SCADA and Related Technologies for Irrigation District Modernization

A USCID Water Management Conference

Vancouver, Washington
October 26-29, 2005

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

Edited by

Charles M. Burt
California Polytechnic State University

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

USCID

The Mission of the United States Committee on Irrigation and Drainage is to foster sustainable, socially acceptable and environmentally responsible irrigation, drainage and flood control systems and practices for providing food, clothing and shelter to the people of the United States and the World.

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

USCID is the United States member of the **International Commission on Irrigation and Drainage** (ICID), an association of more than 70 countries. Founded in 1950, ICID is a non-governmental organization dedicated to the sound and responsible management of water resources. Its central purpose is to promote the development and application of the sciences and techniques of irrigation, drainage, flood control and river channel stabilization.

USCID publishes the *USCID Newsletter*, proceedings of USCID meetings and special reports; organizes and sponsors periodic technical meetings and Conferences; and distributes ICID publications.

Since 1986, USCID has organized a number of regional, national and international meetings throughout the U.S. These meetings address contemporary issues affecting irrigated agriculture, offering a multi-disciplinary evaluation of problems and solutions.

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

USCID accepts no responsibility for the statements made or the opinions expressed in this publication.

Preface

The papers included in these Proceedings were presented during the **USCID Water Management Conference**, held October 26-29, 2005, in Vancouver, Washington. The theme of the Conference, sponsored by the U.S. Committee on Irrigation and Drainage, was *SCADA and Related Technologies for Irrigation District Modernization*.

Today's irrigation and water districts face ever-increasing challenges in their daily operations. These include increasing 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. 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).

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.

Charles M. Burt
San Luis Obispo, California

Conference Chairman

Contents

Modernization Case Studies

Interactive Visual Presentations

OVERVIEW OF SUPERVISORY CONTROL AND DATA ACQUISITION (SCADA)

Charles M. Burt[1]

ABSTRACT

The term "SCADA" encompasses many combinations and variations of remote monitoring and control. SCADA systems are now successfully operating in irrigation districts throughout the western U.S. An emphasis on good planning, with the use of high quality equipment and expertise, will help guarantee a successful project.

INTRODUCTION

SCADA systems in irrigation projects have been in existence for several decades. However, the vast majority of functional SCADA systems in irrigation districts – which probably now number at least 150 in the western U.S. – have been installed within the last 10 years. This paper will present a few of the factors that should be considered when contemplating installing a SCADA system. Other papers in the conference will provide specific details about hardware, software, and applications.

Why SCADA?

The real questions are "Why *not* SCADA", or "What form of SCADA is best *at this time* for my irrigation district"? Each district will have individual justifications for SCADA, but there are probably three major reasons why so many districts are investing in SCADA:

1. Irrigation must retire "art" and shift to an industrial control process, in which real-time information is constantly used to make appropriate decisions. Reducing "art" from the process fulfills the need and desire to:
   a. Reduce diversions, to maintain in-stream flows in the rivers.
   b. Provide more flexibility in water delivery to farmers.
   c. Reduce pumping costs.
   d. Conserve water and sell the conservable water.
   e. Remove the mystery of operation details, so that new employees can be easily trained, and so that managers can establish clear and measurable performance guidelines for canal/pipeline operators.

---

[1] Professor, BioResource and Agricultural Engr. Dept. and Chairman, Irrigation Training and Research Center (ITRC). California Polytechnic State Univ. (Cal Poly), San Luis Obispo, CA 93407; cburt@calpoly.edu

2. There is often a need for automation that requires computers (Programmable Logic Computers, or PLCs) at remote locations. Because it is the nature of computers, electronics, sensors, and software programs to have occasional problems, it is prudent to remotely monitor their performance at such sites.
3. Some districts have key trouble spots where water levels historically get too high, or flow rates get too low or high. SCADA provides a means to remotely monitor those sites in real-time – eliminating tremendous labor distractions, vehicle mileage, dust, etc.

SCADA CHARACTERISTICS

In this conference, you will be exposed to a variety of "SCADA systems". Some systems will be quite elaborate and involve automation, and others will simply be able to transmit data from remote locations. However, all SCADA systems have the following components, at a minimum:

1. A sensor
2. Some type of on-site (a.k.a. "local") apparatus that creates an electrical signal that can be transmitted
3. A local power supply to power the sensor and transmission unit
4. Some type of communication system, such as hard wire, radio, satellite, phone, etc.
5. A receiving unit on the other end of the communications
6. Some mechanism to display the information – which may be a simple alarm bell, computer screen, message on a pager, etc.

The minimum components listed above would be capable of "remote monitoring" – which is one-way communication only. However, many systems also include some type of control capability – which requires two-way communication.

A very simplified depiction of SCADA elements with two-way communication is seen in Figure 1.
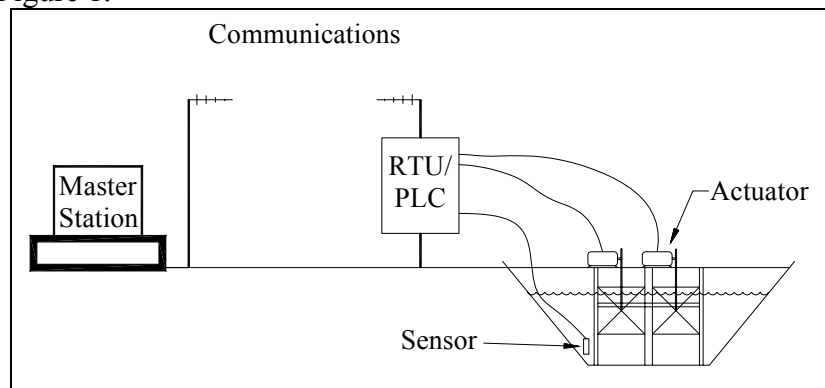
Figure 1. Conceptual elements of an irrigation district SCADA system that involves control.

Many people use the term "SCADA" to denote the collection and transmission of data, *plus* an automation process. An automation process may or may not require SCADA, so I prefer to separate the two. Not all of ITRC's SCADA projects involve automation, and not all of our automation projects involve SCADA. That said, all of our automation projects that use programmable logic controllers (PLCs) also incorporate SCADA for remote monitoring, alarms, and the ability to change target values.

Table 1 is one attempt to categorize various types of SCADA systems.

Table 1. Variations between and within SCADA systems.

Case	Basic Function	Frequency of Sensor Monitoring	Frequency of Data Transmission to Office
1 Monitor	Alarm for high/low values	Continuous	Only if alarm condition exists.
2 Monitor	Alarm for specific values such as height, position, temperature	As often as once/second, as seldom as once/15 min.	Only if alarm condition exists.
3 Monitor	Remote monitoring of specific values such as height, position, temperature. No alarming.	As often as once/second, and as seldom as once/day.	For river basins – often a few times/day. For irrigation districts – often once/minute.
4 Monitor	Cases (2) + (3)	1/sec – 1/day	Once/day remote monitoring can be over-ridden by an alarm exception at any time.
5 Monitor plus manual	Case (4) plus remote manual control of an actuator	1/sec – 1/15 min	1/30 sec – 1/30 minutes. Slower than 1/minute is outdated and cumbersome for operators.
6 Monitor plus Automation	Case (5) plus remote changing of target values for local, independent automation	1/sec – 1/15 min. With modern automation, 1/sec or more frequent is common.	1/30 sec – 1/30 minutes. Slower than 1/minute is outdated and cumbersome for operators.
7* Monitor plus Automation	Case (6) plus feed-forward between local controllers	1/sec – 1/15 min. With modern automation, 1/sec or more frequent is common.	1/30 sec – 1/30 minutes. Slower than 1/minute will often not work with feed-forward. ***This is rarely found in an irrigation district.***
8* Monitor plus Automation	Case (4) plus centralized computation of gate/pump movements	1/sec – 1/15 min. With modern automation, 1/sec or more frequent is common.	1/sec – 1/15 min. ***This is rarely found in an irrigation district.***

* - Denotes forms of automation with few examples of sustained success in irrigation districts.

It is common for an irrigation district SCADA system to contain a combination of the cases in Table 1. For example, a district may have several PLC-automated

sites, plus some sites where PLCs are used with remote manual operation, plus a variety of sites that only need monitoring and perhaps alarms.

Overview of Building a SCADA System with Local Automation (Case 6)

An abbreviated flow chart for the process of building a SCADA system for Case 6 (of Table 1) can be seen in Figure 2. Within each of the action blocks are numerous steps. Within the box labeled "Perform Specific Field Tests", for example, ITRC has several pages of procedures. Likewise, for checking the wiring and calibration of the field PLCs alone we have 12 pages of flow charts.
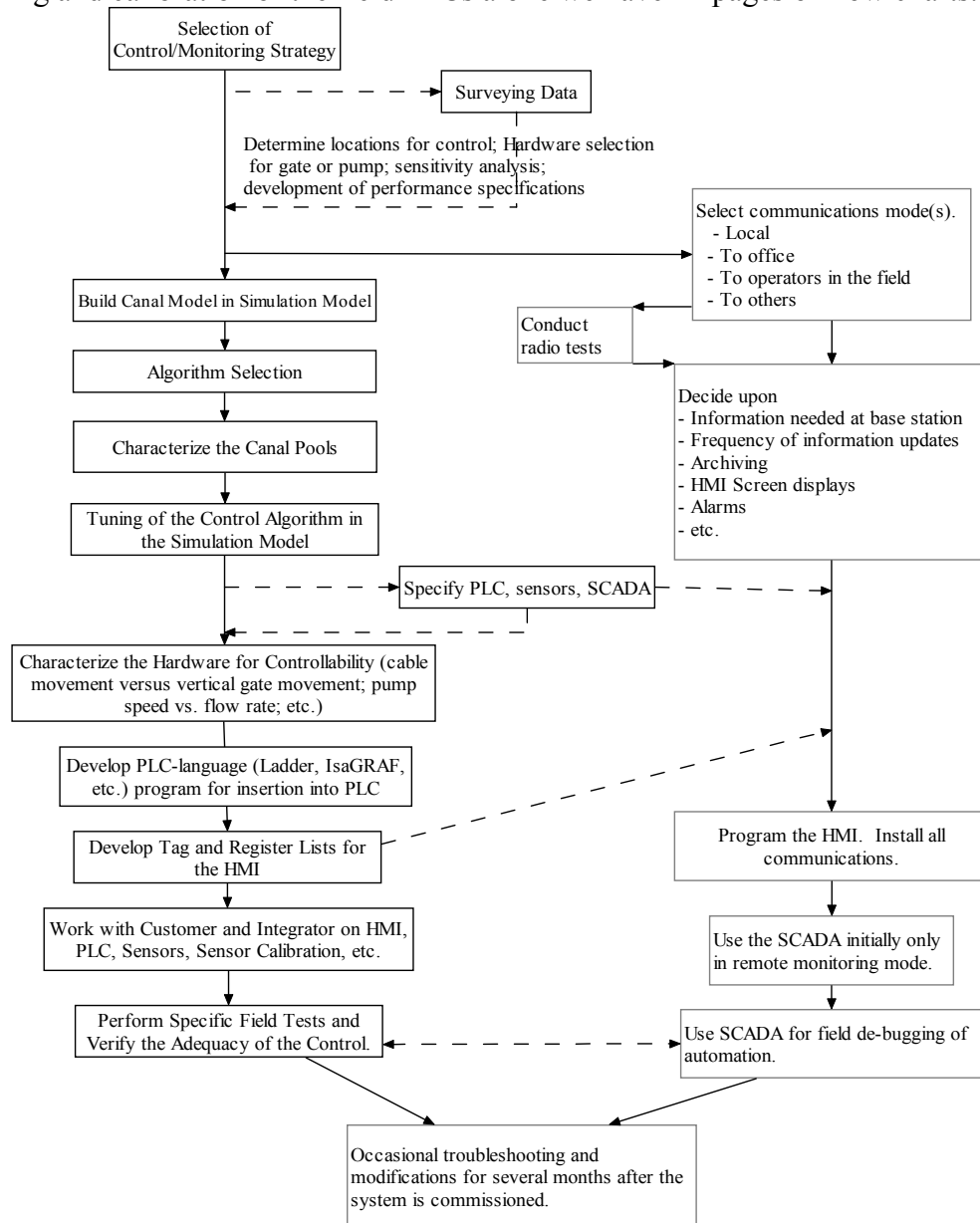
Figure 2. Outline for the Process of Design and Implementation of a Case 6 SCADA System.

Components versus Systems

Figure 2 is meant to illustrate that successful implementation of a SCADA system, especially one involving automation, is much more complicated than simply selecting a PLC and some sensors. SCADA systems are composed of components that have hopefully been selected and connected to work as a seamless system to satisfy specific objectives.

The components must be carefully selected so that everything "matches". For example,

1. A very good sensor might output a voltage signal, but that might be completely incompatible with a requirement that the signal be transmitted over a 3000' cable.
2. A specific brand of water level sensor may be excellent, but if a 10 psi sensor is selected when only a 1 psi sensor is needed, the resolution of the signal will only be 10% of what is possible.
3. 8-bit sensors connected to 16-bit computer input boards cannot give 16-bit resolution, or visa-versa.
4. If a control algorithm requires an average of 60 readings/minute, a PLC that is only capable of obtaining 60 readings in the last 10 seconds of the minute will provide different control capabilities than one that can obtain one reading each second during the 60-second period.
5. The power provided to a PLC must be capable of powering all the sensors, radio(s), PLC, heater, etc. in all weather conditions.
6. Sensors with proprietary software and communications won't easily fold into a complete system that can be updated and added to.

The examples above show that there are "matching" or "compatibility" requirements in two categories:

1. The hardware must be able to physically link together and communicate. This is the job of the "integrator".
2. The hardware must be compatible with the control/monitoring objectives. This is the job of an *irrigation* automation control specialist, who must provide specifications to the "integrator". Control specialists from the chemical, electrical, transportation, etc. industries have not been able to successfully apply their control logic to canal systems.

Without getting into detail, it is important to note that discussing a sensor for a SCADA system is similar to discussing tire selection for a truck. The sensor (tire) doesn't make up the entire system, but the system won't function properly without the correct sensor (tire). Furthermore, discussing the price of a sensor or PLC and thinking that this price is a major part of the SCADA system cost is

similar to treating the tire costs as a major part of a truck purchase – this is clearly the wrong approach.

Another analogy is the cost of "free" software. If your time is free, you have a lot of patience and time on your hands, you won't need updates in the future, and your needs are extremely specific and match the software, then the "free" software may be cheaper than a good commercial software package. However, one must look at the complete <u>system</u> – not special deals on individual <u>components</u>. The emphasis with SCADA systems, in my opinion, is QUALITY, QUALITY, QUALITY – in specifiers, integrators, software, and hardware. Even in systems with the best-quality components, problems arise. The right SCADA team can sort out those problems if there is a willingness to work together and an understanding of the system in its entirety.

<u>So You Are Considering a SCADA System – Expanding on the Thoughts Above</u>

There are numerous very successful SCADA systems. Irrigation districts that have successfully implemented them typically quickly expand them and wonder how they survived without them. But there are also many problem cases. Classic problems are:

1. Cost overruns
2. Failure to achieve performance expectations
3. Failure to reduce operating costs in order to meet payback expectations
4. The thing just doesn't work right

Secondary problems include:

1. Scheduling errors
2. Interfacing problems
3. Incompatible equipment
4. Lack of acceptance
5. Adverse publicity

In my experience, the problems have arisen because of one or all of the following:

1. Districts are looking for a "silver bullet" that will cure problems quickly and with little effort.
2. People focus on a few components rather than understanding that they need to consider a system.
3. There is no clear plan for the present and future.
4. Districts decide to use the "local electrician" because he/she is a nice person and dependable, instead of hiring an experienced integrator with ample successful experience in irrigation district application.

5. Districts (or local government agencies) invent their own sensors, hardware, and software.
6. Districts start too big, too fast.
7. Not everyone accepts the fact that problems will occur, and that there must be qualified people to diagnose problems, service equipment and software, and stick with the problems until they are solved. This takes an on-going budget.

As with any process, there are logical steps to follow in designing and implementing a SCADA system. These include:

1. Master planning
2. Precise specifications
3. Vendor qualification
4. Vendor selection
5. Adequate training and documentation
6. User tools for future changes
7. Spares and warranties
8. Continuous and near-exhaustive testing
9. Realistic schedules

The process can take a long time before any actual installation begins. If the planning is done properly, the installation can be accomplished in a few months. If the wrong people and planning are involved, the installation may never be completed satisfactorily.

Master Plan: A master plan identifies the need for automation, the degree of automation required, what other features are desired, and the budget and cost justification. This represents the guideline for all the work, so it is necessary to carefully understand which options are desired and why. The plan must also consider the impact on operation, instrumentation, training, installation, interfaces to other utilities (such as electric utilities), public relations, manpower requirements, future expansion, and expected life of the new system.

Start with the simple considerations. How much will you do yourself and how much will be contracted out to consultants or vendors? It may well be cost effective to contract out much of this effort because of the high cost of retaining in-house experts in planning, considering options, reading the literature, writing the specifications, training, installing, and programming beyond the normal operating requirements. However, at the minimum, there will need to be someone in a project management position to monitor all this effort and ensure that the system is on time and within the budget.

Integrator: The component selection, matching, installation, and troubleshooting are so complicated that most successful SCADA projects have utilized an

"integrator" that assumes responsibility for the complete package. The integrator generally understands communications, sensors, human-machine interfaces (HMI), actuators, etc. and can make certain that everything physically moves, measures properly, and communicates. It is extremely important to understand that when SCADA is used in a canal automation scheme, the SCADA integrator will rarely, if ever, understand canal hydraulics, simulation techniques, and control algorithms and algorithm tuning. These are separate functions that require an additional expert.

Integrator selection is a very important step since most products and services, which may appear to have similar functions, can be quite different in use and flexibility. Most large jobs today require that integrators be "pre-qualified". Pre-qualification ensures that the vendor can do the job technically, has a track record of delivering on time, has the financial backing to support the job even after it is delivered, and has the in-house project managers to accomplish necessary integration and subcontracting. During this stage, it is worthwhile to discuss the potential integrators with previous customers, who are usually ready to praise their vendor or relate their horror story. Consultants can also be used during the integrator qualification process, since the consultant usually provides the initial specifications that the integrator will bill on. Obviously, the consultant must also have excellent experience and expertise (not necessarily the same things).

HMI: The Human-Machine Interface (HMI) is important. How easy is the system to operate? Are control and monitoring screens straightforward and is information easily accessible? For example, an alarm condition that is missed because it is mixed in with many nuisance alarms is as bad as one that is missed by the instrumentation. Color is a very important component, especially on schematic displays, since different colors can be allocated special meanings easily recognized by the operator at a glance (e.g. blue means open, green means closed, red means alarm). Further, operator acceptance of the new environment and the ease of control can make the difference between project success and failure.

Reliability: Reliability is a measure of the system's ability to minimize downtime by avoiding failure, or at least to keep operating in a degraded mode by using special software and hardware such as an uninterruptible power supply (UPS) and a redundant master computer. The tradeoff includes weighing the extra cost of the additional equipment against the value of this function and the likelihood of an outright failure. No machine will run forever and eventually you will have to shut down your master at least for occasional checkups and preventive maintenance – managers should be prepared to live with these tradeoffs or buy reliability up front. ITRC has decided that for control variables in automated systems, it is essential to have a high level of redundancy in sensors, power supplies, and A/D converters. Yes, this costs extra and may reduce the number of sites that can be automated, but it ensures a better chance of success.

<u>Maintenance:</u> Maintainability is the ease with which fixes or changes can be made to your system. In the case of hardware, consider what you can fix yourself, what spares you may need, and how accessible the vendor is for factory returns and for minor upgrade contracts. Modularity helps maintenance. Placing sensors so that they can be removed for cleaning/inspections, and be replaced in exactly the same location without new calibration, is important.

<u>Price and Schedule:</u> After all other criteria have been considered, how much does it cost and how long does it take to deliver it? Some options may be considerably more expensive than the alternatives, so you must consider an associated cost for every choice you make. Dual masters are more expensive than a single master, but you must bear in mind the associated cost of not having the reliability of redundant machines. If the cost given by your chosen vendor is more than the cost of not having a SCADA system, be prepared to live without it. The same is true of most other features. Any reputable vendor can supply any requirement, given enough time and money.

Therefore, you should itemize your specifications and bids from potential vendors to identify the dollar and schedule impact of each of your chosen criteria. Be sure to leave some flexibility for vendor-recommended alternatives. There may be a better, cheaper way to do what you want done. Every vendor has a "baseline" product that includes a readily available set of easily integrated alternatives that have been proven and tested. That means that one vendor can put together the lowest bid for one set of criteria, while another will bid lowest on a slightly different set. To ensure yourself of the best performance for the best schedule and price, remain open-minded in your choice of options in the original bid specification. Consider each vendor's most cost-effective set of alternatives.

SUMMARY

The potential for new and expanded SCADA systems in their many combinations and variations of remote monitoring and control exists for irrigation districts throughout the western US. However, in order for districts to fully utilize that potential, attention must be paid to all of the details – which, in many cases, can "make or break" a system. An emphasis on good planning, with the use of high quality equipment and expertise, will help guarantee a successful project.

ACKNOWLEDGEMENTS

TOTAL CHANNEL CONTROL™ — THE VALUE OF AUTOMATION IN IRRIGATION DISTRIBUTION SYSTEMS

I. Mareels[1]
Su Ki Ooi[1]
David Aughton[2]
Tony Oakes[2]

ABSTRACT

Total Channel Control™ is a patented automation design for large scale open canal irrigation networks that manages water distribution within capacity constraints to achieve on-demand water delivery whilst maximizing water distribution. Here it is shown that this decentralized and distributed control implementation realizes near globally optimal performance. Furthermore, the performance enhancement above optimally scheduled open loop or manual operations is exemplified.

INTRODUCTION

When considering automation, with its requirements to invest in a considerable information infrastructure to realize this automation, inevitably there arises the question of what is the economic value of this investment/automation. In the best of circumstances, this is a difficult question to answer. It is the subject of much research in the control and systems engineering communities.

Indeed, especially in the context when automation is considered for the first time, there is simply no experience with the behavior of the system under the automation regime to be introduced. Even in the situation where manual operations are being mimicked through automation, the mere presence of automation always leads to new possibilities in operating or managing the system that more often than not were simply inconceivable before the automation was realized. Without a thorough understanding of this behavior, it is difficult if not impossible to ascertain what the economic impact will be. So typically, pilot studies are called for to quantify the impact automation can make. Pilot studies enable one to evaluate realistically the behavior realized under the automation regime, how it differs from the open-loop, manually managed system behavior and consequently one may confidently predict what impact automation has on the bottom line.

[1] National ICT Australia, Ltd, & Department of Electrical and Electronic Engineering, The University of Melbourne, Victoria 3010, Australia
e-mail contact: i.mareels@unimelb.edu.au, fax: int+61+3+83 44 74 12 (secure)

[2] Rubicon Systems Australia Pty Ltd, anthony.oakes@rubicon.com.au

Alternatively, simulation studies can be completed, to predict the potential changes in behavior, with the aim of deducing or predicting what the (economic) impact can be. This requires that a good simulation model is available for the system under consideration, one that allows for the consideration of the automated behavior over time scales that enable economically valid conclusions. This is not a simple task in general, requiring information from very different realms of expertise, which is not easily integrated.

In this paper a simulation study for the case of automating an open channel irrigation system is considered. The simulation study considers a number of various scenarios. The study benefits from the hindsight of a number of completed pilot and commercial implementations of Total Channel Control™ (see patents [1,2]) in Victoria, Australia. Nevertheless, the simulation study does not evaluate the economic impact, but rather emphasizes the achieved quality of service in water distribution through channel management, as measured by regulation accuracy, water on-demand and water efficiency. This study must be complemented with an economic model that considers the value of water and the affected crops, as well as a model for the infrastructure cost and depreciation costs to arrive at an economic impact statement. This is outside the scope of this paper.

The paper is organized as follows. In the next section Total Channel Control (TCC™) is briefly described. In the following section the simulation study is introduced. There TCC™ is compared with a manual regime and a globally optimal management regime. The former is an idealized representation of a near optimal manual exploitation for the channel system under consideration. The latter is an automation regime where all information is available at all regulator sites. This regime represents the ideal true globally optimal management strategy. The outcomes of the simulation study are discussed in the next-to-last section, before the concluding remarks.

TOTAL CHANNEL CONTROL

TCC™ is a model based automation design implemented in Victoria Australia by Rubicon Systems Australia, Pty Ltd, based on joint research and development completed at the University of Melbourne, Australia. TCC™ is implemented in a purely gravity fed irrigation district. The quality of service is determined by three main features:
- how well the water levels are regulated in the canal,
- how much the water demand is met in real-time,
- how small the out-flows at the bottom end of the irrigation canal are (water distribution efficiency).

TCC™ as implemented in Victoria consists of an information infrastructure where all the regulator structures and water off-take gates along the canal are on a radio network. The logical structure is represented in Figure 1. A relatively low

bit rate, packet based radio network, managed in an internet like fashion forms the back bone of the communication network. The regulators and off-take gates are the lowest level nodes in the communication network. Within a limited range they can communicate in peer-to-peer mode or broadcast mode. A single router can accommodate a number of local networks, characterized by a different carrier frequency to ensure radio communication. The router communicates over a higher bit rate channel to a major router, which communicates over optical fiber to the central command node.
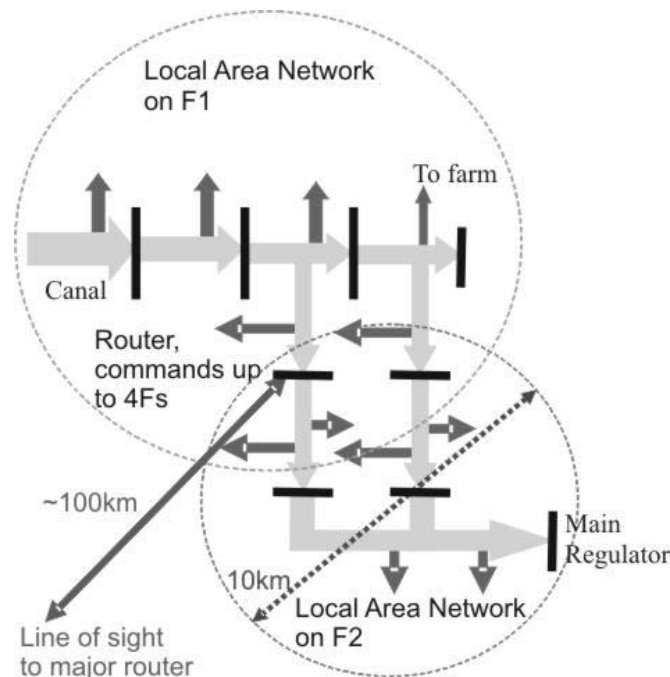
Figure 1: Logical Structure of Radio Based SCADA Network for TCC™.

A picture of the actual hardware implementation is shown in Figure 2. It represents an in canal regulator and a few off-take gates in the pilot project. The radio antennae are seen on top of the solar panels that provide the energy for the regulator actuator and communication hardware.

Figure 3 represents the typical flow of information in TCC™, from a water order to its implementation. It identifies the main nodes in the system, a central node that functions as the overseer, repeater nodes relaying messages, canal nodes where the main control action takes place and on farm nodes that provide automation of water delivery, and ensure water accounting. The farmer does not have direct command over the on-farm water delivery gate (apart from an emergency override function). All automation is requested via the central node, which arbitrates water order requests (orders and cancellations; timing, flow, volume) and implements these on behalf the requestors. Depending on the local authority's policy, water orders require some lead time, which may be as short as

an hour. Although in this paper we will consider TCC™'s ability to deliver water on-demand, where the lead time is simply the time required to verify the physical system limits to respond to the requests. In case the decision is negative, i.e. the required water cannot be met, a delay time that allows the request to be met will be indicated.

Figure 4 represents the generic TCC™ distributed control law which is implemented on the canal nodes. The control action for the (overshot) gate consists of a feed forward term and a feedback term. The feed forward term compensates for the known downstream water demand (the sum of the water demand in the downstream pool and the water demand over the next regulator structure. The feedback term ensures that water level regulation is achieved for the distant downstream water level in the pool. The feedback also compensates for any leakage or other disturbances in the pool. Both feed forward and feedback control actions are low pass filtered to ensure that the actuator action does not excite any standing waves in the pool. Moreover, a simple anti-windup action is implemented to ensure that the control gates provide smooth control action without getting stuck at the control limits (fully open/fully closed). For more details about the actual control algorithms refer to [3,4].
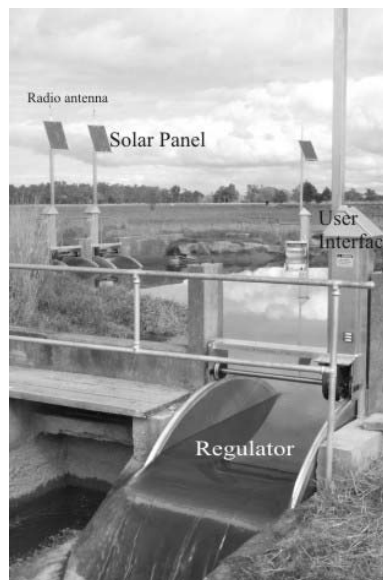
Figure 2. Automation Infrastructure for TCC™.

The controller structure in TCC™ is distributed, and requires only local information exchanges (only neighboring regulator structures must be able to communicate with each other) to realize the actuator commands. The information exchange is event driven, i.e. information is only exchanged when a significant (downstream) regulator change is implemented or a significant (downstream) water level change is detected.
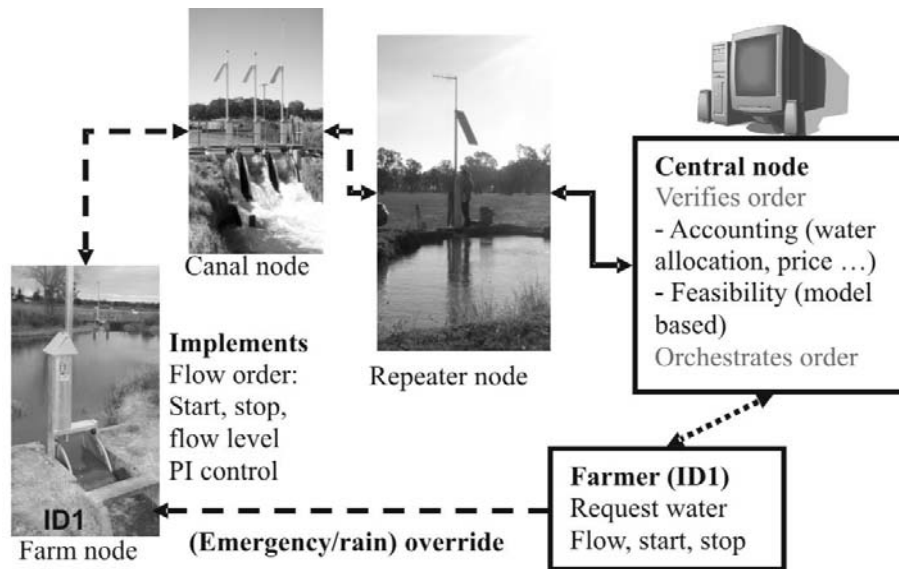
Figure 3: TCC™.

Besides the more frequent local communications, some information requires network wide communication. The set points for the water regulation form part of the system set up, and can be updated as needed. It requires peer-to-peer communication from the central command node to the particular regulators for which the set points need to be updated. Also the water demand must be managed on a canal wide basis. TCC™ enables in as much as feasible water on-demand management. Water requests are communicated to the management centre, where the scheduling software determines whether the water order can be met in real-time. If so, this water request is immediately communicated to the off-take gates, and this information is also communicated to the up-stream in-canal regulators. If not, the scheduler suggests an alternative irrigation period that can be accepted or rejected by the requestor. These water demand events are relatively infrequent[3] and can easily be managed over the radio based SCADA network.

The actual control algorithms implemented in the feedback and feed forward and filter blocks that determine the gate actuation are maintained in a data base at the central node, and can be updated through the radio network as required. This may be necessary in case of hardware failures.

The control algorithms implemented on the canal nodes are a function of the network topology and the functionality of the regulators. In case of hardware failures, sensors or actuators, or in case actuators are essentially out of the loop because of saturation (as would be the case under maximum flow conditions), the

---

[3] Without TCC™, farmers place water orders on a semi-regular basis with on average a single major irrigation every two weeks over the season. Under TCC™ a significant shift in behavior is observed, with more and smaller (in time and volume) irrigation requests being placed based on actual crop conditions.

control algorithm must be adjusted to reflect the new situation. The latter is taken care of by the anti-wind-up schemes, and is really considered part of the normal operation of the system, but the failure situations have to be approached in a different manner. Due to the inherent redundancy in the hardware (multiple sensors and actuators in parallel), or the system redundancy (due to the dynamic dependency between the variables being manipulated or sensed) there is significant potential to exploit this redundancy to have the performance degrade gracefully with hardware failures. This is achieved through a reconfiguration of the information loops underpinning the control loops, which will typically involve changes in the controller settings. For example, in the unlikely event a regulator would fail (say in the open position), a new situation arises in which one less water level can be regulated, and the upstream and downstream regulators must be now be retuned to reflect this situation (new information loops, new pool model, new controller settings). The performance will degrade on two pools, (down stream and upstream of the affected regulator) but the main consequences of this fault are essentially isolated to just these two pools (with only a minor degradation in overall performance). Similar scenarios can be worked through for other sensor and hardware failures.
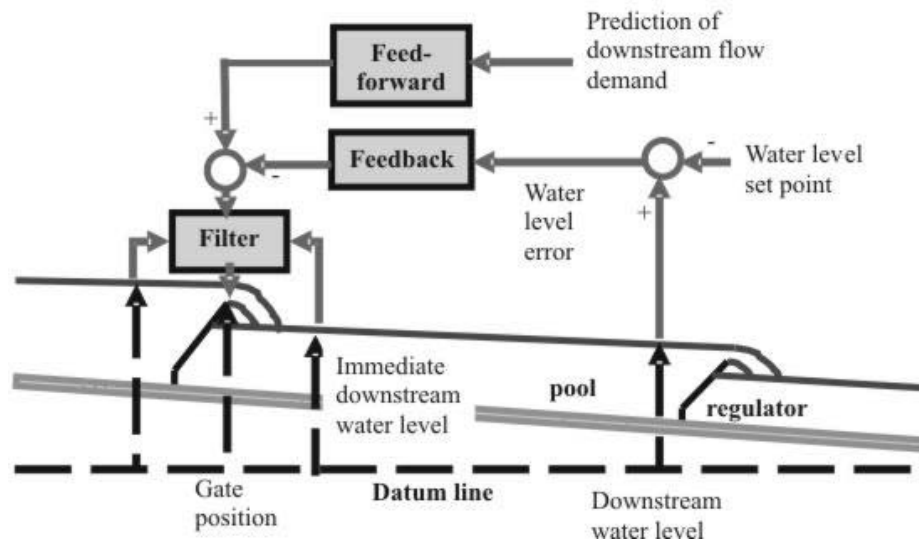
Figure 3: TCC™ distributed real-time control structure for water distribution and in-canal water level regulation.

SIMULATION SCENARIOS

Two main scenarios are considered. The first consists of the management of a canal consisting of 3 consecutive pools; the next scenario considers a canal with 8 pools in line. All regulators are overshot gates. The canal models reflect actual major canals in Australia. The data used to represent the canals/scenarios are derived from previous pilot projects. The simulation scenario runs over a period of 9 days (12960 min).

The canal considered in either scenario has a freeboard of 20cm above the set point. Acceptable quality of water level control is defined as a water level not less than 10cm below the set point, and not higher than 20cm above the set point. Three figures of merit are considered to compare the various management strategies:

- Water efficiency; defined as one minus the ratio of total water volume flowing over the downstream end of the canal to the total water volume dispatched into the canal. (This way the unavoidable losses of leakage, seepage and evaporation, which cannot be affected by automation are not considered in the efficiency calculation.)
- QST (Quality Service Time); defined as the ratio of the total duration of time where the water level is 10cm below the water level set point (on any pool where on-farm water delivery takes place) or 20cm above the water set point and the total simulation time. A QST of 100% means that all water orders are met in real time.
- Critical loss of service time (CT); defined as the ratio of flood time over the total rain time.

Scenario 1: Three Pools

The pools in the channel have the following characteristics:
- Pool 1: delay time 5min, wave period 15min, length 1600m,
- Pool 2: delay time 3 min, wave period 10min, length 900m,
- Pool 3: delay time 11min, wave period 29min, length 3200m.

The maximum flow capacity in the channel is 270Ml/day.

Four different management strategies (the details are described in [5]) are compared:
- Manual[4], where the regulators are set to a constant position over a period of one day, and the requested demand is rescheduled to minimize wastage.
- TCC™ without feed forward compensation, only using a feedback strategy.
- TCC™ as described above, using both feed forward and feedback.
- Globally optimal scheduling and control.

The actual events in the Scenario 1 are presented in Table 1. No water off-take is required on Pool 2, and hence Pool 2 does not play a role in the computation of the figures of merit. The maximum water demand is 67Ml/day, well below the maximum capacity in the channel. Scenario 1 does not explore the capacity limits of the channel.

---

[4] The Manual regime considered in the Scenarios is actually an open loop optimal strategy; i.e. from all possible responses characterized by constant regulator positions over 24h periods, this response that achieves the best quality of service is selected.

The figures of merit for the different management strategies are presented in Table 2.

On the basis of the figures of merit in Table 2, it is not possible to distinguish between the various automation strategies. The improvement over the manual regime is significant. Notice that the requested off-takes were scheduled in such a manner as to not require rescheduling under the manual regime.

The time that there is a flood on the canal is due to the rain event occurring at a time where there is major demand on the canal. (The flood event only affects pool 3.) The 24h time between regulator changes in the manual regime cannot cope with the excess water, and a significant flood event is simply unavoidable. In the automated regime, all water off-takes on the farm are stopped. The fact that no flood occurs and that the water efficiency is still 100%, is due to the fact that the available canal storage (freeboard) is sufficient to cope with the rain event. In case the rain event would be so significant that the canal storage is insufficient, the automated regime will spill water as to avoid floods along the canal.

Table 1. Event list for Scenario 1.

Activity	Pool	Start time (min)	Duration (min)	Finish (min)	Size
Rain	1,2,3	3300	600	3900	25mm
Off-take	1	2040	1260	3300	22Ml/day
	1	3900	5820	9720	22 Ml/day
	1	2700	600	3300	25 Ml/day
	1	3900	960	4860	25 Ml/day
	1	7500	2160	9660	13 Ml/day
	3	600	2700	3300	20 Ml/day
	3	3900	2700	6600	20 Ml/day
Off-take refused	3	6000	600	6600	-20 Ml/day

In order to distinguish between the various forms of automation, the actual response time and actuation effort has to be considered. The global optimal management strategy wins in terms of response time and also in terms of overall regulation accuracy but this performance comes at a price. Global optimal management requires substantially more control effort[5] than either form of TCC™.

---

[5] It is possible to formulate a global optimal control strategy with stringent constraints on the actuation effort. However this was not considered. Instead an unconstrained optimization was performed. This leads to better overall performance, which is however cannot be realised in practice.

TCC™ with feed forward action comes very close to the global optimum but requires less control action than the globally optimal strategy. TCC™ without feed forward action is significantly less responsive, and requires substantially more control actuation than TCC™ with feed forward, but less than the globally optimal control strategy.

Table 2. Scenario 1 Figures of Merit.

Management strategy	Efficiency	QST	CT
Manual	78%	78%	210%
TCC™ (without feed forward)	100%	100%	0%
TCC™ (with feed forward)	100%	100%	0%
Global optimum	100%	100%	0%

Scenario 2: Eight Pools

On the basis of the outcomes in Scenario 1, Scenario 2 is limited to a comparison between the manual control strategy and the two TCC™ strategies. The Scenario 2 activities are listed in Table 3, and the figures of merit are listed in Table 4.

The channel consists of 8 pools in line; Pools 1, 2 and 6 in Scenario 2 have the same characteristics as Pool 1 in Scenario 1, Pools 3 and 7 in Scenario 2 have the same characteristics as Pool 2 in Scenario 2 and Pools 4, 5, and 8 in Scenario 2 are like Pool 3 in Scenario 1.

Under this Scenario, TCC™ with feed forward is the best strategy. It clearly outperforms both TCC™ without feed forward and is vastly superior to the manual management regime. The manual regime achieves good efficiency, but set point regulation requirements are only met over less than half the simulation span. As a consequence water orders are poorly met, and the actual water delivered to the farmers is less than what is requested.

A more careful analysis of the individual pool responses shows that for the manual regime, the most downstream pools are most difficult to manage, whereas for TCC™ the most upstream pool is most difficult to manage. Under this Scenario, using the manual management regime, Pools 5 to 8 receive reasonably poor water level regulation, whereas the first 4 Pools are very well managed. Pool 5 is the worst managed in terms of meeting water demand, and Pool 8 experiences a flood condition during the rain event (for about half the time of the actual rain event).

Table 3. Simulated events under Scenario 2.

Activity	Start (min)	Duration (min)	Finish (min)	Size
Rain (all pools)	3300	600	3900	2.5cm
Off-take Pool 1	6000	2160	8160	15Ml/day
Off-take Pool 4	1200	2100	3300	8 Ml/day
Off-take Pool 4	9600	1800	11400	15 Ml/day
Off-take Pool 5	2100	1200	3300	5 Ml/day
Off-take Pool 5	5700	2880	8580	7 Ml/day
Off-take Pool 6	1440	1860	3300	15 Ml/day
Off-take Pool 6	3900	4620	8520	15 Ml/day
Off-take Pool 6	2400	900	3300	25 Ml/day
Off-take Pool 6	3900	660	4560	25 Ml/day
Off-take Pool 6	6900	2160	9060	13 Ml/day
Off-take Pool 8	600	2700	3300	20 Ml/day
Off-take Pool 8	3900	2700	6600	20 Ml/day
Off-take refused Pool 8	6000	600	6600	-20 Ml/day

In TCC™ mode the only pool where water delivery is not met 100% on-demand is in Pool 1. Allowing for a 4h delay in meeting the water orders would have realized 100% efficiency with 100% of all demand met.

Table 4. Figures of merit for Scenario 2.

Strategy	Efficiency	QST	CT
Manual	90%	45%	50%
TCC™ with feed forward	100%	99.9%	0%
TCC™ without feed forward	100%	98%	0%

CONCLUSION

The simulation scenarios presented show the success of TCC™ in implementing near on-demand (see Figure 3) water delivery.

It may be observed that the two scenarios do not explore the physical limits of water flow capacity of the channel. Rather a low demand scenario is explored, which presents indeed a significant advantage for the manual regime. The situation of high water demand is also not very interesting from a comparison point of view, because when demand is close to full flow capacity the potential for automation is rather limited. This is clear because automation does not provide for extra flow capacity in the channel. More importantly however, rain events and refused water orders would show even greater advantages for the automated

regimes in a high demand regime as compared to the presented scenarios in a low demand exploitation situation. Indeed a manual regime simply does not have the responsiveness of the automated regimes to cope with a large rain event, which essentially demands the management of a significant transient. Because, transient phenomena underscore the flexibility of the automated regimes, a low demand scenario is preferred in the comparison. It places the manual regime in the best possible situation. Therefore it is clear that the advantage of automation is very significant indeed.

This is consistent with the experience in the various pilot and commercial implementations thus far in Victoria. TCC™ is water efficient, and rejects disturbances such as rain events, or refused water orders extremely well. Compared to manual control (an idealized optimally computed open-loop scheduling) significant improvement in water distribution efficiency is achieved, combined with much better water level regulation.

The observation made in Scenario 2 that under TCC™ the most upstream pool is most difficult to manage is explained in [3,4]. It is a consequence of the upstream disturbance propagation, which is an unavoidable consequence of the combination of the delay on the channel and the feed forward action. It is this disturbance effect that essentially determines the limits of TCC™ performance.

REFERENCES

[1] I. Mareels, E. Weyer and D. Aughton (2000). Rubicon research Pty Ltd, Control Gates. WIPO Number WO02/16698, PCT Number PCT/AU01/01036 priority date for Australia 21 Aug 2000. (Status: pending approval.)

[2] I. Mareels, E. Weyer and D. Aughton (2001). Rubicon Systems Australia, Pty, Ltd. Fluid Regulation: Model and Control, WIPO Number 02/071163, Australian Application Number 2002233060 PCT/AU02/00230, priority date for Australia 2 March 2001. (Status: granted, world-wide protection.)

[3] Iven Mareels, Erik Weyer, Su Ki Ooi, Michael Cantoni, Yuping Li, Girish Nair Systems Engineering for Irrigation Systems: Successes and Challenges, 14th IFAC World Congress, Prague, July 2005.

[4] Michael Cantoni, Erik Weyer, Yuping Li, Su Ki Ooi, Iven Mareels and Matthew Ryan, Control of Large-Scale Irrigation Networks, submitted to IEEE Proceedings, July 2005.

[5] Su Ki Ooi, Simulation Studies for TCC™, Internal Report, Department of Electrical and Electronic Engineering, The University of Melbourne, Feb 2005.

DESIGN AND IMPLEMENTATION OF AN IRRIGATION CANAL SCADA

Manuel Rijo[1]
Adriano Lanhoso[2]
Miguel Nunes[3]

ABSTRACT

In Portugal all of the upstream controlled canal systems work with flexible water delivery schedules and therefore canal operational losses can be significant. Real-time technologies can allow the canal managers to continuously compare the real operation with its optimal or target value and to take appropriate corrective steps as required and minimize the water operational losses. The paper presents the design, field solutions and tuning of an implemented SCADA system on a Portuguese upstream controlled canal. Remote monitoring allows the data acquisition of water levels, gate positions and inflow and outflow computations. Remote control allows the operator to send control orders to gates. Two networks, including their remote terminal units and the needed communication and control software are parts of the presented SCADA system. This system controls the inflows to the main canal and main laterals, as well as the main outlets to the drainage system with gate controlled orifices. All the discharge equations are tuned in the field. The outflows through weirs or Neyrpic automatic siphons from the main laterals are also monitorized and their discharge equations are also tuned in the field.

INTRODUCTION

In Portugal, all the open-channel irrigation perimeters have upstream controlled systems and were designed for a rotation water delivery method. In practice, this delivery schedule was never implemented. Irrigation systems work on an arranged delivery schedule basis (Clemmens, 1987). Delivery gained flexibility, but the daily operation of the conveyance system itself is more complex, difficult and inefficient in the water use. Operational water losses in the conveyance and distribution systems are significant. Most of these systems are still empirically operated and according to personal judgments. In the particular case of the Sorraia Irrigation Project, here presented, the system manager cannot measure the inflow rates and, in order to be sure that deliveries match demands in all delivery points, he operates the system, most of the time, at full capacity. So, spills are common.

---

[1] Hydraulics Professor, Universidade de Évora, Apartado 94, 7002-554, Évora, Portugal, rijo@uevora.pt
[2] Electrical Engineer, OREY Técnica e Industrial Lda, rua Saint-Léger, 20, 1300-442 Lisboa, Portugal, Adriano.lanhoso@orey.com
[3] Mechanics Engineer, INAG, Av. Almirante G. Courinho, n°30, 1049-066 Lisboa, Portugal, miguelna@inag.pt

For the sub-system under modernization (main and lateral canals, all of them concrete lined canals), Rijo & Almeida (1993) presented an estimation of the conveyance efficiency (ratio between delivered and inflow water volumes) of 40%, considering the entire irrigation seasons of the years 1987 and 1988.

The main canal systems of these projects are now the focus of a new rehabilitation and modernization policy, with the main purposes of saving water and installing more flexible water delivery rules, like on-demand schedules (Clemmens, 1987). The final objectives are to make possible new irrigation methods and give some degrees of freedom for irrigation water management to farmers. The proposed field implementation of this policy was to maintain the system architecture, to install supervisory control and data acquisition systems (SCADA) and, when possible, to install buffer and control in the form of off-channel reservoirs (Rijo & Paulo, 1998).

The SCADA systems allow the water manager to continuously compare the actual hydraulic state of the delivery system with its optimal hydraulic state, and to take appropriate corrective steps as required. These systems allow the manager to react rapidly and effectively to the changing conditions, thereby accommodating both high and low flow conditions and reducing canal spillage and seepage.

The preliminary study of the SCADA of the Sorraia Irrigation Project was already presented by Rijo (1999). This paper describes implemented solutions (control and equipments) and the correspondent tuning.

BRIEF DESCRIPTION OF THE SORRAIA IRRIGATION PROJECT

The Sorraia Irrigation Project (Figure 1) is located along the narrow alluvial valley of the Sorraia River, a tributary of the Tejo River, near Lisbon (Portugal).

Water sources are two large dam reservoirs (Figure 1 and Table 1). The main irrigation system is an open lined canal network (main and secondary canals or laterals). AMIL radial gates (Kraatz & Mahajan, 1975) provide potentially good operation conditions for the Neyrpic orifice module intakes (Kraatz & Mahajan, 1975) to tertiary systems (canals or buried low pressure pipes) and to the fields. Irrigation areas and main crops are also presented in Table 1.

REAL-TIME SUPERVISORY CONTROL OF THE MAIN SYSTEM

General Presentation

The central control of the conveyance and water delivery network is only appropriate and efficient when reliable information exists about the real-time hydraulic state of the system. As already mentioned by Rijo (1999), therefore, a central control of an open-channel system must involve:

Figure1. Sorraia Irrigation Project Scheme. Field Stations of the SCADA

- a real-time remote monitoring action in order to keep abreast of the hydraulic system conditions or in order to obtain its actual state; this action is guaranteed by the SCADA;

- a remote control action in order to lead the system to the desired state, an action also guaranteed by the SCADA; the correction of the system (the closed loop control action) is taken care by the actuators in the control devices, namely gates;

- a management action to support operational decisions, ensuring the desired service performance, regarding the real and expected demands, the available storage volumes, and economic factors.

The SCADA system involves: remote terminal units (RTU), to collect local data (water levels, flow rates, gate positions) and command local equipment (gates); a command center, to supervise/manage all the RTU; a communication system, to link the RTUs to the command center.

Table 1. Main characteristics of the Sorraia Irrigation Project

Water storage volumes:	
Maranhão dam reservoir	180.9×10^6 m^3
Montargil dam reservoir	142.7×10^6 m^3
Conveyance and distribution system:	
Conveyance canals	112.9 km
Distribution canals	98.5 km
Buried low pressure pipes	171.6 km
Maximum design flow	17.0 m^3/s
Control devices	
AMIL gates	303
AVIS gates	85
Modules	567
Turnouts to farms	2026
Farmers	2000
Operational and maintenance staff	90
Irrigated areas (means of 1990-2000)	
Corn	4135 ha
Rice	3979 ha
Tomato	1281 ha
Other crops	2395 ha
TOTAL	11790 ha

RTU units are the interfaces between SCADA and the hydraulic system. For safety, they are located inside field stations (Sta.). The RTU units main purposes are: controlling inputs and outputs of field devices (intakes, offtakes and gates); monitoring field devices such as water level and gate position sensors and log alarms; reporting to the master station and carrying out the commands set they receive from these stations. The field stations can be of three types: control unit (RTUc), control and monitoring units (RTUcm) and monitoring unit (RTUm).The Sorraia Irrigation Project SCADA has 23 Field Stations with RTUcm or RTUm.

Field Stations with Control and Monitoring Units (RTUcm).There are 13 Field Stations with RTUcm. All of them include remote monitoring of water levels (upstream and downstream) and gate positions (Figure 1 and Table 2).

- to control inflows to main canals – from Maranhão and Montargil dam reservoirs (respectively, Sta1and Sta4), Furadouro diversion dam (Sta2);

- to control inflows to main laterals – Camões (Sta1); Sebes (Sta4); Erra (Sta5); Gamas (Sta9); Salvaterra (Sta13, Sta15); Trejoito (Sta17); Montalvo (Sta20); Samora (Sta22);

- to control wasted outflows at main outlets to the drainage system – Sorraia Canal (Sta8, Sta12); Salvaterra Lateral (Sta14).

Field Stations with Monitoring Units (RTUm). There are 13 Field Stations with RTUm. All of them include remote monitoring of the hydraulic device upstream water levels (*Su*) and the correspondent flows (*Q1*) (Figure 1 and Table 2).

- to monitor inflows to laterals – Entre-Águas (Sta3); Sebes (Sta4);

- to monitor wasted outflows through Neyrpic automatic siphons – Erra Lateral (Sta6); Montalvo Lateral (Sta21); Samora Lateral (Sta23);

- to monitor wasted outflow through downstream terminal canal weirs – Erra Lateral (Sta7); Gamas Lateral (Sta10); Salvaterra Lateral (Sta16); Trejoito Lateral (Sta18);

- to monitor wasted outflow through side weirs – Sorraia canal (Sta11, Sta13, Sta22); Salvaterra Lateral (Sta15).

Master Station. At the present development of the SCADA, there is only the Master Station at the central office of the Irrigation Project Association (Coruche, Figure 1).

All the controllers (see next chapter) are already installed in each Field Station and tuned, including the pre-definition of the daily operation schedules for the gates. For the developed SCADA application, only the pre-definition (daily, weekly and monthly) operation schedules are being developed. The communications with each RTU are also installed and used successfully.

Table 2. Summary of the equipments and control of the SCADA Field Stations (*)

Sta	Controller	Monitoring	Gate N°	Weir	Bottom orifice	Siphon	Commu nication	Power	Description
1	D, P, Q	Su	2	no	not	not	PSTN	EDP	Camões Lateral Intake
2	D, P, Q	Su	1	yes	no	not	GSM	EDP	Furad. canal Intake; Div. Dam weir
3		Su, Q1	8	not	not	not	GSM	solar	Entre-Águas Lateral Intake
4	D, P, Q	Su, Q1	1	not	not	not	PSTN	EDP	Sebes Lateral Intake
5	D, P, Q	Su, Sd	1	not	not	not	GSM	EDP	Erra Lateral Intake
6		Su, Q1	--	not	not	yes	GSM	solar	Erra Lateral Neyrpic siphon
7		Su, Q1	--	yes	not	not	GSM	solar	Erra Lateral end
8	D, P, Q, WL	Su	--	not	yes	not	GSM	EDP	Sorraia canal gate controlled orifice
9	D, P, Q	Su, Sd	1	not	not	not	GSM	EDP	Gamas Lateral Intake
10		Su, Q1	--	yes	not	not	GSM	solar	Gamas Lateral end
11		Su, Q1	--	yes	not	not	GSM	solar	Sorraia Canal weir
12	D, P, Q, WL	Su	--	not	yes	not	GSM	EDP	Sorraia Canal gate controlled orifice
13	--	Su, Q1	--	yes	not	not	GSM	EDP	Sorraia Canal weir
	D, P, Q	Su	2	not	not	not			Salvaterra Lateral Intake
	D, P, Q	Su	1	not	not	not			Sorraia Canal gate
14	D,P,Q, WL	Su	--	not	yes	not	GSM	EDP	Salvaterra Lateral gate controlled
15	--	Su, Q1	--	yes	not	not	GSM	EDP	Salvaterra Lateral weir
	D,P,Q WL	Su, Sd	--	not	not	yes			Gate controlled Inverted siphon
16		Su, Q1	--	yes	not	not	GSM	solar	Salvaterra Lateral end
17	D, P, Q	Su	1	not	not	not	GSM	EDP	Trejoito Lateral Intake
18		Su, Q1	--	yes	not	not	GSM	solar	Trejoito Lateral weir
19		Su	--	not	yes	not	GSM	solar	Sorraia Canal gate controlled orifice
20	D, P, Q	Su	2	not	not	not	GSM	EDP	Montalvo Lateral Intake
21		Su, Q1	--	not	not	yes	GSM	solar	Mont. Lateral Neyrpic siphon
22	D,P,Q	Su	2	not	not	not	GSM	EDP	Samora Lateral Intake
		Su, Q1	--	yes	not	not			Sorraia Canal weir
23		Su, Q1	--	not	not	yes	GSM	solar	Sam. Lateral Neyrpic Siphon

(*) Used notation presented in the text.

The Master Station is equipped with a computer where runs the SCADA application, a synoptic panel, a master controller, communication equipment and receives the relevant data from all Field Stations, treat all the received data and shows it to the manager for control decisions (manually centralized control) and permits also the visualization of the installed local automatic water level controllers (*WL*, Table 2):

Communications. Guaranteed by public switched telephone network (PSTN, Table 2) or by GSM network (GSM, Table 2).

Power supply - The RTU are supplied by the national electrical power network (EDP) or by solar panels (Table 2).

IMPLEMENTED SCADA SOLUTIONS AND TUNING

Direct controller (*D*, Table 2). The Direct controller is responsible for the control orders sent to the actuators of the different controlled gates. For the example of the Figure 2, one of three installed controllers decides if it is necessary to adjust a certain gate and *D* sends the order to the actuator of this gate (Table 2 presents the number of gates for each station.). Sta 3 has 8 gates, but it is the only case that maintains the original baffle modules. For the other controlled intakes, the modules were replaced by larger and motorized sluice gates installed over the Neyrpic weir (Kraatz & Mahajan, 1975) associated with the modules (see Table 3).
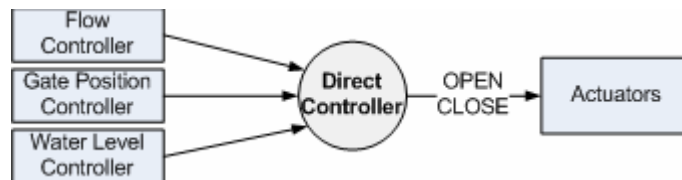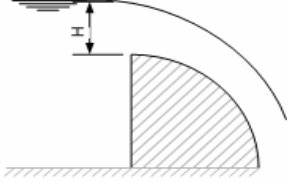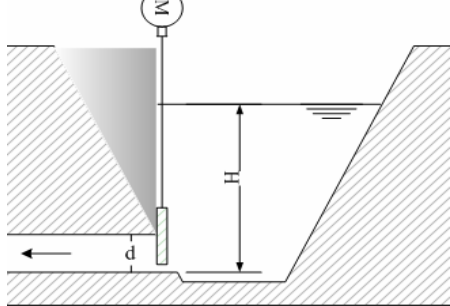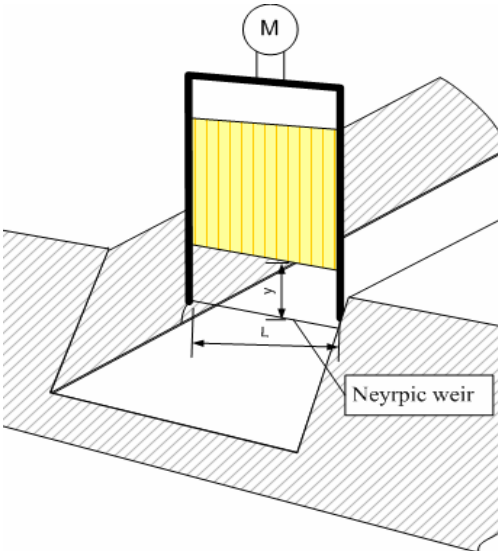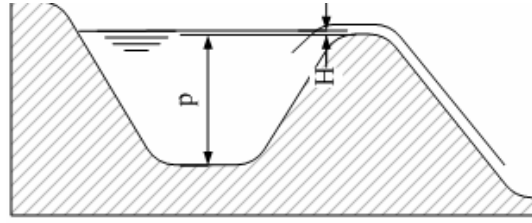
Figure 2. Direct controller connected with other controllers.

Gate position controller (*P*, Table 2). The gate positions of the main controlled intakes and gate controlled bottom orifices (Table 2 and Table 3) are controlled by a *Bang-Off-Bang* controller with a deadband (Figure 3) (Ogata, 1997). With this controller, if the error (difference between the gate position set point and the measured gate position, $ey = yset - ymed$) is grater than the defined deadband (Δy), the actuator must to open the gate and close the gate if ey is less than Δy (the defined values for all the gates is 5 *mm*).

Flow controllers (*Q*, Table 2). Flow controllers were installed for the gates located at the controlled main lateral intakes and for the gate controlled bottom orifice outlets (Table 3).

Table 3. Flow algorithms computation (*Q1* and *Qnominal*)

$$Q = K L \sqrt{2g} \, H^{3/2}$$

Weir
Q = f(L,H)

$$Q = K A \sqrt{2g H}$$

Gate Controlled
Bottom Orifice
Q = f(A,H)

$$Q = K A \sqrt{2g} \, H^{3/2}$$

Gate Controlled
Neyrpic Weir
Q = f(A,H)

$$Q = K H^{n}$$

Siphon
H <= HweirMax: Q = f(H,n)
H > HweirMax And H < Hmax: Q = (f(H,n)+Qmax) / 2
H ≥ Hmax: Q = Qmax
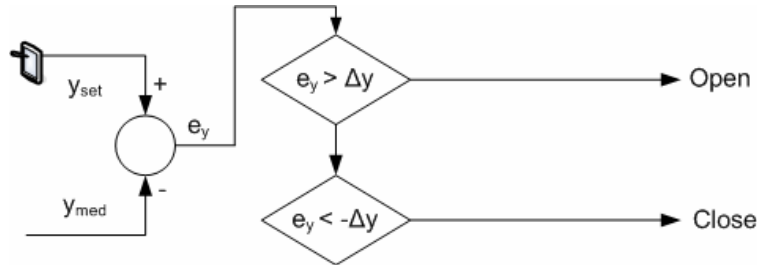
Figure 3. Gate position controller.

The Figure 4 shows the algorithm for a single gate. As shown, the algorithm is similar to the gate position controller. *Qset* is the flow set point and *Qnominal* is the estimated flow for the tuned flow equation of the installation. The flow equation was tuned in the field for each installation, using a flow meter and considering different flow situations and gate positions. In the figure, C1 is the single gate considered (there are field installations with two gates installed in parallel, Table 2). The value considered for the deadband *ΔQ* is 5 *l/s*, independently of the maximum flow of the installation, which can vary between 0.2 m^3/s and 4.0 m^3/s.
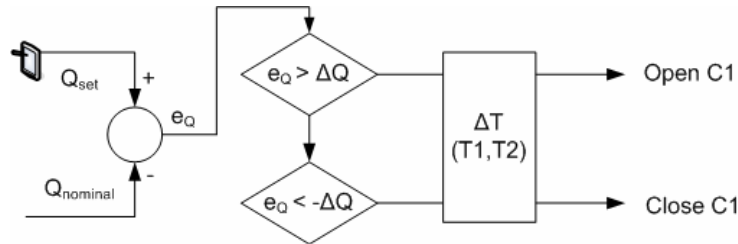
Figure 4. Gate flow controller.

Table 3 shows the most common situations: schemes, standard equations and flow computation algorithms. In the table, *A* is the orifice area, *d* is the pipe diameter, *K* is the coefficient of discharge (a calibration parameters), *L* is the length of the crest, *n* is also another calibration parameter, *Q* is the flow (*Q1* or *Qnominal*) and *y* is the gate opening. Table 3 also shows two typical installations used to monitor the main outflows (*Q1*, Table 2) – the canal side weir and the automatic siphon.

Water level controllers (*WL, Table 2). For the gate controlled bottom orifices of the Sta8, Sta12, Sta14 and Sta15, an automatic local WL controller was also installed in order to keep the water level inside the canal under a pre-defined set point.

Other installed softwares. The developed SCADA application also has alarms, considering pre-defined conditions, messages and recipients (for the alarms messages) and also permits the computation of a few operational statistics (minimal and maximal flow, daily water volumes,…).

FINAL CONSIDERATIONS

Today, real-time monitoring and control systems are within the cost range of almost all water user groups, including irrigators, canal companies and water districts. For the present project, the total cost of the project was 1.08 million US dollars, 0.18 for software and field tuning and 0.90 for the equipment and installation.

The installed SCADA application will permit to reduce conveyance losses and waste, to increase ability of meeting real-time demands by the water users and to reduce operation and labor costs. The authors think that the SCADA will contribute for: the conservation of the actual irrigation area and inclusion of new irrigation areas outside of the gravity dominated perimeter; the installation of medium pressure pipe distributors prepared for water delivery on demand basis; the definition of a monitoring and automation system for new pressure pipe distributors; the reduction of the exploitation costs – workmanship, power and maintenance; the evolution, after some field experience, to a central automatic control for the main network – conveyor, main laterals.

ACKNOWLEDGEMENTS

REFERENCES

Clemmens, A.J. (1987) Delivery system schedules and required capacities, in *Planning, operation, rehabilitation and automation of irrigation water delivery systems* (ed. Zimbelman, D.D.), ASCE, New-York, pp. 18-34.

Kraatz, D.B.& Mahajan, I.K. (1975) - Small hydraulic structures. *Irrigation and Drainage Paper*, nº26, FAO, Rome.

Ogata K. (1997). *Modern Control Engineering*. Prentice Hall International Inc., International edition.

Rijo, M. (1999) - SCADA of an Upstream Controlled Irrigation Canal System. In: A.J. Clemmens & S.S. Anderson (eds.), **Modernization of Irrigation Water Delivery Systems** (Proc. of the USCID Workshop, Phoenix), USCID, pp. 123-136.

Rijo, M. & Almeida, A.B. (1993) - Performance of an automatic controlled irrigation system: conveyance efficiencies. *Irrigation and Drainage Systems*, (7): 161-172.

