-look’ sensor or a bubbler sensor than incur the expense of installing a new stilling well. Similarly, if heavy silt loads periodically bury intakes to stilling wells and thus cause the water level in the stilling well to no longer track with the water level in the stream or canal, then an ultrasonic sensor may be preferred. Silt loads flowing into stilling wells as water levels rise will typically settle out and remain in the stilling well. Over time, this accumulation of silt in the stilling well can bury submersible pressure transducers and leave them less responsive to level changes. This silt build up can also prevent floats from following lowering levels down if they ‘bottom-out’ prematurely on silt deposits. Periodic cleaning or flushing of the stilling well would then be required to maintain sensor accuracy. In such circumstances, it is advantageous for the data logger to be compatible with a variety of sensors. Table 2 provides a quick reference for 2006 of which sensors could be connected to the various data logger systems.

Table 2. Data Logger and Sensor Compatibility

	KPSI 330	SR50	SE-107	Thalimedes	PTX 1230	PT2X Smart Sensor	TFLI	PS9800	MicroSpan LU05	Laser Level-Watch	SDR	SE-109	SPXD 500	Type F Chart Recorder	Level-Watch	Nimbus
Sutron SDR (stage discharge recorder)											X					
Hach/OTT Thalimedes				X												
INW PT2X Smart Sensor						X										
Hach/OTT Nimbus																X
Automata MINI-SAT Field Station	X		X		X		X	X	X	X			X	X	X	
Campbell Scientific CR200	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
IC Tech C44P	X				X		X	X	X	X			X	X	X	
Control MicroSystems SCADAPack100	X				X		X	X	X	X			X	X	X	

WATER LEVEL SENSOR COMPARISON

Northern Water staff developed an in-house protocol for bench testing the calibration and accuracy of sensors. It should be noted that the average error measured on the test bench should always be less than the manufacturers’ warranted accuracy for an individual measurement. Additionally, the bench tests were conducted in a controlled environment with near constant temperatures. Field conditions are generally harsher on sensor performance. Results of these bench tests are summarized in Table 3.

Table 3. Water Level Sensor Comparison

	Manufacturer	Model	Type	Signal	Expected accuracy ft	Bench test error, ft	2006 cost
1	Esterline/Keller	KPSI 330	Submersible pressure transducer	4-20 mA	0.005	0.0018	$736
2	Campbell Scientific	SR50	Ultrasonic distance	SDI-12	<0.033	0.0024	$1,200
3	Enviro-Systems	SE-107	Shaft encoder	Up/down pulse	0.01	0.0030	$799
4	Hach/OTT	Thalimedes	Shaft encoder	SDI-12	<0.007	0.0032	$850
5	GE Druck	PTX 1230	Submersible pressure transducer	4-20 mA	0.014	0.0032	$743
6	Instrumentation Northwest	PT2X Smart Sensor	Submersible pressure transducer w/ temperature		0.012	0.0034	$1,275
7	Vishay alpha beam load cell	TFLI	Buoyancy	0-5 VDC		0.0036	$195
8	Instrumentation Northwest	PS9800	Submersible pressure transducer	4-20 mA	0.012	0.0044	$612
9	Flowline Components	MicroSpan LU05	Ultrasonic distance	4-20 mA	0.008	0.0052	$561
10	Automata	Laser Level-Watch	Laser distance	0-5 VDC	0.016	0.0055	$395
11	Sutron	SDR	Shaft encoder	SDI-12	0.01	0.0071	$1,257
12	Enviro-Systems	SE-109	Shaft encoder	SDI-12	0.01	0.0074	$1,099
13	RMT/KWK Technologies	SPXD 500	Submersible pressure transducer	4-20 mA	0.012	0.0075	$645
14	Potentiometer on existing Stevens Type F Recorder	Vishay 533 25K	Gear set & after market potentiometer	0-2.5 VDC	0.013	0.0082	$156
15	Automata	Level-Watch	Submersible pressure transducer	4-20 mA	0.058	0.0082	$336
16	Hach/OTT	Nimbus	Bubbler	SDI-12	<0.03	0.0116	$1,325

Bench tests for all sensors typically consisted of 20 or more readings evenly distributed over their measurement range, with 50 percent during rising levels and 50 percent during falling levels. Test data was processed using a linear regression resulting in a calculated slope and offset, as well as an average error.

Bench tests of submersible pressure transducers, bubblers, and laser distance sensors were limited to a range of 9.5 feet because of the height of the available 6-inch diameter clear PVC well. Buoyancy sensors were limited to a range of 3 feet because of their designed range. Manual readings of the ‘staff’ or tape on the side of the clear PVC well were visually interpolated (best guess) to the nearest 1/1000 foot.

Bench tests of shaft encoders, ultrasonic distance sensors, and float and pulley potentiometers were limited to a range of 4 feet. These tests were accomplished 'in-the-dry' using stacks of ¾ wide particle board squares. These range limitations were not considered overly restrictive as the standard recorder chart used by the State of Colorado has a 4 foot range. Hence calibration of sensors over a 4 foot or greater range was applicable to nearly all irrigation flow measurement structures encountered in 2006.

TELEMETRY COMPARISONS

All of the data logger systems included telemetry except the HOBO H8. Each of the eight systems with telemetry was successfully configured for automatic polling on at least an hourly basis. In some cases (such as OTT Hydras 3), automatic polling was accomplished through use of third party software – Advanced Task Scheduler and Workspace Macro Pro.

Telemetry systems should first and foremost be reliable, with low error rates in data transmission. In addition they should be robust – with low susceptibility to storm damage and forgiving of poor site conditions (such as tall trees along river bottoms that attenuate radio signals). Initial telemetry costs are not wholly determined by per unit equipment costs. Radio equipment that minimizes the need for repeaters can potentially result in lower overall costs. This can be realized either through capabilities for communication over longer distances or through 'store and forward' technology where other remotes sites can retransmit data from outlying stations. Equipment also needs to be economical to operate with low ongoing costs or fees. Table 4 provides a simple summary comparison.

Table 4. Telemetry Comparison

		Antenna gain	Typical mast height	Typical transmission distance
AirLink Raven cdma modem on Verizon		3 dB gain omni	6 ft	n/a
Automata satellite modem		3 dB gain omni	6 ft	n/a
Campbell Scientific RF401 spread spectrum radio	100-mWatt	6 dB gain yagi	10 ft	1 – 5 miles
Cirronet HN-291 spread spectrum radio	500-mWatt	6 dB gain yagi	20 ft	6 – 9 miles
MDS 9810 spread spectrum radio	1-watt	6 dB gain yagi	20 ft	10 – 15 miles
FreeWave FGR-115RC spread spectrum radio	1-Watt	6 dB gain yagi	20 ft	10 – 15 miles
IC Tech licensed radio w/ 'Tru-Lock Sync'	5-watt	9 dB gain yagi	16-20 ft	18 – 27 miles

Generally it does not take long for irrigation company staff to realize that once they have functional electronic flow monitoring equipment, the addition of telemetry back to a central site is desirable. The additional costs for telemetry are often recovered quickly in reduced operating costs, improved service to share holders, or prevention of damage to equipment and facilities. Telemetry can result in overall cost savings for their operations. The expense of routinely sending personnel to remote sites to download data is avoided. Additionally, proper operations at remote sites can often be confirmed without necessitating personnel traveling to that site, particularly during storm events when travel over unimproved roads could be hazardous.

SOFTWARE

Table 5 includes a brief summary of the principal software associated with each data logger system and its cost. Included are three third party software packages utilized to improve functionality, particularly in automated polling activities.

Table 5. Software Comparison

	Software	Version	Cost
Sutron SDR (stage discharge recorder)	Sutron SDRPoll Sutron SDRComm	2.3 2.3	n/c
Hach/OTT Thalimedes	OTT Hydras 3 Basic	2.12.0	$125
INW PT2X Smart Sensor	INW Aqua4Plus INW Aqua4Push	1.5.18 2.1.0	n/c variable
Hach/OTT Nimbus	OTT Hydras 3 Basic	2.12.0	$125
Automata MINI-SAT Field Station	Automata Field Vision 97 for Windows Automata Logger Vision Automata Field Vision Database Automata Mini Configuration Program	1.0 4.07s 4.01d 2.08s	$150
Campbell Scientific CR200	Campbell Scientific LoggerNet	3.2.2.76	$565
IC Tech C44P	IC Tech Software Toolbox	3.30	n/c
Control MicroSystems SCADAPack100	Control Microsystems SCADALog Control Microsystems TelePACE	2.0 3.00	$487
HOBO H8 w/ Stevens Type F	ONSET Boxcar Pro	4.3	$ 99
AirLink Raven cdma modem on Verizon	AirLink Raven CDMA Setup AirLink Raven Setup Wizard AirLink Wireless Ace 3G		n/c
Cirronet HN-291 spread spectrum radio	Cirronet HNWizard	5.20	n/c
MDS 9810 spread spectrum radio	MDS Radio Configuration Software	2.4.0	n/c
FreeWave FGR-115RC spread spectrum radio	FreeWave EZ Config	2.7	n/c
Automated schedule (OTT)	Southsoftware Advance Task Scheduler	1.5	$40
Create virtual COMM ports (cdma modems OTT & INW)	Tactical Software Serial/IP Redirector	4.6	$50 +$50/port
Automated polling (OTT)	Tethys Solutions Workspace Macro Pro	6.5.1	$65

COST COMPARISON OF DATA LOGGER SYSTEMS

The list price of a data logger may or may not include built-in sensors, voltage regulators, radios, etc. Related equipment, software, and additional telemetry costs can significantly affect the overall cost of a data collection system.

Although quite simplified, Table 6 attempts to provide a cost comparison of data logger systems complete with sensors, required appurtenant equipment, and available telemetry. The HOBO H8 data logger connected to a potentiometer retrofitted on an existing Stevens Type F chart recorder does not include any telemetry. It is simply an economical data logger that must be downloaded manually by personnel visiting the site. For comparison purposes, any ongoing monthly costs (such as Verizon Wireless billings) were summed for three years and included in the telemetry costs.

Table 6. Cost Comparison of Data Logger Systems

	LCD display	Data logger	Added sensor	Access-ories	Telemetry	Total
HOBO H8 w/ existing Stevens Type F recorder	Not available	$ 75	$ 164	$ 56	Not available	$ 295
Campbell Scientific CR200	Not included	$ 390	$ 195 TFLI	$ 514	$ 876 AirLink cdma modem	$1,975
Hach/OTT Thalimedes	Included	$ 820	n/a	$ 317	$ 926 AirLink cdma modem	$2,063
Control MicroSystems SCADAPack100	Not available	$ 608	$ 195 TFLI	$ 550	$1,034 Cirronet SS radio	$2,387
Sutron SDR (stage discharge recorder)	Included	$ 953	n/a	$ 579	$ 876 AirLink cdma modem	$2,408
INW PT2X Smart Sensor	Not available	$1,045	n/a	$ 275	$1,106 AirLink cdma modem	$2,426
Hach/OTT Nimbus	Not available	$1,125	n/a	$ 487	$ 876 AirLink cdma modem	$2,488
Automata MINI-SAT Field Station	Not included	$ 975	$ 395 Laser	$ 200	$1,073 Satellitemodem	$2,643
Control MicroSystems SCADAPack100	Not available	$ 608	$ 612 PS9800	$ 550	$1,034 Cirronet SS radio	$2,804
Campbell Scientific CR200	Included SE-109	$ 390	$1,099 SE-109	$ 514	$ 876 AirLink cdma modem	$2,879
IC Tech C44P	$ 195	$1,895	$ 195 TFLI	$ 367	$ 450 Licensed radio	$3,102
Automata MINI-SAT Field Station	$ 250	$ 975	$ 612 PS9800	$ 200	$1,073 Satellite modem	$3,110
Campbell Scientific CR200	$ 345	$ 390	$ 612 PS9800	$ 514	$1,451 FreeWave SS radio	$3,312
IC Tech C44P	$ 195	$1,895	$ 612 PS9800	$ 367	$ 450 Licensed radio	$3,519

If more than one sensor is needed at the same field site, the cost will double when using the four systems having single sensor with integrated data logger, as they are constrained to use only the single built-in sensor. However, the cost of the four multi-sensor data logger systems will increase by only the cost of an additional sensor. Hence these systems are less costly for sites requiring more than one sensor. Additionally, two or more configurations are included for each multi-sensor data logger to demonstrate their increased adaptability.

SUMMARY

The purpose and intent of the equipment demonstration and comparison was not to identify a single best data logger, sensor, and/or telemetry system. Each has different features and strengths, as well as varying costs. For each specific flow monitoring application, different equipment may be preferred or better suited than other equipment. However, the 2006 demonstration and comparison should provide a reference point for those seeking to become more knowledgeable in equipment selection while avoiding unpleasant surprises.

DISCLAIMERS

Northern Water does not in any way endorse or recommend equipment from any particular manufacturer or distributor. Mention of specific make or model of equipment is provided for informational purposes only and is not intended to imply any preference, higher quality, better value, etc. The authors recognize that numerous other manufacturers market comparable equipment well suited for irrigation flow monitoring. However, limited resources prohibited inclusion of all but a relatively few in the 2006 demonstration. No comprehensive review of available equipment or any formalized screening process for selection of equipment was attempted.

Listed equipment costs are provided for comparison purposes only and are not intended to constrain manufacturers in pricing and marketing their products. Northern Water neither implies nor guarantees equipment availability at referenced prices. Actual costs are independent of any and all information included in this paper and are set by equipment manufacturers and distributors according to their individual business practices, with ongoing adjustments as they so determine.

ACKNOWLEDGEMENTS

Northern Water expresses appreciation for the cooperation of the manufacturers and distributors of the equipment included in the 2006 demonstrations. Their knowledgeable, friendly assistance proved invaluable and was much appreciated.

REAL-TIME DECISION SUPPORT IN WATER RESOURCES

Steve Malers[1]
Ian Schneider[2]

ABSTRACT

Real-time decisions are necessary for water resource management to respond to extreme conditions, such as flooding and drought. It is often important to detect critical situations as soon as possible, in order to minimize risk and avoid more difficult decisions in the future. Decisions in water resources involve spatial and temporal aspects that are particularly challenging; for example, evaluating snow pack for future water supply and flooding and analyzing how water is diverted and reused as it travels through a basin. In order to address these challenges, Riverside Technology, inc. (RTi), has developed the RiverTrak® System for: real-time data management and archiving; data analysis and modeling; and data tests, alarms and notification. Workflow is defined as a sequence of tasks necessary to process data and produce products in order to make decisions. The RiverTrak® System can utilize both observational data and processed data (e.g., results of a model or external input). The framework allows the introduction of additional models and analysis to support more complex decisions. The system's final data products are those needed by water managers for decision-making. Integration with SCADA provides observational data as input to the RiverTrak® System and facilitates execution and monitoring of operational decisions.

OVERVIEW OF REAL-TIME DECISION SUPPORT SYSTEMS

A Decision Support System (DSS), in the context of water resources, is a computerized system that helps users make better decisions when managing water resources. The ability to make better decisions is related to the collection, analysis, and processing of relevant data, to support making a decision as soon as possible. Supervisory Control and Data Acquisition (SCADA) can support a more complete DSS. The following types of decisions illustrate increasing complexity in decision support systems.

Observation-based Decision Support

Observation-based decision support systems rely on timely data collection and in many cases are best suited for systems where detection of an event triggers some immediate or near real-time response. These systems are typically very robust,

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given that real-time decisions need to be made using reliable observations. Typical SCADA systems and ALERT flood warning systems are examples of data-driven DSS where decisions are based on observations.

Trend-based Decision Support

Trend-based systems rely on a certain amount of historical data being maintained, allowing decisions to be based on observed values and rate of change, perhaps with extrapolation of future values. This type of system is an extension of observation-based systems, but requires more data management to handle historical data. Many systems can utilize trends as controlling criteria because processes are well understood.

Forecast-based Decision Support

Forecast-based systems rely on data analysis and/or modeling to generate an estimate of future conditions. It is important to validate the overall approach based on results from operating a system over a period of time. A model that is calibrated using historical data should perform similarly with real-time data.

Regression techniques may be used to compare current conditions with historical conditions. For example, the forecast of stream levels may be generated based on regression analysis of snowpack and streamflow. Although regression may work well for gross estimates (e.g., weekly or monthly data), it may not perform well for real-time data or may not handle variable conditions during a forecast period. Another approach is to use simple lookup tables or equations to determine a response based on input (e.g., look up the amount of irrigation water to apply based on observed soil moisture).

Modeling (simulation) approaches also may be used but may require additional input data. For example, a hydrologic model may be used to estimate runoff, requiring forecasted temperatures and precipitation as input. The forecast will only be as good as its input data and approach. A model-driven DSS is typically more complicated than data-driven DSS but provides an additional level of information for decision-making.

The following figure illustrates a streamflow forecast using RTi's RiverTrak® System, showing one result with zero quantitative precipitation forecast (QPF) and a different (higher flow) result based on a likely QPF. The observed data are provided by a data collection system (e.g., SCADA), whereas the forecast is a product of the simulation.

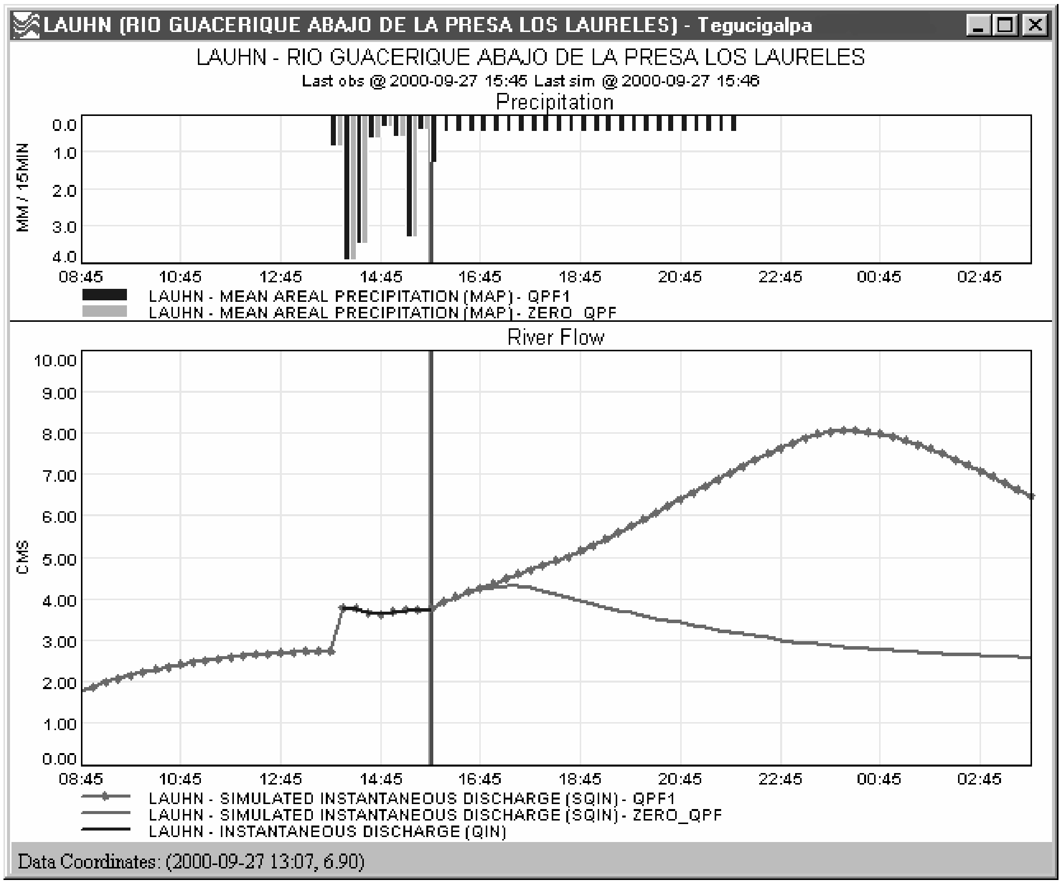

Figure 1. Example of Streamflow Forecast Product

In the above figure, the vertical lines indicate current time, beyond which the forecast is produced. The upper graph indicates the observed (left of vertical line) and forecasted (right of vertical line) precipitation. The lower graph illustrates a forecast with zero QPF (lower right line) and estimated QPF (upper right line). The figure illustrates that recently observed precipitation has increased soil moisture, which will result in significant runoff if additional precipitation occurs. The additional forecast information can greatly improve operational decisions.

Probability-based Decision Support

Probability-based systems can vary in complexity. Where historical data are not available, stochastic approaches may be used to generate synthetic data. An ensemble approach can be used if historical data are available, in which historical input data traces (each representing possible future occurrences of data) are input into a forecast model (e.g., a hydrologic simulation model). The resulting output can be analyzed in order to evaluate probabilistic- or risk-based decisions. Figure 2 illustrates how exceedance probabilities can be used to evaluate operating decisions.

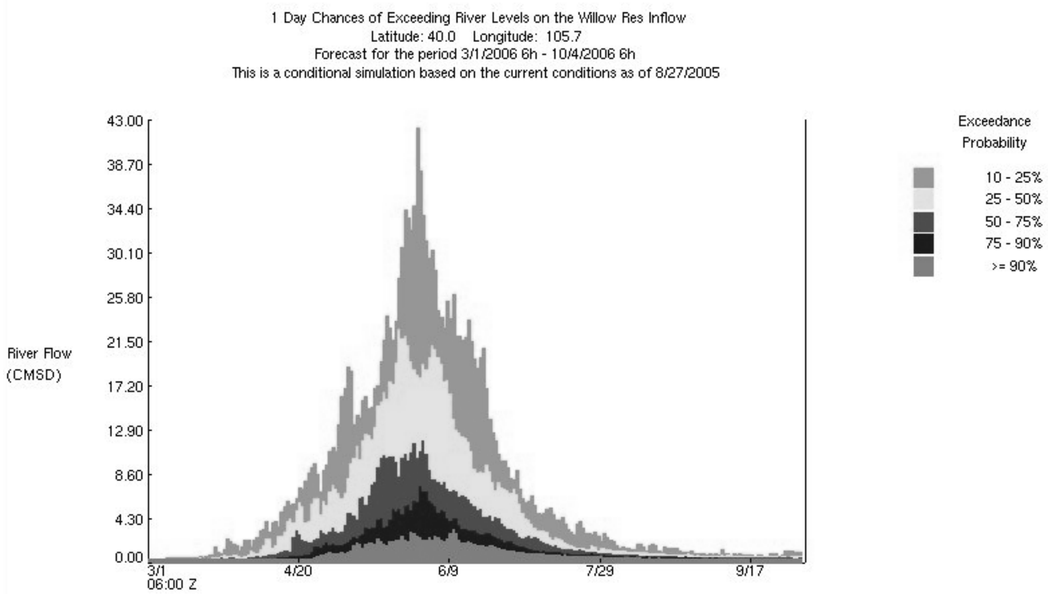

Figure 2. Example Streamflow Forecast Product – Flow Exceedance Probabilities

For example, high variability in forecasted snowmelt runoff probabilities may indicate that there is a higher risk in any decision, whereas a close banding of snowmelt runoff probabilities indicates that results are likely to be within a narrow range, regardless of input. If the probabilistic forecast includes the impacts of operational decisions such as reservoir operations, then an evaluation can also be made to determine whether operations in one part of the system are sensitive to operational decisions in other parts of the system. The probabilities can be evaluated in making water management decisions to maximize water supply, optimize power generation, and support other decisions.

More Complex Decision Support

The previous sections illustrated increasing complexity in approach when implementing a DSS. However, additional complexities in a system may be due to political/jurisdictional issues (e.g., due to agreements between agencies), additional technical issues (e.g., need to perform groundwater, coastal, or other modeling), data limitations (e.g., additional risk may be present in forecasts due to a lack of timely or quality data), or other reasons. These complexities require that domain experts be utilized to implement the appropriate DSS solution. This may result in more complex modeling or workflow. In some cases, a knowledge-driven DSS must be implemented that utilizes the insight of system operators at key decision points.

THE INCREASED NEED FOR REAL-TIME DECISION SUPPORT SYSTEMS

There is an increased need for real-time decision support systems in water resources, due to:

- increased population and changing land use, thereby increasing the property and population that is impacted by decisions, as well as higher demand on natural resources,
- increased recognition of dynamic conditions such as climate change and increased variability in weather,
- recognized value of risk-based analysis in making decisions,
- ability to detect critical conditions as early as possible to facilitate response.

The above reasons apply to private and public systems, with variability in need based on the mission of an organization and its ability to generate firm revenue for system implementation and maintenance expenses. For example, a water district that collects fees from its user base may have more economic resources than an agency that depends on annually negotiated budgets. By evaluating an organization’s overall needs, it may be determined that there are redundant decision support investments, resulting in higher implementation and support budgets. In these cases, a single real-time DSS may be able to provide data collection, management, analysis, and decision support for multiple purposes, reducing overall costs.

THE RiverTrak® SYSTEM APPLIED FOR REAL-TIME DECISION SUPPORT

The RiverTrak® System developed by RTi provides features to address a number of challenging real-time DSS requirements:

- automated and continuous processing
- real-time and historical data management
- ability to import data from various sources
- ability to process data and provide modeling for decision processes
- ability to perform ensemble-based processing to support probabilistic forecasting
- ability to generate data products and perform notification

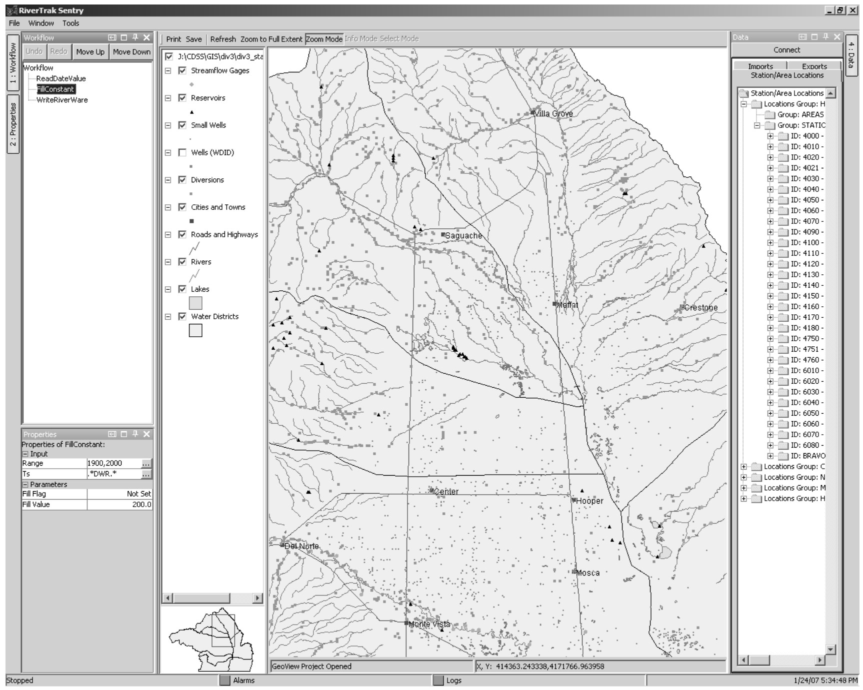

Figure 3. RiverTrak® Sentry Interface Illustrating Workflow and Output Displays

RiverTrak® System Overview

The RiverTrak® System was originally developed by RTi as a flood forecasting system, using models patterned after the National Weather Service River Forecast System (NWSRFS)[1], including the Sacramento Soil Moisture Accounting Model, a snow model, a basic reservoir model, routing model, and various supporting models. Although the initial requirements focused on flood forecasting, the system design was flexible to allow additional processing modules to be added. Subsequent enhancements have adding a more sophisticated reservoir model, additional data imports, time series processing, output product generation, and notification. The current software can be utilized for data collection and management, and streamflow forecasting and other hydrologic and natural resources modeling, in order to support decision making in operational systems. Implementations on highly regulated rivers involving agricultural and municipal water demands are becoming more common.

Examples of RiverTrak® System implementation include systems for the New Hampshire Department of Environmental Services [2] and the Northern Colorado Water Conservancy District (NCWCD) [3], the latter including implementations to provide streamflow forecasts for basins that are managed by the NCWCD as part of the Big Thompson Project, which supplies water to the Colorado Front Range. Current RiverTrak® System development is focused on the Sentry product, which provides complex data analysis and notification features. The following sections present important RiverTrak® System features used in a real-time DSS.

RiverTrak® Workflow

A key feature of the RiverTrak® system is the implementation of a general workflow manager. Processing logic is divided into groups of workflow controllers (e.g., to import data, process data, perform modeling, and other tasks), with specific tasks being managed by the controller. A graphical user interface is provided to configure the workflow and display processing information as the system runs. The flexible design allows an appropriate decision support system to be configured based on the specific needs of a user.

The following figure illustrates workflow for a simple streamflow forecast system and a broader water supply analysis system. These workflows are automatically executed on a configurable frequency in order to process input data and generate results that can be utilized in decision-making.

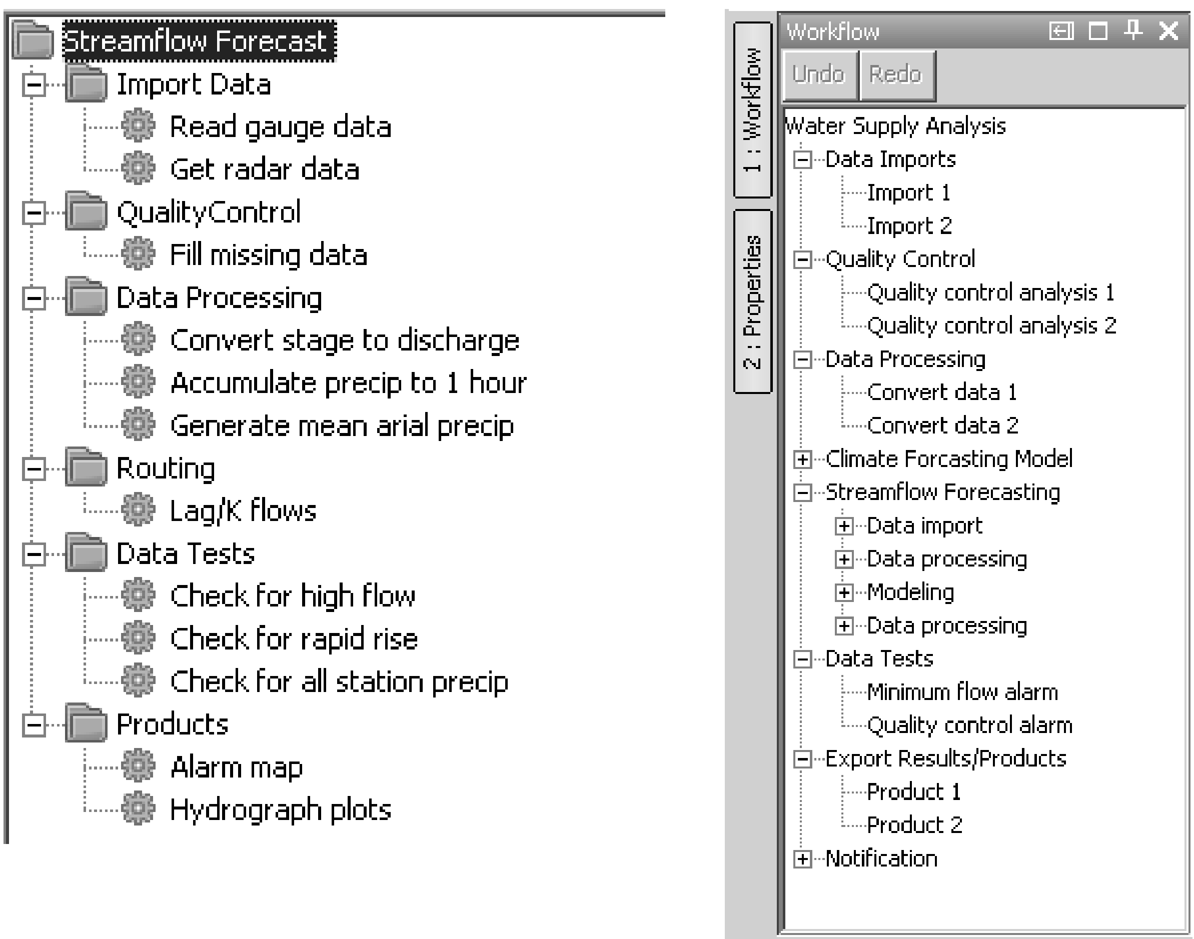

Figure 4. Example RiverTrak® Sentry Workflows for Streamflow Forecasting (left) and Water Supply Analysis (right)

RiverTrak® System Data Import/Processing Options

The real-time nature of the RiverTrak® System requires that data be imported from available real-time data providers. Although government Internet sources may be available for some information (e.g., precipitation and streamflow), there may be delays and/or quality problems with provisional data, which may be unacceptable for an implementation. For this reason, and because quite often customers have invested in or have access to local data collection systems, a RiverTrak® System is often implemented to read data files or databases that are directly available. If a format is not supported, it can be added.

Most RiverTrak® Systems do not interact with a SCADA system. Instead, real-time data imported from a SCADA system may be utilized simply as observational data. However, greater integration of SCADA and DSS, as presented in this paper, can increase the value and functionality of both systems for a customer.

In addition to simple date/value observational inputs, the RiverTrak® System supports use of spatial data, including gridded precipitation observations and forecasts, representing two-dimensional spatial data inputs. Gridded data present additional import, management, and processing challenges, but can provide valuable insight when making decisions.

RiverTrak® System Options For Decision-Making

The RiverTrak® System can complement data collection systems provided by various vendors, and provide higher-level decision support tools, in particular where specialized data analysis and/or modeling are needed. The RiverTrak® System supports probabilistic modeling and gridded spatial input products. Implementation of these systems requires experienced modelers who can perform historical data analysis and model calibration. The ability to perform short and long term forecasting can enhance decision making in systems where longer-term issues are present, for example, water supply systems that depend on seasonal precipitation and management of water storage structures. This information may allow operators to optimize system performance rather than responding only to current conditions.

RiverTrak® System Test/Alarm Features

The RiverTrak® system provides features to perform data tests on input and output time series. An expression evaluator allows multiple criteria to be checked to form complex data tests. This is often required where simple range checks or change in rate checks are insufficient. For example, a test may consist of checking for a threshold value and a rate, for a particular time of the year. The results of data tests are reflected in the database and displays, and can trigger notification via email or an external notification package.

Integration of RiverTrak® Results with Scada

The results generated by a RiverTrak® System typically consist of graphical products, reports and notifications. The numerical values to support these products are maintained in an integrated database and can be used for additional system control, for example via a SCADA system. This can occur through a direct data export, triggering an automated response. It may also be appropriate to collect information on a visual display to allow a knowledgeable operator to determine if a forecasted condition warrants overriding the automated operations of the system. Use of data tests and notification, as well as visual cues, can help operators understand the timing and severity of conditions. Probabilistic results can provide valuable input to the decision process; however, interpretation of the results may require additional training for operators. The integration of SCADA and RiverTrak® System can improve system operating decisions.

CONCLUSIONS

Implementing integrated SCADA/DSS solutions can have the benefit of more directly serving the needs of operators, in particular for operational decisions that require specialized analysis. Advanced modeling in a DSS can supplement the basic decision support in a SCADA system. For example, the DSS can provide probabilistic seasonal forecasts of water supply utilizing historical data, which can support daily operating decisions. The DSS output can be updated as frequently as appropriate to allow decisions to be evaluated and operational adjustments made. Although progress has been made in linking SCADA and DSS, additional progress will be made as communication and data management technologies become more standardized (and less proprietary), and as economic and other reasons encourage increased sharing of information and other decision-making resources. Although day-to-day operations may continue to rely on traditional SCADA system implementations, the use of DSS to provide more advanced decision support can support the core operational objectives of an organization.

REFERENCES

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[2] New Hampshire Department of Environmental Services RiverTrak® System Implementation, http://www.des.state.nh.us/rti_home/.

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10 YEARS OF SUPERVISORY CONTROL AND DATA ACQUISITION MODERNIZATION IN NORTHERN CALIFORNIA (1996 – 2006)

Mr. Dennis Perkins[1]
Dr. Stuart Styles[2]

ABSTRACT

The Bureau of Reclamation, Mid-Pacific Region, Water Conservation Field Services Program (WCFSP), and the Irrigation Training and Research Center (ITRC) at Cal Poly State University, San Luis Obispo, have been working with Reclamation irrigation water contractors and others on district delivery system modernization and Supervisory Control and Data Acquisition (SCADA) development for the past 10 years. In 1994, the WCFSP encouraged the ITRC to develop concepts for district modernization to improve water delivery efficiencies. Dr. Charles Burt and the staff at ITRC observed that in many instances, water delivery systems were operated as more of an art than a science. Every canal or pipe system was different and required intricate knowledge and visual observations by the operators to maintain relatively crude levels of flow balance. The development of affordable, non-proprietary automation systems were considered feasible as SCADA applications were becoming common in other industries such as the automotive manufacturing industry. Coupled with mechanical canal level management equipment design improvements over the years, the industry has made large advances in affordable district level water technologies over the last decade.

MOVING FROM ART TO SCIENCE

"If it isn't broken, don't fix it". A common response when talking with districts is: "We've been doing this for a hundred years, and it's worked so far, so why should we change now?" The response to this could be another question: What comprises "broken"? Broken might be perceived as the lack of response to changing water supply and demand conditions. Those practices that "worked" fifty or a hundred years ago might not work as well today because of the overwhelming public, agricultural, and environmental demands on a fixed and occasionally deficient water supply. While the terminology and definitions may

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be debated, the need for increased efficiency and conservation has undeniably accelerated significantly in the past fifteen years.

Albert Einstein said, “The significant problems we face cannot be solved at the same level of thinking we were at when we created them.” This principle also holds true for irrigation distribution systems. Dr. Burt (Chairman of the Board, ITRC) once shared with us his theory of, “moving from art to science.” Art is like an artist’s stroke on canvas, where each one is unique. Science, on the other hand, is repeatable, constant, understandable, and lends itself to explanation. For decades, water management has been dependent on the skill of the ditch tenders to manipulate an artistic balance between canal supply and farm turnout diversions. Each canal requires a different “stroke”. This has worked for a hundred years, but with a highly competitive demand for water, we are now challenged to improve management efficiency. Art does not lend itself well to consistent and repeatable efficiency improvements. Science, however, does.

The first step towards a scientific approach to water management requires a consolidation of information. While parallel efforts on modernization have been on-going at Reclamation’s Denver Technical Services Center and in other Reclamation Regions, the ITRC afforded the Mid-Pacific Region professional and student staffing that provided expanded opportunities for literature and technological research. Testing and prioritizing SCADA systems or components that were non-proprietary, the researchers prepared lists of available equipment and software for review and testing. The equipment was tested and subsequent component ratings and recommendations were made available for the development of conceptual modernization plans.

SCADA systems have been around for over twenty-five years. Systems constructed in the 1970’s and 1980’s were unique and were comprised of hand-constructed components and proprietary programming which tied the district user to the single provider. The proprietary nature of these early systems was the primary hurdle. Parts were expensive because of lack of competition and interchangeability. Likewise, if the programmer ceased business or moved out of the area, there was a problem when it came time for program maintenance.

Recent systems were first used for reporting information. While the architecture of the systems was designed for expansion and automation uses, the early applications were utilized on monitoring propeller meters fitted with electronic heads. The SCADA equipment would send the information to the district office, collecting and displaying real time flow, totalized meter flow, and accumulated (multiple meters) flow measurements. Where pumps were used to divert water, the SCADA equipment was used to monitor pump operation and supply stage status. Alarming was also a capability of the SCADA systems. Alarms were used to call attention to low or high water levels, electrical shut-downs, and pump, operational, or measurement malfunctions.

In the beginning, planning was, and continues to be, a challenge. Like building a house one room at a time, it is vital to have a conceptual plan to work from. Designing a SCADA system that is expandable has proven to save time and significant amounts of resources. Today, non-proprietary programs and equipment are available that can be accessed and understood by a wide sector of the workforce. Parts are interchangeable, highly competitive, and robust.

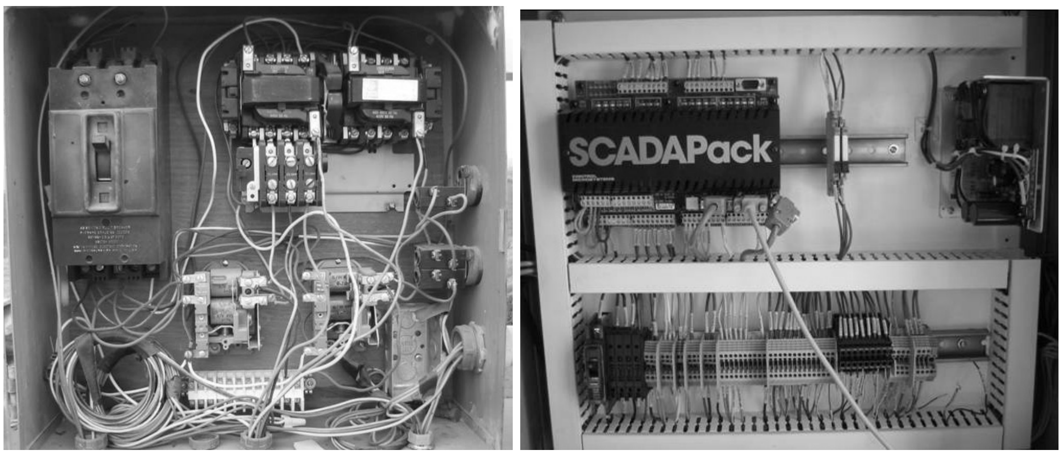

Figure 1. SCADA panels then (left) and now (right)

Water Districts have been encouraged to take a phase-in approach to implementing SCADA and automation technology. It has been Reclamation's experience that many district boards were initially reluctant to move to a system built around computer automated systems. The usual concerns are initial cost, personnel training requirements, reliability, maintenance, and trust. As a result, working through Reclamation and California water conservation grant programs, cost-share funding was provided to assist the districts in initiating demonstration programs.

These base programs usually included setting up the district office with a computer and connectivity (radio or wire), at least one pump station (usually with multiple pumps), and a SCADA package. This would allow the districts to see how the system operates, provide information on a real-time basis, save operator travel time, improve information accuracy, and give the district an opportunity to become familiar with the programming. In this stage, although capable, the SCADA unit is not yet tasked with full operational automation. Rather, it is used for remote turn-on, turn-off, monitoring information and alarms. This provides an opportunity for the operators to verify and develop a level of confidence and understanding of the equipment's operational capabilities.

Finding an Integrator

SCADA system installation requires an electrical engineer or other professional with equivalent experience in system electronics integration. Early integrators were few. There was little demand and even fewer trained integrators available who had knowledge of irrigation district needs. A "request for proposals" for a district's integration would bring one established integrator from Nevada, one from Central California, and several proposals from turf system "integrators". It was important and very necessary to review the experience of the integrator in making a selection.

Over the years we have determined that all integrator bids should require cost breakdowns as well as identification of manufacturers of component parts. If the integrator is not willing to provide that, it may be appropriate to have a specification sheet from which all applicants can bid. This keeps the field level for the competition and makes sure that the reviewer knows what the district is getting. It also is a way of assuring the district that the equipment for this portion of the project will communicate with the later additions.

A complete SCADA package includes the screens that allow both information-at-a-glance, and automation control. When designing the interface that communicates the essential information to the district's office staff, it is important that the integrator/programmer has all the requested data points that are anticipated to be needed. The district staff should visit other districts with SCADA systems and note the information being collected. A complete package also must include full documentation of wiring schematics, input/outputs and programming specifications for future maintenance.

APPLICATION RESULTS

SCADA has proven to be a vital tool in overcoming common challenges faced by irrigation districts. For example, gravity pipe systems often struggle to "keep the pipe full". When filters become plugged, supply canal levels fall too low or a pump fails to start, a priority situation is created. Or a pipe rupture may result from the water hammer caused by entrained air or sudden valve closure. SCADA monitoring can provide 24/7 immediate alarming phone calls with a description of the problem, as well as collect historic data on the events that led up to the problem. District field staff now have the potential of utilizing mobile internet technology to connect to the office, which will allow them to evaluate the problem from wherever they happen to be at the time. Remote SCADA monitoring also provides simple but timely opportunities to adjust diversion flows or turn on a pump that was stopped due to a power interruption.

From the district office, managers and supervisors can monitor flows, fluctuations, flow totals, pump status and efficiencies, line pressures, reservoir or tank stage, canal level status, upstream or downstream canal conditions, alarms, alarm resets, diversions, demands, power fluctuations, and history. Along with improving supply reliability, these systems provide opportunities to improve operational efficiencies and save electricity, man hours, fuel, and vehicle mileage.

The historic data also proves valuable in management decisions such as contract discussions, delivery disputes, identifying maintenance priorities, and overall system supervision.

Reclamation and District SCADA Interface

In Northern California, Reclamation has responsibility for metering Federal water supply contract diversions from the Sacramento River. In 1996, with the Area Manager's support, the water conservation program developed what was referred to as a "lead the field" program. In this program we looked at how Reclamation in Northern California served its customers and how diversion information was gathered for which Reclamation was responsible. Following guidelines similar to those developed for districts, Reclamation looked at metering accuracy, maintenance schedules, and how we might modernize to better improve efficiency. This was a parallel effort to the WCFSP where we encouraged the districts to do the same.

While most of the over 300 meters along the Sacramento River were the standard propeller meters, we found a few sites with less than desirable measurement results and set priorities for modernizing these sites. In keeping with implementing change slowly, the water meter staff are still going to the field each month and gather the meter data as before. However, things are changing, significant improvements have occurred in data accuracy at many sites, and the confidence in the reported numbers is likewise improving. Erroneous meter functions are recognized much sooner with less travel and oversight. Many of the needed measurement sites that were once considered difficult for quality measurement are now providing good, reliable and highly accurate measurements.