Rijo, M. & Paulo, V. (1998) – Canal water delivery automation. A case study. In: *Water and the Environmental* (ed. L.S. Pereira & J. Gowing), ICID, London, pp. 274-282.

ALL AMERICAN CANAL MONITORING PROJECT

David Bradshaw[1]

ABSTRACT

Imperial Irrigation District (IID) will strategically place four independent sensor setups along the All American Canal (AAC) for better monitoring of flow in the canal. More accurate measurement is needed of flow into the Imperial Valley as well as for the diversions along the AAC upstream of Pilot Knob, and to Mexico at Pilot Knob. Increases in measurement accuracy will allow IID, which operates the AAC, to better account for supply and more efficiently distribute the water in order to manage the canal under the conditions of the Colorado River Quantification Settlement Agreement of 2003 (QSA). This monitoring project is expected to produce the result that three geographic areas (Mexico, Coachella Valley, and Imperial Valley) receive their proper amount of water for agricultural, municipal, and industrial uses; eliminating most delivery discrepancies and expensive overuse paybacks to the river.

ALL AMERICAN CANAL DIVERSIONS

Imperial Irrigation District (IID), which is the largest irrigation district in the United States and the sixth largest electrical utility in the State of California, is responsible for operation of the All American Canal (AAC). In recent years, but prior to the signing of the Colorado River Quantification Settlement Agreement of 2003 (QSA), around 4.8 million acre-feet (ac-ft) of Colorado River water have been diverted each year at Imperial Dam (Station 60) near Yuma, Arizona, into the 82-mile long earthen AAC.

In 2004, the first full year in which the QSA was in effect, this amount was reduced to 4.4 million ac-ft. In future years, the diversion will be reduced further in accordance with the QSA schedule of deliveries.[2]

Some of water transported in the AAC is supplied to users along the AAC upstream of Pilot Knob (Station 1117), while deliveries to Mexico for use in the Mexicali Valley are made through a channel downstream of IID's Pilot Knob hydroelectric plant. Historically around 300,000 ac-ft annually have been diverted into the Coachella Canal for delivery to the Coachella Valley Water District (CVWD) for use in the Coachella Valley. Under the QSA, this amount

---

[1] Assistant Superintendent General, Resources Planning and Management, Water Department, Imperial Irrigation District, 333 E. Barioni Blvd, Imperial, CA 92251; debradshaw@iid.com

[2] For QSA documents, see http://www.iid.com/water/transfer.html

will increase by up to 424,000 ac-ft annually. IID obtains the benefit of running water that is delivered to CVWD and to Mexico through its Pilot Knob Power Plant before these deliveries are made.

The Imperial Valley's sole source of water is the Colorado River. Prior to the QSA, IID was transporting around 3.1 million ac-ft per year into the Imperial Valley where agriculture thrives and provides the nation with over $1 billion worth of agricultural products. The water also serves the Imperial Valley's municipal and industrial needs for a population of over 160, 000. In 2004, under the QSA, IID's delivery was reduced to less than 2.8 million ac-ft, and future years will see IID reduce its delivery by as much as 492,200 ac-ft per year.

IID FACILITIES

IID operates a number of large facilities, including Imperial Dam, the ACC, six regulating reservoirs, three lateral interceptor systems with four reservoirs, and six hydroelectric power plants. In addition, IID is responsible for an extensive drainage system that discharges around 1 million ac-ft per year of water into the New and Alamo rivers, and ultimately to the Salton Sea. General information about IID is provided in Table 1 below.

Table 1. IID Service Area - General Information.

Area Served	Acres
Gross acreage	1,061,637
Irrigated area	462,202
Water Use & Delivery	Acre-feet/year
Average Agricultural (varies per crop & soil type)	5.6 /acre
Water delivery via AAC (prior to QSA)	3,000,000/yr
Water delivery via AAC (by 2020, post QSA)	down to 2,645,300/yr
Canals & Drains	Miles
Main canals	230
Lateral canals	1,438
Concrete lined or pipelined	1,109
Drains	1,406
Irrigation Structures	
Delivery Gates	5,591
Lateral headings	493
Lateral checks	3,426

Source: http://www.iid.com/aboutiid/iidbackground-facts.html

IID diverts water from the AAC into three main canals in the Imperial Valley for distribution to nearly 500,000 acres of farmland. The AAC originates at the

Imperial Dam 20 miles north of Yuma, Arizona and completes its journey at the southwest corner of the Imperial Valley. As part of the QSA, a portion of AAC will be lined to conserve up to 67,700 ac-ft/year of seepage.

IID OPERATIONS

Each Wednesday, IID staff prepares a master water order for the upcoming week (Monday through Sunday) and submits the order to the Bureau of Reclamation. The master order is based on judgment, cropping patterns, and historical deliveries. The master order can be, and typically is modified according to trends in water orders, weather conditions and other factors. Master schedule modifications require four days of advance notice to the Bureau of Reclamation.

As a spot check, IID staff on the Colorado River at Imperial Dam conducts current metering on the AAC at Imperial Dam (Station 60) and below Pilot Knob (Station 1117), see Figure 1, twice a week. Metering is done on Sunday and Wednesday, which typically are the low-flow and high-flow day, respectively.

The purpose of metering at these sites is to check whether the flow is on-order; that is, to find out if the AAC flow is the amount IID requested on its master schedule order. If the flow is not on-order, Imperial Dam staff adjusts flow at Station 60 by changing the setting of roller gates at Imperial Dam. Subsequent settings for the days between each metering are based on that adjustment. The assumption is that the flow is on-order until it is measured again. Flow fluctuates between the meterings, and IID's Water Master conservatively estimates a discrepancy of approximately 100 cfs/day (approximately 200 ac-ft/day).

IID makes scheduled changes at Pilot Knob once a day. IID also measures the flow at AAC Drop 1, downstream of the Coachella Canal Heading. AAC Drop 1 (Drop 1) is where the operational requirement for IID's service area is set. When a flow increase is scheduled, water is pulled from the upstream reach of Drop 1 via the hydro- electric plant or by opening check gates in the AAC. An acoustic velocity meter (AVM) is located in the AAC below the check gates and power plant. In the event of AVM failure, reported flow through the check gates may vary by approximately 10% from what would be reported by the AVM. The existing AVM cannot take readings when AAC level is this low.

Overall, increased measurement accuracy is expected to result in approximately 37,500 ac-ft/yr. This accuracy will be used to increase IID's efficiency in distribution of delivered water. This is a matter of heightened importance, because flow at Station 60 is the amount for which IID and Coachella Valley Water District (CVWD) are charged against their allowable consumptive use according to the schedule of Quantification Settlement Agreement (QSA) of 2003.
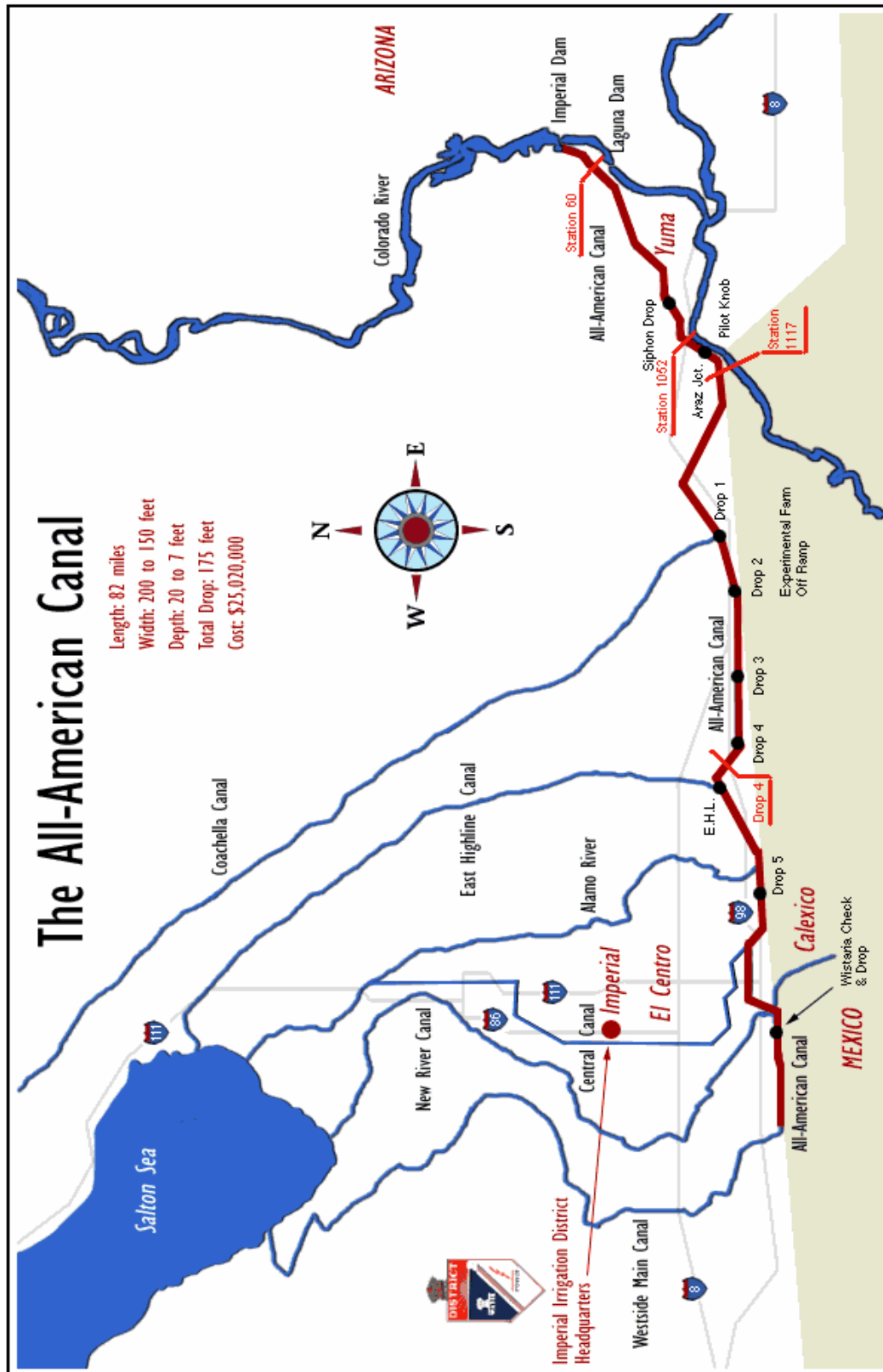
Figure 1. All American Canal, including proposed monitoring site.

IID DELIVERY

Prior to the QSA, IID received around of 3.1 million ac-ft of water each year from the Colorado River. Imperial Dam serves as a diversion structure for water deliveries throughout southeastern California, Arizona and Mexico. The operations of IID's River Division Office at Imperial Dam, as well as system wide water distribution, all fall under the direction of the Bureau of Reclamation, U.S. Department of the Interior.

Three main canals; the East Highline, Central Main and Westside Main receive water from the AAC and are used to deliver water through an extensive system of canals and laterals that serve growers in IID's service area in the Imperial Valley. IID zanjeros divert water directly from the laterals to farm delivery headgates for irrigation of approximately 479,000 acres of farmland within IID's boundaries.

IID delivers water to approximately 5,600 delivery gates for irrigation purposes. IID charges a water availability charge of $3.80/acre/year, while the cost for delivery of water is $16.00/ac-ft. IID operates and maintains more than 1,438 miles of lateral canals, 230 miles of main canals and the 82-mile-long All American Canal.

IID also provides raw water to the nine rapidly growing communities located in the Imperial Valley. These cities are responsible for treating the water and delivering it to their users. IID Energy Division and Water Department employ over 1,200 persons in the Imperial (water and power) and Coachella (power only) valleys.

Crops grown in the Imperial Valley fall into three categories – in 2004 there were around 90,000 acres of garden crops, 390,000 acres of field crops, and 20,000 acres of perennials. Within these categories the crops are many and varied, ranging from artichokes to zucchinis, alfalfa to wheat, and asparagus and citrus to pasture. In 2004, over 65,000 acres were multi- cropped (two or more short crops per year) with annuals, or the remainder was multi-year cropped with field crops and perennials. Irrigation methods are mainly flood and row, but include sprinkler for germination, drip for citrus and some other high-value crops, and some level basin.

PROJECT BACKGROUND

At the AAC Drop 1 site, flow is measured using a transit-time meter with four sensors, two located on each side of the AAC. They are placed across the channel in a diagonal and must me aimed directly towards each other for proper measurement. During low flow periods at least two of the sensors become exposed above the water level and skewed readings give false flow data. All

sensors are dependent upon each other to give correct readings. This system will be removed when the new RDI Channel Master 600 ADCP sensors are installed.

IID will install RDI Channel Master 600 ADCP sensors at Imperial Dam (Station 60), as well as at upstream of Pilot Know (Station 1052) and at Station 1117. The new technology is needed at Station 1052, because water is delivered to a number of agencies between Station 60 and Pilot Knob. Accurate flow measurement upstream of Pilot Knob will allow staff to account for deliveries, seepage and evaporation, and to know how much water is available for diversion to IID, CVWD, and Mexico. A fourth station will be installed below AAC Drop 4 (Drop 4) to encourage IID's hydro plant operators to hold a steady flow and to allow IID Water Control Center (WCC) to determine the amount of water entering the IID service area.

Improvements in flow measurement have the potential of allowing IID to account for nearly all of the water in the AAC, however, it is likely that even with the improved system discrepancies will still exist. IID conservatively estimates that 50 percent of the current measurement discrepancy will be accounted for and that, as a result, IID will be charged for less water due to better accounting in the amount of about 37,500 ac-ft/yr. Thus overall increased measurement accuracy is expected to result in 37,500 ac-ft/yr of increase in efficiency in distributed water.

PERFORMANCE MANAGEMENT

AAC water distribution improvement will be monitored and transmitted to IID's Water Control Center at 15-minute intervals. The data will receive IID's standard quality control procedure and will be housed in IID's Water Information System (WIS). IID will analyze this data and use the resulting information to make adjustments at diversion sites to facilitate correct deliveries to all affected parties.

The proposed monitoring project allows placement of four independent sensor setups for monitoring AAC flow at two locations – before and after the diversion to Mexico and before and after the diversion to the Coachella Canal. This project will provide correct flow data for Imperial Valley as well as the other two entities, CVWD and Mexico.

INSTALLATION OF MONITORING EQUIPMENT

IID has chosen electronic sensing devices over a concrete structure. The reason for this is that the structure would cost approximately $2 million, require more maintenance due to heavy silt load in the Colorado River water, and have to be removed by 2007 when the AAC lining project, which is part of the QSA, will go into effect in these areas. To verify accuracy and develop a calibration between the output of the Channel Master and the real discharge of the new flow meters, IID will obtain a 'RiverCat' instrument which will be used to make independent

discharge measurements. The RiverCat is an acoustic Doppler profiler that is deployed on a small catamaran and thereby used to make transects across the canal to measure the complete velocity profile and determine the discharge. The RiverCat will be operated from improved or newly constructed cableways at each site.

CONSTRUCTION METHOD

IID would like to accurately meter the flow in the All American Canal at four separate locations, at Imperial Dam (Station 60, upstream of Pilot Knob (Station 1117), downstream of Pilot Knob (Station 1052), and at the Drop 4 Station).

At each location there would be a sensor setup installed into the water approximately five feet from the bottom providing for the silt buildup and 15 feet from the surface 'low water' level mark formed during low draw on the river. There will be stairs built in the side of the canal down to a meter bridge that extends over the water thirty-five feet. This will ensure acceptable placement of the sensor. There will be a cableway and 'RiverCat' setup at each site for proofing, indexing, and quality control.

All of the sites would tie into the radio-based telemetry system that is in place for real-time display of canal operations data on existing computer screens in the Water Control building at the main headquarters of IID and at the River Division Offices located at Imperial Dam, 20 miles north of Yuma, AZ. Daily the data is compiled and stored in the Water Information System (WIS) at the Water Control Building at IID Headquarters in Imperial.

CONSTRUCTION SCHEDULE

Table 2 below summarizes the installation of the sensors, cableways, and meter bridges and associated timelines.

Table 2. Sensor, RiverCat, and Access Ramp Installation Schedule (work days).

Installation Schedule				
INSTALLATION RATE	**AAC DROP 4**	**STA 1117**	**STA 1052**	**STA 60**
Metering Bridge	4	4	4	4
Sensor	2	2	2	2
RTU	2	0	2	0
Cableway	3	0	2	0

The estimate for installation is less than the 24 month allotment. IID considers this of utmost importance and intends to have this project completed within this time period. IID staff has experience in both cableway installation and meter

bridge construction, so no excess time will be spent learning these aspects of the project.

WATER CONSERVATION MEASURES

Presently, IID uses 'average' flow for yearly delivery accounting purposes. The average is determined by IID staff on the Colorado River at Imperial Dam when they conduct current metering on the AAC at Imperial Dam (Station 60) and below Pilot Knob (Station 1117), twice a week. Metering is done on Sunday and Wednesday, which typically are the low-flow and high-flow day, respectively. This data is used to determine the average flow. Currently, IID does not have the capability to make more accurate flow measurements on the All American Canal. Accurate accountability (within reason) is critical to account for transfers to the San Diego County Water Authority and Metropolitan Water District, as well as deliveries to the Salton Sea. Accurate distribution of entitlements for the three entities, Imperial, Coachella, and the Mexicali Valley is a priority.

WATER SAVINGS

The proposed monitoring project would allow for accurate measurement of flow from the All American Canal to three entities. Past use of average flow measurement based on hand readings would be abandoned and accurate (real time) measurement of this valuable resource would replace it, eliminating serious discrepancies in actual delivery of entitlements, and helping to resolve difficult water issues facing IID.

USE OF MONITORED WATER

IID recognizes that mediocre accounting for water is not acceptable. The use of the new meters will ensure more accurate measurement of the amount of water delivered to three entities. With the West experiencing water shortages, IID must have the most accurate data available and past reliance on average spot check data is no longer considered accurate enough. Water that is measured more accurately is considered water conserved. IID is cognizant of the fact that good conservation begins at the system level, and delivery accuracy to all three entities is where this begins. IID anticipates that using more accurate measurement devices will reveal 37,500 ac-ft of water that has gone unaccounted for on an annual basis.

FUNDING PLAN

The estimated budget cost of the project is $230,452.

CONSTRUCTION BUDGET

IID intends to have the sensors installed by IID staff. The IID Engineering Department intends to construct the meter bridges and install the cableways. IID SCADA personnel will maintain calibration with the RiverCat and complete all necessary operation and maintenance tasks.

TAKING CLOSED PIPING FLOWMETERS TO THE NEXT LEVEL – NEW TECHNOLOGIES SUPPORT TRENDS IN DATA LOGGING AND SCADA SYSTEMS

Michael Kohlmann[1]
Peter Miramontes[2]

ABSTRACT

We are seeing some clear trends in water distribution and management systems which are especially true in the irrigation market where water is a precious, but sometimes scarce resource. Among these trends are usage regulations, advances in water monitoring equipment, data logging capabilities, and Supervisory Control And Data Acquisition (SCADA) systems or wireless telemetry systems. These trends require more sophisticated closed-pipe flowmeters with better accuracy, reduced maintenance, and less complicated retrofits into the existing piping system. New innovations in ultrasonic and electromagnetic flowmeter technologies bring battery-powered systems to remote locations where power is limited or too expensive to install. These new flowmeters allow full operation and offer extended battery life of up to 6 years. They also have beneficial features including alarm call up via cell phone modules, SMS text messages, drive by readings, and even web-based data transmission.

INTRODUCTION

Artificial rain

According to www.irrigation.org, 97% of the water on earth lies in the oceans and seas, and 2% is locked up in glaciers. This leaves only 1% available for human consumption. The sources for the remaining 1% include rivers, lakes, streams, canals, and ground water wells.

Agricultural irrigation alone accounts for approximately 85 to 90% of surface water withdrawals. These withdrawals can reduce a river's flow 100%, essentially drying it up. In addition, underground aquifers are being depleted and some existing wells are no longer deep enough to reach water.

In some areas, overuse and heavy demands on these sources are depleting them at an alarming rate. Because of these challenges, agricultural irrigation is fast

---

[1] Product Manager, Magnetic Flowmeters, Siemens Energy & Automation; michael.kohlmann@siemens.com
[2] Irrigation Manager, Siemens Energy & Automation; peter.miramontes@siemens.com

becoming the target for regulations and many state, county, and local agencies already have, or soon will have, requirements to register wells and to monitor the water usage. Some of these agencies are simply monitoring, while others are actually limiting the usage. As stricter water management practices are implemented, flowmeters will become mandatory to document water usage. As an example of stricter regulations, California Senate Bill 820, known as the Mega Water Bill, would require all users extracting more than 25 acre-feet annually to file a report with a state agency. Failure to do so would result in penalties, including fines, the potential forfeiture of water rights, and ineligibility for future state grants.

Real-time Resource Management

The most powerful and utilized tool in water management is Supervisory Control and Data Acquisition (SCADA) systems. With the ability to remotely monitor real-time flow rates, water consumption, soil moisture, and reservoir inventory levels, irrigation districts can distribute water in the most efficient manner. Key components of SCADA management systems are the monitoring and integration of such points.

Even though many well heads or down-stream water distribution points already have equipment to monitor their output, the majority of them do not have monitoring equipment at all. Wherever new regulatory laws take effect, users will be required to comply by installing or retrofitting a flowmeter, often into short piping systems not originally designed to accommodate them.

Other benefits of monitoring usage with an accurate flowmeter include ensuring that the scheduled amount of water is actually applied, avoiding over-watering, minimizing fertilizer runoff, and eliminating surface and groundwater contamination. Accurate and repeatable record keeping is necessary for planning, managing, and annual water budgeting or cost estimation. Monitoring the flow of irrigation water is an essential aspect of efficient irrigation management.

At a minimum, flowmeters indicate instantaneous flow rate and keep a running total of the volume over time. Most flow rate indicators report in gallons per minute (gpm) or in cubic feet per second (cfs). Total flow indicators or totalizers typically report in gallons, acre-feet, or cubic feet. Monitoring and managing these resources not only requires an accurate flowmeter, but one that is reliable.

Mechanical Flowmeters

The industry standard flowmeter for well monitoring is a propeller-type flowmeter. Because propeller flowmeters are mechanical devices, they pose many challenges: integration with SCADA systems, frequent maintenance, difficult to meet installation requirements, dirty water supply, and sabotage.

Propeller meters are mechanical devices that require costly non-standard add-ons to integrate with SCADA systems to provide minimal information, such as the totalized flow. Although this option exists, the typical method of bringing data from propeller flowmeters into a SCADA system is by manual readings followed by manual data entry.

With internal parts that move and subsequently wear, propeller flowmeters require periodic maintenance to keep them in working and reliable condition. They also require at least 15 straight pipe diameters in front of them to properly condition the flow profile.

Adding the required piping to accommodate a propeller flowmeter is not always an easy task. In typical installations, the piping system after a well pump head is limited and usually consists of a short length of horizontal pipe that takes a 90-degree turn downward and is buried underground to minimize the above ground obstruction, leaving it useful for farming. This short run of exposed pipe is not the ideal location for a propeller flowmeter. In order to accommodate the flow conditioning requirements of a propeller flowmeter, the user is required to dig up the existing underground piping and place a longer straight section of pipe above ground.

Another installation requirement is having a relatively clean water source. Propeller flowmeters are prone to clogging with trash and algae from open channels, while silt and sand from rivers will accelerate maintenance frequency. Occasionally, saboteurs may purposely clog the propeller flowmeter for financial gains.

When installed correctly, mechanical flowmeters are reasonably accurate. Without the straight pipe installation, however, accuracy suffers considerably. Retrofitting the pipe to accommodate a propeller flowmeter can be a difficult and costly endeavor.

Because of growing demand and technical advancements, there are new breakthroughs in flowmeters specifically designed for the irrigation market. Based on advancements in electromagnetic and acoustic technologies, these new flowmeters offer increased accuracy, require virtually no maintenance, operate on a replaceable internal battery with up to 6 years of operation without the need for solar panels or additional power sources, provide more flexible installation condition requirements, and easily integrate with SCADA systems.

Electromagnetic flowmeters

Electromagnetic flowmeters, often called magnetic flowmeters or simply magmeters, are based on Faraday's law of electromagnetic induction. The first

practical version was created in the late 1930's. When an electrical conductor of length L is moved at velocity v, perpendicular to the lines of flux through a magnetic field of strength B, a voltage Ui is induced at the ends of the conductor.
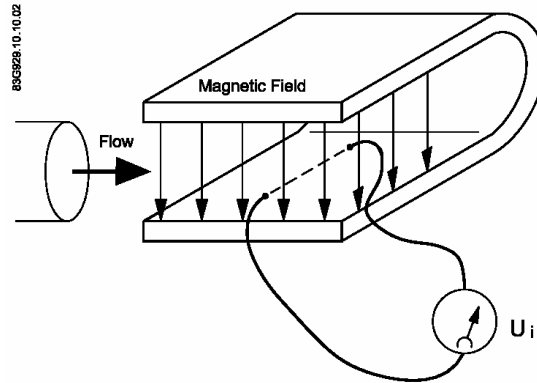
Simply stated, when a conductor is passed through a magnetic field, a voltage is generated. The amplitude of the voltage is directly proportional to the velocity of conductor. In a magnetic flowmeter, a coil within the housing creates the magnetic field. When a conductive liquid passes through the flowtube, a voltage is induced. The voltage is measured between two electrodes which come in contact with the fluid. The cross-sectional area within the flowtube is constant as is the distance between the electrodes. The only variable is the velocity of the fluid as it moves past the electrodes. The faster the fluid travels, the greater the amplitude of the voltage.

Because of the operating principals, magnetic flowmeters require a fluid with some electrical conductivity (i.e., the ability to conduct an electrical charge), typically above >5 μS/cm (microSiemens/cm). Most aqueous solutions have enough conductive dissolved solids to meet this requirement, however, ultra-pure water, some solvents, and most hydrocarbon-based solutions do not.

Since electromagnetic flowmeters have no obstructions, they create little or no pressure drop, an important factor in piping design with respect to pump size and their associated energy costs. This is especially true in gravity-fed applications that have very little pressure to begin with. Since they have no moving parts to wear out, maintenance is greatly reduced or nearly eliminated in many applications. The new battery-powered electromagnetic flowmeters offer greater accuracy than propeller-type flowmeters even in non-optimum installation conditions. Whether line-powered or battery-powered, both offer exceptional linearity over a wide measuring range, even in bidirectional flow applications

Ultrasonic flowmeters

There are two different types of ultrasonic flowmeter designs; Doppler and Transit Time.

Doppler ultrasonic flowmeters have a transducer mounted at an oblique angle in relation to the pipe. The transducer generates and focuses an ultrasonic sound wave into the fluid. Suspended particles or air bubbles within the media reflect the sound waves back to the transducer, which now acts as a receiver listening for the return echo. The delay in the echo is measured and directly correlates to the velocity of the particle, which is assumed to be equal to the fluid velocity.
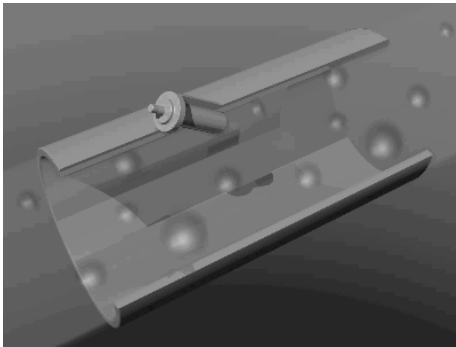
Transit Time ultrasonic flowmeters have two transducers, again mounted at an oblique angle to the pipe and flow stream. One transmitter sends sound waves through the media to a second transmitter mounted on the other side of the pipe. The transducers alternately send the sound waves through the fluid, both upstream and downstream. The time it takes for the sound to travel from one transmitter to the other is precisely measured. Velocity measurement is accomplished by comparing the time the sound wave takes to travel with the flow versus against the flow (Δ Time). Some transit time flowmeters (generally permanent installations) make use of multiple acoustic paths to better sample the flow profile.
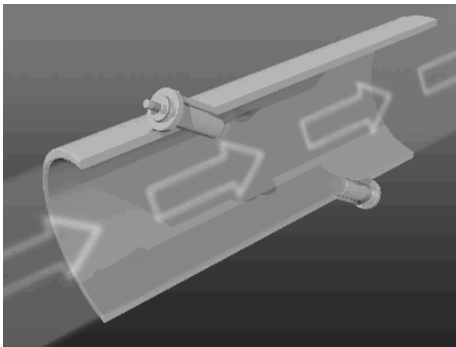
The signal in a Doppler type flowmeter is easily attenuated by the process so viscous fluids or suspended solids in the fluid may cause a loss of signal. Transit time flowmeters are still susceptible to this, but to a much lesser degree. Transit time principal has an advantage over Doppler in that it is independent of variations in the actual sound velocity of the liquid, such as temperature.

Like electromagnetic flowmeters, additional benefits include reduced maintenance, exceptional linearity over a wide measuring range, and even bidirectional flow measurements. With both types of flowmeters, overall performance increases, while the total cost of ownership is sharply reduced.

Additional benefits of non-mechanical flowmeters

With both electromagnetic and ultrasonic flowmeters being microprocessor based, they come with additional benefits, such as data logging, diagnostics, and digital communications. Localized data logging eliminates the need for daily meter runs and allows irrigation districts to utilize their resources more efficiently. Visual diagnostics can better prepare technicians to remedy problems without having to pull flowmeters out of service. On-board digital communications, such as Modbus, allow for seamless integration into existing SCADA systems providing real-time data and diagnostics. In some cases, electromagnetic and ultrasonic flowmeters provide an open communication platform to incorporate emerging communication technologies as they gain traction such as GSM, Satellite, Zigbee, Wireless Ethernet, etc.

SUMMARY

Traditional mechanical flowmeters require periodic maintenance to ensure their functionality. New, non-mechanical, microprocessor-based flowmeters provide long-term, trouble-free accuracy and are capable of seamlessly integrating data with SCADA and other telemetry systems. They also often have a wider velocity measurement range than mechanical meters and can usually measure reverse flow.

With better water management practices, recent advancements in flowmeter technology, and modern communication platforms, efficient and effective irrigation is now possible. Better technology in water management not only saves time and money, it helps secure the future of one of our most precious resources: water.

REFERENCES

www.irrigation.org web-site
The Irrigation Association Statesman – May 2005

REAL-TIME MODEL-BASED DAM AUTOMATION:
A CASE STUDY OF THE PIUTE DAM

Matthew S. Maxwell[1]

ABSTRACT

For over five years, Piute Dam in the Sevier River Basin of Utah has been equipped with an automatic gate to regulate releases into the downstream irrigation delivery system. This system has allowed the water commissioner to remotely set the desired flow target. The gate then automatically adjusts itself to provide the specified outflow. Although this has been very convenient, the determination and setting of the target release flow rate has remained a human-initiated action. Recent improvements to the system have now automated this part of the process to provide a greater degree of convenience and efficiency.

Currently, Piute Dam is being used as a test bed for automation technology. In conjunction with the Sevier River Water Users Association (SRWUA), the Bureau of Reclamation's Provo Area Office developed software to enable automation of the Piute Dam outlet gate. Software used in this process includes the OpenBasin software package for real-time data acquisition, a model developed for Piute Reservoir by Abedalrazq Khalil and Mac McKee of Utah State University, and other software used to develop Internet-based control and reporting. Furthermore, the software developed to provide supervisory control, policy enforcement, and diagnostics was integrated into the OpenBasin software package. This software is open-source and available for free. This allows other water districts to apply these tools to their own automation projects.

INTRODUCTION

The successful implementation of a real-time model-based dam automation system is an important step toward developing a convenient and efficient water management strategy. Furthermore, dam automation is an important hurdle to overcome on the path towards a fully automated river basin. Currently, Piute Dam in the Sevier River Basin of Utah is being developed as a test bed for automation technology. This technology is designed to collect real-time data from sensors along the river, use these data to calculate a desired reservoir release according to a hydrologic model, and autonomously adjust the outlet gate on the dam to reach the desired release.

For the purposes of this paper, 'dam automation' will refer the process of changing the reservoir release gate to accommodate a change in downstream demand without human intervention. The two terms 'model-based' and 'model-

---

[1] Computer Assistant, U.S. Dept. of the Interior, Bureau of Reclamation, Provo Area Office, 302 East 1860 South, Provo, UT 84606-7317

driven' indicate that the desired reservoir release is dictated by a hydrologic model and will be used interchangeably.

This article will present a brief overview of the Sevier River Basin and the technology implemented there, describe the model-driven automation process from data acquisition to remotely controlling the reservoir's release gate, highlight supervisory controls built into the automation software, and discuss future developments in the Piute Dam automation software.

SYSTEM DESCRIPTION

Sevier River Basin

The Sevier River Basin is a closed basin located in rural south-central Utah. It covers approximately 12.5% of the state of Utah and is managed by the Sevier River Water Users Association (SRWUA). The majority of water in the basin is used for irrigation purposes. The basin is divided into five regions as represented in Figure 1: Upper, Central, Gunnison, Lower, and San Pitch. Piute Reservoir is located in the Upper region.   Valuable run-off collects in Piute Reservoir each spring. Releases from this reservoir flow down into diversions located along the river in the Central region. Excess water runs over the Vermillion Dam (near the border of the Central and Gunnison regions) and is lost to water users in the Central and Upper regions.
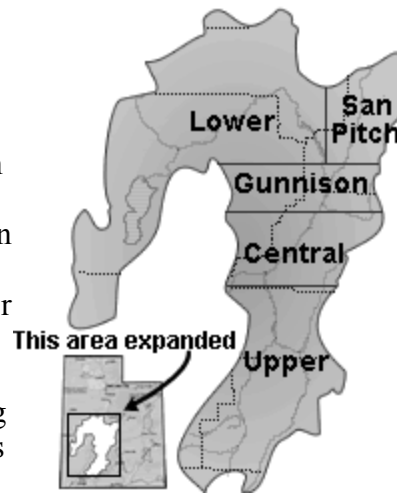
Figure 1. Sevier River Basin Map.

Because the Sevier River Basin is located in an arid climate and generally uses all possible water resources each year, effective management of Piute Reservoir is a high priority. To facilitate a more efficient water management system, the Sevier River Basin has been heavily instrumented and has many diversions and release structures that can be controlled remotely via the Internet. The gate controlling releases from Piute Dam is one of these remotely automated structures. This automated gate is a key component of the Piute Dam model-based automation project.

Technology Configuration

Three servers form the core of the Sevier River Basin's technology implementation: the data collection server, the model server, and the database server. The reason for these three servers is twofold: to accommodate existing technologies and to balance the workload. The data collection software and the modeling software both require extensive resources to perform properly and in a timely manner. To better facilitate resource utilization, these two applications are

placed on different servers. Both of these applications require the Windows operating system; however, the database and website generation software runs under the Linux operation system. For this reason the database and website software must also reside on its own server. These three servers each have their own specialized responsibility and communicate with each other by sharing data through networked directories.

The data collection server is responsible for communicating with the remote stations via radio and for collecting data from these stations every hour. This server is also responsible for communicating desired reservoir releases to the remote terminal unit (RTU). The software that interfaces with the radio communications is the LoggerNet software package by Campbell Scientific, Inc. Not only does this software provide a graphical interface to interact with remote stations, but an additional software development kit (SDK) can be purchased to facilitate automation. Since LoggerNet only works on Windows machines, this server is running Windows XP.

The model server is a high performance machine dedicated to running complex models in a timely manner. This server is configured with all of the software needed by the hydrologic model. In this instance, the MATLAB software package by MathWorks was needed to run the hydrologic model developed by Utah State University. Due to model requirements, this server also runs Windows XP.

The database server is responsible for storing the data collected from remote stations by the data collection server. In addition to storing historical data in a database, this server hosts the SRWUA web page (http://www.sevierriver.org) and the web-based controls for dam automation. Data storage and dynamic website administration is achieved using the OpenBasin software package developed by the Bureau of Reclamation's Provo Area Office and StoneFly Technology. Due to requirements of both the database and the OpenBasin software package, this server runs the Linux operating system. It is also the main server in the automation process and orchestrates the interaction of the other servers.

The RTUs used in the Sevier River Basin are Campbell Scientific CR-10x dataloggers. In addition to recording battery voltage, water height, gate height, and calculating water flow, many of these RTUs are connected to automatic gates and programmed to allow automatic gate adjustments. One such programmed feature allows a user to input a desired flow into a storage register in the datalogger. The RTU will then automatically move the gate until it reaches the flow and further adjust the gate to maintain the flow. The dam automation software uses this feature to automatically input model-based reservoir releases into the datalogger at Piute Dam. From there, the software simply allows the RTU to adjust the gate accordingly.

The interconnection between these servers and the dataloggers is illustrated in Figure 2.
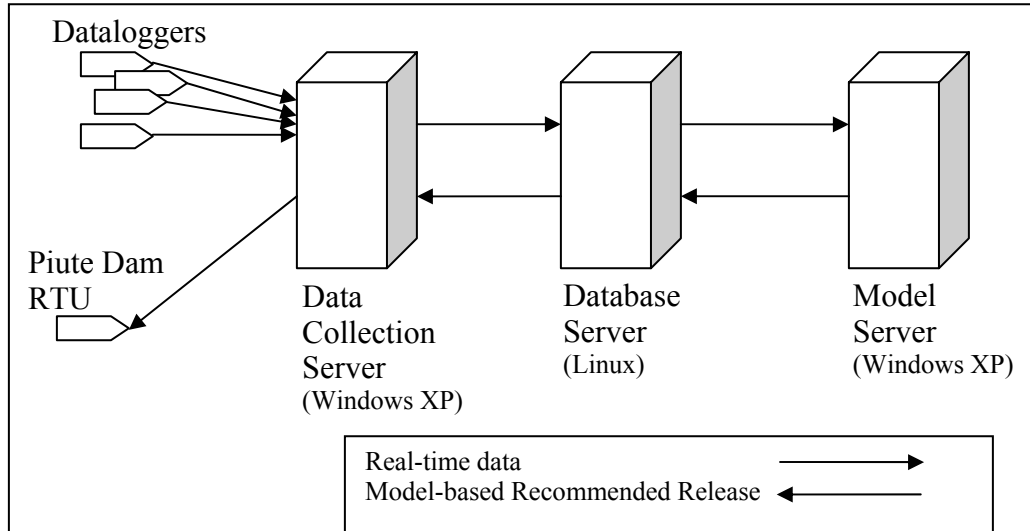
Figure 2. Flowchart of Technology Interconnections.

Model Description

The hydrologic model used for this dam automation project was developed by Abedalrazq Khalil and Mac McKee of Utah State University. The model is a Bayesian adaptive learning model that is not based on physical models of the basin; instead, this statistics-based model is able to detect changes in water demand and compensate for those changes. Relevance vector machines (RVMs) were used to detect abnormalities and drift in the system (Khalil and McKee, 2004). The input to the model includes real-time data from downstream stations and the current reservoir release. The output of the model is the recommended release from the reservoir based on the statistical analysis of river basin conditions and previous data. This recommended release is sent to the RTU that controls the Piute Dam gate.

AUTOMATION PROCESS

The purpose of the automation project is to regulate the reservoir release to a specified amount as recommended by a hydrologic model. This is done without human-intervention. Recommended releases are calculated by the model every hour and are immediately applied to the dam release gate. Furthermore, bounds are set on the automation process to prevent erroneous behavior, and the model can be overridden through human interaction at any time.

There are three main steps in the dam automation process. First, real-time data used by the model must be collected and stored. Second, these data must be inserted into the model. Third, the model results must be automatically applied to

the gate on Piute Dam. Furthermore, in the Sevier River Basin, this process is complicated by the fact that the data collection software, database, and model all reside on different computers. Through a series of shared directories between the computers and specialized software applications on each server, the OpenBasin software is able to communicate with the other computers and complete the automation process.

Data Acquisition

Communication with the remote stations is performed entirely by the Campbell Scientific LoggerNet software. This software is configured to automatically radio to each remote datalogger, collect the associated data, and store it to a text file each hour. The directory in which these data files are stored is accessible from the database server. The OpenBasin software, running on the database server, checks the data files on the data collection server every 10 minutes and inserts new records into the OpenBasin database.

System/Model Integration

Once OpenBasin has detected that it has all of the required information to run the model, OpenBasin will assemble a text file used as input for the model. OpenBasin will drop this file into a shared directory on the model server. In order for the model to run, we developed a small software application called the Model Server Monitor that runs on the model server. This application checks for the presence of the model's input file. Once this file is detected, it will automatically run the model using the file as input for the model. The model usually takes about 5 minutes to finish; however, if the model detects novelty in the system (i.e. the model needs to adapt to new conditions), it can take up to 30 minutes before completion. The results of the model are stored in an output file. Once the OpenBasin software detects the presence of this output file, it parses the file and stores the model's output into the OpenBasin database. After the data are successfully stored in the database, both the input file and the output file are deleted to allow the process to continue correctly on the next iteration (i.e. the next hour when the entire process is repeated).

Automating the Dam

After the model's results are stored in the database, OpenBasin begins the process of automatically adjusting the gate to achieve the desired reservoir release. This is done by generating another input file and storing it in a specific directory on the data collection server. Like the model server, the data collection server has a software application called the Datalogger Server Monitor that checks for the presence of this input file. However, unlike the Model Server Monitor, which immediately runs the model after detecting the input file, the Datalogger Server Monitor has a specific window of time within which it can make radio connections. This window of time is approximately 10 minutes before the next hour (data collection for the remote stations begins on the hour). The Datalogger

Server Monitor will wait until it enters this window before processing the input file and sending the target flow rate to the RTU. The communications to the datalogger are performed through the LoggerNet software and automated using the LoggerNet SDK.

After the parameters are correctly set on the RTU, the RTU will automatically adjust the gate height to reach and maintain the desired release. The flow through the gate is measured by a remote station located just below the dam. Periodically, this value is communicated to the RTU at the dam via radio and a PI feedback controller is used to determine gate movements required to regulate the flow. Through the same process used by the Model Server Monitor, the Datalogger Server Monitor stores its output into a file, and OpenBasin parses the file and stores the results into the database. As the final step in the automation process, a diagnostics report is made to document the model/automation status. From start to finish, the entire process takes nearly one hour (including waiting time), and it begins again as soon as new data is available.

SUPERVISORY CONTROLS

Throughout the whole automation process, errors may occur. Errors in the data acquisition process may cause erroneous data or missing data. Imperfections in the model may recommend impractical or incorrect reservoir releases. Additionally, the user must be able to turn the model-based automation on and off easily and override any release recommended by the model. For these reasons, the dam automation process must be robustly implemented in order to successfully handle errors, and failsafe mechanisms must be implemented to ensure that failure in the dam automation process will not adversely affect the actual reservoir.

The supervisory controls developed for this automation process allow a user to specify a range of normal behaviors and dictate corrective actions in advance. Consequently, an hour-by-hour approval for the dam release is not necessary. The model-based automation will proceed without human intervention until a detectable error has occurred. At that point the process will take corrective action as determined in advance and alert the user. Depending on the nature of the error and the corrective action configured, the automation process may be able to continue correctly without human intervention at all.

Policy Enforcement

To help ensure that the dam automation works as desired, a number of policies were hard-coded into the automation program. The policies are defined by configuring a corrective action to take when a specified error has occurred. The first step toward enforcing these policies is the detection of abnormalities. Examples of abnormal behavior include prolonged absence of real-time data, model errors, recommended releases surpassing predetermined minimum and maximum values, and too much variation of reservoir release values. These

abnormalities are indications of either erroneous data collection or a malfunctioning model. Detection of abnormalities happens automatically within the dam automation software running on the Database Server.

When abnormalities are detected, an associated corrective action is taken. Example actions include ignoring the recommended release for the given time step, automatically shutting down the model-based automation to prevent further abnormalities, and falling back to a "safe" reservoir release as determined by the user. Additionally, the policies may be configured so that the model-based automation may automatically turn itself back on if the model's estimates return to normal. These corrective actions are all determined beforehand and happen without intervention. When corrective actions are taken, the system alerts the user and reports that it has encountered abnormal behavior so that the user can further decide how to respond.

Each type of abnormality can have a grace period associated with it to prevent actions from taking effect until a number of consecutive abnormalities are detected. For example, the policies can be configured so that the model will ignore any reservoir release above or below the set minimum and maximum values and automatically shut down the model and return to a "safe" reservoir release if the model continues to request abnormal releases for five continuous time steps. The parameters used to detect abnormalities, associate corrective actions, and set grace periods are all configured through the web-based control panel.

Web-based Control Features

The web-based control panel provides the user with supervisory control over the model-based automation process. From the website, the user can turn the model-based automation on and off, override the model's recommended release, and configure policy enforcement parameters. The existence of a web-based control panel allows the user access to these features from any Internet-enabled computer. For improved security, this website is password-protected so that intruders may not maliciously affect the reservoir release.

Additionally, as an emergency shutdown mechanism, the user can connect to the RTU with the LoggerNet software and turn the model off completely by setting an appropriate value on the datalogger. The software designed to automate the reservoir release checks this value before making any automatic gate changes. This manual shutdown may be used when the web-based control panel is unavailable or in any other emergency situation.

Diagnostic Information

The dam automation software meticulously records the status of its operation and generates alarms, notifications, and status reports based on these records. Each time the model runs, it checks for erroneous data, model error, and other abnormal

behavior. If any of these errors occur, the type of error encountered is stored in the database. Additionally, if the dam automation software successfully runs, it stores the reservoir release amount into the database as well. With this information, one is able to see an hour-by-hour view of exactly what is occurring with the dam automation.

Since a complete hour-by-hour view may be too complex to easily decipher, the software aggregates these data and displays it via the Internet in different levels of detail. Low-detail views can be used to get a general idea of how the model-based automation is currently working while high-detail views can be used for troubleshooting errors.

This diagnostic information is deployed using the Really Simple Syndication (RSS) protocol. The use of a standard protocol allows a greater degree of interoperability between software. For example, free programs called RSS readers can be installed on a user's computer. These programs can be configured to check the diagnostic information for the dam automation software. Every time the diagnostic information updates, the RSS reader will gather the new diagnostic information and load it onto the user's computer. This ensures that the current diagnostic information is easily accessible by all who need to access it. For even greater accessibility, these RSS files are displayed on the web-based control panel and on other diagnostic web pages.

FUTURE DEVELOPMENTS

Although functional, the current set of technologies used to implement model-based automation of Piute Dam could be improved in many ways. First, the current software package is very dependent on the setup of the SRWUA systems and may require a certain degree of customization to transfer the software to another system. Developing the software with network programming techniques would make inter-computer communications more reliable and eliminate the platform-dependence of the software. Second, building upon the current diagnostic tools, an alarming system that can communicate via email or phone would be a useful addition for times of emergency or uncertainty. Third, the accessibility of the web-based control panel could also be improved by designing a special version of the control panel for web-enabled cell phones.

Network Programming

The current software used to automate Piute Dam is very dependent on the network setup of the Sevier River Basin. Specifically, the use of shared directories between servers may not always be possible in the case of hydrologic models hosted offsite. Additionally, the Model Server Monitor and the Datalogger Server Monitor only run on the Windows XP operating system. Through the use of network programming techniques, the automation software, model software, and datalogger software could all communicate in the same way computers communicate through the Internet. This would remove all platform

dependencies of the software and enable the automation software to be more easily implemented on systems with different configurations.

Email/Phone Alarms

The current system of diagnostics and alarms provides a great way to display information for those who monitor the automation software's status. However, during times of extreme abnormality it would be useful for the program to pro-actively contact the user. Two ways of facilitating this are email- and phone-based alerts. Email-based alerts could be readily added, but they do not assure immediate communications to the same degree that phone-based alerts would. Fortunately, properly configured policies in the automation software should gracefully handle errors without immediate intervention. Alarms via email or cell phones would be extremely useful if integrated into an alarming system for the entire river basin's technology implementation. Current development on this system is underway.

Cell Phone Supervisory Control

The job of a water commissioner is often one requiring much time out of the office and away from technology. One of the current features of the OpenBasin software package is its ability to display the real-time status of river basins on special text-based web pages for cell phones. In addition to this feature, the development of a system that would allow supervisory control functionality via a web-enabled cell phone would greatly increase the accessibility and usefulness of the model-based dam automation software. Additionally, the control panel could be extended to provide supervisory control of more parts of the river basin via the Internet or a web-enabled cell phone.

Software Integration

After the software described in this paper is refined and enhanced, it will be bundled with the OpenBasin software package. The OpenBasin software is used to collect, store, manipulate, and display data easily via the Internet. It is available for free on the OpenBasin website (http://www.openbasin.org). After these additions are made, the dam automation software will be immediately available to various river basins throughout the state of Utah that use this software and have similar automation technology installed.

CONCLUSION

The techniques and software used to implement real-time model-based automation at Piute Dam have proven to be very effective. The process undertaken to accomplish the dam automation project has been described from data collection to automation of the release gate. Additionally, a description of the technological setup has been given. Future improvements upon the automation software's usefulness, features, and techniques are still being actively

developed and refined. After finishing a more unified version of the technologies described in this paper, the software will be bundled with the OpenBasin software package. Additionally, the software used in this automation project will be applied to other water districts within the state of Utah in the near future and improved upon each step of the way.

REFERENCES

Khalil, A. and M. McKee. 2004. Hierarchical Bayesian Analysis and Statistical Learning Theory II: Water Management Application. 2004 USCID Water Management Conference Proceedings, 445-455.

EFFECTIVE IMPLEMENTATION OF ALGORITHM THEORY INTO PLCS

Xianshu Piao[1]
Charles Burt[2]

ABSTRACT

A major constraint for implementation of automated canal control is the complicated, tedious, and potentially error-ridden task of programming the control algorithm and associated overhead into PLCs (Programmable Logic Controllers). A typical control program may easily occupy 100 pages of Ladder logic that must be painstakingly developed and programmed. The most common argument in favor of Ladder logic – that local electricians can get into the program and modify it if needed – is flawed because (1) local electricians do not understand the logic, and (2) Ladder cannot easily perform many mathematical tasks that are simple in other programming languages. In addition, the Ladder programmed on one brand of PLC is not directly programmable onto another brand because each brand has its own variation of the Ladder language.

ITRC's approach to canal automation simulation includes building a model with an excellent hydraulic simulation program, characterizing each pool for storage and resonance, Matlab optimization of the control logic's parameters based on hydraulic properties, and writing the logic in ISaGRAF. These services cannot be performed by integrators, who rarely, if ever, understand the theory behind modern canal control. This has been misunderstood by districts when planning their long-term canal automation strategy, putting at stake large investments into the controller and software programming.

INTRODUCTION

When assisting districts in developing automated irrigation control systems, the Irrigation Training and Research Center (ITRC) of California Polytechnic State University (Cal Poly) has historically provided integrators with large detailed flow charts of logic. However, the ITRC's approach has changed since learning about a new programming language used by PLC manufacturers – typically sold under the ISaGRAF® label. The interesting thing about ISaGRAF is that if a control program is written in this language in a sufficiently simple manner (which, though simple, is still extremely powerful), that program can be used in most of the major, industrial-strength Programmable Logic Controllers (PLCs).

---

[1] Control Specialist, Irrigation Training and Research Center (ITRC), California Polytechnic State University, San Luis Obispo, CA 93407 xpiao@calpoly.edu
[2] Chairman, ITRC cburt@calpoly.edu

There is no need to rewrite the program to match the PLC. ISaGRAF allows the programmer to use any combination of five IEC 1131-3 languages plus flow charts within the same, inter-linking shell. ITRC prefers to use the flow chart language for the backbone, with background details programmed in structured text. C and Ladder are other options.

ITRC has now worked on two large projects in which all of the integrator company's skills in selecting/configuring hardware, radios, sensors, HMI, etc. were utilized, but the traditional integrator role of doing the actual algorithm programming into the PLCs was bypassed. Based on the success of these projects, ITRC has decided to follow this path on all future endeavors.

HYDRAULIC SIMULATION

Over the past few years, ITRC has continuously improved the canal automation procedures that include developing and optimizing the control logics inside an unsteady, open-channel hydraulic simulation model and implementing those control logics in the field.

The first step is to decide upon the control strategy to use. Once that is done, one must build the canal model inside the simulation program, which has been tailored by ITRC over the past 10 years to examine the control of gates and pumps in canals. It simulates actual flows, velocities, and water depths throughout a complete system and can provide specific information for any position within a pool in time increments as small as one second. ITRC normally starts a simulation by building the canal model based on district-provided canal physical dimensions, roughness, and other information, or actual data surveyed by ITRC using GPS and/or Total Station instruments.

The simulation program provides the following capabilities:
a. Customize the control file based on the actual control scheme and availability of the sensors;
b. Export the data that can be used to plot out the actual workings of automatic controllers on each check structure in response to simulated changes in flow at turnouts and at the entrance to the canal for visualizing the canal system response.

Basically, the effects of any control logic with the chosen parameters for any specific multi-pool canal system can be simulated.

Optimizing the Control Algorithm's Associated Parameters

The general control algorithm by ITRC for upstream or downstream control (there are many variations of these) usually utilizes either Proportional or Proportional-Integral or Proportional-Integral-Differential. Most algorithms selected by

integrators are some variation of a "littleman" control. Almost all of the parameters of these algorithms are chosen empirically by integrators either in the field or while programming regardless of the high/low flow conditions or the pool and gate dimensions. This is a shortcoming since there is no control effect verification of these logics and their associated chosen parameters.

It is known that in most cases, the wave travels along the pool; when it hits a check structure, it is reflected back and travels up to the next check structure on the upstream side. The wave travels back and forth forming resonance, which can be amplified along the canals and results in gate/pool instability at the 1st downstream control check structure and at the last upstream control check structure. This phenomenon is most common in flat canals using downstream control, and can cause serious control problems with canal control systems that did not use simulation, and where the control logic and associated parameters were empirically chosen.

With hydraulic simulation, ITRC is able to simulate how the wave travels along the pools as well as simulate the best performance of each gate and the associated controlled pools under different control logics and optimized parameters. ITRC found that the PIF (Proportional-Integral-Filter) control logics, which are obtained by adding a Filter to the Proportional-Integral-Differential control logics with optimized parameters, can greatly eliminate waves and improve upstream and downstream control. The optimized parameters are specifically obtained from the Matlab routines that were developed by P.J. Van Overloop and J. Schuurmans of the Netherlands. These Matlab routines have been continuously updated over the past five years, and are based on the hydraulic characteristics of surface area, resonance peak and delay time of the pools to optimize the control logic parameters. Currently, these Matlab routines are getting to a start-of-art point that can directly optimize a set of parameters without the need to finely tune them.

LIMITATIONS OF LADDER LOGIC OR OTHER PLC LANGUAGES

After the control logic and the optimized parameters are chosen with the simulation, ITRC would previously draw the control logic in a non-executable flow chart. Then the integrator would program the control logic according to the ITRC-provided flow chart in the language environment of Ladder logic or another modular language that is proprietarily supported and supplied by the PLC manufacturer.

Different PLC manufacturers may provide totally different software programming environments though they provide the common digital/analog inputs/outputs. The most common are:
- A Ladder logic programming environment provided by the manufacturer;
- A modular programming environment provided by the manufacturer, with the option of including a higher language such as Basic for higher end PLCs;

- The manufacturer's own software combined with a 3rd party software such as ISaGRAF as a software programming tool. In this case, users have the option of choosing which language to use when programming the control logics.

It is worthwhile to mention that some PLCs are only suitable for monitoring and performing simple control actions such as turning pumps on and off or raising and lowering gates with extremely simple logic. Additionally, some PLCs are unable to receive or transmit ASCII commands/characteristics through a COMM port, which means they do not have the potential to take readings from some electronic flow meters. Some simple modular PLC software cannot be programmed for multiple gates and the combination of both the gate and pump controls, because they lack a clear execution sequence between the modules that perform the arithmetic and logic functions. In this case, even if the PLCs already exist at a site, the user must use another PLC of the same type but of a higher quality, or switch to another type of PLC – if better control is needed. Because the cost of a PLC is only a very small part of the total cost of hardware, programming, and implementation, there should be absolutely no hesitation about purchasing excellent PLCs.

Most industrial PLCs use the Ladder language. But we have found that (i) the Ladder language used in a Modicon controller is different from that used in a SCADA-Pak, for example, and (ii) integrators often prefer a specific PLC brand because they have already programmed their "proprietary" code to do certain functions, such as calibration of instruments. When programming some PLCs, the ITRC-provided flow charts needed to be created from scratch each time by each integrator for each PLC. This limits development possibilities, since every programming inevitably includes error, which takes time and effort to correct. On one project, ITRC found that programming a control logic by a well-known integrator took seven tries and more than one year to review and correct after the integrator first programmed the ITRC-provided control code in Ladder logic. To avoid such hassle and frustration, ITRC has decided to switch to ISaGRAF software, which allows the programmer to easily transfer a control code that has been tested in the field to other, different PLCs that also accept ISaGRAF.

ISaGRAF: INTRODUCTION AND EXPLANATION

ISaGRAF is a product of ICS Triplex. The ISaGRAF program is consistent with the standards of IEC 61131-3 industrial control languages, and is sold to PLC manufacturers. ISaGRAF was originally introduced in 1990 for bridging the gap between microcomputer systems and PLCs; currently, it is suitable for both centralized and distributed control systems that support 32, 64, 128, 256, or unlimited input/output points.

There are basically two ISaGRAF versions that most PLC manufacturers buy:

a. Version 3.32 (latest version 3.54): Most PLCs support this version, a 16-bit application. One ISaGRAF 3.## control code is run within one PLC.
b. Version 4.5 Work Pro: Newest version with some new features such as language editing enhancement and XML (eXtended Markup Language) that provides the basis for the well-known HTML (Hyper Text Markup Language). It is a 32-bit application; one ISaGRAF 4.5 Work Pro can control many PLCs, and is capable of centralized control.

With ISaGRAF, the controller gains features such as data quality, millisecond time stamping, and sequence of events, etc.

PLC manufacturers rarely buy ISaGRAF Version 2.4 Enhanced anymore, though it is still available. This version was provided earlier and many of its features have been incorporated into the 4.5 version by ICS Triplex.

The relationship between ISaGRAF and the PLC is shown in Figure 1.
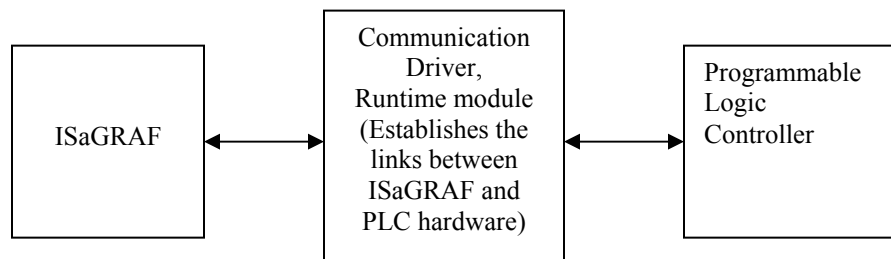
Figure 1. Relationship between ISaGRAF and the PLC.

The driver and runtime module are normally obtained from the PLC manufacturer at an insignificant or no cost. The ISaGRAF license fee may also vary depending on how many PLCs need to be run. Some PLCs need to be upgraded with an ISaGRAF chip.

ISaGRAF is independent of hardware and software during the control code development. In order to program and simulate the control code inside ISaGRAF, the user needs to have a WorkBench module, which can be purchased from either ISaGRAF (ICS Triplex) or from the PLC manufacturer. The simulation tool inside ISaGRAF enables the programmer to examine how the code is running and what the value/state for each variable is when the actual PLC is not connected. This is a powerful tool since it provides the capability to run and debug the control code before the PLC controller is chosen. The debug tool inside ISaGRAF requires the PLC to be connected, in which case the user needs to have the ISaGRAF Runtime module that normally can be provided by the PLC manufacturer.

ISaGRAF IEC1131 Compliance

IEC 61131-3 is the basis on which the organization PLCopen operates (http://www.PLCopen.org). This standardized programming interface allows people with different backgrounds and skills to create different elements of a program during different stages of the software lifecycle: specification, design, implementation, testing, installation and maintenance. Via decomposition into logical elements, modularization and modern software technique, a program that meets IEC 61131-3 standards is structured with the goal of increasing its re-usability, reducing errors and increasing programming and user efficiency. Since the release of the IEC 61131-3 programming standard, users are able to exchange their programs, libraries and projects between development environments.

There are other software packages such as MULTIPROG® (KW Software, www.kw-software.com) and 4Control (Softing, (www.softing.com), which also meet the criteria established by IEC 61131-3. ISaGRAF commands 60% of the market because of its nice interface and wide compliance with various brands of PLCs. Users such as integrators purchase an ISaGRAF program that may contain the PLC-specific modules (depending on the PLC) or the ISaGRAF license from the PLC manufacturer.

The ISaGRAF Application Development Workbench supports all of the standard IEC 6-1131 control program languages plus Flow Chart. These six languages are:
1. Sequential Function Chart (SFC)
2. Function Block Diagram (FBD)
3. Ladder Diagram (LD)
4. Structured Text (ST)
5. Instruction List (IL)
6. Flow Chart (FC)

Any or all of the control languages may be needed in an application. Typically, a Flow Chart in Structured Text can do almost all of the programming; this is the style used by ITRC for all control logic programming in ISaGRAF. Figure 2 is an example of the ISaGRAF programming, in which a Flow Chart (left window), along with Structured Text (right window) is used. The execution sequence follows the arrow that is drawn out in the left side of the flow chart.
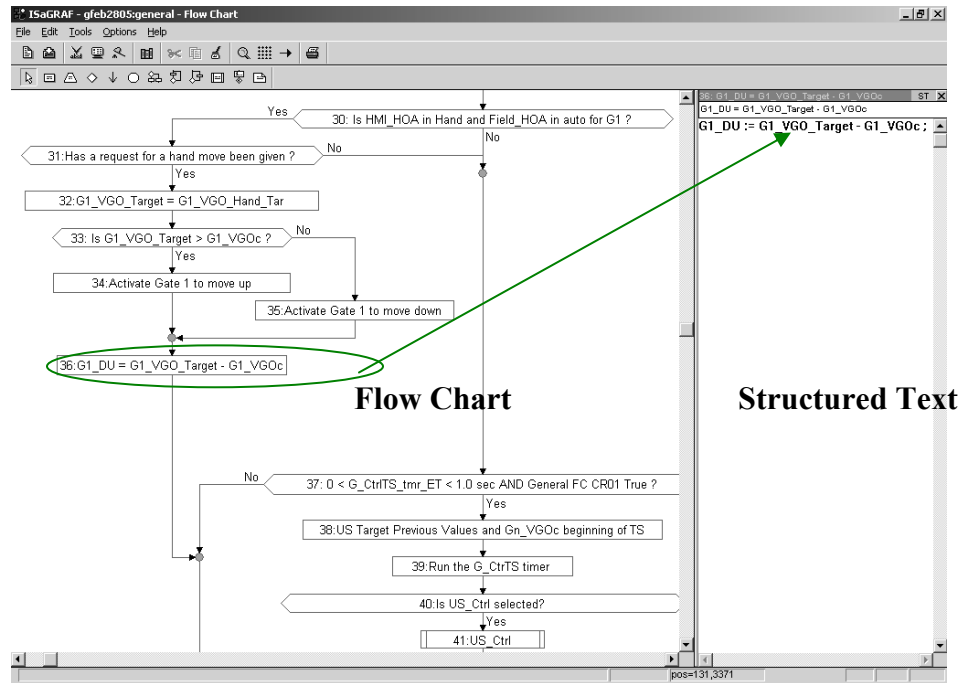
Figure 2. Example of ISaGRAF programming environment.

Customized Libraries

PLC companies such as Allen-Bradley, ABB, Divelbiss, ICS, NEC, Omron, Philips, Sixnet, Control Microsystems, and many more have taken this "basic" programming environment and have developed customized libraries or extensions with functions that duplicate common and often unique capabilities that reside within their controllers. In general, ITRC does not use those customized libraries, because it limits our ability to use a "universal" version of ISaGRAF. We have not found a need to use any of the special routines; the standard ISaGRAF provides sufficient flexibility and ease of use.

Some special functions such as feed and forward variables between controllers may require using some special functions from the PLC manufacturer's customized library, but this can be easily added as separate modules or language functions inside ISaGRAF. Since this is normally just a small amount of programming work, it does not constitute a shortcoming for ISaGRAF.

Engineers and ISaGRAF

Some might say that it is much more difficult to learn the ISaGRAF languages than it is to learn standard Ladder language, and there may be some discussion regarding the merits of an integrator or electrician's ability to understand Ladder versus ISaGRAF. For a programmer who has used Ladder logic for a long time, it might be true that he is very used to determining which function block is being executed by looking for the energized shunts inside the Ladder language.

However, for the same arithmetic and/or logic function, there is no doubt that the Structured Text language is more understandable than the Ladder logic block function for a first-time learner, and ISaGRAF takes less time and less effort to grasp than Ladder logic.

For an organization such as ITRC, the problem comes in the field where the electricians understand Ladder logic but don't have a clue about the control logic, flow charts, or other languages. If they do make changes to the Ladder, the electricians more often "correct" something that is already right, or do not make any improvement to the thing that is wrong. It is very typical for an electrician to never "touch" the control code that is programmed by the integrator in Ladder language, even when the electrician understands the Ladder. Therefore, it is not necessary to program the control code in Ladder for the electricians' sake. Moreover, if the electrician were able to familiarize himself with ISaGRAF, it would be easier for him to make changes if needed.