In order to capture the diversion data at Red Bluff Diversion Dam, Reclamation installed SCADA monitoring to the Tehama-Colusa Canal to monitor the pumping and diversion flow activities at the canal diversion and research pumping plant (test site of two 350 hp Archimedes Screw lift pumps for river diversions). With SCADA on the Tehama-Colusa Canal diversion and on many of the Sacramento River districts, it became evident that with a little more effort and expense, it was possible to set up a system with district cooperation that allowed Reclamation to view data from pumping sites in near real-time. Agreements were reached that allowed the Reclamation office to link to district offices for instantaneous flow, flow totals, river stage, and short-term use forecasts. In order for Reclamation to link to districts, agreements were made that the information would be considered draft and confidential, and not be publicly released until verified by and through both office managers. Upon agreement, the district's SCADA computers were programmed with virtual firewalls to prevent access to sensitive data, and thus allowing Reclamation to access the districts for the water information.

Figure 2. Red Bluff Diversion pumping plant

Currently, with the SCADA monitoring function, the districts and Reclamation's Northern California Area Office can respond significantly faster to discrepancies in function or operation. Reclamation staff can view diversion flows, totals and stage data on a near real-time basis (hourly, or more frequent if needed). The target for this office was to have 85% of the diversions monitored from the office; currently we are monitoring over 81% of the total water diversions allocated under federal contract from the Sacramento River by monitoring just 10 districts and one canal diversion representing an additional 17 districts. While there are 7 more districts with potential to be included, diversions by these seven districts represent only 4% of the total water under contract. River stage data is now available for approximately 160 miles along the river from Anderson to near Sacramento.

Figure 3. HMI computer at district control office

SPREADING THE KNOWLEDGE

Throughout the process, the Cal Poly ITRC staff has continued gathering data on new measurement and automation technologies. As the new technologies were identified, tested and recommended, Reclamation encouraged demonstration sites at the districts, implementing recommended modernization measures and devices. Through these programs, districts have installed SCADA systems into their main offices by which they monitor pump stations' flow and operational data.

Cal Poly State University, San Luis Obispo, has provided excellent training facilities for many years. However, it has not been feasible for many Northern California water district staff to travel to San Luis Obispo (in southern California) to participate in the programs offered there. As a result, Reclamation has explored the development of satellite teaching facilities for district and industry participation. With oversight from Cal Poly (ITRC), and the cooperation of California State University at Fresno, Center for Irrigation Technology, California State University, Chico now has a training facility that provides opportunities for training on district, canal and on-farm level SCADA, pumps, flow monitoring and canal flow and level control devices. This makes it convenient for both district personnel and farm managers, located in the Sacramento Valley, to attend modernization classes and industry presentations. As a result of expanded educational programs, training facilities, and SCADA training and integration curriculum in the universities, the number of user districts and pool of integrators is growing. It is rapidly becoming much less difficult to plan, build, and find integrators for district SCADA system water control programs.

CONCLUSION

Over the last decade, advances in SCADA systems have lent to a highly efficient means of remote water monitoring and control. The user-friendly technology has gained a foothold in the Sacramento Valley due to the financial and technical assistance from Reclamation and ITRC. Districts have expanded their use of SCADA, primarily for data acquisition, emergency notification of delivery system malfunctions and automated controls; however, several other benefits have ensued. The use of SCADA improved operational and staff efficiency, decreased operation and maintenance costs, increased water delivery reliability, and significantly improved water measurement at diversion sites along the Sacramento River.

In the next several years, Reclamation envisions a continued acceleration in SCADA implementation throughout the Sacramento Valley. As competition for limited water resources increases, there will be mounting pressure on districts to manage their allocations as efficiently as possible. This work done by Reclamation and ITRC provides a solid foundation for SCADA automation throughout the Valley.

IMPLEMENTATION AND USE OF SCADA FOR THE SOUTHERN WATER SUPPLY PROJECT

Carl Brouwer, P.E., PMP[1]

ABSTRACT

The Northern Colorado Water Conservancy District (NCWCD) provides approximately 210,000 acre-ft of raw water to much of Northeastern Colorado via the United States Bureau of Reclamation Colorado – Big Thompson Project (C-BT). Deliveries through C-BT began in the 1950's and were predominately for irrigation. However, over time as the Colorado front range has developed, the portion of water delivered to the municipal and industrial (M&I) sector has increased substantially. As this shift from agricultural deliveries to M&I has occurred, pipelines have been added by NCWCD to the original canal system to provide for more flexible and reliable year-round deliveries.

In the mid-1990's, NCWCD began the construction of the Southern Water Supply Project (SWSP). The SWSP consists of 110 miles of pipeline connecting numerous municipal water providers in the southern and eastern portions of NCWCD to the St. Vrain Canal at Carter Lake Reservoir. In addition to the pipelines, three booster pump stations have been added to the system to increase the system delivery capacity. In total, the SWSP has the delivery capability of 110 cubic feet per second.

The implementation of the SWSP necessitated the installation of a Supervisory Control and Data Acquisition (SCADA) system throughout the new system. The delivery system contains seven flow control structures, three pump stations, and several intermediate valve and metering structures along with the operation of the Carter Lake Reservoir outlet works. This highly reliable system utilizes a distributed control system. Local control functions such as delivery control are made via programmable logic controllers (PLCs) at each individual site. These sites communicate via radio system to NCWCD where overall system control and water orders are made. This system acts to primarily make desired water deliveries. However, fail-safe features area also integrated to provide integrity to the pipeline in the event of system outages or pipeline failure.

This paper will provide information on the planning and implementation of the SCADA system as well as lessons that have been learned through both the implementation and continued operation of the system.

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SOUTHERN WATER SUPPLY PROJECT

The Southern Water Supply Pipeline (SWSP) conveys water from the Windy Gap and Colorado-Big Thompson projects to various Front Range cities within the Northern Colorado Water Conservancy District (District) and the Municipal Subdistrict of the Northern Colorado Water Conservancy District (Subdistrict) boundaries. A map of the project is shown in Figure 1. The project consists of 110 miles of steel pipe ranging in diameter from 45 inches to 16 inches. The total project cost was $65,000,000.

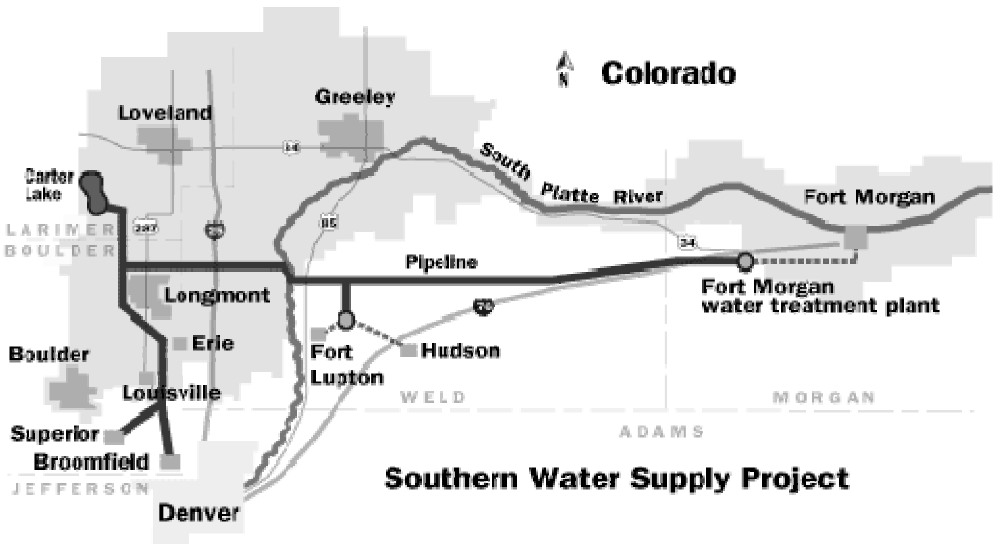
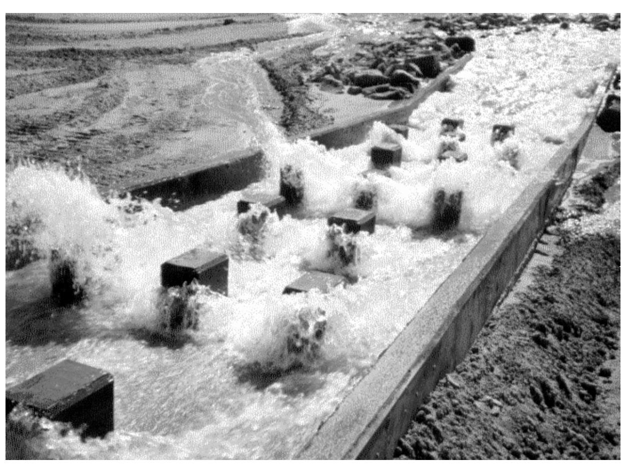


Figure 1. Conceptual Map of the SWSP System

Construction on the first phase of the pipeline, from Carter Lake to Broomfield, began in November 1993. The second, from Platteville to Fort Lupton and Hudson, was completed in July 1996. Construction on the last 41-mile section, from Platteville to Morgan County, was completed in August 1999.



First Filling of Fort Morgan's Reservoir

The Northern Colorado Water Conservancy District (District) owns the pipeline. Participants in the project own the contractual rights to the water. Participants include the cities of Fort Morgan, Fort Lupton, Broomfield, Hudson, Berthoud, Longmont, Erie, Louisville, the Morgan County Quality Water District, the Little Thompson Water District, Central Weld Conservancy Water District and the Superior Metropolitan District. Each paid its share of the design and construction costs.

The total capacity flow capacity of the original pipeline system was 62 cubic feet per second (cfs). Beginning in 2002, a series of booster pump stations were added to the system to boost the overall capacity of 110 cfs, an eighty percent addition. Thus far, two of the three pump stations have been installed, with one site remaining for construction. The estimated cost to add this capacity is approximately $10,000,000.

SWSP OPERATIONS

The SWSP system was designed to operate with minimal flow disruption and minimal labor. Water flows through the outlet works at Carter Lake, through a half-mile of covered canal, then into the pipeline. The flow is regulated at each participant's flow control structure. All of the system is operated via a SCADA system that can be controlled from the District's east slope office or from the operation center at the Farr Pump Plant on the Western Slope. This section describes the operations of the system and includes a description of the SCADA system that is used.

General Operations

Outlet Works: The Carter Lake outlet was historically used only during the irrigation season from approximately April 1 through October 31 of each year. The addition of the SWSP necessitated the need for year-round operations. The operations of the outlet works are now divided into summer and winter operations. In each case, a canal order is received from the SCADA system, and the gates are adjusted based upon a feed-back loop with the downstream parshall flume. During winter operations, when there is no flow down the St. Vrain Supply Canal, an overshot gate is raised into an *up* position and the canal gates are set to the SWSP order. Since there are inherent inaccuracies between the Parshall flume flow measurement and the SWSP measurements, a pool is maintained within a prescribed maximum and minimum level. If the pool falls outside of these limits, a correction of up to 10 percent is made to the SWSP flows using the canal gates. If that correction fails to compensate, then a correction is made at the gatehouse. All of this is designed to minimize the number of times the Carter Lake gates must be operated. A schematic of this system is shown on Figure 2.

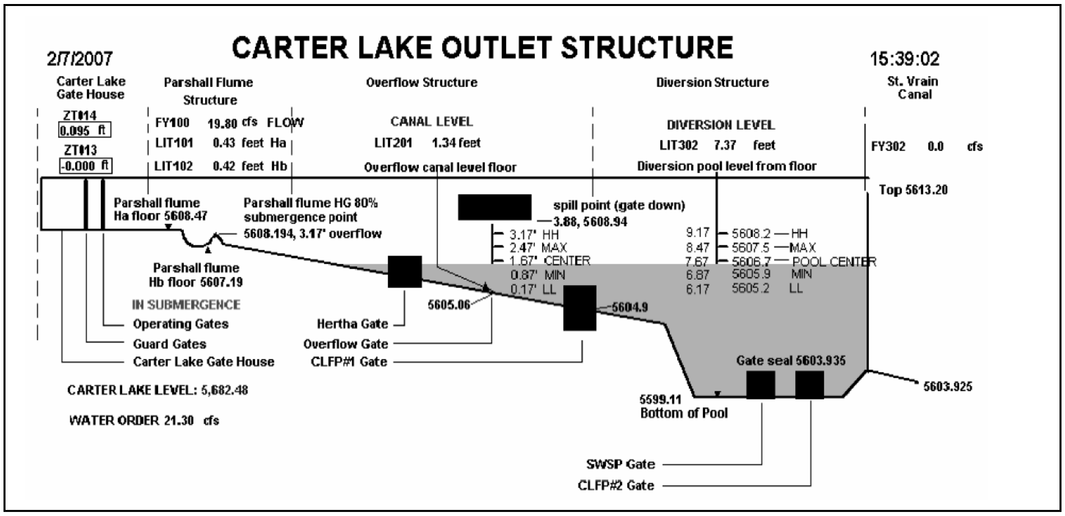


Figure 2. Schematic of St. Vrain Canal Pool Operation

During the summer operations, when there is a canal order, the overshot gate is lowered to the *down* position and the SWSP project flows are simply included into the canal water orders. During the "shoulder" periods between full summer and winter operations when canal orders are below 50 cfs, the overshot gate is put into an intermediate position in order to maintain a pool above the SWSP intake.

<u>Pipeline Operations</u>**:** Except for the Louisville/Superior pipeline, the SWSP operates under gravity flow. The flow control stations utilize CMB Industries Bailey Polyjet 305 valves. These valves are specially designed to control flow and dissipate energy without causing cavitation damage. The valves are controlled using the hydraulic pressure of the pipeline and are opened or closed using 24-volt solenoids attached to the SCADA system. The Louisville/Superior Pump Station operates in a way similar to the flow control stations except that instead of valves regulating flow, variable speed pumps are used to regulate flow.

Mainline valves are provided throughout the pipeline project. In general, the valves are located approximately between 8- and 10-mile spacing. The Broomfield Pipeline has two mainline valve vaults, one on the north side of Longmont at the Fort Lupton/Hudson Pipeline turnout and one on the south side of Longmont. The north mainline valve is connected to the SCADA system and can be automatically shut off. The remaining mainline valves in the system are buried high performance butterfly valves with manual operators. The manual operators were selected since the pipeline is generally only brought down for maintenance once a year.

<u>Booster Pump Station Operations:</u> The booster pump station addition to the SWSP allows the system to flow at a higher rate by making up for the additional pressure loss in the pipelines due to higher flow. The pumps are all equipped

West Longmont Pump Station with 4-500 hp pumps

with variable frequency drives (VFDs). The VFDs allow the pump speed to range from 50% to 100% of the rated pump speed. The desired flow and/or pressure can then be adjusted. The startup and shutdown of these stations needs to be closely integrated with the downstream flow control facilities so the system stays in “sync.” When the booster stations are turned on or off, this represents a change in state for the entire pipeline system from “Gravity Mode” to “Pump Mode.”

Emergency Shutdown: In the event of a pipe rupture the entire SWSP is shut down. The system compares the flow at the Master Meter to the sum of the meters downstream. If the Master meter is greater than the sum of the meters, the SWSP valves are closed and the Carter Lake gates are adjusted to the accordingly. This is likewise true for the Fort Lupton/Hudson Pipeline and the Morgan pipeline, both of which have a meter at the beginning of each pipeline. A tolerance of approximately 5 cfs is allowed to take into consideration differences in metering error or travel time in flow changes from downstream to upstream. In addition to all automated valves being shut on the pipeline, the outlet works flow is also reduced by the amount of pipeline flow order.

SCADA Operations

The SCADA system operation is based upon water orders from the various participants. Participants are allowed to place up to different three water orders each day by phone to the District. The District staff in turn place the orders into the system through a water order screen. The desired flow rate is then sent to individual sites for execution.

Each flow control site acts autonomously from the remainder of the system. When a new water order is executed, the local PLC looks at the flow rate and adjusts the valve position or pump speed until the desired water order is achieved. Since the pipeline system is dynamic – a change in flow at one site may change the pressure at another site – a constant feedback loop at the local PLC is employed. This feedback loop continually monitors required flow or pressure and makes adjustments to the valve position or pump speed as necessary.

In addition to the adjustment of flow, the local PLCs monitor various data and report the information back to the District every few seconds. Such data includes flow, pressure, valve position, pump speed and temperature, intrusion, and high water. Based upon this information, various alarms will signal at the District PC if parameters are outside set tolerances. Additionally, all information is logged into a database for troubleshooting and in the case of flow, water accounting.

SYSTEM DESIGN AND IMPLEMENTATION

The planning for the SWSP SCADA system began well before the first joint of pipeline was laid. Critical to the overall planning was integration of the Operations and Maintenance (O&M) department's ideas and concerns since ultimately the operation and maintenance of the pipeline would fall under their control.

The District contracted with Leedshill-Herkenhoff, Inc. of Albuquerque to provide for the basic design of the system. The primary consideration was to keep the majority of the system operational even if an individual site went down. Hence, a *distributed control* system was selected as the overall structure. Leedshill-Herkenhoff assisted District staff in the selection of the equipment and overall system logic.

A general specification and system outline was then given to Ener-Tech of Albuquerque for implementation. Ener-Tech was required to provide a successful bench test of the entire system prior to installation. This step proved invaluable since several tries were required before the system operation was successful. Had this step been attempted in the field, the time required to implement the process would have been greatly increased and the O&M staff's confidence in the system greatly decreased.

Following successful testing, the system was installed with a combination of District staff and Ener-Tech staff. Testing of the system was then made and the SCADA system became operational. As additional sites have been added to the system, all installation and programming has been done by District staff.

In all cases the pipeline and pump station contractors were required to install all instrumentation and bring all the wiring to a terminal box. The District then installed the connection to the PLC cabinet.

SCADA EQUIPMENT AND OPERATIONS

SCADA Equipment

The District uses a PC-based SCADA system that can control the SWSP either from the District's headquarters on the east slope or from the west slope operation center at the Farr Pump Plant. Since the Farr Pump Plant is manned 24 hours a day, the default operations are made from that plant.

Figure 3 shows conceptually how the SCADA system operates. The system uses distributed control - the actual control of valves is made at the individual sites - and the computers at the District only send out water order commands. The two PC controllers are connected via the District's east slope-west slope fiber optic/microwave communication system. All of the sites in the system report via radio to the Bald Mountain microwave site, located west of Loveland. At that point, the information going in and out is connected to the east slope-west slope communication system.

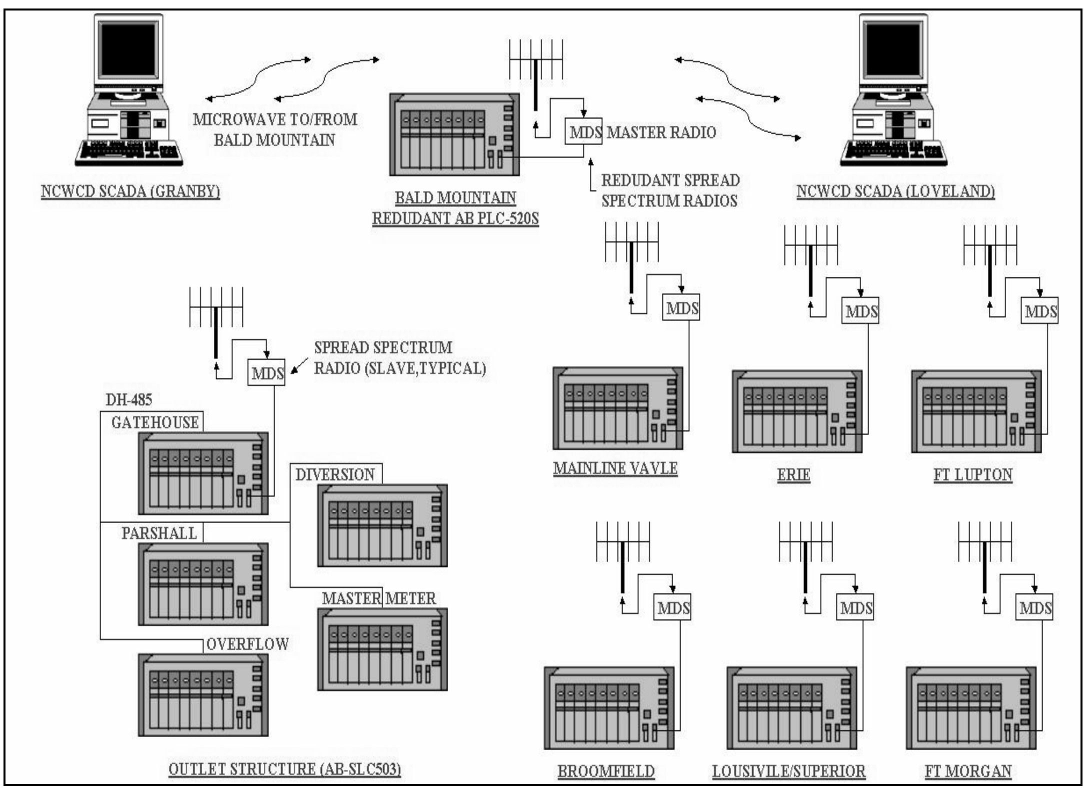


Figure 3. Original SWSP SCADA Layout

The controls performed in the field are made via Allen-Bradley "Slick 500" Programmable Logic Controllers (PLCs). The PLCs take in miscellaneous data in either digital or analog format. Programming is achieved using "ladder logic." Such data includes pressure sensors, flow sensors, valve position, intruder alarms, and high water alarms for a typical flow control station. This data is constantly radioed back to the District. When a water order is sent to a PLC, the PLC compares the water meter flow value to the new value and adjusts the valve accordingly. In the case of the Louisville/Superior pump station, the same type of logic is used to adjust the speed of the pumps.

Communication between the sites and Bald Mountain are made via a 900 Mhz spread spectrum radio signal. The radios are Microwave Data Systems 1-watt radios with a range of nearly 60 miles. This type of communication was chosen over other communication medium such as telephone and fiber optic because of its relatively low cost and high reliability. The spread spectrum signal is unlicensed which may produce signal conflicts in the future. The approach was chosen as opposed to a licensed 900-Mhz system only because there are currently no channels in that frequency bands available from the FCC.

The interface between the radio signals and the District's data network is made at Bald Mountain. An Allen Bradley PLC 5 acts as the interface between the distributed network and the District data system.

The overall control is performed using a PC-based SCADA interface. The system was designed using Intellution's FIXDMACs software (now GE). This software provides a graphical operator-system interface for data display and system control. A sample display of showing the system overview is shown on Figure 4. The system is also used to report alarm conditions and archive data.

LESSONS LEARNED

After twelve years of operation, there are several important lessons learned from the SWSP SCADA system.

1) The SCADA system is reliable. Since the SWSP is the major or sole source of water for the Participants, extended downtime is unacceptable. Fortunately, the SWSP SCADA system has proven to be exceptionally reliable. Even with the occasional lightning strike or communications failure, the nature of the distributed control allows the system to stay functional when one particular site has a problem. The equipment selected however has proven to be durable and long lasting.

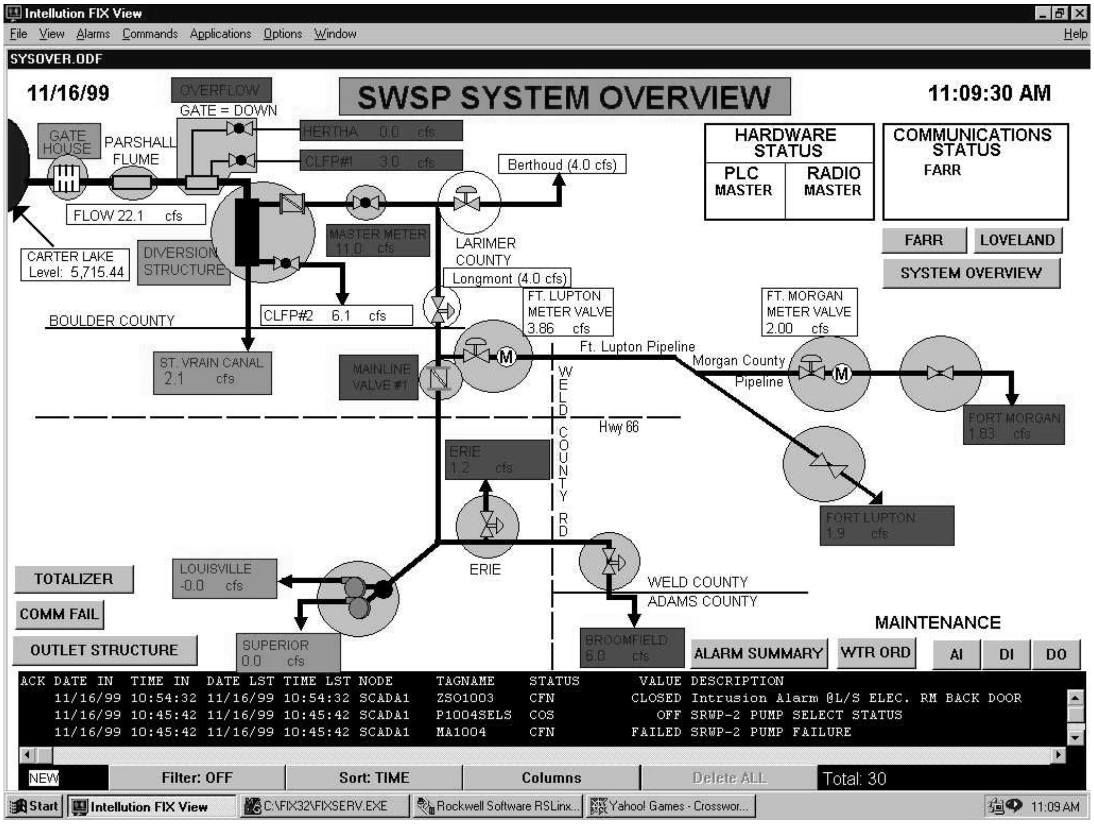


Figure 4. SWSP System Overview Screen

2) SCADA can improve system operations. The SWSP SCADA system has enhanced the overall operation of the delivery system. Firstly, the operation of Carter Lake Reservoir outlet is now run automatically based upon water orders versus the previous manual operation. Hence, operations personnel no longer are required to attend to the outlet when flow changes are made. More importantly, the quantity and quality of the information obtained throughout the system allows for rapid troubleshooting should operational problems arise.

3) SCADA is not maintenance free. SCADA is not something that once installed, can be left alone. The District has two employees who are dedicated to the maintenance of the District's SCADA system which includes the SWSP and other facilities throughout the collection and distribution system. Since the operation of the system is only as strong as the weakest piece of equipment, upkeep and calibration of the instruments and SCADA equipment is imperative. While the SCADA PLC and radio systems provide the communication conduit and commands, the actual instruments – flow measurement, pressure measurement, valve position, etc. – are the backbone of the operation.

4) SCADA systems are adaptable and expandable. The SWSP implementation was staged over 12 years. The first part of the system – the Carter Outlet Modification and the Broomfield pipeline – served as the initial backbone of the project. Initially the system started with the canal outlet area, two automated mainline valve stations, and two flow control structures. Over time, two additional mainline valve stations, five additional flow control stations, and three pump stations have been added. Additional structures are planned in the future. With the expertise of the two District SCADA and instrumentation staff members, the expansion of this system by nearly 200 percent has been straightforward and cost effective. System logic has been modified, and in certain instances, equipment has been upgraded.

5) SCADA as is cost effective. Of the original $67,000,000 project cost before the pump station additions, SCADA represented about $1,000,000 of the cost or about 1.5%. Considering the cost of manual operation – at least two to three full time people operating the SWSP system – the cost of the system has been money well spent.

MODELING EVAPOTRANSPIRATION FOR IRRIGATED CROPS IN JORDAN USING REMOTELY SENSED DATA

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ABSTRACT

A study was conducted in Mafraq, Jordan, between 32°15′ and 32°50′ north latitude and 36°15′ and 36°50′ east longitude, to investigate the potential use of remotely sensed data to estimate evapotranspiration (ET). Evapotranspiration values were estimating by integrating high resolution (ASTER) and coarse resolution (MODIS) data in the ALARM model. The first part of the study focused on identifying crop types and developing a relationship between plant canopy height (PH) and Normalized Difference Vegetation Index (NDVI) from ASTER. The second part of the study concentrated on modeling actual ET through the integration of data from the previous stage and from the MODIS satellite with the ALARM model. Field surveys and data collection, from March to October 2005, included 37 farms with a total of 247 plots representing irrigated vegetable crops in the area. The ET was calculated using the ALARM model with input parameters of land surface temperature, leaf area index, surface albedo, view angle, view time from 1-km MODIS data and plant canopy height derived from its empirical relationship with ASTER NDVI.

Results showed that ASTER satellite imagery could provide an adequate identification of different irrigated vegetable crops in the study area. The use of estimated PH derived from its relationships with ASTER-NDVI instead of ground measurements was not a significant source of error for estimating ET. The average performance of the ALARM model showed a strong spatial variability

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from one site to another depending on the individual components of each site (total irrigated area and type of irrigated crops). The calculation approach of ET using the ALARM model with MODIS satellite data and crop parameters from ASTER data can be used to provide spatial distribution of actual ET. Therefore, the calibrated approach from this study could be used as a new tool for estimating ET for the irrigated area of Mafraq and similar irrigated regions in Jordan. The study also demonstrated the importance of radiometric correction for satellite images before using them in similar studies.

INTRODUCTION

Irrigated agriculture in Jordan has been growing rapidly. The irrigated highlands in Jordan increased from approximately 3,000 ha in 1976 to more than 43,000 ha in 2007. Groundwater is the main source of irrigation in the highland areas of Jordan. Approximately 6,000 ha are irrigated with fossil water in Disi and Jafer areas and about 33,000 ha are irrigated in the Jordan valley. The available fresh water supplies in Jordan were approximately 826 million cubic meter (MCM) in 2003 of which 520 MCM were used in agriculture (63.5 % of the total water use in Jordan). Urban water uses accounted for approximately 32.5% while industrial uses accounted for 4%. The total available water resources per capita are decreasing as a result of population growth (annual rate of 2.5% in 2004) and are projected to fall from the current 160 m^3/capita/year to about 90 m^3/capita/year by the year 2025.

Conventional field surveys and traditional mapping methods are fairly comprehensive and reliable for estimating crop evapotranspiration. However, they are often subjective, costly, time consuming and are prone to errors due to incomplete ground observations. Consequently, objective, standardized and possibly cheaper/faster methods that can be used for differentiating crop types, estimating cropped area and monitoring crop growth and requirement are imperative. As an option, remotely sensed data (RS) can provide systematically high quality spatial and temporal information about crop type, crop area and crop evapotranspiration (Sawasawa, 2003).

The RS technology can provide real-time monitoring system of cropped areas at an acceptable accuracy (Apan *et al*., 2003). Also, it can regularly provide objective information on the agricultural conditions of large land surface areas as well as small areas with reasonable cost. The use of remote sensing for mapping, assessing and monitoring agricultural crop conditions has been increasing. Several studies have focused on developing methodologies for mapping crop types and areas. These studies have either focused on the use of remotely sensed vegetation indices derived from spectral reflectance of near infrared (NIR) and red bands or focused on the use of digital classification techniques of single satellite imagery.

In Jordan, there has been relatively little practical contribution from remote sensing regarding irrigated areas in the highlands of the country. Further studies are needed to correlate crop parameters (plant canopy height and fractional vegetation cover) to remotely sensed vegetation indices and to identify and select image processing algorithms pertinent to vegetation assessment and monitoring and produce a quantitative data in time and space. Therefore, the first part of this study focused on developing a methodology for differentiating crop types and correlating crop parameters (plant canopy height, fractional vegetation cover and crop coefficient) with Normalized Difference Vegetation Index (NDVI ;defined as the difference between the near-infrared and red reflectance of vegetation normalized with their sum) from Advanced Spaceborn Thermal Emission and Reflection Radiometer (ASTER) satellite and correlating crop parameters with days after planting (i.e. seasonal behaviour and patterns).

The second part of the study focused on integrating the data from previous stage and that of Moderate resolution Imaging Spectroradiometer (MODIS) satellite in the Analytical Land Atmosphere Radiometer Model (ALARM) to investigate and assess evapotranspiration rates in Mafraq area. The advantage of this approach over traditional methods is that ASTER-derived parameters like NDVI provide information on ground cover, plant height, and planted area at high spatial resolution while, MODIS-derived data are available free on the Internet and on a daily basis and do not require in-situ crop measurements. However, the integration of these products with models like ALARM has not been investigated in many areas of the world including Jordan. The overall goal of this study was to examine the perspective potential of remotely sensed data to estimate evapotranspiration by integrating ASTER and MODIS derived data in ALARM model.

STUDY AREA

The total area of Jordan is about 88,778 km^2 and more than 80 % of the country's area is arid and receives less than 200 mm of annual rainfall. The average annual precipitation rate over Jordan is about 93.6 mm. Generally, the climate is Mediterranean, with a long dry hot summer, a rainy winter, and a relatively dry spring and autumn seasons. Irrigated agriculture in Jordan (76,000 ha) falls under two categories in term of management and source of water. In the highlands (43,000 ha), privately managed individual farms are irrigated by groundwater from private wells. In the Jordan Valley (33,000 ha), the publicly managed irrigation system uses surface water of Yarmouk River and side wadis as well as recycled wastewater. Agricultural development in Jordan depends mainly on the availability and quality of water resources, and this requires further improvement of irrigation water management (Jitan, 2005).

The Mafraq Governorate constitutes one of the most important irrigated areas of the highlands of Jordan. Within four years between 2000 and 2004, the area under cultivation in the governorate has increased by 60%, (from 30,900 ha to 49,800 ha) (DOS, 2004). The study area represents the most important irrigated area in Mafraq Governerate, about 100 kilometers north-east of the Capital Amman. The study area is located between latitudes $32^{o}15'$ and $32^{o}50'$ North and longitudes $36^{o}15'$ and $36^{o}50'$ East and covers about 700 Km^2 (Figure 1). The average altitude is about 686 m above sea level.

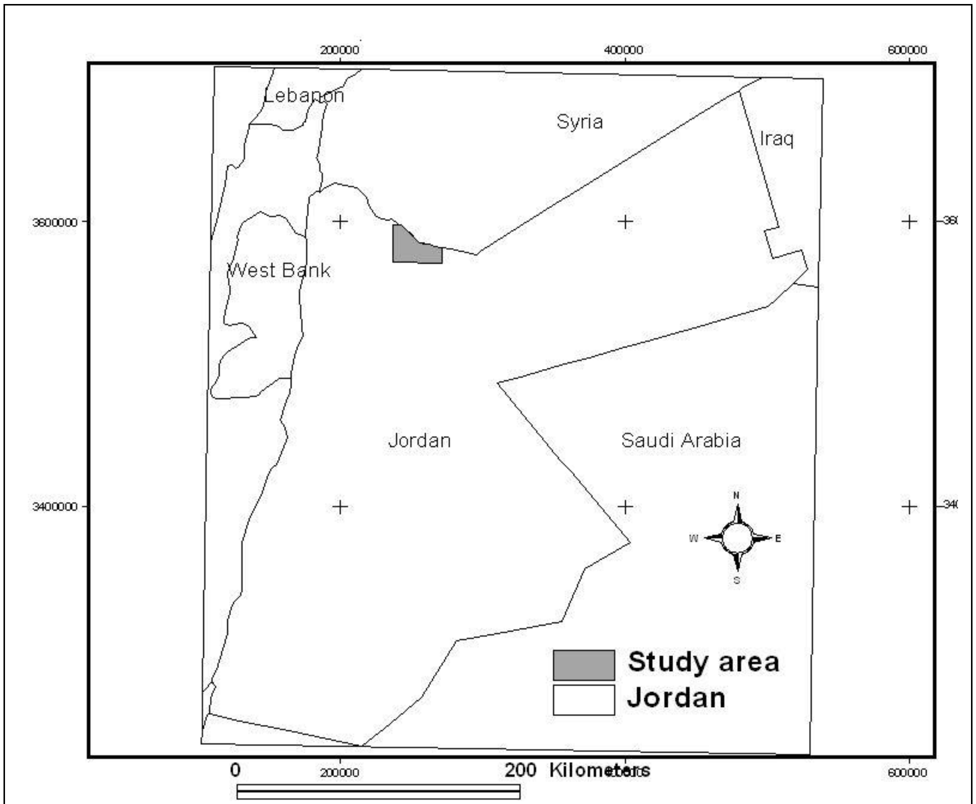


Figure 1. Location of the study area.

The study area is located in the Arid Mediterranean, cool bioclimatic zone, with a long dry hot summer, a cold winter, and a relatively dry spring and autumn seasons. The main irrigated vegetable crops are tomatoes, water melon, cauliflowers, cabbage and sweet melon. Drip irrigation is the dominant form of irrigation in this area.

METHODOLOGY

Assumptions

Vegetation density is the most obvious physical representation of cropped areas. The density and health of plants can be monitored using remotely sensed images that measure chlorophyll activity and vegetation vigor. The spectral reflectance is a manifestation of all important factors affecting the agricultural crop and the cumulative environmental impacts on crop growth and is strongly correlated to the canopy parameters. These parameters are mainly affecting crop evapotranspiration and spectral data (NDVI) is an indicator of crop type and its parameters (Singh *et al*., 2002). This assumption is supported by the high resolution of ASTER (15 m) and the reasonable spectral width of Near Infrared (NIR) and red (R) bands.

Remotely sensed vegetation indices:

The unique spectral signature of green plants is the principle behind the use of vegetation index (VI). The VI offer a quick and easy technique for converting image data from several wavebands to a single value or visual representation that can be interpreted by someone with little training in remote sensing technique, may have some relationship to the amount of vegetation in a given image pixel and can tell something useful about vegetation (Terrill, 1994).The vegetation indices provide information on the state of vegetation on the land surface; vegetation is the result of a complex relation between land and land use, and provides means for monitoring and estimating changes over time. The most commonly used vegetation index is the normalized difference vegetation index (NDVI): This is a ratio based VI, ranges between -1 and +1, and calculated by the difference of the Near Infrared (NIR) and red (R) bands as ratio to their sum (Sawasawa, 2003).

Since satellite data can help in estimating some key-variables related to vegetation phenology. VIs offer opportunities for monitoring the spatial and temporal variability of K_c. Use of remotely-sensed vegetation indices, such as NDVI has been tested to predict crop coefficients at field and regional scales (Ray and Dadhwal, 2001; Jitan, 2005).

Radiometric correction of ASTER satellite imagery

Hand-held multispectral radiometer (Cropscan Inc., USA) was used to measure both incoming and reflected radiation for five optical spectral bands. Including red (0.63–0.69 µm) and near-infrared (0.76–0.86 µm) bands. The NDVI calculated from these measurements was defined as field measured NDVI (difference between near-infrared and red reflectances divided by their sum). Field measured NDVI was taken on 12 May, 2005, i.e on the same day of ASTER image acquisition. Digital numbers associated to red and near-infrared channels were extracted from ASTER satellite imagery and used to calculate ASTER NDVI. Values of ASTER NDVI were compared to the corresponding field measured NDVI for each field using linear regression analysis. For most crops, significant linear relationship with strong correlation was observed. Except for squash, the correlation coefficient (r^2) ranged from 0.93 to 0.98 for the different irrigated vegetable crops.

The overall correlation between ASTER and field NDVI values for all irrigated crops had an r^2 value of 0.96 and slope of about 0.5 which indicated strong and significant ($p=0.05$, $n=60$) linear relationship (Figure 2). Based on the above results, the images from April, June and September, 2005 were radiometricaly corrected using May image as a base image (master) (Emar Suifan, 2006).

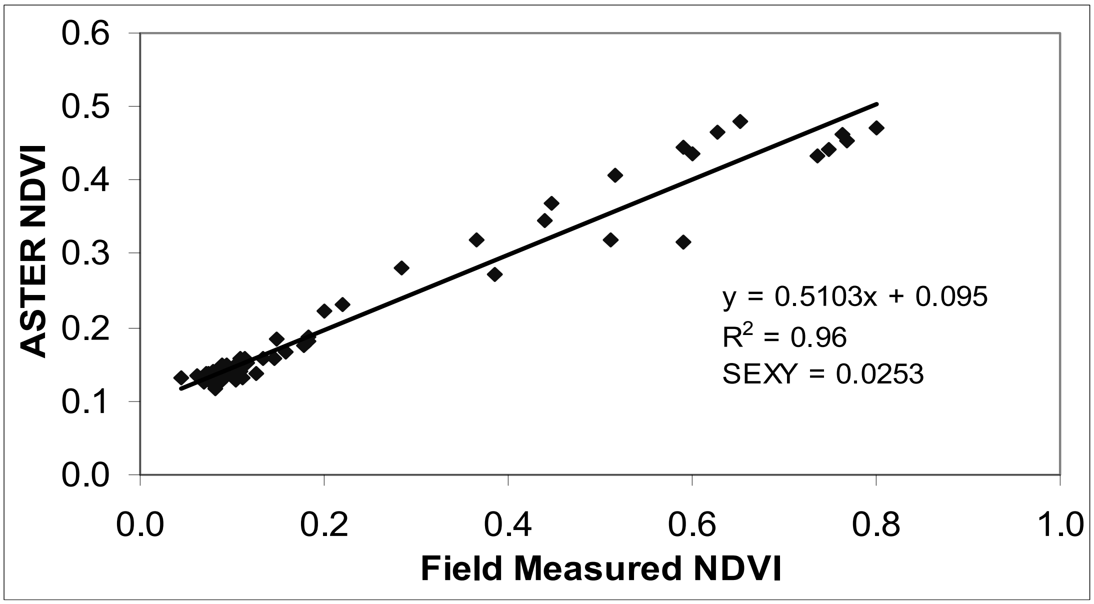


Figure 2. Relationship between ASTER-NDVI and Field measured NDVI for all crops, used for absolute radiometric correction of ASTER image of May, 2005.

RESULTS AND DISCUSSION

The relationships between plant canopy height (PH) and fractional vegetation cover (GC) for various vegetable crops in the study area were determined (Emar Suifan, 2006). The two crop parameters exhibited similar seasonal patterns. Significant correlations were observed between PH and day after planting (DAP) and between GC and DAP. The correlation coefficients (r^2) between PH and DAP ranged from 0.77 for sweet melon to 0.96 for squash. The correlation coefficient between GC and DAP ranged from 0.80 for cauliflower to 0.95 for squash. Additionally, correlations for GC and DAP did not follow a similar trend to PH and DAP. For eggplant, as an example, r^2 between PH and DAP was 0.82 while r^2 between GC and DAP was 0.93. The minimum r^2 between GC and DAP was higher than that between PH and DAP.

Average, maximum and minimum values of plant canopy height and fractional vegetation cover for different irrigated vegetable crops for one season are summarized in Table 1. These values and derived mathematical relationships were considered as the first guideline for irrigated vegetable crops in Mafraq area and can be used in the different applications, particularly estimating crop evapotranspiration. In this study, these empirical relationships were used to estimate daily plant canopy height required for estimating the surface roughness and aerodynamic resistance for heat transport which is needed for estimating daily evapotranspiration and adjusting crop coefficient (K_c) for local conditions.

Table 1. Mean, maximum and minimum plant canopy height (PH) and fractional vegetation cover (GC) for different irrigated vegetable crops.

Crop Type	Growing season (day)	Mean		Minimum		Maximum	
		PH (cm)	GC (%)	PH (cm)	GC (%)	PH (cm)	GC (%)
Cabbage	105	25	51	2	0.2	50	99
Cauliflower	126	36	56	4	1	73	99
Eggplant	158	56	49	2	2	100	92
Pepper	188	42	30	2	1	92	68
Sweet melon	132	15	52	3	1	26	99
Watermelon	107	14	34	2	1	30	76
Tomato	170	34	42	3	1	57	73
String beans	102	22	22	1	1	45	44
Squash	102	48	55	1	1	70	95

NDVI for irrigated vegetable crops

The core element of the use of remote sensing technology in monitoring irrigated crops was the identification of crop type and the derivation of crop coefficient (K_c). Initial results of correlating NDVI with days after planting (DAP) showed a significant polynomial relationship with correlation coefficient values being more than 0.90 for the different irrigated vegetable crops. Visual interpretation of the relationship between DAP and NDVI (Figure 3) showed that the NDVI values were nearly constant during the initial stage of most irrigated vegetable crops. This period varied from one crop to another. Similarly, the length of development stage varied according to crop type with sharp increase in NDVI values for some crops and uniform increase over a large period for others.

The relationships between FAO-K_c and NDVI for each crop are shown in Figure 4. The relationship between K_c and NDVI is linear with high correlation coefficient (above 0.94) for all irrigated vegetable crops. These results agreed with the previous comparative studies of linear relationship between K_c and NDVI (Jitan, 2005). Therefore, one can conclude that it is possible to use remotely sensed satellite data to derive K_c for the different irrigated crops in our study area and similar environments.