If the programmer sticks with the standards of the IEC 1131 programming language, then he/she will be able to compile and run the control code in most applicable PLCs. Another merit of ISaGRAF is that all variables (tags) can be used as in C or Fortran without assigning the registers while doing the programming or debugging. After everything has been compiled and is running correctly, only those tags that will be input through or displayed in the Human Machine Interface (HMI) software need to be assigned with registers. This makes the programming procedures less painful and avoids the confusion of registers being repeated for different purposes.

DISTRIBUTION OF IMPLEMENTATION TASKS BETWEEN ITRC AND INTEGRATORS

Currently, ITRC is responsible for providing:
- ISaGRAF control code for the proposed control logic, to minimize the hassles of leaving the programming to the integrators and reviewing their work to correct errors;
- correct control actions in both manual and auto movement mode and the correct alarm generation when needed.

The integrator is responsible for:
- sensor selection and installation;
- PLC wiring and labeling;
- radio and repeater;
- alarm auto-dialing;
- HMI design.

The line that distinguishes the ITRC-provided ISaGRAF control code and the integrator's work is the assigned registers for each site. ITRC provides to the

integrator a full explanation of the tags and the assigned registers and their associated recommended values that need to be designed and displayed in HMI. The integrator ensures that the ITRC-listed HMI variables that are assigned with the associated registers can be either input through or displayed in HMI either through radio or other communications mode.

The key in such a co-operation is a clear line between tasks and responsibilities. Using this approach, ITRC has completed control logic programming in ISaGRAF and it has passed the bench-testing for upstream water level, downstream water level, flow control and some special spill control situations for on-site parallel check structures. One customer has already finished transferring the previously programmed Ladder logic to ISaGRAF for the upper part of the canal's upstream level control, and finished the programming in ISaGRAF for lower part of the canal's automation with some additions of customized changes such as downstream level control and flow control for gates and pumps, both with and without Variable Frequency Drives (VFDs). ISaGRAF has facilitated the transfer of the control code between controllers, and the development of the control code for a new system takes much less time. This, combined with the revised roles of ITRC and the integrator, makes the field implementation of the control code much quicker and more efficient.

REFERENCES

http://www.PLCOpen.org

http://www.isagraf.com

Burt C.M and X.Piao. 2002. Advances in PLC-Based Canal Automation, Proceedings of USCID/EWRI Conference held in San Luis Obispo, CA. pp 409-421.

OPTIMAL FUZZY CONTROL FOR CANAL CONTROL STRUCTURES

O. Begovich[1]
J. Iñiguez[1]
V. M. Ruiz[2]

ABSTRACT

This paper presents an application of a SCADAPack Remote Terminal Unit to regulate the level in an irrigation canal prototype. The designed upstream level regulator consists of two Linear Quadratic Gaussian (LQG) controllers switched with fuzzy logic. The control scheme developed was implemented on "C" at a SCADAPack installed in a Mexican laboratory canal. The adequated closed-loop performance obtained suggests the evaluation of the developed scheme on field applications.

INTRODUCTION

Adequate water administration and distribution in agricultural requires particular attention, since agricultural is the biggest water consumer activity. Distribution of water usually requires an extensive canal network to transport water from storage reservoirs to farmers. These canals must satisfy the water demand in spite of weather variations and the physical and hydraulic canals' limitations. Currently, canals are operated manually, with a large staff, to obtain reliable irrigation service. To improve canal operation and irrigation service, automatic control offers an attractive solution.

The CINVESTAV and the Mexican Institute of Water Technology (IMTA) are working in the design of an upstream level regulator to download it to Remote Terminal Units used for monitoring and remote operation of canal control structures in Mexico. To do that, several experiments have been performed to control level in a Mexican irrigation canal prototype. In the reference 2, a LQG controller was implemented in real-time to regulate levels in a three-pool canal prototype of 50m length. Also, for the same prototype in reference 3, a predictive control was tested. In these experiments a simple Input/Output (I/O) model obtained by identification was used to design the controller and in spite of simplicity of the used model, in all experiments the closed-loop performance has

---

[1] CINVESTAV-Gdl., López Mateos Sur 590, 45232, Guadalajara, Jalisco, México, Tel: +52 (333)134-5570 Fax:+52 (333)134-5579, obegovi@gdl.cinvestav.mx, jiniguez@gdl.cinvestav.mx
[2] Instituto Mexicano de Tecnología del Agua, 62550, Jiutepec, Mor., México, Tel/Fax: (73) 194041, vmruiz@tlaloc.imta.mx

been very satisfactory. A non linear controller also was tested in Ref 4, to only one pool of the above prototype.

This paper will present the design and test of an upstream level regulator consisting of two LQG controllers switched with fuzzy logic and presenting robustness to flow changes through the control structure. Normally, the performance of a simple level upstream regulator degrades when the flow through a control structure changes from the original flow condition considered. To avoid this problem the global controller proposed here uses fuzzy logic to combine control actions of two optimal LQG regulators designed for two different flow conditions present on a control structure. To determine how the local control laws will be combined, this regulator uses fuzzy rules based on the measured downstream level from the control gate. This information helps to indicate if the flow condition is free or submerged.

The control scheme developed is implemented through a "C" language program, stored and executed on a Control Microsystems SCADAPack PLC [Ref 7] installed in the "Short Canal" available at IMTA Laboratory, see Fig. 1. As will be explained later, the satisfactory closed-loop performance obtained, suggest the evaluation of the developed scheme in open canals of Irrigation Districts (I.D.) in Mexico, such as the canal of Carrizo I.D. or Mexicali I.D, where actually a SCADAPack is installed to regulate the position of a control structure.

For the canal considered in this paper: the model to design the controller is a Input-Output (I/O) model obtained by identification; the canal operation is *constant level downstream* [Ref 5] at the end of the first pool and the control method used is *upstream control.* The control variable is the gate opening. To evaluate the regulation performance, flow variations introduced by the first pool lateral outlets act as disturbances.

This paper is organized as follows. First the characteristics of the laboratory canal are presented. Next, we describe the methodology to obtain the linear I/O model used to design the proposed controller. After, the preliminaries needed and details about the control design are explained. Then the ScadaPack implementation and real-time results are presented. Finally, conclusions and future work are stated.

LABORATORY CANAL

The prototype (Fig. 1) used in this application is a concrete trapezoidal canal of 25m long and 70cm height. The Manning coefficient is 0.1 and the slop 0.0005. The control structure is a slide gate that divides the canal in two pools. In the first and second pools there are outlets. At the downstream end of the canal the level is regulated by a manual overshot gate. The slide gate is equipped with two potentiometer float level sensors (upstream and downstream), a potentiometer for gate position and limit switches (maximum and minimum gate opening). The

system is designed considering manual operation and RTU (Remote Terminal Unit) operation. For this aim a SCADAPack from Control Microsystems [Ref 7] is used to control the downstream level of the first pool. A portable PC is used to download programs in "C" to the SCADAPack.
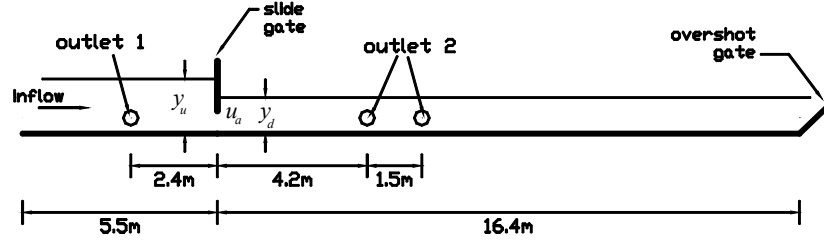
Figure 1: Canal prototype.

MODEL

The flow in an open canal is described by two nonlinear partial differential equations called the Saint-Venant equations [Ref 6]. This model is used to study the flow behavior in open irrigation canals, but in general, it is not used for control design due to its complexity. To design our controller two linear models are obtained by identification, one for each flow condition through the gate, i.e. one for free flow condition (defining the first set point): $q_c = C_d \ B \ u_a \ \sqrt{y_u - (u_a/2)}$ and one for submerged flow condition (defining the second set point): $q_c = C_d \ B \ u_a \ \sqrt{y_u - y_d}$ where q_c is the flow through the gate, C_d is the discharge coefficient, B is the gate width, u_a is the gate open height, y_u is the water depth upstream of the gate and y_d is the water depth downstream of the gate.

The transfer functions of linear models are estimated using a standard identification procedure [Ref 10]: 1) The first step is to determine the input and output variables. For each linear model, the gate opening deviation from its set point is the input variable. They are denoted as u_i (i = 1, 2), where i denote the model i. The level deviation upstream of the gate from its set point is the output variable (controlled variable). They are denoted as y_i (i = 1, 2). The set points used to obtain models 1 and 2 are presented in Table 1. Note that the level set point is always the same.

2) During the second phase, the variation in the water level y_i (i= 1, 2) is registered, when it is applied a pseudo-random binary signal (PRBS) on the respective opening gate set point. The downstream level's evolutions obtained are presented in Figure 2. In this figure the levels are normalized with respect to its set point. The data were obtained directly from the prototype each 10 s, the selected sampling time.

Table 1: Set points.

	set point 1	set point 2
Inflow	110 l/s	110 l/s
Upstream level y_u	36cm	36cm
Downstream level y_d	19cm	33cm
Gate opening u_a	16cm	23cm

3) Proposed model. From Fig. 2, it is observed, that level responses are similar to those of linear systems, and that is why we propose the next structure for our model:

$$y(t) = \frac{B(q^{-1})}{F(q^{-1})} u(t) + e(t) \qquad\qquad (\text{eq 1})$$

4) Parameter identification: The estimation of coefficients of polynomials F and B (parameters) is easily achieved using the instruction **oe** of the *Matlab System Identification Toolbox*, which use least square method to adjust parameters. The inputs for this instruction are: proposed orders for polynomials B and F and the data (u_i, y_i) previously registered. To measure quality of the identified model, we use the instruction **compare**, which compares the registered canal level with the response of the identified model using a performance index. Figure 2 shows the response of the identified models, and it can be seen, the model responses follow the real level responses.
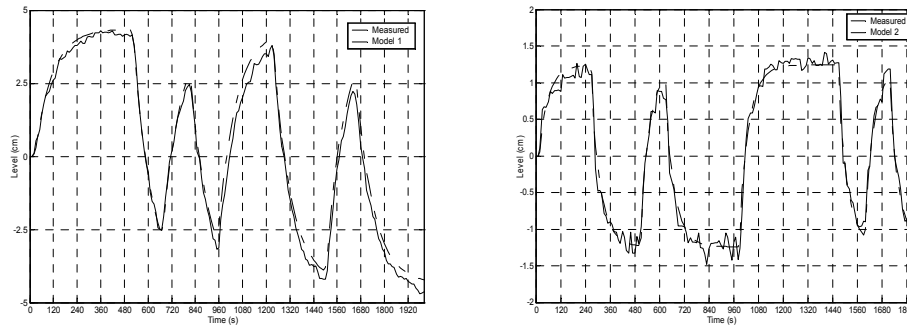
Figure 2: a) Measured level evolution at the set point 1 and Model 1 response
b) Measured level evolution at the set point 2 and Model 2 response.

4) At this stage, a model (equation 1) is obtained for each set point and they are noted as Model 1 for the response obtained using the set point 1 (free flow condition), and Model 2 for that obtained using the set point 2 (submerged flow condition). Next, these models are transformed into the following transfer functions:

$$G_1(z) = \frac{y_1(z)}{u_1(z)} = \frac{-0.05533(z^2 + 1.565z - 3.069)}{z^2(z - 0.893)}$$

$$G_2(z) = \frac{y_2(z)}{u_2(z)} = \frac{-0.03654(z + 5.5665)(z - 0.3417)}{z^2(z - 0.8063)}$$
(eq 2)

CONTROLLER SYNTHESIS

The principal goal of the controller designed is regulate the downstream level at the end of the first pool in face of disturbances and changes in flow through the gate.

Preliminaries of LQG control

Let a minimal state representation of a linear plant

$$x(k+1) = Ax(k) + Bu(k) + v(k); \quad y(k) = Cx(k) + w(k)$$
(eq 3)

where x is the state, u the input, y the output, v and w are noises and A, B, C are matrices of appropriate dimension and k is the discrete time. Under habitual assumptions, the LQG signal u [Ref 1] that minimizes,

$$J = E\{x^T(k)Q_c x(k) + u^T(k)R_c u(k)\}$$
(eq 4)

it is given by: $u(t) = -K_c \hat{x}(t)$, where K_c is the LQ gain and $\hat{x}$ is the Kalman estimated. The Kalman estimated state [Ref 1] is obtained from a Kalman filter which is given by

$$\hat{x}(k+1) = A\hat{x}(k) + Bu(k) + L(C\hat{x}(k) - y(k))$$

where L is the Kalman gain, and A, B, C are the matrices of the system (eq 3). This filter can be seen as a copy of the system containing a correction term. It is useful when the plant state is not accessible. The values of K and L are the core of LQG, and can be calculated easily using **dlqr** instruction of the *MATLAB Control Toolbox*. The LQG control is a simple and modern technique, well known in control theory, that in many control problems offers very attractive solutions. The interested lector can be referred to [Ref 1].

Preliminaries about Functional Fuzzy Systems

In a functional fuzzy system, the i-th Rule has the form [Ref 12]

If z_1 is $M_{i1}, \ldots, z_j$ is $M_{ij}, \ldots, z_g$ is M_{ig} Then $b_i = f_i(\cdot)$

where z_j $(j=1,...,g)$ are the premise variables; $i=1,...,r$ are the fuzzy rules; M_{ij} are the fuzzy sets and $f_i(\cdot)$ is a function in the argument $(\cdot)$. The premise of this rule is defined as in a standard fuzzy system. The consequent, instead of a linguistic term with an associated membership function, is a function. The argument of each f_i can be the premise variables but other variables may also be used. The choice of these functions depends on the application being considered. Defuzzification may be obtained by

$$b = \sum_{i=1}^{r} b_i \varphi_i(z) \bigg/ \sum_{i=1}^{r} \varphi_i(z)$$

where $\sum_{i=1}^{r} \varphi_i(z) \neq 0$; $\varphi_i(z) = \prod_{j=1}^{g} \mu_{ij}(z_j)$; and $\mu_{ij}(z_j)$ is the membership function of z_j

and $z^T \doteq \begin{bmatrix} z_1 & \cdots & z_g \end{bmatrix}$

Disturbance reject

In order to reject disturbances due to lateral outlets, the following integral action is added to canal model

$$\frac{z}{(z-1)} \qquad \text{(eq 5)}$$

Design of each LQG controller is then effectuated using the model resulting from a serial connection between the linear model i from (eq 2) and the integral action model (eq 5). This model is referred to as the i-th augmented plant, and noted G_{ai}, $i=1,2$:

$$Ga_1(z) = \frac{z}{z-1} \cdot \frac{-0.05533(z^2 + 1.565z - 3.069)}{z^2(z - 0.893)}$$

$$Ga_2(z) = \frac{z}{z-1} \cdot \frac{-0.03654(z + 5.5665)(z - 0.3417)}{z^2(z - 0.8063)} \qquad \text{(eq 6)}$$

State space realization

A LQG controller is designed using a state space realization of a system, in our case, it is necessary then to obtain the realization of the transfer function of the augmented plant i (eq 6). The realizations A_i, B_i and C_i ($i =1, 2$) obtained can be found in [Ref 9].

Specifications

The closed-loop canal must satisfy the following specifications:

- The gate-opening rate should not exceed 0.11 cm/s.
- The largest gate opening is given by the canal limits.
- Level must be within the limits given by the canal dimensions.
- Sample rate must be larger than 3 s.

Controller design

The first step to derive the proposed controller is to design a LQG for each augmented model. To do that, matrices *A, B, C* of the augmented plant are needed and also the synthesis parameters Q_c and R_c of (eq 4) and the noise spectrums of $v(k)$ and $w(k)$, which are noted as Q_f and R_f. In this work spectrums Q_f and R_f are in reality synthesis parameters to get good performances in the state estimation. The synthesis parameters giving satisfactory close-loop performance and the gains obtained are shown in Table 2.

Table 2: Synthesis parameters and gains.

Model 1		Model 2	
$Q_c = I_3(0.15)$	$Q_f = I_3(0.008)$	$Q_c = I_3(0.15)$	$Q_f = I_3(0.0015)$
$R_c = 3500$	$R_f = 0.0394$	$R_c = 700$	$R_f = 0.0442$
$K_1 = \begin{bmatrix} 0.0785 & -0.0676 & 0 \end{bmatrix}$		$K_2 = \begin{bmatrix} 0.1047 & -0.0807 & 0 \end{bmatrix}$	
$L_1^T = \begin{bmatrix} -2.0445 & -1.7736 & -1.4703 \end{bmatrix}$		$L_2^T = \begin{bmatrix} -2.2191 & -1.9842 & -1.6228 \end{bmatrix}$	

The second step is to propose intelligent fuzzy rules to switch smoothly between the two designed controllers. Because we are interested in passing the control from one controller to the other when a change in the gate flow condition regime occurs, we propose the fuzzy rules given in Figure 3. These membership functions were stated based on the next condition:

$$y_d > (2/3) y_u \qquad \text{(eq 7)}$$

where y_d is the water depth downstream of the gate and y_u is the water depth upstream of the gate. When (7) is satisfied the flow regime is submerged otherwise the flow regime is free.

The switching rules are:

$$\textbf{If } y_d \text{ is } M_1 \textbf{ then } b_1 = -K_1 \hat{x}_1$$
$$\textbf{If } y_d \text{ is } M_2 \textbf{ then } b_2 = -K_2 \hat{x}_2$$

The global control law is given by:

$$u_m(k) = \frac{M_1(y_d)\cdot(-K_1\hat{x}_1) + M_2(y_d)\cdot(-K_2\hat{x}_2)}{M_1(y_d) + M_2(y_d)}$$

where K_i ($i=1,2$) are the LQ gains (Table 2) and $\hat{x}_i$ ($i=1,2$) are the Kalman estimated states. This signal u_m is integrated before to be applied to the canal. This action can be represented by: $u_a(k) = u_a(k-1) + u_m(k)$. The scheme used to implement the global controller is shown in Fig. 4.
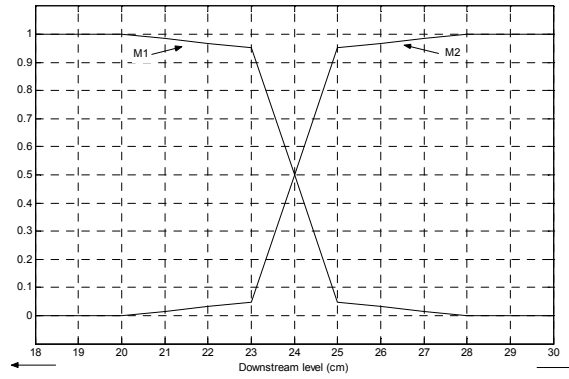
Figure 3: Fuzzy sets.
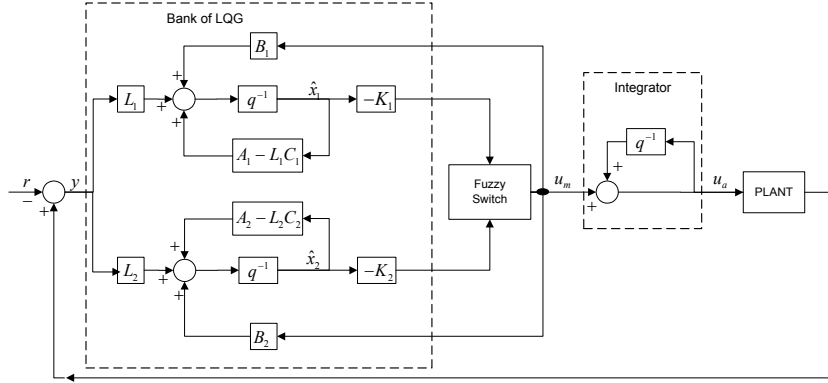
Figure 4: Controller scheme.

SCADAPACK IMPLEMENTATION

The control algorithm in Fig. 4 was implemented through a SCADAPack C program [Ref 8], [Ref 11]. This program uses the sensors measured values at each sampling time (10s) to calculate the gate opening required to maintain level at its set point. Program uses 29 registers from SCADAPack I/O register data base, three of them are user assigned and are related to level sensors, the rest of them

are general purpose registers. The A_i, B_i and C_i (i=1,2) model matrices and K_i and L_i (i=1,2) gains are set in the C program; therefore they only can be changed by rewriting the program and downloading it again. Controller parameters such as set point reference, dead zone, gate opening limits and calibration parameters are registers in the I/O data base and they can be read and changed by any MODBUS device. Implementation in SCADAPack is simple, since the algorithm is programmed using only addition and multiplication of matrices [Ref 9].

REAL-TIME RESULTS

Figure 5 shows the experimental results of the proposed controller. This experiment is started at the following point: $y_u = 36$, $y_d = 27$, $u_a = 16$ (submerged regime). At time t = 240 s outlet 1 is opened allowing a withdrawal of 40 l/s. After the controller rejects this perturbation, the outlet is closed at t = 1200 s. Note that there is an adequate regulation of the downstream levels in spite of changes in flow regime through the gate taking place between t = 480 s to 1300 s. Furthermore, gate opening does not exceed its physical limits and the opening-rate is below the specification. In general, adequate performance is obtained in the closed-loop system.
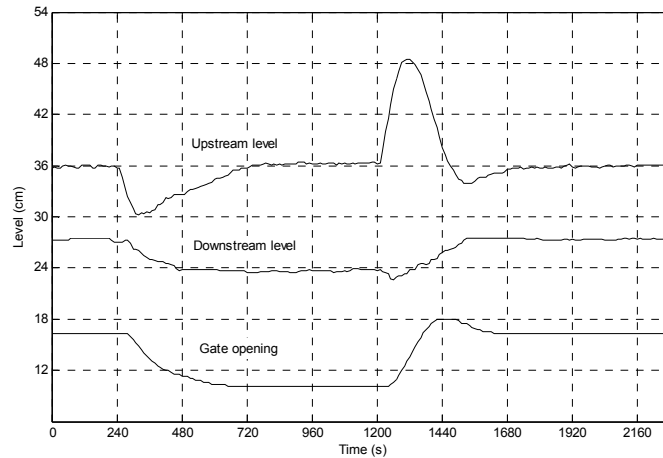
Figure 5: Responses of levels and control gate opening.

CONCLUSIONS

A controller based on a bank of two LQG controllers using functional fuzzy logic to switch them was designed and implemented in real-time in a SCADAPack to regulate the downstream level of the first pool in an irrigation canal prototype. The closed-loop real-time performance of both the level and the gate openings obtained with this control was very satisfactory in spite of the changes in the flow through the control gate. Implementation in SCADAPack was simple, since the algorithm was programmed using only addition and multiplication of matrices.

The adequate closed-loop performance and the simplicity in the real–time implementation suggest the evaluation of the developed scheme on field applications.

REFERENCES

1. Anderson B.D.O. and Moore J.B., *Optimal Control: Linear Quadratic Methods*, Prentice Hall, Englewood Cliffs, NJ, USA, 1990.

2. Begovich O., Ruíz V.M. y Zapién J.C., "Implementación en tiempo real de un control LQG en un prototipo de canal abierto de riego de varios tramos", *Ingeniería Hidráulica en México*, vol. XIX, n. 2, pp. 5-15, 2004.

3. Begovich O., Aldana C.I, Ruiz V.M., Georges D., Besançon G., "Real-time predictive control with constrains of a multi-pool open irrigation canal ", *XI Latin-American Automatic Control Congress "CLCA2004"*, La Habana, Cuba, 2004.

4. Besançon G., D. Georges, V. Ruiz-Carmona, O. Begovich, C. I. Aldana López, "First experimental results of nonlinear control in irrigation canals", *2nd IFAC Symposium on System, Structure and Control* "SSSC2004" Oaxaca, México, December 2004.

5. Buyalski C. P., Ehler D.G., Falvey H.T., *Canal Systems Automation Manual*, A water Resources Technical Publication. Bureau of Reclamation. Denver, Colorado, 1991.

6. Chow V. T., *Hidráulica de canales abiertos*, McGraw Hill Interamericana S.A., Colombia, 1994.

7. Control Microsystems, *SCADAPack Product Data Sheet*, Canada, November 2004.

8. Control Microsystems, *TelePACE C Tools User and Reference Manual*, Canada, 2003.

9. Iñiguez J. *Diseño de un control robusto ante cambios en el régimen de flujo en la estructura de control de un prototipo de canal de riego.* M. in S Thesis, Cinvestav-Gdl, Mexico, September 2005.

10. Ljung L. *System Identification: Theory for the user*, Prentice Hall Ptr, New Jersey, 1987.

11. Microtec Research Inc., *MCCM77 User′s guide*, Santa Clara, CA, 1993.

12. Passino K.M. and Yurkovich S., *Fuzzy Control*, Adison-Wesley, USA, 1998.

SCADA OVER ZIGBEE™

E. Skafidas[1]
I. Mareels[1]

ABSTRACT

The Zigbee™ alliance seeks to develop an open standard for reliable, cost-effective, secure wireless interconnectivity of monitoring and control products. The ZigBee™ technology is better suited for control applications, which do not require high data rates, but must have low power, low costs and ease of use. In this paper we investigate the applicability of Zigbee™ to Supervisory Control and Data Acquisition (SCADA) systems an investigate issues relating to: Networking, Security, Reliability and Quality of Service.

INTRODUCTION

The Zigbee™ alliance (see [1]) seeks to develop an open standard for reliable, cost-effective, secure wireless interconnectivity of monitoring and control products. In National ICT[2] Australia (NICTA), Victoria Research Laboratory a significant group of engineers and researchers is actively engaged with the Zigbee™ alliance and the formulation of the open standards. The team (see [2]) is also developing a wireless Zigbee™ ready communication device, NICTOR™[3], able to interface with a variety of sensors and actuators.

Devices, such as NICTOR™, could become the back bone of a new generation of low cost, low maintenance SCADA networks, creating new opportunities and enhanced automation services. In this respect, it is worthwhile to observe that the OnWorld Wireless Sensor Network [3] report identifies agricultural monitoring and agricultural SCADA as one of the top 5 market segments for wireless sensor networks in the near future (home-automation, industrial automation, building-automation). NICTA researchers are exploring ways in which wireless sensor networks can be deployed to great advantage in the irrigation industry.

Wireless communications, in particular in the unlicensed part of the radio spectrum comes with its own set of problems: reliability of interconnectivity and security are perhaps the two most obvious issues. It is our thesis that security and data integrity are well catered for in the Zigbee™ standard and that the more

---

[1] National ICT Australia, Ltd, & Department of Electrical and Electronic Engineering, The University of Melbourne, Victoria 3010, Australia, e-mail contact: i.mareels@unimelb.edu.au, fax: int+61+3+83 44 74 12 (secure)
[2] ICT stands for Information & Communication Technology
[3] NICTOR refers to a particular communication device, it has no other meaning, it is not an acronym.

interesting problem is that of reliability, and quality of communication service, in particular in those applications were communication power is severely constrained.

In this paper we discuss some of the limits of reliability, and focus on how reliability can be addressed through network topology and network management, in particular adaptive radio technology. The same aspects that address the reliability issue make a Zigbee™ network potentially extremely user friendly and offer the potential to make a Zigbee™ sensor network practically application independent. Moreover, new standards, like sensorML, are being developed to create the middle ware which enables the seemless integration of newly developed data services with standard compliant sensors in a very transparent and flexible manner.

The paper is organized as follows. First we discuss in general terms the Zigbee™ network. Next address the security and data integrity issues. Reliability and adaptive radio mechanisms are discussed next. An application in the area of irrigation is presented.

ZIGBEE™ NETWORKING

ZigBee™ is built on top of the IEEE 802.15.4 (see [4]) low power networking standard. The 802.15.4 standard is a simple packet data protocol for lightweight wireless networks. The standard is capable of operating in the unlicensed 2.4GHz band worldwide, 915Mhz band in the Americas and 868Mhz in Europe. There are 16 channels in the 2.4GHz band, 10 in the 915MHz band, and only 1 in the 868Mhz band. The 2450MHz physical layer employs a 16-ary quasi-orthogonal modulation technique. During each data-symbol period, four information bits are used to select one of 16 nearly orthogonal pseudo-random noise (PN) sequences to be transmitted. The PN sequences for successive data symbols are concatenated, and the aggregate chip sequence is modulated onto the carrier using offset quadrature phase-shift keying (O-QPSK). Essentially, this modulation format can be thought of as coded O-QPSK and is typically implemented with a table look-up for generating channel symbols which reduces transceiver cost.

The IEEE 802.15.4 standard has a simple packet frame structure and is specifically designed to enable devices to join and leave the network (Association and Disassociation) as required by the applications on the network (without human intervention). The 802.15.4 standard supports 64-bit IEEE-assigned addresses (assigned in the same manner as an Ethernet addresses, i.e. one preconfigured address per device) and a 16-bit short address, for network-specific addressing (similar to an IP address which is assigned to a device on a local network). This addressing supports a maximum network size of 2^{64} nodes with several thousand devices per node.

The standard supported data rates are 250, 40 and 20 kb/s. The standard supports contention based channel access based on Carrier Sense Multiple Access / Collision Avoidance and contention free Time Division Multiple Access which maintains quality of service (QoS) and bandwidth guarantees by allocating guaranteed time slots. The physical layer medium access control (MAC) protocol is a fully acknowledged protocol for reliable data transfer. It caters for low power consumption, more so than most other wireless standards, by enabling each device to have Energy Detection and Link Quality Indication. The 802.15.4 standard supports Periodic data transfer for applications or devices with an Application defined rate such as sensors that are required to produce periodically a sample. It equally supports an Intermittent data mode to support an Application where an external stimulus defines the need for data transfer. Examples of such applications are a sensor from which data are only required if the monitored variable has changed by more than a preset threshold, or an actuator node, such as an irrigation gate, where the actuation depends on an external event, or Repetitive low latency data. Each of these traffic types mandates different attributes from the Medium Access Controller. The IEEE802.15.4 MAC is flexible enough to handle each of these types. Periodic data can be handled using the beaconing system whereby the sensor will wake up for the beacon, check for any messages and then go back to sleep. Intermittent data can be handled either in a beaconless system or in a disconnected fashion. In a disconnected operation the device will only attach itself to the network when it needs to communicate saving significant energy. Low latency applications may choose the guaranteed time slot (GTS) option. GTS is a method of QoS in that it allows each device a specific duration of time in each Superframe to do whatever it wishes to do (including nothing at all) without contention or latency.

The 802.15.4 standard supports star or peer-to-peer operation. In any 802.15.4 network there are three types of devices
- Network Coordinator: Hands out addresses and coordinates the forming of the network as devices join and leave the network.
- Full Function Device (FFD): Could be a sensor or control node but also provides packet routing and forwarding.
- Reduced Function Device: Does not provide packet routing or forwarding, intended as a low cost node dedicated to a specific purpose such as sensing a condition or controlling a device.

A ZigBee™ network built on the IEEE 802.15.4 standard can support up to 254 client nodes plus one FFD, as master. The protocol is optimized for very long battery life measured in months to years (see [1] for the sales pitch). It has been conceived for building automation, including such diverse items as control for lighting, air conditioning, smoke and fire alarms, and other security devices. The responsibilities of the ZigBee™ network layer include several mechanisms used to join and leave a network, and to route frames to their intended destinations. The routing may involve using multiple intermediate relay devices within the network.

The discovery and maintenance of routes (there is no preset routing table) between devices devolves to the network layer. Also the discovery of one-hop neighbors and the storing of pertinent neighbor information are done at the network layer.

The default routing in a Zigbee™ network is based on a tree-topology. This has the significant advantage that Routers do not have to maintain extensive tables but more importantly do not have to perform route discovery. Notwithstanding this, Zigbee™ Routers have the capability to discover shortcuts, and they can maintain a routing table for these shortcuts of the form (D,N) – (destination, next device). The particular mechanism to discover a shortcut is based on the Request/Response part of the Ad-hoc On Demand Distance Vector (AODV) protocol. The actual network protocol in Zigbee™ is a combination of this AODV, Motorola's Cluster-Tree algorithm and Ember Corporations Gradient Routing in ad hoc networks. Zigbee™ allows for ad-hoc network formation, which makes the network robust to the failure of any one node.

ZIGBEE™ SECURITY

In Zigbee™ networks security is performed at two levels, at the physical layer as implemented in the 802.15.4MAC and at Zigbee™ network layer. It provides for state of the art time varying, and application dependent security facilities.

The MAC layer security is responsible for single-hop MAC command, beacon and acknowledgement frames. The 802.15.4 medium access controller is based on the Advanced Encryption Standard (AES) as the core cryptographic system. When the MAC layer transmits a frame with security enabled, it Retrieves first a key associated with the destination Processes frame and uses this key according to security mode associated with that key. The Upper layer selects and manages all the various keys and security levels more generally. The MAC frame header has a bit indicating whether security is enabled or not.

In order to protect against other types of attacks such as replay attacks, where an un-authenticated user may re-transmit one or more sensor or actuation messages or repeats intercepted messages or commands, the IEEE 802.15.4 protocol has a message integrity system which detects such messages and ignores these. The MAC header creates a Message Integrity Code (MIC) that consists of 4, 8 or 16 octets and is right-appended to the MAC payload. If confidentiality is required Frame and Sequence counts (nonce) are left-appended. Nonce prevents replay attacks. Upon receipt of a package, the MIC is verified first, after which the payload is decrypted. Sending devices increment the frame count and receiving devices keep track of the last frame received.

The 802.15.4 standard supports security at three levels:

- Encryption at the MAC layer using AES in Counter (CTR) mode, (without authentication)
- Authentication or Integrity AES in Cipher Block Chaining (CBC-MAC) mode (without encryption)
- Combined Encryption and Integrity where the AES implements both CTR and CBC-MAC. This is called CCM.

A Zigbee™ network uses the MAC layer to do the security processing, but it uses the upper layers, to set up the keys, determine the security levels and control the processing. As described previously when the MAC layer transmits (receives) a frame with security enabled, it looks at the destination (source) of the frame, retrieves the key associated with that destination (source), and then uses this key to process the frame according to the security suite or mode designated for the key being used.

The network layer uses a variant of the AES based on the CCM* mode of operation. The CCM* mode of operation is very similar to the CCM mode used by the MAC layer. It includes an encryption and integrity mode of operation, and additionally offers encryption-only and integrity-only capabilities and eliminates CTR and CBC-MAC modes. Also, the use of CCM* in all security modes allows the use of a single key for all different security modes. Since a key is not strictly bound to a single security mode a Zigbee™ application now has the flexibility to specify the actual security mode to be applied to each Network frame, not just whether security is enabled or disabled.

When the Network Layer transmits (receives) a frame using a particular security mode it uses the Security Services Provider (SSP) to process that frame. The SSP looks at the destination (source) of the frame, retrieves the key associated with that destination (source), and then applies the appropriate security mechanisms to the frame. The Network Layer is responsible for the security processing, but the upper layers control this processing as it sets up the keys and determines which CCM* security mode is to be used for each frame.

In conclusion, the Zigbee™ network is secure and immune to most security type of attacks provided that the key distribution integrity is appropriately considered.

ADAPTIVE RADIO AND COEXISTENCE

Where security is not a real issue for a Zigbee™ network, interference is a real problem. This problem is inherent in all wide band communication services over radio. A Zigbee™ network is a radio based network and hence subject to jamming, the more so as low power consumption in the nodes is an important design feature of the Zigbee™ network.

How does one then ensure that the system is robust to jamming and denial of service attacks given the potentially critical nature (e.g. fire alarming and protection in a building) of Zigbee™ networks?

Appropriate enhancements need to be added here to ensure that a SCADA network based on Zigbee™ is robust, both in terms of interference caused by other radio networks that may operate in the same environment or malicious interference such as jamming. First it must be understood that it is not possible to safeguard against a continuous very powerful (as in transmit power) radio jamming signal (but of course such jamming contravenes the use of the radio spectrum). Accepting that the Zigbee™ network is operating within a zone where the use of the radio spectrum is subject to the general rules, which are law enforced, the Zigbee™ network makes use of adaptive radio [5,6], that is a radio that

- monitors its own performance (errors of transmission),
- monitors the path quality through sounding or polling (evaluates the environment for jamming and interference),
- varies its general operating characteristics, such as frequency, power, coding and data rate, or spatial diversity and
- uses closed-loop control action to optimize its performance by automatically adapting from time to time any of the four mechanisms available to combat interference: transmit power, transmit frequency or channel, code and/or spatial diversity.

In this manner a Zigbee™ network ensures that is utilizes the available radio spectrum in the best possible way, without itself causing undue interference to other users of the same spectrum. Within the physical limitations of the radio medium (frequency channels available), the available power and energy, this is the best one can do to alleviate the problems posed by interference caused by other users of the same radio spectrum, be it malicious or otherwise. The precise algorithms underpinning the adaptation of its radio transmission form part of the particular realization of the Zigbee™ network, and may be application dependent. These algorithms are not necessarily open source, nor is it necessary that these are open source, as they are transparent to the user and application layer.

Another important aspect of interference the Zigbee™ network must cope with is the issue created by having potentially in the same radio spectrum licensed and unlicensed users (like Zigbee™ low power nodes). Here the unlicensed users have to cope with any interference of the licensed users, that typically transmit at higher power and yet themselves cannot impede the licensed users in any way. The same ideas of adaptive radio overcome this issue too. These aspects are often referred to as cognitive radio, a radio which is aware of who are the different users of the same spectrum, and what their legitimate claims are on the spectrum, and takes appropriate action to ensure that at any time the appropriate radio frequency usage rules are observed. For further information about cognitive radio, and its potential and limitations we refer to [9].

SENSOR ML AND SENSOR NETWORK PLUG AND PLAY

A critical component of any SCADA system is how easy it is to maintain and develop. Scaling, or expanding a SCADA network is a natural requirement and the incorporation of new sensors and/or actuators in a plug and play fashion are essential to the development of sensor networks in general. It is also important that both sensor/actuator and network management data are readily accessible for archiving and processing. Any closed loop operation of the network will depend on the data being readily available.

The importance of the long-term monitoring of an irrigation system (on time-scales compatible with the physical hardware, i.e. over a number of decades, if not a century) or environment monitoring raises the need for the preservation of the low-level sensor data as well as the information required for processing the raw sensor data over such time scales. To a lesser extent the same applies to actuator nodes, where interface information is needed to determine how information sent to the actuator leads to a physical action. Unfortunately, such information is often lost or difficult to find after the system has initially been deployed. The SensorML (see [7,8]) standard is one step toward preserving part of the vital information required for processing of sensor data for both real-time and archival observations.

SensorML provides a standard means by which sensor and platform capabilities and properties can be published and discovered. SensorML also provides information that allows for processing of the sensor observations without a priori knowledge of the sensor's properties. This provides a significant advantage in that it reduces the time lag between making measurements and applying those measurements in decision-making. Time savings are particularly noticeable in the management of time critical events such as emergency response, advanced warning systems, and forecasting.

Traditionally, low-level sensor data processing has required writing or utilizing software specifically designed for that sensor system. The availability of a standard model language for describing platform position and rotation, as well as instrument geometry and dynamics, allows for the development of generic multi-purpose software that can provide geolocation for potentially all remotely sensed data. The availability of such software, herein referred to as an Observation Dynamics Model, in turn provides a simple, single Application Programming Interface (API) for tool developers to incorporate sensor data and processing into their application software. The SensorML standard allows the development of software libraries that can process these files and data and also for a number of derivative standards concerned with storage and transmission of sensor dynamics, platform location and rotation in order to ensure that such formats are also maintained, available, and readable by similar APIs in the future.

Typically, sensors fall into one of two basic types. In-situ sensors measure a physical property within the area immediately surrounding the sensor, while remote sensors measure physical properties at some distance from the sensor, generally by measuring radiation reflected or emitted from an observed object. Regardless, any geometric properties described within the SensorML schema are defined within the sensor's local coordinate frame and are only related to the geospatial domain through it frame's association with the platform, mount, and their association with some geospatial reference frame.

A SensorML document can be considered a "living" description of a sensor. The SensorML document can begin as a template document, which is initially created using the sensor model design and is then appended or altered during the manufacturing, calibration, deployment, maintenance, and ultimately the removal of the sensor from service. Much of the specification of a sensor is shared by all sensor instances of the same model-number from the same manufacturer. This will typically include a description of measurement properties (with fields for such items as accuracy, scale, raw data format, linearity, repeatability, response rate), sample geometry, and the geometry and dynamics of any internal sampling arrays (such as scan patterns or frame camera properties). This initial template may include in addition some calibration parameters.

However, a SensorML document describing a particular sensor instance will acquire additional information that will distinguish it from other instances of the same model. In particular it may acquire unique identifiers such as ID and serial number. It will further be attached to some platform that will provide it with location and orientation within a known geospatial-temporal frame. In many cases the sensor instance will also have (for example) additional calibration information specific to its deployment (e.g. a datum level for water level measurements). As a sensor progresses through these stages, the SensorML document will not only gain additional property information, but it will also record the changes to the sensor and the document itself through the inclusion of a history description. SensorML will permit new sensors and devices to be easily plugged into a sensor network with minimal effort and maximal reliability.

CONCLUSIONS

Zigbee™ networks are well suited to SCADA applications. Moreover, it is our thesis that mere sensor networks will not provide the real driver for Zigbee™ networks, but rather true SCADA networks where closed loop control is enabled to provide innovative services.

Zigbee™ provides excellent levels of security and data integrity; is extremely end-user friendly as the network auto-configures itself and can be deployed in stages. Unavoidably, because of their low power features, they are subject to jamming and denial of service from a powerful jammer or interference source.

Nevertheless, the adaptive and cognitive radio features, which form an integral part of any Zigbee™ network implementation, provide the best protection against any interference within the physical power/energy limitations of the network devices.

The standardization which comes natural with the communication network is being developed further to encompass also sensors and actuators. (The Zigbee™ specifications are publicly available.) The development of open-source interfaces for a new generation of sensors (like SensorML) and actuators is essential to achieve the true potential of this new technology. Amongst the manufacturers embracing Zigbee™ and SensorML standards are multinationals such as Honeywell International Inc., Philips Electronics NV, Samsung Electronics Co. and Motorola Inc.

We are in the process (see [2]) of implementing a Zigbee™ based SCADA network based on the NICTOR™ platform for low-cost on-farm irrigation and general on-farm automation.

REFERENCES

[1] http://www.zigbee.org

[2] http://nicta.com.au/director/research/programs/sn.cfm

[3] http://www.onworld.com/

[4] http://www.ieee802.org

[5] http://www.atis.org

[6] http://au.itpapers.zdnet.com

[7] http://mail.opengeospatial.org/mailman/listinfo/sensorml

[8] http://vast.nsstc.uah.edu/SensorML/

[9] http://www.fcc.gov/oet/cognitiveradio/

SYNCHRONOUS RADIO MODEM TECHNOLOGY FOR AFFORDABLE IRRIGATION SCADA SYSTEMS

Tom Gill[1]
Robert Einhellig[2]

ABSTRACT

Engineers at Reclamation's Water Resources Research Laboratory, funded through Reclamation's Science and Technology program, and in cooperation with the Colorado Division of Water Resources (State Engineer's Office), the Lower South Platte Conservancy District (LSPWCD), and the South Platte Ditch Company (SPDC), have established a demonstration project to monitor and evaluate control equipment that features an innovative radio technology. Irrigation practices in the South Platte valley in Northeast Colorado include extensive conjunctive use of both surface diversions and pumped groundwater. As a result of extended drought conditions and court rulings that have altered the administration of groundwater pumping in Colorado, the region is currently facing a dramatic increase in the number of sites at which flow measurement is required. The State of Colorado is facing an associated exponential increase in the amount of data that needs to be acquired and processed.

The control/communication equipment under evaluation is produced by Integrated Controls Technology Inc. (IC Tech) [Formerly Control Design Inc.] The primary objective of the field study is to assess the potential of the IC Tech equipment as a cost-effective means of collecting and transmitting flow measurement data. The equipment was put into service in early March, 2005, at two sites on the SPDC's artificial recharge system. One of the units was relocated in late April, 2005, to the SPDC main flume to continue performance observations through the irrigation season. Flow data from the demonstration sites is telemetered over distances extending up to twenty miles via signal pathways that do not provide clear line-of-sight transmission paths.

The IC Tech units evaluated include both a radio modem for communication and a programmable logic control system capable of monitoring flow rates, recording data, and controlling canal gates. The cost of the IC Tech radio/controller units is competitive with other popular controller-only systems. Depending on the water-level sensor selected, a solar powered station with an IC Tech unit can be installed at a canal structure for a price in the range of the cost of paper-chart recorders

---

[1] Hydraulic Engineer, Bureau of Reclamation, PO Box 25007, Denver CO 80225-0007; Phone 303 445 2201; e-mail tgill@do.usbr.gov
[2] Hydraulic Engineer, Bureau of Reclamation, PO Box 25007, Denver CO 80225-0007; Phone 303 445 2201; e-mail reinhellig@do.usbr.gov

which are currently used at most open channel flow recording stations in the region.

This paper provides documentation of performance of the IC Tech equipment during 2005 in the Northeast Colorado demonstration study. General performance information supplied by the Lower Rio Grande Conservancy District – which has been using similar IC Tech equipment over multiple seasons – is also included.

INTRODUCTION

A vital component of successful Supervisory Control and Data Acquisition (SCADA) systems for canal operating systems is a reliable two-way communications system. Radio telemetry is often an attractive communication option since the operational costs are usually minimal after the initial installation costs have been expended. Other wireless communication alternatives typically have monthly fees (i.e., cell phones) or charges based on volume of information transmitted (i.e., low-orbit satellite systems). Once a radio system is in place, there are no non-maintenance operational costs (other than periodic licensing fees for systems operating on licensed frequencies). A chief concern with radio communications systems is adequate signal strength. Frequently, costly towers and/or extensive repeater systems are necessary radio network components that can dramatically increase system costs.

As part of the Bureau of Reclamation's water-management mission, the Water Resources Research Laboratory (WRRL) has an ongoing program to identify and evaluate new or alternative techniques and equipment that can enhance water conservation and delivery efficiency while lowering costs. The Middle Rio Grande Conservancy District (MRGCD) reported that they were having positive results in this area using radio/control equipment from IC Tech of Albuquerque, New Mexico, for remote data acquisition and control. Their experience indicated that IC Tech equipment was both reliable and cost competitive compared with other control/communications systems MRGCD had tried.

Based on the information provided by MRGCD plus contacts with IC Tech, WRRL staff concluded that the IC Tech equipment would be a good candidate for a field evaluation. The goal of the evaluation was to determine if such equipment might be an appropriate option to help further cost-effective water conservation efforts for other Reclamation partners. The Northeast Colorado demonstration site selected is in an area where a strong need for information on technologies of this nature exists, and it offers a convenient proximity to the WRRL's location in Denver.

CONTROL SYSTEM HARDWARE

The IC Tech radio/control units feature a programmable logic controller (PLC) and a radio modem installed on the same circuit board, eliminating the need to pass information between the modules through a communications port. The IC Tech radios feature what the company describes as a synchronous modem technology that, according to IC Tech, enables a superior degree of signal acquisition compared with conventional modem technologies. The company reports that signal transmissions of up to 120 air miles are being utilized in existing deployments of their equipment. It is the apparently unique radio technology and potential range which makes the IC Tech equipment particularly intriguing for applications in irrigation delivery systems.

The systems are Modbus compatible and programs for the PLC are written using the BASIC 52 programming language. Six radio module options are available. These radio options include one unlicensed and two licensed VHF bands plus three licensed UHF bands. Selection criteria for the appropriate radio option includes the required distance of transmission and the type of terrain. Radio modules used in the field demonstration site are UHF units operating in the 450 – 470 Mhz band.

Three PLC configurations are offered. The high-end "A" unit were used in the field demonstration tests. These units were equipped with the optional 4 X 20 LCD display and 2 X 5 keypad.   The "A" units are equipped with the following standard features:
- Eight available 12 bit analog inputs (one of which can be configured for SDI-12 inputs)
- Eight optically isolated digital inputs (four can be used as runtime and pulse counters)
- Four relay isolated digital outputs
- 128K battery-backed non-volatile SRAM
- 64K non-volatile flash memory
- Real-time clock with battery backup
- Charging controller for solar or other DC sources
- Three communications ports
    - Com0 RS232 (BASIC 52 port)
    - Com1 RS485 (MODBUS port)
    - Com2 RS232 or RS435 (Modem port)
- Switched sensor excitation voltage (battery voltage)
- Switched sensor excitation onboard 24 volt converter
- LED indicators for power and modem functions
- Industrial grade components, rated -30°C to 70°C (radio) and -40°C to 85°C (all other components)

- Approximately 16500 MODBUS floating point data storage registers that may be used for storing data to be telemetered by radio and/or for onsite datalogging

Two office locations in the study were equipped with less costly "B" units. The optional display and keypad were not installed on these units since they were connected to the office computer systems. The standard configuration of the "B" units is identical to that of the "A" units with the following exceptions:
- Four available analog inputs (none is SDI-12 compatible)
- Four digital inputs (no pulse counters)
- Two relay isolated digital outputs
- Switched battery (12V) excitation voltage only (no 24V converter)

The third PLC option, "C" units, have the same capabilities as the "B" units but cannot be equipped with a display and keypad.

FIELD TEST SITE BACKGROUND

Irrigation in northeast Colorado's South Platte Valley dates back to the late 1860's. Canal systems were constructed to carry water diverted from the South Platte River. The limited river flow during the latter summer months led to construction of several off-channel reservoirs in the region. These reservoirs began storing water from the non-irrigation and spring runoff periods during the early part of the 20th century. By the 1930's irrigators began drilling groundwater wells to supplement surface-water supplies. Well drilling expanded rapidly during the extended period of below average precipitation in the 1950's. With an increasing number of wells in operation, the effect of well pumping on stream flow in the South Platte River became a growing issue.

A Colorado law enacted in 1969 requires that well users have available sources of augmentation water that could be used during times of demand to offset depletions to stream flow resulting from past groundwater pumping. The purpose of the law was to ensure that senior surface-water diversion rights would not be injured by the diversions of junior wells. In the early 1970's, irrigators began to construct and operate artificial groundwater recharge systems. Return-flow credits from the recharge systems, along with releases from off-channel reservoirs serve as sources of augmentation water. A pair of Colorado Supreme Court rulings handed down in 2002 and 2003 dramatically changed the way in which the 1969 law was to be administered by the State Engineer's Office.

One impact of the rulings was that the amount of augmentation water required to offset injury due to groundwater pumping was dramatically increased. To meet this increased demand, the rate of development of recharge systems rapidly expanded. A second impact of the rulings was that every well would need to be equipped with a totalizing flow meter. While many wells were already equipped with flow meters, a large percentage were not. Over a two year period, the

number of sites from which flow data needs to be accumulated and processed by the State Engineer's Office increased several fold. State budgetary issues have necessitated that this be accomplished without an increase in the State Engineer's Office staffing.

Prior to 2005, the overwhelming majority of open-channel flow measurement sites with flow recorders installed were equipped with paper chart recorders and nearly all pumps with meters were equipped with mechanical meters. Data handling for these systems requires extensive field travel for on-site data acquisition plus manual transfer of data records into digital format. Adoption of automated discharge data acquisition and transmission processes would significantly reduce the labor required to collect such data and speed up the availability of processed information. The water users and the State Engineer's Office are key stake holders which would benefit from such a system.

The LSPWCD was created to be the local management entity for Reclamation's Narrows project on the South Platte. This project was authorized in the late 1960's but was never funded. Since its inception, the District has played an active role in the full spectrum of water issues facing area users, including development and administration of augmentation plans and artificial recharge facilities. Beginning this year, the LSPWCD is providing a field office for the State's Division One River Commissioner at their office complex in Sterling, Colorado. An IC Tech base unit installed at the LSPWCD office is linked to a PC in the River Commissioner's office on which radio telemetered data is stored in a text file.

The SPDC developed one of the earliest (and most senior in right) artificial recharge projects which has been in operation since 1974. SPDC also holds the senior irrigation diversion right in Water District 64 on the South Platte River. As a result of these two factors, diversion activities are ongoing for much of the calendar year. This condition made SPDC an attractive partner for a demonstration test site. A second base station was set up at the home of one of the SPDC board members. This station enables the SPDC to independently monitor both flow conditions and performance of the telemetry system. It also provides a redundancy in storage of flow data from the 15-minute data-retrieval intervals.

DEMONSTRATION PROJECT INSTALLATIONS

The IC Tech units were initially installed at two measurement structures on the SPDC recharge project in early March, 2005. One was installed on a trapezoidal venturi flume identified as the G2 site. The second was installed on a contracted rectangular weir identified as the Sandhill site. Flow at both sites had previously been recorded on Stevens paper chart recorders. The Stevens recorder at the Sandhill site had been damaged by livestock during the summer of 2004 and was

not functional for the Spring 2005 recharge season. The Stevens recorder at the
G2 site was operated to provide flow recording redundancy as the performance of
the IC Tech equipment was being monitored.

Figures 1 and 2 show the SPDC G2 and Sandhill flow measurement sites. The IC
Tech unit installed at the G2 trapezoidal venturi flume (shown in Figure 1) is
mounted to the pole supporting the solar panel. The radio antenna is attached to
the solar panel mounting bracket. An ultrasonic water-level sensor is installed
over the center of the flume approach section approximately 2.5 ft above the
flume walls. The existing Stevens recorder is mounted in the box atop the stilling
well. Figure 2 shows IC Tech founder Jim Conley (on ladder) and SPDC Board
Member Charles Bartlett installing a IC Tech radio/controller unit near the
Sandhill suppressed rectangular weir.

Figure 1.   Figure 2.

The G2 site was equipped with an LA15 ultrasonic water-level sensor from
Flowline. Ice is often a problem during the recharge season, and the SPDC
selected the ultrasonic technology as an affordable sensor alternative which has
no components in contact with the water. Sensor slope and offset values were
field calibrated after installation. A stage-discharge table for the G2 trapezoidal
venturi flume – apparently developed by the State Engineer's Office – was
provided by the River Commissioner. A fourth-order polynomial curve was
identified that provided a near-exact fit to the rating table data. The curve
equation was written into program code allowing the PLC to compute the
discharge from the water-level sensor data.

The Sandhill site is located a few hundred feet from a well-traveled gravel road,
(unlike the G2 site which is in a pasture almost a mile from the nearest public
road). With the enhanced accessibility of the Sandhill site, both the River
Commissioner and the SPDC expressed an interest in expanding the
demonstration aspects of the site by installing two water-level sensor
technologies. An LU05 ultrasonic sensor from Flowline was installed over the

weir approach flow and a Sutron SDI 12 shaft encoder was installed in the stilling well. At initial installation, depth of flow as determined by the shaft encoder was utilized for calculating discharge and totalized volume values. Flow depth calculations from both level sensors, along with computed discharge and totalized volume values for this site are written to polling registers for radio transmission of data.

The IC Tech base unit installed at the LSPWCD office is located in a communications closet at the rear of the office complex, as shown in Figure 3. From this location, information is passed via a previously unused telephone wire pair to a desktop computer in the River Commissioner's office at the front of the building. The antenna is mounted on a 10 ft mast attached to an outside wall adjacent to the communications closet. Figure 4 shows the antenna at the LSPWCD office. As mounted, this antenna is approximately 18 ft above the ground and appears to be at a lower elevation than the roof of a nearby building (seen at lower right in the background of Figure 4) which is in the line of the signal paths to both measurement sites.

Figure 3.

Figure 4.

The second IC Tech base unit is located at a SPDC Board Member's residence, approximately 1.5 miles from the Sandhill measurement site and 2.5 miles from the G2 measurement site. At both the LSPWCD office and at the SPDC Board Member's residence, the IC Tech base radio units are programmed to poll each of the field measurement sites at 15 minute intervals. This information is then passed to a personal computer where it is recorded to a text file on the computer hard drive. With both units independently polling and storing information, a redundancy in data storage exists.

To provide a further level of data storage redundancy, the flow level computed for each 15 minute polling cycle is datalogged on-site in the IC Tech units in MODBUS data storage registers. A date stamp is entered for the first polling cycle after midnight each day. As programmed, fifteen-minute water-level data is stored for more than 160 days before the oldest data begins to be overwritten.

The data stored in the IC Tech units may be accessed either by connecting a laptop computer to the field unit, or by use of polling commands entered into any remote IC Tech unit in communication with the site.

SPDC MAIN CANAL INSTALLATION

With the start of irrigation season and associated wind-down of the recharge season, the IC Tech unit installed at the SPDC Sandhill site was relocated to the upper measurement flume of the SPDC main canal on April 20, 2005. This allowed for continuous evaluation of the equipment both prior to and during the irrigation season. The water-level sensor installed at this site was the ultrasonic LU05 sensor from Flowline which had been used at the Sandhill site. The direct-path distance between the upper flume site and the LSPWCD office is approximately 20 miles, and no features of the town of Sterling (location of the LSPWCD office) are visible from the site.

DEMONSTRATION PROJECT PERFORMANCE OBSERVATIONS

IC Tech Data Radios

Availability of a suitable radio signal path was a primary concern during planning and equipment installation for the demonstration project. From the Sandhill site, only the tallest structure in the town of Sterling (a grain elevator) is visible. As seen in Figure 4, between the LSPWCD office and the SPDC field measurement sites, a nearby building presented an immediate line-of-sight obstacle. A further complication is that the LSPWCD office is in the northeastern part of Sterling while the SPDC is located southwest of town. The signal path crosses in excess of a mile of town including numerous structures and electrical transmission lines that would potentially impact radio signal transmission. The SPDC had made arrangements with a local wireless internet provider for temporary installation of a repeater station on a tower clearly visible from all project installation sites in the event that problems with radio signal reception were experienced.

At the initial power-up of the radio system on March 4, 2005, signal strength was measured between both of the field measuring stations and each of the base stations. The signal received at the LSPWCD office was found to be near the low end of the recommended range. The IC Tech representative assisting with installation suggested that putting the demonstration project in service without installing a repeater station would be appropriate for evaluating the performance of the IC Tech equipment under less-than-ideal conditions.

Over the first three months of operation, the data reception rate at the base stations was evaluated. The transmission routes of up to 20 miles between the SPDC recharge system field sites and the LSPWCD office (as expected) proved to have lower successful data transmission rates than rates observed at the closer

SPDC board member's home. During the time period from March 4, 2005, through June 6, 2005, there was an 88.6 % successful transmission rate with the LSPWCD office for signals from the G2 site, where the transmission path is obscured by a hill. For the period from March 4, 2005, thru April 19, 2005, there was a 99.3% successful transmission rate with the LSPWCD office from the Sandhill site. From April 27, 2005, thru June 6, 2005, there was a 99.6% successful transmission rate with the LSPWCD office from the SPDC Main Flume.

IC Tech Programmable Logic Control Units

The IC Tech control units – which are programmed using the BASIC 52 language – include features that make them versatile for a broad spectrum control applications on canal structures. The setup of Modbus registers allows simplified access to stored data and for viewing or changing program execution variables. The programming structure and the included features combine to make the training requirements needed to become functional with the IC Tech equipment comparatively straight forward. No operational problems were encountered with the IC Tech control units during the March 4 through June 6 2005 time period.

Associated Non-IC Tech Equipment

The primary non-IC Tech equipment in the demonstration sites include solar panels – which have given no indication of problems – and water level sensors. As stated above, an ultrasonic LA15 sensor from Flowline was installed at the G2 site. This sensor generally performed well. An apparent glitch in sensor output that was experienced on two occasions was later found to be the result of the control unit analog input circuits returning to default settings when the unit experienced momentary shutdown due to a detected surge (caused by lightning strikes in the proximity). The analog input default setting issue was easily corrected by adding two commands to the system initiation portion of the operating program.

At the Sandhill site, the original setup included a Sutron SDI-12 shaft encoder (provided by the State) as the primary unit and a Flowline ultrasonic LU05 sensor to provide a second level reading. Within the first few days of operation, problems were encountered with the shaft encoder. The problems seemed to be related to power connections internal to the sensor. By all appearances the unit would be without power, however checks using an electrical multi-tester showed full excitation voltage at the terminals on the IC Tech unit and at the plug connection coming into the shaft encoder.

After repeated toggling of the power switch on the Sutron unit, it would power up and remain functional for a period of time not longer than a day. After the first visit to investigate the shaft encoder shutdown, the primary-secondary

relationship of the two level sensors was reversed by editing the program code. Depth of flow derived from input from the ultrasonic sensor was utilized to calculate discharge and totalized flow. When the equipment from the Sandhill site was relocated to the SPDC main flume, only the LU05 ultrasonic sensor was transferred.

FEEDBACK ON IC TECH RADIO/CONTROLLER UNITS FROM OTHERS

On June 14, 2005, WRRL engineers were participating in a tour of canal systems with remote communications capabilities that included a visit to MRGCD in Albuquerque NM. MRGCD Hydrologist David Gensler, who is in charge of implementing MRGCD's ongoing modernization efforts, related that MRGCD is utilizing IC Tech equipment exclusively for its radio communications with field sites after having limited success with other radio equipment.

The MRGCD system features a repeater located atop Sandia Peak from which line-of-sight paths are available to field sites in the northern part of the district. Gensler stated MRGCD is getting "essentially 100% successful transmission rates" over distances of up to 70 miles. MRGCD is utilizing IC Tech radio/control units both for flow measurement sites as well as for locally-automated gate control. Gensler also noted that MRGCD is able to purchase the IC Tech radio/control units at approximately one-half the cost of control-only units available from the company from which they have been purchasing overshot canal gates.

FUTURE DEMONSTRATION PROJECT PLANS

For the 2006 season, the SPDC will add automation of spillway structure gates and monitoring of flow at a near-by lift pump to the tasks handled by the IC Tech unit installed at their main flume site. They also plan to install an IC Tech radio/control unit at their river diversion structure, located approximately 2 miles upstream from the main flume. Diversion structure gates will be automated to maintain constant diversion rates, despite fluctuations in river flow. The SPDC goal is to be able to send a flow set point to the unit monitoring the main flume and controlling the spillway. Then – based on this target discharge and on flow conditions at the spillway – this unit would generate set points for the diversion structure and wirelessly communicate set point changes to the diversion control unit.

The SPDC is also working on agreements with two neighboring ditch companies interested in independently performing flow monitoring and automated control tasks on their systems, while using a common radio frequency license and common data collection and data processing systems. Interest in this cooperative effort is the result of observations of the 2005 SPDC demonstration project made

by shareholders of the other districts. The districts have jointly applied for funding through the Colorado Water Conservation Board for a 2006 project expansion of the demonstration project.

SUMMARY AND CONCLUSIONS

Engineers at the WRRL are continuously seeking information on technologies needed for modernization of canal operations that represent enhanced value – either in terms of improved performance, or in terms of providing a similar performance level at lower cost. The demonstration project that is the focus of this paper is in a region facing critical needs for enhanced technologies for obtaining, transmitting, and distributing flow measurement data.

The demonstration project – set up with a limited budget – includes only IC Tech radio equipment. No inference in comparative performance between the IC Tech equipment and other commercially available radio systems is intended by WRRL based on the observed performances reported. Rather, the observations of this study simply suggest that the IC Tech radio equipment provided a promising level of performance under less than ideal conditions for radio signal transmissions. Based on these observations, IC Tech equipment offers intriguing potential as a cost effective communications and control alternative for SCADA canal operating systems.

DISCLAIMER

No warranty is expressed or implied regarding the usefulness or completeness of the information contained in this paper. References to commercial products do not imply endorsement by the Bureau of Reclamation and may not be used for advertising or promotional purposes.

A SUGGESTED CRITERIA FOR THE SELECTION OF RTUs AND SENSORS

Blair L. Stringam[1]
Paul Elser[2]

ABSTRACT

Selecting an appropriate Remote Terminal Unit (RTU) and sensors for an automation project can be daunting. There are numerous devices available with varied capabilities and performance. Factory representatives and specifications can be misleading and confusing. Advances in the electronics industry are seeing tremendous changes and subsequently RTUs and sensors are undergoing new developments. Older models are being redesigned and in some cases losing their integrity. Efforts have been made to test various RTUs and sensors, but they have not been exhaustive and these devices will eventually become obsolete.

Considering the extensive choices that are available and the changes that are continually occurring, a criteria was developed for selecting these devices for automation projects. While basic performance criteria are important, it was concluded that consulting with individuals who have used these components is the most important.

INTRODUCTION

Experts will all agree that automation helps manage and save water. There are numerous devices that have been developed which can be used to automate canal and other water resource systems. As advances are being made in the electronics industry, new devices are coming out on the market and older ones are being discontinued. As engineers undertake new projects they are faced with several questions. What capabilities are required for the project? Is there future growth that is required in the project? Will the equipment that has been used on previous projects work for the new project? Are there automation devices already in place that will have to be merged with the new system? What is the expected life of the automation equipment? Is service available for the selected equipment? How long will replacement parts be available for the new equipment? Will a large time investment be required to understand the new equipment?