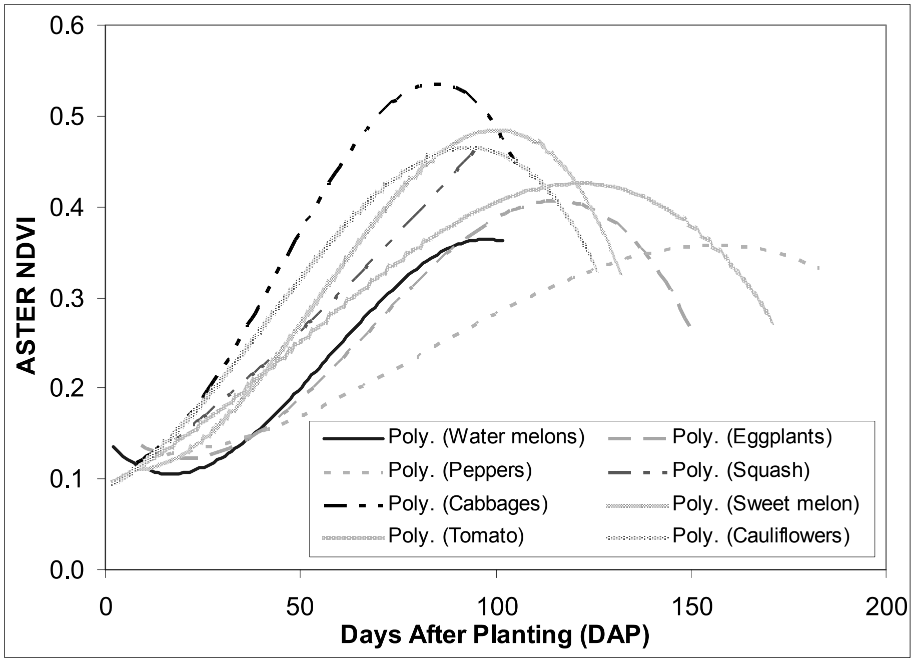
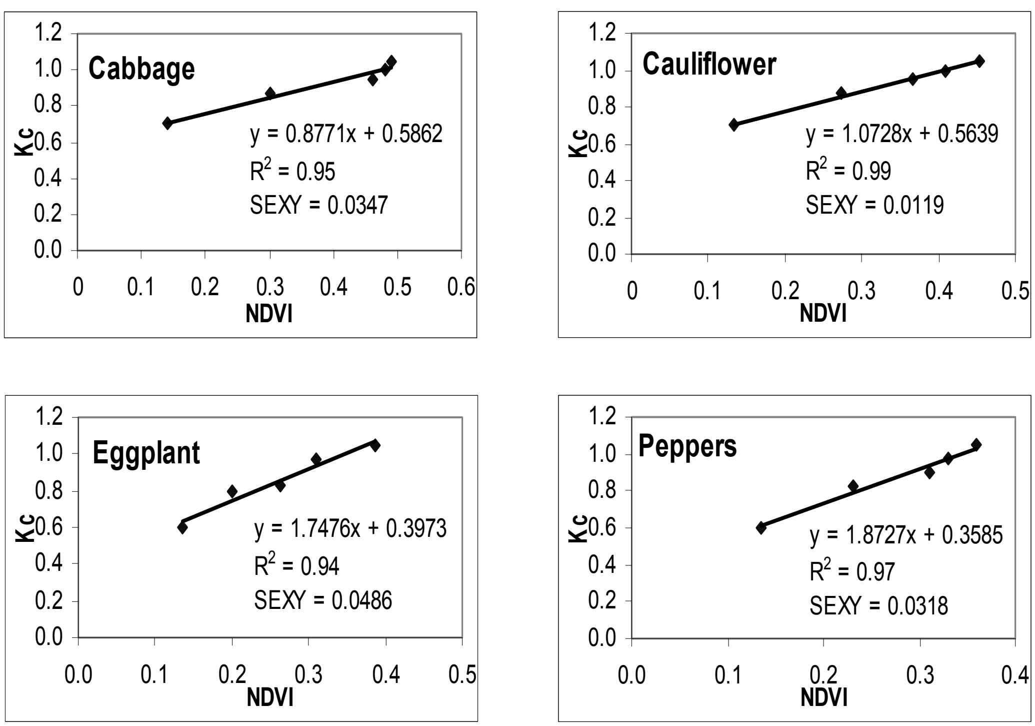


Figure 3. Summary of NDVI-time profile for the different irrigated vegetable crops.



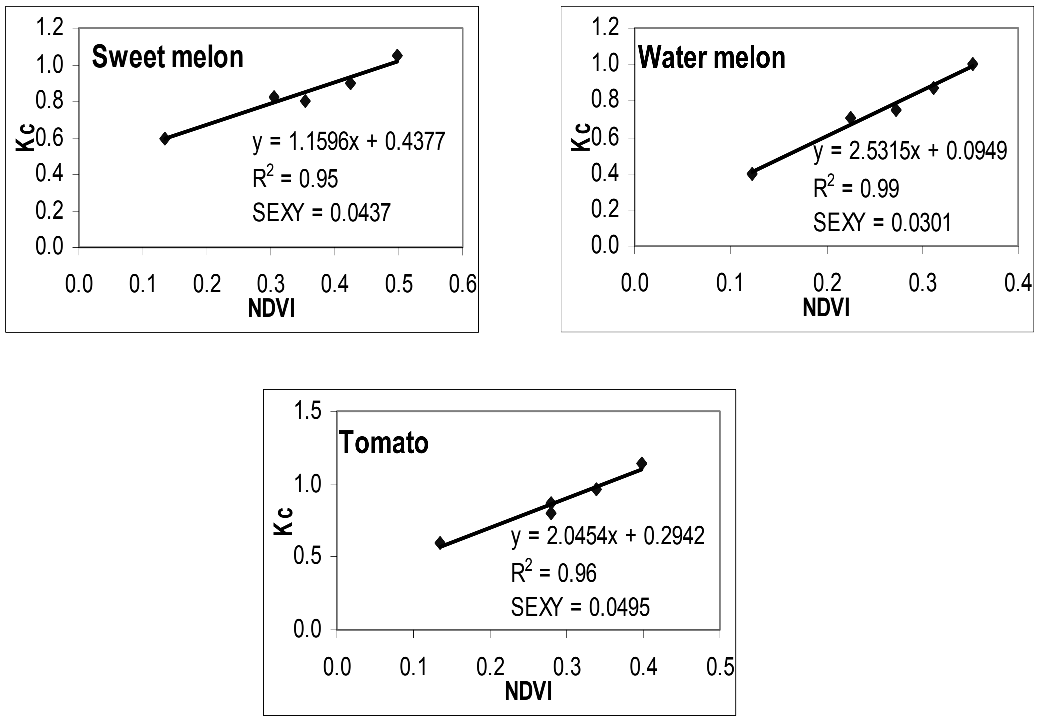


Figure 4. Relationship between ASTER-NDVI and Crop coefficient (K_c) for different irrigated vegetable crops.

<u>Evapotranspiration and Remote Sensing</u>

Daily crop evapotranspiration (ET) values during the summer growing season from first of April to the end of September 2005 were calculated by two methods: First, using the reference (grass) evapotranspiration (ET_o), and the crop coefficient (K_c), ($ET=ET_o*K_c$). The ET_o was calculated using the FAO-56 Penman-Monteith equation. It was developed for a hypothetical well-watered and actively growing uniform grass of 0.12 m height with a surface resistance of 70 sm^{-1} and albedo of 0.23 (Emar Suifan, 2006). Standard crop coefficient (Kc) values of every growing stage (initial, mid and end) and for every crop planted in the study area were taken from FAO-56 document and were adjusted for local conditions.

Second, using the Analytical Land Atmosphere Radiometer (ALARM) model to estimate actual crop evapotranspiration (ET), with input parameters like leaf area index, surface albedo and land surface temperature from the low resolution MODIS satellite images; climatic data from Maqraq Air Port weather and plant canopy height was either measured in the field or estimated from the empirical relationships (derived between plant canopy height and DAP or between plant canopy height and ASTER-NDVI). Since MODIS image had pixels with a resolution of about 1 km^2, ALARM was used to estimate the daily crop evapotranspiration for crops planted in a pixel area. Consequently, the weighted average plant canopy height for the crops planted in the pixel was computed for the use by the model.

The ALARM model was applied for 19 MODIS pixels to compute daily crop evaportanspiration (ALARM ET) for the days in which ASTER images were acquired. Different data were used in the model including measured plant canopy height, estimated plant canopy height from days after planting (PH vs DAP), and estimated plant canopy height from ASTER-NDVI (PH vs NDVI). The plant canopy height was necessary to calculate crop aerodynamic resistance for heat transport. The daily ALARM ET values, estimated from the three plant canopy height values were compared to observe the differences and to check the validity of equations derived between plant canopy height and both DAP and NDVI.

Some, but not significant, variations were observed among the different ALARM-ET values estimated from the three plant canopy height values. However, the maximum difference between ALARM-ET values calculated using measured plant canopy height and estimated plant canopy height from days after planting and estimated plant canopy height from NDVI was ±0.06 mm/day for pixels 1, 3, and 4 for the Julian days of 100, 192, and 248. Meanwhile, there were no differences between ALARM-ET values estimated from the three plant canopy height values for other pixels and other Julian days. These results indicated that the use of estimated plant canopy height from the derived relationships of plant canopy height from days after planting (DAP) or from NDVI instead of ground measurements is not a significant source of error for estimating ET.

The ALARM model was applied in every MODIS pixel to compute the actual daily crop evaportanspiration (ALARM ET). Additionally, weighted average crop evapotranspiration for each pixel was calculated based on FAO-56 Penman-Monteith equation (FAO-PM ET). The daily ALARM ET and the daily FAO-PM ET values were compared to evaluate the differences, as presented in Figure **5**. The weighted average ET from FAO-56 PM in a specific pixel for a given period was calculated as the sum of individual crop evapotranspiration calculated for each irrigated crop divided by the total area of the pixel.

Evaluation and calibration of the ALARM evapotranspiration results

To adjust daily crop evapotranspiration values, which were estimated from ALARM model using MODIS remotely sensed data, the estimated daily ALARM-ET for each pixel was compared with the corresponding weighted average daily crop evapotranspiration calculated using FAO-56 PM equation. Regression analysis was performed between the ET values computed from ALARM and FAO-56 PM, and consequently, a calibration coefficient (C) was calculated for each pixel using linear regression analysis and the least square error technique.

The regression analysis showed that the calibration coefficient for ALARM-ET values ranged from 0.26 to 0.86. The daily calibrated ALARM-ET for each pixel was calculated using the corresponding calibration coefficient (C). Daily ET values from the both ALARM and calibrated ALARM were compared to the FAO-PM values.

Evapotranspiration values obtained from FAO-56 Penman-Montieth equation with those obtained from ALARM model had a RMSE range of 0.76 - 2.80 mm/day with an average RMSE of 1.64 mm/day compared to a RMSE range of 0.18 - 0.64 mm/day with an average RMSE of 0.40 mm/day obtained using calibration coefficient.

The difference between ALARM ET and FAO-PM ET values was evident and varied from one pixel to another. The average performance of ALARM model showed a strong spatial variability from one site to another depending on the individual components of each site (total irrigated area and type of irrigated crops). Generally, the difference between ALARM ET and FAO-PM ET decreased with increasing the irrigated area planted with vegetable crops and fruit trees or with increasing the total irrigated area and decreasing the rangeland area. On average, the ALARM model gave the highest overestimation in the sites with the lowest average irrigated area (vegetable crops and/or fruit trees) or with the highest rangeland area, and gave ET values close to FAO-PM ET values in the sites with relatively large irrigated area or with relatively small rangeland area.

The evapotranspiration values, which were derived from ALARM model using MODIS remotely sensed data, were higher than the evapotranspiration values derived from the FAO-56 PM method. This might be attributed to a lower radiometric surface temperature obtained from MODIS than the actual land surface temperature.

When the calibration coefficient (C) was used to adjust ALARM ET values to fit the FAO-PM ET values, the ET values became very close. Regression analysis of both linear line and second degree polynomial line were drawn between FAO-PM ET and calibrated ALARM ET for each pixel, the latter gave the better trend. The best relationship between calibrated ALARM ET and FAO-PM ET for all pixels (for the study area) is shown in Figure 5. A second degree polynomial line with a correlation coefficient of 0.97 was obtained for this correlation which emphasizes the need and the importance of calibrating modeled ET with other methods.

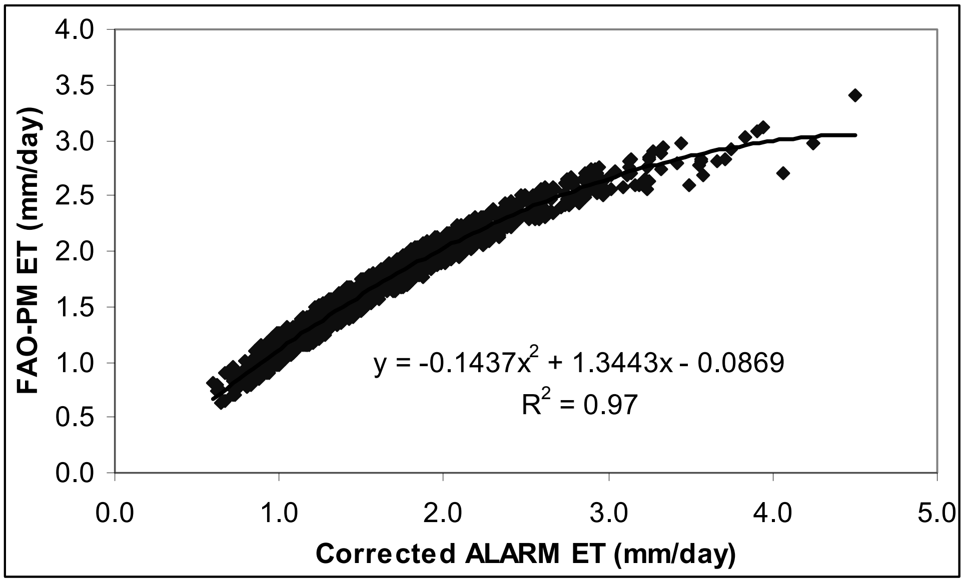


Figure 5. Relationship between calibrated ALARM ET and FAO-56 PM ET (mm/day).

The use of accurate and real time results of ET at regional scale is highly recommended for better management of water resources in the irrigated highland areas of Jordan. It was possible from ALARM-ET to build regional ET and to provide the spatial and temporal changes of ET, these results could provide the decision makers with the required data about the water budget in the irrigated areas for sustainable operation and management strategies of these areas.

The ALARM model can be used to estimate actual crop evapotranspiration (ALARM ET) for an area of 86.49 ha with input parameters like leaf area index, surface albedo and land surface temperature from low cost MODIS satellite images. ASTER satellite imagery or any other high resolution satellite imagery can be integrated with the model to estimate total irrigated area and crop type. Calibration coefficient (C) for ALARM ET can be estimated from the empirical relationship derived between C and the total irrigated area or C and the total rangeland area. Calibrated ALARM ET can be calculated by multiplying ALARM ET with the corresponding calibration coefficient. The FAO-PM ET can be calculated from the derived relationship between calibrated ALARM ET and FAO-PM ET. This approach can be used as a guideline and tool capable to provide consistent, frequent and real time data ET data for the region.

CONCLUSIONS

The calculation approach of ET using the ALARM model with MODIS satellite data and crop parameters from ASTER data can be used to provide spatial distribution of actual ET. The calibrated approach from this study could be used as a new tool for estimating ET for the irrigated area of Mafraq and similar irrigated regions in Jordan. The study also emphasized the importance of radiometric correction for satellite images before using them in similar studies.

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DESIGN AND IMPLEMENTATION OF WATER ACCOUNTING DATABASE FOR RIVERSIDE IRRIGATION DISTRICT

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ABSTRACT

The Riverside Irrigation District (RID) provides irrigation water to about 22,474 acres in northeast Colorado. Its primary water supplies, direct flow and reservoir water, are supplemented by District wells and farmer owned wells. The wells' water rights are relatively junior; therefore, without augmentation to replace out of priority depletions, senior water rights could be injured. RID has developed a plan of augmentation for replacement of out-priority depletions. The plan involves the use of accretions from groundwater recharge as the primary source of replacement water with reservoir water as a backup supply. A database has been developed for RID that allows it to manage RID's augmentation plan to ensure that all out-of-priority depletions to the South Platte River are replaced. The database includes tools for accounting of well pumping, recharge diversions, wellhead depletions, net recharge, streamflow depletions and accretions and farm unit crop water use. An extensive reporting section of the database allows RID to meet its reporting requirement to Colorado's State Engineer and to plan participants.

INTRODUCTION

The Riverside Irrigation District (RID) provides irrigation water to about 22,474 District Acres in Weld and Morgan Counties, Colorado. It is located about 120 miles northeast of Denver, Colorado, and is in the South Platte River basin. The primary water supply for RID is provided by the Riverside Reservoir and Land Company (The Company) and RID's direct flow water rights for 417 cfs. RID owns about 80 percent of The Company. The physical facilities of The Company and RID include about 100 miles of canal, Riverside Reservoir (63,000 acre-feet), Vancil Reservoir (6,000 acre-feet) and seven wells. Within RID, numerous landowners have irrigation wells that are used to provide supplemental water. The wells are tributary to the South Platte River. The wells' water rights are relatively junior; therefore their depletions of the South Platte River could cause injury to senior water rights if they are not replaced in time and amount. RID has developed a plan of augmentation for replacement of out-priority depletions. The plan involves the use of accretions from groundwater recharge as the primary

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source of replacement water. The senior reservoir rights of the plan participants back up the groundwater recharge. Operation of the plan of augmentation is monitored using a relational database. This paper describes the design and functionality of the relational database that imports well data, calculates water use, well stream depletions, recharge stream accretions and available augmentation water, and includes special reporting features used to meet tracking and reporting requirements for RID and the State of Colorado's Department of Water Resources.

Water within RID is proportionally distributed using District Acres. Each District Acre represents one acre of irrigable land on which District taxes are paid, and entitles the owner to a proportional share of the total District water delivered from Riverside's reservoir, direct flow water right and recharge accretions.

RID PLAN OF AUGMENTATION

RID's plan of augmentation is currently pending in Colorado's Water Division One Water Court. RID has operated an annual plan, approved by Colorado's State Engineer, since 2004. In its pending water court application and its approved annual plan, RID replaces out-of-priority stream depletions attributable to the historical pumping and current year pumping using 1) recharge accretions, and, 2) augmentation water stored in Vancil Reservoir by exchanging it up-ditch to Riverside Reservoir from where it will be released to the river. Furthermore, should the need arise; five District wells are used for augmentation. The recharge accretions are available to RID from several decreed recharge plans for which the recharge and diversions facilities have been developed. RID or The Company use from 50 to 100 percent of the accretions or recharge credit available from the decreed plans. Owners of District Acres are entitled to a prorata share of The Company's portion of those plans. RID currently has 99 wells to be included in its plan of augmentation.

DESCRIPTION OF RID DATABASE

Careful monitoring of water resources of the District plan participants is key to successful operation and management of the RID plan of augmentation and to preventing injury to other South Platte River water rights. Operation of the plan of augmentation is monitored using a relational database. The database imports well, groundwater and recharge data, calculates water use, well stream depletions, recharge stream accretions and available augmentation water, and includes special reporting features used to meet tracking and reporting requirements for RID and the State of Colorado's Department of Water Resources. The database can be used to project the impact of future pumping and recharge prior to authorizing additional water use by District members. It allows the District to project depletions and accretions in future years. The power of relational databases allows large quantities of data to be easily recorded and managed. RID has implemented this multipart database to record and track aquifer impact due to well pumping and depletions for 99 wells, as well as recharge diversions and accretions for around 140 recharge sites for a 20 year period.

DATABASE DESIGN

RID's relational database consists of four parts: Owner Information and Billing, Well Pumping and Depletions, Farm Unit Maintenance and Crop Calculations, and Augmentation/Recharge Sites. Each part performs distinct functions, but all necessary data is shared within the four sections. The design of each database section includes 1) a program, and 2) all the necessary data tables. This modular design allows changes to be made to the program portion without having any impact on the existing data. Additionally, the data tables are segregated by plan year to reduce the size of the operational database. Historical data is kept separately and utilized during report generation.

Owner Information and Billing

This portion of the database allows RID to maintain owner information and to bill well users based on actual pumping vs. annual pumping allocations. Owner data tracked includes name, address and contact information. Also within this portion of the database, annual bills are prepared using the reported well pumping and calculated wellhead depletions maintained in the Well Pumping and Depletions portion of the database. Annual pumping allocations are made and owners are billed based on their actual pumping and wellhead depletions. Over-pumping charges and any additional fees can be assessed as necessary.

Farm Unit Maintenance and Crop Calculations

The Farm Unit Maintenance and Crop Calculations portion of the database allows maintenance of farm units, weather importing, crop evapotranspiration calculations, calculation of farm unit water balances and reporting.

Farm Unit Maintenance: The RID office maintains farm unit information. An ID number as well as a farm unit description identify each farm unit. The number of District Acres, sprinkler and flood irrigated acres and surface or well-irrigated acres are recorded, along with a listing of all wells assigned to the farm unit. Crop types and acreage are specified and the headgates used to supply surface water are listed. The type of wellhead depletion calculation used for the farm unit is selected, either the WHDF or CWR method. These methods are described in detail later in the paper. Finally, any additional sources of surface water (not supplied by RID) are included. The farm unit irrigation efficiency is determined based on the extent of use of flood and/or sprinkler irrigation for the farm unit.

Weather Importing and Crop Calculations: Weather data is a key element of the crop calculations. Currently the database utilizes weather data from Northern Colorado Water Conservancy District's (NCWCD) Brush weather station. This data is downloaded from the NCWCD website on a monthly basis, and the daily records are imported. Weather data includes maximum, minimum and average temperature, average relative humidity, average dew point, total precipitation, maximum wind speed, and total wind. The database has the capability of adding other weather station data as it becomes available.

Crop growing season information is required by the crop calculations. The start and end dates for the major crops in RID's area are updated annually. These crops include corn, beets, beans, grain, sorghum (silage and hay), winter wheat (fall and spring), alfalfa and grass. Other crops can be added as required. The crop dates section includes a temperature-plotting feature in order to determine the growing season for alfalfa and grass.

<u>Operation during the Irrigation Season:</u> Each headgate in the RID system has been assigned a soil type with corresponding soil parameters. This information, along with the appropriate crop data and the daily weather data, is utilized to calculate all the relevant parameters necessary to generate each crop's consumptive irrigation requirement (CIR). CIR values for each crop type by headgate/soil type are recorded for use with the water balance calculations.

<u>Calculation of Farm Unit Water Balances:</u> In general, each farm unit utilizes surface water in addition to well irrigation. When metered pumping data is not available, well usage can be determined by calculating the overall farm unit CIR. The RID office records surface water information, for both direct flow and district allocation. This information is imported into the database by headgate. Crop ET is calculated using a calibrated Hargreaves with monthly calibration coefficients to estimate standardized reference evapotranspiration long (Etrs) and mean monthly crop coefficients, (Kcrs). CIR on the lands under each farm unit is calculated on a monthly basis. The portion of CIR met by surface water is determined as the measured surface water deliveries times the farm unit irrigation efficiency. The remaining CIR is then assumed to be met by well pumping. Currently, the RID farm units are not utilizing this option.

<u>Farm Unit Reports:</u> There are many reports that can be generated from this section of the database. Farm unit surveys are printed annually and sent to each well owner. These reports give the owner all information used the previous year - District Acres, acreage by irrigation type and crop, and any additional sources of surface water. The owner notes any changes and the report is returned to the RID office. There is a farm unit summary report, which gives the RID manager a quick view of all farm units, including total District Acres and number of wells. The crop calculation report lists all crop coefficients, precipitation and CIR by crop and soil type. And the farm unit water balance summary report shows all water sources, crops and wells, and lists the farm unit CIR and consumptive use factors by month.

Wells and Recharge

The Well and Recharge portions of the database are generally very similar in their design, operation and function. There are, however, a couple of exceptions that will be noted. On the operating menus of the Well and Recharge accounting, RID has several options which include entering and maintaining structure information, viewing and editing current data, meter reading entry and monthly pumping or recharge calculations, calculation of projected pumping or recharge, wellhead depletions or net recharge and stream impacts (depletions, accretions and net impact), and preparation of various reports, including the monthly required submittal to the State Engineer's Office. The Well portion has the added functions of entering or editing farm unit data. The Recharge portion has the added function of importing recharge data from the accounting of decreed recharge plans.

Structure Information: The RID office maintains structure information. Each well or recharge structure is identified by an ID number, as well as a farm unit designation. A farm unit is group of wells or recharge sites that are owned or operated by a single owner or entity. Well farm units are separated from recharge farm units even if they have the same owner. The structure description, type of impact (depletion or accretion), parameters for calculation of stream depletions or accretions, along with the location, legal description, water right information, and water measurement parameters are maintained. Additional information required to project monthly pumping or recharge diversions or calculate wellhead depletions, net recharge or stream impacts is also recorded here. This information includes pro-rate factors, years of actual data, final year for estimated data, and the projected or future data estimation method. There are six options for estimating projected data. They include using the amount from the previous year, setting a pumping water order or net recharge diversion that is distributed over the operating year, using the average, minimum or maximum value of all recorded data for the structure, or zero. Estimating methods are set for each well or recharge structure. Currently, all RID wells are pumping limit is set by RID's Superintendent. The projected recharge diversions are calculated using either average net recharge or zero.

In the Well section of the database, the RID office can record the monthly depletion factors by well, and the monthly water orders and water order distributions (used for pumping projections) by farm unit. These values are used for the projected pumping calculations discussed later.

Meter Reading Entry and Monthly Pumping/Recharge Calculations: Monthly pumping or recharge data can be entered or calculated in several different ways. Individual meter readings can be entered, and the monthly pumping or recharge diversion amount is automatically calculated based on the flow meter parameters. There are 13 methods that can be used for meter data entry, including kilowatt usage, electric meter readings, four different units for flow meter volume readings, four different units for flow meter volumes, hours pumping, hour meter readings, and a manual calculation entry. Multiple meter readings can be imported monthly using an Excel spreadsheet with a specific format. These meter readings are recorded and the appropriate method used to calculate the monthly pumping or recharge diversion amounts. Monthly pumping or recharge diversion amounts for a structure can be imported directly from an Excel spreadsheet with a set format, and finally monthly data can be entered directly by structure. Pumping or recharge diversion records can be printed from this section if desired. The pumping or recharge diversion data can be viewed by month for each individual well or recharge structure.

Annual Projected Pumping, Wellhead Depletions and Stream Impact: The RID database offers a projection feature for well pumping that is used for annual planning. Pumping by farm unit is allocated based on allowable wellhead depletions per District Acre. Each farm unit is given an initial pumping allocation based on the District shares for each individual farm unit owner. The RID manager can then apply a unit factor to this pumping allocation in order to arrive at the overall annual pumping allowance for all well owners in the District's plan. This annual planning process is an iterative process in which the RID manager assigns water orders, projects pumping, calculates stream impact, and then compares this data with available replacement water for the year. These steps are repeated until the overall pumping/replacement plan values are satisfactory. Final farm unit water orders are then set by the RID manager using the final allocations and his judgment. Projected pumping is calculated using the water order and the water order distribution for each farm unit. The projection calculation distributes the water order evenly between all wells in a farm unit based on the monthly percentage values set by the farm unit's water order distribution.

Annual Projected Recharge and Stream Impact: The RID database offers a projection feature for recharge that is used for annual planning. Each farm unit is given an initial recharge allocation based on each decreed plan's limitation. The RID manager can then apply various factors to this recharge allocation in order to arrive at overall annual recharge estimation. For these projected amounts, each individual recharge farm unit is assigned a different amount of net recharge depending upon the projection criteria set-up for each farm unit by the RID superintendent. Generally, the projected amount will be an average amount or zero. Projected recharge is calculated using the estimated recharge and monthly distribution for each farm unit. The projection calculation distributes the estimated recharge evenly between all structures in a farm unit based on the monthly percentage values set by the farm unit's recharge estimation distribution.

Irrigation Season Well Operations: As actual measured monthly pumping is recorded, the projected pumping calculation distributes the remaining farm unit water order over the subsequent months in the plan's year. This feature allows the RID manager to track actual pumping progress versus planned pumping throughout the year. Each month after the pumping data has been recorded and the remaining projections calculated, wellhead depletions and stream impact are generated. Wellhead depletions can be calculated using two methods - wellhead depletion factor (WHDF) and crop water requirement (CWR). Currently, all wells use the WHDF method: the CWR method is a backup methodology in case of a flow meter failure.

Wellhead Depletions by the WHDF Method: In this method, wellhead depletions are determined based upon the amount of water pumped times a wellhead depletion factor (WHDF). The WHDF's vary depending upon the use of the wells. The wells in RID's proposed plan of augmentation are used for either irrigation use or livestock feed yard uses. Each well has an individual set of monthly WHDFs. When the wellhead depletion calculations are done using this method, each monthly pumping value is multiplied by the appropriate monthly WHDF. These values are for used in the stream depletion calculation. The following WHDF's were described in the RID's April 2002 augmentation plan application and are currently in use:

- For surface irrigation by groundwater in either a supplemental or sole source supply the WHDF shall be 0.40.
- For sprinkler irrigation by groundwater the WHDF shall be 0.75.
- For use other than irrigation, such as feedlot or dairy operation, a WHDF is determined by a separate calculation.

Wellhead Depletions by the CWR Method: In this method, wellhead depletions are calculated by estimating the amount of the crop consumptive irrigation requirement (CIR) not met by surface water. For each farm unit, CIR is the depth of irrigation water, exclusive of precipitation, stored soil water, or ground water (not provided by a well) that is required consumptively for crop production. Under the RID system, it is crop Et minus net precipitation.

Crop ET is calculated using a calibrated Hargreaves with monthly calibration coefficients to estimate Etrs and mean monthly Kcrs coefficients. Net precipitation is calculated using the SCS method described in USDA, 1970. Weather data from a nearby weather station is used in the calculation. The database has the capability of adding weather data from other stations.

Measurement of delivery of surface water from all sources to the individual farmer and laterals headgates is required. Each spring, plan participants report type of crops and number of acres irrigated for each crop to the RID manager. In this method, wellhead depletions are calculated as the total farm CIR minus CIR met by surface water.

CIR on the lands under each well is calculated on a monthly basis. The portion of CIR met by surface water is determined as the measured deliveries times the farm unit irrigation efficiency. The farm unit efficiencies used are 65 percent for surface irrigated systems and 75 percent for sprinkler-irrigated systems. For those farms that are delivering their surface water through an unlined ditch lateral, an estimated 5 percent loss in the lateral is also deducted. For those farms that are delivering their surface water through a lined ditch lateral or closed conduit lateral, no additional loss occurs. These values were assumed based on similar augmentation and recharge plans decreed in the South Platte River Basin.

Wellhead depletions for actual and projected pumping values become input data for a groundwater unit response model, which calculates the allowable pumping and estimated stream depletions for the time period selected by the RID manager. This calculation is generated using the data for the current plan year. Reports can be viewed showing stream impact for the current plan year, or with all historical impact included as well. Reporting options are discussed in the next section.

Recharge Operations: As actual measured monthly diversions are recorded, the projected recharge calculation distributes the remaining farm unit recharge estimation over the subsequent months in the plan's year. This feature allows the RID manager to track actual recharge progress versus planned recharge throughout the year.

Each month after the diversion data has been recorded and the remaining projections calculated, stream impacts are generated. Diversion values for actual and projected recharge become input data for a groundwater unit response function model, which calculates the allowable recharge and estimated stream depletions for the time period selected by the RID manager. This calculation is generated using the data for the current plan year. Reports can be viewed showing stream impact for the current plan year, or with all historical impact included as well. Reporting options are discussed in the next section.

End of Year Operation: At the completion of the operational year, the final stream impact for the year is archived into a separate historical database. The totals from this database are included when historical impact values are used for reporting.

Reporting

There are many reports that can be generated from the report menu of the Well and Recharge sections of the database. All reports have options for changing the first year of data to view and selecting the number of decimal places to show. All data is provided by month and year. Pumping data, wellhead depletions, recharge diversions, net recharge and stream impact reports are available by individual structure (well or recharge site). Net stream impact for the current year or for the current year plus all historical data can be viewed, along with detailed net stream impact itemized by structure. All input data used to calculate the stream depletions or recharge accretions of a structure is available for viewing or as a printed report. Pumping reports include annual allotments, pumping to date by individual well, and a summarized pumping to date report. All input and net impact for a single structure can be selected, or the RID manager can view all structure information, monthly pumping, and net stream impacts on a well-by-well basis. There are also reports for pumping or stream impact by user groups. The RID manager can designate a user group, or selection of structure, if specific location or well type summaries are desired. Additionally, an overall summary report can be printed.

Reports with specific formats in Excel must be submitted monthly to the State Engineer’s office, and these are automatically generated from the database for electronic submittal. These reports include the well owner information report and the RID Augmentation Plan report. The Augmentation Plan report includes a summary of the monthly impacts due to current well pumping, recharge, water transfers and historical pumping, daily net impact values, daily depletions, daily accretions and daily transfers.

AUTOMATED OUTLET STRUCTURE DESIGN FOR WINDSOR LAKE TO IMPROVE IRRIGATION OPERATIONS AND ATTENUATE FLOOD FLOWS

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ABSTRACT

Windsor Lake (Kern Reservoir) serves as a storage facility, an equalizer reservoir for the Greeley No. 2 Canal, and a regional detention pond for the Windsor Basin. The affect of rapid urbanization surrounding the Town of Windsor created the need of a regional detention pond for a portion of the nearby Law Basin. Windsor Lake is capable of serving this purpose, though several feet of reservoir storage will need to be surrendered. The New Cache La Poudre Irrigating Company, (owners of the Greeley No. 2 Canal), and Kern Reservoir and Ditch Company (owners of Windsor Lake) have agreed to give up the reservoir storage with the stipulation that the outlet structure is replaced with an automated structure to improve reservoir and canal operations for shareholders.

Requirements for the new outlet structure are to control and measure irrigation releases up to the decreed flow rate of 600 cfs, and serve as the primary spillway for two different 100-year flood scenarios. The first scenario models the existing conditions in the basins and the second models the future condition in which both basins are assumed to be fully urbanized. In addition, the Dam Safety Branch of the State Engineer's Office requires the structure to pass a flood event equating to 17% of the Probable Maximum Flood (PMF). Furthermore, the structure is required to be capable of functioning during the winter months to measure and control small releases for augmentation purposes. Two alternative designs were evaluated during a feasibility study. Rubicon Flume Gates[tm], a type of overshot gate, are utilized in the final design to meet the outlet structure requirements. The new structure gives The New Cache La Poudre Irrigating Company (NCLPIC) efficient control over the discharges in their system and reduces the flood potential for downtown Windsor.

INTRODUCTION

In the past Windsor Lake has served as an equalizer reservoir for the Greeley No. 2 Canal and provided water storage for the Kern Reservoir and Ditch Company. Windsor Lake is a Class 1 (High Hazard) Intermediate Dam under jurisdiction of

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the State Engineer's Office (SEO). Water is diverted from the Cache La Poudre River into the canal for delivery to shareholders for irrigation purposes. The canal is routed through the reservoir to help attenuate fluctuations in the canal discharge resulting from the rise and fall of the river throughout the day. The existing outlet consists of radial gates and a rated concrete section for flow measurement.

The canal also intercepts flood flows from the Windsor Basin and either transports them to Windsor Lake, or overtops, in which case the water eventually makes its way to the lake (see Figure 1). In this manner, Windsor Lake has served as a detention facility for the Windsor Basin. The nearby Law Basin has historically entered the Bypass Canal and joined the Greeley No. 2 Canal downstream of the Windsor Lake Outlet structure. This has resulted in flood flows from the Law Basin continuing down the Greeley No. 2 Canal unabated.

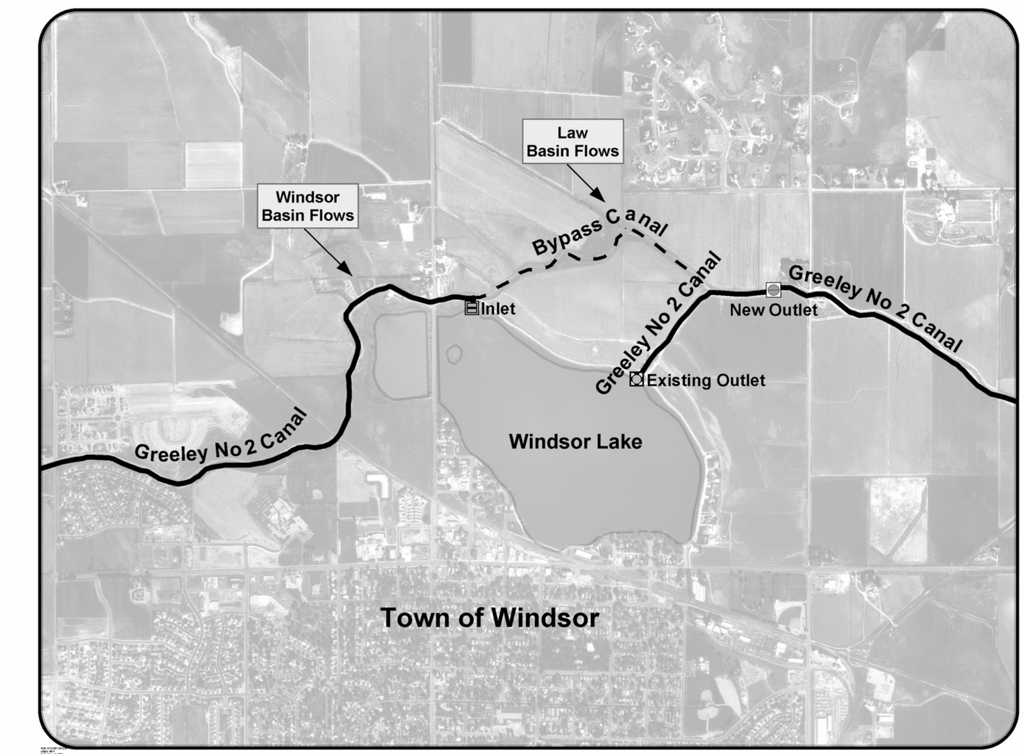

Figure 1. Vicinity Map

The master drainage plan for the Town of Windsor, prepared by Anderson Consulting Engineers, Inc[1], identified the need for a regional detention pond for the Windsor Basin and a portion of the Law Basin. Relocating the Windsor Lake Outlet further downstream on the Greeley No. 2 Canal allows flood flows from the Law Basin to be routed through Windsor Lake. The master drainage plan estimated that the maximum normal water surface elevation needs to be decreased by approximately two feet to provide the required flood storage. In addition, normal irrigation flows will pass down the bypass canal and then either enter Windsor Lake or exit through the outlet structure and continue down the canal.

The canal between Windsor Lake and the new outlet will be capable of flowing in two directions. When the canal discharge from the river exceeds the desired discharge, the excess water will flow from the canal into Windsor Lake. When the canal discharge is short of the desired discharge, water will flow from the lake and supplement the canal discharge.

The Kern Reservoir and Ditch Company and NCLPIC agreed to surrender the required storage volume if the existing outlet and flow measurement structures are replaced with an automated structure capable of both controlling and measuring discharge. Tetra Tech RMC used the hydrographs from the master drainage plan to perform unsteady hydraulic modeling of the system involving the Greeley No. 2 Canal, the two drainage basins, and Windsor Lake. This modeling was performed in conjunction with the drainage plan for the Greenspire Subdivision bordering the canal and Windsor Lake on the north and east. [(2) (3) (4)]

Three separate storm scenarios were analyzed. The first represented the existing basin conditions during a 100-yr precipitation event and the second modeled a future 100-yr precipitation event which assumed the basins are fully developed. The future scenario assumes that new development within the basin would be required to detain the 100-yr flood event and release it at the historic 10-yr peak flowrate. Therefore, the first scenario has the highest peak flows and a short duration while the second has lower peak flows but a much longer duration.

The new outlet structure is required to control both 100-yr flood events in such a manner as to not allow Windsor Lake to rise above the crest of the emergency spillway at an elevation of 4,797.10 ft. (NAVD 88). Rules and regulations set forth by the SEO also require the structure to safely pass the Probable Maximum Flood (PMF) unless a smaller flood can be justified through an incremental damage analysis (IDA). Tetra Tech RMC performed an IDA to reduce the Inflow Design Flood (IDF) to 17% of the full PMF. The new outlet structure design must satisfactorily pass these three flood scenarios assuming that the canal is carrying 600 cfs. of irrigation water.

Tetra Tech RMC's analysis models the outlet structure as a 12 ft wide overshot gate which would function as the primary spillway at an elevation of 4,793.50 ft during a flood event. A 114-ft long concrete weir at an elevation of 4,798.00 ft is also required to meet design requirements for the existing 100-yr and 17% PMF flood events. However, this structure does not include a measuring structure, and the overshot gate specified cannot measure flowrate within the $^{+}/{-}$ 2% accuracy desired by NCLPIC under submerged conditions.

FEASIBILITY STUDY

Design Criteria

New Cache La Poudre Irrigating Co. requested Applegate Group, Inc. to perform the new outlet and measuring structure design. Two design alternatives were examined in detail during the feasibility study. The first used simple overshot gates to control releases from Windsor Lake, and a separate structure to measure discharges. The second alternative combines the two structures into one by using Rubicon Flumegates^{tm} to control and measure discharges.

Accurate discharge measurement is a necessity for NCLPIC. The canal has two typical operating regimes. Canal discharges during the irrigation season range from 100-600 cfs. During the fall and winter months the canal releases smaller discharges of approximately 2-100 cfs to replace evaporative losses from the surface of the canal during the summer months, as required by the SEO. Therefore, the outlet structure must be capable of measuring discharges ranging from 2 to 600 cfs with an accuracy of +/- 2%. The new outlet structure must also be capable of releasing water at reservoir elevations ranging from 4,785.00 ft to 4,793.50 ft. Finally, the structure needs to be capable of controlling storm flows for the three flood scenarios described earlier.

Alternative 1

For the first alternative Obermeyer Gates are used to control releases from the reservoir. Obermeyer gates consist of a gate leaf placed atop an air bladder which is raised and lowered by adjusting the air pressure in the bladder. A separate structure is required to attain the desired flow measurement accuracy of +/- 2% under submerged conditions. A Supervisory Control And Data Acquisition (SCADA) network will tie the two structures together and allow the NCLPIC to automate and remotely operate the structure. A long-throated flume is the preferred flow measurement device for a couple reasons. First, typical flumes require a significant change in water surface elevation to obtain accurate flow measurement which will decrease the available operating range of lake elevations for a given discharge. Long throated flumes can typically obtain the required flow accuracy with a 2.00 inch change in water surface elevation which will maximize the operating range of the lake. Second, a long-throated flume is capable of measuring a wide range of discharges with the desired accuracy.

Alternative 2

The second alternative utilizes Rubicon Flumegates^{tm} to control and measure discharge through the structure. Rubicon Flumegates^{tm} are a type of overshot gate manufactured in Australia. The gate includes four piezometers to measure water levels upstream and downstream of the structure and a digital shaft encoder that measures the position of the gate leaf. Using this information, the gate software calculates an instantaneous discharge with a measurement accuracy of +/- 2% with as little as a 2 inch change in water surface elevation across the gate. This measurement accuracy has been verified through independent testing performed by Hydro Environmental[5] on the Goulburn-Murray Water system in Australia. Nearly 2,000 of these gates are have been installed throughout Australia and they are rapidly gaining popularity in the United States with approximately 100 gates in service at the time of publication. The user can set the Flumegate[tm] to maintain a specified upstream or downstream water surface elevation, or maintain a desired flowrate, and the gates can be tied into NCLPIC's existing SCADA system to facilitate remote operation of the gates.

Figure 2. Rubicon Gates in Operation at Windsor Outlet

The feasibility study concluded that it would be more economical to build a single structure with Rubicon Flumegates[tm] than building two separate structures. Therefore, the second alternative is selected for final design.

FINAL DESIGN

Irrigation Modeling

The first step in the final design is to determine the gate size necessary to discharge irrigation flows up to 600 cfs. Rubicon Systems recommends that the gates be manufactured to the maximum dimensions of their standard shipping crate to prevent damage during shipping. This results in a gate that is approximately 7.50 ft wide and 7.25 ft long. A gate this size is capable of discharging a maximum of 351 cfs, assuming that there is no backwater on the gate and Windsor Lake is at a maximum operating water surface elevation of 4,793.50 ft. However, backwater from the Greeley No. 2 Canal decreases this maximum discharge to approximately 233 cfs, thereby requiring three gates to obtain the design discharge of 600 cfs. Using three gates in this structure will increase the maximum irrigation discharge to 700 cfs with backwater conditions and allow NCLPIC a little flexibility in the operating range available for the design flowrate of 600 cfs. The only problem with this gate size is that it can only release water down to an elevation of 4,787.75 ft, which will further restrict the operating range of the lake. To address this issue the gates will be built on removable stoplogs which allows the gate to be moved to a lower position to release water down to the design elevation of 4,785.00 ft. It is anticipated that this will only be required during periods of extreme drought and is therefore an acceptable solution to NCLPIC. Figure 3 displays the operating range attainable for the new outlet structure and data points from previous years. The total width of the gate section is 27 feet and it is located in the center of the outlet structure.

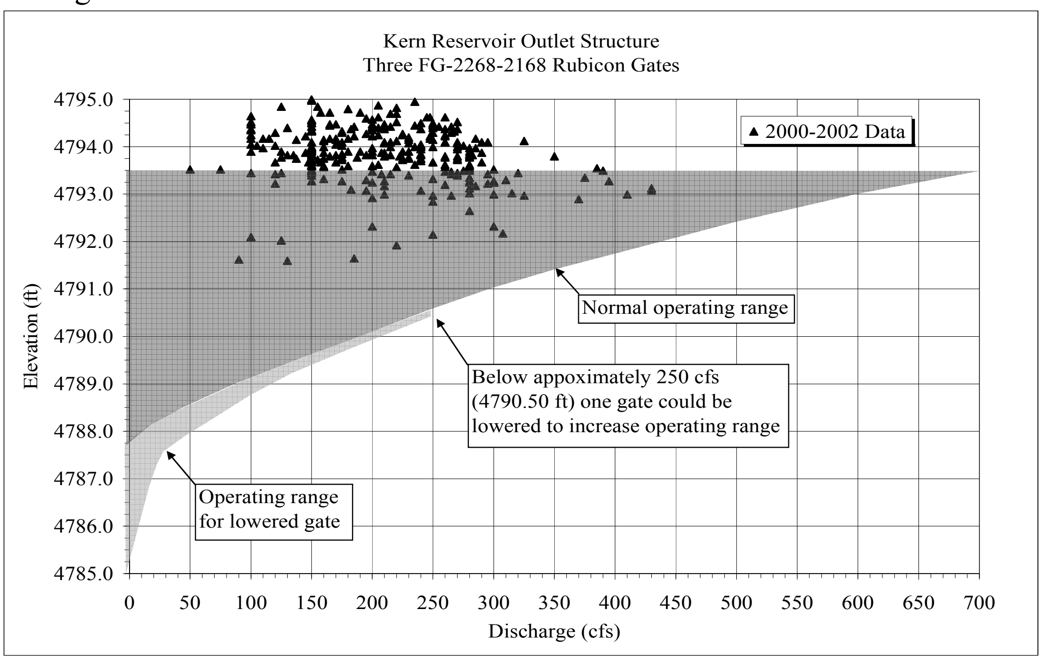

Figure 3. Operating Range of Windsor Lake Outlet

Flood Modeling

As mentioned earlier, the structure must pass two different 100-yr flood events without allowing water to rise above the elevation of the existing emergency spillway on Windsor Lake. All flood water in these two scenarios will exit the reservoir through the Greeley No. 2 Canal. Tetra Tech RMC determined that the peak discharge through the structure for the existing and future conditions is 1,029 cfs and 865 cfs, respectively.