---

[1] Assistant Professor, 333 Leon Johnson Hall, Montana State University, Bozeman, Montana, 59717; telephone: (406) 994-5778; email: blairs@montana.edu [2] SCADA Systems Manager, Alberta Environment, Regional Services – Water Management Operations, 200 – 5th Avenue S., Lethbridge, Alberta, T1J 4L1; Phone (403) 381-5289; email: Paul.Elser@gov.ab.ca

If there is a break down in the automation system, precious time, data, energy, and water can be lost. This motivates the design engineer to error on the costly side to try to avoid expensive problems. However, expensive equipment does not necessarily mean reliable. It must also be realized that irrigation systems are harsh on equipment (Stringam 1992). There will be breakdowns (Burt and Piao 2004) and components will have to be replaced. Considering all of these factors, a criteria was developed for selecting control units and sensors.

Control Unit Selection

The control unit or remote terminal unit (RTU) is the device that is placed out in the field to perform manipulations that will cause or force the system to respond in a desired manner. One must be careful when selecting these devices. They range in cost from $100 to more than $8,000. They have varied capabilities and different weaknesses. Some RTUs have demonstrated field problems such as unexplainable stalling when executing program code, loss of data, unexplainable breakdowns, inability to handle the environment, intermittent communication, loss of programming code, unusual sensor readings, and little or no factory support. In some cases, RTUs did not perform as claimed by factory representatives. In order to select an RTU, the control engineer obviously must understand the basic operation. They should be aware of potential problems so that they can discriminate between a reliable RTU and one that will cause problems.

As mentioned earlier, electrical control devices are undergoing change. Older devices are being discontinued and new ones are being brought on the market. In other cases, control requirements dictate that a newer device is required to properly operate the project. Control engineers are often faced with having to select new control RTUs that will handle the project requirements. There are the usual requirements like:

- How many analog inputs will the RTU accept or how many control inputs or outputs are available?
- Can the control inputs and outputs be expanded if required?
- Can the analog input capability be expanded?
- Does the RTU have SDI-12 capabilities?
- What are the communication capabilities?
- Can the RTU communicate with another RTU in the system?
- How many communication ports does the RTU have?
- What are the programming languages that are used in the unit?
- Is the RTU reliable?
- What type of warranty and service is provided by the manufacturer and the system integrator?

- How long has the manufacturer been in business and what kind of track record do they have in the industry?

All of these questions should be asked by the design engineers and the potential users of the system. The first questions are just physical capability questions. It is just a matter of looking up factory specifications. A simple question can be asked for each control site: How many sensors are required and is there a possibility that more sensors will be added in the future? The same is true for digital control outputs and digital inputs (I/O). If a control gate motor is being operated, two output I/O are required. One I/O for moving the gate up and one for moving the gate down. If a limit switch input is required, one digital input I/O is required to read it.

Once the control requirements are determined, an RTU that will handle these requirements can be selected. It should be noted that it is good practice to use a device that has one or two extra analog inputs and extra I/O. There may be times where the extra sensors and I/O are required and more inputs must be used. As users of the control system become familiar with the system, they may ask for additional sensor inputs. If the RTU has expandable I/O, this is not a concern.

Controller Architecture

The RTU or programmable logic controller (PLC) can be either a fixed or modular design. The fixed design is typically a single board unit that has a fixed number I/O and may or may not offer the ability to expand the I/O. The modular design typically allows for the selection of I/O modules to match the control needs fitted into a rack arrangement. In either case, the control unit usually consists of a central processing unit (CPU), analog to digital inputs (A to D), digital input and outputs (I/O), communication ports, and possibly communications devices such as radios or phone modems. Some fixed units offer an integrated human machine interface (HMI) that provide text or graphics based information and push button keys for information access and manipulation. Modular units generally require a separate HMI to be connected to one of the communications ports. All of these components must perform seamlessly with the CPU for efficient uninterrupted control of irrigation sites.

Analog Inputs

The analog inputs of the controller should be able to interface with industry standard transmitters and provide a minimum of 12-bit resolution. The most readily available transmitters provide a 4-20mA output which can be converted to a voltage by using a current dropping resistor. A 4-20mA signal can be converted to 1-5 Vdc with a 250 ohm resistor and 0.5-2.5 Vdc using a 125 ohm resistor. Some controllers provide 0-5 Vdc or 0-2.5 Vdc inputs which means that the 20% of the input resolution will be lost unless the input can be adjusted to measure

over a reduced range where the bottom end is offset. It is important that the analog inputs have as close to the same span as the sensor in order to maximize the measurement resolution.

The digital resolution of the analog inputs is important to resolve the input signal to a fine enough increment to be able to perform good control. A 12-bit resolution provides for 4096 unique steps over the measuring range of the sensor. For example, 12 bit resolution provides better than 0.001 foot resolution on a transmitter with a four foot span. Controllers with 12-bit resolution are pretty common today, although 14, 15 and 16-bit resolution are also becoming more popular with the use of more powerful microprocessor units in the design of controllers.

An important consideration when assessing analog inputs is input surge protection. Analog inputs are highly susceptible to damage caused by surges typically caused by lightning. Some controllers provide a limited form of surge protection on the input circuitry, but if the input is damaged, the module or the entire controller may have to be replaced. The design of any control system should include separate lightning protection units (LPU) when there is a significant amount of cable between the control unit location and the sensor location.

SDI-12 Inputs

RTUs that have SDI-12 capability can greatly expand the sensor input potential. An SDI-12 input allows for several sensors to be connected to one input port. The sensor input is fed into the RTU using a digital communication protocol that identifies each individual sensor and the sensed value. Some RTUs allow for several sensors to be connected to one port. It must be realized that if these sensors are used, there is a few second delay for each sensor reading.

Discrete Inputs

Discrete inputs monitor the status of sensing devices that are either on or off, such as limit switches. Discrete inputs are designed to operate with dc voltage or ac voltage, but typically not both, and depending on the type of control application, the correct input voltage range must be selected. Discrete inputs typically have a voltage operation range with threshold levels that the controller recognizes. These threshold levels indicate the on state and off state of the device. The input voltage range is important to select depending on the voltage used to monitor and control an irrigation gate controller, however it is generally desirable to use dc voltage where practical.

The threshold value is generally not an issue when dry contact devices, such as a micro switch, provide the input status. However, when using electronic devices

such as proximity switches, the threshold value is important as proximity switches typically have an off state leakage voltage that may exceed the on-state threshold voltage of the discrete input. The selection of discrete sensors should be carefully considered when designing a control system.

Discrete Outputs

Discrete outputs on controllers come in various forms and care must be taken when selecting a controller and designing the control circuitry on an irrigation gate control system. Discrete outputs are available as 5 Vdc TTL, open collector (sinking or sourcing), triac and dry contact. Care must be taken when directly driving loads to ensure that the voltage and current limitations of the output circuitry are not overloaded. TTL outputs are especially susceptible and the selection of controllers with this type of output should be avoided.

In most cases it is good design practice to utilize an interposing relay between the controller output and the field device. An interposing relay can be switched by lower voltage and current outputs and is capable of switching higher voltage and current required by the load. The biggest advantage of using an interposing relay is that the relay can be easily replaced at a lower cost in the event of a problem.

Communications

Communication capabilities are becoming the most important feature in a control system. The ability to communicate remotely with an irrigation control site reduces travel and discovery time, and allows an entire system to be operated more efficiently. Generally, a control unit should have a minimum of two communications ports for connection of a local HMI and remote communication device. These ports should provide access to both the data area and program areas of memory. This allows the local and remote interfaces to view operational data, manipulate set point data, and to also make programming changes.

Generally, control units should support a communications protocol that enables multiple units to communicate within a system. A protocol is a language that control units will understand and respond to when a message is addressed for a specific unit. Today there are many different protocols that can be classified as "open" or "proprietary" protocols. The selection of an open protocol generally allows the data area of different control units to be read from and be written to but doesn't necessarily allow the program area to be modified. Today, open protocols are generally supported by many different brands of control units and allow control units from multiple vendors to be purchased and implemented in an overall control system. This offers some flexibility to the end user especially down the road when a control unit needs to be upgraded or when the vendor no longer manufactures the control unit or has gone out of business.

Proprietary protocols are typically developed by the vendor and are only supported by control units they manufacture. For the end user who is developing a telemetry network, this means they must buy from the same vendor so that new control sites are compatible with existing sites. As long as the control units are cost effective, reliable, and meet the design specification, standardizing on one controller can simplify design, implementation and maintenance of a control system.

Modbus is currently considered an industry defacto open serial communications protocol. Many control unit manufacturers purport to supporting Modbus protocol and most do in fact faithfully implement the protocol as laid out in the protocol manual available from Modicon. However, there are different variations of Modbus that have been developed in the past few years and some are not compatible with standard communications drivers used for remote telemetry applications. The authors are aware of one RTU device that was advertised to have Modbus communication capability, but when an RTU was purchased and tested, it was discovered that the device would not communicate with other devices using Modbus. When tech support was contacted, the response was that the manufacturer was not responsible for the problem and the system integrator would have to find a solution.

Other serial protocols, such as Allen-Bradley DF1, are also supported by a few vendors and there are many communications products available today that can be configured to convert one protocol to another. Serial communications are not the only mode available today, although they are considered to be a very secure method of transferring data. The advent of wireless Ethernet radios has thrust TCP communications into the limelight in recent years, and many controller vendors are offering an Ethernet port as standard. Ethernet is regarded as a good choice due to its inherent peer-to-peer communications capabilities, although with radio communications it is the radio equipment that defines the communications flexibility. With the right radios even Modbus, traditionally considered a master-slave protocol, can be implemented as a peer-to-peer network.

Human Machine Interfaces

The human machine interface (HMI) provides the ability for the operator to interface with the control unit to monitor current status and modify set points as required. Including a local HMI as a part of the control system design, either as a built in feature or as a stand-alone device is highly benifical. HMI's can be as simple as a single line display of 10 characters and a couple of pushbutton keys, or as elaborate as a color touch screen with graphics capabilities.

The selection of an HMI is dependent on the type of control unit selected and the complexity of the process being controlled. A simple upstream level control gate with only one level transmitter connected would probably operate satisfactorily

with a simple text-based HMI, where as a multiple gate check structure providing upstream level control with high and low flow over rides would benefit from the additional features afforded by a graphical interface. The power source for a site will also dictate this selection because a power hungry graphical display may not be a good choice for a solar powered gate site.

Controller Programming

Control units are programmed using many different types of logic including BASIC or a vendor specific form of BASIC, compiled C, ladder logic, both compiled C and ladder logic, Graphset and IEC-1131-3. In most cases, vendors usually provide compatibility for using program logic in all controllers in a product family, but programs from one brand of controller cannot be directly used in anther brand. Programs will always have to be re-written and tested for the target controller.

IEC-1131-3, a graphical and function block oriented programming language, was originally conceived to be the one programming language that would allow programs from one platform to be used in another. However, vendors have developed extensions of the language specific to their control units and the ability to convert programs directly is not currently available.

Learning to become proficient in a new computer language is time consuming. It is not just a matter of becoming familiar with the programming language, there are often unique functions that make programming more efficient. Considering that there are many choices in RTUs, it is recommended that an RTU is selected that uses a language that the programmer is familiar with. This reduces development time and cost. Technical support for the controller hardware and its programming language should be carefully considered when selecting a control unit.

There is an RTU that is presently on the market that is difficult to program because of the programming language that it uses. This device was given poor ratings in a report by the ITRC (1999). The authors of this paper agree that it is a difficult device to program however, they have found it to be an extremely reliable and durable device.

Sensors

The field sensors that are connected to the control unit allow it to retrieve information about the outside world. There are many types of sensors that are available, but this paper will focus on sensors used in canal automation. An understanding of some of the common sensors will help to limit the errors that can occur. The most common sensors connected to an irrigation gate control system are water level and gate position.

Every sensor has limitations. There are applications where they perform well and others where they are constrained. In order to select the right sensor, some of the following questions need to be asked:

- What is the usual life span of the sensor (be honest)?
- What type of installation is required for the sensor?
- What type of environment will the sensor be exposed to?
- What is the required measurement range?
- Is the sensor signal compatible with the control unit?
- What is the power requirement for the sensor?

Life span is always a concern. As mentioned earlier, an irrigation environment is harsh on sensors. A system integrator is often faced with the decision of selecting a longer life less precise sensor or vice versa. Individuals who have struggled with maintaining an instrumentation system in an irrigation environment are usually willing to sacrifice some precision for reliability.

Water Level Sensors

Water level can be measured using float and pulley sensors, float and cable-extension-spring-return sensors, submersible pressure transducers, ultrasonic sensors and bubbler systems. In all types of water level sensors, an analog signal proportional to the water level is transmitted to the control unit.

Float and pulley type sensors are probably the simplest and most reliable sensor to utilize and are very easy to calibrate. The float and cable-extension-spring-return sensors are also reliable and easy to calibrate, but are more expensive than the float and pulley type due to the mechanical requirements. Pressure transmitters are becoming quite common and more cost effective to install, however, the accuracy of the electronics needs to be carefully considered when selecting one. Ultrasonics have also become very popular but installation considerations including stilling well size and potential air temperature gradients must be carefully considered in the design. Bubbler systems are considered highly accurate and have been used for many years but are complicated.

Float based sensors tend to have the longest life. It is believed that there are three reasons for this. First, the sensors are out of the water and this prevents water from getting into the electrical portion of the sensor. Second, they are electrically non-contacting making them less susceptible to damage from lightning, and third is that the sensors are simple and rugged. Whether this type of sensor is a float and pulley type or a spring loaded type, a float is required to transfer a water level via a cable to the potentiometer unit. This means that a stilling well is required to keep the float from moving down stream. When this sensor is placed in a stilling well, cobwebs and other things can interfere with the sensor. One note of caution

when using spring loaded type float sensors is that linearity is affected by the spring rate of the sensor whereby the float will actually become more buoyant as the cable is extended.

Submersible pressure transducers seem to have the shortest life span. They are in the water and have problems with water leaking into the electronics or condensation running down the vent tube to the electronics. Even the newer transducers where manufacturers claim to have eliminated these problems fail. These sensors are very convenient to install. They may be simply hung off an irrigation structure into the water, or an open ended pipe can be fastened to the structure and the transducer can be hung inside the pipe. A special effort must be made to make sure that the transducer does not stretch out the cable over time and change the base reading. Many experienced instrumentation people will mention phantom measurements that occur with these transducers. This measurement occurs when a transducer makes consistent "reasonable" measurements for an extended period of time then there is a sudden drastic change. This value will differ from the previously measured values by several feet. Then the transducer will return to making normal measurements. If this is understood, the RTU can be programmed to compensate for these strange readings. There are many manufacturers of submersible pressure transducers and the cost is typically proportional to the accuracy available.

Some may argue that bubbler based sensors are also out of the water and should subsequently have a long life, but they are more complicated and have more things that can go wrong. They are usually made up of a pressure sensor, a pump or gas mechanism, a regulator, and a devise that controls the sensor operation. They can be mounted in an instrumentation enclosure and have a small pipe that extends down to the water where air or gas can be bubbled out. The span on many of these sensors can be adjusted for optimal operation. If this device uses a compressor, it requires much more power to operate than other sensors.

Ultrasonic sensors are also mounted out of the water and have shown that they can be very reliable. They can be placed over a water surface and determine the water level by sending out a sound wave that bounces off the water surface and back to the sensor. The sensor can determine the depth by measuring the time it takes for the sound wave to leave the sensor until it returns. These devices do not require a special installation platform except that they need to be placed over a calm water surface. They must also have a clear path to the water surface through the entire measuring range so that false echoes are not created by objects in the sensors beam path. The sound waves are affected by temperature and humidity, so if there is a temperature/humidity gradient between the sensor and the water surface, there can be an error in the reading. Some of the ultrasonic sensor manufacturers try to compensate for these gradients with varied results. If the sensor can be placed over a water surface where there is free air movement, the sensor is supposed to perform better. These sensors tend to draw more power

than a pressure transducer and a potentiometer, but less than a bubbler that has a compressor.

Gate Position Sensors

Measuring gate position is entirely dependent on the type of gate being used. Gates that use a rotating shaft to operate the gate can be fitted with a rotary type of sensor. Gates that have a vertically rising stem can use a spring-return-cable-extension or a continuous chain drive connected to the stem to convert linear motion into rotary motion.

In all types of gate position measurements, it is important to protect the electronic components and the small mechanical devices to ensure that position sensing is reliable and repeatable. It is extremely important to design and install a well protected and rugged gate position sensing system when flow measurement and control is based on gate position.

Sensor Signal Outputs

Sensors are available with a number of different signal output options including voltage, current, digital and serial. The selection of the type of sensor must be carefully considered in the design stage to ensure that the signal reaching the control unit is not affected by outside interference and truly represents the measurement.

Transducers that have a current output are probably the most common type of sensor available today and offer the best performance characteristics for the cost. Typically these transducers, or transmitters as they are generally referred to, are of the 2- wire or 3-wire type. Two wire or loop-powered transmitters include R-to-I cards connected to potentiometers, pressure transmitters and some ultrasonic transmitters. The R-to-I card type transmitters can be found in float type sensors or used in rotary gate position sensing when coupled to a rotating shaft. 3-wire transmitters include some types of pressure transmitters and ultrasonic transmitters as well as some encoder based rotary sensors. Current transmitters will typically operate with a dc power supply between 15 and 30 Vdc, however the lowest voltage required for the loop is based on the loop resistance and these transmitters generally operate best with a potential of at least 18 Vdc. Loop powered transmitters are the preferred type of transmitter as the maximum current draw is 20mA where as 3-wire transmitters can require several times that amount to power the electronics and provide the current signal. Again, it is important to use lightning protection with analog sensors transmitting signals over significant cable lengths.
Another output option becoming more common in recent years is the digital encoder, which can provide either an incremental or absolute signal output. Encoders, which can be used on any type of rotary sensor, are considered digital

because they use discrete outputs connected to discrete inputs on the control unit. This makes them virtually immune to electrical interference (noise). Incremental encoders provide two signal lines that provide switching signals that are ninety degrees out of phase, thus allowing control unit programming to be developed to sense movement and direction based on which input is leading the other. Absolute encoders typically provide multiple discrete lines connected to multiple discrete inputs which can be directly decoded by the control unit as a binary pattern.

Serial interface sensors come in many different forms including SDI-12, DeviceNet, Profibus, Interbus and simple ASCII. These sensors are usually considered "smart" in that serial communications is bi-directional and sensor parameters are set-up by writing to the sensor and then sensor readings are read from the device. Typically, these sensors are more expensive than traditional voltage and current input sensors due to the intelligent aspect of them, but they provide a direct digital reading of the signal that can be communicated to the control unit. Depending on the number of sensors on the communications bus and speed of the communications, there can be a delay in retrieving information from the sensors, which needs to be considered when programming an automated control system. In addition, as these devices are connected using cables, it is important to protect the sensors and control unit input with appropriate surge protection units.

CONCLUSIONS

Much of the selection of RTUs involves the basic exercise of determining system needs, then selecting the device that meets those needs. RTUs should be selected with an adequate number of analog inputs and digital inputs/outputs that meet the requirements of the system. There should be additional analog inputs and inputs/outputs available for future expansion, or the RTU should have expansion capability. The RTU must perform its programmed operations without stalling. Where ever possible, the system integrator should not have to learn a new programming language. The RTU should satisfy all the communication requirements and it should perform communications successfully. It is best if the RTU can communicate using an industry standard such as Modbus.

When selecting sensors, the sensor signal should match the analog input on the RTU. In other words, if the RTU has a sensor input range of 0 to 5 Vdc, the sensor should have the same output range. If the RTU had an input range of 0 to 2.5 volts, and the sensor signal varied from 0 to 5 volts, half of the sensor range is useless.

For what ever reason, factory representatives/salesman do not fully understand the automation requirements of your canal system. They may be trying to give you honest advise, but there is a tremendous difference between the performance of

their RTUs or sensors in a factory compared to an irrigation canal. It is best to talk with other technicians and engineers who have extensive field experience to determine the best device for your application. Manufacturers can also be asked for a list of companies that use their instrumentation device. In most cases, these people are aware of good and bad points of the device.

REFERENCES

Burt, C.M. and Piao X. (2004). "Advances in PLC-based Irrigation Canal Automation," The Journal of the International Commission on Irrigation and Drainage, ICID, 53(1), 29-37.

IRTC, (1999) "Water Level Sensor and Datalogger Testing and Demonstration," ITRC Report No. R99-002, (http://www.itrc.org/reports/WaterLevelSensor/ Water LevelSensor.html)

Stringam, B.L. (1992), "A Canal Automation and Control System," Masters thesis, Utah State Univ., Logan, Utah.

IRRIGATION CANALS IN SPAIN: THE INTEGRAL PROCESS OF MODERNIZATION

Prof. José Liria Montañés [1]
Laura Cózar Fernández [2]

ABSTRACT

Efficient use of water is a driving force in Spain, a mostly an arid country, having an adverse hydrological regime and insufficient rain for the practice of irrigation. Water needs increase continuously and there are almost no suitable places for new dams. The irrigation demand is the most important consumption use. Saving water would be the solution.

This paper will focus on the first element of the irrigation net; that is, water transportation / distribution by canals. Many irrigation canals are old and regulated by elemental systems, with frequent water losses. In order to improve them, there are several structural and non-structural responses under way now, fostered by the Spanish Government.

Regulation was introduced in Spain forty years ago with downstream and upstream constant water level gates. Nowadays the use of mixed gates combined with an upstream reservoir , completely centralized from a remote command centre, is becoming very frequent and profitable. The system is complemented with "all or nothing" jump distributors moved by compressed air, which regulate lateral turnouts.

HYDROLOGICAL SITUATION OF THE COUNTRY CONCERNING IRRIGATION

For millennia, Spain, a country featured by its dryness and its extremely irregular hydrological regime, has been practicing irrigation in order to take advantage of its favorable sunshine. Nowadays, irrigable areas demand more than 75% of the total quantity of regulated water within the country. Water necessities grow for human consumption, industry and agriculture and it is very difficult to increase availabilities, because the natural hydraulic regimen is very irregular and there are almost no suitable places for building new dams.

---

[1] Engineering Consultant- 34-91-5618871- jliria@ciccp.es

[2] M.Sc. Civil Engineering -GETINSA-Empresa Consultora de Ingeniería-34-91-5542129- lcozar@getinsa.es

Efficient water use is essential and the effort should be directed toward irrigation activity, the main and wasteful consumer. Nowadays in Spain, big efforts are being made to save water, with modern, automatically controlled systems, integrated with SCADA.

Consequently, one way of resolving the problem might be the improvement of water management, focused here now in irrigation canals, most of them very old and regulated by elemental systems, with frequent overspills and other water losses, water theft and unscheduled irrigation.

FAO has defined modernization as "a process of technical and managerial upgrading of irrigation schemes combined with institutional reforms, if required, with the objective to improve resource utilization and water delivery service to farms" (Facon and Renault, 1999).

In this sense, Spanish Public Administration is developing structural responses such as canal lining and others works of upgrading, and at the same time it is fostering non-structural responses related to technical improvement in regulation systems (on one hand canal operation, and on the other the electronic, electrical and mechanical components that direct the regulation).

Efforts of the Ministry of Environment to Ameliorate the Situation:

The Ministry of Environment, in charge of surveying most irrigation canals, has decided to help its own technicians and Irrigation Districts having canals, to improve management by updating their regulation and control systems. Therefore, it has launched a project, called "Upgrading of large infrastructures for transport and distribution of water." Its aim is not to update a specific canal, but to provide some help to technicians in order to upgrade management of most canals in the country.

The firm GETINSA, was selected by the Ministry to develop the project. The first phase is composed of two complementary parts:

Drafting of a Technical Guide for canal instrumentation: The aim is to advise the designer when choosing the equipment of the canal and find the most suitable solution adapted to its specific conditions. As element of scientific divulgation, this document reflects the "state-of-the-art", concerning all the equipment and electronic components: hydraulic gates, valves, automatisms, sensors etc.

Open mathematic model of simulation of unsteady flow in canals: It is an useful computing tool -called RIEGA 1.0 (acronym of Regulation of Water Transport and Distribution Infrastructures, in Spanish)- for the calculation of canal response

to gates operation or variations in the functioning regime. It can detect overflow or lack of water in different stretches. It is particularly helpful when planning the flow schedule. The results of the different trials feedback the system and provide the canal manager with valuable knowledge when taking decisions, both during the design phase of a new project and when improving working canals. It is a model based on known techniques, but with the peculiarities of being flexible and at free disposal of the technicians of the Ministry. The source code is open and the algorithms compose an understandable and modular structure, which will allow to be adapted and/or developed depending of the future necessities.

CURRENT STATE OF THE SPANISH IRRIGATION

Traditional Systems

Canal system control methods are slowly improving from local manual systems, passing through local automatic, to supervisory and combined ones, but still with elementary systems. In fact, almost all of the Spanish irrigations that have been improved with automatic gate systems, are regulated by methods of hydromechanics. Canal regulation has traditionally been based on downstream operation in primarily demand-oriented systems, and upstream operation in supply-oriented ones.

Nevertheless, in spite of the said great improvement in some aspects, there are still some regulation problems. In general, canal operation can hardly face the variation of consumption needs in the different turnouts. So, it is useful or even essential, to be able to calculate the canal inflow schedule with an accurate mathematic model, that also represents properly the lamination effect in water level.

New Systems

Since a few years ago, mixed water level control gates are placed more frequently. They regulate downstream levels by assuring, in addition, maximum-minimum safety levels. They are controlled by hydromechanics systems and they work thanks to the effect of weirs and valves housed in chambers connected to the canal. We will not explain here how they work, because this is very well known, however, we will remind that the mixed gate situated in a canal establishes correspondence relations according to predefined laws between these two water levels (upstream and downstream). Downstream level is fixed through the crest height of a small spillway inside the chamber. On older gates, it is constant and fixed from the moment they are implemented. Nowadays it can be modified from the control center, and the regulated level may be changed according to the water schedule. Given the great variety of its functions, the mixed gates are reserved for

equipping big channels with sufficient volume and are capable of making separate reserves and also compensate the demand and contribution of the daily water needs .

The functioning curve is as in Figure 1, in which upstream and downstream levels are linked, (Axis YY) and (Axis XX).
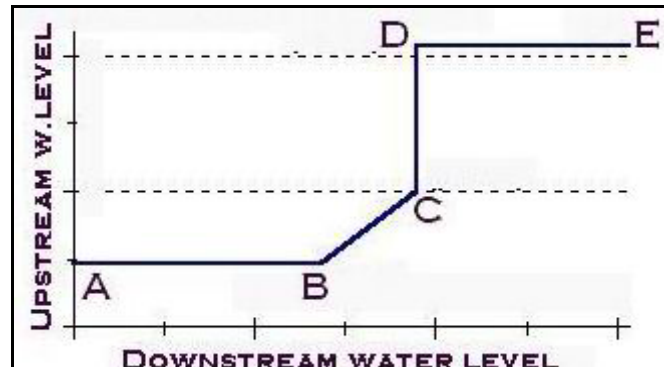
Figure 1. Diagram of a constant upstream/downstream water level gate.

Normal functioning stretch is CD, in which, for any upstream level, the downstream level is constant. Stretch DE is a security stretch, in which independently from the downstream level, upstream level is constant and equal to the maximum permitted, in order to avoid overspills. AB is a security stretch, in which the upstream water discharge is avoided when it is insufficient, by maintaining the minimum level adopted. Stretch BC corresponds to transition situations.

The possibility that the upstream level had important value fluctuations is very useful to combine one of these gates with an upstream reservoir. It stores the excess of inflow water during abundance periods but during shortage periods the stored water is released, always keeping the fixed downstream level. This aspect is very interesting when the canal operation aim is to keep constant levels on certain stretches. It is enough to place a complementary gate at a certain distance downstream of the gate, which only allows flowing planned discharge by taking advantage of the constant level obtained. The mixed gate will open or close according to the target discharge.

The combination of mixed gates and associated reservoirs is very useful to regulate the canal automatically. They were used on several occasions in Spain, such as, in the Paramo Bajo canal (please refer to photograph number 2) supplied by Einar company. This photo shows the storage area as a lateral structure, connected hydraulically with the canal on its side, and the mixed gate connected

to the canal. (The photo also displays a safety spillway in the canal that does not affect our explanation.)

Figure 2. Paramo Bajo canal-Constant upstream/downstream water level gate combined with a reservoir.

However, irrigation needs require more sophisticated systems. Water demands are not constant throughout the year. They depend on the season, on the surface irrigated at each moment, on the type of sown culture, etc. which force to find a more flexible operation able to be adapted to changes on water schedule.

Traditional mixed gates such as the ones explained, used to be installed with the selected data of the functioning curve, which were conditioned by the height of the spillway crest and some other additional elements that define the geometry of gates.

The Einar mixed gates used now in Spain, built and placed by said company, show several possibilities. The crest of the spillway is mobile, so it can be elevated or dropped according to orders received from the management center. Therefore, at each moment, the instructions can be changed. We find a sort of SCADA systems, with quite a wide potential value in developing process. Of course, the pure hydro mechanicals regulation systems do not nave the ability of transmitting information to the control centre, a defect that should be solved. In short, it is important to achieve higher flexibility when managing canals, modifying the orders from a centralized command centre.

But regulating water levels and flows is not enough when talking about the necessary upgrading. The system needs to be able to operate the turnout gates of different Irrigation Districts from the managing center, in order to deliver the demanded flows at any time. This item is already successfully solved in many cases, for instance, in San Sebastián distributor and in Aragón and Cataluña Canal.

From our point of view, the sort of lateral turnouts which works the best, regarding to the accuracy on responding to planned levels and flow rates, is the one called jump distributor or baffled weir. When water level is between the maximum and minimum limits of fixed range, baffled weirs can maintain an accurate flow rate. They work by an "all or nothing" system (totally open or closed) and with the possibility of supplying some fractions of the maximum derivable flow rate. It is because they are sub divided into several minor gates. A right canal operation guarantees the desired water levels and flows.

There are many irrigating areas in Spain equipped with this sort of lateral gates, but up to now all of them were managed by hand, with substantial staff expenses. The San Sebastian Distributor is monitored from a centralized command. Each group of gates is provided with a hut in which there is an air compressor moved by a small engine, of approximately .2 horsepower. Compressed air keeps stored at five atmospheres in a 50 litres (thirteen gallons) tank.

Figure 3 shows the interior of the hut with the tank, engine, battery, compressor and the wardrobe where there are placed some air filters and electro valves.

Electro valves are activated when a gate operation is required, allowing compressed air to act over some pneumatic cylinders. So they react opening or closing the gate with a strong instantaneous effort. The energy is obtained thanks to a small surface external solar panel, linked to storing electric batteries (the number of daily movements of the gate is very small so the amount of energy obtained like this is quite enough). Among the batteries and the energy stored in the pressurized air, there is no difficulty in the storage of the energy produced by the small power of the engine.

Figure 3- Interior of the hut. Motor, compressor, tank, batteries, etc.

Figure 4 displays the whole hut and the distributors set. There are two types of distributors or modules:

- Sector type shape.

- Smaller plain board shape

Figure 4. Whole hut and modules.

The detail of the moving cylinders is different according to the size of the module. Photograph number 5 shows small modules of plain board.

Figure 5. Detail of pneumatic cylinders of the plain modules.

On the other hand, in the bigger sector gates, cylinders are horizontally placed, fact that favors its rotation, as can be seen on photograph number 6.

Figure 6. Sector modules, with horizontal pneumatic cylinders.

New Irrigation Networks Control solution, integrates cutting edge technologies such as Supervisory Control And Data Acquisition (SCADA) systems, remote terminal units (RTUs), network operational control centers and irrigation management applications interconnected via wireless communications and the Internet.

Central-control automation in San Sebastian irrigation area allows the information to be communicated from the different RTUs (placed in check structures) to the central control unit, that processes the multi-site data and sends control signals back to the individual RTUs. Data transmission is through GPRS system, so for this reason, the huts are fitted with suitable aerials that act over a programmable automatic device (PLC). The orders are given from the central PC with rather a simple software. As a safety device, there is a rod submerged into the canal that sends an alarm signal in case of water shortage and, consequently, cuts the power.

Nowadays, the San Sebastián Distributary is working like that, irrigating around 7500 acres (3.000 Has). It forms part of the Aragón and Cataluña Canal, that waters more than 375.000 acres (150.000 Has). This Canal is divided into various Irrigation Districts. They find the system very profitable because of several reasons: water saving, guarantee of a good service rendered and saving of staff expenses, etc. There is a very promising tendency to move to the new system, taking great advantage of it.

FUTURE PERSPECTIVES

Our main purpose has been to show an overview of the way initiated in a traditionally irrigated country as Spain. A country accustomed to water scarcity, that is trying to solve its problem through an integral process of modernization, focused now on reducing the water losses rate in canals.

As a conclusion, our opinion is that future can be contemplated with optimism:

On one hand, the Spanish government, worried about saving water, is fostering the hydraulic engineering research and is also helping to improve techniques related to regulation systems of irrigation canals and water delivery.

On the other hand, there are some Irrigation Districts just understanding the economic advantages of innovative solutions, as well as the practical benefits of implementing SCADA systems. In fact, they willingly accept it and they are promoting themselves the improvement, because modernization is pursuing efficiency in the use of water but also reducing energy and operating costs in general. Our personal experience makes us strongly believe in this way: the easy and quick transmission of the new techniques from farmer to farmer, and from an Irrigation District to another, based on successful experience and trials.

We conclude that, step by step and thanks to all the parties involved (Ministry of Environment, Irrigation Districts, farmers, technicians, etc.), the forenamed process of modernization will be able to become real and profitable.

TEN YEARS OF SCADA DATA QUALITY CONTROL AND UTILIZATION FOR SYSTEM MANAGEMENT AND PLANNING MODERNIZATION

Bryan Thoreson[1]
Lindsay Mullins[2]
Anisa Divine[3]
Grant Davids[4]

ABSTRACT

Supervisory Control And Data Acquisition (SCADA) Systems can be used to collect the historical flow data that is needed to support good water management decisions; however, insufficient attention is typically given to data quality-control and storage. Initially driven by the unique requirement to verify water savings achieved by a water conservation program, the Imperial Irrigation District (IID) implemented a data warehouse with attendant quality-control and reporting applications as a SCADA data repository. Over the past 10 years, IID's Water Information System (WIS) has gained recognition for the benefits it now provides to ordinary operations, including reduced staff time, reduced reporting costs, improved data accuracy and overall improved water management. IID's SCADA system now includes 250 remote sites that feed data into the WIS.

This paper briefly describes the IID WIS and the primary functions it currently supports pertaining to water conservation administration, support of daily operations, strategic analysis and data reporting. The quality control procedures for data management are presented, along with recently implemented improvements. Performance of quality-control algorithms is also discussed.

INTRODUCTION

Sound water management requires accurate flow measurement and complete historical flow records. Supervisory Control And Data Acquisition (SCADA) systems can be used in irrigation distribution systems to collect water level and flow data, as well as to automate water system structures and acquire data on timing and rate of flow. Monitoring and data records for operational analysis are

---

[1] Project Manager, Davids Engineering, Inc.; 1772 Picasso Avenue, Suite A; Davis, CA 955616-0550; bryant@de-water.com
[2] Project Engineer, Davids Engineering, Inc.; 1772 Picasso Avenue, Suite A; Davis, CA 955616-0550; lindsay@de-water.com
[3] Senior Planner, Imperial Irrigation District, P.O. Box 937, Imperial, CA 92251
[4] Principal Engineer, Davids Engineering, Inc.; 1772 Picasso Avenue, Suite A; Davis, CA 955616-0550; grant@de-water.com

often cited as advantages of installing a SCADA system. However, planning for data storage and analysis is too often an afterthought in SCADA system design.

All irrigation water purveyors use some form of monitoring to ensure that their service goals are met. Monitoring systems vary widely in scope and intensity depending on service area size, location, physical characteristics and layout among other factors. Most purveyors are under some level of pressure to improve their water management. Achieving and documenting these improvements will, in many cases, require improved monitoring systems.

Effective monitoring systems provide flow data that can be transformed into useful information. Accurate and complete data, along with well designed transformation processes (analyses), are required to provide reliable decision making information. However, the mechanical and electrical equipment components that comprise SCADA systems experience problems and failures from time to time. Experience has shown that it is necessary to regularly check incoming data to ensure prompt repair of failures.

This paper describes the experience of Imperial Irrigation District (IID) with quality control of data acquired through a SCADA system that presently has over 250 remote sites. IID's intensive quality control program was prompted by a unique requirement to verify water savings associated with the 1988 Water Transfer Agreement between IID and the Metropolitan Water District of Southern California (MWD). Meanwhile, the importance of high quality flow data for developing water balances and improving water management continues to gain recognition within IID.

First, some of the data uses and benefits of the quality-control and storage system are described. This discussion is followed by a brief description of the quality-control system and recent improvements based on ten years of experience.

DATA USE

IID has recognized the importance of placing SCADA (and other) data in a central data repository. This data repository, called the Water Information System (WIS), is a state-of-the-art, computer-based system that is used to store, process, retrieve, analyze and report high-quality, historical flow data. The WIS receives data from a number of sources, applies quality control routines to assure that the data stored are complete, consistent and accurate, and generates both standard and special information reports (Figure 1).

The WIS was developed as a data warehouse for storing large sets of quality-controlled, historical flow data needed for analyses to support the IID/MWD Water Conservation Program. However, it has been expanded to support other crucial IID functions and has become an integral part of routine IID operations. It

enhances staff productivity, improves service and reduces operating costs. The WIS facilitates automatic report preparation, thereby increasing staff productivity, decreasing the cost of responding to information requests (such as from regulatory agencies), increasing IID analytical capabilities and, ultimately, increasing resource management opportunities for IID.

Primary WIS Functions

The WIS serves four primary functions that save the IID Water Department both time and money. The savings result from the ability to produce standard and special reports literally at the "push of a button," thereby filling data and analytical requests efficiently. More importantly, the data used for these reports and analyses are of the best possible quality, which means that IID decisions are based on highly accurate data. The four primary functions are described below.

IID/MWD Water Conservation Agreement Support: Administration of the IID/MWD water conservation agreement requires that IID prepare three major water reports annually.

1. Processed Flow Data,
2. Projected Water Conservation Savings, and
3. Systemwide Monitoring Program Annual Report.

WIS applications have been developed that allow the first two documents to be prepared with a minimum of staff time. The Processed Flow Data and Projected Water Conservation Savings reports have previously been described in Archer, et. al (1999) and Thoreson, et. al (2003b). Another WIS application that is under development will enable efficient production of the third report. Without the WIS, these reports would require months of IID staff time to prepare.

IID Daily Water Operations Support: Routine water operations require that daily and monthly reports be prepared summarizing flow and water level information at many water control sites within IID. Prior to implementation of the WIS, operators were required to transcribe all of this data by hand from computer screens for transfer to a spreadsheet, or the necessary values could be extracted by manipulating countless individual data files. Either way, the process consumed much staff time and was prone to human error. To prepare monthly reports, operators had to wait for data to be received from other operating sections and
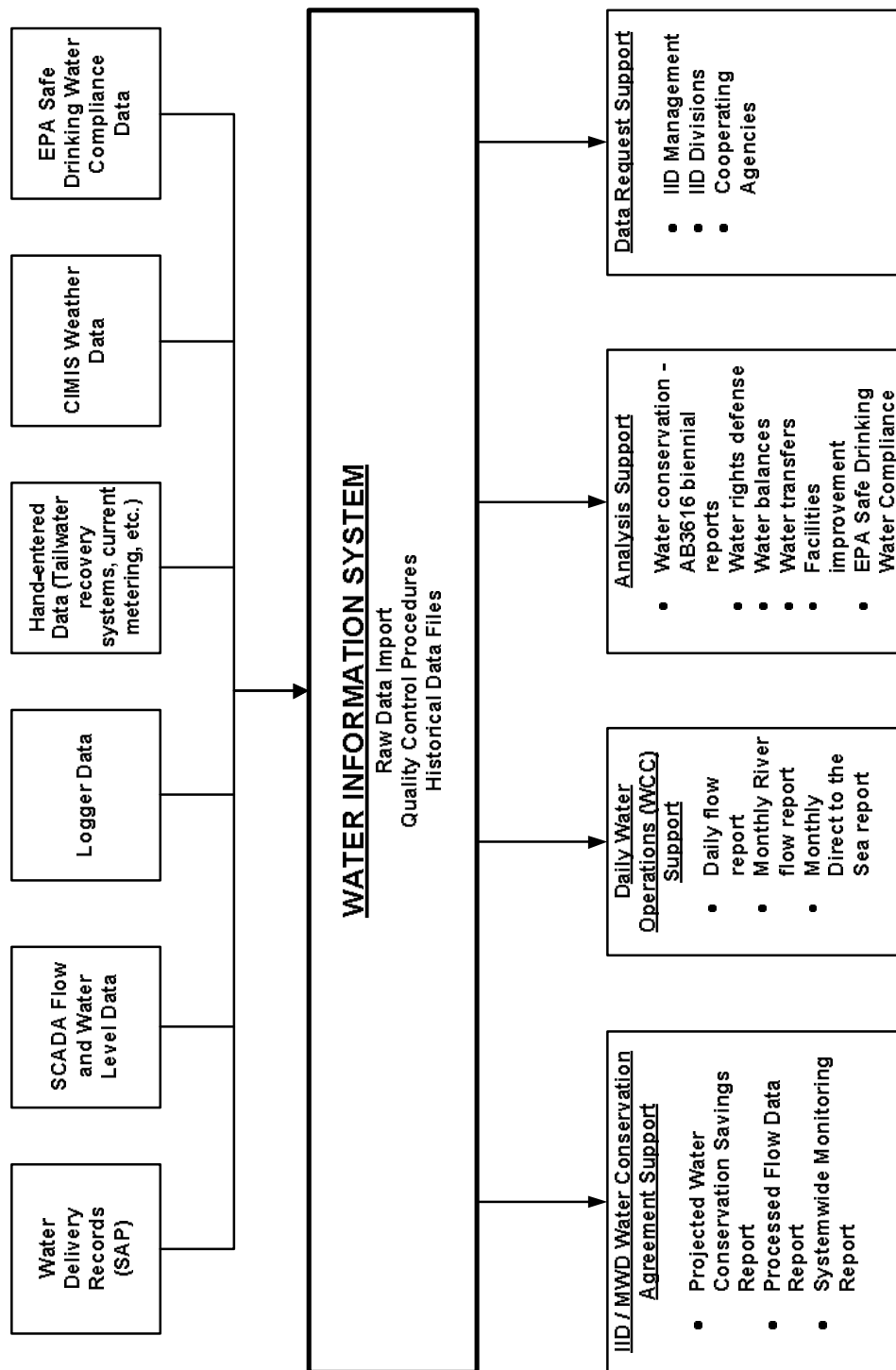
Figure 1. Schematic Diagram of IID's WIS

then manually enter it into spreadsheets. With the WIS, many of these reports are now prepared automatically, reducing IID's labor requirements and improving the timeliness, consistency and accuracy of reporting.

Water Operations historical flow and crop acreage data have been stored electronically in IID's business systems since 1986. Implementation of SAP (an enterprise-wide computer business process software package) in 2000, however, did not include these historical data. Hence, WIS applications have been developed to collect these data from SAP on a regular basis and add them to the pre-existing historical base of information, all residing on the WIS. The WIS and the quality-controlled SCADA data it stores are currently being integrated into a broader Water Management System that will incorporate water order entry and scheduling of main canal flows and customer delivery (Young, et. al, 2005).

Analysis Support: IID is constantly faced with the need to analyze its system operation and water use. Some of these analyses support historical analysis and planning efforts, while others respond to or support IID's efforts to comply with regulatory or quasi-regulatory requirements, such as those stemming from the federal Clean Water Act and the State Efficient Water Management Practices Act (AB3616). Furthermore, operations data are analyzed to support routine as well as strategic planning of facilities improvements and water conservation measures. The data analysis and reporting features of the WIS support all of these activities.

Four examples of operations analyses that have benefited greatly from the availability of quality controlled flow data in an easily accessible format are: 1) the Vail Canal operations decision-support system initial study and development (Thoreson, et al, 2003a), 2) the lower Westside Main Canal operations study, and 3) a system improvement study that is currently underway. Planning for system improvements in response to the 2003 Quantification Settlement Agreement, which includes water transfer to San Diego, is expected to be benefit greatly by this quality controlled data set.

Data Requests: The data available on the WIS allow IID to respond to both internal and external data requests in a timely manner with minimum interruption to IID staff regular duties. Importantly, identical data requests result in identical responses.

DATA QUALITY CONTROL

History and Basic Procedures

The IID SCADA system initially had three types of sites: 1) remote monitoring sites, 2) small canal sites and 3) major sites (Villalón and Korinetz, 1998). The remote monitoring sites provide level and flow information via telemetry and are not used for operations. The small canal sites provide level and flow information

via telemetry and local control. These sites are not monitored by operations personnel. The major sites enhance operation of the main canals by providing remote monitoring and control capabilities for operators in addition to level and flow data via telemetry.

Once the remote monitoring and small canal sites had been installed and commissioned, they continued to collect data. After some months of data collection during the first year of operation, text files of data from these sites were manually reviewed. The review showed significant gaps and anomalies in the data due to various system failures. The primary failures included: 1) radio communications outages, 2) computer downtime on the receiving end, 3) battery failure at the remote location and 4) sensor failure at the remote location.

These problems resulted in the development of a FORTRAN program that was run weekly to check the data as part of a weekly data review process. Due to the number of sites, this process generally took about one-half of a person-day. It was also found that, with weekly data review, a site could be inoperable for up to two weeks before a problem was discovered and a crew dispatched to repair it. Thus, data gaps of longer than a week could occur. The WIS was developed to handle the large amount of data that was being collected and apply quality control checks more frequently, thereby eliminating long data gaps and reducing staff time requirements.

The WIS was implemented in an Oracle database, and the FORTRAN program was reprogrammed as a PL/SQL procedure in the Oracle database. The SCADA system puts data in text files that are loaded into a table on the WIS early each morning. The PL/SQL procedure checks the data, moves them to a quality-controlled table and provides a report listing sites with more than five percent of the data missing or otherwise coded.

The daily programmatic quality control is followed by a monthly manual (human) review. Upon completion of the monthly review, the 15-minute data are used to calculate hourly and daily volumes in the WIS. Daily volumes include estimates for missing 15-minute values and, thus, provide a complete record for use in analyses and reporting.

Results

The WIS identifies days when more than 50 percent of the flow volume on that day was estimated. The FORTRAN program was used to quality control data from 1993 through 1995. The PL/SQL program was used beginning in 1996 and is simply a translation of the FORTRAN program. In other words, the same

quality control checks were completed based on the same criteria. Thus, the percent of total days with estimates can be tracked from 1993 through 2004 (Figure 2).
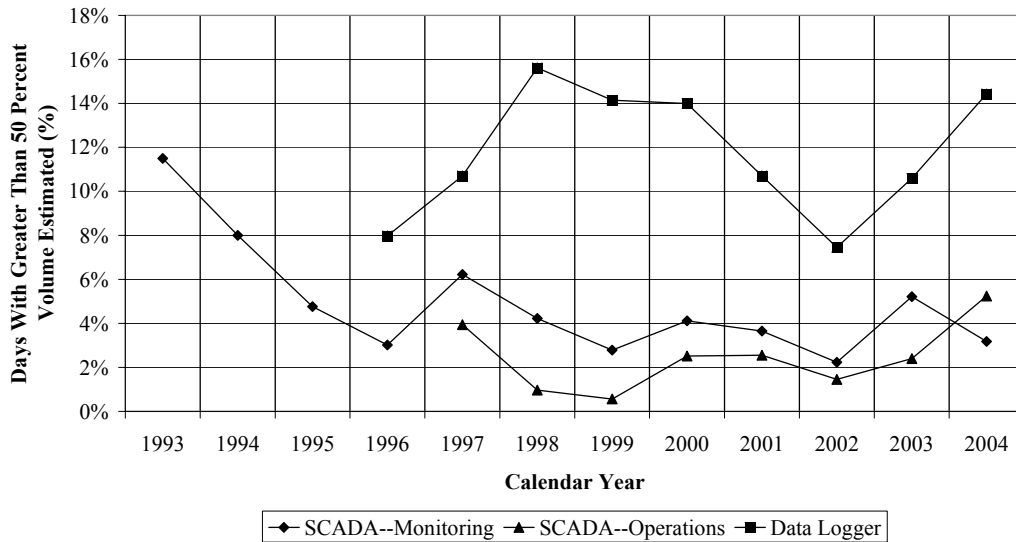
Figure 2. Percent Days with more than 50 Percent of Volume Estimated for Sites with SCADA Telemetry and Data Loggers.

For SCADA sites, the percent of total days with more than 50 percent of the flow estimated dropped steadily from nearly 12 percent in 1993 to about three percent in 1996, remaining between two and four percent except for 1997 and 2003. Operations sites were not initially included in the WIS because they were monitored by dispatchers (distribution system operators) and a technician was dispatched almost immediately to repair these sites as needed. Beginning in 1997, theses sites were included in the WIS and they will be part of the broader integration of order entry and scheduling in the Water Management System. Because of immediate attention to problems, the number of days with more than 50 percent of the volume estimated is less for the operations sites than for SCADA or data logger sites every year except for 2004.[5]

IID also has data loggers that are visited roughly once every two weeks when data are downloaded. These data have also been loaded into the WIS since 1996 and they are also coded when more than 50 percent of the flow on a given day has been estimated. Primarily due to the bi-weekly visits compared to daily review of the SCADA data, their record has varied from just under eight percent to almost

---

[5] In 2004, a single site classified as an operations site because the data are included in operations reports had a maintenance problem for much of the year. This site measures flow in the Alamo River coming into the IID service area from Mexico, which averages around one cfs and does not affect customer service. Thus it had a low priority for repair.

16 percent of the days having more than 50 percent of the flow volume estimated. Replacing data loggers with SCADA telemetry reduces the number of site visits and consequent labor cost and also improves data quality. These facts along with reduced WIS maintenance cost due the elimination of the data logger WIS applications culminated in a decision to eliminate data loggers in favor of SCADA equipment (Figure 3).
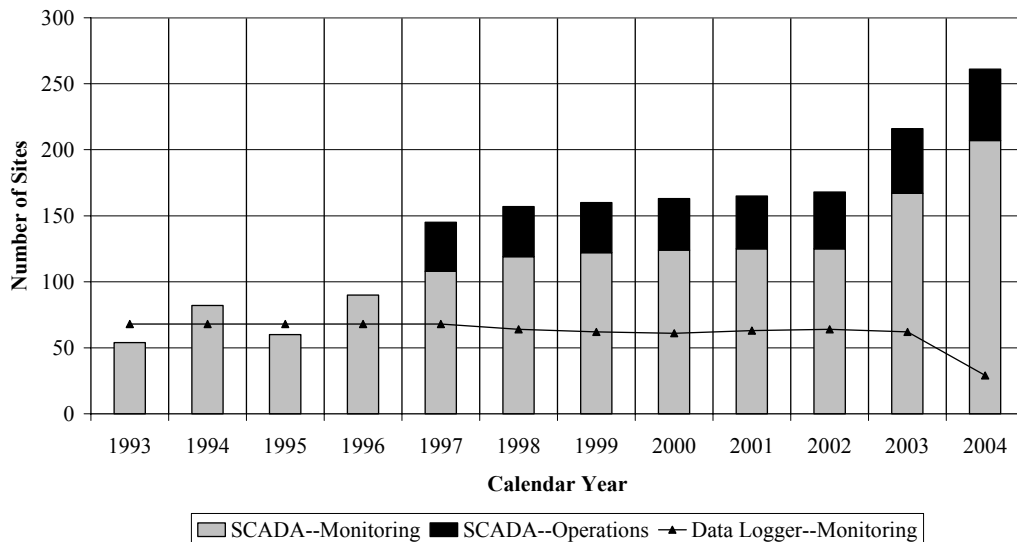
Figure 3. Annual changes in the number of SCADA Monitoring, SCADA operations and data logger monitoring sites on the WIS.

DATA QUALITY CONTROL IMPROVEMENTS

Over the last 10 years of quality control, including nine with the current PL/SQL procedure, the program has performed superbly. However, with time the need for some improvements were identified. These improvements include checking all data values prior to computation of flow, breaking the procedure into three procedures that run consecutively and correcting minor conceptual inconsistencies in the use of parameters to check reported levels and flows. In addition to these improvements, a fourth procedure was developed to consistently identify large changes in levels that occasionally occur for a duration of one or two 15-minute readings. These level changes are called "spikes" and previously were identified by reviewing graphs as part of monthly manual (human) quality control. In a typical month, between 50 and 100 spikes are identified. Although they have little effect on total flow volume, spikes raise concerns about data integrity and distract attention from more serious issues. It was decided to develop the logic to reduce human intervention in this task.

Spike Criteria Development

The WIS criterion for identifying a spike is: "The water level decreases or increases by greater than 0.2 feet from one record to the next, remaining greater than 0.2 feet different than the initial level for four records or less, and the record immediately following the last record at the new level is within 0.05 feet of the trend line of the original reading." A procedure was developed to mimic this by comparing each new level to a running average of preceding levels. When the new level differs from the running average by a prescribed amount, the new level is identified as a spike. Using existing records with human identified spikes, the number of records in the running average and the prescribed level difference were varied. Table 2 shows the results from this work for a moving average of five records. Similar tables were developed for other moving averages. The five-record moving average and a prescribed difference from the moving average of 0.2 ft. were selected as the best criteria for identifying most of the spikes while incorrectly identifying as spikes only a very small number of good records. A second set of existing records with human-identified spikes was used to validate the spike procedure.

Table 1. Development of spike criteria based on manually identified spikes.

Level Difference, feet	Correctly Identified as Spikes, %	Incorrectly Identified as Spikes, %
0	100%	100%
0.1	97%	64%
0.2	90%	2%
0.3	85%	0%
0.4	82%	0%
0.5	78%	0%
0.6	69%	0%

Using these criteria, the logic correctly identified 99 percent of the manually identified spikes and incorrectly identified only three percent of the good records as spikes in the validation data set.

Testing on the Entire Data Set

When testing the routine on the entire data set, it was noted that procedure was occasionally incorrectly identifying actual flow changes at the heads of canals as spikes. The change of flow at a canal heading often results in a large level change from one 15-minute record to the next. Since the data are quality-controlled in 24-hour blocks, it was possible to add a forward-looking moving average to the backward-looking moving average. This eliminated the misidentification of changes in flows at headings as spikes.

CONCLUSIONS

Monitoring and data reporting for system control and operations analyses are often cited as advantages of a SCADA system. Experience at the IID has shown that SCADA sites used solely for monitoring must be part of a rigorous quality control program, where data are reviewed, preferably daily, and transformed into information on a regular basis for the information to be accurate and, thus, useful. The existence of a large, quality-controlled data set has found many uses and enabled IID staff and others assisting them to increase their productivity.

REFERENCES

Archer, M.C., A. J. Divine and B. P. Thoreson. 1999. Irrigation Flow Data Collection, Quality Control, Flow Computation and Site Monitoring. ICID 17th Congress, Granada, Spain. Volume 1A, p.289-299.

Thoreson, B. P.; A. J. Divine and M. C. Archer. 1999. IID Water Information System – Irrigation Database Principles and Management. In *Contemporary Challenges for Irrigation and Drainage*, Proceedings from the USCID Water Management Seminar, Denver, CO. pp. 41-54.

Thoreson, B. P.; C. Villalón, M. Kidwell and K. Dimmitt. 2003a. Initial Development of a Decision Support System for Operating a Lateral Interceptor Reservoir System. In *Water for a Sustainable World – Limited Supplies and Expanding Demand*. Proceedings from the USCID Second International Conference on Irrigation and Drainage, Phoenix, AZ. pp. 313-322.

Thoreson, B. P.; P. Kosciusko, J. Burns, G. Davids, K. Dimmitt, J. Keller and M. King. 2003b. Water Conservation: Savings Determination in Near Real-Time. In *Water for a Sustainable World – Limited Supplies and Expanding Demand*. Proceedings from the USCID Second International Conference on Irrigation and Drainage, Phoenix, AZ. pp. 747-756.

Villalón, C. Z. and J. H. Korinetz. 1999. IID/MWD Water Conservation Program – Improved Irrigation Water Management Through System Automation. In *Contemporary Challenges for Irrigation and Drainage*, Proceedings from the USCID Water Management Seminar, Denver, CO. pp. 1-28.

Young, G., B. Thoreson, A Baro and C. Villalón. 2005. Development of a Water Management System to Improve Management and Scheduling of Water Orders in Imperial Irrigation District. *Water District Management and Governance.* Proceedings from the USCID Third International Conference on Irrigation and Drainage, San Diego, CA. pp. 253-261.

MODERATELY PRICED SCADA IMPLEMENTATION

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

ABSTRACT

In northeastern Colorado, and many other western states, mutual irrigation companies have functioned effectively in delivering raw water for agriculture since the late 1800's. Mutual irrigation companies are shareholder organizations that hold the decree or decrees and were mostly farmer financed initially and even to this day. As many of these canals are modernized, an appropriate technology for consideration is Supervisory Control and Data Acquisition System (SCADA) to provide either monitoring or both monitoring and control of canal operations from a centralized location. Data and information such as canal flows and reservoir storage data can also be easily posted to the canal company's web site for management and shareholder access.

SCADA systems were once perceived to be too costly for most mutual irrigation companies but the hardware and software is increasing in function, decreasing in cost, and becoming much more affordable for these private enterprise situations. The opportunity, the costs, and the benefits of SCADA for mutual irrigation companies are explored in this paper.

Several case studies are cited. In particular, the efforts of the New Cache La Poudre Irrigating Company are described to include SCADA implementation for both initial monitoring of flows and later to include remote manual gate actuation. SCADA implementation by Riverside Irrigation District is also described in which a satellite uplink is used to keep costs reasonable to the District.

BACKGROUND AND INTRODUCTION

SCADA is an acronym for Supervisory Control and Data Acquisition. SCADA has been with us a long time but mostly with industrial process control and monitoring circumstances that could afford the technology. Irrigation, for many years, was not an industry that warranted the steep hardware cost until some irrigation manufacturers began to develop a specialized type of SCADA from their own proprietary hardware and software. In the mid 1980's we began to see adapted SCADA systems that were specifically intended for irrigation projects that could afford it — golf irrigation, in particular. In landscape irrigation, we

---

[1] Chairman / Vice President, Aqua Engineering, Inc., 4803 Innovation Drive, Fort Collins, Colorado 80525. E-mail address: swsmith@aquaengr.com.

[2] Manager, New Cache La Poudre Irrigating Co., Lucerne, Colorado.

referred to these systems as "centralized irrigation control." These early control systems were further adapted to accommodate distributed sites such as school districts or municipal park departments. In 1986, the City of Pueblo became the first city in the country to implement centralized irrigation control for distributed park sites. During this period, specialized SCADA systems found a niche in irrigation and those systems, by a myriad of different proprietary names, have been with us for almost 25 years.

Where was agricultural irrigation to be found in this picture? There were a few irrigation central control systems to be found in agriculture, but comparatively few. Agriculture could generally not afford the rather steep cost of the SCADA systems of the past. During the early 1990's, the cost of implementing SCADA on a per site basis was in the range of $5,000 to $10,000 per site without gate actuation hardware. This cost was quite high in comparison to the cost of a classic chart recorder installation on a weir or flume, or for that matter, the cost of manual actuation of valves, headgates, and checks by the canal company's ditch rider.

The current cost of SCADA implementation has decreased in recent years to a price point where SCADA is affordable to mutual irrigation companies. Often smaller mutual irrigation companies do not have an office or a staff per se, but a SCADA central system can be located anywhere that is practical. SCADA can provide smaller companies a lot of cost effective features which result in significantly improved canal operations, improved deliveries to shareholders, and reduced liabilities.

SCADA CONCEPTS

Generic definitions are appropriate to help describe basic SCADA concepts. The "central system" is microcomputer based and interface software is used to communicate with remote sites. The software that provides an umbrella over everything is called a "human-machine interface" or HMI. The key hardware at remote sites is a "remote terminal unit" or RTU.

The HMI software can be proprietary and published by the manufacturer of the hardware or it can be more generic and published by software companies that write HMI programs that are compatible with the hardware of many manufacturers. Flexible and broadly compatible programs are known as Wonderware, Lookout, and Intellution, as examples.

Communication can be via wire line (hard wired), telephone, fiber optics, or radio. Radio for most canal operations is preferred although the canal easement does present the potential for easy fiber optic installation3. The SCADA industry

---

[3] The Dolores Project in Cortez, Colorado utilizes fiber optic communication.

has standardized largely on a communication protocol called "Modbus" which is quite flexible but also considered antiquated by many because it was developed for wire line applications and not the higher speeds possible with other approaches to communication such as radio.

Remote terminal units are essentially a small computer that can be programmed for the specific requirements at individual sites. The RTU is also the point at which sensors are connected. A site with only one requirement, *e.g.* monitoring the water surface elevation in a flume or weir, would have a water level sensor wired to it. The RTU then communicates to the central system or conversely, the central system can initiate a call to the RTU. The preferred communication is two-way communication. In other words, the central can call the RTU or the RTU can call the central. It is important to note that the RTU can be monitoring one or more sensors and perform logical operations and even create an exception report or alarm. If flows or water levels exceed a pre-set limit at a point in the canal system, an alarm can be raised or action can be taken in the form of gate or check adjustments. Alarms can appear at the central computer or even be transmitted to a cell phone or pager.

There are multiple levels at which SCADA can be implemented. Beginning with monitoring only, and then expanding the initial system to other sites and adding capability and features to sites is quite appropriate.

Four levels of SCADA implementation can be described by their respective function and utility to the canal company.

- ❑ Monitoring (only).
- ❑ Remote manual operations.
- ❑ Local control.
- ❑ Fully automated operations.

Each level results in increasing capability within the SCADA system, but each level costs more. The additional cost is largely at the remote sites, not at the central workstation. The central workstation becomes a fixed cost except for HMI upgrades and the inevitable computer hardware upgrades.

Figure 1 shows a simple SCADA monitoring site installed in a rated canal section historically used by the New Cache la Poudre Irrigating Company (NCLPIC) in Lucerne, Colorado. For many years, water surface elevations have been monitored at this location using a Steven's recorder and by manually reading the gauge twice per day by the ditch rider. With SCADA, data is transmitted by radio to the central computer on a frequent basis. At the central computer, the data is reported continuously on the HMI screen. NCLPIC is currently investigating full SCADA for improving canal operations and monitoring and reporting of the company's well augmentation plan.

Figure 1. An example of a rated canal section which is remotely monitored using a SCADA system. RTU equipment is 12-volt DC powered from a solar panel that maintains a charge on a battery. Communication with the site is via radio.

The HMI screen can be, and should be, unique to the user and the circumstance. Figure 2 shows an example of the HMI screen in use by district staff at the Dolores Project near Cortez, Colorado. This screen is simple and intuitive in nature. Radial gate (check structure) positions are depicted graphically, each in a somewhat lower position in the HMI screen, to indicate the canal itself. The operator may raise or lower gates, and therefore water surface elevations in canal pools, by using very small incremental gate movements. Interestingly, Delores Project staff can and do make changes in their own HMI software interface without assistance from an outside consultant or system integrator.

With simple monitoring using a SCADA system, sensors are installed that meet monitoring requirements such as water level sensors. Data is collected on the central system and can then be directly viewed by a system operator or plotted depending on needs and functional requirements.
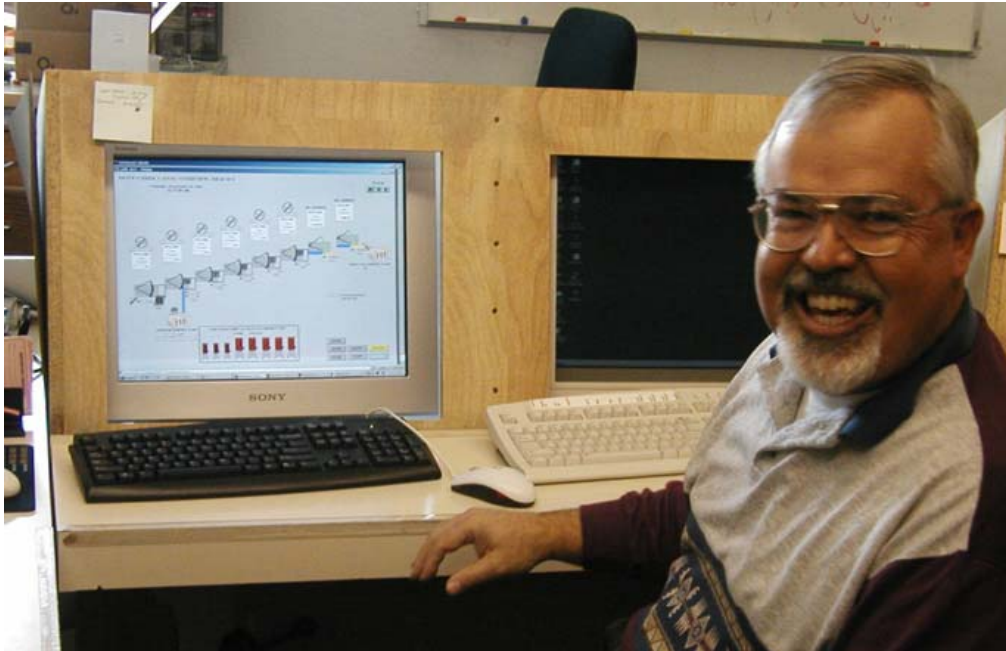
Figure 2. Chuck Lurvey, district engineer for the Dolores Project in Cortez, Colorado, is sitting in front of the SCADA central computer. Radial gate icons on the HMI screen indicate the water surface level in the canal and the gate positions of the radial gates at checks along the canal.