It is believed that allowing these flood flows to pass freely over the Flumegate^{tm} will damage the gate controls located in the pedestal above the gate. To reduce the potential for damage, a concrete wall placed in front of the gates will direct water to the primary concrete spillway located to the side of the gate section at an elevation of 4,793.5 ft. This wall extends up to an elevation of 4,798.0 ft and will begin to function as a spillway at that elevation. During the existing 100-yr flood event and the 17% PMF, water will pass over this wall and flow around the gate pedestal and over the gate leaf. It is anticipated that the gate controls will not sustain damage during either of the 100-yr flood scenarios (see Figure 4).

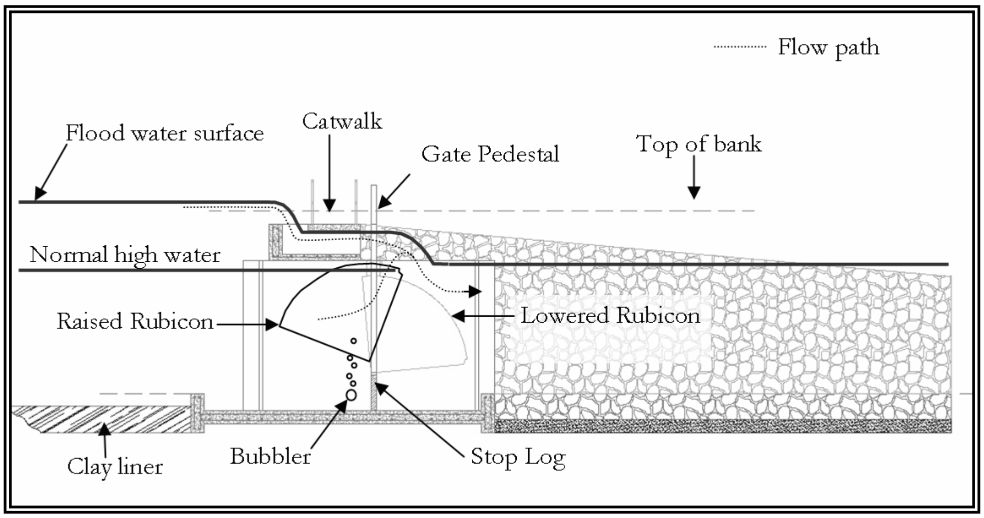

Figure 4. Outlet Gate Profile

Modeling the structure with Flumegates^{tm} during a flood event in which the reservoir elevation exceeds 4,793.50 ft is somewhat complicated. When the gates are fully raised the gate leaf is at an elevation of 4,793.50 ft. Magnets embedded in the gate panels and frame do not let the gate rise any higher and the gate does not seal the remaining opening between the gate leaf and frame. This results in a horizontal opening of 6.48 ft by 2.04 ft. When the lake level rises above 4,793.50 ft water passes through this opening and then flows over the gate leaf. A submerged rectangular orifice equation and a free flowing weir equation are used to model this opening.

$$Q_{gate-orifice} = C_d A \sqrt{2g}(h_1 - h_2)^{0.5} \tag{1}$$

$$Q_{gate-weir} = CL(h_2)^{1.5} \tag{2}$$

Where:
Q = discharge (cfs)
C_d = orifice coefficient (0.60)
A = orifice area (ft^2)
g = gravity constant (32.2 ft/s^2)
h_1 = upstream water depth above gate leaf (ft)

h_2 = downstream water depth above gate leaf (ft)
C = weir coefficient (3.3)

An iterative process which equates the weir discharge to the orifice discharge is used to calculate h_2 for a given value of h_1. Then equation (2) is used to calculate the discharge. Repeating this process for different values of h_1 results in a stage-discharge curve for the gate orifice assuming that the gate is in the fully closed position and h_1 is between 4,793.50 and 4,798.00 ft. Above an elevation of 4,798.00 ft water will flow over the upper weir and combine with the flow passing through the gate orifice before flowing over the gate leaf. The discharge passing over the weir is calculated using Equation 2. The total discharge equation is written as Equation 3.

$$Q_{gate-weir} = Q_{gate-orifice} + Q_{concrete-weir} \tag{3}$$

After modeling the gate section of the structure as described above, the spillway widths on either side of the gate section are adjusted to best match the discharge curve for the structure designed by Tetra Tech RMC. This avoids significantly impacting the unsteady hydraulic modeling of the reservoir and ditch system upstream of the gate. Decreasing the primary spillway width at an elevation of 4,793.50 to 4 ft. sufficiently accounts for water passing through the gate orifice. The upper spillway width at 4,798.0 ft must be increased to 140 ft to best match the curve from Tetra Tech RMC. A comparison of the Flumgate™ design to Tetra Tech RMC's preliminary design is shown in Figure 5.

SUMMARY

The new automated outlet structure for Windsor Lake is able to meet the needs and requirements of several entities, including the Kern Reservoir and Ditch Company, New Cache La Poudre Irrigating Company, the Town of Windsor, and the State Engineer's Office.

The use of Flumegates™ in the structure allows the ditch company to remotely operate the gate and provide more accurate water deliveries to shareholders. The new outlet represents a significant improvement to the flood control system for the Town of Windsor. Construction began in November 2005 and was completed by April 2006 in time for the irrigation season.

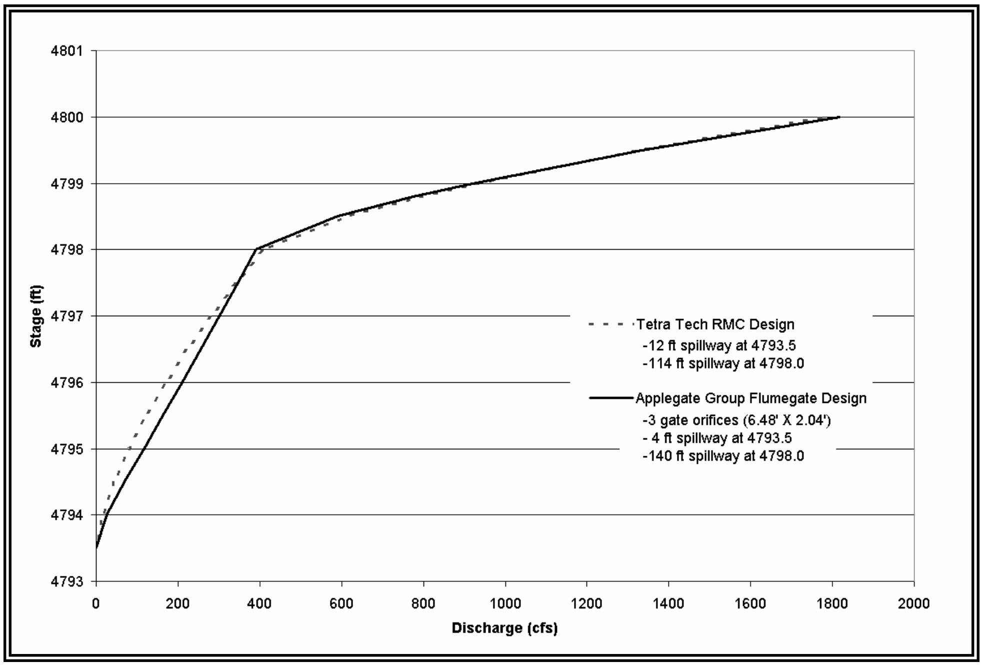

Figure 5. Outlet Structure Rating Curve Comparison

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MODERNIZING CANAL CHECK STRUCTURES WITH BI-FOLD OVERSHOT GATES

Ram Dhan Khalsa[1]
Robert E. Norman[2]

ABSTRACT

Modernization of canal check structures is an important step in improving canal operation and reducing operational spills. This paper is a case study of retrofitting existing manually operated concrete canal structures with automated bi-fold overshot gates on the Government Highline Canal in Grand Junction, Colorado.

INTRODUCTION

Grand Valley Project

The Government Highline Canal is part of the Bureau of Reclamation's Grand Valley Project, located in Grand Junction, Colorado. The canal construction was started in 1913 and completed during the Great Depression. The canal extends 52-miles from the diversion dam on the Colorado River flowing westward through the Grand Valley. Two Federal environmental programs spanning a 25 year period have had a dramatic impact on the modernization of the Highline Canal. This paper discusses the use of bi-fold overshot gates in modernizing four existing canal structures and a gate application in a new pumping plant.

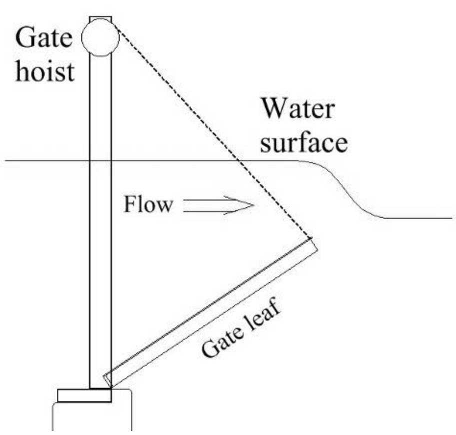

Figure1. Typical Overshot Gate

Overshot Canal Gates

The typical canal overshot gate, Figure 1, has a gate-leaf horizontally hinged near the bottom of the canal, with the gate-leaf extending downstream. Water flows over the gate-leaf, which acts as a horizontal weir. The gate actuator is a hoist mechanism that moves the downstream end of the leaf up and down, or in some designs an air bladder under the leaf is used to move the leaf.

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The bi-fold overshot gate, Figure 2, has a double leaf, horizontally hinged on the bottom frame and between the lower and upper leaf. The lower leaf extends upstream and is hinged to the upper leaf that folds over the top and is extending downstream. The hinged gate leaves form a horizontal upstream wedge, with the frame hinge and the top of the leaf crest nearly in a vertical line. Because the gate-leaf and hoist mechanism are upstream of the mounting hardware, the gate can be mounted on the vertical upstream face of an existing canal structure.

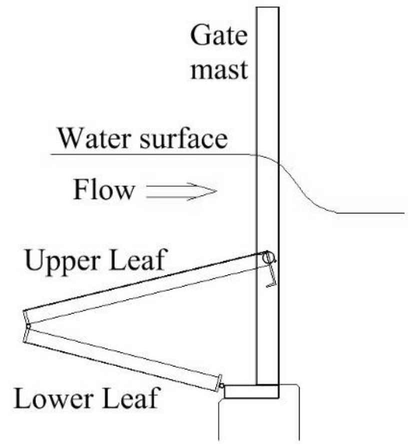

Figure 2. Bi-Fold Overshot Gate

Langemann Bi-Fold Gate

The bi-fold gates used on the Government Highline Canal were invented by Peter Langemann. The Langemann Gate and controller were developed as a cooperative effort between the St. Mary River Irrigation District in Alberta, Canada and Peter Langemann. The patented design is recognized and accepted for its simplicity, overshot technology, control capabilities, and low power requirements. Aqua Systems 2000 Inc. manufactures and sells the "Langemann Gate".

Before embracing the technology for other applications within the irrigation project, the decision was made to install and test one Langemann Gate in an existing three bay stop-log structure, six miles from the river diversion. The stop-log structure had three 7-foot wide bays that create a fore-bay pool for a hydraulic pump penstock. Significant flow changes in the canal required adding or removing stop-logs in an attempt maintain a stable water surface level in the fore-bay. This type of control was difficult. The original check structure was made by forming four massive vertical concrete gussets that create the three 7-foot wide bays. To help install the stop-logs, the stop-log slots and gussets were sloped.

Modified Stop Log, Gate Installation

To provide a vertical surface to mount the Langemann gate, the center two gussets were cut to create two vertical columns. A short concrete stem-wall was doweled into the base of the concrete structure.

Figure 3. Gate Installed in Modified Stop Log Structure

The base frame sets on the stepped stem-wall and the mast channels are supported by vertical steel angle sections bolted to the inside of the outside concrete gussets. The completed installation has a 25-foot wide automated bi-fold overshot gate, mounted in a modified 90-year old three bay concrete stop-log structure. The assembled gate, Figure 3, was placed into the modified structure using a crane.

The gate functions as a vertically adjustable weir. The long horizontal gate-leaf slices through the canal current like a wing. The forces are somewhat balanced; the lower-leaf has an up lifting force that is countered by the downward force on the upper-leaf. With this “balanced” load it is possible to operate the gate hoist with a fractional-horsepower DC motor, which is powered by batteries. The batteries can be charged either by solar panels or an AC/DC battery charger. The total up-lift force on the gate frame and masts is a function of the differential head across the gate and the position of the gate leaf. With a small differential head across the gate, securing only the gate masts to the adjunct structure is sufficient to counteract the up-lift force. If a large differential head is present, the bottom frame needs to be anchored the structure foundation.

Gate automation is accomplished with a programmable logic controller (PLC). Standard control options for a Langemann Gates are upstream water level control and flow control. Aqua Systems 2000 description of there, “Original Level Control Algorithm” (Level & Flow Algorithms Notes, ©2007):

> “In general, the level control algorithm senses four increments of dead band on either side of the set point, and makes gate movements that are proportional to the amount of error and that reflect the hydraulic characteristics of the site.

> As the distance from the set point increases, successive gate moves become more aggressive. All corrective gate moves are delayed by a predetermined control cycle time. The first three moves are initially one-shot, and are only repeated after a relatively long reset cycle time. The fourth move is repeated on a relatively short retry cycle time. Gate moves are made until the water level returns toward set point, or until the preset maximum or minimum gate position is reached."

The gate PLC, with its open architecture, can be easily programmed to run custom control algorithms. In addition, this gate was supplied with an optical encoder to determine gate position, rather than the typical potentiometer indicator.

The purpose of this installation was to maintain a constant upstream water surface level in the pump fore-bay. The gate performs well, running on the manufactures automation software, and the decision to install four addisional gates on the irrigation project was implemented.

Removing The Amil Gate / Stop Log Installation

The second site is six miles downstream from the first gate. This structure contained a Waterman D-450 Amil gate and six stop-log bays, three on each side, Figure 4. The purpose of this canal check was to change and maintain the upstream water surface in the canal to prevent upstream freeboard encroachment at high canal flows, and to allow upstream turnout deliveries to be made during low canal flows. Although the structure was built in the 1990's, it was poorly designed and did not work. The Amil gate performed as expected but it was not the correct type of gate for this application.

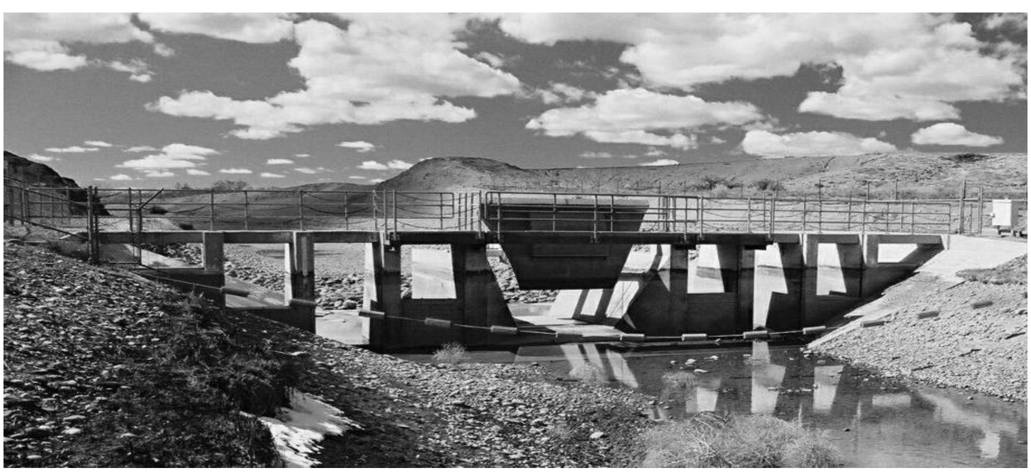

Figure 4. Amil Gate / Stop Log Structure

Amil gates have a trapezoidal gate-leaf and massive concrete buttresses. A large concrete saw was used to cut the buttresses from the floor of the structure. The Amil gate, the concrete buttresses, and one stop-log bay on each side of the buttresses were removed. A short concrete stem-wall was doweled into the floor of the check structure.

Figure 5. Langemann Gate Installed in Existing Structure

A 28-foot Langemann gate was installed in the open span, Figure 5. There is a small difference in water surface elevation across the gate-leaf, so that the hydrostatic pressures are nearly equal. Of the remaining stop-log bays, the two adjacent to the Langemann gate were fitted with manually operated electric sluices gates. These gates are open during high canal flows and closed during low flows. The outer most stop-log bays are only half the depth of the canal and the stop-logs are permanently in place. The automation at this canal check is accomplished by the Langemann gate algorithm, similar to the previous pump fore-bay Langemann gate.

Controlling the Siphon Inlet

The third gate was placed at the entrance of an 800 CFS siphon, crossing the Colorado River. The purpose of this installation was to maintain automated flow control and flow measurement into the siphon.

Over 1600 CFS is diverted into the Highline Canal at high demand. A bifurcation five miles downstream in the canal splits the flow approximately in half. Originally the bifurcation was controlled using two radial gates, with hand-crank gate hoists. One radial gate controls the Highline Canal and the other controled the siphon. The gate on the Highline Canal had been rebuilt recently, and as part of the canal modernization, it was upgraded with an automated electric hoist. This radial gate controls the upstream water level at the bifurcation. So, if a shortage occurs here, the siphon will continue to receive the target flow, the radial gate will close as much as is necessary to maintain the level, and the canal downstream of the radial gate will receive the shortage.

The Langemann gate in the entrance to the siphon is used to control flow. Aqua Systems 2000's "flow control" (Level & Flow Algorithms Notes, ©2007):

> "The algorithm can perform automatic flow control based on an operator adjustable flow set point. The flow control routine continuously monitors the head on the gate (H) and compares it to the desired head for the current gate flow set point (Q_{sp}). The gate flow set point is calculated by subtracting the current gate flow from the total system flow:
>
> $$Q_{sp} = \text{System flow set point} - \text{Current gate flow}$$
>
> If the difference between the actual head and the desired head (error) is greater than the control dead band, the flow control cycle timer will start timing. If the error becomes less than the control dead band before the timer times out, then the timer stops timing and is reset. If the error is greater than the control dead band when the timer expires, the gate is adjusted based on the instantaneous head error."

The installation was similar to the previous Langemann gates, but flow conditions were different, Figure 6. The entrance water velocity is over 6-feet/second and the water freefalls over the gate-leaf into the throat of the siphon. Even though the bi-fold leaf balances the approach velocity head on the gate, the hydrostatic difference across the leaf causes the gate to want to float or lift.

Figure 6. Siphon Inlet Flow Control

To counteract this lift force, the bottom beam of the gate was securely anchored to the concrete stem-wall and the upstream side plates were bolted to the concrete side walls. The greater hydrostat force across the gate-leaf required high inrush current to the motor to start the gate moving. Because of increased the inrush current through the motor, the DC motor solenoids were replaced with a solid-state soft-start device. DC motor soft starters were installed on all five of the project gates, and are now standard equipment on Langemann gates.

One unexpected site improvement was a significant reduction in the trapped air belching back from the siphon inlet. The high velocity discharge under the old radial gate pulled air into the siphon. The water velocity over the Langemann gate-leaf is reduced and the energy is dissipated in the siphon intake. The gate at this site is presently operated in local hand mode. When the flow control performance has been field tested and the site tied into the SCADA radio network, it will be locally automated and remotely operated.

Side-Channel Spillway Control

The forth gate was placed downstream of an emergency siphon on a side-channel spillway from the canal, Figure 7. The purpose of this installation is to maintain an automated constant upstream water surface in the canal, and to measure the canal water operational spilled into Highline Lake, Figure 8. Historically a siphon would be started by a high water level in the canal and then break suction when the canal water level was drawn down ½-foot. With the Langemann gate installed in the spillway, the three sluice gates in the bottom of the canal are opened and the siphon is inoperative.

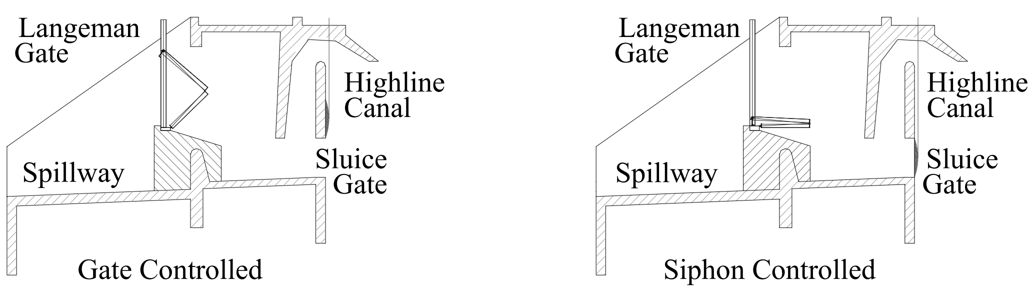

Figure 7. Side-Channel Spillway, Siphon & Gate

Figure 8. Highline Lake, Side-Channel Spillway

This Langemann gate has the same hydraulic control challenges as the gate at the bifurcation siphon inlet. The lake spill is 44-miles from the canal diversion point, and there are a series of 14 canal check structures upstream from the spill.

The canal checks are operated in upstream control mode, and the mismatches between canal diversion and irrigation deliveries are accumulated downstream at the Highline Lake spill. The Water Users' Association has "short-term storage arrangement" in Highline Lake. Operational spillage can be pumped up for use in the canal within 72 hours of the time that it spilled.

This gate is 13-feet wide and the spill flow ranges from 0 to 200 CFS. The gate must respond quickly to maintain the canal water surface level. Aqua Systems 2000 responded to this situation with "Fuzzy Logic" (Level & Flow Algorithms Notes, ©2007):

> "The main problem with the original Langemann level control algorithm is that its response is usually somewhat sluggish when dealing with rapid, large upsets in the upstream level. In a few applications, even a temporary drift from set point was unacceptable. In these cases, if the algorithm was tuned to be more aggressive for large errors, it could result in being too aggressive on small system upsets and system stability was compromised. Originally, this problem was addressed with a redundant emergency level control relay to immediately drive the gate in the correct direction if a dangerous upstream canal level appears. This concept was successful in most, but not all applications.