With remote manual operations, as the name implies, the operator can raise or lower gates and thereby effect the canal operation from the central computer. This is called remote manual because gate movements are implemented by the canal company staff, just as if they were at the gate or check. But gate adjustments can be made much more frequently and therefore canal operations, overall, can become more real time and precise.

With local control, the RTU at a particular site is programmed to maintain a set upstream water surface level or to open a gate if a water surface level increases beyond a set point as with a storm event.

Full canal automation is possible. This ultimate benefit of SCADA has been widely discussed for two decades but there are actually very few canals operated under what would be called full automation. One semantical note is important here. Some would refer to a canal as being automated, with any SCADA implementation, but what they often mean is that the canal is operated under a remote manual scenario using SCADA equipment. For the purposes of this paper, full canal automation means a system in which computer programs control processes from irrigation order inputs through algorithm-driven gate adjustment

schedules for some future timeframe. This level of automation is not an easily programmed or implemented process.

Figure 3 shows an actuated canal check structure which is integrated with SCADA.

CASE STUDIES

Central Arizona Irrigation and Drainage District

The Central Arizona Irrigation and Drainage District (CAIDD) has implemented SCADA over much of the district's 60 miles of canal. CAIDD has utilized SCADA for many years but it is noteworthy that they have in recent years upgraded their old SCADA system at a relatively low cost. With the upgrade, using the existing gates, actuators, and other infrastructure, the district staff installed new SCADA equipment on 108 sites for an equipment cost of approximately $150,000.

Figure 3. This check structure is controlled by Rubicon gates which are integrated with the SCADA system and used for water surface level control or flow control..

Most of the district's checks are operated in remote manual mode. See Figure 4 which shows the day operator at the central system where the upstream water surface elevation at all 108 check structures can be viewed simultaneous with three side-by-side computer monitors. Using SCADA, gate adjustments can be made in increments of $1/8^{th}$ inch which coincidentally equates to a change in flow of roughly one cubic foot per second through the check.

Figure 4. An operator at the Central Arizona Irrigation and Drainage District (CAIDD) near Phoenix monitors primary flows and water surface elevations in the 60-mile canal. This SCADA system was implemented at relatively low cost using affordable RTU equipment and spread spectrum radios for communication.

Additionally, a 15-mile lateral reach of the CAIDD sister district's (Maricopa Stanfield Irrigation and Drainage District or MSIDD) canal system is operated by Water Conservation Lab staff under full automation using a program that was developed by the Agricultural Research Service (USDA-ARS), Water Conservation Laboratory, in Phoenix, Arizona. SacMan, which stands for Software for Automated Canal Management, has been under development for approximately five years. SacMan runs in parallel with the HMI software and interface and is used to operate a key MSIDD canal in a fully automated mode.

A key approach to affordable SCADA for CAIDD was spread spectrum radios. These radios do not have a federal licensing requirement. The radios look for a clear frequency, use that frequency if it is unused, or proceed to another frequency if necessary. The line of sight range for a spread spectrum "loop antenna" is two miles and the line of sight range for a "directional antenna" is five miles. Of particular note, any one antenna can serve as a "repeater" radio to other radios. So, with a linear project like a canal system, communication can be achieved by using the radios in a daisy-chained fashion to increase the effective communication distance.

Figure 5 shows a spread spectrum radio and a directional antenna installed on a galvanized steel pipe at one of CAIDD's check structure sites.

Figure 5. The SCADA system at Central Arizona Irrigation and Drainage District (CAIDD) uses spread spectrum radio which is a relatively new type of radio system that does not require federal licensing. The spread spectrum radio is housed in the white enclosure and the directional antenna shown has a line-of-sight range of approximately 5 miles**.**

New Cache La Poudre Irrigating Co. (Greeley #2)

New Cache La Poudre Irrigating Company (NCLPIC) 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 decrees are in priority. In recent years, NCLPIC has also initiated a well augmentation plan for more than 100 member wells within the company's historic service area.

In 2003, the company commissioned an initial demonstration of SCADA (monitoring) with one of the key rated sections on the Greeley #2 system. This demonstration 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.

After considerable study, including tours of CAIDD, the Dolores Project near Cortez, 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 outlet gates. Rubicon gates were selected because of suitable flow measurement accuracy that is possible along with gate actuation. One existing radial gate was actuated with a Limitorque actuator. 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.

Because Rubicon gates were selected, the Rubicon TCC (Total Channel Control) HMI was evaluated and ultimately selected for implementation. The system currently consists of five Rubicon gates, one actuated radial gate, and monitoring of one rated section. A key 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.

Riverside Irrigation District

Riverside Irrigation District located in Fort Morgan, Colorado operates a canal that is more than 100 miles in length. The company delivers water to well recharge structures which must be monitored to meet the required reporting demands for flows and volumes associated with recharge. Automata RTU equipment, specifically the Automata Minisat, was used and linked to satellites. Data is accessed through an internet web page. Although there is an annual recurring cost for satellite communication, this approach allows a very low SCADA entry cost and minimal capital investment to meet the requirements of the site without having to travel to individual recharge sites for data collection. Currently six sites are in operation. Riverside Irrigation District has invested approximately $18,000 to date since early 2004 and expects to gradually expand the system as may be warranted and as can be afforded.

AFFORDABLE IMPLEMENTATION

Table 1 contrasts SCADA implementation costs at varying levels and compares those costs to collection of flow data using a Stevens recorder device, as might have been most common in the past. So, for example, if it were necessary to replace an existing Stevens recorder at a flume or weir at $2,450 (second column), the existing equipment might be replaced with an RTU using satellite communication at a cost of approximately $3,000 plus annual costs of $435 (third column). This incremental additional cost is likely quite palatable given the ease of data collection.

Additionally, assuming a central computer is already in place, the cost of real time assess to the additional site would be approximately $3,000 as well (fourth column). If the added features and sophistication of alarm condition reporting is desirable, then this cost increases to approximately $4,000 (fifth column).

SUMMARY

SCADA has become more affordable in recent years and is likely quite useful now to mutual irrigation companies for monitoring, remote manual operations, or even for full canal automation in the not so distant future. The technology has changed somewhat rapidly and can be expected to continue to change and become more flexible, more intuitive, and available at lower cost. This will encourage mutual irrigation companies to adapt to and adopt these technologies to the increasing demands of canal operations.

REFERENCES

Clemmens, A.J., R.J. Strand, and L. Feuer. 2003. Application of Canal Automation in Central Arizona. USCID Proceedings of the 2nd International Conference on Irrigation and Drainage, Phoenix, Arizona. 12 to 15 May.

Clemmens, A.J., R.J. Strand, L. Feuer, and B.T. Wahlin. 2002. Canal Automation System Demonstration at MSIDD. USCID Proceedings of the 2002 USCID/EWRI Conference, San Luis Obispo, California. 9 to 12 July.

Hansen, R.D., B. Berger, and A. Hilton. 2002. www-Based Monitoring and Control for Over-Stressed River Basins. USCID Proceedings of the 2002 USCID/EWRI Conference, San Luis Obispo, California. 9 to 12 July.

Oakes, A., and B. Rodgerson. 2003. Advanced SCADA Networks Optimize the Operation of Water Resource Management Systems. USCID Proceedings of the 2nd International Conference on Irrigation and Drainage, Phoenix, Arizona. 12 to 15 May.

Table 1. Cost Comparison for Various Means of Recording
Flow Data at a Measurement Structure

	Chart Recorder[4]	Log Data & Upload to Satellite[5]	Log Data & Upload to Local Central Computer[6]	Log Data, Upload to Local Central Computer, and Create Alarm Condition[7]
Equipment Cost, $	$2,200	$2,500	$2,500	$3,500
Installation Cost, $	250	$500	$500	$500
Total Installed Cost, $	$2,450	$3,000	$3,000	$4,000
Monthly Recurring Cost, $	$0	$435 per year ($36 per month)	$0	$0

---

[4] Presumed to be a Stevens Recorder type chart recorder device.
[5] Presumed to be an Automata Mini-Sat device with a satellite uplink and no central computer. Data is accessed via a web site.
[6] Presumed to be an existing SCADA implementation based on Automata equipment using spread spectrum radio communications.
[7] Presumed to be an existing SCADA backbone installation with Motorola M RTU with either spread spectrum or UHF licensed radio communications.

INCREASING PEAK POWER GENERATION USING SCADA AND AUTOMATION: A CASE STUDY OF THE KAWEAH RIVER POWER AUTHORITY

Randy S. Hopkins[1]
Charles M. Burt[2]
J. Paul Hendrix[3]

ABSTRACT

The Kaweah River Power Authority (KRPA) is a joint powers authority comprised of the Kaweah Delta Water Conservation District (KDWCD) and Tulare Irrigation District (TID) in Central California. The KRPA operates a 20 megawatt (MW) generator at Terminus Dam (Dam) on the Kaweah River. In 2002 with the assistance of the Irrigation Training and Research Center (ITRC) at California Polytechnic State University, San Luis Obispo, the KRPA developed a plan to generate and supply more power during the peak demand hours (12 p.m.–6 p.m.). This was accomplished through a change in power plant and river operations, along with the installation and use of SCADA and gate automation at key points along river and canal system. The SCADA system also provided water management benefits to Tulare Irrigation District (TID) and Kaweah Delta Water Conservation District (KDWCD).

INTRODUCTION

Prior to the project, the KDWCD, TID and other users on the river would attempt to manage their irrigation water behind the Dam in a manner that would optimize power generation while still serving their main purpose of delivering irrigation water to the area's growers. The KRPA has a long-term contract with Southern California Edison (SCE) to purchase the power generated at the Dam. The structure of the contract is such that during the late spring and summer (June through September) the price paid for power generated during the peak hours is at a premium. Also, in light of the recent energy problems in California, the California Energy Commission (CEC) had grant funding available for water districts and growers for projects that would reduce the peak power demands on the state's power grid.

[1] Project Engineer, Provost & Pritchard Engineering Group, Inc. (P&P), 286 W. Cromwell Ave., Fresno, CA 93711, rhopkins@ppeng.com
[2] Chairman, Irrigation Training and Research Center (ITRC), California Polytechnic State University (Cal Poly), San Luis Obispo, CA 93407, cburt@calpoly.edu
[3] General Manager, Tulare Irrigation District, P.O. Box 1920 Tulare, CA 93275, jph@tulareid.org

In 2002, the ITRC began working with the KRPA, TID, and KDWCD to try to develop a means to help increase the amount of peak power generated at the Dam – which the CEC accepted as an alternative project to one that would remove peak load consumption from the grid. The idea formed during those discussions was to vary deliveries from the Dam. During peak hours, higher releases would be made. During off-peak hours, lower releases would be made. Potentially, the flowrate could change 400 cubic feet per second (cfs) from peak hours to off-peak hours. Overall, the releases made at the Dam would deliver the volume of water ordered by downstream irrigators for the day. TID is the largest demand on the river, and has two reservoirs near the head of its system – located approximately 24 miles downstream of the Dam. These reservoirs would be used to re-regulate the deliveries to the growers at a constant rate. By doing this, TID's growers would not experience any undesired fluctuation in their water delivery.

One problem was that during the height of the irrigation season, the water demand from the Dam can exceed the capacity of the generator. When this occurs, the extra water is delivered through a bypass penstock in the Dam to the Kaweah River, and some potential power production is lost. To overcome this, TID can increase the water they receive from the Friant-Kern Canal (FKC) (which diverts water from the San Joaquin River) during times when the Kaweah and St. Johns River demands exceed the power plant capacity. On days when the plant does not anticipate bypassing deliveries around the power plant, then TID can take their Kaweah River water and maximize the generation operations.

KDWCD and TID had the basic transportation facilities (canals and diversions) in place needed for the project. However, the Districts needed to make changes in how they operated their systems. Neither KDWCD nor TID had a SCADA system or automation on any of the en route structures. The KRPA had only a local SCADA system at the power plant. Automation, with SCADA for monitoring, was essential to the project since the flow fluctuations made at the dam during the day may not arrive at the various diversion points until late at night when the number of operations staff is limited.

ITRC identified a number of sites that would need to be modified. Figure 1 below is a map of the Kaweah River system that shows where the projects are located. Beginning at the Dam, the flows would travel down the Kaweah River to McKay's Point. At McKay's Point, the flow downstream to the Lower Kaweah River would be controlled, and the flow fluctuations would be sent down the St. John's River. Once in the St. John's River, the fluctuations would travel to Rocky Ford where TID takes delivery of their Kaweah River water supply. At Rocky Ford, the fluctuations in flow would be delivered into TID's Main Intake Canal (MIC). However, along the way, there were other diversions from the river that needed to be modified and monitored so that they were not impacted by the changed operations.
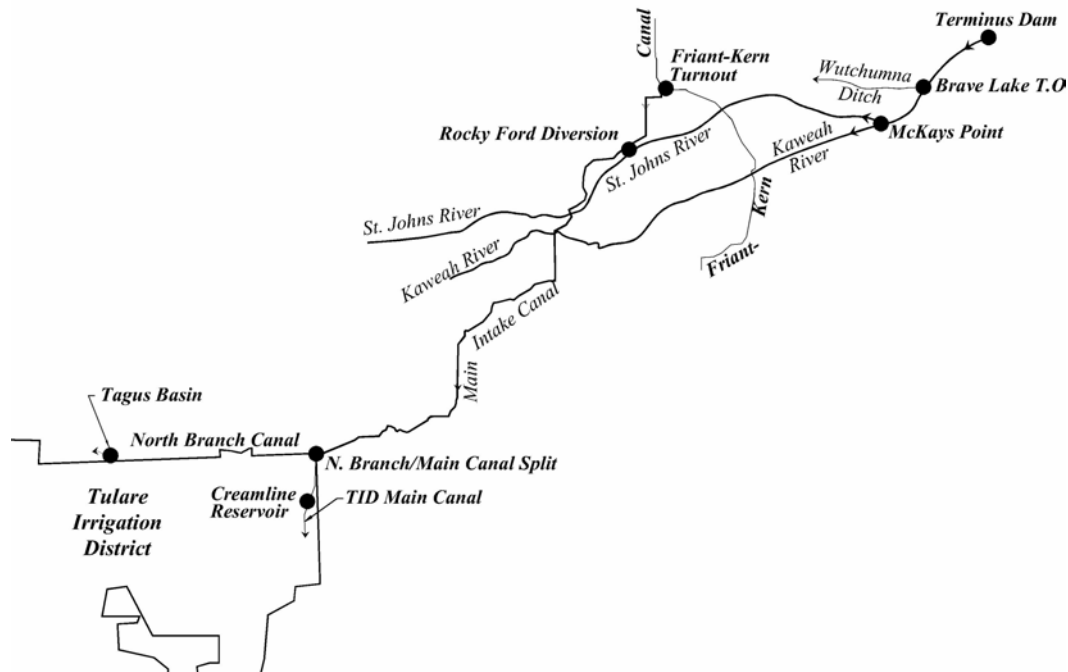
Figure 1. Map of the Kaweah River System and Locations of the Project's Components.

ITRC and KRPA approached the CEC for grant funding for the project. Their approach to securing the grant funding was that the project helped meet the state's goal of alleviating the stress on the power grid by providing more peak power, rather than reducing peak power consumption. The CEC concurred, and approved $512,000 in grant funds for approximately half of the estimated project costs to help the KRPA to implement the project. The grant was performance based; half of the grant would be paid when the project was built, and the other half would be paid upon successful demonstration that the project worked as designed.

DESIGN AND CONSTRUCTION

Overview

The automation of control structures and the use of SCADA to monitor performance and remotely change target flows and target depths (distributed control) allows the flow fluctuations to be routed to TID's diversion from the St. John's River and then on through TID's system to its regulating reservoirs. Gate automation for either upstream water level control or flow control is used at major control points and at diversions in the system to ensure that the flows to the other water users on the river are held constant, and to provide safe operation in the main route. Remote monitoring and control of TID's regulating basins and

other sources of water deliveries allow TID to verify the system is operating properly, and alert them to potential problems.

ITRC developed the design and specifications for the SCADA system and developed the control algorithms used at three of the control sites. Provost & Pritchard Engineering Group, Inc. (P&P) was hired by KRPA to help prepare construction documents for the Districts to build the project, to assist in soliciting bids from qualified integrators, and to coordinate the efforts of the agencies and integrator.

The specifications developed by ITRC mandated a number of things that are crucial to the success of any SCADA project.

1. <u>Open Architecture</u>. The integrator was required to submit full documentation of the software prior to installation. This gave the KRPA the ability to troubleshoot programming using either its own staff, or any integrator/programmer of their choosing.

2. <u>Editable Constants.</u> All of the constants used in any calculations had to be able to be changed through a screen in the Lookout® program at the human machine interface (HMI) in the offices. By requiring this, the KRPA and TID can easily change variables for initial calibration and future recalibration, without reviewing and editing the ladder logic.

3. <u>Redundant Sensors.</u> At all automation sites, two different types of sensors were used to collect the data for each variable needed for control. In the event that the primary sensor is found to be faulty, then the operators can change which sensor is used for computations at the site's remote terminal unit (RTU). The redundancy also applied to the analog to digital signal converters. Each sensor sends the 4-20 ma signal to its own analog-to-digital (A/D) converter which then sends the digital signal to the RTU.

4. <u>Training and Spare Parts.</u> The contract with the integrator specified that the KRPA, KDWCD, and TID staff be trained on how to use and troubleshoot the equipment. The contract also specified that a number of spare sensors and other equipment not readily available be provided for the project in the event that a component failed during the irrigation season.

The algorithms for water level control developed by ITRC were based on proportional-integral-filter (PIF) control logic. A proportional algorithm was used by ITRC for flow control.   Three sites were supplied with the algorithm: Wutchumna Ditch Turnout, North Branch Split, and Creamline Reservoir. The algorithm was modified slightly to fit the needs of each site. Control diagrams for each site were then provided to the integrator to incorporate into the sites'

programming. The integrator however, was responsible to develop the programming for the communications, HMI screens, and data collection.

The construction schedule for the project was fairly aggressive. The project was bid to integrators in October 2003. Concepts in Controls (CIC) of Visalia, CA was selected as the integrator for the project. After some redesign of the project facilities to reduce costs, preparation of license agreements with other agencies and landowners to install some of the SCADA equipment, and negotiations with the integrator, construction began in February 2004. The CEC grant deadline was July 2004. This gave approximately five months to order, install, program, and field test the system. Ultimately, the deadline was extended because of the tight schedule and the diligent prosecution of the work by the Districts' staff.

Terminus Dam

KRPA has at the power plant an existing SCADA system used to run the plant. KRPA did not want to incorporate the plant's SCADA system into this project, so a separate RTU was placed at the Dam that retrieved selected information from the plant's system. This information included the flow rate through the generator, water level behind the dam, and other ancillary data. The information was then radioed to each of the Districts offices. At the offices, the Districts could only view the data and had no ability to change the operations of the plant.

Badger Hill Repeater Station

Because some sites were located in the foothills and some on the valley floor, a repeater station needed to be built. The Badger Hill site was chosen because many other communications facilities existed at the top of the hill, and space could be leased inexpensively with very little improvements required to install the repeater. All of the data for the project was sent to the repeater, and was relayed to the two offices (KDWCD and TID).

Wutchumna Ditch Turnout

The diversion to Wutchumna Ditch is owned and operated by the Wutchumna Ditch Company (Wutchumna). This site is upstream of McKay's Point, so fluctuations in water level caused by the flow changes would affect the flow into the Wutchumna Ditch. To alleviate any problems that could be caused by the flow changes, the gates were automated to control the downstream water level in a rated section in the ditch. Wutchumna gave permission to the KRPA to install the SCADA system and electrically actuate and automate two of the three existing manually operated slide gates at the diversion.

ITRC developed an algorithm that stabilized the flow in the ditch within five minutes of a change in flow. Wutchumna's operators would be able to move the gates using the actuators to the position they desired, similar to their previous

operations. After the operators set the gate positions, the RTU would take over automation of the site and maintain the downstream water level. Since the actual flow would not be measured by the SCADA system, the gates would maintain downstream water level in the ditch, thereby maintaining the downstream flow, at least as well as the previous operations. A stilling well with level sensors was placed downstream of the diversion in the ditch.

McKay's Point

McKay's Point is the location where the St. John's and Kaweah Rivers split. At this location, two Langemann Gates, 24 feet wide, manufactured by Aqua Systems 2000, Inc. (AS2000) were installed. These gates were chosen for a number of reasons.

1. They come from the manufacturer as a package unit. The manufacturer supplies the gate position sensors, PLC, control programming, motors, solar power cells and batteries. Having solar power was also beneficial because the nearest power source was approximately one-quarter mile away.

2. They have the ability to collapse virtually out of the flow area of the structure. KDWCD found this feature to be a benefit during times when large flood releases and maximum capacity is needed.

3. The gates programming can be toggled to either control downstream flow, or upstream level. This ability gives the KDWCD the flexibility to change operations as they see necessary.

At this site, an AS2000 algorithm was used to control gates based on the flow desired in the Lower Kaweah River. This control regime then forced flow fluctuations and the large changes in flow due to peak power operations to flow down the St. John's River. To accomplish this, level sensors were placed upstream in the pool created by the diversion structures in the river, and in an existing stilling well positioned at a rated section on the Lower Kaweah River. These sensors provided the data used in the control algorithm. The gates were programmed to stabilize the downstream flow if a 100 cfs change in flow occurred, and do so within five minutes.

The KDWCD has historically operated this site, and was given control of the SCADA and gates for this site. TID was able to monitor the operations of the gates.

Rocky Ford

At Rocky Ford TID diverts water from the St. Johns River to their MIC. The MIC also brings water from TID's FKC turnout, upstream of Rocky Ford. The

MIC has a capacity of approximately 825 cfs. ITRC determined that a capacity of approximately 1,100 cfs would be needed to handle the increased flows during peak hours. As a result, choke points in the canal were modified to increase the capacity of the canal.

Two Langemann gates were also used at this site – one 11 feet wide, and the other 17 feet wide. The gates were chosen for the same reasons as at McKay's Point. At this site though, the gates would control the upstream level using an AS2000 algorithm. These gates kept the level constant over the diversion weir in the St. John's River so that flow changes could be captured by TID without impacting the downstream water users. As a safety feature, the gates can switch automatically into downstream flow control if the flow measured in the MIC downstream of Rocky Ford exceeds the 1,100 cfs capacity of the canal.

Two side-looking acoustic Doppler flow meters were used to measure the flow rate upstream and downstream of Rocky Ford. These flow meters were used because there was not enough head available to obtain an accurate flow measurement using a Replogle flume or similar flow measurement structure. The MIC is an earthen canal, so to provide a constant cross-section for the flow meters concrete lining was poured at each location. The flow meters were mounted to a shoe that slid on an I-beam mounted to the concrete lining. The design of the shoe and the slide allowed TID to remove the sensor from the canal when the canal was dry and place it back in the canal, in the same position, when the canal was in use.

Friant Kern Canal Turnout to TID

TID's turnout from the FKC needed to be monitored to ensure correct operations of the project. Since it is not uncommon for TID to take delivery of water from the FKC at the same time as they divert water from the St. Johns River, the potential existed to overtop their MIC when peak hour flow changes reached the canal. By monitoring the turnout, then KRPA and TID could determine how much water could be used for peak power generation without overtopping their canal.

North Branch Split

The North Branch Split is located in the northeast corner of TID, and is approximately 10 miles downstream of their Rocky Ford diversion. At this site, flows are split into the North Branch Canal and Main Canal. Each canal has a Parshall flume downstream of the bifurcation. TID had Stephens chart recorders in each stilling well to track the amount of water entering the District. These recorders were kept in place, but sensors were added to measure the level and flow through the Parshall flumes.

There are four existing sluice gates at the site – one hydraulically actuated, and the other three are manually operated. Two electric actuators were placed on two of the manually operated gates. Gate positions were monitored for all four gates. ITRC developed an algorithm to control the gates at this site, similar to the algorithm used at Wutchumna Ditch.

The design of the site was such that TID had the flexibility to direct the flow changes either down the North Branch Canal or down the Main Canal. Typically, the flow changes would be sent down the Main Canal to the Creamline Reservoir. However, using a toggle in the programming, the direction of the flow changes could be switched. The gates would be controlled based on the flow measured in the chosen canal.

Creamline Reservoir

Creamline Reservoir is an existing 56 acre reservoir with approximately 300 AF of storage capacity. The reservoir is divided into four cells with two on either side of the MIC. Lateral weirs and culverts connect the reservoir to the canal. The reservoir water level "floats" with the water level in the MIC upstream of the radial gate. A Littleman controller controls the radial gate movements to maintain a constant downstream flow in the MIC.

The new SCADA design updated the technology used at this site. An RTU was installed at the site to control the gate and replace the Littleman controller. ITRC developed an algorithm to control the gate based on downstream flow.

Based on information provided by TID, the existing maximum flow rate delivered to Creamline was 250 cfs, or 496 AF per day. Using the information, calculations were performed to determine if Creamline needed to be expanded. The calculations showed that if TID reduced the maximum delivery during the off-peak hours to 175 cfs at Creamline, then the full 300 cfs flow change could be absorbed at Creamline, and still meet the downstream user requirements. Figure 2 below illustrates the results of the calculations. For this project to work, Creamline would need to have at least 110 AF of storage available prior to peak flows arriving at the site.
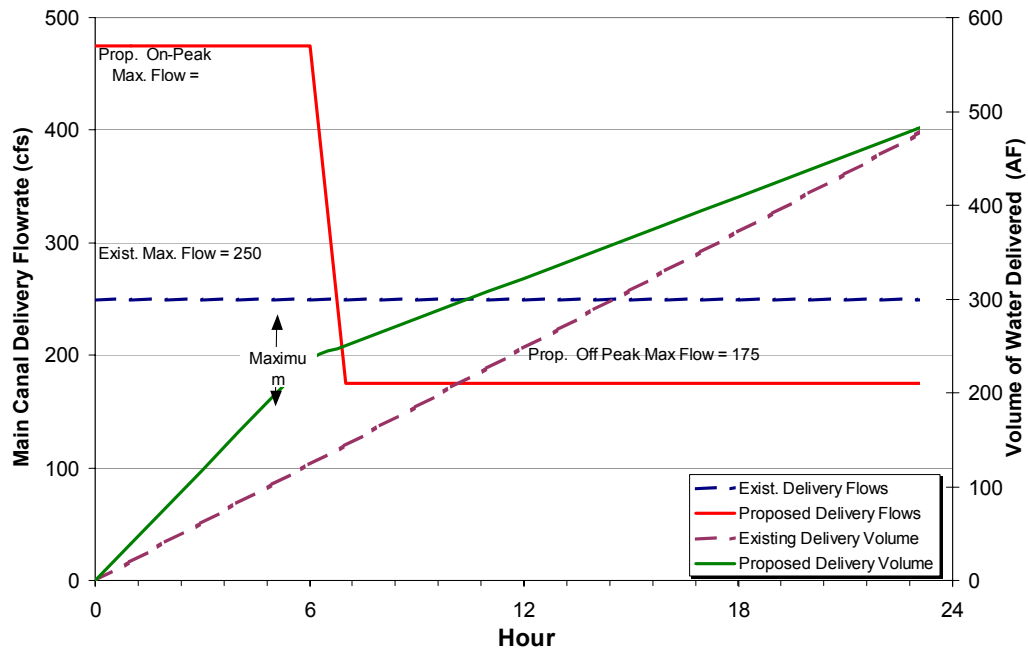
Figure 2. Proposed and Existing Operations at Creamline Reservoir.

Tagus Reservoir

In the event that Creamline Reservoir is not available to take the flow changes, TID could change the operations at the North Branch Split, and send the changes to the Tagus Reservoir. Because Tagus would be a back up in the system, the level in the reservoir was only monitored. The outlet gate was not automated.

District Offices

The HMIs for each office were designed virtually the same. The only notable difference was which office had control over which site. However, each office was able to view all of the information for each site. Each office purchased a new top-of-the-line computer dedicated to the SCADA project. Each office also purchased a laptop computer to take to the field in the event that a site's controls needed to be modified, or troubleshot.

PERFORMANCE

Upon substantial completion of construction, the various project elements were tested. ITRC was responsible to test the control algorithms, and to index and calibrate the acoustic flow meters at Rocky Ford. The flow meters were indexed using a method developed by the ITRC (Styles, et. al 2003).

Beginning in July 2004 CIC began to debug the system. After initial debugging, a 300 cfs flow change was made at the Dam to test the system. During the test, the gates generally moved as required. Some tuning was still needed though. The test identified some areas where the system needed adjustments and improvements. Over the next couple of weeks, the improvements to the HMI's were made, constants were adjusted and deadbands tightened.

In late July, tests were run again on the control sites to verify that the changes made worked. After reviewing the data from the second test, it appeared that the project was operating satisfactorily, although some minor adjustments were still needed.

CHALLENGES

The tight timeline posed serious challenges – especially scheduling contractors, getting manufacturers to produce equipment on time, debugging the systems, and obtaining access to a radio relay site. Nevertheless, through tight coordination, those challenges were overcome. The lesson learned is that it is essential to have a good project coordinator and full cooperation of the complete team.

A second challenge was to develop/implement the control algorithms and verify the degree of control that could be obtained. This project combined two very different approaches to selecting and tuning gate automation algorithms. AS2000 has a "resident" algorithm built into its package. AS2000 does not use hydraulic simulation modeling to develop and test algorithms and constants, but rather uses a heuristic approach. ITRC did provide some modeling results to AS2000 to provide an idea of the response times before the gates were installed – but the tuning requires actual field observations and adjustments. ITRC uses hydraulic simulations, combined with knowledge of gate dimensions, to develop and tune its algorithms so that they are capable of working in extreme conditions "out of the box" with minor tuning using field measurements. It should be noted that field verification is essential not only because of the algorithm tuning, but also because sensors may not be calibrated properly, there may be mistakes in programming, etc. Therefore, there is no true "out of the box" solution.

Three different entities – ITRC, CIC, and AS2000 were involved in various portions of control and the SCADA system. The HMI, developed by CIC, could not be implemented and tested until CIC received all of the register and tag number/names from ITRC and AS2000. This requires close coordination between the entities.

One of the challenges was to get everyone comfortable with various flow measurements. The districts had historical means of estimating flow rates. This project required some new flow measurement devices, and calibration of existing devices. In some cases, the SCADA-reported flow measurements did not agree

with the operators' estimation of actual flow rates, and the inclination of the operators is to just disconnect the automation because the numbers don't agree – even if the automation is working fine to maintain whatever target it is assigned. The lesson learned is that it takes several years of patient troubleshooting and talking to resolve problems and to ensure accuracy and confidence by the operators.

SUMMARY

KRPA is now able to generate more power during peak demand hours, which helps alleviate the stress on the power grid, and provides an opportunity for them to generate more revenue that ultimately helps reduce the cost of providing water to the KDWCD and TID landowners. Furthermore, TID and KDWCD both now have the backbone of SCADA systems installed in their offices. TID is beginning an aggressive program to expand automation and monitoring throughout the remainder of its system.

REFERENCES

Styles, S., M. Niblack, and B. Freeman. 2003. Canal Velocity Indexing at Colorado River Indian Tribes (CRIT) Irrigation Project in Parker, Arizona using the SonTek Argonaut SL. Presented at the 24th Annual Irrigation Association International Irrigation Technical Conference and Show. Tampa, Florida.

EASTERN IRRIGATION DISTRICT CANAL AUTOMATION AND SUPERVISORY CONTROL AND DATA ACQUISITION (SCADA)

Ron Hust[1], P.Eng.
Gerald Veldman[2], C.Tech.
Greg West[3], B.Sc.

ABSTRACT

The Eastern Irrigation District (EID), located in southern Alberta, Canada, is a farmer owned entity that delivers water to 300,000 acres (121,500 ha) of irrigation and encompasses a total area of 1.5 million acres (607,000 ha).

EID implemented automated level control on major water control structures in its system. The first controllers used were industrial-rated computers. The technology now employed has evolved with the industry and Programmable Logic Controllers (PLC) have replaced the computers for control functions.

The SCADA system was developed with Wonderware's Intouch graphical user interface. This interface is used to extract data from the PLC's and display it graphically as well as provide central trending and call out alarms. Operators can connect to the system via the Internet using a password protected remote control program, or call in using a touch-tone phone and retrieve the latest flow and level data.

The EID recognized the need to provide Internet access to the local area, and therefore started operating as an affordable Internet Service Provider (ISP) to district water users. Being an ISP allowed the EID to provide a unique communications backbone for their SCADA system. Recently the EID has teamed up with a wireless Internet provider (IP Plus Wireless Corp.). Existing control structures are in the process of being upgraded to take advantage of this infrastructure to allow secure, cost effective, collection of data and structure monitoring.

INTRODUCTION

The Eastern Irrigation District is one of thirteen Irrigation Districts operating in Alberta. The EID has the largest land base and the second largest irrigated area of these Irrigation Districts.

[1] President, MPE Engineering Ltd., Suite 300 714 5th Ave South, Lethbridge, AB T1J 0V1; rhust@mpe.ab.ca.
[2] Project Manager, MPE Engineering Ltd.; gveldman@mpe.ab.ca.
[3] Senior Systems Analyst/Programmer, MPE Engineering Ltd.; gwest@mpe.ab.ca.

The Canadian Pacific Railway Company (CPR) originally developed the Irrigation system in the early twentieth century. The land base was given to the CPR as part of the payment of land by the Dominion of Canada for building a railroad across the country. The CPR believed that irrigation would encourage settlers to the area and, in the process, give the CPR income from land sales and increased use of the railroad to ship crops.

Construction of the irrigation system began in 1910, with the first irrigation water flowing in 1914. The original concept of settlement and crop transportation was basically sound, but the railway company found that the cost of operating the irrigation system was prohibitive. In 1935 a delegation of irrigation farmers negotiated a deal with the CPR to take over control of the project. Thus began the present day structure of the Eastern Irrigation District.[4]

Presently there are 1.5 million acres (2,350 square miles) within the District's boundaries, making the EID larger than the State of Rhode Island. The Red Deer River forms the northeast boundary and the Bow River the southwest boundary of the District. The area within the EID includes 300,000 acres of irrigated cropland, 600,000 acres of prairie grasslands owned by the EID, with the remainder comprised of non-irrigated cropland, privately owned grasslands and three Provincial Parks (Kinbrook Island Provincial Park, Tillebrook Provincial Park and Dinosaur Provincial Park).

HISTORY OF AUTOMATION AND SCADA AT EID

The Eastern Irrigation District identified a need to improve the management of its water resources. Prior to the 1990's water control was performed by ditch riders operating gates and manipulating stop logs by hand. The ditch rider had to balance the ever-changing needs of the irrigators with the flows in the canal by continuously moving gates and stop logs as more or less water was needed. This system of operation tended to result in water being wasted as it was in the ditch rider's best interest to ensure that farmers did not run short of water. Finer control was needed to reduce water wastage and to assist the ditch rider in better managing the water resource.

In the early 1990's, the EID made the decision to implement an automated control system on their major canals. The objectives for automation at EID were as follows:

    1) Provide automatic upstream level control,
    2) Estimate canal flow at all head gates, check structures, turnouts and weirs,
    3) Provide remote access and control of the structures,

---

[4] Source: EID's web page at http://www.eid.ab.ca/about.htm.

4) Accumulate trend data for analyzing canal operations,
5) Provide alarm callout and logging for abnormal conditions.

In the initial stages EID automated 8 check structures that were presently controlled by electrically operated overshot and radial gates. The automation consisted of automatic upstream level control, flow calculations, and alarm call out. The ditch rider could enter an upstream level set point and the gates would adjust automatically to achieve the desired level. Each structure used either PI (proportional-integral) or PID (proportional-integral-derivative) control algorithms to maintain a constant upstream water level while minimizing the number of gate moves. For most canals the simpler PI controller is used. The PID is used for canals that need more predictive controllers to prevent canal level oscillations. Since radial and overshot gates move through an arc pattern, equations were developed to calculate correct gate height from the gate position transmitter.

With the upstream water level held constant by the automated check gates, consistent flow could then be diverted through the manually operated turnout sluice gates. When the ditch rider changed the turnout flow, the check gates would react to maintain the desired upstream water level.

Each of the control structures operated independently. The ditch rider could access each structure via telephone and a PC by using "pcAnywhere" remote access software. Each structure was fitted with an auto-dialer so that emergency conditions such as high flow, low or high level, equipment failure, or loss of power would be called out to the ditch rider. Depending on the severity of the situation, the ditch rider has the option of simply acknowledging and resetting the alarm, or going to the structure to further investigate the situation.

Due to the success and operator acceptance of the initial efforts at automation, more structures were added to the system.

Some control structures are located in remote areas of the District and do not have a readily available source of AC power. Recent advances in solar panel and motor/gearbox technologies have made available PLC's and gate motors that can operate on 12 or 24 volts DC. These advances offered EID the ability to automate remote structures without the expense of constructing power lines to isolated locations.

In the initial stages of development, the controllers were Industrial PC Computers, which could easily handle complicated flow and gate position calculations. Trending was performed on each of the local computers to aid in trouble shooting. Microsoft DOS was the primary operating system and the control programs were written in C++. Modicon PLC's were used as Input/Output (I/O) devices to transfer gate positions, reservoir levels, and limit switch signals, etc to the PC.

Water level was measured using ultrasonic probes and gate position was measured using variable resistors and a transducer. The water level transmitters and gate position indicators would send the PLC a 4-20 mA signal. From these signals, gate position, canal level, and flow rate were calculated.

Initially the ditch rider had to call each structure individually to retrieve the current status at that structure. To get the status of the entire canal, a call had to be made to every structure, which proved to be a time consuming activity. Also, since each structure had its own auto-dialer, if a call-out phone number changed the auto-dialer at each structure would have to be reprogrammed to reflect the new number. The net result of this architecture was that it was very difficult to view the operation of the entire system.

To aid in viewing the entire system a scheduled automatic call-in was programmed. Data was extracted from the structures and stored on the EID local area network. A custom written Java interface was used to display data on a map with other structure data and a time stamp was used to indicate the last update. A web browser was used to run the Java application and display the SCADA information. Trending data remained on each structure's computer so the ditch rider could still call into the computer to view the local history.

PRESENT AUTOMATION AND SCADA

Over the past few years, PLC's have increased in their ability to perform more complex computations, which means that PC-based control was no longer required. Modicon's Momentum PLC has proved to be a good fit for the EID. A Human Machine Interface (HMI) is used to allow the user local control of the system.

The variable resistors and transducers used for gate position measurements tended to be problematic and error prone. They were also difficult to recalibrate mid-season. As an alternative, optical Interbus encoders were adopted to give more reliable and accurate gate position measurements. The encoders are programmable so they are easier to recalibrate than with the earlier technology. The encoders also solved the problem of signal float common to the variable resistor/transmitter system.

A Modbus serial radio network is used to connect structures to the network. The radio network allows full time connection without requiring a dedicated telephone line. Repeaters are strategically placed throughout the District to allow connection to remote structures. The radios and repeaters are addressed to allow secure communication to the structures.

A data concentrator PLC is used to poll data from each remote site and to push changes back to the sites. This PLC is used to give fine control over the

communication to and from the sites. It can poll each site for a specified interval and, after either a successful communication or a time-out, move to the next site.

A SCADA system was developed for the EID using Wonderware's Intouch interface software. Intouch communicates directly with the data concentrator PLC's. Intouch is set up with access codes such that if a user is logged off, a limited set of screens can be viewed and control changes are not allowed. Once the user is logged on to the system then access is permitted to more screens and changes to the control system are possible. Alarms can be viewed and called out from a central location. After a period of inactivity the user will be logged off the system.

The SCADA system also keeps a trend of structure data, such as gate positions and water level. This information can be viewed locally or extracted for use in a spreadsheet or another database program. Trending is very useful for troubleshooting the control system and is also used for fine-tuning the control algorithm for each structure.

The SCADA system has two auto-dialers, a software auto-dialer and a backup hardware auto-dialer. The software auto-dialer gives the users the ability to both receive calls and to call in to the auto-dialer from any touchtone phone and receive the latest level and flow information. A time stamp is used to let the user know when the last update occurred. If the primary software auto-dialer fails, a backup (hardware) auto-dialer alerts the users of the potential problem.

Authorized users can connect to the system using a password protected freeware remote control program called Virtual Network Computing (VNC). VNC operates on an Ethernet network and requires a single port to be opened in an Internet firewall to allow access. Once connected, passwords are required to make control changes. pcAnywhere is also run on the same computer for administrative updates and monitoring. Should one remote control package fail, access can be accomplished with the other package.

Ethernet as a Communications Backbone

While serial Modbus communication is reliable, the high cost of repeater towers and the limited versatility of the Modbus networks led to investigation of Ethernet as a communications backbone.

In the Brooks, Alberta area there was no Internet Service Provider (ISP). EID took the opportunity to become an ISP to provide a much-needed service as well as to provide high speed Internet access for their office. As technology has progressed over the years EID has kept up in providing both high and low speed Internet to its customers. Having this technology in place has enabled EID to take

advantage of the latest communications advances in the PLC market, which includes Ethernet.

Ethernet is a fast communications protocol that is being widely adopted. Ethernet enables users to get past the limited bandwidth of serial communications and it also enables bidirectional communication. For example, in a typical Modbus network there is one master and multiple slaves. The master has to poll each slave and request information. Typically the speed of the equipment is limited to 9,600 baud or 19,200 baud and is restricted to serial I/O communication only. Ethernet has the ability to communicate at higher speeds.

Ethernet equipment is less expensive than high-speed networks of proprietary PLC suppliers. Ethernet is also more versatile as it supports bidirectional and multiple communication paths. Manufacturers like Modicon and Allen Bradley encapsulate their protocol into Ethernet packets and transmit it to other devices on the network. With an Ethernet "backbone," information from a variety of devices by a variety of manufacturers can be transmitted on the same infrastructure. Cameras (such as web cams) can also be connected directly to Ethernet. As newer, faster Ethernet technologies come out, the communication equipment can be upgraded without having to replace the PLC equipment. This gives the end user the ability to expand the system to take advantage of new technologies as they are developed.

The EID selected Modicon Momentum PLC's, as these units are capable of Ethernet communications. A continuous connection is made to the EID office using a full time dial-up link to the EID-owned ISP. A 3-Com 56K Lan Modem blends an Ethernet Hub, Server, Gateway, and modem all into one small, cost effective device. The device is able to call in over a landline and connect the local network to the Internet. Once connected, the PLC transmits data through an Internet socket (using Modicon's port 502) to a data concentrator located in the EID office. Security was built into the PLC program to force users to input an access code before changes are allowed. Without the access code, data can only be monitored.

Communications Security

When connecting any Ethernet device to the Internet, security becomes a concern. In a world of hackers, viruses, and worms, network systems everywhere have the potential of being a target. Various methods may be employed to secure the network, such as using PLC's "hidden" behind Network Address Translation (NAT) pushing data to a data concentrator.

NAT allows the PLC to be hidden from the outside world. The PLC uses its own internal address. Outside PLC's cannot get beyond the router to access the PLC. The data concentrator PLC needs to have a static address and a port opened in the

firewall to access the PLC. An internal password is needed to make changes that will be sent back to the remote PLC's.

Another secure method is to use a Virtual Private Network (VPN). A virtual private network can be set up between the host and remote systems. The VPN creates a secure encrypted data tunnel to each PLC. All the PLC's and other devices can then be on the same network. The central PC can access each of the PLC's directly and this information can then be displayed on a SCADA screen.

INTO THE FUTURE

Currently only one user at a time can connect to the SCADA software. Products like Microsoft's Terminal Services make it possible for multiple users to connect to the system at a given time.

At present, a PC is required for access. As technology progresses, PDA's will be able to directly access the network to give the user remote control and access.

Using high speed Ethernet gives the system the ability to install web cameras to assist in monitoring structures. Cameras can provide viewing, send alerts and save pictures during an alert condition.

SUMMARY

The Eastern Irrigation District began with automated control of single check structures on its major canal systems using PC's as controllers and PLC's as data concentrators. Initially each structure was a stand-alone facility that the ditch rider could access via telephone to retrieve structure information. Auto-dialers provided alarming in case of abnormal operations.

As technology evolved, the EID implemented a network system that employs Ethernet communications via both dedicated telephone lines and radio, and makes use of Internet connectivity to gather, store, and disseminate data. Security features ensure only authorized personnel have access to the structure and control functions.

As with any new technology it takes time for personnel to develop trust in a computer to perform functions and make changes to gates that have historically been made by the ditch riders every day. The staff at the EID were initially slow to embrace the changes that were being thrust upon them but they are now eager to have new structures added to the control system.

CASE STUDY ON DESIGN AND CONSTRUCTION OF A REGULATING RESERVOIR PUMPING STATION

Ram Dhan Khalsa[1]
Bob Norman[2]

ABSTRACT

The case study is on the recently constructed pumping station on the Government Highline Canal, Grand Valley Project, Grand Junction, Colorado. The pumping station is part of a canal modernization project that includes new canal check structures, local automation, and a SCADA system. The pumping station design and construction process involved four areas: pumps, hydraulic structures, power distribution, and automation. The pump aspect included determining the needed pumping capacity, operational sequencing, pump selection, specifying and purchasing pumps. Hydraulic facilities work included the design of the intake structure, isolation gate, trash rack/fish screen, pump control house, pump discharge piping, and canal delivery structure. Power distribution work included extension of 3 phase power service 1.5 miles, selection of variable frequency drives and soft starts compatible with the power distribution system, connection of power to the pump control house, development of pump control strategy, and implementation of that strategy in the automation system. This pumping station is not necessarily a model for other projects, but rather a documentation of this project's requirements and the lessons learned.

INTRODUCTION

Grand Valley Project, Government Highline Canal

The Government Highline Canal was constructed in the first part of the 20th century. Water is diverted from the Colorado River into the Highline Canal, which flows 55 miles and serves 24,000 irrigated acres in the Grand Valley Water Users' Association (GVWUA) project area. Most of the earth laterals were converted to pipe in the 1980's as part of the Colorado River Salinity Control Program. The resulting elimination of lateral tail-water increased the volatility of flows in the Highline Canal. A canal modernization study was initiated and included the U.S. Bureau of Reclamation (Reclamation), the Irrigation Training and Research Center (ITRC), and the GVWUA. The Study evaluated the

---
[1] Design Engineer, Western Colorado Area Office, Northern Division, United States Bureau of Reclamation, Grand Junction, Colorado 81506
ramdhan@uc.usbr.gov
[2] Planning Engineer, Western Colorado Area Office, Northern Division, United States Bureau of Reclamation, Grand Junction, Colorado 81506
rnorman@uc.usbr.gov

potential to reduce diversion from the Colorado River while and enhancing fish flows in the historical low-flow fall season. The study analyzed three years of daily canal delivery data using the Canal-CAD hydrodynamic computer model. From this study, a recommendation was made to incorporate a regulating reservoir and pump station at Highline Lake as part of the modernization package. The project was funded with non-federal endangered fish recovery money.

The Highline Canal has a major administrative spillway structure from the canal into Highline Lake. The lake is located six miles from the end of the canal, and is upstream of 6,000 acres of irrigated project land (the "West End"). The sole water supply for the lake is spill from the Highline Canal. When full, the lake has a surface area of 140 acres, and there is a 38-foot static lift to the canal's normal water surfaces. The Highline Canal upstream of the lake is operated with an upstream control logic, which passes any mismatch in supply or demand to the next downstream pool. Therefore, the plan was to have all flow mismatches accumulate at the Highline Lake spill. Any surplus water would be spilled and stored in Highline Lake and supply shortages would be supplemented by pumping from the lake..

PUMPS

Determining Needed Pumping Capacity

The spillway and pumping plant re-regulate the last six miles of the canal, which is now operated in downstream control mode. When supply exceeds demand, water is spilled into Highline Lake. Spilling water into the lake has been the historical operating method. By operating the canal with a smaller spill margin, there are times when demand temporally exceeds the available supply in the canal and water is pumped from Highline Lake to makeup the shortfall. The ITRC modeled the pumping requirements using historical daily demands with an added level of random errors to determine the maximum required pumping capacity. They determined that 75 cubic feet per second (cfs) would be sufficient to meet the largest historical daily demand change. The canal design flow at the start of the West End (the last 6 miles of the canal) is 160 cfs. The dynamic nature of flow in canals and the changing water demands can create shortages and spills in a variety of flows and durations. The pumping station responds incrementally to these supply shortages.

Operational Sequencing

To match the variability and unpredictability in canal flow shortages, a flexible pumping response is required. Three pumps were chosen to achieve the desired flexibility. The lead pump (Pump One) was slightly larger pumping capacity than the other two pumps and is driven by a motor coupled to a variable frequency

drive (VFD). Pump Two is one of the smaller capacity pumps and also has a motor with a VFD. Pump Three is a fixed speed pump with motor and soft-start.

The operational strategy developed by the ITRC was that the large pump is the first pump to start and the last pump stop in responding to a canal flow shortage. The minimum flow for the VFD pumps is 4 cfs and the maximum flow for the large pump is 29 cfs, with a maximum flow for the smaller pumps of 25 cfs each. The first pump operates in the flow range of 4-29 cfs. Although it is possible to operate the pumps below 4 cfs, due to prevalent manufacturers recommendations and operational need, a 4 cfs minimum was selected. Pumps one and two operate in the flow range of 29-54 cfs, and pump three is used in the rare situation of a flow shortages above 54 cfs, or as a spare pump in case of a pump failure. The important concept in this arrangement is that the large pump overlaps the maximum flow rate of the smaller pumps, so that there is no flow jump in changing from one pump, to two pumps, to three pumps. In other words, a flow rate of 29 cfs can be accommodated by pump one operating at full speed, or pump one operating at 4 cfs and pump two operating at 25 cfs without any discontinuity in flow.

Another operating strategy considered, but abandoned, was putting a VFD on a small pump and ramping it up and down while switching larger pumps on and off incrementally as the flow demand increases. This strategy requires a lot of pump sequencing and did not seem to offer the greatest flexibility and redundancy.

Pump Selection

Pump selection started by calculating the Total Dynamic Head (TDH) using the flow range for each pump. The static head is 38 feet and the dynamic head at maximum flow rate is calculated at 7 feet, for a TDH of 45 feet. This results in a flat system curve where over 80 percent of the TDH is from static head.

Based upon the assumption that slower turning motors and pumps would last longer, and that single stage pumps would be more simple and less expensive to maintain, only single stage pumps designed for 900 RPM or less were considered. Searching the single stage vertical turbine pump curves with a TDH of 45 feet at 29 cfs yields a group of pumps with a bowl diameter of 26-30 inches and a motor speed of 900 rpm.

Generally on VFD applications with a flat system curve, the full speed operating point is to the right of the pump's Best Efficiency Point (BEP) on the curve and as the pump rpm decreases, the operating point moves through the BEP. The next requirement is that the pump curve has a moderate slope and no inflection over the intended operating range. Figure one shows the selected pump curve for various pump speeds and the system curve. Not that at full speed, the system curve is to the right of the BEP. As the pump slows down, efficiency actually

increases for an operational range before efficiency starts to decrease. This was done because due to the staging of the pumps it is more likely that the pumps will be operating at less than full speed more often than they will operate at peak output.
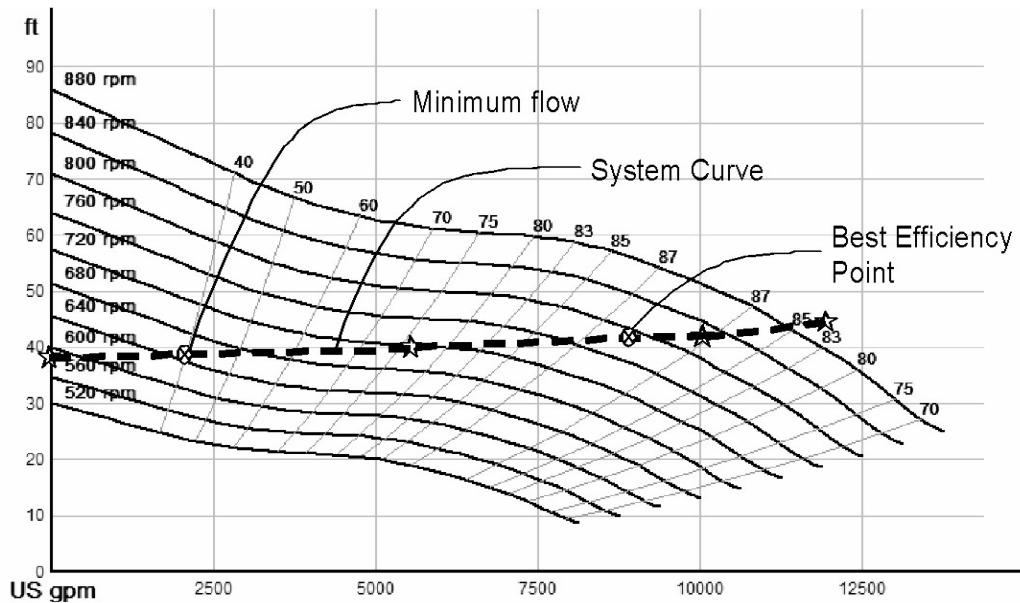

Figure 1. Selected pump curve with system curve.

Again, in the interest of simplifying maintenance, three identical pumps were selected. To achieve a higher flow, Pump One has a full size impeller and requires a 200 hp motor which will be driven by a VFD. Pumps Two and Three have trimmed (reduced diameter) impellers and require 150 hp motors. Pump Two has a VFD and Pump Three has a soft-start.

The engineering departments of the pump manufacturers having pumps with promising pump curves were contacted to ask for help in determining if the pump is well suited for the intended application and what other recommendation they have to offer. Once it was determined that a particular pump was a good fit, the next step was to ask for a recommendation of a supplier who is focused on the installation and maintenance of the type of pump being considered.

Specifying and Purchasing Pumps

The pump suppliers, who were recommended by the pump manufactures, were helpful in finding a solution to the pumping application. Established suppliers should have the field experience to achieve a good installation. The suppliers prepared a factory pump specification for selecting their pump. Factory specifications include features that tend to exclude the competitors' pumps. Comparing factory specifications between reputable pump competitors, was

helpful in distilling a more generic specification that was specific about the needed pump features for the project, but open enough to encourage competition among pump suppliers with pumps of acceptable quality. Included in the specifications were requirements for installation and start-up to be preformed by the supplier. The bids were ranked by their conformance to the specifications. Unacceptable bids were eliminated. Two things that were helpful in the bid processes were: there was a select list of bidders with known capabilities, and the low bid was not automatically awarded the contract.

Even with the above criteria, there were some interesting lessons in the processes. The low bidder (a friend of a friend who should not have been invited to bid) was 20 percent below the other proposals. They ignored the details in the specifications, sent in some cut-sheets, and stated that they met the specification (prove that we did not). They wanted to protest that they were not selected as the low bidder when their bid was eliminated. The high bidder (a local supplier) did not like the specifications and felt that they could deliver a better product if they were sole sourced as the pump supplier for the project. A very competitive and competent bidder wanted to redesign the large pump using a 34 inch bowl and slower turning motor (the pump structure would not accommodate this pump). The bid processes prevailed and good pumps were purchased from a good supplier.

HYDRAULIC FACILITIES

Intake structure

The principles of redundancy and simplicity guided the design of this pump station. The pumps share a common structure, but have individual pump bays. The intake structure is a monolithic reinforced concrete structure. The design is based on guidelines from the Hydraulic Institute and the book *Pump Station Design*. The design incorporates three parallel pump bays with the dimensions that are a function of the pump's bell diameter. The structure was designed around a 30 inch diameter pump bell. Ultimately a 26 inch pump was selected for the project. The structure design and the start of construction preceded the final pump selection, without determining whether or not over-sizing the structure by 15 percent is going to be a problem. Had the pump selection been made before the structure was designed, the structure would have been smaller.

The deck of the structure is designed to be 2 feet above the spillway elevation of the dam. Highline Lake was under a 5 foot water surface restriction in the 1990's due to excessive seepage through the dam. The leak has been repaired and the restriction removed. To protect the operation from similar limitations in the future, the pumping structure is designed with additional 5 feet of submergence over the pumps.

A construction contractor was selected based on their excellent performance on a previous bid for canal check structures, and the pumping structure was built on a cost plus basis. The greatest unknown in constructing the pump structure was the condition of the foundation material. The structure is located on a finger of the lake, normal to the centerline of the canal spillway. The plunge pool for the spill has been under water since the lake was constructed. The underlying material is shale with occasional gypsum lenses. This material decomposes rapidly when exposed to air and water and, is not a good foundation. Consequently, the sub-base for the foundation was over-excavated and back-filled with 177 yards of concrete before the structural foundation was formed on top of the concrete back-fill. The plunge pool for the canal spill now has a 5-foot thick concrete floor.

Isolation gate and trash rack/fish screen

Highline Lake is stocked with non-native sport fish for recreational fishing. These fish are predators of the native endangered fish that are being re-established in the Colorado River. To prevent fish escapement from the lake, into the canal, and possibly into the Colorado River, two 8-foot wide combination trash rake/ fish screens were installed in front of the pump fore-bays. The ¼-inch slotted screens serve as the pump intake screen and a fish barrier. A Langemann gate is installed in front of the fish screens to isolate the pump structure from the lake and prevent debris from canal spill from accumulating in front of the screen during non-pumping periods. An unanticipated problem was the high silt load that accompanies the spring runoff that is spilled into the lake in front of the pumping structure. Silt migrates into the structure despite the fact that the pumps are not operated and the isolation gate is closed. A periodic silt flushing routine is incorporated into the pump operations.

Pump Control House

The control house contains the electrical equipment that powers the pump station. The requirements for the control house are that it shields the electrical equipment from the environment and vandalism. The control house also includes two air conditioners to control the temperature inside the building. The power distribution requirements are: 480 volt 3 phase power for the pumps; 480 volt 3 phase power for the two power trash rakes; 240 volt single phase power for the two air conditioners; and 120 volt power to run the Langemann gate and the building lights. An additional requirement is to locate the VFDs reasonably close to the pumps to prevent harmonics from developing in the power cables between the pumps and the VFDs. The control house is located 5 feet above the pump-deck over the pump discharge piping. The house has a cast-in-place concrete deck supported by a steel frame. The walls of the house are constructed split-face masonry blocks. The roof is cast-in-place light concrete decking. The building is made of steel and concrete and is essentially fireproof.

Pump Piping and Canal Structure

Each pump has an individual pipeline, check valve and dissipater that discharge water into the canal. The size of the pump column and discharge head is 24-inch diameter pipe. To isolate the pump from the pipeline there is a rubber coupling and short spool connect the pump discharge head to a 24-inch check valve. The check valve is a massive spring loaded 45-degree swing-gate type valve. The valve can be serviced through a top port, without removing the valve body from the pipeline. The valve is anchored to the pump structure deck and serves as a thrust block as well as checking the 1,100 cubic feet of water in each pipeline between the pump station and the canal. Each of the three conveyance pipes are 300 feet of 27 inch, SDR-51 Plastic Irrigation Pipe, with fabricated steel elbows. The canal discharge structure is a three-compartment box, one for each pump, which dissipates the velocity head before spilling water into the canal. There are drain valves on both ends of the check valves, and there are no isolation valves required to service either the pumps or the check valves.

Using three conveyance pipelines, rather than one that requires for a manifold with a single pipeline, allows each pump to have an individual system curve. It would be very difficult to manage two VFD pumps and a fixed speed pump in parallel with high efficiency in a single pipeline conveyance.

ELECTRICAL POWER

Power Utility

The electrical utility company is a relativity small power company serving the rural areas of the Grand Valley. The closest three-phase power was a mile and a half from the pump station. The utility company was contracted to extend the three-phase power lines to the pump station and supply a 750 KVA transformer and service. The electric utility requirements were that the pump motors be "soft-started" at no more than 65 percent reduced voltage, and that any harmonics back-feed from the VFDs into their distribution system meet IEEE 519 section 1.06 standards. The reduced voltage pump start is necessary, because of power distribution limitations.

At this point in the program an electrical engineering consultant with an extensive background in power and VFDs was hired. The consultant task was to analyze the installation, write VFD specifications, prepare a bidders list, analyze the bid proposals, and make recommendations. To confirm performance of the VFD's and establish a baseline, the consultant will measure the harmonic levels feed-back to the distribution lines.

Selection of Variable Frequency Drives

The process of specifying the VFD, the electrical consultant marries the pump motor to the utility service. The pump motors were specified for VFD service at 5,000 feet elevation. The utility service was evaluated by calculating the three phase symmetrical fault current, which is 12,000 amps, with an x/r = 1.15 (inductance/resistance). These calculations were provided by the power utility company and were included in the VFD specifications. The electrical consultant found that the power distribution system has a high impedance source, which is referred to as "soft power". Therefore, the VFD has to run the pumps, operate on "soft power" provided on the tail-end of a rural service line, and create a limited amount of harmonic feed-back to the service lines.

To provide some redundancy, two 200 hp VFDs were purchased. One will be on the 200 hp pump and the other will be on the 150 hp pump. Even though purchasing a 200 hp VFD for the 150 hp pump was more expensive, it was possible to purchase one spare parts package for both VFDs, thus overall this was a reduction in costs. A VFD on each pump is expensive and considered over-kill. Based on the field conditions, the consultant's recommendation was an 18 pulse VFD. The specification was loosened up to include 6 pulse VFD with a front end filter to control the feed-back harmonics. A 200 hp VFD can drive a 150 hp motor, but the front end filters must match the horsepower rating of the motors. The supplier with the 18 pulse drive had the best proposal, but 8 weeks after being notified as the selected bidder they had not ordered the VFDs and would not be able to meet the delivery schedule. The second best proposal, a 6 pulse drive was given the contract. Even hiring a professional does not guarantee the process will go smoothly.

Compatibility

To assure system electrical compatibility it may be necessary to evaluate the power supply system, the supply transformer, the VFD, the harmonic filters and the pump motor. The need for this type of analysis increases as the pumping horsepower increases.

CONTROL STRATEGY

Pump Control Strategy

The pump control algorithm Proportional Integral Filtered (PIF) that the ITRC uses for canal gate control was used to control the pumps. The pump station control PIF constants were tuned as part of the Highline Canal Canal-CAD model by the ITRC. The strategy for control is a bit complicated, because it was decided to use the adjacent canal pool storage to minimize the number of pump starts. There are canal turnouts on the adjacent pool, and because the downstream check

structure is automated for downstream control, minimal variations in the pool water surface elevation are required to prevent water delivery service problems. The pumps are activated when the canal water surface drops one foot below the spill elevation. The pumps then attempt to maintain the water at that level. An operating rule to keep it simple is that only one VFD speed is changed per time step.

CONCLUSIONS

An appropriate conclusion might be a list of lessons learned:
- You do not know everything about everything; ask for help. If you really don't know what you know, hire an expert.
- Keep it simple and make it redundant.
- Put the VFD on the large pump and insure there is sufficient overlap between pumps.
- The pump-curve needs some slope when the system curve is flat.
- Get help from the pump manufacturers in putting the pump specification together.
- Select the pump size before completing the pump structure design.
- Silt Happens!
- Each pump has a separate isolated discharge pipeline if possible.
- The electrical power considerations include both the supply and the demand.
- The VFD is not the entire solution.
- Control strategy is everything; think hardware last.

REFERENCES

(1), Engineered Software, Inc., Goulds Pump Selection, copyright 1996-2002 by Engineered Software, Inc.

(2), Robert L. Sanks, Pump Station Design, Second Edition, copyright 1998 by Butterworth and Heinemann

(3), ANSI/HI 2000 Pump Standards, copyright 2000 by Hydraulic Institute

SAVING WATER WITH TOTAL CHANNEL CONTROL®
IN THE MACALISTER IRRIGATION DISTRICT, AUSTRALIA

Paul Byrnes[1]
Tony Oakes[2]

ABSTRACT

Southern Rural Water is undertaking a major automation project on the Main
Northern Channel System in the Macalister Irrigation District, Victoria, Australia.
The objectives of the project are to save water by reducing operational losses and
to significantly improve customer service. The Victorian State Government is
funding the project in exchange for the water savings, which they will use to
increase environmental flows in the Macalister River. This paper predominantly
looks at the water saving aspect of the project, and focuses on one spur channel,
which has the most detailed measurement.

Commencing in 2004, the first stage of the two-year project involved a trial of the
automation technology (Total Channel Control®) and establishment of a water
measurement network at a sub-system level. A water balance study supported the
business case to progress to Stage 2 and provides a benchmark to verify the
savings achieved by the project.

The study's water accounting framework identifies the main components of the
water balance. The study provides an opportunity to improve the understanding
on how channel losses can vary both spatially and throughout the irrigation
season.

INTRODUCTION

The introduction of Total Channel Control® (TCC®) has revolutionised the
operation of the Main Northern Channel system. Prior to this project the channel
operation was typical of most earthen channel systems, with one main regulation
per day on the main channel and its offtakes to spur channels. A combination of
its slow responsiveness, poor measurement facilities, basic control functionality
and focus on maintaining customer service levels led to a conservative manual
operation regime, that in turn resulted in significant outfall losses. TCC® has
broken the historic service-efficiency dichotomy; that held the view that it is only
possible to improve operational efficiency by reducing customer service.

---

[1] Manager Distribution Assets, Southern Rural Water, 1 Tower Road, Werribee,
3030 – Telephone 61 3 9974 4717 Email paulb@srw.com.au
[2] Director, Rubicon Systems Australia Pty Ltd, PO Box 114, Camberwell, 3124,
Australia – Telephone 61 3 9882 3433 Email Anthony.Oakes@rubicon.com.au

BACKGROUND

Macalister Irrigation District

The Macalister Irrigation District (37.6^0 South and 148.6^0 East) is located in Gippsland, 175 kilometres southeast of Melbourne (**Figure 1**) and is the largest irrigation district that Southern Rural Water (SRW) manages. Its main source of water is the 190,000 ML Glenmaggie Dam located on the Macalister River. The District spans three river catchments and has significant groundwater resources (typical use 24,000 ML/year) and rainfall (595 mm/year). Within the District approximately 33,500 Hectares are irrigated predominantly (90%) for pasture, which supports the main business enterprise of dairy. Other enterprises include beef and vegetable production.
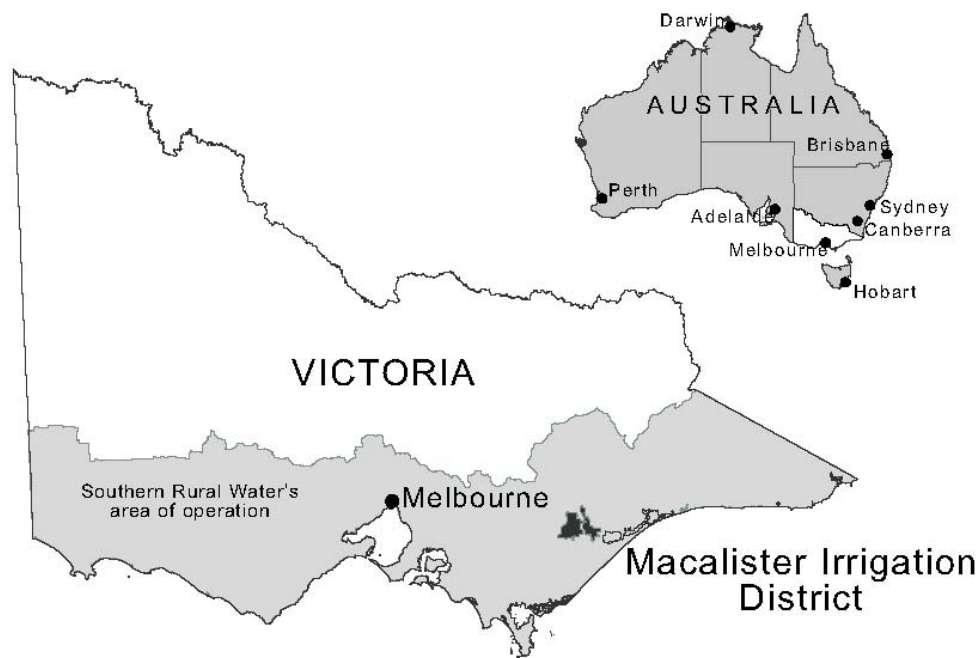
Figure 1. Locality Map.

Total Channel Control[®]

TCC[®] is an integrated system of advanced communications, modelling and control software. The FlumeGate[®], a uniquely designed overshot gate, which is the subject of several patent applications, is a key component of the TCC[®]. The gate has been designed for mass production, ease of installation and support, high duty cycle, long life and incorporates a proprietary system of flow measurement**.** This measurement system provides high accuracies in both free and submerged

flow conditions and independent testing by the Manly Hydraulics laboratory has demonstrated accuracies of ± 2% for the 626*620 model gate by referencing it to a high-accuracy magnetic flow meter, as shown in **Figure 2** following.
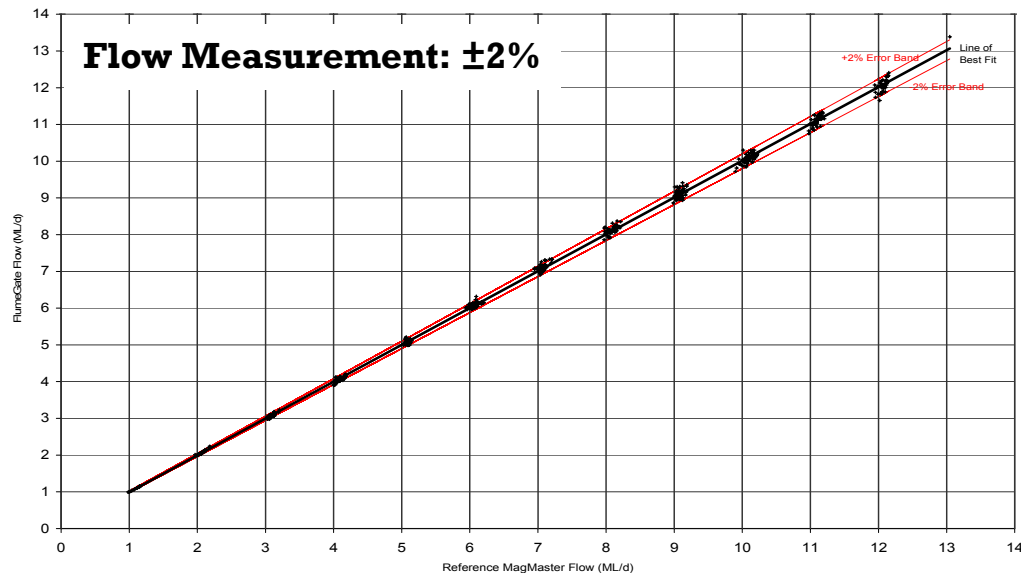
Figure 2. FlumeGate® Flow Measurement Accuracy.

Main Northern Channel

The Main Northern Channel system delivers approximately one quarter of the water in the District and diverts an annual average volume of 55,200 ML. Historical distribution efficiency ranged from 61% to 63%. The system contains approximately 260 regulating structures and has 600 customer outlets.

Constructed in the 1920s the channel offtakes from Glenmaggie Dam with a maximum capacity of 550 ML/d. It traverses eastward mainly following an escarpment and then crosses from the Macalister River catchment to the Avon River catchment via the 900-metre Boisdale tunnel. The channel has a range of characteristics that result in it being the most difficult channel to operate in the District. These characteristics include:

> ➢ Long flat channel pools (4.5 to 12.5 km long with grades of 1:7000)

> ➢ Complex hydraulics due to 11 siphons and one partly submerged tunnel

> ➢ Major and uncontrolled inflow during rain events

> ➢ Regulators that operate under highly submerged conditions at high flows

> ➢ Very uneven customer demand on one of its major spur channels (Valencia Creek channel)

Valencia Creek Channel

Valencia Creek channel is a major spur system in the Main Northern system. The channel has a peak flow of 100 ML/d and is the main source of supply to the Boisdale pipeline, where most customers place orders to pump over-night, to take advantage of lower electricity tariffs. The 6.5 km channel only has two operating pools; the first pool is 4.3 km long and includes three siphons; the second pool is 2.2 km long and includes one siphon. The channel generally follows a contour, receiving significant uncontrolled inflows during rain events.
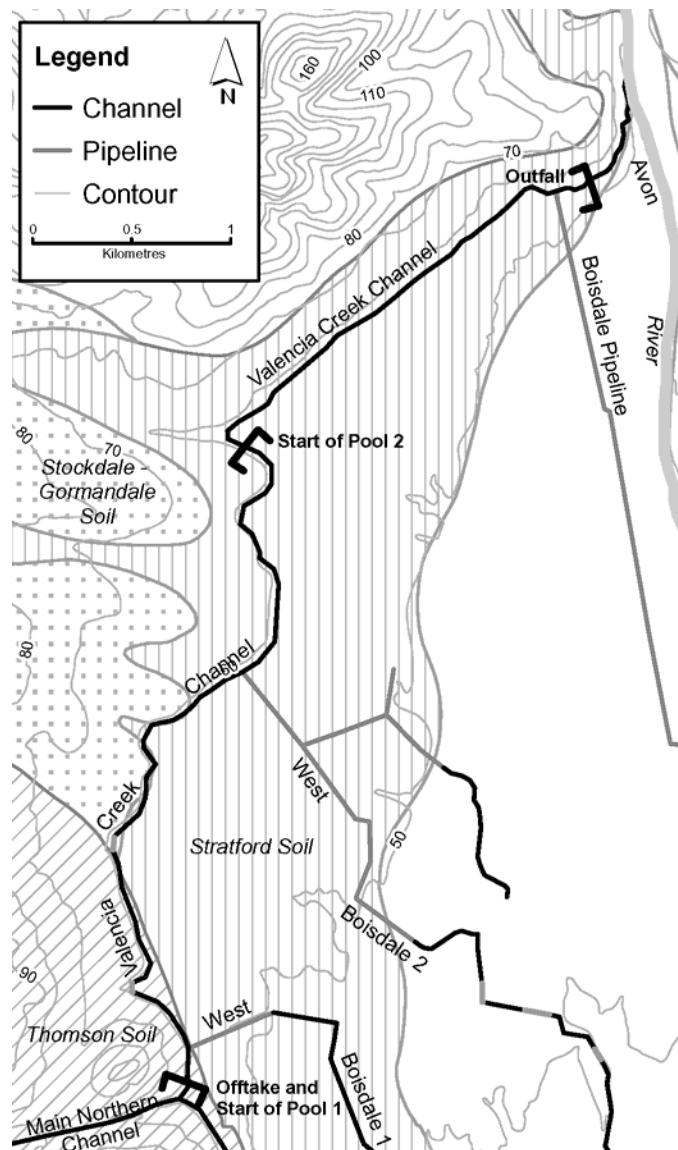
Figure 3. Valencia Creek Channel Locality Map.

The channel in the first pool intersects three soil types, whereas the second pool only has only one soil type. From a channel loss perspective, the first pool includes two soils (Stockdale-Gormandale[3] and Thomson[3]) with relatively moderate permeability characteristic plus one type with very low permeability (Stratford[3]), whereas the second pool's only soil type is Stratford. Figure 3 shows the location of the soil types and the channel.

In 2001 SRW engaged consultants Sinclair Knight Merz to undertake a seepage study on the Valencia Creek (SKM, 2002). This involved an electro-magnetic survey (EM34) of the first channel pool and then a subsequent pondage test on the 530-metre section (Stockdale-Gormandale soil) that the survey indicated had the highest seepage. The pondage test undertaken at the end of the irrigation season in May 2002 showed a seepage rate of 13.5 mm/day or 0.13 ML/day/km. By international standards this seepage is relatively low and is below the performance threshold for adequately lined channels of 30 mm/day as specified by FAO, as cited in by Plusquellec (Plusquellec, 2004).

Due to the heavily skewed demand pattern combined with its manual operation limitations and emphasis on meeting customer demands, this channel historically lost an estimated 2,000 ML per year at its outfall. The outfall volume represents over twenty percent of the channel inflow.

PROJECT BACKGROUND AND OVERVIEW

Main Northern Channel Automation Project

Like many Australian water authorities, Southern Rural Water (SRW) has been under increasing pressure to improve the efficiency of its distribution system and to provide water for environmental purposes. The Victorian Government has made funding available for infrastructure upgrades to return water to the environment through its Water Trust program[4].

Following an option assessment SRW chose Rubicon's TCC® as the most cost effective method of delivering these savings. TCC® had significant additional advantages over the other options in terms of service improvement, creating major opportunities for improving on-farm efficiencies for flood irrigation and an opportunity to gather data that enables an improved understanding of how the channel performs.

The first stage of the project invovled installing fifty-five automated regulators (FlumeGates®), of which thirteen were for customer metering applications with

---

[3] Refer Department of Primary Industry web site for soil details
www.dpi.vic.gov.au/dpi/vro/wgregn.nsf/pages/wg_soil_index
[4] Refer Victorian Water Trust program at www.dse.vic.gov.au

the remainder used to form the water measurement network. TCC® has been used to control and measure the main channel, its offtakes and all outfall points. The Valencia Creek channel operated under full TCC® (regulator and outlets automated) and the 20 km section of the Main northern channel from its offtake to the Valencia Creek offtake operated under TCC® mode. The automation on the Main Northern included control of three hydraulically controlled 900 mm vertical sleeve valves that release water from Lake Glenmaggie into the Main Northern channel.

The remaining 80% of the system operated along traditional manual lines, except for the operators remotely controlling the FlumeGates® located at in-line regulation sites. The operators were able to monitor outfalls and in many cases operated the FlumeGates® to control inflows to reduce outfalls.

Based on the results from Stage 1, SRW developed a targeted implementation program for TCC® across most the remainder of the Main Northern channel system. The design objective of Stage 2 is to deliver the most cost-effective savings whilst ensuring the solution is operationally acceptable. SRW reached agreement with the Government for the Government to contribute $7 million ($AUS) to fund the project in exchange for 5,000 ML of water saving.

The water savings will largely come from reduced outfalls (91%) with the remainder coming from accurate measurement of the customer outlets. The second stage of the project involves the installation of another 150 FlumeGates® with 80 of these for customer meter outlets that will be fully integrated with the TCC® water ordering software. All the works for Stage 2 will be operational by October 2005.

WATER BALANCE STUDY

Definition of water losses used for the study

A major water loss study by Sinclair Knight Merz (SKM, 2000) defined the elements in an earthen channel water balance. The following table presents the typical loss elements, grouped into two main categories, being: inherent system losses and operational losses. Inherent losses are those losses that are largely inevitable with an earthen system, whereas operational losses are largely controllable by management decisions. Inherent losses include: system filling and emptying, evaporation, leakage and seepage[5]. Operational losses include: outfalls, theft, unmetered domestic and stock supplies and under-recording of customer meters. These elements are all subject to measurement error to varying degrees.

---

[5] ANCID Rural Water Industry Terminology and Units – refer ancid.org.au/publications

Figure 4 following shows the estimate of the various components prior to commencing the project. The dark segment in the chart highlights the traditional poor closure in water balance studies and this high degree of uncertainty was the reason for focusing on water measurement in Stage 1.
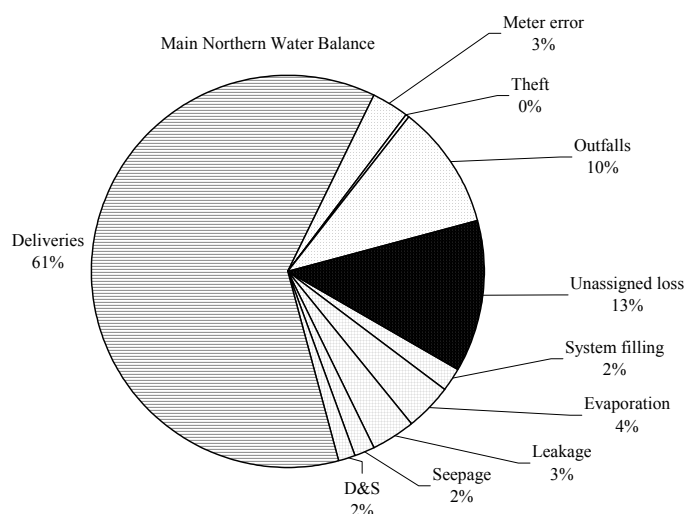
Figure 4. Historical water balance for Main Northern Channel
with estimated losses.

Results

The water balance was undertaken on two levels. The first supports the funding-water saving agreement and looks at an aggregated water balance at a whole system scale and the second looks at a disaggregated water balance at the sub-system level. SRW engaged consultants Sinclair Knight Merz to undertake the water balance study.

Whole system analysis

The evidence demonstrating the project water savings is improved efficiency of the entire Main Northern system, noting that the project involved automating just 20% of the system. Table 1 following lists the system-scale water balance results for the 2003/04 and 2004/05 season.

Table 1. Water Balance 2003/04 and 2004/05.

Water balance element	2003/04 Pre-project		2004/05 Post Stage 1	
	ML	% inflows	ML	% inflows
Inflow[1]	57,574	100%	54,131	100%
Deliveries[2]	36,568	63.5%	36,243	67.0%
Outfalls[3]	5,860	10.4%	6,238	11.5%
Other losses[4]	15,146	26.3%	11,663	21.5%

Notes

1	Measured by same sharp-crested weir for both years
2	Measured by Dethridge outlets for 2003/04 and for 2004/05, except for 13 new outlets in 2004/05
3	Operator estimates for 2003/04, except for one sharp-crested weir, FlumeGate$^{®}$ measurement for 2004/05
4	Other losses = Inflows less deliveries less outfalls

Main Northern Water Balance - 2003/04 Season
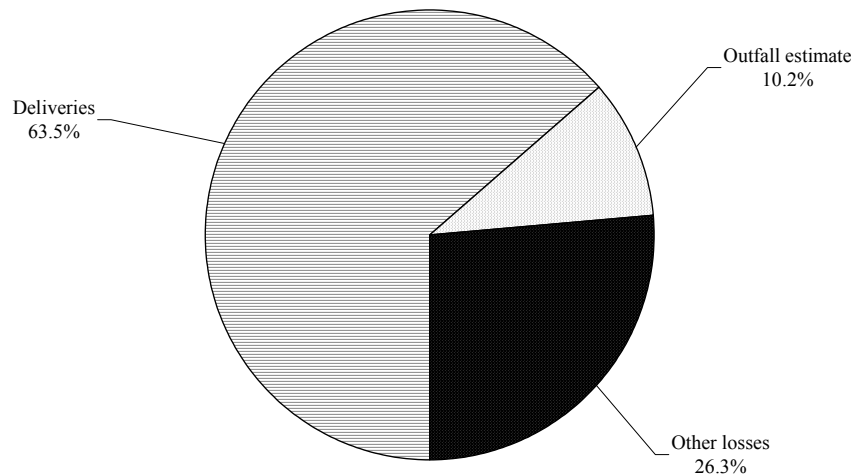
Figure 5. Water balance 2003/04.

The only significant difference at the whole system scale relates to the measurement of outfall volumes. The 2003/04 estimates, like previous years, rely on operator estimates, which at best, rely on one daily spot measurement. The measurement of outfall flow using the FlumeGate$^{®}$ offers significant advantages in terms of accuracy and frequency of measurement. Evidence of sites within the project area and from other sites in the irrigation district typically results in the annual outfall volumes measured by a continuous recorder, being 50% to 100% greater than the historical operator estimates. For example, the 2003/04 operator estimate for the outfall volume for Valencia Creek was 1,000 ML, whereas a rated weir recorder that covered the last four months of the season indicated that the annual outfall volume was 2,000 ML.

Notwithstanding some seasonal variations with some of the inherent channel losses, the accurate and continuous measurement of outfalls provides the most likely explanation for the major reduction in unaccounted water (15,146 ML in 2003/04 to 11,663 ML in 2004/05).

Main Northern Channel System - 2004/05

Figure 6. Water balance for 2004/05.

Sub-system water balance

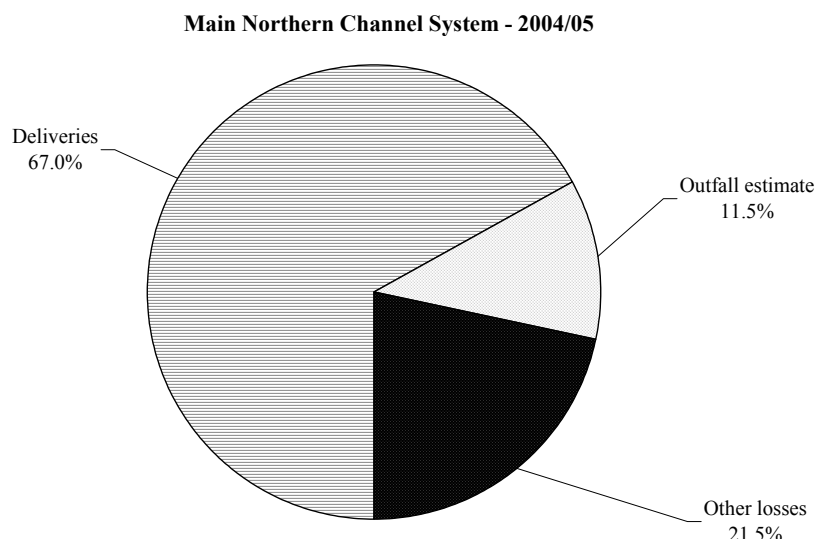The sub-system water balance is significantly more complex and has had more limitations due to a range of data issues including: delays in establishing some of the measurement sites at the start of the season, some intermittent instrument failures, inherent inaccuracy with traditional meter outlets (Dethridge wheels), sections with high rainfall run-off inflow and problems with some of the FlumeGates® operating in highly submerged conditions for parts of the season, which affected their accuracy at high flows. The next section of the report looks at the Valencia Creek sub-system in detail, as this system has the most dense measurement network and is representative of the type of analysis possible with full implementation of TCC®.

Water balance analysis for the Valencia Creek Channel

From a water loss perspective the Valencia Creek channel is unrepresentative of most channels in Australia, in that being a contour channel it receives significant rainfall runoff and most likely sub-surface inflows from adjacent recharge areas located to the west of the channel. From 1 September to 15 May the rainfall and pan evaporation was 376 mm and 1060 mm respectively. There was only one major rain event, which was 54 mm on the 3 February.

The two pools in Valencia Creek had a combination of modern and accurate measurement devices as summarised in Table 2 following.

Table 2. Measurement devices for Valencia Creek.

	Measurement devices	
	Pool 1	Pool 2
Inflow	FlumeGate®	FlumeGate®
Passing flow[1]	FlumeGate®	No passing flow
Spur offtakes	FlumeGate®	Ultrasonic meter
Deliveries	9 FlumeGates® and 1 magnetic flow meter	3 FlumeGates® and 1 magnetic flow meter

1– Passing flow to Pool 2

Due to delays in commissioning all measuring devices, data only covers part of
the year. For the top pool the water balance data starts from 1 September and so
misses part of the initial filling. For the second pool, the Panametric ultrasonic
meter that measures the flow leaving the lower pool into the Boisdale pipeline
was commissioned in late October and so it is only possible to review the water
balance for this pool from November onwards.

Figure 7 shows the water balance over most of the season for the top pool. The
very high efficiency of the channel is likely to result partly from the unmeasured
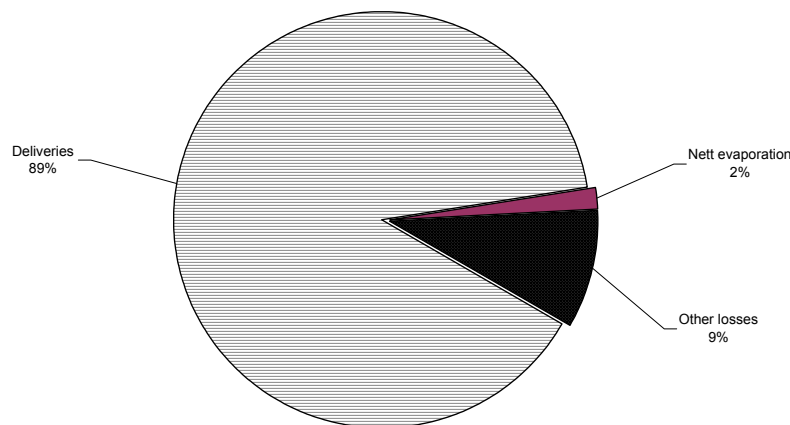inflows into the channel.

Figure 7. Valencia Creek water balance from September 2004 to May 2005.

Figure 8 following shows a more interesting picture of the channel loss characteristics. This indicates relatively high losses in the first part of the season then relatively low losses up to end of January and then ongoing minor net inflows into the system after the major rain event at the start of February. The results show that losses can vary significantly within a season and aggregation of the loss over the season, even with good measurement, could mask the actual loss performance of the channel.
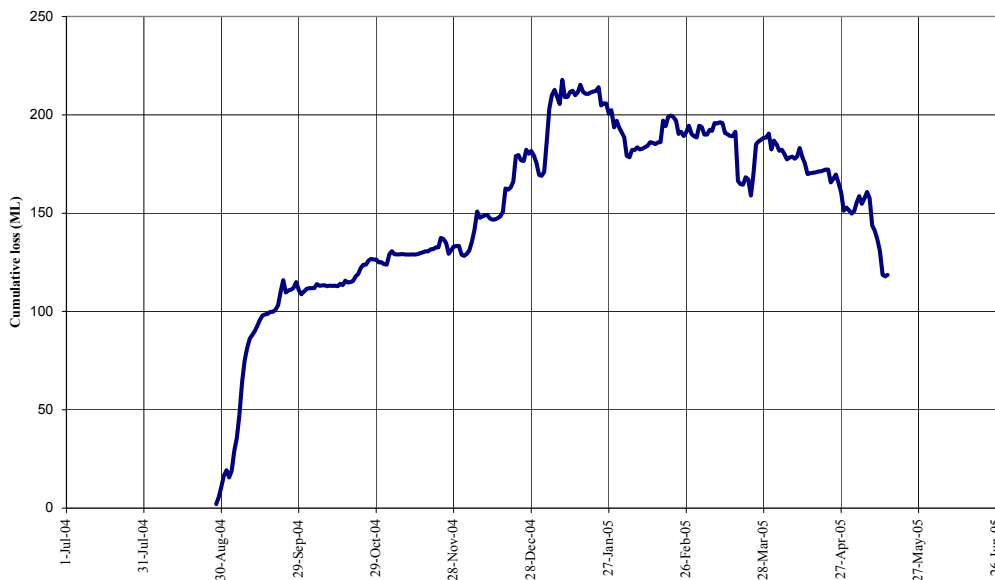
Figure 8. Valencia Creek Channel top pool– Cumulative loss
September 2004 to May 2005.

The results for the second pool showed that it received slightly more water than it lost which would mean that it has both a very low seepage and leakage rates and at times receives surface and sub-surface flows. An analysis of an eight-day period (12 to 20 March) late in the season demonstrates that the channel has very low seepage and leakage. During this period there were no deliveries in the pool, no outfalls, 6.2mm of rain spread over four days and the only water leaving the pool entered the Boisdale pipeline. Figure 9 following shows during this period that of the 195.3 ML measured entering the pool by the FlumeGate®, the ultrasonic meter recorded 194.4 ML flowing into the pipe. This indicates a conveyance efficiency of 99.5%.

This project in its early stages has demonstrated that accurate and continuous monitoring of flows can provide significant insight into quantifying channel losses and how they vary both spatially and temporally. Measurement and analysis of water losses will continue as part of the project and following its completion we plan to enhance water balance reporting tools within the system.
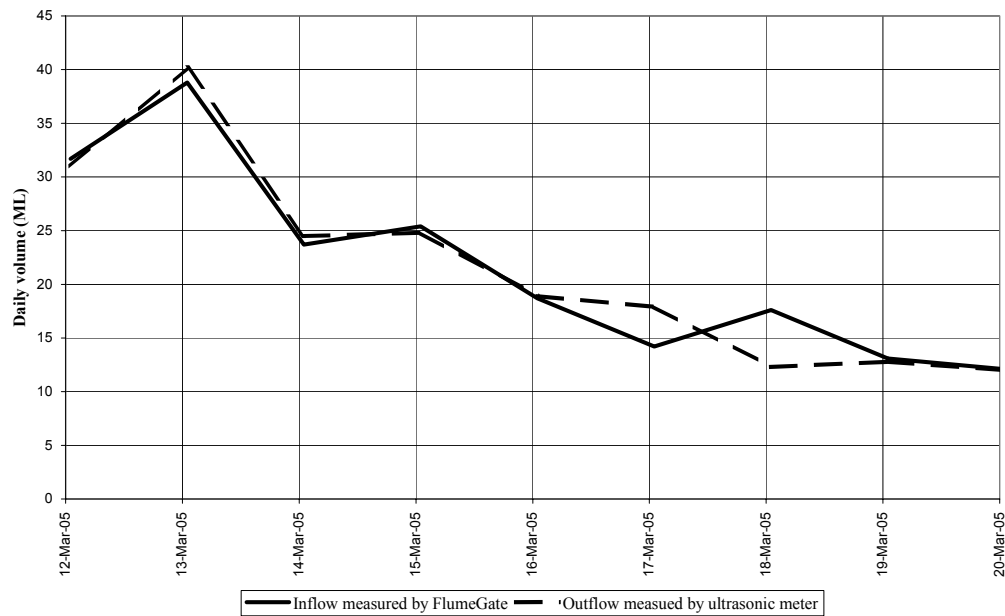
Figure 9. Valencia Creek Channel – Bottom pool inflow and outflow.

CONCLUSIONS

The TCC® has proven to be extremely effective in reducing outfalls from the system and delivering permanent water savings, whilst improving service levels. The system provides a vast amount of data that enables managers of earthen channel supply systems to monitor losses continuously and as a consequence provides an opportunity to greatly increase their understanding of the system performance.

REFERENCES

Sinclair Knight Merz (SKM), 2000, *Water Savings in Distribution Systems* – Report prepared for Department of Natural Resources and Environment and Goulburn Murray Water June 2000

Sinclair Knight Merz (SKM),, 2002 *Macalister Irrigation District, EM-34 surveys along the Valencia Creek and Northern Channels as an indication of channel seepage – Final* Southern Rural Water January 2002.

Plusquellic, H (2004), *Application of Geosynthetics in Irrigation and drainage Projects*, ICID, ISBN 81-85068-88-7

LEVERAGING SCADA TO MODERNIZE OPERATIONS IN THE KLAMATH IRRIGATION PROJECT

Beau Freeman[1]
Jon Hicks[2]
Charles Burt[3]

ABSTRACT

The U.S. Department of Interior's Bureau of Reclamation (Reclamation) operates the Klamath Irrigation Project in Oregon to divert, store and supply irrigation water to over 200,000 acres of farmland below Upper Klamath Lake. Reclamation has partnered with irrigation districts to undertake an active modernization program including the implementation of a Real-Time Water Management SCADA System for remote monitoring of the main diversions on the Project boundaries and at key control points within individual irrigation districts. Data are recorded at frequent intervals, transmitted to base station computers in headquarters offices where it is displayed, manipulated, and stored. This paper presents an interim assessment of the complex issues concerned with SCADA project implementation in a basin-wide environment with multiple irrigation districts, describing the engineering points of particular innovative, and field-tested concepts. Performance specifications and design standards are discussed to illustrate the specialized details critical for successful integration.

INTRODUCTION

Background

The U.S. Department of Interior's Bureau of Reclamation (Reclamation) Klamath Irrigation Project is a system of main-stem and tributary dams, diversion structures and pumping stations that store and deliver water for agricultural water users and national wildlife refuges on about 240,000 acres through a system of over 1,400 miles of canals and drains. The water must be managed in accordance with legal obligations arising from the Endangered Species Act (ESA) and federal tribal trust responsibilities.

---

[1] Senior Water Resources Engineer, Irrigation Training and Research Center (ITRC), California Polytechnic State University (Cal Poly), San Luis Obispo, CA 93407. bfreeman@calpoly.edu
[2] Water Conservation Coordinator, Klamath Basin Area Office, U.S. Bureau of Reclamation, Klamath Falls, OR 97603. jhicks@mp.usbr.gov
[3] Chairman and Professor, ITRC, Cal Poly, San Luis Obispo, CA 93407. cburt@calpoly.edu

To a majority of farmers in the Klamath Irrigation Project, the irrigation curtailment in 2001 drew attention to the existing water delivery system's limitations involved with delivering specific quantities of scarce water under reduced supply allocations. The physical infrastructure design and functions in the Project – based mainly on +50-yr old hardware and technology – limited the ability of managers and users to effectively respond to water shortages due to drought or reallocations for environmental requirements.

Efficient use of water diverted for irrigation requires the capability to deliver precise flow rates and volumes to known points throughout this complex system, and to quickly respond to changing demands. Rapid Appraisal Process (RAP) evaluations and water balance analyses conducted by the Irrigation Training and Research Center (ITRC) of California Polytechnic State University, San Luis Obispo, identified priority sites for modernization and recommended technical solutions, according to an assessment of the overall modernization and water conservation objectives.

Modernization efforts undertaken by irrigation districts in the Klamath Irrigation Project include, among other actions, upgrading existing telemetry systems to provide remote control and monitoring on a real-time basis at key points, improving water delivery service to water users. The work completed to date has been possible due to a coordinated effort between the USBR Klamath Basin Area Office, irrigation district staff, professional engineers from ITRC, and Watch Enterprises of Grants Pass, Oregon. This project was primarily funded by the Bureau of Reclamation, Mid-Pacific Region, Klamath Basin Area Office, with irrigation districts providing cost sharing.

Real-Time Water Management System

One objective of the Real-Time Water Management Supervisory Control and Data Acquisition (SCADA) System is to collect and disseminate high-quality, accurate and reliable data to partner irrigation districts in the Klamath Irrigation Project, who use the information for real-time decision-making about water deliveries. A second objective is to directly provide some of this real-time information, and additional information from Reclamation-operated sites, to the Reclamation Area Office in Klamath Falls. Prior to this project, Reclamation had no project-wide SCADA capabilities.

The location and function of each SCADA site is summarized in Table 1. At present there are seven (7) sites being remotely monitored as part the Klamath SCADA Project and another six (6) sites are under construction. As part of the system, base stations with human-machine interface (HMI) computer systems were established at four irrigation districts and the Area Office. An additional six (6) sites have been identified and preliminarily designed for the next phase of the system.

The first portions of the SCADA system were made operational in August 2004.

Table 1. SCADA sites in the Klamath Irrigation Project.

No	*	District	Site	Description	Purpose
1	pp	Langell Valley Irrigation District	North Canal	Replogle flume and RTU	Remote monitoring
2	pp		West Canal	Hydroacoustic flow meter and RTU	Remote monitoring
3	cp		East Malone L.	Hydroacoustic flow meter and RTU	Remote monitoring
4	cp		Office	Master RTU and Computer HMI	Base station
5	ip	Horsefly Irrigation District	Harpold Dam	Langemann Gate automated for upstream water level control	Remote monitoring Auto. level control
6	ip		Office	Master RTU and Computer HMI	Base station
7	cp	Klamath Irrigation District	Miller Hill Pumping Plant	GE Panametrics ultrasonic flow meters (wetted transducer) and RTU	Remote monitoring
8	cp		B Canal	Automated radial gate upstream water level control RTU and Hydroacoustic flow meter	Remote monitoring Auto. flow rate control
9	cp		C Canal	Hydroacoustic flow meter and RTU	Remote monitoring
10	cp		D Canal	Hydroacoustic flow meter and RTU	Remote monitoring
11	ip		Office	Master RTU and Computer HMI	Base station
12	pp	Tulelake Irrigation District	D Pumping Plant	GE Panametrics ultrasonic flow meters (wetted transducer) and RTU	Remote monitoring
13	ip		Drain 9	Hydroacoustic flow meter and RTU	Remote monitoring
14	ip		Drain 10	Hydroacoustic flow meter and RTU	Remote monitoring
15	pp		Drain 11	Hydroacoustic flow meter and RTU	Remote monitoring
16	pp		Drain J-14	Hydroacoustic flow meter and RTU	Remote monitoring
17	pp		Drain J-20	Hydroacoustic flow meter and RTU	Remote monitoring
18	cp		Office	Master RTU and Computer HMI	Base station
19	ip	KBAO	Office	Master RTU and Computer HMI	Base station

* Status current in June 2005.
  cp: completed
  ip: in-progress – under construction
  pp: planned

Data collected by the SCADA system will also be helpful for future water balance analyses, for example to quantify the realistic, true water savings from water conservation efforts (Clemmens and Allen, 2005). Accurate and comprehensive historical records are essential for producing reasonable environmental modeling, and providing verification of water for drought allocations, water banking and water transfers. Uncertainties in surface discharge records accounted for nearly 40% of the total variance in the annual water balance of the Project, accounting for an "error" equivalent to a volume of ±55,000 acre-feet (ITRC, 2003).

SCADA FOR IRRIGATION DISTRICTS

Supervisory Control and Data Acquisition (SCADA) is a process control and measurement system that enables an operator to remotely control and/or monitor sites in an irrigation system. Real-time monitoring, automated control, troubleshooting, automatic data reporting, and archiving are some of the possible capabilities of an irrigation district SCADA system.

SCADA sites with control functions, either automatic or remote manual, can only be accessed through a secure HMI computer terminal system. Information from individual remote sites can be networked to other fixed base stations or mobile stations, some with limited, monitoring-only capabilities such as flow rate information for specific time intervals.

A schematic of the transmission of real-time information from a remote terminal unit (RTU) in the field at a flow monitoring station to the HMI computer is illustrated in Figure 1.
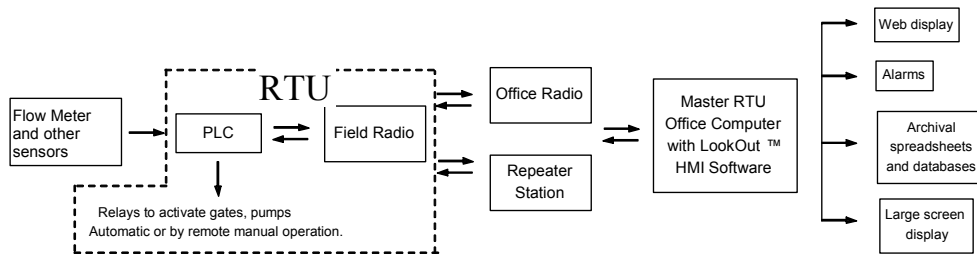
Figure 1. Schematic of the SCADA data transmission network.

The five major components of the irrigation district SCADA systems in the Klamath Irrigation Project are:

  I.   Remote Terminal Units (RTUs). RTUs refer to equipment (including a Programmable Logic Controller [PLC], sensors, radio, antenna, etc.) installed at a field site. The electrical cabinets and power systems are housed in a bullet-resistant (armored) vandalism enclosure. Key information such as flow rate and battery voltage can be read continuously on a small LCD screen at the RTU.
 II.   Programmable Logic Controllers (PLCs). A PLC is the mini-computer inside the RTU box. Different brands/types of PLCs have been used in the Klamath Irrigation Project for various functions. The PLCs for remote monitoring sites are RUG3 models, Rugid Computer Co. The PLCs for control sites are SCADAPack (ISaGRAF 3.x equipped) from Control Microsystems, or equivalent.
III.   Communications Equipment. Each PLC is connected to a radio with a data communications cable, using the widely accepted Modbus communication protocol. The RTUs communicate with the Base Station HMI computer in

the district headquarters office by transmission on a licensed fixed-frequency radio channel (460 MHz band). Radio transceivers (9600 bps) from Microwave Data Systems (MDS model 4710) installed in each RTU use either point-to-point (directly with the district office) or repeater-relayed signal communication.

IV. <u>Primary and Secondary Sensor Instrumentation</u>. Real-time water management information, such as the current flow rate in engineering units (cfs or feet elevation) at major canal diversions, is collected by several types of instruments at flow monitoring stations. SonTek/YSI Argonaut flow meters use digital signal processing techniques and Doppler transducers to measure discharge at sites with the requisite conditions. Other types of sensors may include water level transmitters, gate position sensors, and ultrasonic pipe flow meters.

V. <u>Base Station HMI Computer</u>. All inputs, outputs, and memory register values are transmitted to the HMI computer located in the district headquarters office running National Instruments LookOut™ software. The HMI computer displays real-time and historical information, sends out alarms, and archives information.

SCADA benefits modernization by allowing better accounting of water on a real-time basis in the system, more accurate record keeping for historical analysis and forecasting, and faster responses to user inputs or alarms. This, in turn, is the basis for irrigation districts and water users to manage pending challenges such as the electricity rate hikes and the consequences of proposed water use restrictions due to Total Maximum Daily Loads (TMDLs) or in-stream flow requirements for environmental uses.

MODERNIZATION PLANNING AND SCADA

SCADA is a popular tool in modernization programs, but the initial enthusiasm of managers and engineers has evolved into greater understanding of the costs, technical complexities, and unique difficulties involved with this technology. Responding to external pressures to introduce new technologies and modern modes of operation – both requiring a thorough prior understanding of the internal process in the system– has been a major challenge for irrigation districts.

Creating a SCADA system for multiple irrigation districts, with different needs, operating budgets, and in-house technical resources, as in the Klamath Irrigation Project, is not a simple task. In this case, it required very detailed, comprehensive planning with many meetings and trips to the field. However, the modernization plans for the irrigation districts developed as an outcome of the Rapid Appraisal Process (RAP) diagnostic evaluation serve as the roadmap (Burt and Styles, 2004).

The involvement of ITRC occurs at all stages in the implementation of a SCADA system leading to final field deployment of the system through a series of steps:

1. Rapid assessment of irrigation district system and operations.
2. Introductory SCADA presentation and specific site review
3. Communications evaluation and radio tests
4. SCADA System report
5. Board presentation of SCADA system report (only when specifically requested)
6. Request for Proposals (RFP)
7. Construction
8. Continued support with operation

An RAP evaluation of the service area includes systematic investigations of the primary water distribution canal system and control structures, data collection and surveying, field interviews with project managers and operations staff, and engineering analysis to improve understanding of the internal processes. One of the first decisions made after a RAP is if SCADA is even required in conjunction with PLC controls, or whether a simple device like a flap gate or long-crested weir could provide an adequate solution. For the Klamath Project, a modernization report and SCADA recommendations were developed in consultation with the Districts and Reclamation.

Once a SCADA system is envisioned and approved by an irrigation district Board, it must be considered integral to the modernization package and planned for in all aspects of the construction phase and also, just as important, in terms of follow-up support and budget. To start with, there must a transparent evaluation of the costs and benefits of the different levels of SCADA investment. Most irrigation districts enter into SCADA gradually, starting with a few remote monitoring sites, and then move into control and automation, learning about the possibilities as they use the system.

Once the integration team is assembled, specific tasks can be assigned and scheduled. The planning information was presented, along with proposed project descriptions for each site, in the SCADA system specifications report. All participants knew their responsibilities and what the sequence of steps would be.

Due to the typical in-house nature of districts' O&M activities, districts are often hands-on involved with deployment of the system while at the same time dealing with a steep learning curve on new technology. Basic maintenance chores and set-up procedures must be clearly described in a detailed O&M manual with system back-ups. Manufacturers are tailoring their software programs and devices to the irrigation market, but working with SCADA requires a high level of computer programming knowledge that districts must prepare for.

SCADA systems are complex and expensive investments, and have many parts that can fail and many details that can go unnoticed in the planning stages. As a result, there are many bumps on the road that must be handled in a timely and effective manner so that predictable problems don't excessively frustrate the district. Obtaining outside expertise, desirably from a specialist in irrigation applications, is necessary, but there must also be a designated person in overall charge of the system at the district. Communication must occur on a regular basis at all stages of the project. Getting the right integrator is absolutely critical.

SCADA System Guide

The specific conditions and data/control options at each proposed SCADA location require a thorough field investigation and analysis and result in project-specific details. However, there are many areas, such as sensors and instrumentation, where the quality of data in a SCADA system is established through adherence to standardized specifications. The *SCADA System Guide* prepared by ITRC for an irrigation district sets forth the specifications and performance requirements for the design, specification, installation, and operation of the system. The subjects covered in the technical report prepared include:
- SCADA site descriptions and functions
- Guidelines for SCADA integration services
- Project specifications and system configuration

The purpose of the *Guide* is to provide a detailed technical overview of how the package of SCADA components fits into a modernization plan whose performance capabilities conform to standard specifications and guidelines, which are set forth in specific performance requirements. Project management benefits from following detailed specifications; these reduce the risks and costs associated with design, construction, and integration of the SCADA system.

To help irrigation districts in planning and contract consultations the *Guide* contains guidelines for integration services pertaining to the following areas:
  a) Deliverables – what the Integrator will deliver to the irrigation districts in regards to training, warranty, backup software, etc.
  b) Ownership of Work
  c) On-Site Assistance – specifying what the Integrator will provide assistance at installation and start-up of SCADA equipment.
  d) Quality Control – quality control of PLC programming used for control.
  e) HMI Development
  f) Controller PI Logic and Tuning – ITRC recommends that a certain form of Proportional-Integral Filtered (PIF) logic be used to control the action of gates and variable frequency drive (VFD) pumps. For canal control, the tuning constants for the PIF logic must be carefully selected – and selection by trial-and-error in the field is not acceptable.

KLAMATH IRRIGATION DISTRICT SCADA SYSTEM

An example within the Klamath Irrigation Project is the Klamath Irrigation District, which supplies water to approximately 54,000 acres of irrigated land within its service area boundaries. The district operates and maintains the A, B, C, D, E, F, and G Canals, in addition to the associated drainage system and pumping plants. While the physical features and operational methods have been well-established and time-tested over these many years, they did not reflect the benefits made available by newer telemetry control systems and hydraulic control structures.

The District has to perform real-time control and monitoring of flows, canal water levels, and pumping plants over an extensive water distribution and drainage system. Their prior telemetry systems had some limited remote monitoring capability, but did not have the features of modern SCADA systems widely adopted by California irrigation districts over the past 8 years. With support from the Reclamation, the District has proceeded with a modernization program that includes new hardware and control strategies, water measurement devices, communications equipment, and integration into the district's existing SCADA system.

The service area does have some physical characteristics that make modernization more expensive and difficult than may typically be the case for other irrigation districts. Key challenges included:
- The district has some very long canals, which typically wind around to follow the contours, rather than being laid out in a simple rectangular grid.
- Most of the canals are fairly old, often without good year-round access.
- The system has almost no modern control structures.
- Many of the fields within the service area have irregular shapes and are relatively small.

Even with the ability to utilize operational spill at multiple points and internal recirculation, the canal check structures within the system make it difficult to quickly and frequently make flow rate changes throughout the system without adversely impacting flow rates to turnouts and to laterals (Burt et al., 2000).

To combat these difficulties, a strategy (Figure 2) was adopted starting with the main arteries of the delivery system, making them easy and efficient to manage with flexibility. If the long canals can be effectively managed, this gives tremendous flexibility to the short canals. Once the main canals have been modernized, the district can move further down into the system. There is little justification for putting extremely accurate flow meters on farmer turnouts, for example, if the deliveries to those turnouts are not very well controlled.
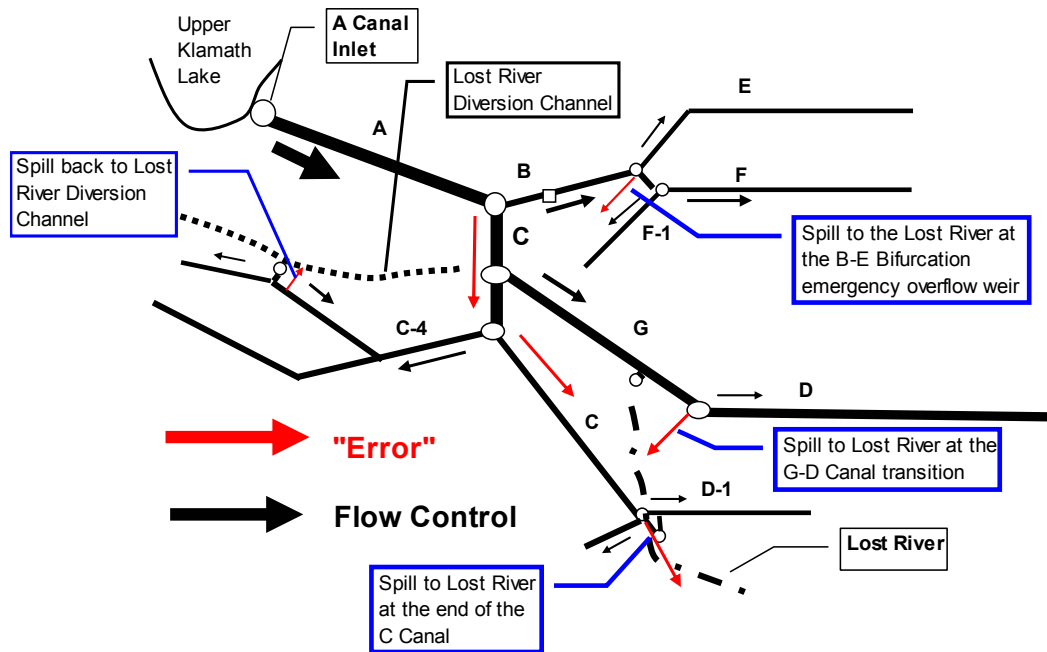
Figure 2. Proposed main canal operating logic with modernized control structures and centralized management of the Klamath ID main canals.

Therefore the process begins with improved measurement and control at the heads of main delivery canals, with SCADA-equipped flow meters and new sensor systems, so that the operators and users deal with a manageable (although limited) supply of water. The improvements fall into broad inter-related categories:
1. Centralized dispatching and control of the main canals
2. Physical improvements to the main canals
3. Advanced SCADA system upgrades and HMI computer

The following sections describe examples of innovative techniques used to set up two different types of SCADA sites:

B Canal: automatic flow rate control and remote monitoring using a hydroacoustic flow meter

Miller Hill Pumping Plant: Remote monitoring of a pump station with old concrete and steel pipe with ultrasonic transit-time flow meters

B Canal

The B Canal is a critical operations point, with a capacity of about 300 cfs. The headworks, a 17-ft single radial gate, is shown in Figure 3. Historically there had been problems with steady and reliable control of the headgate, partly due to the hydraulic conditions of this reach of canal that results in very low head across the gate. To improve the automatic control and provide accurate flow measurement, a new RTU running an ITRC control algorithm has been installed that uses real-time data from a hydroacoustic flow meter.

Figure 3. Automated flow rate control on the B Canal radial headgate.

The B Canal headworks was automated for flow control using a hydroacoustic flow meter [SonTek/YSI Argonaut Side-Looking (SL) Doppler] mounted in a 70-ft lined section installed by the District 300 ft downstream of the headworks. The Argonaut SL flow meter is solar powered and serial data is output directly to the RTU via a short-distance, spread-spectrum radio. Standard 4-20mA signal converters were not required. The PLC unit is programmed with a parsing program to select the flow rate computed in the sensor, along with data on water level and flow area.

The concrete lining is recommended for creating a stable cross-section and to protect the sensor from weed growth. The lined banks make it easier to retrieve the sensor for maintenance. An aluminum mounting frame was designed for easy installation and retrieval of the sensor (Figure 4).

Figure 4. Side-looking hydroacoustic flow meter.

Determining the proper timing intervals for sampling and averaging the raw electronic flow meter data required successive field testing. Hydroacoustic flow meters typically output signals with a tremendous amount of noise that eventually (perhaps in 15-30 min. or so) average out properly. The control algorithm must be properly programmed to recognize this noise. Hydroacoustic flow meters must also be calibrated using a statistical regression analysis technique called the Velocity-Index relationship (Styles et al., 2003). Two indexing sessions have been carried out at low-mid flows and more data will be collected per the guidelines.

This project also involved installing a new upgraded RTU, which had to be integrated with the incoming data from existing water level and gate position sensors. The solar-powered RTU is equipped with necessary alarms and the system can switch between using the flow meter and computing flow based on head differential.

Miller Hill Pumping Plant

A modernization recommendation for the District was to eventually install a VFD controller at the Miller Hill Pumping Plant to better match pumped diversions with operational needs in the C4 Canal system it serves, after first installing flow

meters. Previously, if an operator wanted to pump only 10 cfs for orders, they had to actually turn on one of the 35 cfs pumps and spill the rest back to the Lost River Diversion Channel.

To set up the remote monitoring at the plant, new hydroacoustic sensors (GE Panametrics AT868W ultrasonic flow meter, single channel) were installed on the buried discharge pipelines outside the pump house using custom access vaults (Figure 5) built for each sensor. The corrugated pipe vaults have lockable lids with a simple drainage system and gravel bottom. The RTU and display panels for the meters were mounted in adjacent vandalism enclosures.
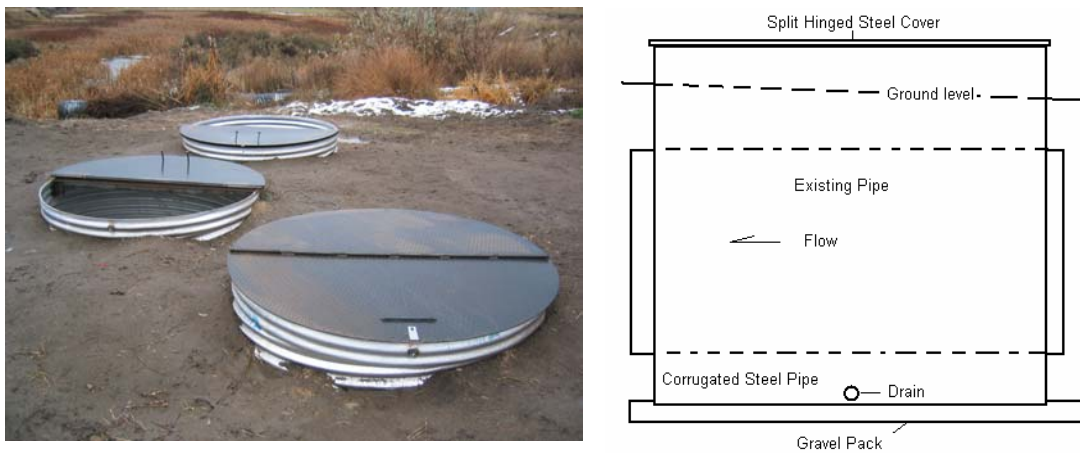
Figure 5. Vault design for transit-time flow meters with wetted transducers on buried concrete pipe.

The wetted transducers on the two (2) concrete pipelines had to be installed using stainless steel saddles as shown in Figure 6. Weld-o-lets fixed at the site were used to install the transducers on the steel pipeline.

Figure 6. Existing concrete and steel pipelines at Miller Hill Pumping Plant showing the saddles used to install GE Panametrics wetted transducers.

At a future date, a water level sensor, installed in the C4-E lateral, can be connected to the RTU to provide real time information to the headquarters. Remote manual on-off capability can also be added to the PLC by connecting to the pump motor starters. The result will be to provide the district with an accurate measurement of the flow rate, the effect of the flow rate on the C4-E Canal, and the ability to modify the flow rate by turning on or off a pump.

Dealing with Accuracy and Reliability of Electronic Data

Accuracy, consistency, and precision all depend upon the combination of good equipment, proper installation and initial calibration, and good maintenance. Excellent maintenance practices are required for long-term reliable discharge records collected by an irrigation district SCADA system. There are several sources of error in discharge measurements that were considered, including:
- The index equation coefficients used to predict the mean channel velocity statistical relationship with measured velocity from the sensor
- The validity of the index equation over the entire range of flows and stages (water depths)
- Errors in calculating the cross-section "area" of the channel or pipe
- Time averaging intervals and computer processing of raw data signals
- Environmental changes to the hydraulic conditions at the site
- Deployment parameters such as the alignment angle and water depth
- Excessive sedimentation or vegetation obstructing the acoustic signals
- Instrument precision

Disclaimer: Reference to any specific process, product or service by manufacturer, trade name, trademark or otherwise does not necessarily imply endorsement or recommendation of use by either California Polytechnic State University, the Irrigation Training and Research Center or the U.S. Bureau of Reclamation. No party makes any warranty, express or implied and assumes no legal liability or responsibility for the accuracy or completeness of any apparatus, product, process or data described previously.

SUMMARY

SCADA is a valuable tool with tremendous potential for modernizing the operation of irrigation districts. This paper describes the implementation of a Real-Time Water Management SCADA system in the Klamath Irrigation Project. Planning, SCADA specifications, and other guidelines, are discussed.

REFERENCES

Burt, C.M., A. Mutziger, and D. Cordova. 2000. Benchmarking of Flexibility and Needs of Irrigation Districts in the Mid-Pacific Region of the USBR. Irrigation

Training and Research Center. California Polytechnic State Univ. San Luis Obispo, CA. 47 p.

Burt, C,M. and S.W. Styles. 2004. Conceptualizing Irrigation Project Modernization through Benchmarking and the Rapid Appraisal Process. Irrig. and Drain., 53(2): 145-154.

Clemmens, A.J. and R.G. Allen. 2005. Impact of Agricultural Water Conservation on Water Availability. U.S. Water Conservation Laboratory, 4331 E. Broadway Rd., Phoenix, AZ. pp.1-14.

ITRC. 2003. Hydrologic Assessment of the Upper Klamath Basin: Issues and Opportunities. Draft Report for U.S. Bureau of Reclamation, Klamath Basin Area Office.

Styles, S.W., M. Niblack and B.J. Freeman. 2003. Canal Velocity Indexing at Colorado River Indian Tribes (CRIT) Irrigation Project in Parker, Arizona using the SonTek Argonaut SL. Irrigation Association, International Irrigation Technical Conference, San Diego, CA.

A 2005 UPDATE ON THE INSTALLATION OF A VFD/SCADA SYSTEM AT SUTTER MUTUAL WATER COMPANY

Frederick F. Schantz[1]
Stuart W. Styles[2]
Daniel J. Howes[3]

ABSTRACT

In 1999 Sutter Mutual Water Company (SMWC) and Cal Poly ITRC began work together with the USBR on a project effort to install a VFD unit and a SCADA system into the Portuguese Bend Pumping Plant, one of SMWC's four pumping plants that convey water from the Sacramento River onto 46,746 acres of farmland in the Sutter County sub-basin. The project was formulated and implemented in order to reduce the high amount of power consumed by the existing 30-year-old equipment, to minimize maintenance and labor costs, and to improve control of the in-stream flows to achieve more efficient use of limited water supplies.

After commissioning the equipment, a number of operational problems were encountered. These were resolved once their causes were clearly identified and adequately addressed. Work completed included installing an adequate cooling system for the VFD unit and replacing an air-release valve in place of an outdated siphon breaker that continually adversely affected water flow. Benefits realized from the new technology have included a reduction in power use, cost of labor and maintenance, and a dramatic improvement in the district's ability to control in-stream water flow through the automatic control of motor and pump performance.

INTRODUCTION

Sutter-Mutual Water Company (SMWC), a farmer-owned, non-profit water company, decided in 1998 to begin modernizing its irrigation facilities in an attempt to reduce its increasing operation and maintenance costs while conserving water and power resources. The original paper on this effort, a 1999-2001 status report on what has become an ongoing modernization effort, was presented at the July 9-12, 2002 USCID conference on Energy, Climate, Environment and Water - Issues and Opportunities for Irrigation and Drainage in San Luis Obispo, CA.

---

[1] Operations Manager, Sutter Mutual Water Company (SMWC), P.O. Box 128, Robbins, CA 95676; ffschantz@aol.com
[2] Director, Irrigation Training and Research Center (ITRC), California Polytechnic State University (Cal Poly), San Luis Obispo, CA, 93407; sstyles@calpoly.edu
[3] Senior Irrigation Engineer, ITRC; djhowes@calpoly.edu

This paper is a 2005 update of the effort, and presents the reduction in operation and maintenance costs due to the performance of the VFD/SCADA unit.

The on-going effort has been continued due to a coordinated effort between company personnel and professional engineers from the Irrigation Training and Research Center (ITRC), California Polytechnic State University (Cal Poly), in San Luis Obispo, California; Concepts in Controls in Visalia, California; and Wilson Pumps in Woodland, California. This modernization project was partially funded by the United States Bureau of Reclamation (USBR), Mid-Pacific Region, Northern Area Office, through a Field Services Program Grant and technical support agreement with ITRC.

The effort encompassed a project within the company's service area, located within the boundaries of California's largest reclamation district, Reclamation District 1500. The project included the automation of the pumping plant at Portuguese Bend with a new Variable Frequency Drive (VFD) pump and a Supervisory Control and Data Acquisition (SCADA) system, completed in 2001.

The anticipated and ultimately realized benefits of the modernization effort included a savings to the company due to a reduction in the amount of water diverted, power consumed, and number of personnel required to operate and maintain its system.

BACKGROUND

For over 80 years SMWC has operated and maintained its irrigation facilities, initially using mostly vintage technology that has proven to be very reliable. In the 1960-1970s, three new pumping stations were built and more efficient turbine pumps were installed to help reduce power consumption and to increase water diversion efficiency. For economic and operational reasons, it was decided in 1999 to begin installing additional technology in some of the plants in order to take advantage of the substantial savings offered by such technology.

Agricultural Energy Use for Irrigation Water in California

In 2003 the Irrigation Training and Research Center completed an analysis of agricultural energy use for irrigation water in California for the California Energy Commission (CEC). The results of this analysis were published in a report titled "California Agricultural Water Electrical Energy Requirements" (ITRC, 2003). Results from this study showed the bulk of the energy used for agricultural water is from on-farm groundwater pumping and on-farm booster pumping. Irrigation district (water district, water company, etc.) surface water pumping was a relatively small portion of the overall energy requirement during an average precipitation year. However, ITRC has determined that proper investment in

surface water supply infrastructure, specifically at the irrigation district/water company level, has a significant impact on current and future energy demands.

Improved district delivery flexibility will allow the following:

- *Drip and microspray irrigators will be able to use surface water instead of groundwater.* Historically, groundwater pumping was used to supply water requirements above what could be met by surface water supplies. In general, surface water supplied approximately two-thirds of statewide water demand and groundwater was used to supply the remaining one-third. Irrigation districts were designed to provide high flow rates to water users relatively infrequently (every 7-14 days), which is appropriate for most types of gravity irrigation methods. Drip and microspray require lower flow rates more frequently.

- *Water users using pressurized systems will be able to utilize off-peak pumping, reducing electricity costs.* District infrastructure improvements such as the addition of automated gates that maintain water levels regardless of flow rate, VFDs, and re-regulating reservoirs coupled with SCADA, can improve the districts' surface water delivery flexibility and reduce on-farm pumping demand.

Drip and microspray irrigated acreage has increased from approximately 1.6 million acres in 1978 to over 4.2 million acres today and there is no indication of slow-up. As the drip and microspray acreage doubles, ITRC estimates that the total agriculture water energy demand will increase by over 20% under current conditions. District improvements such as those discussed in this paper are key to reduction.

Description of Sutter Mutual Water Company (SMWC)

Formed in 1919, SMWC was one of the first water companies to be established in the state of California. The company's physical location (Figure 1) is approximately 45 miles northwest of Sacramento, California and is bordered in the north by the Tisdale Bypass, in the west by the Sacramento River, and in the east by the Sutter Bypass. The southern boundary is located at the southern end of Sutter County near the Fremont Weir where the Sacramento River and Feather River join. The company's 46,746 irrigable acres (18,917 ha), which are part of the 67,850 (27,470 ha) gross service area that is maintained by Reclamation District 1500 flood control and drainage personnel, are served by approximately 400 turnouts. Approximately 200 miles (322 km) of canals and laterals in the distribution system convey water to the fields.

Figure 1. Map of Sutter Mutual Water Company service area.

INSTALLING A VFD UNIT AND SCADA SYSTEM AT THE PORTURGUESE BEND PUMPING PLANT

In early 1999 the company decided to proceed with the installation of a Variable Frequency Drive (VFD) unit and a Supervisory Control and Data Acquisition (SCADA) system at the Portuguese Bend pumping plant (Figure 2). ITRC staff explained the technology and detailed the work to be done, the equipment to be used, and the cost and benefits of the project. The VFD, in a manual mode, was successfully installed by the end of the year after three unique problems, critical to the successful operation of the new technology, were identified, evaluated and resolved. The solutions included (1) an adequate radio signal between the office and field site, (2) proper siphon breaker operation, and (3) adequate cooling of the VFD unit.

Figure 2. Portuguese Bend Pumping Plant on the Sacramento River.

The Variable Frequency Drive (VFD) Unit

Constant-speed AC motors drive many pumps used for water distribution and delivery at the district or grower level. When flow control is needed to accommodate changes in downstream demand, two methods are typically employed to control the flow rate and pressure: (1) a downstream throttling valve is used to alter the system curve, and (2) some of the output is by-passed back into the intake.

With these two methods, a considerable amount of energy can be wasted doing unnecessary work just to achieve the desired flow rate. VFD units provide an effective way of reducing the speed of the pump drive motor, thereby allowing the flow rate or pressure to be adjusted to the desired level without the additional energy from throttling or by-passing. Basically, the VFD is an electronic device that is used in conjunction with a constant-speed AC motor. The VFD accepts the

standard line voltage and frequency, and then converts the signal into a variable frequency and voltage output that allows the standard constant-speed AC motor to be varied in speed.

Advantages of a VFD: VFDs provide the potential for system automation of pumping plants such as Portuguese Bend. Water level sensors can be used as feedback into the controller to continuously adjust the VFD speed for varying downstream conditions. In general, this allows water deliveries to be provided to growers on-demand. In return, growers are able to schedule irrigations to match crop water requirements rather than district limitations. This type of VFD operation also offers the potential for labor savings over manual adjustment. The further advantages of VFD systems include the following:

- *Softer starting*. The device limits the current inrush to the motor, providing for a smooth, non-shocking acceleration of the pump shaft speed up to its operational RPM.
- *Elimination of pressure surge*. Bringing the system up to operating speed slowly removes the pressure surge caused by an almost instantaneous acceleration of the water to its operational flow rate.
- *Reduction of operating costs*. Reducing the energy input over previous control methods (by-pass) can reduce operating costs.
- *Reduction of mechanical stress on motor windings*.
- *Reduction of peak demand charges*. By reducing the energy loads, the overall peak demand of the facility can be reduced.

Disadvantages of a VFD: There are important issues to consider when VFD devices are being used:

- *Increased motor stress*. Electrical stress increases due to the steep voltage wave that forms in the power supplied by the inverter. Newer VFDs that include "soft switching output technology" can significantly reduce motor stress and interference from harmonics. However, older motors with inferior insulation may have problems. Typically, the motor should be dipped and baked twice.
- *Increased maintenance*. While VFD units are very reliable, they are still an additional item requiring maintenance. In critical applications, it is essential to have spare parts and maintenance expertise or to retain the ability to by-pass.
- *Harmonics*. With the increasing number of control systems going on-line, the line interference produced by some VFD units can cause problems.
- *Environmental conditions*. Most units require relatively dust-free enclosures with some type of temperature control. Most of the pumping VFD applications can utilize a simple water-to-air radiator type cooling system (simple and effective).