> Aqua Systems 2000 Inc. decided to undertake development of a new algorithm to achieve higher performance while maintaining stable operation. AS2I refers to this new algorithm as the 'Fuzzy Logic' level controller because the original intent was to start with a blank sheet of paper and develop an entirely new algorithm that followed formal Fuzzy Logic programming techniques. Through research and development, it was determined that the original Langemann algorithm has a great deal of merit, and already contained 'fuzzy' style elements. The result was to take some additional fuzzy logic concepts and apply them to the original algorithm to create a new high performance control algorithm that overcomes the pitfalls of the original design. The new algorithm probably does not truly qualify as 'Fuzzy Logic' in a strict academic sense; however it is very simple, reliable, and stable. In addition, it has fantastic set point holding power for both large and small system upsets, and is easier to tune than the original Langemann Algorithm."

The Fuzzy Logic algorithm was used on the side-channel spillway gate to make the gate move aggressively. Events upstream from this gate have caused dramatic and rapid changes in canal flow. Even with the use of Fuzzy Logic, canal water level control has not been completely successful. Effort to tune the algorithm continue, but it is unknown if this control algorithm will be able to control the water level at this site.

Pump Station Debris Guard

The fifth gate was placed at the entrance of the Highline Lake pump back station, Figure 9. The pump station is operated to supplement canal supply during short-term increases irrigation demand or supply shortages. The purpose of this gate installation is to prevent debris from building up on the pump screens when the pumps are not running. A trash rake cleans the screens when the pumps are operation. A low water level in the canal will cause the Langemann gate in the spillway to rise and stop the spill. If the canal water level falls below the pump target level, the pump PLC will lower the pump station Langemann gate in front of the screens prior to starting the pump. When the pumps stop, the gate is raised to block debris from entering the screens.

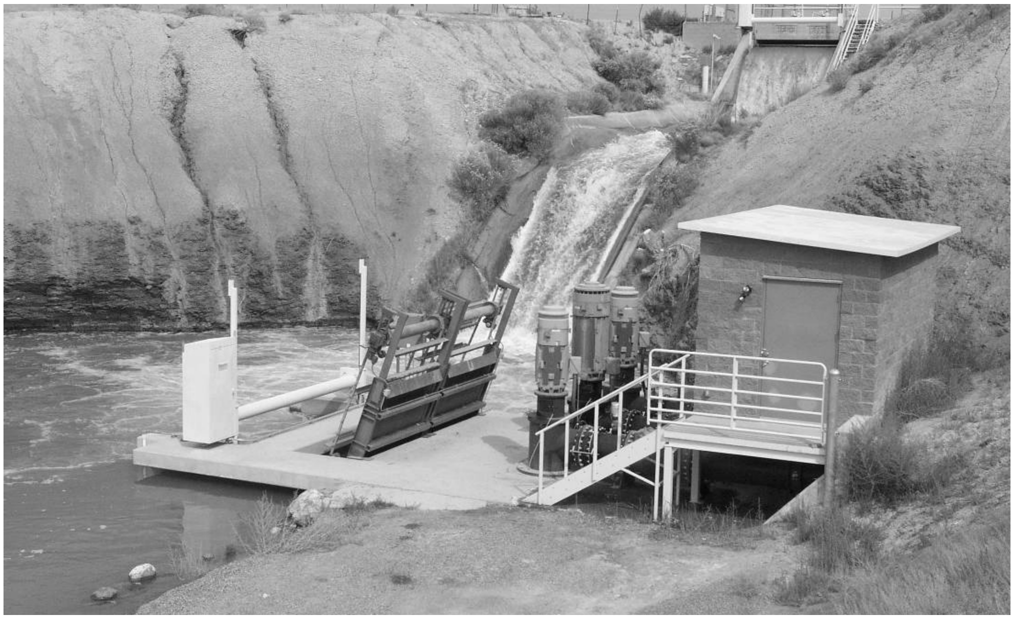

Figure 9. Langemann Debris Guard

CONCLUSIONS

Canal modernization, with bi-fold overshot gates was successful on the Highline Canal. The gates performed well in most water control applications. With more algorithm “tuning” control may meet system requirements at the remain sights. These gates are custom engineered for each site and designed with the water control feature desired by the user. With simple modification of existing structures or simple design of new structures, the bi-fold design is extremely cost effective. The low power requirement and the minimal concrete work needed for installations, makes the Langemann gate a versatile and economic tool for modernizing old canals or constructing new canals.

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IMPLEMENTATION OF MODERATELY PRICED SCADA FOR THE RIVERSIDE IRRIGATION DISTRICT

Don Chapman [1]
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ABSTRACT

In northeastern Colorado, water resources are under tremendous pressures brought about by drought conditions experienced over the past seven years. Some mutual irrigation companies and irrigation districts have implemented SCADA as a means of collecting and recording accurate and timely information for water surface levels, canal flows, and recharge structure deliveries throughout the service area.

Fortunately, the cost of SCADA implementation is less than it used to be in the past and software, hardware, and communication advances have allowed new installations to be accomplished with low to moderate investments. Hardware and software is increasing in function, decreasing in cost, and becoming much more affordable for these private enterprise situations. SCADA implementation by the Riverside Irrigation District is described in which low-cost RTUs and a satellite uplink is used for communications to keep costs reasonable to the District.

INTRODUCTION

The Riverside Irrigation District (Riverside) service canal is approximately 90 miles in length stretching from the Riverside Reservoir in southern Weld County to the eastern edge of Morgan County in Colorado. The District serves about 150 farm owners utilizing 114 turn outs. The District also provides and manages recharge water for six augmentation plans using another 25 turnouts. The canal is used for delivery of irrigation water and filling of Vancil Reservoir, about 75 miles downstream.

The long lag time between reservoir releases and the turnouts ordering release make for ongoing flow management challenges. Ditch loss variability, storm inflows and flow measurement handicaps also contribute to make delivery precision elusive. The various main canal flumes and weirs are visited and recorded only once per day by the district's ditch riders. This provides the superintendent with a spot measurement of the flow with which to base reservoir release requirements for the ensuing three-day lag. As total deliveries change

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during the day with some users coming in and others going out, perhaps above and below the various gaging stations and those daily changes registering after the daily ditch rider visit, some uncertainty was always present concerning the exact amount of water available and if any corrective action was necessary. A SCADA system was conceptualized because it would allow for continuous flow monitoring, and help to account for many of the variables that have plagued the system.

ORIGINAL SCADA SYSTEM

In early 2004, Riverside Irrigation District asked Aqua Engineering to help develop SCADA system concepts and costs for the requirements that Riverside envisioned. There was need to measure and report the flow at five critical points on the system it was also desirable to log the level in one reservoir without reporting the values on the SCADA network. See Figures 1 and 2. A system was designed to meet these requirements. Initially the concept was to utilize spread spectrum radios to link the stations together and feed directly to the Riverside

Figure 1. This installation of an RTU is on a rated section of the main canal. A small generator was used for incidental power needs during installation. A fence protects the equipment from grazing cattle.

Figure 2. Riverside Irrigation District has several rated sections with wet wells available for WSL sensors.

office in Fort Morgan. After radio signal testing, it was concluded that spread spectrum radios were insufficient in power to see one another over the distances and topography. This left the option of more powerful, licensed radios or satellite links. Riverside opted for the satellite based communications system. This would entail a greater annual cost, but a reduced up front cost. It would also enable us to easily have our data available on the internet from any location without having to develop and maintain a permanent web site. This is important as more than one user has a need for the real-time data and neither may be in the office to see it when decisions are to be made.

The initially installed equipment consisted of Automata mini-station loggers, Automata level watch submersible sensors, satellite radios, solar charged deep cycle batteries and the required software. The average installed cost per site was about $3,700.00. See Figure 3.

Figure 3. In several cases, the existing Stevens recorder was replaced with a SCADA RTU with the replacement electronics costing less, by comparison, than a new replacement Stevens recorder.

EXPERIENCE

Installation of the stations, sensors and radios was performed by Aqua Engineering working together with Riverside staff.

The sensors have adjustments that must be made from time to time to stay in calibration. These adjustments tend to be more frequent during times of the year when the water temperature change is greatest (spring and autumn). Silting in wet wells also can cause sensor drift. If these adjustments are not made, the reported data from the sensors becomes useless. In some circumstances calibration must occur daily. This was noted most often by the first generation of sensors that we installed, which were all ceramic submersible transducers. Because we were not always able to fine tune as often as needed, the data became less reliable.

Within about one year of installation all of the ceramic sensors had failed. Some failed for unknown reasons, while the demise of three was believed to be caused by nearby lightning strikes. We were careful to adequately ground all equipment in accordance with the manufacturer's instructions. Automata provided replacements at no cost to us for some of the sensors. The replacements were a much heartier metal submersible transducer. These proved more accurate and much less prone to drift.

During 2006, Riverside's accumulated data was moved to Automata's new web site. This move greatly enhanced our ability to access the data and plotted data can now graphed in a more useful manner. We could now easily tune the sensors from any location, provided that we had a spot visual measurement from a particular station at a known time. We could also now have a better graphical representation of the levels being measured by the sensors and any trends.

Our experience with lightning made us leery of the continued use of submersible transducers in our system, especially in close proximity to a reservoir. Therefore, we replaced one lost sensor with a Stage Discharge Recorder (SDR) made by Sutron. See Figure 4. The SDR was connected to the Mini-Station using an SDI interface card that converts the digital output of the SDR to analog use for the Mini-Station's logger and radio. The SDR has a plastic float in contact with the water, which should provide increased isolation from stray voltage associated with nearby lightning strikes. The SDR also has an easy method to download data quickly using a hand held computer. This is useful because outside in the glare of the sun a laptop computer is very difficult to see and not tolerant of the elements. The download time of a comparable data set from the SDR is dramatically less than that from the Mini-Stations. The sensor drift is also very easy to correct at the site by pressing a few buttons, but unlike a Mini-Sat correction cannot be accomplished remotely.

Figure 4. Several WSL sensors were tried before focusing on a float and wheel arrangement that has proved to meet expectations for accuracy.

CONCLUSIONS

Real time water flow data is invaluable to us and we have become reliant on the continued use of our SCADA equipment. We sometimes wonder how we operated without it. Our daily water delivery is less prone to error. When the skies open up and pour rain (as they rarely do) causing uncontrolled inflows into a full ditch it is very useful to be able to monitor the progress of the swell and its accompanying affects as they migrate downstream on the canal. We can now detect and repair "holes" in the ditch flow a day sooner due to the SCADA monitoring. We can now process flow data and update accounting on our schedule rather than being dependent on others.

Our advice to ditch companies seeking to wade into the SCADA pool is to prioritize carefully your requirements and to be realistic with your expectations. This is a long term relationship, so assess your level of commitment. Can you devote the additional time and resources to maintaining and operating the SCADA system? What level of measurement precision does your SCADA network need? Can you tolerate periods of no data when sensors have been lost or malfunctioned. How frequently will you be able to calibrate and verify the reporting accuracy? Do you have the technical competence to swap out sensors, make minor modifications and troubleshoot the system?

Our SCADA requirements and expectations were probably unrealistic. The sensors, loggers and communications devices are not plug and play, nor are they install and forget. These are sensitive devices placed in an inhospitable environment.

Ditch companies operate in a different environment than most other water users. We have a real need for this technology, but we lack in-house IT departments that can keep them functioning reliably at a low cost. Riverside's IT department consists of me, the superintendent, and a voltmeter. This should inspire confidence in only the most desperate. We also lack deep pockets to afford the finest equipment that requires less maintenance. This explains why agriculture has been slow to come to the SCADA table. Fortunately, there are some vendors like Automata and Aqua Engineering that are aggressively trying to meet our needs.

IMPLEMENTATION OF ACTUATED AND FLOW-MEASURING GATES ON THE GREELEY NO. 2 CANAL IN NORTHEASTERN COLORADO

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

ABSTRACT

New Cache La Poudre Irrigating Company (http://www.newcache.com/) began the first phases of modernizing the 114-year-old canal in recent years. The Company has built new equalizer reservoirs, a 30 CFS pump station, and a new 3,000 acre foot storage reservoir using concessionary loans available from the Colorado Water Conservation Board. Further, the outlet works out of the Company's long-time equalizer reservoir on the Greeley #2 Canal has been replaced and modernized. As an integral part of the overall canal modernization, various approaches to actuating gates, measuring flows, and initiating SCADA were evaluated. The Company studied and toured SCADA installations in four states of the United States and in two states of Australia. Ultimately, the Rubicon actuated and flow measuring gates were selected and eight gates have been installed on the canal in the past two years. Portions of the Greeley #2 Canal, the river diversion on the Cache La Poudre River, and the discharges from two reservoirs can now be monitored and controlled from the Company's office in Lucerne, Colorado. The process of evaluating SCADA and actuated gates will be described as well as current operations. Further expansion of the system is anticipated in the future that will likely lead the Company toward full canal automation. The current short term strategy for future expansion of the system will be described.

BACKGROUND AND INTRODUCTION

New Cache La Poudre Irrigating Company (referred to here as NCLPIC or "the Company") operates one of the larger canal systems in northeastern Colorado which is known as the Greeley #2 Canal. The company holds decrees on the Poudre River and diverts approximately 600 CFS when all the direct flow decrees are in priority. An affiliate company, managed under the umbrella of the New Cache companies, holds storage decrees as well. Further, many farmers under the Greeley #2 utilize owned or rented water in the Colorado-Big Thompson system which is the late season supplemental water in the region. In recent years, NCLPIC has also initiated a well augmentation plan for more than 80 member wells within the company's historic service area.

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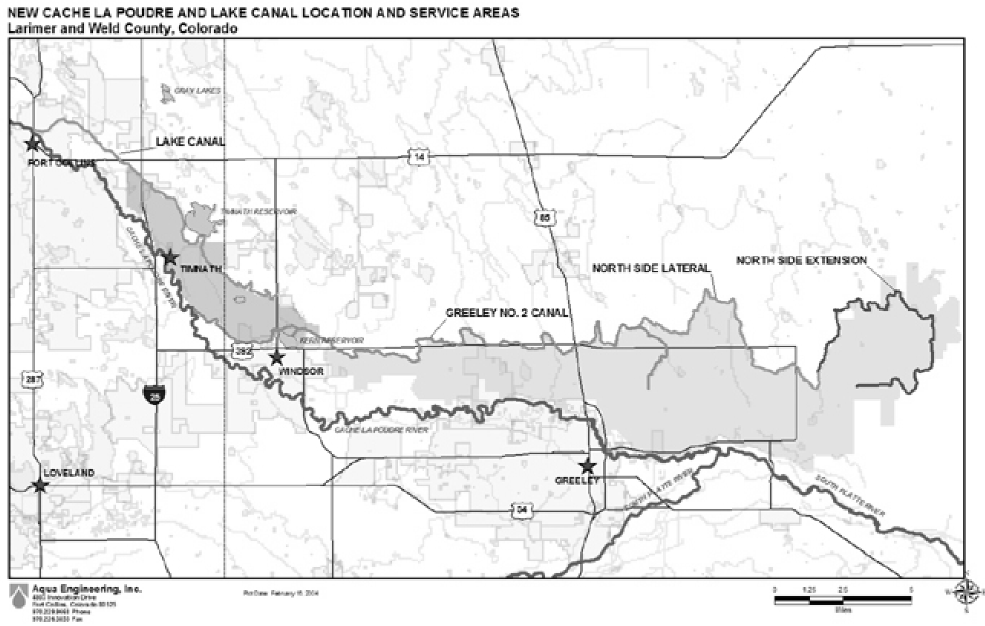

Figure 1. The Greeley #2 Canal dates back to the late 1800's and is one of the four major canal systems on the Cache La Poudre River in northeastern Colorado. The canal is approximately 45 miles in length and provides irrigation water to approximately 35,000 acres.

In 2003, the company commissioned an initial demonstration of SCADA (monitoring only) with one of the key rated sections on the Greeley #2 system. This demonstration complemented an existing Stevens recorder device and showed clearly that real time data could be effectively used and that improved monitoring was a significant help in managing day-to-day operations as well as annual reporting of flows and deliveries.

THE DISCOVERY PROCESS

After considerable SCADA study and evaluation, including tours of Central Arizona Irrigation and Drainage District, the Dolores Project near Cortez, Colorado and Imperial Irrigation District in California, the Company elected to implement SCADA for further monitoring of flows as well as gate actuation at key checks and reservoir outlets. Concepts of differing approaches were evaluated and costs estimated over an evaluation period of approximately 9 months. It was gratifying to learn that, in general, the costs of implementing SCADA for canal operations are down from the 1990's when it was still quite costly to acquire many of today's affordable features.

It is important to note that the Company took a suitable period of time and made very deliberate efforts to understand options and costs. The differences between not only the technical specifications of differing equipment and the over riding philosophy are not easily understood.

Ultimately, the Company's Board of Directors made the decision based on the evaluations and ideas presented to them in early 2005. One notable demonstration for the Board was related to the real time benefits of SCADA. During a March 2005 Board meeting, it was possible to log onto the Goulburn-Murray Rural Water Authority's system in Australia to see water flowing. Because of the internet-based interface to this SCADA system, flow trends could be monitored and gates moved as a demonstration of functionality and remote access.

The Company continues to study potential expansion and future features for consideration. In the fall of 2006, Don Magnuson and Stephen Smith visited three irrigation districts in Victoria and New South Wales, Australia to better understand the full or near full automation of canals that has been achieved there.

ELEMENTS OF THE IMPLEMENTATION

Rubicon gates were ultimately selected because of suitably accurate flow measurement that is possible combined with gate actuation in one structure. One existing radial gate was actuated with a Limitorque actuator and another with a Rotorque actuator. The RTU's in the Rubicon gates and the other sites are Motorola MOSCAD units, either M or L devices.

Both spread spectrum and conventional UHF radio communications were evaluated. After that process was completed, a UHF radio frequency was licensed to the company and the communications for the entire system are facilitated using a repeater on a water tower near the Company's offices near Lucerne, Colorado and a tower on a property owned by the Company near Timnath, Colorado. The radio infrastructure is currently capable of providing radio coverage to the entire 35,000 acre service area under the Greeley #2 Canal.

Because Rubicon gates were selected, the Rubicon SCADAConnect HMI was evaluated and ultimately selected for the human-machine interface at the central computer. The system currently consists of eight Rubicon gates, two actuated radial gates, and monitoring of one rated section. A key radial gate outlet used to waste excess water in storm events allows for continuous monitoring of canal water surface elevations. Storm flows can be dumped to avoid increased liability and risk of a canal breach.

More specifically, the SCADA-driven elements of this canal modernization project include:

- Automation of a radial gate at the river diversion on the Cache La Poudre River.

- Automation of the outlet from Kern Reservoir, an equalizer on the main canal.
- Automation of two checks on the main canal.
- Monitoring of flows at a historic rated section on the main canal.
- Automation of a radial gate that can be used to release excess flows such as storm flows back to the river.
- Automation of diversions into equalizers on the lower end of the system as well as a pumping station.

FINANCING OF THE IMPROVEMENTS

The Colorado Water Conservation Board provides low interest loans for raw water related projects. The interest rate for a 30-year term loan has been 2-1/5% and this is likely to drop some in 2007. The program has been quite successful in encouraging ditch and canal companies to make much-needed improvements to their systems.

NCLPIC applied for a loan after completing an engineering feasibility study and was granted a loan for approximately $7m in 2004. Several years of design and construction improvements are coming to fruition during 2007.

FUTURE EXPANSION OF THE SCADA SYSTEM

Currently, the operational scheme for the Cornish Plains project is being developed and implemented. Cornish Plains consists of two equalizer reservoirs, a storage reservoir, and a pump station. The pump station is operated in either of two modes to 1) make up canal flow shortages in order to hit required downstream deliveries or 2) pump water into the storage reservoir.

A short section of the canal at Cornish Plains will soon have Rubicon's Total Channel Control (TCC) system implemented which will allow for a continuous and automated process. The pump station discharge will be varied over time to achieve a downstream delivery set point based on available flows in the canal.

Further future implementation of TCC will be evaluated. Considerable expense time will be required if the Company is to automate more of the checks on the 45 mile canal and thereby allow for more TCC. It is also possible that individual laterals off the main canal will be considered for TCC. Costs and benefits are key to understanding future expansion of any of the system.

SUMMARY

For the New Cache La Poudre Irrigating Co., considerable deliberation and evaluation of hardware and software has culminated in the first phases of what will likely be a canal modernization effort spanning decades. SCADA is integral to the improvements that have been made with a $10m total construction package that was financed ($7m) with low interest loans from the Colorado Water Conservation Board. The process was enlightening and fulfilling and, most importantly, successful.

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Figure 2. One of three gates on the Greeley #2 canal is re-installed during the spring of 2007 following a repair that was accomplished over the winter when the canal was out of operation.

Figure 3. Three gates operated concurrently can handle the 600 CFS flow delivered from the Kern Reservoir which is an equalizer on the Greeley #2 Canal.

Figure 4. A bifurcation in the Greeley #2 has historically been used to move storm flows down preferred reaches of the canal and to serve as a place to waste excess flows back to the river in order to avoid a breach of the canal. The photograph shows a Rubicon gate used to hold deliveries on a portion of the canal. A radial gate on the other leg of this bifurcation can be opened to release storm flows.

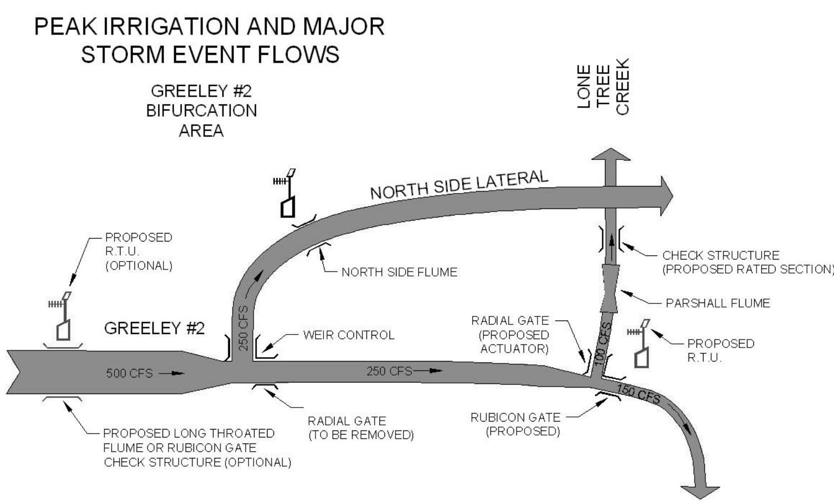

Figure 5. As a storm event materializes, excess water is first pushed into the Lower Division up until the lateral reaches its maximum capacity. When the water surface level in the canal reaches a threshold setting, the radial gate will open and excess storm flows will be released back to the river.