Energy Savings: VFD units usually reduce pumping costs by reducing the pump drive motor speed to match the desired operating conditions, thereby reducing energy input. Without a VFD device this is typically accomplished by using either a by-pass set-up or a downstream throttling valve. The system layout for a typical by-pass installation consists of a pump and by-pass piped into a standtank. With this arrangement, the by-pass maintains a constant head in the standtank regardless of flow, as there is less downstream demand. The excess flow is by-passed to the pump intake to maintain a constant head in the standtank or canal. Determining how a pump will operate in a given situation requires an understanding of the pump and system curve. The pump characteristic curve for a standard centrifugal pump shows that the pump, at a fixed speed, has a flow rate associated with a particular pressure; high flow, lower pressure vs. low flow, higher pressure. The intersection of the pump curve and the system curve shows the point of system operation.

If, instead, the pump speed is modified using a VFD device to control head just below the by-pass, flow and head are reduced together along the system curve. A comparison of the relative pump water horsepower with (i) VFD, and (ii) by-pass installations are shown by the shaded areas in Figure 3.
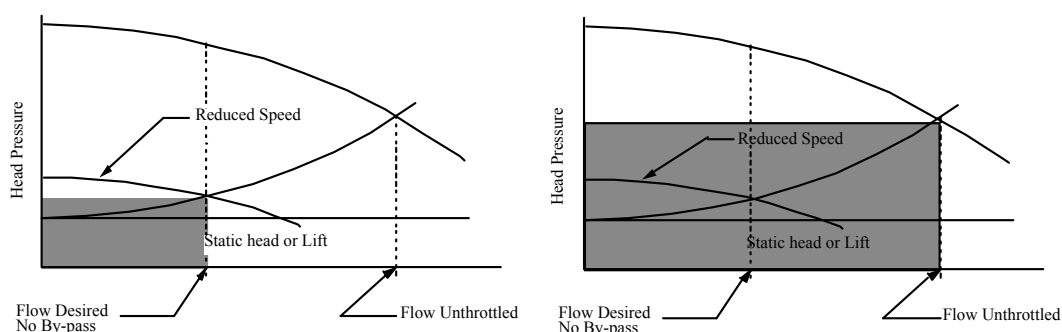
Figure 3. Water horsepower (shaded area) for pumping plant with (i) VFD and (ii) by-pass.

However, the water horsepower differences above are only some of several factors to consider. To properly compare the actual cost savings of a VFD system, the overall pumping plant efficiencies with and without the VFD device also need to be considered. The major additional losses that must also be considered in determining the overall pumping plant efficiency are as follows:

- As the system curve changes or the pump speed is reduced, the operating efficiency of the pump changes. Therefore, for each operating point the pump efficiency must be checked.
- VFD units have some losses associated with the conversion process to the new operating frequencies. In general, the units are relatively efficient at 95%. However, as the frequency is lowered, some units do become less

efficient. The individual specifications should be obtained for the VFD being considered.

- Electric motors, if sized properly near maximum loading, can be very efficient. With VFD units used in pumping, the motor loading is reduced as the speed is reduced. This reduction in motor loading can reduce its efficiency and drive motor losses will result.
- Drive friction losses can be reduced with VFD applications. As the speed is reduced, the mechanical friction on drive shaft components is reduced.

In addition to the items above, it is important to consider the relative volume pumped each season. Small pumping volumes generally produce small savings and do not justify VFD installations.

Cost Savings Analysis: To determine the total savings due to the VFD unit, a detailed cost savings analysis was started on the VFD installation on pump #1 (100 hp motor) at the Portuguese Bend pumping plant. Initial savings have already been realized, with the reduction of one employee who had been needed to constantly monitor and reset the plant's three pumps as dictated by flow requirements out of the plant's main canal. The main costs, now under evaluation, involve two other components: (1) energy savings as a result of eliminating the by-pass practice (before meter) to control delivery flow, and (2) reduction of spilled water out of the canal, which reduces metered pumping of a purchased volume, plus the additional energy savings associated with the reduction in pumped volume. Neither portion of the savings analysis takes into consideration the specific time of use rates; both are based on the total monthly values. The reduction in canal spill and the associated energy savings are only achievable with the new SCADA system.

Table 1 shows the actual energy savings at Portuguese Bend after the VFD was installed and after the control algorithm was added to the controller. The cost savings analysis is based on an estimate of the average pumping costs before and after the installation of a VFD unit.

Table 1. Actual energy savings – pre-VFD compared to post-VFD installation with 1996-2004 actual average and maximum volume of water pumped.

Item	Pumping Cost $/AF	Annual Energy Savings based on 9,136 AF/ Season	Annual Energy Savings based on 13,424 AF/ Season
without VFD	5.6	---	---
with VFD	4.2	$13,125	$19,285
with VFD and control algorithm	3.8	$16,641	$24,450

In addition, the actual average pumping cost with a VFD using a control algorithm is included to illustrate the additional cost savings when operating with

the new SCADA system. Note that the average cost to pump a single acre-foot (AF) of water has increased from $0.08/kWh to $0.11/kWh since the original analysis was completed. It should also be noted that the 1996-2004 average and maximum volume of water pumped (9,136 AF and 13,424 AF) was significantly higher than the ballpark estimates used in the original analysis (6,000 AF and 8,000 AF).

Table 2 shows the anticipated annual savings of approximately $2,000 to the company on Portuguese Bend's main canal due to the reduction in spilled water along the canal. The data from Table 1, combined with the estimated savings shown in Table 2, indicates an average annual savings of over $18,000 per year, which will increase even more in the future as energy costs continue to increase.

Table 2. Average annual savings anticipated from a reduction in Portuguese Bend canal spill with the new VFD and SCADA system.

Description	Amount
Approximate annual spill at end of canal (acre-feet)	200
Possible reduction in spill with VFD (acre-feet)	120
Water value as missed opportunity to sell ($/acre-feet)	$12.00
Possible revenue from missed sales annually ($)	$1,440
Approximate pumping cost $/acre-feet (from pump test data)	$4.18
Energy savings from reduced pumped volume ($)	$502
Total Anticipated Canal Spill Savings	**$1,942**

Table 3 shows the pumping volume and electricity billing data from 1996 through 2004. The key values to note are the energy requirements to pump a single acre-foot (AF) of water, shown as kWh/AF. After the VFD with control algorithm was installed, the average kWh/AF dropped approximately 25%.

Table 3. Actual energy savings data comparing pre-VFD, post-VFD, and post-VFD with control algorithm.

	Pre-VFD				
	1996	**1997**	**1998**	**1999**	**Average**
Plant Meter Volumes (AF)	9,683	6,863	4,314	6,441	6,825
Plant Meter readings (kWh)	412,480	342,400	256,160	334,300	336,335
(kWh/AF)	42.6	49.9	59.4	51.9	**50.9**
Total Electric Bill ($)	34,813	29,153	21,837	26,070	27,968
Average Electricity Cost ($/kWh)	0.08	0.09	0.09	0.08	0.08

	Post-VFD		
	2000	**2001**	**Average**
Plant Meter Volumes (AF)	11,512	8,555	10,034
Plant Meter readings (kWh)	439,120	321,840	380,480
(kWh/AF)	38.1	37.6	**37.9**
Total Electric Bill ($)	33,474	29,868	31,671
Average Electricity Cost ($/kWh)	0.08	0.09	0.08

	Post-VFD & Algorithm			
	2002	**2003**	**2004**	**Average**
Plant Meter Volumes (AF)	10,978	10,457	13,424	11,620
Plant Meter readings (kWh)	390,560	345,760	463,280	399,867
(kWh/AF)	35.6	33.1	34.5	**34.4**
Total Electric Bill ($)	48,498	41,011	44,417	44,642
Average Electricity Cost ($/kWh)	0.12	0.12	0.10	0.11

The SCADA System

Overview: The basic objective of the automation at Portuguese Bend was to vary the pump flow rates from the pumping plant in order to maintain a target water level in the canal. This required the integration of a VFD unit at the pumping plant and a new SCADA system. Specifically, this involved the ability to remotely monitor the system (water levels, flow rates, pumps on/off, etc.), manually control operations from SMWC's administration office, and to eventually automatically control the system using the new VFD unit. This required the integration of data acquisition components (sensors for water level, electronic flow meters, etc.) with computerized controllers for implementing supervised commands. Monitoring and controlling operations at a remote site such as Portuguese Bend further required a two-way communications network between the remote office location and the control site. Such a system is often referred to as a Supervisory Control and Data Acquisition (SCADA) system.

SCADA is a tool that allows irrigation companies or districts to acquire real-time information and control operations at remote sites from a central location, usually in the main office or at an operations center. By having this real-time information available at the office, the system can also be managed on a real-time basis, thereby providing the ability to achieve maximum water conservation and operational flexibility.

In the water industry, earlier SCADA systems installed were one-of-a-kind systems custom-designed for a specific job. As a result, these systems were not industrially hardened in most cases. Their relatively short-term design efforts did not address all of the day-to-day conditions the components would be subjected

to. Consequently, system reliability was low. In addition, the communication protocols were all unique within these proprietary systems; therefore, no interchangeability between components and different vendors was possible. The overall communication systems used also added to the unreliability of early SCADA systems. The older systems typically used lower frequency voice radios for data transmission and were prone to many outside disturbances.

Current SCADA systems are now being designed under a term called "open architecture". This new approach uses off-the-shelf, industrially hardened components, which can be linked together using common communication protocols. One such protocol currently adopted by the industry is Modbus. The current system's configuration assembles individual components, called Remote Terminal Units (RTU's), to control or monitor each site independently. These standard components are then configured (programmed) for the specific task. The site RTU information is then linked back to the central location via radio communication. The open architecture and industrially hardened components have allowed increased scalability and reliability.

Radio communication for SCADA systems has also improved. Equipment and FCC regulations have allowed the operation frequencies to increase, thereby improving reliability. One notable advance in radio communication has been the FCC approval of a technology known as Spread Spectrum radio. This is an unlicensed 900 Mhz frequency 'hopping' technique that provides reliable communication within about a 15-mile range. The range can be extended with a repeater configuration.

Project Phases: Due to the complex nature of installing a SCADA system into an irrigated area, successful implementation is best accomplished in phases. Initiating change in the routine operation of key facilities and altering the day-to-day activities of company or district personnel can create significant uncertainty. It is therefore necessary to address this uncertainty during each step of the process and gradually build up a level of confidence in the participants. Achieving this critical "buy-in" from the people who will actually use the system is essential for the success of modernization projects. This phased approach has important benefits, including maximizing reliability while allowing an irrigation company or district to prioritize critical modernization needs and implement components on a site-by-site basis. Styles et al. (1999) further describes phased approached advantages based on experience in modernization projects in irrigation districts.

The Project Phases used for installing a SCADA system for SMWC are:

- Phase 1 (Completed in April 2001). The first phase of the SCADA part of the project was to install, test and calibrate a new water level sensor in the head of the main canal at Portuguese Bend. The new sensor located in a stilled area at the start of the canal was connected to the RTU/PLC at the Portuguese Bend

pumping plant. The new sensor installation was set up so that water levels in the canal were measured once per second and transmitted via radio to the RTU/PLC, where the levels were stored in a data table and averaged over a one-minute time interval. Upon completion of this task, the Lookout® screens at the district office included information on the canal water levels at two locations, the river stage, the status of each pump (on/off and speed) and target depth (water level setpoint). In addition, the Lookout® screens were configured so that the target depth could be remotely changed from the office (for future automatic control) and so that up to 15 coefficients used for the distributed automatic control could be remotely changed from the office. However, the ability to change these coefficients were "hidden" so that only authorized personnel could change the values.

- Phase 2 (Completed in June 2001). This was the first step toward automating the site, although nothing was actually automated at this stage. The VFD pump was tested on-site in manual mode with occasional remote manual operation, in which the operator sets the motor speed control using the percent speed control located in the pumping plant. This phase facilitated testing of new communications equipment, sensors, VFD controls, connection to the office computer, a new air/vacuum relief valve, etc.

- Phase 3 (Completed in October 2001). This was the second step toward automating the site. There was a continuation of the remote manual mode of operation, but it was expanded to include a new flow meter. Rather than using only water levels as feedback, the operators now had information on specific flow rates at the pumping plant. A new electronic flow measurement device (Panametrics acoustic meter) was installed on one of the three pumping units and the flow rate was available to the operator. The digital display screens for the new Panametrics meters are shown in Figure 4. This did not mean that operators were expected to make hourly changes from the remote office location. This step required at least two months of operational testing that extended into the peak irrigation season.

Figure 4. Digital display screens for new Panametrics flow meters inside the
Portuguese Bend pumping plant.

- Phase 4 (Completed in December 2001). This was the third and final step of
  automating the Portuguese Bend pumping plant. A Proportional-Integral-
  Filtered (PIF) algorithm for control of the site was programmed into the
  RTU/PLC and implemented. The control algorithm was a PIF algorithm
  supplied by ITRC and not the internal Proportional-Integral (PI) equation
  supplied by the VFD's manufacturer.

  The Lookout® screens in the office necessary to support this automation were
  already in place. The ladder logic and additional site programming were
  completed during this stage. At this time the effect of fluctuations in the
  Sacramento River level was factored in and added to the ladder logic
  programming, allowing the minimum VFD speed to shift with the river level.
  The Lookout® screens were modified to allow a person in the remote office
  location to shift the pumps to automatic or manual control. In the case of
  remote manual control, this meant the ability to control the speed of the VFD
  and the number of pumps operating from the office. This final step allowed
  for the fullest possible (or desirable) automation of the site.

CanalCAD Modeling: During the modernization effort, ITRC completed several
unsteady flow hydraulic simulations on the first pool of the Portuguese Bend
canal to determine the optimum control scheme for the new VFD unit. The
algorithm uses PIF control logic based on water depth measurements 1,800 feet
downstream of the Portuguese Bend pumping plant. The algorithm controls that
water depth using the VFD and single stage pumps in the pumping plant.

The following is the control logic with optimized algorithm parameters:

VFD pump speed change: DS =1.3 * Round (DQ, 3)
Required flow rate change: DQ=35.315*[KP*(FE1-FE2)+(KI*FE1)]
                  with: FE1 =fc*FE2+(1-fc)*ENOW
                            FE2 = FE1 of previous step.
                            KP = -6.50
                            KI = - 0.18
                            fc = 0.84

Simulation Results: Figure 5 summarizes the best modeling results and algorithm for controlling the water depth about three-quarters of the way downstream from the Portuguese Bend canal. The graph demonstrates satisfactory water level control with frequent flow rate changes over a relatively short period of time using the ITRC-selected control algorithm. The target water level to maintain is 3.4[4] ft and the control location is 1,800 ft downstream of the pumping plant. This is the location of two transducers for measuring water depth[5].
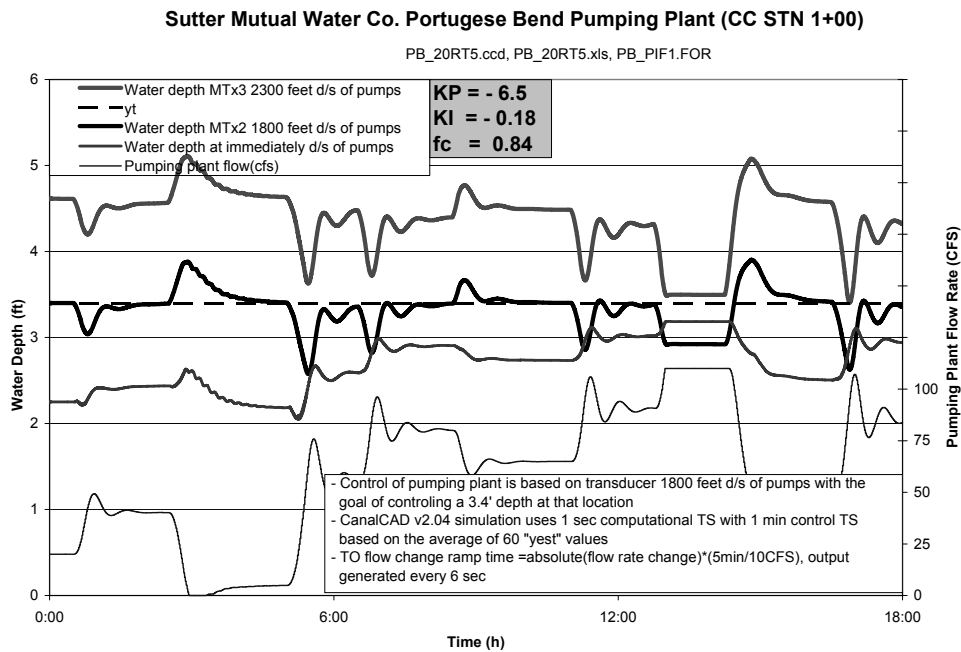
Sutter Mutual Water Co. Portugese Bend Pumping Plant (CC STN 1+00)

PB_20RT5.ccd, PB_20RT5.xls, PB_PIF1.FOR

Figure 5. Water level control results when turnout flow changes occur at a rate of 5 minutes for every 10 cfs change.

---

[4] The target water level was later changed to 5.6 ft after the canal was de-silted and the sensor height adjusted.
[5] A redundant measurement (Y2) is used to check the integrity of the (Y1) measurement, which is used in the control logic.

The control action occurs once a minute based on the average of at least 60 measurements of water depth. The graph presents the control results for nine simulated end-of-canal turnout flow changes that range from 5 to 110 cfs and that occur over an 18-hour period. The turnout flow changes occurred based on five minutes per every 10 cfs change in flow.

The graph shows the following information:
- Water depth immediately downstream of the pumping plant,
- Water depth at 1,800 ft downstream of the pumping plant,
- Water depth at 2,300 ft (end of the pool), and
- Pumping plant flow rate

Documented VFD Response: The documented response of the Portuguese Bend pumping plant from field tests conducted in December 2001 is shown in Figure 6. During the final evaluation, the demand flow was varied with multiple flow rate changes to test the response time, stability and robustness of the VFD and SCADA systems. The flow changes were made manually by the operator adding or removing weir boards and opening or closing the gate at the check structure located at the downstream end of the first pool of the Portuguese Bend canal.
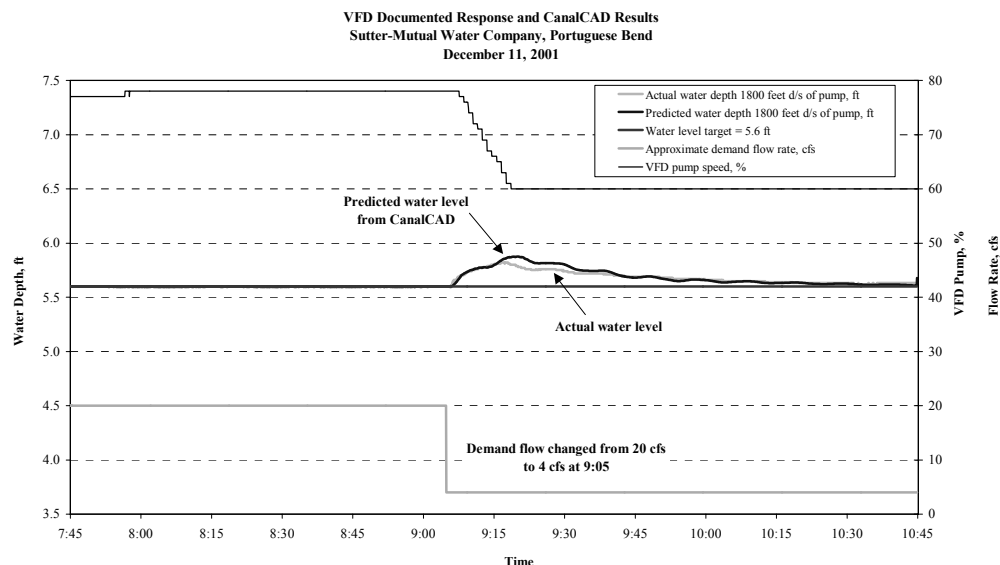

Figure 6. Documented VFD response, water level control results and predicted water depth with an 80% change in demand flow.

SUMMARY

The modernization effort at SMWC continues. SMWC intends to install a SCADA system in its two Tisdale pumping plants during the construction of a 300-foot long positive barrier fish screen begun in July 2005 and scheduled for completion in 2007. Savings resulting from the installation of the VFD and

SCADA system at the Portuguese Bend pumping plant have shown important benefits to the water company and reclamation district as a whole, especially in the area of conserved water and reduced energy costs.

REFERENCES

Schantz, F.F., S.W. Styles, C.M. Burt, D. Stevens, and B.J. Freeman. 2002. Modernizing Irrigation Facilities at Sutter Mutual Water Company: A Case Study. Presented at the USCID Conference on Energy, Climate, Environment and Water - Issues and Opportunities for Irrigation and Drainage. July 9-12, 2002. San Luis Obispo, California.(http:www.ffschantz@aol.com).

Irrigation Training and Research Center. 2003. California Agricultural Water Electrical Energy Requirements. ITRC Report No. R 03-006, Available at (http://www.itrc.org/reports/energyreq/energyreq.htm).

Styles, S.W., C.M. Burt, M. Lehmkuhl, and J. Sweigard. 1999. Case Study: Modernization of the Patterson Irrigation District. Presented at the USCID Workshop on Modernization of Irrigation Water Delivery Systems. Oct. 17-21, 1999. Phoenix, Arizona.

TRUCKEE-CARSON IRRIGATION DISTRICT TURNOUT WATER MEASUREMENT PROGRAM

David Overvold[1]
Stuart Styles[2]

ABSTRACT

The Irrigation Training and Research Center (ITRC) has been working with TCID and USBR as part of the Newlands Project in the Truckee and Carson River basins of California and Nevada. In 1997, ITRC developed a volumetric measurement program to provide documented and reasonably accurate turnout delivery measurements in TCID. This program has involved a series of steps for implementing a volumetric water measurement program, including elements for categorizing, prioritizing, designing, and installing flow measurement devices at turnouts that account for 75% of deliveries (by volume). Since that time, TCID has incorporated ITRC recommendations and has greatly exceeded expectations. As a result of this Water Measurement Program, TCID and USBR have jointly advanced the water measurement program to a point where an accuracy of +/-10% has been achieved on many of the district turnouts.

INTRODUCTION

The Irrigation Training and Research Center (ITRC) of California Polytechnic State University, San Luis Obispo, has been working under a technical assistance contract with the Truckee-Carson Irrigation District (TCID) to provide technical support and training to improve the performance of the Newlands Project in conjunction with other agencies. The Newlands Project has included projects related to water measurement, canal modernization, operational strategy and resource planning, on-farm water management, and SCADA systems.

Background

The Newlands Project is located in the Truckee and Carson River basins of California and Nevada as shown in layout map in Figure 1. Water used for irrigation on approximately 73,700 acres of water-righted land is diverted from both the Truckee and Carson Rivers. There are approximately 391 miles of main canals, laterals, and sub-laterals that deliver irrigation water to an estimated 1,500 farm head gates. Lahontan Valley wetlands, including primary wetland habitat in the Stillwater National Wildlife Refuge and Management Area and the Carson

---

[1] District Engineer, Truckee Carson Irrigation District 2666 Harrigan Road Fallon, NV 89407 dave@tcid.org 775-423-2141
[2] Director, Irrigation Training and Research Center, California Polytechnic State University. San Luis Obispo, CA 93407. sstyles@calpoly.edu 805-756-2429.

Lake Pasture and Marsh, and numerous "secondary" wetlands habitats, are included in the project.
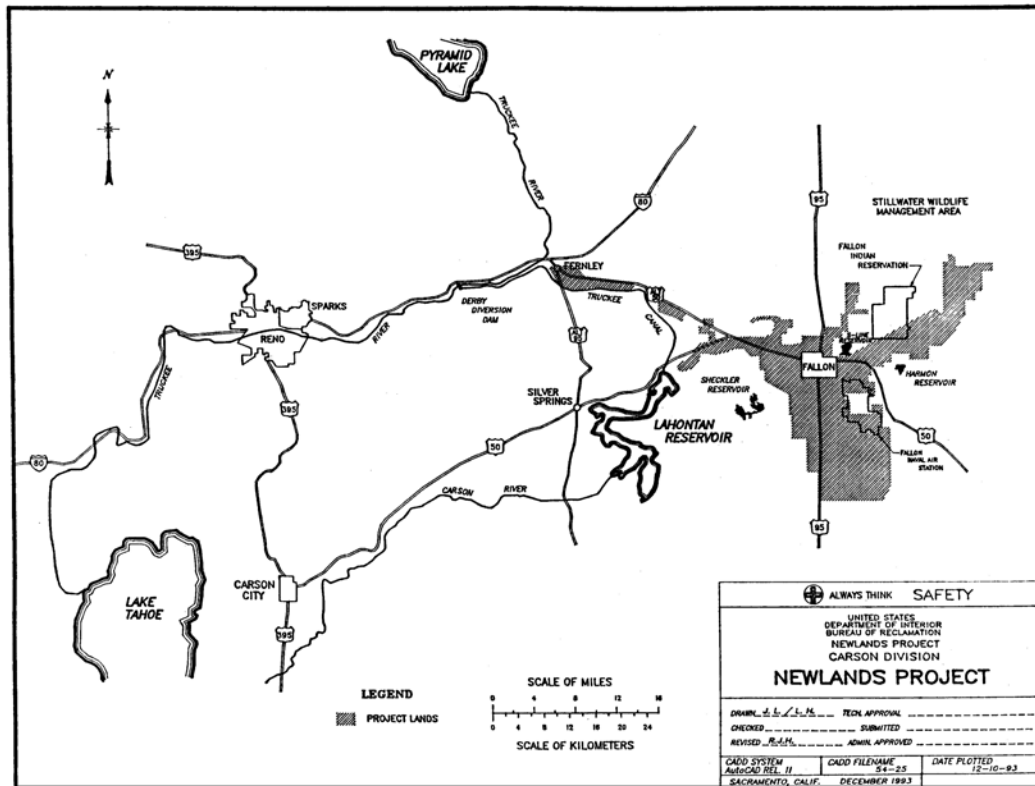

Figure 1. Newlands project layout map.

The Newlands Project is governed by an Operations and Maintenance Contract (no. 7-07-20-X0348) between the United States Bureau of Reclamation (USBR) and TCID, which was signed in 1996 and approved by the Nevada 3rd Judicial District Court in 1997. The O&M Contract contains a Water Management provision that requires the preparation of a Water Conservation Plan, continuation of a water measurement program, and the establishment of a Water Conservation Fund, among other obligations. In addition, the Operating Criteria and Procedures (OCAP) approved in 1998 and incorporated into Public Law 101-618 sets forth provisions for calculating the maximum annual allowable entitlements and implementation of conservation measures to improve project efficiency, including penalties and incentives related to phased efficiency targets. In a full entitlement year, the established target for project efficiency is 68.4% after a phased-in period.

The Volumetric Measurement Program

In 1997, ITRC was asked to develop a volumetric measurement program to provide documented and reasonably accurate turnout delivery measurements in TCID. The resulting ITRC study listed a series of steps for implementing a volumetric water measurement program, including elements for categorizing, prioritizing, designing, and installing flow measurement devices at turnouts that account for 75% of deliveries (by volume). To fund these activities, TCID committed the entire Water Conservation Fund established under the O&M Contract to the water measurement program. The water measurement program requirements as outlined by ITRC in March 1997 are outlined in Table 1.

Table 1. Original water measurement program requirements.

Step 1	Categorize the turnouts	• Location/available head • Delivery life (based on lands that may be sold for water rights) • Probability of errors
Step 2	Develop software and procedures for recording volumes	• Review of electronic measurement devices • Review of potential sites to demonstrate units • Incorporate data into existing water delivery procedures
Step 3	Categorize/prioritize the turnouts	• Ten categories based on criteria
Step 4	Develop timelines and verification procedures	• To be completed after Steps 1-3 are finished
Step 5	Design new structures	• Complete site investigations • Need at least one person to complete this task
Step 6	Install new structures	
Step 7	Train operators	• Includes both field operators and office staff • Modified operation will need to be incorporated into billing
Step 8	Compare results	• Compare historical delivery data to new data • Verify procedures
Step 9	Re-assess the program	• Annual re-assessment required • Evaluate TCID's actions

Evaluation Approach

In order to make appropriate recommendations for district improvement, it was necessary to complete a preliminary water balance and water quality analysis. The water balance analysis was based on USBR water budget guidelines, modified to more appropriately follow what was actually occurring within the district. One of the major recommendations for the district included enhanced monitoring of district inflows and outflows to improve future water budgets.

The water balance was completed for 1994 to 2000. 1993 was the last year of a 7 year drought the plagued the western U.S. During this time the wetland acreage dropped to as low as 2,400 acres in the entire valley. Since the end of the drought, the wetland acreages and depleted lakes and reservoirs have been steadily increasing in size within the water budget boundaries increasing the overall storage within the district boundaries.

During 1999 and 2000, a total of 352 sites were evaluated and categorized. The completed review concluded that while Replogle flumes were a viable option for approximately 42% of the sites evaluated, this method of flow rate measurement could not be used at every turnout.

Taking into account the information gained from the water balance and a water quality analysis, as well as the current level of system performance and the cost-effectiveness of installing flow measurement devices, ITRC identified recommendations for TCID as part of an updated operational plan. These recommendations involved several water management and hardware options, including:

- Automated control structures

- Communication systems

- Flow measurement devices (Replogle Flumes and Doppler meters)

- Water level control options

- Recirculation facilities

Figure 2. Flow measurement flume at TCID.

RESULTS

As required in the Water Management provisions of the O&M Contract, the district has implemented the recommended water measurement program and cooperated with annual reassessments of related activities.

TCID is one of the few irrigation districts in the Western US that has taken the extra steps required to measure water accurately to the farm using traditional water measurement structures. The results of their overall efforts can be clearly seen in the reductions of diversions from the Lahonton Reservoir (Figure 3).
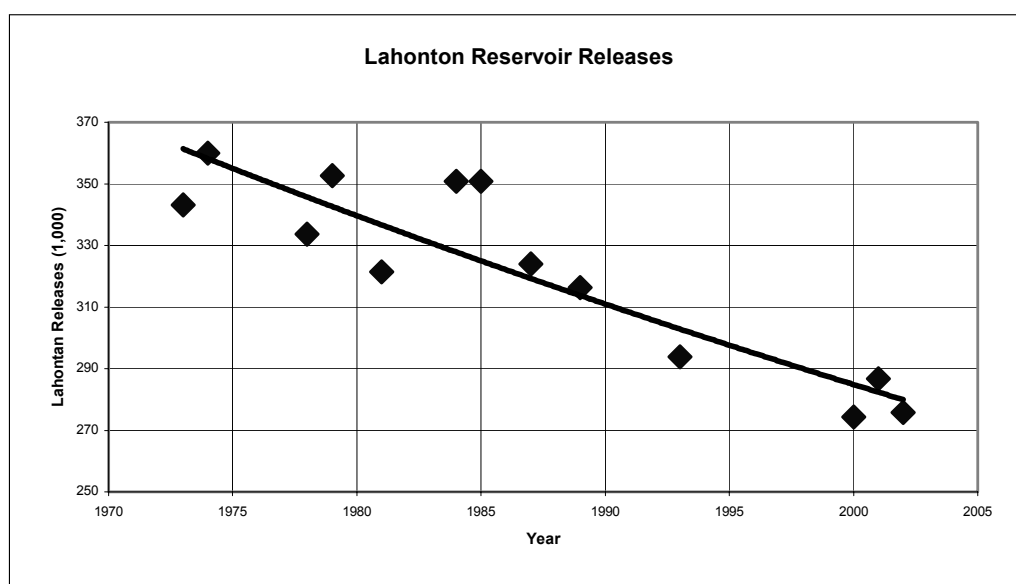
Lahonton Reservoir Releases

Figure 3. Reduction of annual diversions from Lahontan Reservoir from 1978 through 2004 (USGS).

Following ITRC recommendations through the Turnout Water Measurement Program, TCID has accomplished and continues to achieve the following:

- Prioritization of turnouts for inclusion in the water measurement program and installation of Replogle flumes at high priority locations.

- Investigation of new electronic Doppler flow meters for non-standard turnout sites, as well as laterals and major diversion points in the district.

- Construction of a team of technicians with responsibility for current meter verification and calibration.

- Dedication of the appropriate level of resources for ongoing activities related to the water measurement program, such as flushing stilling wells, removing

moss and debris from stations, changing batteries, collecting data, calibrating stations, and repairing devices.

As a result of this Water Measurement Program, TCID and USBR have jointly advanced the water measurement program to a point where an accuracy of +/-10% has been achieved on many of the district turnouts. In the past several years, TCID has actually surpassed the requirements imposed upon the district, and has implemented each step of the Water Measurement Program quicker than expected (Figure 4).
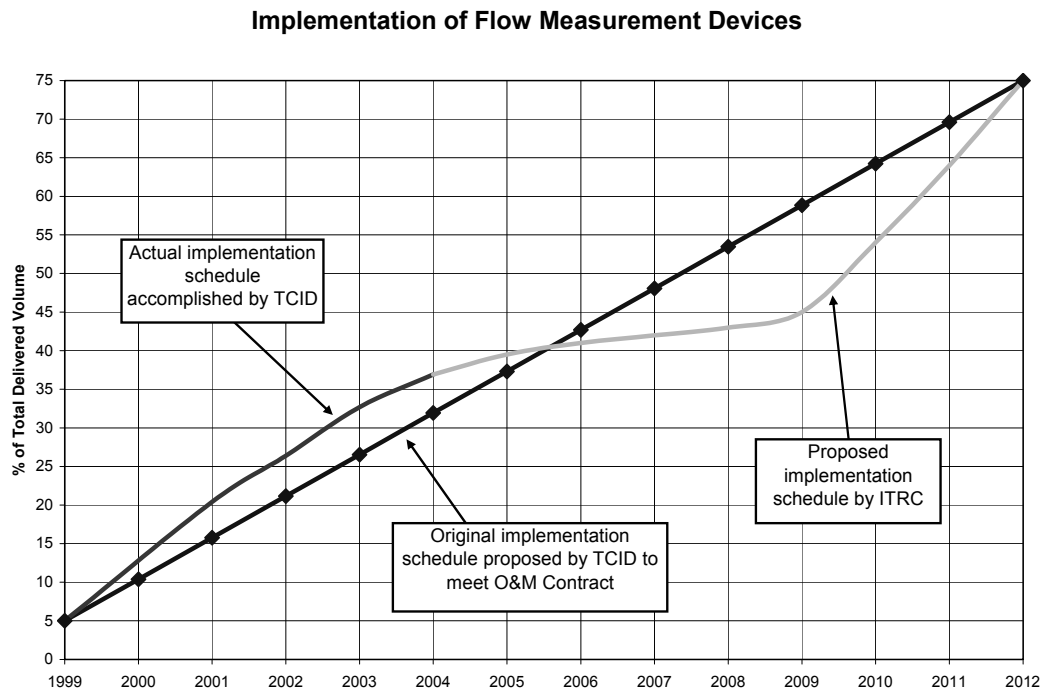
Implementation of Flow Measurement Devices

Figure 4. Implementation schedule for water measurement devices since 1997.

CONCLUSION

Both TCID and USBR recognize the critical need to develop new strategies for improving project efficiency. To address this situation, the ITRC has recommended that a comprehensive study be conducted that examines what has been done to date as a result of the Water Conservation Plan and prioritizes future actions as part of an overall strategy to improve project performance.

This type of modernization evaluation requires a holistic approach that takes into account the current level of system performance and the cost-effectiveness of installing additional flow measurement devices at this time. The proposed study will identify modern water management and hardware options (control structures, communication systems, flow measurement devices, recirculation facilities, etc.)

and make recommendations for implementing these options as part of an updated operational plan. It is essential that hardware or automation recommendations be linked to a feasible operation plan if the investment is to provide maximum benefits.

There are two considerations that suggest a fresh look be taken at modernization options:

1) The cost of flow measurement sites (including design, data collection, site surveying, construction, calibration, and maintenance) has exceeded by a significant amount the initial estimates in the Water Conservation Plan, and furthermore, the next level (priority 2) will likely have an even higher cost to measure a relatively smaller volume of delivered water

2) TCID has exceeded the mandated OCAP efficiency with only the priority 1 flow measurement devices installed (55 devices). This re-assessment of priorities would ensure that the best possible use is made of limited resources – funding, staff time, and technical assistance.

By continually re-assessing the water measurement program at TCID, it is ensured that the district will be offered the most up-to-date and accurate recommendations to improve its modernization efforts. The district and USBR's willingness to participate in such a far-reaching program indicates that even far better water conservation successes may be achieved through this combination of cooperation, research, and implementation.

THE MYTH OF A "TURNKEY" SCADA SYSTEM
AND OTHER LESSONS LEARNED

Robert E. Norman[1]
Ram Dhan Khalsa[2]

ABSTRACT

The Bureau of Reclamation's Western Colorado Area Office has been working on a canal modernization project on the Grand Valley Project for roughly 11 years. During that period we have built seven new check structures, a pumping plant, made several modifications to structures along the canal and, finally installed a SCADA system to accompany automation of check structures and pumps. The cast of characters in implementing our SCADA system was the water user organization, the Cal Poly Irrigation Training and Research Center (ITRC), the SCADA "integrator," and the Bureau of Reclamation. The concept of a turnkey SCADA system is that you outline what you want your SCADA system to be able to do, write technical specifications to achieve that objective, and then hire a SCADA integrator to make it happen. Is it plausible that the technical specifications can explain the existing system to the extent an integrator can accurately estimate the cost of the SCADA system? Did the person writing the technical specifications understand what SCADA can and cannot do? Did that person understand what the water users wanted the system to be able to do? There are many steps to implementing a SCADA system. The next step of often guided by what happened on the last step. We would like to share our experience for having this cast produce a final product and what steps we took along the way. Hopefully, your path to a final product will be more direct than ours.

This paper will discuss the process used to implement a canal modernization program, which included a SCADA system, and more importantly some of the lessons learned. But before discussing "turnkey" SCADA it is important to provide a brief background.

BACKGROUND

Although we have been working on the canal modernization project for 11 years we are not yet done. This project was pursued to reduce river diversions and leave more water in the river to benefit endangered fish. There are several non-endangered fish benefits, but ultimately, the goal is to help recover endangered fish. The fact that there are other beneficiaries made the project politically possible. The modernization project was funded by an endangered species program. The improvements were a one-time shot so it was in our interest to make sure we did the job as well as we could. While this is true for any project,

---

[1] Planning Team Leader, Bureau of Reclamation, Western Colorado Area Office, 2764 Compass Drive, Suite 106, Grand Junction, CO 81506, rnorman@uc.usbr.gov.
[2] Civil Engineer, Bureau of Reclamation, Western Colorado Area Office, 2764 Compass Drive, Suite 106, Grand Junction, CO 81506, rkhalsa@uc.usbr.gov.

since the endangered species program was more interested in saving water than they were the cost of saving water, we had the funds to take a thorough look at the project and select what we thought would be the best strategy both in water savings and a robust system.

The 55-mile long canal, 70 laterals, and diversion dam are part of the Bureau of Reclamation's (Reclamation) Grand Valley Project. It is Reclamation's project number 8 and celebrated its 100 year anniversary this year. Our project canal had few existing check structures, very limited local automation, and no system storage. There were radial gates, slide gates and a few stoplog check structures.

We used the term "our project" because that is the way we see it. The project is technically owned by Reclamation and operated by the Grand Valley Water Users' Association (GVWUA). So the "our" is the combination of GVWUA and Reclamation. This perception is both interesting and important. It is interesting because it is not even shared throughout the Western Colorado Area Office much less Reclamation. While we have a wide range of relationships between the Western Colorado Area Office and our projects operators, there is even a broader range in other Reclamation offices. At some locations and times, these relationships even become adversarial.

In implementing the canal modernization program on the Grand Valley Project the relationship between GVWUA and Reclamation is important because of the nature of both organizations. The project serves about 24,000 acres with an annual budget of about $1.2 million. Grand Valley Water Users' Association is run by a manager and a staff of 12. The manager oversees the daily operation of the canal and gives orders to his operation staff. The Board of Directors of the GVWUA are more concerned that the manager understand irrigation and farming practices and do not require, and maybe, do not even prefer that the manager have an engineering background. The Association does not have an engineer on staff, but it does have a lot of experience of what does and what does not work. Reclamation staff, in general, have a more technical background but, for the most part, are not strong on the understanding of minute-to-minute canal operations - especially how those operations interface with irrigation and farming practices. As we sought the application of SCADA to our canal system it was imperative that we maintained a close relationship with the GVWUA, specifically the manager, to make sure that the improvements are compatible with their operation.

THE SCADA TEAM

This relationship and the abilities of GVWUA and Reclamation staff significantly contributed to the approach for accomplishing the modernization and SCADA project. A district with engineering staff would likely approach the project quite differently as would a district without the technical resources of an agency like Reclamation.

As part of our modernization project we hired Cal Poly's Irrigation Training and Research Center (ITRC) in San Luis Obispo, California. One of their tasks included computer modeling of our canal hydraulics. Through the use of this

model they determined the best location and design for 7 new canal check structures. In addition, ITRC determined the correct algorithm and appropriate constants to use in the gate control algorithm using the model. Simply put, the algorithm is the logic behind how to open or close a gate and how far to move the gate. We hired an integrator to write the program to implement the algorithm within the Programmable Logic Controller (PLC) and to install the SCADA system hardware and HMI.

With four players, GVWUA, Reclamation, ITRC, and an integrator, coordination was essential. We feel that one of the key requirements in having a successful SCADA system is that one of the team members have a working knowledge of what the other team members contribute. Since GVWUA had very little SCADA experience, and Reclamation had worked with ITRC on the canal study, the project oversight role was filled by Reclamation.

THE MYTH

Why do we call turnkey a myth? We think we had one of the strongest SCADA teams you could assemble when we put our system together. At the start, we did not know much, but our knowledge grew as we proceeded through the project. The ITRC has a lot of technical and hands on experience with SCADA implementation and we hired what we feel is one of the best integrators around. But even with this team, there were problems. Sometimes the "key" in the turnkey did not turn. The good news is that all of the problems were solved.

WHERE TO START?

In the beginning, the Association had no SCADA experience and Reclamation at Grand Junction had a rudimentary understanding. So we needed to develop an understanding of what SCADA is and how to implement it. One of our first steps was an ITRC SCADA short course, plus and a Canal Modernization Class conducted by Reclamation's Denver Office. What we quickly learned is that there are a lot of experts with both technical and practical expertise with a wide range of opinions.   Two key areas that the experts do not agree on are, the location of the "Supervisor," and the gate control algorithm. We are not going to attempt to resolve these issues here. The point is that it is necessary to understand the different strategies and make the decision that is best for your project.

SUPERVISORY CONTROL

The phrase "Supervisory Control and Data Acquisition" sounds simple enough. But who is the Supervisor, where does the supervisor reside in relation to the canal structures, just what is the supervisor controlling, and how is he communicating? On our canal system our goal was to control the water level in the canal in some places, and to control flows at other locations. This is done by adjusting the amount of water entering into the canal and then by opening and closing the 15 check structures along the canal.

Central Control

One school of thought is that a central decision making computer should make all control decisions. In most canal automation literature, it is assumed that the algorithm is running on a central computer. Using the algorithm, the central site would calculate the required gate movements and convey that information to each site. Control computations happen in a central location. With this form of communication, is possible to operate the canal as a whole. As an example, if water is needed at a location far downstream, all of the gates upstream from that point could in theory be opened in unison thus using some of the canal storage potential to move a change quickly through a canal. This type of control requires very reliable communication between the central site to the remote sites. In selecting this type of control, it is necessary to assess the reliability of your communications as well as the consequences of failed communication.

Central Guidance - Local Control

Another school of thought is to provide targets from a central location to the PLC at each canal structure. The central location should maintain and disseminate that information to each site. For us the disseminated information is the upstream target water level, downstream water level or target flow. Guidance can happen from an operator panel at each site or from a central location via some form of electronic communication. The algorithm actually runs on a PLC at each site. Therefore, the local computer or PLC would decide whether to open or close a gate and then issue those commands to the gate. The sites along a canal are hydraulically connected. That is, if a gate upstream opens, it would allow more water through. Eventually a downstream gate would sense this increased flow by an increase in water level. This "hydraulic" communication is slow but it is reliable. Of course, there are situations when the speed of the control is more than adequate, and other situations when it is not.

The decision for what type of control to use on our project was largely based by what happens if the communication between the supervisor and control site fails. The discussion about the best method of communication is another debatable topic but for several reasons we opted for licensed radio communication. On our sites, if the communication is lost for prolonged periods of time it is possible to provide a new target or guidance though the operator panel at each site. How likely it is that communications will be lost? In the "Other Lessons Learned" portion of this paper will discuss one of the challenges we have experienced with our radio system.

Gate Control Algorithm

We find this to be one of the most hotly debated topics of our project. The PIF gate control algorithm we use on our canal is promoted by ITRC. ITRC contends that in order to calibrate the algorithm for a particular canal with multiple gates and intervening pools in series, canal modeling is required. Reclamation's Denver Office uses a PID algorithm. They contend that calibration of the

algorithm can be accomplished through a software application without canal modeling.

Some gate control algorithms seem to be more focused on tuning a gate. Other algorithms seem to be more focused on tuning the gate to perform in a canal. When the effects of a gate downstream extend to an upstream gate, it is especially important that the algorithm tunes the gate to perform in a canal as well as being customized for individual gate characteristics. This is one of the benefits of using canal modeling to calibrate the gate algorithm. Our canal is set up so that the effect of a downstream gate reaches the next gate upstream. Without this ability, our canal water surfaces would fall to unacceptable levels. If the canal modeling had not been done as part of the modernization project and if we had not had the financial resources to prepare the canal model, we are not certain we would have come to the same conclusion.

The PIF algorithm we are using is able to respond to drastic flow changes. To get a feel for the resilience of the PIF algorithm, we decided to run a test. Late one irrigation season, when there was not much demand, we manually closed both of the radial gates on the most upstream check structures. Then we turned on the logging function for all of the downstream checks (all of which were operating on upstream control). When the pool above the upstream check got as high as we dared, we completely opened both 12-foot radial gates sending a wave downstream. The log files from the next downstream check indicated that the water level never deviated more 0.1 feet. By the time the wave got to subsequent check structures the deviation was even less.

These are not the only two gate control algorithms. Most integrators have one or two they have used with purported success. AquaSystems 2000, a gate manufacturer, has at least two different algorithms for their gates. They tune their algorithm based upon site conditions and expected flow changes.

It appears to us that that as the flexibility of the canal to respond to large flow rate or target depth changes increases, it becomes more important to model the canal system. Said another way, if you move the gates slow enough or if you make small changes in flow, you might not need to model the canal. It should be noted that most existing automation system actually operate with minimal flow rate changes, so we are not convinced that those non-modeled systems are capable of responding to dynamic sudden changes.

DATA ACQUISITION

Water Level Sensors

This area of SCADA does not seem as contentious as the control and algorithm issues. Not all hardware for data acquisition is equal. On our SCADA system we needed to measure two different physical parameters: gate position and water level. There are several ways to measure each one of these parameters. If you ask a handful of water districts and a handful of integrators, you would probably end up with two handfuls of options. Our decision on water level measurement we largely influenced by the independent testing performed by the ITRC. Based upon their findings we measured water level using pressure transducers. Our goal is to measure the water level to within the nearest 0.01 feet, which has been possible using the pressure transducers having the proper depth range.

Gate Position Sensors

As we mentioned before, part of the modernization project included the construction of 7 new check structures. The specifications required the gate manufacturer to provide a gate position sensor. The optical encoder used by the manufacturer has proven to be one of the best pieces of equipment we have seen for gate position. Gate position is calibrated based upon gate shaft rotation. With the optical encoder we are using we are able to calculate the gate position well within the required 0.01 feet.

Redundancy

The ITRC strongly encourages SCADA systems to include redundancy whenever possible. With the cost of sensors at about $500 to $650 we were a bit hesitant to take this step. Our belief was that if you get good quality equipment and have spare parts on the shelf, redundant sensors should not be required and we did not want to "gold plate" the project. In the end, the ITRC convinced us to install redundant sensors. As a result we have two upstream water lever sensors, two downstream water level sensors and two gate position sensors on each gate. For the new sites this was eight sensors. We are now on our 4th year of operation and the redundant sensors have really paid off. Even with lightening protection hardware, we have had two sensors fail due to nearby lightning strikes. Two other failures occurred when wires in a conduit broke. We think the wire broke due to freezing water in the conduit. Every time the redundant sensors continued to work.

SCADA INSTALLATION

There are several approaches to installing a SCADA system. For us, we were not only concerned about how to get the SCADA system installed, but we were also concerned about how we were going to maintain the system.

SCADA by Bid

If you plan on asking for bids for a SCADA system, some form of specifications will be required. If you have never done a SCADA system before we think it would be very difficult to prepare a set of specifications to build a turnkey SCADA system. It does not seem possible to anticipate all of the field conditions that will be encountered. For example, sometimes the limit switches on our new radial gates did not work. We also found out that the gate manufacturer wired the gate position sensors backwards.

Without good specifications an integrator has a few choices: 1) bid the job and have a high allowance for unforeseen conditions, 2) bid the job as presented and correct for unforeseen conditions through changes orders, or 3) alert you to the shortcomings of the specifications and resolve the issues before bidding. If an integrator chooses option 1, and since you may not have a good grasp of what goes behind putting a SCADA system together, you will be shocked at the bid price. You will then either think that it is not worth the price or go back and work on understanding SCADA more thoroughly. If an integrator chooses option 2, you will be frustrated by the "nit-picking" changes and additional costs the integrator wants and may end up at odds with each other. Although option 3 may be the best of the 3 options, it is difficult for an integrator. What you essentially would be asking the integrator to do is correct your specifications when the company submits the bid. If your end result was to then re-bid the project, it would be necessary to compensate the integrator for this assistance.

Turnkey SCADA is a lot like building that house - the more you understand the options, processes, and what the end result should look like, the easier it will be to define what you want. For example, you tell a contractor to build a house. You turn the key to get into the house and find that it has no water heater, heating or maybe even no windows. That may sound silly but it sounds silly because everyone knows that all houses have those components. So after your first turnkey house you know to tell the contractor to include windows, a water heater, and heating and air conditioning systems. Only this time, when you turn the key you realize that you forgot the wood trim, carpet and painting. We think the point is clear - we do not think it is possible to specify a "turnkey" SCADA system unless you have a fairly good understanding of what goes into one. And, since all canals are a little different, it will still be a "custom turnkey."

SCADA by Time and Materials

Another option would be to solicit for integrators based upon their qualifications and experience. Once you have an integrator you are comfortable with, install the system on a time and materials basis. This takes out the risk part of the bidding process for the integrator which can translate to having the project cost what it needs to. There has to be a fair amount of trust and good communication to make this work, but it is worth considering.

SCADA by Example

In our case, there are not any SCADA integrators in the Grand Junction area who have done canal systems. There are a lot of gas and oil field integrators but none with canal experience. In the end we wanted to be more self-sufficient so we opted for a hybrid model. We selected an integrator from out of the area that has a background in canal automation. We then asked that integrator to provide us a bid to build two SCADA boxes, do the necessary programming, develop the operator panel software and then install one of the SCADA boxes at one of our sites, and then make that site fully functional.

After that project was done we paid the integrator on a time and materials basis. Using the second of the two original boxes, we made the remainder of the SCADA boxes. Don't misunderstand me, there was a lot of hand holding at first. But as we built and installed subsequent SCADA boxes, our understanding grew as well as our comfort level. For us, that was one of our objectives – we wanted to be personally involved in a "hands-on" manner.

As a result of that effort we can now make modifications to our system and incorporate new sites. When we get into areas where we are unsure about the correct way to do something, we ask an integrator.

OTHER LESSON LEARNED

Radio Challenges

During the discussion of supervisory control we mentioned the possibility of losing communication. Communication in our SCADA system is accomplished through a licensed radio system. There are many manufacturers of radios that will work in SCADA systems. Some have a more proven track record than others and some seem willing to tell you anything to sell you a radio. After talking to several SCADA integrators, the ITRC, and our local radio experts, we purchased a Microwave Data Systems (MDS) radios. We chose a frequency that we felt would do the best job due to the terrain and distances on our project. Due to our terrain we needed a repeater station. We contracted through a local company that specializes in repeater sites. Since its repeater site was located on a 10,000 ft mountain peak, about 5,000 feet above our valley floor, lightening is a known problem. Consequently, we took all the precautions we could for lightening protection.

When we first started the system up we were getting interference from a nearby frequency. The radio company installed a filter on the antenna that allowed our radio to see only our frequency. At that point our radios were working nearly flawlessly.

This operation continued for over a year and then in the first week of May 2004, we started losing the ability to talk to our sites as well as get status information from the sites. We initially thought we were trying to get too much information too frequently from our sites, so we spent some time making adjustments to our

software. After this things seemed to be better but not fixed. The next step was to examine some of the radios' settings which controlled how long the radios would wait for a response before timing out. This seemed like it helped a little but we were still having problems. We then tried upgrading the radio software. They called it the radios' firmware. Again, the problem did not go away.

It seemed like something was interfering with our system. Our radio experts were fairly sure we were trying to get too much information through the system, thus causing us to interfere with ourselves. This search lasted most of the summer and we never did find the problem. At the end of our irrigation season we turned all of our radios off. With the remote radios off, we were still receiving information at the master station. At this point we knew the interference was coming from another radio system, only we had no idea where.

Our radio license was granted by the Federal Communication Commission (FCC). Supposedly, when they issue a license they will not issue the same frequency within 75 miles. The FCC has a comprehensive web site on which it is possible to check for all licenses within a defined radius. So we asked their system to list anyone who had a license on our frequency within 200 miles of our repeater site. There were 7. We went through the list one by one and mostly for terrain reasons were able to eliminate all by one, Chevron Oil. They have a repeater site 78 miles from our site on the same frequency. With all of our radios off, our radio company went up to the repeater site and was able to listen to the Chevron sites on a hand held radio.

What is even more amazing about this problem is that our radios are MDS model 4710A. They will only talk to other MDS 4710A radios. So not only did Chevron end up on the same frequency, they ended up with the same radios. Chevron tried turning down the power output of their radios but we were still getting interference. The final solution is that Chevron is in the process of getting a new license on a new frequency.

The point I would like to make is that the entire time we were experiencing these problems, since control occurs at each site, the sites continued to run. We were able to communicate often enough to change the water levels if required so the system was still functional.

Programming Challenges

Page 2 of the March 2003 Irrigation Training and Research Center's SCADA Short Course training manual has the following list of SCADA components: sensors, actuators, the PLC/RTU, communication link and a Master Station. While this is a good list of the hardware required for a SCADA system, it does not include what we found to be the most challenging, the software. In our system we currently have at least 3 different software applications. The program in the PLC/RTU, the operator panel at the site used to interface with the PLC/RTU, and the interface at the Master Station. Of these software applications, the PLC/RTU program was the most challenging.

There are different programming languages that can be used for the PLC program. Some tie you to specific hardware more than others and some may be easier for you to understand. The language we initially used for our SCADA system is an excellent tool for the application but we found it difficult to understand. In addition, the language only worked in the PLC/RTU of one manufacturer. We wanted to understand the PLC program and we wanted to not be tied to specific hardware. So we changed the programming language during our SCADA development. Fortunately, our PLC/RTU did support the alternative programming language.

Some of the programming languages actually look like flow charts. Consequently, they are easier for non-technical people to understand. If you want to be able to be involved at this level, it is worth discussing this aspect during your SCADA development process. We have gotten involved to the point that we do a large portion of the programming (but not the development of the algorithm itself). At the very least, we recommend that you choose a PLC that can be programmed in a non-proprietary language.

IN SUMMARY

The concept "turnkey" implies that you don't need to worry about attention to detail, persistence, and cooperation. Alarms should go off if someone says that they will create a turnkey system when they have not taken the time to understand your irrigation system. The reality of the situation is that if you want the system to work well, you have no choice but to get involved at least to some degree. The SCADA implementation process takes persistence and cooperation. There may be minor hurdles along the way but everyone should look at them a learning opportunities. Team work with an identified team coordinator is essential. There are a lot of details that when they work together correctly, create a well working SCADA system. Don't leave them to chance.

During the drought in the 2002 and 2003 irrigation seasons the canal modernization and SCADA system have proven to be invaluable. The SCADA system and canal improvements have allowed GVWUA to operate the canal during this period of drought and still meet the demands of water users. Without these improvements, all upstream storage would have been depleted. This did not only benefit the Grand Valley Project but all water users throughout Colorado.

To us the success of the system revolved around team work, education, and being willing to get involved with every step of the process, and doing as much of the work as we can. The "Myth" of turnkey SCADA is largely due to the fact that no two canals are the same. Some will have different algorithms, some will have to deal with winter operations, some will have large flow changes and some may be nearly steady state. Maybe you could make a McDonalds turnkey, but you would have a hard time getting them to turn an existing restaurant into a McDonalds.

CANAL MODERNIZATION IN CENTRAL CALIFORNIA IRRIGATION DISTRICT – CASE STUDY

Charles Burt[1]
Robert Stoddard[2]
Russell Landon[3]
Chris White[4]
Beau Freeman[5]

ABSTRACT

Central California Irrigation District (CCID) provides water from the Mendota Dam northward approximately 110 miles, through and to its service area of approximately 120,000 irrigated acres. CCID enjoys a substantial advantage of having some of the most senior water rights in California, but is simultaneously challenged by serious (and increasing) water quality restrictions for its return flows into the San Joaquin River.

Recent California law recognizes water transfer as a reasonable and beneficial use of water. Therefore, CCID has begun an aggressive program to modernize its canal system with the goal of improving water delivery service and increasing project irrigation efficiency. Funds received from conserved and transferred water are used to expand the modernization program. The net effect is improved water supply to other users and improved water management for the downslope drainage system.

This paper will address the district's motivation for modernization, the development of the modernization plan, challenges encountered, the roles of various players (consulting engineer, district, integrator, contractors, ITRC), and technical details regarding project implementation. Currently, approximately 40% of the initial modernization plan has been implemented, including downstream control, upstream control, and a large regulating reservoir – all automated with Programmable Logic Controllers (PLCs).

---

[1] Chairman, Irrigation Training and Research Center (ITRC), California Polytechnic State University (Cal Poly), San Luis Obispo, CA 93407; cburt@calpoly.edu
[2] Principal Engineer, Stoddard and Associates Los Banos, CA; rms-sa@pacbell.net
[3] Engineer, Central California ID (CCID), Los Banos, CA; ccidengr@sbcglobal.net
[4] General Manager, CCID; ccidwhite@sbcglobal.net
[5] Senior Engineer, ITRC; bfreeman@calpoly.edu

INTRODUCTION

Location

The CCID service area encompasses approximately 140,000 acres (120,000 irrigated acres) in the central San Joaquin Valley, with the district headquarters in Los Banos. An overview of CCID's location in California is shown in Figure 1. CCID is part of the San Joaquin River Exchange Contractors Water Authority (Exchange Contractors), which holds pre-1914 water rights for water from the San Joaquin River.

Central California Irrig. Dist. (CCID)

Figure 1. Location of CCID in Central California.

The Delta Mendota Canal (DMC) was constructed in the 1940's to provide an additional water supply to the Exchange Contractors' Service Area. In turn, the new canal allowed for the construction of the Friant Unit of the Central Valley Project. Sacramento River water was diverted through the DMC to the Mendota Pool, which continues to serve as the primary diversion point for the Exchange Contractors. The DMC flows southward to the Mendota Pool, which is the location of the original water right point of diversion from the San Joaquin River.

The Mendota Pool serves as the headworks of the two primary canals (the Main Canal and the Outside Canal), which then flow northward.

Figure 2 illustrates the general layout of the CCID canals. The details of the lateral canals are not important for this paper, but one can see that there is a clustering of lateral canals in the southeastern area, and another in the northern area, and numerous consumer operated and maintained ditches serviced by head gates on the two major canals. The Main Canal is about 80 miles long, with a capacity of 1600 CFS; the Outside Canal is about 73 miles long with a capacity of 500 CFS.
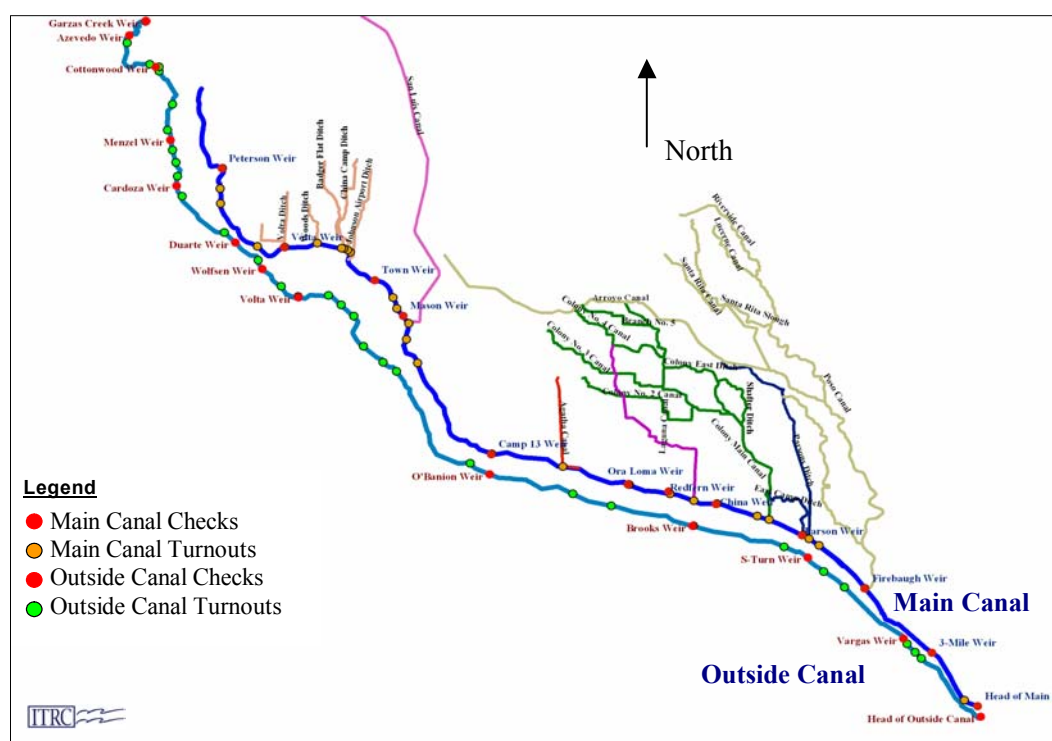

Figure 2. CCID canal layout.

The two primary canals are fairly flat, winding, unlined canals that have remained in about the same condition for the past 100 years. There are also several direct connections from the DMC to the Outside Canal on the western boundary of the service area, which serve as bypasses to provide additional capacity and operational flexibility. Surface drainage outflows from CCID flow northeast into neighboring irrigation districts and into the grasslands and the San Joaquin River.

The schematic layout of the CCID Main Canal and Outside Canal system with storage facilities and bypasses (interconnections) is shown in Figure 3 below. The Ingomar Reservoir is new; it was installed during this modernization program.
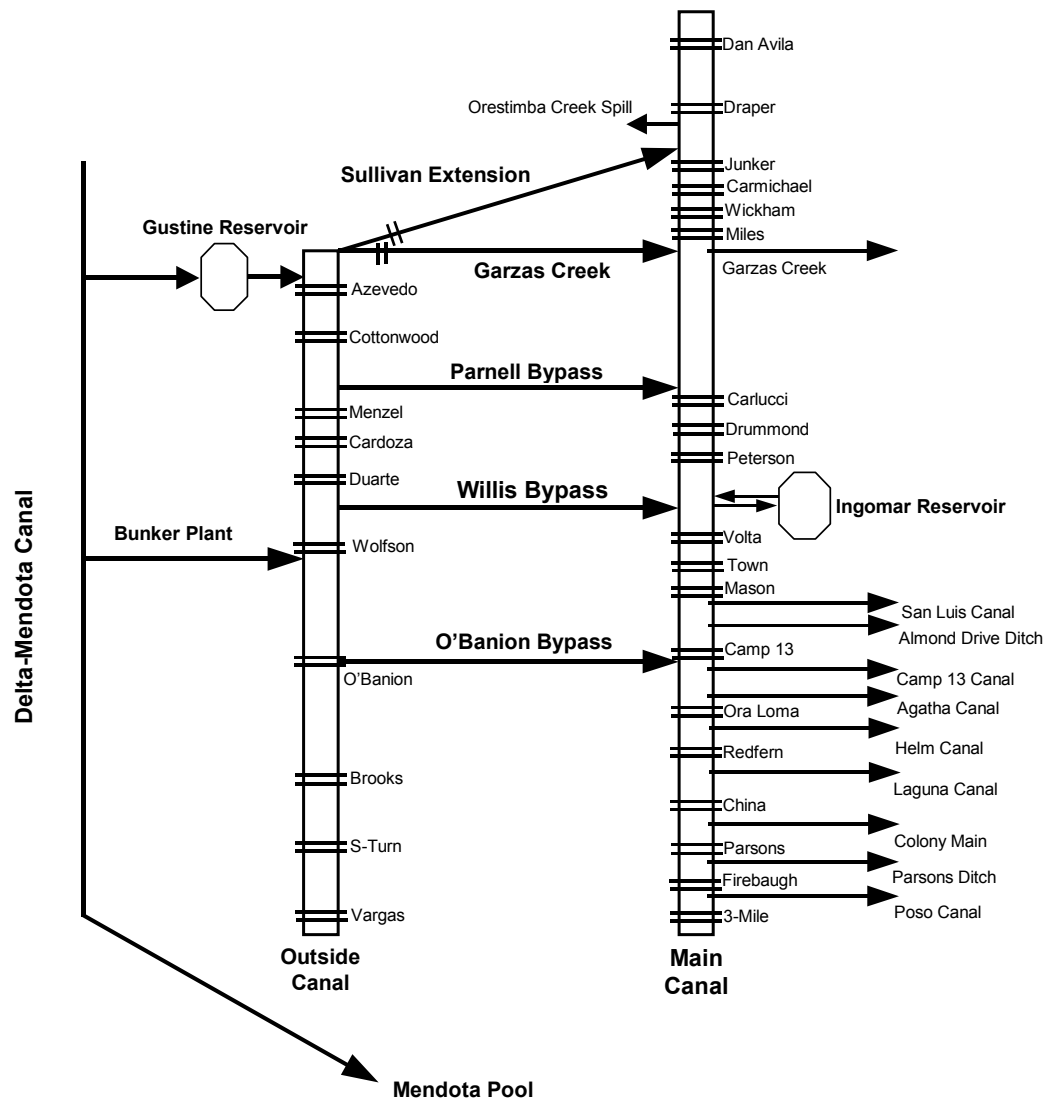
Figure 3. Layout of the CCID Main Canal, Outside Canal and Bypasses.

Modernization Process

In 1992, the CCID Management and Board of Directors decided to improve canal operations. The first step was to examine ways to reduce the operational spill and quantify the water savings. This work was performed by Stoddard & Associates in 1992. This study recommended that new structures be constructed on the Lower Main Canal and the gates be automated on "downstream control". A new regulatory reservoir was recommended to be built between the Upper Main and the Lower Main. Changing the control strategy to "downstream control" was based on the demand responsiveness characteristics, the canal geometry, and the desire to locate storage within the system rather than at the terminus of the canal. Prior to that time, the canals were operated with upstream control, using manual

flashboards in check structures. The "Lower Main Canal" begins at the Peterson Check and extends northward to the Dan Avila Check (refer to Figure 3).

New water control structures were built and fitted with dual radial gates. Initially the gates were operated on upstream control and a SCADA system to remotely monitor the operations of the Lower Main Canal was installed. This was an important first step, as the CCID staff gained practical experience, and recommendations were provided regarding SCADA components such as sensors, radios, remote monitoring, gate actuators, etc. The plan was to get the Lower Main canal automated on upstream control to gain experience with the new technology as the District proceeded with construction of the reservoir and refine the modernization plan including modeling by the ITRC to develop control algorithms and predict the performance of the Lower Main Canal operation under downstream control before placing the canal operation in this mode.

During this time, CCID also co-sponsored water balance studies (conducted by ITRC) for itself and neighboring districts. These studies gave CCID a good idea of what types and amounts of conservable water were available.

The District expanded the modernization project to include the remainder of their major canal system. The overall control strategy for the two canals and the interties between the canals needed to be developed as well as what type of hardware and software would be best, and what quality of water level control was needed. Staff also had a sense that the original SCADA system and existing controls needed some modification based on the experience gained in operating the Lower Main Canal. There were several motivating factors for expanding the canal modernization including:

1. Stabilizing water levels in the canal would stabilize water delivery flow rates which would improve water use efficiency.

2. The understanding that farm runoff was having a noticeable impact upon water quality and quantities. With better canal control, it was anticipated that CCID would be able to stabilize water levels to stabilize water delivery flow rates to reduce farm runoff.

3. A sense was beginning to develop in California that, regardless of each district's individual water rights, the over-riding water rights rule lies in the Public Trust Doctrine. One interpretation of the Public Trust Doctrine states that it is the responsibility of the irrigation districts to ensure efficient and reasonable use of their water – regardless of what their present water right is. Down the road, water rights might be reduced for districts that are not proactive in making efficient use of water.

4. The canal system operation depended heavily upon the personal experience of a few individuals with many years of experience. Upon their eventual retirement, it is important to have better operational tools in place for those who will replace them.

5. Many of the existing water control structures were in need of replacement and CCID desired "state of the art" facilities and control.

In 2003 ITRC worked together with Stoddard & Associates and CCID to develop the strategic modernization plan for the Main Canal and Outside Canal and to identify the potential for water savings (conservation) associated with the implementation of the project. The final modernization plan was intended to provide:

1. An inventory of current water operations and management,
2. A strategic plan for how water would be controlled throughout the main canal network,
3. Modernization needs at each control point including equipment, operational strategy, communications, SCADA, etc.,
4. Preliminary estimates of annual water savings with the modernization plan fully implemented, and
5.   Approximate preliminary costs for hardware and software at each site.

The emphasis of the modernization recommendations for CCID was five-fold:

1. Providing upgraded water delivery service to users, and
2. Simplifying water operations for CCID staff, and
3. Conserving water.
4. Replacing the aged water control structures with new structures.
5. Reestablish the capacity of the Outside Canal lost to regional land subsidence over the years.

The strategic plan envisioned how the complete network of the primary canal system would work together. It provided a means for quickly adjusting to new flow demands anywhere in the system, and automatically moving excess and deficit flows to manageable locations.

The key physical and routing ingredients, presented in Figure 4, include:

1. Automated upstream control, with new check structures on both the upper Main Canal and the Outside Canal.
2. A new regulating reservoir (Ingomar Reservoir) to absorb variations in demand.
3. Improved interties between the Outside Canal and the Main Canal.

4. New linkages to the DMC for quick response in the downstream reaches of the CCID canal system.
5. Downstream control on the Lower Main Canal, downstream of Ingomar Reservoir.
6. New flow control structures at various heads of canals and interties.
7. A comprehensive SCADA system that will monitor numerous variables at all automated structures, and enable an operator at the office to make target flow or water level changes remotely and also monitor canal operations at remote locations.

To accomplish the modeling of the Lower Main Canal, Stoddard & Associates provided detailed surveying of the canal profile and cross sections to ITRC for modeling purposes, which was to be operated under automatic downstream control using ITRC's control algorithm.

Together, ITRC and Stoddard & Associates, in conjunction with WAVE Engineers and CCID staff, developed specifications for the integrator work. CCID decided to utilize the integrator who had furnished and installed the initial SCADA system.

Similar work has been completed on the Upper Main Canal and is underway on the Outside Canal. New control structures have been designed and constructed on the Upper Main utilizing a new type of control gate based on ITRC recommendations and an evaluation of gate options performed by Stoddard & Associates. Separate sets of plans and specifications were prepared for construction of the electrical systems and for system control.
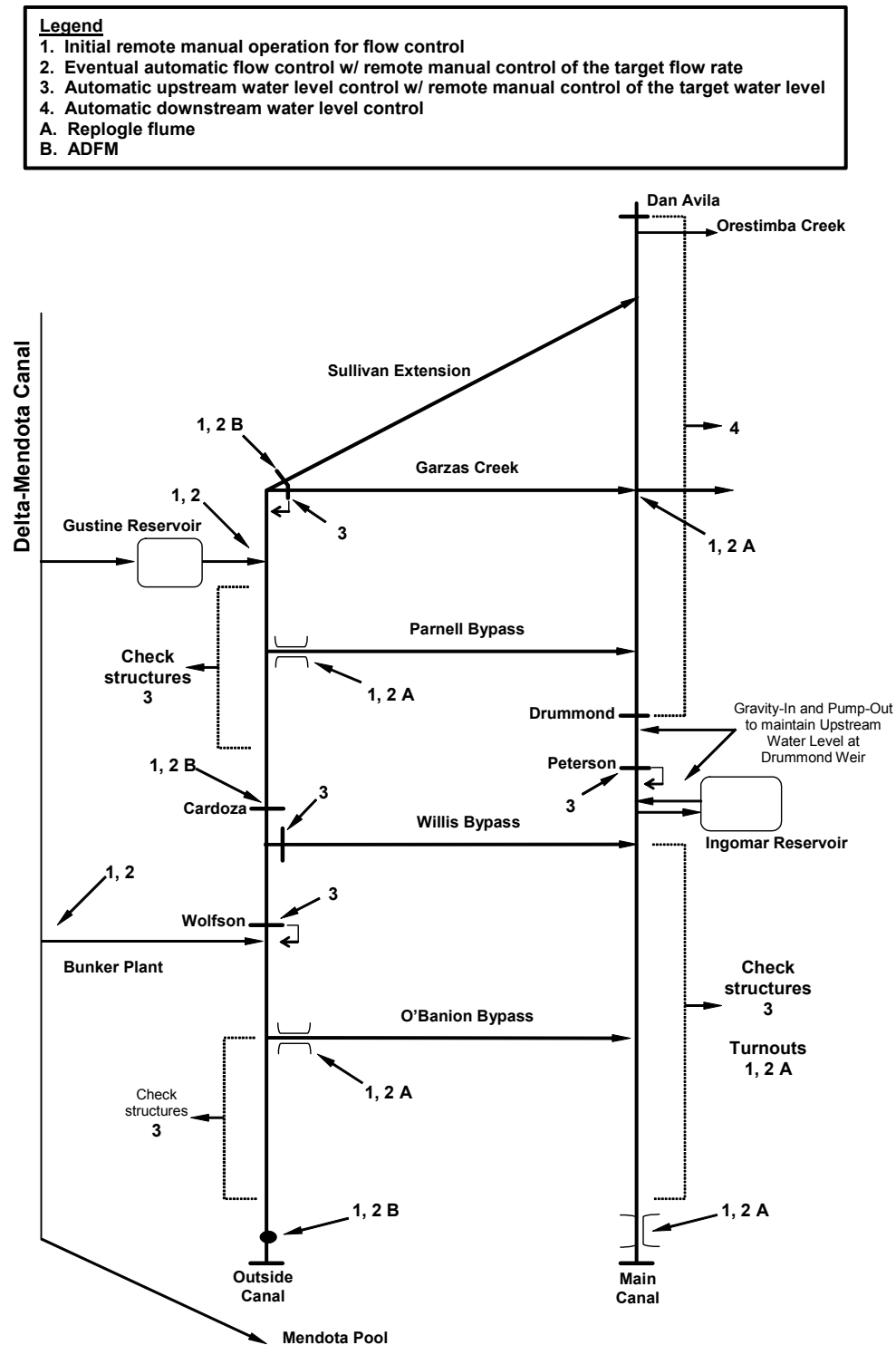
Figure 4. Strategy for future control throughout CCID's primary canal network.

Construction of the new structures required installation of canal bypasses around the structure sites with capacities up to 1000 cfs. At many sites right-of-way was restricted. The project was competitively bid, and bids substantially exceeded the

engineer's estimates due to the project risk perceived by the contractors. The contractor procurement method and the construction contracts were revised. The new proposals received were near or below estimates. Canal profile and cross section data has been gathered to support the canal modeling to develop the control algorithms.

Pre-design level planning proceeded on the Outside Canal. The canal has been subsiding as a result of regional land subsidence due to groundwater overdraft to the point that demand on the canal cannot be met when water delivery is solely from Mendota Pool. A new canal profile has been established to better utilize the available energy (head) in the system. As with the Upper Main Canal, the programming of the PLCs will be performed by the ITRC utilizing the profile and cross section data.

STATUS OF THE PROJECT IN AUGUST 2005

As of August 2005, the following items have been completed:

1. The Ingomar Reservoir has been constructed with inflow automatically controlled with gravity inlet gates and outflow automatically controlled by pumps (with 1 VFD pump and 2 single speed pumps). The inlet/outlet controls maintain a target water level at the downstream end of the next pool, at the head of the Drummond Check. The purpose of controlling the water level at this point is that Drummond Check is the first in a series of downstream-controlled check structures. Water must be available on a very flexible basis at that point. The Peterson Check, which controls the water level in the canal adjacent to the reservoir, operates on automatic upstream control. The reservoir captures operational spill from the Upper Main Canal and water that would otherwise be lost in the Lower Main Canal. The water is then stored and available to meet future demands on the Lower Main.

2. The SCADA system, including the base station with Wonderware HMI, is operating excellently.

3. The downstream control in the Lower Main Canal (8 check structures) is excellent.

4. New Langemann gates have been installed in new check structures on the Upper Main Canal – replacing the old flashboard structures. The Upper Main Canal has been modeled for automatic upstream control, and the programming for the PLCs has been 90% completed by ITRC.

5. The Outside Canal structures are in the design stage and an evaluation is underway to determine the most cost effective way to reconstruct the canal

banks to allow all demand to be satisfied by water taken from the Mendota Pool if required to do so.

MOVING FROM PLANNING TO THE PRESENT STATUS

Successful SCADA and modernization projects are processes that require dedication, persistence and acceptance of new challenges by all the parties involved. It is rare that everything works flawlessly at the beginning – and this project is no exception. The process of completion had a variety of challenges. Some are listed below:

1. The optimum site for the Ingomar Reservoir was immediately upstream of the Drummond Check as this would make the control relatively simple. Because that site was deemed to be a wetland by the US Army Corps of Engineers, another site was chosen further upstream, which made the automatic control of the water level upstream of Drummond considerably more challenging. The Peterson Check could not be operated on downstream control because of the characteristics of the pool between the Peterson Check and the Drummond Check.

2. Unsatisfactory shallow groundwater levels appeared adjacent to the reservoir which required installation of an interceptor tile drain.

3. The biggest challenge occurred with the original integrator. The tasks of installing the PLCs, designing and debugging the HMI, solving radio communications problems, programming the ITRC control algorithm, etc., should have taken about 4 months. Instead, the task took about 18 months. Some of the specific difficulties that occurred were:

    a. The integrator had a team of persons working on the project, but those individual team members appeared to shift with time, creating a lack of cohesive effort.
    b. The integrator thought the job would be much the same as similar jobs they had previously performed. It appeared that as the integrator budget ran low, there was increased reluctance to address problems as they arose.
    c. ITRC had originally assumed that the integrator would take an expanded description of the control algorithms and program them into ladder logic, as was ITRC's experience with other integrators. ITRC would then review the integrator's ladder code and provide appropriate feedback. In the end, in order to get the job completed, ITRC ended up deeply involved in the ladder programming. As a result of that experience, ITRC now prefers to provide all or about

90% of the completed PLC programming to the integrator, with
more carefully defined lines between responsibilities.
   d. The coordination between people programming the PLCs and
those programming the office HMI was not as good as it should
have been.

For the Upper Main Canal work currently underway, CCID has selected another
integrator.

4. After implementation, operations personnel still were unclear on a few
points of how the system was supposed to operate and what they could
and could not do within the capabilities of the new system. For example,
the system was designed to operate automatically under downstream
control, which means that a check structure midway down the canal
cannot be taken out of automation and operated manually. This was not a
major challenge – it just points to the need for checking progress after
implementation when the system is actually being operated.

5. Early in the automation implementation, the downstream control began to
function poorly – waves developed that propagated upstream to
Drummond Check. There was a natural tendency of CCID operators to
want to adjust algorithm tuning constants in an attempt to resolve the
problem, even though the modeling indicated that the control was not the
source of the problem. It was discovered that the primary downstream
water level sensor on one of the check structures was reading water levels
in a stilling well with a partially plugged access hole, significantly
dampening the response in the stilling well. Once the control was shifted
to the redundant sensor (in a redundant location – not the same stilling
well), the problem was immediately corrected.

This, plus similar ITRC experiences in other critical automation projects,
confirms the importance of having robust redundancy in terms of the
sensors (two different types), sensor locations, A/D boards, and PLC
power supplies. All of these components have failed at some time or
another on ITRC projects – even with very good equipment. Redundancy
allows operators to quickly spot a problem, and then allows the automated
control to proceed immediately while the poor sensor is repaired/replaced.

Despite these inevitable challenges, it is important to note that CCID has moved
forward a tremendous distance in a relatively short amount of time, and the
project components completed thus far are functioning as originally planned.

SUMMARY

The CCID experience with canal modernization demonstrates the following points:

1. A district modernization program that utilizes a team of district personnel, a consulting engineering firm, an integrator, and a firm specializing in canal modernization/automation can provide an excellent product.

2. Successful modernization is a process that requires significant effort beyond planning and theoretical analysis. Furthermore, the process will always have hurdles. The challenges are to learn from the hurdles, to expect to encounter new ones, and to persevere until a quality product is obtained.

3. Close cooperation is required between all parties.

4. Once a new SCADA/automation system is "up and running", problems will still appear. The team must have sufficient financial and technical capacities, as well as resolve, to solve those problems as they appear.

5. Until the system works as planned, the operators will rightfully look at the new process with a high degree of skepticism. They must live with the system on a minute-to-minute basis, and they are the ones who receive complaints. In addition, an automated system removes some of the control from their hands that they took years to develop and refine. Putting reliance on an unproven, automatic system is asking a lot from the operators. It is imperative that these operators be asked frequently if there are any problems or questions. They must also be involved in the early discussions of system configuration.

6. It was pointed out in the initial feasibility which recommended automation of the Lower Main Canal that operation and maintenance costs would increase because the nature of the work to maintain an automated water control system is vastly different compared to a manually operated system. One should expect that it may take more than one irrigation season to "work out the bugs" and gain operating experience such that district personnel gain confidence in and are comfortable with the new system. This learning curve must not be overlooked and the operators, upon which much of the success of the project rests, should be engaged the process early to provide adequate transition time and some sense of "ownership".

REMOTE MONITORING AND OPERATION AT THE COLORADO RIVER IRRIGATION DISTRICT

Victor Ruiz[1]

José Anguiano[2]

Julio Navarro[2]

Francisco Delgado[2]

Mario Paredes[2]

Ofelia Begovich[3]

Bernardo Andrade[2]

Javier Ramirez[1]

ABSTRACT

The Colorado River Irrigation District is the last irrigation district and water user on the Colorado River. It obtains 80% of the allocated volume to the district from the Colorado River. The inflow to the district presents fluctuations. The first 27 km of the mail canal are used as buffer reservoir. Between 2002 and 2004 to improve water management, the National Water Commission, Mexican federal agency responsible of water reclamation, installed a remote monitoring system for the head control structures. The system was integrated around MODBUS as communication protocol, Lookout from National Instruments as man machine interface, SCADAPack from Control Microsystems as remote terminal units, "The Probe" from Milltronics as level sensors, Transpak potentiometer transmitters for gate opening and MDS 4710 and 4910 radios from Microwave Data Systems for communication. The remote monitoring system installed was complemented with the remote operation of one control structures. The system starts operation on February of 2005. The remote monitoring system reduces the time required to know, to quantify and to correct the flow and level fluctuations present on the head control structures.

INTRODUCTION

In many regions of Mexico as in Mexicali, water is the main limiting factor for development. The marked competition between the municipality, industry and agriculture is pushing toward more efficient use of this limited natural resource. Agriculture, the largest water consumer, is looking for new technologies to improve water and soil conservation. Remote monitoring and control systems are one of these technological alternatives under analysis in Mexico.

To improve water use and management, the management of the irrigation districts was transferred to user associations and modernization programs were done.

---

[1] Instituto Mexicano de Tecnología del Agua. Paseo Cuauhnahuac 8532, Jiutepec, Morelos 62550, Mexico,{vmruiz, jramirez}@tlaloc.imta.mx

[2] Distrito de Riego 014, Río Colorado, Comisión Nacional del Agua. Reforma y Calle "L", Colonia Nueva, Mexicali B. C. Mexico jnavarro@grpbc.cna.gob.mx

[3] CINVESTAV-Gdl., López Mateos Sur 590, 45232, Guadalajara, Jalisco, México, obegovi@gdl.cinvestav.mx

While the first action was successful in the more profitable districts, the second presented innumerable problems. New infrastructure and remote monitoring-control systems were installed without realistic operational plans and experience making the modernization projects obtained limited results.

Previous Experiences

Between 1988 an 1992 the National Water Commission ("Comisión Nacional del Agua", CNA), federal agency in charge of water reclamation in Mexico, made two remote monitoring projects "El Canal Alto" in the Yaqui River Irrigation District and "Bachimba" in the Delicias Irrigation District. Both projects fell short of expectations as a result of the limited experience of the CNA and the companies making the system integration. The bad selection of the gate opening sensors, remote terminal units and communication system contributed to the limited results. The remote monitoring systems installed had never been used and they are partially dismantled.

Since 1994 the Mexican Institute of Water Technology and CINVESTAV had been working on the remote monitoring and operation of irrigation canals. Today, the first canal operation experiences done in simulation had been transformed into real time experiences on laboratory and field. The laboratory evaluations and the exchange of experiences with National and International agencies helped IMTA and CINVESTAV to obtain the necessary experience to fulfill the supervision and integrations of the remote monitoring systems the CNA requires. Two laboratory canal models were instrumented to evaluate sensor, actuators and remote terminal units. Some multi-input multi-output and single input single output algorithms had been tested on both canals.

In this paper we describe the experiences on the integration of the remote monitoring for the Colorado River Irrigation District (CRID). In the first section of the paper we describe the irrigation district and the remote monitoring project as part of a modernization project for the district. On a second section we describe the system integration process and the experience obtained.

COLORADO RIVER IRRIGATION DISTRICT

The CRID is on of the largest irrigation district in northwestern Mexico. It is located on the northeast of the State of Baja California close to the border with the USA with an average altitude of 25 m. The irrigation district supplies water to 210,000 ha. property belonging to 16,500 farmers. The CRID has been divided into 22 User associations and one User Association Federation. The district was created in 1955, however some land had been irrigated since 1935. The maximum temperature in the summer is 55 $^{\circ}$C and minimum in the winter is - 5.0 $^{\circ}$C. The water sources are the Colorado River with and annual allocation of 1.85 billion m^3 and 550 wells that supply annually 500 million m^3. The Morelos Diversion Dam

channels the Colorado River water onto the Reform Canal. The Reform canal and its two main secondary canal, "Independence" and "Revolution" conveys and distributes the water (Fig. 1). Lining has been placed in approximately 70 % of the main canals and 60 % of the distribution network. The control structures along the canals are radial and slide gates.
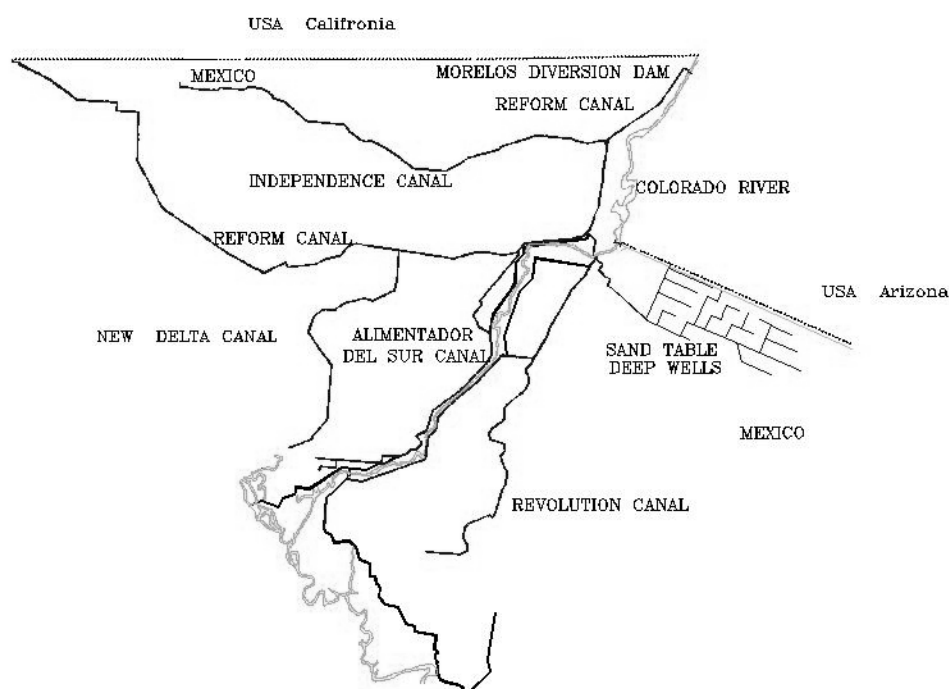

Figure 1. Colorado River Irrigation District canal network.

The turnouts to secondary canals and farm outlets have a capacity of 0.1 m^3/s to 35 m^3/s. The main turnouts are located at the downstream end of the reaches however many small turnout are located along the reaches. The turnout structures are radial and slide gates for the secondary canal and Miller gates for the farm outlets. Parshall flumes are located at the head of some secondary canals for flow measurement. Constant downstream water-depth is used as pool operation method [Ref 1]. Manual upstream regulation is applied as control method [Ref 1].

The CRID is divided into three irrigation units. The name of the unit is given by the canal that distributes the water in the unit, Independence, Reform and Revolution.

The main crops in the CRID are wheat (70%) during the winter, Cottom (60%) in the summer and alfalfa (30 %). The main on-farm irrigation method is furrow (80%); other methods are drip and sprinklers for some vegetables and for the first irrigation for many crops. The users have allocated an average of 14000 m^3 for each hectare registered in the irrigation year.

The Colorado River water is scheduled according an international agreement between Mexico and USA signed in 1944. On October and November the district and the Users Associations prepare the delivery program for the next year determining the volume required each month. On December the Mexican and USA international water commission approves the volume requirements for the next year. The International agreement establishes a minimum flow and the possibility to change the volume allocated for any month no more than 20% with notice of at least a month in advance. The weekly delivery program is requested with 7 days in advance in agreement with the volume authorized for the month.

Modernization project

In 1997 the Colorado River irrigation district made a modernization project to improve canal operation. One of the components considers the use of the first 27 km of the Reform Canal as a buffer reservoir and concentrates the operation problems on the Revolution canal where 66 deep wells from the "Sand Table" (Fig. 1) will compensate flow variations. To supervise the first 27 km of the Reform Canal and the turnouts for the "Independence" and "Revolution" Canals, a remote monitoring system was considered.

REMOTE MONITORING PROJECT

On 1999 CNA made a contract to design a remote monitoring system to supervise the Morelos Diversion Dam, the first 27 Km of the Reform canal and its two main turnouts the Independence and Revolution Canals. The remote monitoring project was solved using a master slave communication system with Modbus as protocol. The system was designed around the Smart Wire Remote terminal Units from Control Microsystems, potentiometer Float (Celesco) sensor for level, Transpak transducer potentiometer- current loop for gate position and Modpac Plus spread spectrum radios from Curry Control. The master station will be at the CNA operation office located at the control structure of the Km 27+000 on the Reform Canal.

To integrate the remote monitoring system according the design already done, the CAN made a contract with a local company to acquire and install the system components, in 2002. Simple mistake product of design errors and the no experience of the company on canal data measurement made that the remote monitoring system attained very low performance and its installation took more time than expected (Fig. 2). The light weight floats connected to the Celesco sensors were not able to follow the canal level variations. The gate opening sensors presented calibration difficulties, it is not possible to adjust the zero in some gates, the gates calibration were made without considering the span and zero of the Transpak transducer making the calibration of each gate a unique case. Finally, the Spread Spectrum Curry Control radios do not attain the performance

wished, during some days no communications between the master station and the remote unit were observed. These facts in addition to the lack of well defined training program and the hermetical job made by the integration company on the installation forced the irrigation district to request IMTA to help the district to receive the remote monitoring system and to repair the system to obtain the desired performance.
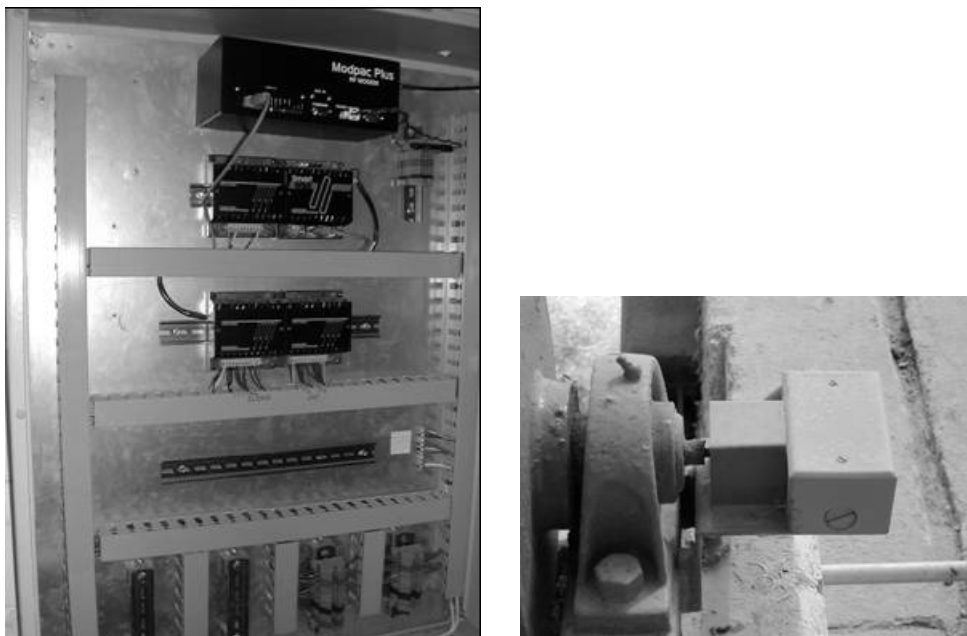

Figure 2. Remote Monitoring System Installed on 2002.

Since the second half of 2003 IMTA have been working with the Irrigation District. IMTA detect the performance problem on the sensors and radio and the impossibility to have a local screen on each remote site to display the local information with the RTU selected on the design. IMTA recommended: the radio must have a minimum performance of 95 % of valid response frames, a local display at the control structures must show de data and gate position to ditchriders, the level and gate position errors must be smaller to +/- 1 cm (minimum resolution of the scales present on the canal). To complete the remote monitoring system CNA requested IMTA to review the 1999 design and update it to install level sensors upstream and downstream the Morelos Diversion Dam, to measure level on the Matamoros control Structure and Sanchez Mejorada Canal (Fig. 3) and consider a remote monitoring and control system for the control structure of Km 4+100 on the Revolution Canal (Fig. 4). With the field experience on the Carrizo District and the help provide by the staff of Imperial Irrigation District the design for the new points considered the next equipment: MDS 4710 B and 4910 B radios for the new communications system, The Probe form Milltronics Siemens as level sensor, Vantage 2210 from Eastech Badger for level transducer and data logger, Transpak for potentiometer – current loop

transducer for gate opening sensor, SCADAPack and Vision from Control Microsystems as RTU and man-machine interface. The selection of the radios was validated with a field test, MDS 4710B radios where used to communicate all the remote monitoring units on operation and design. With the participation Sage Designs Inc. a Free Wave radios used with the SCADAPack were tested to relay the master station with the remote site integrated on 2002. The percentage of valid response frames with the tested radios during a 1 hour test was 100%. The Free Wave radio is a spread spectrum radio as the Curry Control. This confirms that the communications problem was product of the radio selected. The Curry Control radios request 2 repeaters to ensure de communication between the master station and the remote site separated 15 Km (repeater every 5 Km). With the spread spectrum radios from Free Wave no repeater is required, the same conditions for the MDS radios. With the MDS radios, the connections between the master station and the Diversion Dam, the farther remote site to the master station did not require any repeaters. It is only necessary to consider the right size for the antenna´s tower obtained from a line sight study.

As a consequence of the performance evaluation carried out by IMTA on the remote monitoring system CNA requested the integrator to recalibrate the sensor and fix the radio performance. Since the contract signed in 2002 for the integration of the remote monitoring systems did not consider any defect associate to the design, the performance established by IMTA was impossible to attain. By the end of 2003, CNA and IMTA agree to buy the necessary equipment, radios, man-machine interface, RTU, ultrasonic level sensor to obtain the desired performance and simplify the future maintenance of the system under integration. Finally in September 2004 the integrator gave the systems finished to CNA. The remote monitoring system installed presented a very limited performance.

On the second half of 2004, with the equipment acquired by CNA on 2003, IMTA started the installation of the level sensor and data loggers (Vantage 2210) on the diversion dam, Matamoros Control structures and Sanchez Mejorada Canal.

When the integration company gave the remote monitoring systems to CNA, the communication system and RTU was changed. The Spread Spectrum Radio, Curry Control radios was changed by MDS 4710B radios working on 450 – 470 MHz. The Smart Wire RTU was changed by a SCADAPack which made possible the installation of a man machine interface ("Vision") to present the local measurements.
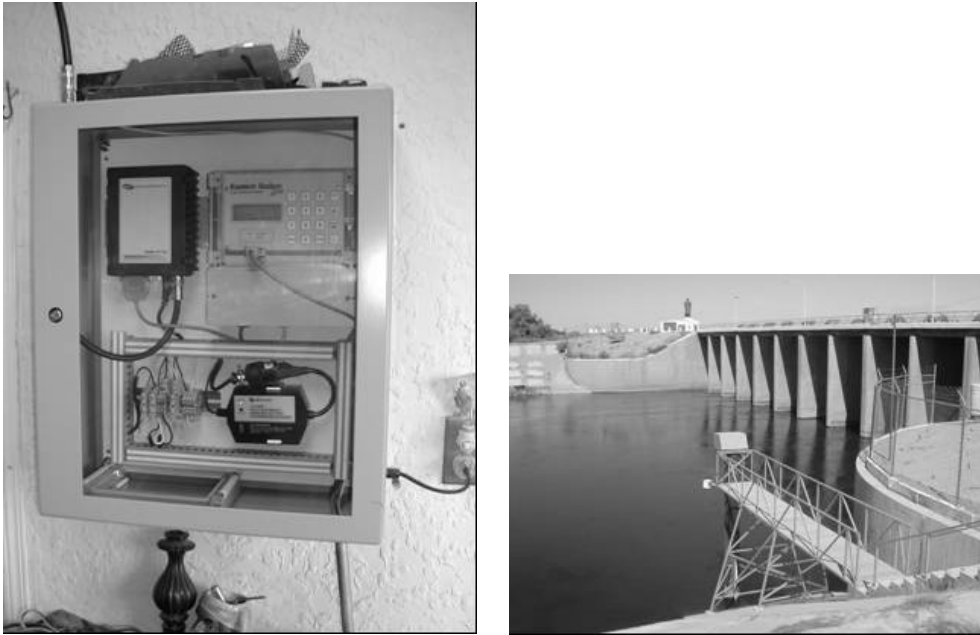
Figure 3. Remote Monitoring using the Vantage 2210.

By the end of 2004 the instrumentation of the Km 4+100 Revolution Canal Control structure started. This control structure has 3 radial gates and its discharge is free. The upstream level was measures with the ultrasonic level sensor "The Probe". For the gate position sensor the opening was determined measuring the turns of a gear on the gear box of the gate opening mechanism. A third order equation was used to relate the turns of the gear with the gate opening. A 10 turn, 10 K potentiometer is used to measure the turns. A Transpak transducer transforms the resistance of the potentiometer on a 4-20 mA loop. Since the number of turns on the gear to measure the gate opening travel was not equal to the turns of the potentiometer a small gear box is used to adjust this difference. This gear box is located between the potentiometer and gear box as group of Roger Hansen from the USBR Provo used on the remote monitoring systems integrated by them. For the operation of the 3 phases motor of the gate actuator the electric circuit of the electromagnetic motor relays was modified to advice the RTU with a digital signal the operation mode of the gate (manual of PLC) and to allow the digital outputs of the RTU turn on the motor on the desired directions. The manual operation of the control structure was not modified.

Figure 4. Remote monitoring systems at the KM 4+100 Control Structure.

The installation of all the equipment made by IMTA the last year was done with the participation of the electromechanical maintenance staff of the CNA´s irrigation district. The participation of IMTA was completed with a training program to allow the district made the daily operation and basic maintenance of the system.

For this year, the irrigation district will complete the remote monitoring and operation of the control structures and main turnouts on the first 27 KM of the Reform canal, install a Acoustic Doppler Current Profiler at the head of the Reform Canal where the lined canal start and consolidate the training on operation and maintenance on the installed SCADA system for the staff of the irrigation district and company selected by the district for the maintenance of the system. The district is looking for a local company that trained by IMTA will be responsible for the maintenance of the SCADA system installed.

CONCLUSIONS

The Colorado River Irrigation District has started to use remote monitoring and operation systems. Today it is possible to follow the canal performance and reduce the effect on any flow variations on the control point where CNA gives water by volume to the User Association Federation in charge of the main canal operation. The good result obtained with the first site motivated the district to complete the instrumentation of all the head control structures of the district and supervise the distribution made by the Water Users Association Federation at some critical points.

Canal remote monitoring is a simple task if the right equipment is used. If it is not the case, it can become a nightmare that never ends.

REFERENCES

1. Buyalsky C. P., Ehler D. G, Falvey H. T, *Canal Systems Automation Manual*, A water Resources Technical Publication. Bureau of Reclamation. Denver, Colorado, 1991.

CALIBRATION AND USE OF IN SITU TURBIDITY SENSORS FOR ESTIMATING SEDIMENT LOAD IN DRAINAGE WATERS

Khaled M. Bali[1]
Peng Gao[2]
Gregory B. Pasternack[3]
Wesley W. Wallender[4]

ABSTRACT

Drainage waters discharged from irrigated fields in California and other states are under ever-closer scrutiny. The quality of drainage waters discharged into waterways in California is regulated under California Water Code Section 13260 and Federal Clean Water Act. Growers and other entities that discharge drainage waters that could affect the quality of waterbodies in the State are required to comply with water quality regulations. Compliance with water quality regulations could be achieved by filing a Report of Waste Discharge (RWD) that complies with State-prescribed Waste Discharge Requirements (WDRs). WDRs could be used as a permit limiting the levels of pollutants that may be discharged in waterways to protect the beneficial uses of waterbodies in the State. Complying with the irrigated Lands Conditional Waiver Program or the Total Maximum Daily Load (TMDL) limits may provide alternates to WDRs for growers in the State.

Sediment and silt in drainage waters have been identified as the leading cause for water quality impairments in rivers and waterbodies in the State. For example, sedimentation/siltation TMDLs for agricultural drains and two major rivers in Imperial Valley have been implemented to address water quality problems in the Colorado River Basin in Southern California. Suspended sediment concentration or load in drainage water is often estimated from turbidity measurements. Accurate and reliable estimates of total suspended sediment or concentration in drainage water are needed to accurately assess the quality of drainage water or to comply with WDRs.

[1] Irrigation/Water Management Advisor, University of California Desert Research & Extension Center, 1050 E. Holton Rd. Holtville, CA 92250; kmbali@ucdavis.edu.
[2] Assistant Professor, Geography, Syracuse University, Syracuse, NY 13244.
[3] Associate Professor and Watershed Hydrologist, Departments of Land, Air, and Water Resources, University of California, Davis., University of California, Davis. CA 95616.
[4] Professor of Hydrologic Sciences and Biological & Agricultural Engineering, Departments of Land, Air, and Water Resources and Biological and Agricultural Engineering, University of California, Davis.

In this paper, we evaluated the accuracy of in situ turbidity sensors and portable turbidimeters in estimating sediment concentration in runoff water from irrigated fields in the Imperial Valley, California. Field and laboratory studies were performed to determine and evaluate the errors associated with in situ measurements of NTU (Nephelometric Turbidity Units) and the estimation of suspended solids concentrations from NTU as compared to standard laboratory methods. The relationship between suspended solids concentration (C) and turbidity (T) were established for various heterogeneous particle size distributions. The use of a linear C-T relationship introduces significant errors in estimating sediment load or concentrations in drainage waters. In addition to accurate C-T relationships, frequent measurements of both turbidity and runoff flow rates are needed to accurately estimate sediment load in drainage waters. The minimum number of NTU and runoff flow measurements needed to accurately estimate sediment load in drainage waters were determined for various irrigation/discharge events.

INTRODUCTION

Irrigation in arid and semi-arid regions has always had two challenges with water quality: finding water of suitable quality to apply to crops and disposing of poor quality drainage water resulting from the need to remove undesirable salts from the crop root zone.   Historically, the main requirement was to leach salts brought in by the applied irrigation water and left behind after crop evapotranspiration. The residual salts comprised mainly of minerals and other elements dissolved in the applied water, but also included naturally occurring salts leached out of the soil profile. With the intensification of agriculture and the addition of fertilizers, pesticides, and other chemicals to enhance crop growth, a greater range of pollutants are found in irrigation and drainage waters, resulting in growing concerns about the quality of water in and around irrigation-drainage systems. Combined with increasing competition for scarce water resources for urban and environmental uses, the quality of water used in agriculture is coming under ever-closer scrutiny.

In order to ensure the quality of water for other beneficial uses, state and in some cases federal government agencies are setting water quality objectives for the reasonable protection of beneficial uses of water or the prevention of nuisance within specified areas, by establishing limits or levels of water quality constituents or characteristics for drainage waters from agricultural watersheds. In California and elsewhere, how much of a pollutant a waterbody can tolerate on a daily basis is determined by setting a Total Maximum Daily Load (TMDL). A TMDL for agricultural drainage is defined as the load allocations for non-point source of pollution and natural background pollution, plus a margin of safety such that the capacity of the waterbody to assimilate pollutant loadings without violating water quality standards is not exceeded. A TMDL can be expressed in

terms of either mass per time, toxicity, concentration, a specific chemical or other appropriate measures.

To comply with TMDLs and mitigate the impacts of agriculture drainage waters on other uses, irrigators and farm managers have to be more attentive to the quality of the water applied and the quality of drainage waters leaving their fields, as they must adjust their irrigation practices to ensure compliance with the regulatory standards. The presence of suspended sediment and other contaminates adsorbed on suspended sediment in waterways has multiple negative impacts on water quality and may cause environmental problems (Henley, et al., 2000, Davies-Colley and Smith, 2001). The 1998 National Water Quality Inventory ranks suspended solids and sediments as the leading cause for water quality impairment of rivers and lakes in the United States (Swietlik, 2002).

Approximately 30% of applied drainage water in the Salton Sea watershed in southern California ends up as drainage water. Estimation of suspended sediment concentration and load is therefore fundamental for implementation of management measures to achieve water quality objectives in the region. Reducing the load and/or the concentration of suspended sediment in runoff has numerous benefits including reducing the amount of water applied and the load of other regulated contaminants such as pesticides and phosphorus that are attached to eroded soil particles. Accurate methods are needed to estimate the concentration of suspended sediment in runoff water to evaluate the impact of various best management practices on water quality to achieve silt/sediment TMDL objectives. In this paper, we discuss the use of in situ turbidity sensors to estimate the concentration of suspended sediment in runoff water.

IRRIGATION AND SEDIMENT AND PHOSPHORUS LOAD IN RUNOFF WATERS

Surface irrigation, by mainly of furrows or border checks, is the primary method for irrigation in the Valley, and is used on more than 90% of the cropped area. Drip irrigation is used on less than 5% of the cropped area and mostly on vegetable crops. Sprinkler irrigation is mostly used to germinate some crops, but growers switch to surface methods once the crop is established.

The average concentration of suspended sediment in Imperial Valley drains and rivers is approximately 350-400 mg/L. Based on the average agricultural drainage discharge of 2.0 ac-ft per acre/year, this figure represents a net loss of approximately 1 ton of soil (in form of sediment) per acre per year. The average sediment load to drains and rivers in the Valley is in excess of 500,000 tons per year. In addition to the loss of productive topsoil, sediment and eroded soil particles contain considerable amounts of P attached to soil particles that eventually end up in the Salton Sea. The average concentration of soluble P in drainage water is approximately 0.5-1.0 mg/L (eutrophication, a major problem in

the Salton Sea, can occur at concentrations as low as 0.02 mg/L). The average load of P in drainage water in form of P_2O_5 is approximately 5-10 lbs/acre (6-11 kg/ha) per year, with an average annual load of approximately 2.5 million lb (1.14 million kg) of P that end up in the Salton Sea every year.

Approximately 22 million lb (10 million kg) of phosphorus (in the form of P_2O_5) is used annually to fertilize the alfalfa crop (Meister et al., 2004), and this amount accounts for almost 50% of the total phosphorus applied to crops in the Valley. Phosphorus is applied once or twice per year as water-run phosphorus during the growing season with subsequent yearly applications in the springtime, or applied at a higher rate prior to planting to meet alfalfa demand for the entire growing season (approximately 3 years). The estimated phosphorus load in surface runoff waters is approximately 10-15% of total applied phosphorus. In addition, phosphorus may move directly to surface waters via sediments carried in the surface runoff, and via cracks in the soil to subsurface drains.

TURBIDITY AND SUSPENDED SEDIMENT CONCENTRATION

In general, suspended sediment load in runoff water is estimated from runoff water discharge rate and the average concentration of suspended sediment (C) in runoff water. C is commonly estimated from standard operation procedure for the determination of total suspended solid (TSS). The standard procedure requires a minimum of 200-500 ml of runoff water samples then the amount of suspended sediment is determined in the laboratory using the filtration/gravimetric method. The method is costly, time extensive, and does not provide real-time estimate for the load or concentration of suspended sediment. A large number of samples are needed to estimate the average concentration of sediment in runoff water due to the large variability in the concentration of suspended sediment in any single irrigation events. The use of turbidity (T) as a mean to estimate the concentration of suspended sediment is more efficient and cost-effective as compare to standard method.

Various optical sensors have been manufactured to monitor continuous sediment concentration in situ, which greatly improves the accuracy of estimating sediment concentration or load in water as compared to the infrequent water sampling. The optical sensors such as optical backscattering (OBS) sensors have been widely used to measure continuous suspended sediment concentration in marine environment (Downing et al., 1981, Jaffe et al., 1984, Kineke and Sternberg, 1992), estuaries (Sternberg, 1989), and continental shelves (Hanes and Huntley, 1984, Wright et al., 1994). The OBS sensors have also been used by hydrologists to estimate suspended sediment concentration in surface waters (Jansson, 1992, Lewis, 1996).

OBS sensors can be calibrated to measure turbidity or suspended solids directly. However, the measurement of turbidity also introduces various problems.

Turbidity measures the degree to which infrared light is scattered or absorbed by suspended particulate material and soluble coloured compounds in water. Therefore, turbidity measurement is an indirect measurement of C, the accuracy of which depends on how well turbidity can represent C. Considerable studies have demonstrated that many factors other than suspended sediment particles may affect the value of turbidity (Gippel, 1995, Hatcher et al., 2000, Sutherland et al., 2000, Sadar, 2002). Among these factors, heterogeneous distribution of particle sizes is the most significant one that affects turbidity values (Foster et al., 1992, Schoellhamer and Wright, 2003). For a given C, samples with different particle size may result in turbidity values that are 10 times in difference (Ludwig et al., 1990, Wren et al., 2000). In addition, turbidity is more sensitive to fine particles than coarse particles (Conner and DeVisser, 1992, Gippel, 1995). Although many studies have been conducted to quantify and offset the effect of particle size variability (Kineke and Sternberg, 1992), no general method can be developed to correct for such effect. Furthermore, the bio-fouling, physical disturbance, and hydrodynamic spike also generate lots of noise in turbidity time series recorded by real-time in situ turbidity sensors. The values of turbidity could misrepresent the real values of C in spite of its numerous advantages. Therefore, OBS sensors must be calibrated with suspended solids from the waters to be monitored and because there is no standard turbidimeter, comparison of turbidity data acquired with an OBS sensor to data from another turbidimeter require inter calibration with a turbidity standard.

METHODOLOGY

Field studies

Runoff water samples used in this study were collected from two alfalfa fields at the University of California Desert Research and Extension Center (UCDREC) near Holtville, CA. The alfalfa fields were planted in 2004 and irrigated according to the standard irrigation practices at UCDREC (approximately 16-18 irrigations/year with an average depth of application of approximately 4.5 inches per irrigation at runoff rates varying from 5-20%). The first field (Field A) contained 20 alfalfa borders (each border 30 ft wide and 1200 ft long). The second field (Field B) contained 98 furrows (40-inch wide and 900 ft long). The field trails were designed to study the impact of irrigation system (furrow vs. border) and various P application rates on the load and concentration of sediment and phosphorus in runoff water. Irrigation and other cultural practices on both fields followed common practices between the time of planting in October 2004 and the first cutting in February 2005. Alfalfa yields were determined from sample cuttings in selected locations (two 0.25 m^2 quadrants along each border check and selected furrows) in each field. Also, immediately after baling, we counted hay bales on each border (or 4-furrow sets), weighted selected bales (one bale from each border or furrow-set), and recorded bale moisture from bales in each border or furrow-set. From bale data, we also estimated hay yields.

Both fields were irrigated at a rate of approximately two irrigations per cutting. The quality and the rate and amount of Colorado River water delivered and the rate, amount and quality of surface runoff were determined for each irrigation event and flow rates were measured using trapezoidal and long-throated flumes, for applied water and surface runoff respectively (see Table 1 for details). In addition to the use of OBS sensors, irrigation and surface runoff water quality parameters (N, P, turbidity, and salinity) were determined using standard analytical methods, as shown in Table 1. The sediment load in surface runoff water was determined from the runoff rate and duration and the corresponding turbidity measurements.

Table 1. Analytical instruments and flow rate measurement methods
and quality assurance objectives.

Parameter	Method	Units	Detection limit	Sensitivity	Precision	Accuracy
Water delivered	Trapezoidal flume	Cfs	0 to 25	0.5 cfs	±4%	±10%
Runoff water	Long-throated flume	Cfs	0 to 9	0.2 cfs	±5%	±10
PO_4	US-EPA 365.2 (Acid Persulfate Digestion)	Mg/L	0-3.5	0.01	±5%	±5%
Salinity	EC (Tanji, 1990)	dS/m	0-3.0	0.05	±2%	±5%
NO_3	Spectrum™ (Cadmium Reduction Method)	Mg/L	0-30.00	0.01	±5%	±10%
Turbidity/ standard method	US-EPA 180.1	NTU	0-1000	0.1	±2%	±5%
Turbidity/ OBS-3 Suspended solids and turbidity monitor	D & A Instrument Company	FTU Mg/L	0.02-2,000 0.1-5,000 (Mud, $D_{50}=10u$m)		2.0% (nonlinearity) 2.0% (nonlinearity	

OBS Sensors and sampling methods

One OBS sensor[*] (OBS-3 Suspended Solids & Turbidity Monitor manufactured by D&A Instrument Company[1]) was stationed next to each runoff flume in each field. Water samples used in this experiment were collected from the runoff water from selected irrigation from the above two alfalfa fields. In addition to runoff water samples, random water samples were taken from first, second and third order drains in selected channel branches throughout an entire subwatershed (Holtville main drain system, approximately 40,000 acres of irrigated land) in the Imperial Valley between September 2003 and March 2004 (Fig. 1). Sample
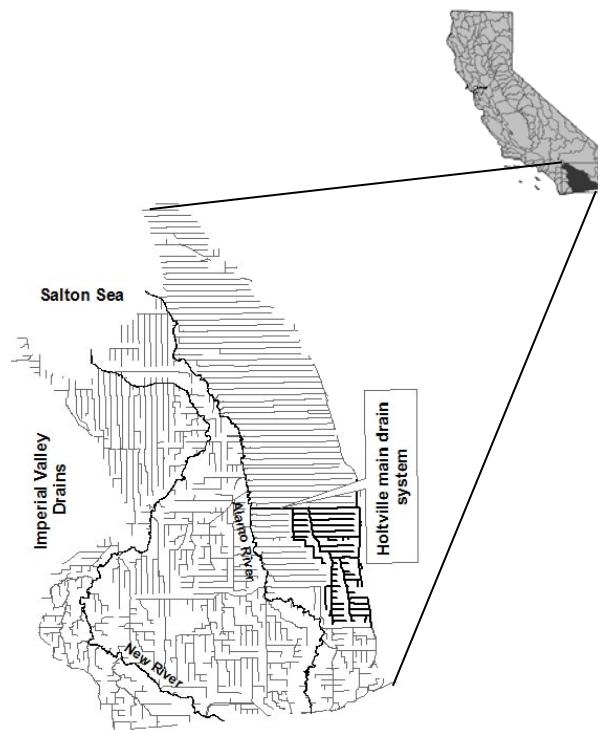

Figure 1. The Imperial Valley agricultural drain system.

collection was designed to cover various spatial scales and to contain the full range of variation of C in the watershed. These samples were used for developing and verifying the C-T relationship and for examining the effect of spatial turbidity variation on the relationship. A separated group of water samples from flows at two sites of first-order drain channels (i.e. a drain channel directly connected to fields and has no other drain channels converge into) and nine sites along east and west channels and the main channel (Fig. 1) were obtained to understand the

---

[*] To simplify our information, it is sometimes necessary to use trade names of products or equipment. No endorsement of named products is intended nor is criticism implied of similar products, which are not mentioned.

correlation between the size and composition of particles and associated C-T relationship. In addition to drain water samples, suspended sediment and associated bed-material samples from the eleven sites in the subwatershed were obtained for the analysis of particle size distribution (PSD).

Collected water samples were analyzed for T and C at UCDREC laboratory. A Hach 2100 p turbidimeter was used to measure the value of turbidity. The turbidimeter was calibrated using three standard formazin samples with NTU values of 3.21, 38.7, and 489, respectively. If the reading exceeded 5% of the standard values, the instrument was recalibrated. The measurements were taken three times and the average value was adopted as the representative of turbidity value for the sample. C for the same sample was measured by the standard gravimetric method. For each group of samples from one location, a sub-sample was analyzed for PSD of suspended sediment using a laser diffraction instrument (Beckman-Coulter LS-230* with a 750 nm laser beam) located at the University of California, Davis. In addition, the corresponding bed-material samples were analyzed for PSD.

RESULTS AND DISCUSSION

Suspended solids concentration-Turbidity (C-T) relationship

Three possible C-T functions were tested by regression analysis (1) linear function, (2) threshold linear functions (i.e. two linear functions for data with NTU < 200 and NTU ≥ 200), and (3) power function. The regression results were compared with one another and the function with the best fit was selected. The variation of the composition of silt and clay in samples was attributed to the developed curvelinear C-T relationship for low C and the curvelinearity was quantitatively interpreted by calculating the comprehensive values of turbidity based on the estimated turbidity values in each of six categories of silt and clay and comparing them with those for samples of otherwise homogeneous particle size. Quantitatively, T for sediment of size greater than 1.2 um may be calculated by (Gippel, 1995)

$$T = 0.95 D_{50}^{-0.52} C = 0.95 KC \qquad\qquad (1)$$

where D_{50} is the medium size of particle. For a given C, the value of T was determined by that of K. Values of K for samples that have heterogeneous particle size distribution were calculated by

$$K = \sum_{i=1}^{n} D_i^{-0.52} P_i \qquad\qquad (2)$$

where n is the number of particle size categories, D_i is the mean of D_{50} in each category, and P_i is the percentage of particles in each category. Values of T for samples of uniform size were also calculated by eqs. (1) in which D_{50} was

computed as the mean of D_{50} for samples of high C where the linear relationship between T and C existed.

For all turbidity measurements, the errors between the reading and the standard values were between 0.2% and 2.4% signifying that the turbidity values measured by the instrument were reliable. The regression results based on the data and their corresponding relations are:

Linear function

$$C = 0.876T + 29.2 \qquad (3)$$

Threshold linear functions

$$C = 1.162T + 18.5 \qquad NTU < 200 \qquad (4a)$$
$$C = 0.898T + 12.1 \qquad NTU \geq 200 \qquad (4b)$$

Power function
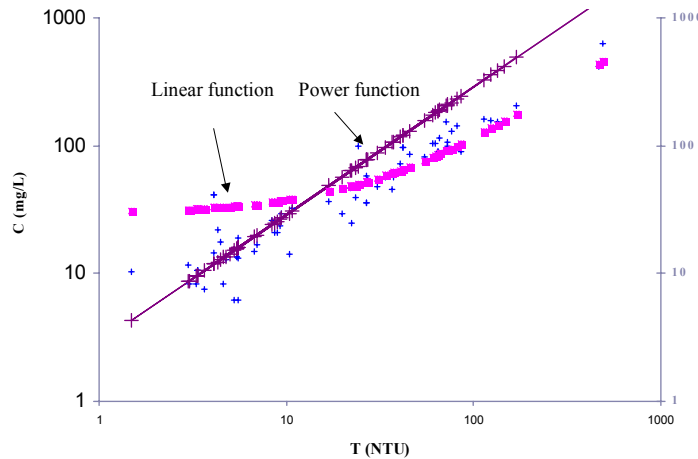
$$C = 3.6T^{0.8} \qquad (5)$$

Figure 2. C-T relationship using the linear and power functions.

Although the linear function fitted the data well for high turbidity values, it over predicted C for T values less than 30. The two threshold linear functions agreed with the data well at high turbidity values but still over predicted C at low turbidity values. In addition, the two intercepts in the two types of linear functions indicated that as turbidity approached zero, C was 29.2 and 18.5 mg/L, respectively. This was contradicting to the value (i.e. zero) generated by pre-programmed formazin calibration. The power function fitted the data well at both low and high turbidity values. Validation of eq. (5) using the data collected in this experiment indicated that the power function represented the best relationship between C and T (Fig. 2). This was further confirmed by comparing the second group of data with the predicted data using the nonparametric Mann-Whitney U test, which signified that the two sets of data were statistically identical (accepting the non-hypothesis at the 81% confidence).

Sediment load and concentration in runoff waters

The average runoff rate as a percentage of applied water for two irrigations in May 2005 is shown in Figure 3 for the border irrigated field (Field A) and in Figure 4 for the furrow irrigated field (Field B). The average depth of applied water for field A was approximately 4.6 inches with an average rate of runoff of approximately 7.6% of applied water (Table 2). The concentrations of suspended sediment in runoff water were determined from OBS-3 sensor based on data collected continuously by a datalogger and averaged every five minutes. The average concentration of suspended sediment in runoff water was approximately 125 mg/L (Table 2) for field A. The average load of sediment in runoff water was calculated from suspended sediment concentration and volume of runoff water for every 5-minute increment during the entire runoff event. The calculated load of sediment for Field A was approximately 4.5 kg/irrigation per acre. Both runoff rate and the average concentration of suspended sediment in runoff water generated from Field B were much higher than those for Field A. The average rate of runoff for field B was approximately 20.2% while the average suspended sediment concentration was 372 mg/L (Table 2). The calculated load of sediment generated from field B was approximately 31.67 kg/irrigation per acre. The load of sediment generated from the furrow-irrigated field was more than six times higher than the load generated from the border-irrigated filed. The erosion rate and sediment load in runoff water was significantly lower in the border-irrigated field due to a combination of lower runoff volume and lower suspended sediment concentration in runoff water. Reducing the inflow rate at the onset of any runoff events can reduce the average load of sediment in the furrow-irrigated field.

Table 2. Average water quantity and quality parameters for two irrigations in May 2005 based on data collected every five minutes.

Parameter	Field A (Border irrigation)	Field B (Furrow irrigation)
Average depth applied (inches)	4.6	4.1
Number of acres	16.53	6.75
Runoff % (runoff water/applied water)	7.6	20.2
Average concentration of sediment in runoff water (mg/L)	125	372
Total sediment load in runoff water kg/irrigation per acre	4.49	31.67

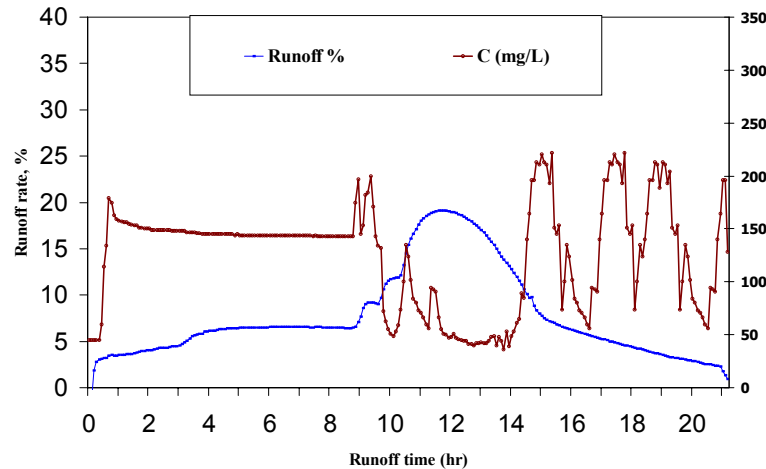Field A (Alfalfa, Border, May 2005, UCDREC)

Figure 3. Runoff rate as a percentage of applied water and sediment concentration in runoff water- Field A- Border irrigation.
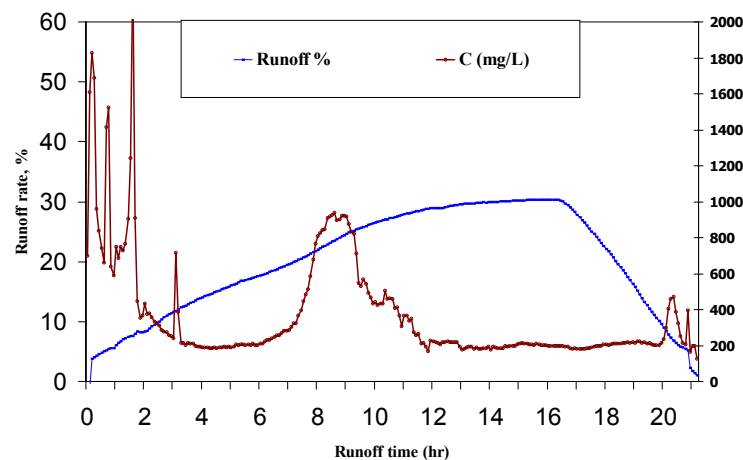
Field A (Alfalfa, Furrow, May 2005, UCDREC)

Figure 4. Runoff rate as a percentage of applied water and sediment concentration in runoff water- Field A- Furrow irrigation.

In addition to the use of OBS-3 to determine suspended sediment concentration in runoff water, we used an autosampler to collect runoff water samples once every 30 minutes. The turbidity values of the runoff water samples were determined in the laboratory and then the concentrations of suspended sediments were estimated from the C-T relationship discussed earlier. We examined the effect of number of samples collected during the 20-hr runoff events and determined the average concentration of suspended sediment as a function of number of water samples collected for both field (Table 3). For the border-irrigated field (Field A), there was no significant difference in the average concentration of suspended sediment

for any number of samples collected at time intervals ranging from 30 minutes to 120 minutes. The average load or concentration of sediment in runoff water could be accurately estimated if one grab sample was obtained every 2 hours (10 samples per 20-hr runoff events). Similar results were obtained for Field B, however, the frequency of sampling should be 90 minutes or less due to the large variability in suspended sediment concentration during the irrigation event. A minimum of 15 grab samples that are needed to accurately predict the average load or concentration of suspended sediment in runoff water (Table3).

Table 3. Average concentration of sediment in runoff water based on samples collected every 30 minutes.

Time interval between samples (minutes)	Number of samples collected	Field A (Border irrigation) C (mg/L)	Field B (Furrow irrigation) C(mg/L)
5	255 (OBS-3 data)	125	372
30	44	128	354
60	22	123	356
90	15	127	340
120	10	129	430

CONCLUSIONS

Utilizing water samples collected within the Holtville main drain watershed, a reliable C-T calibration equation was developed. This relationship was described by a power function, which reflected the effect of non-uniform particle size distribution. Several sets of independent samples representing spatial and temporal variations in the watershed were needed to accurately determine the C-T calibration curve.

In addition to accurate C-T relationships, frequent measurements of both turbidity and runoff flow rates are needed to accurately estimate sediment load in drainage waters. OBS sensors can be used to accurately estimate suspended sediment concentration in runoff water. A minimum of 10-15 grab water samples and runoff flow measurements are needed to accurately estimate sediment load in runoff waters. The erosion rate and sediment load in runoff water are higher in furrow-irrigated fields as compared to border-irrigated field.

REFERENCES

California Regional Water Quality Control Board, 2002, Sediment/Siltation total maximum daily load for the New River and Implementation plan.

Conner, C. S., and A. M. DeVisser, 1992. A laboratory investigation of particle size effects on an optical backscatterance sensor. Marine Geology, 10: 151–159.

Davis-Colley, R. J., and D. G. Smith, 2001. Turbidity, Suspended Sediment, and Water Clarity: a Review. Journal of the American Water Resources Association 37: 1085-1101.

Downing, J.P., Sternberg, R.W. and Lister, C.R.B., 1981. New instrumentation for the investigation of sediment suspension processes in the shallow marine environment. Marine Geology, 42: 19-34.

Foster, I. D. L., R. Millington, and R. G. Grew. 1992. The impact of particle size controls on stream turbidity measurement; some implications for suspended sediment yield estimation. In: Erosion and Sediment Transport Programmes in River Basins, Proceedings of the Oslo Symposium, August, 1992, IAHS Publ. No. 210: 51-62.

Gippel, C. J., 1995. Potential of turbidity monitoring for measuring the transport of suspended solids in streams. Hydrological Processes, 9: 83-97.

Greenwood, B., Osborne, P.D. and Bowen, A.J., 1991. Measurements of suspended sediment transport: prototype shore-faces. In: N.C. Kraus, K.J. Gingrich, D.L. Kriebel (Editors), Coastal Sediments '91. Proc. Specialty Conf. on Quantitative Approaches to Coastal Sediment Processes. Am. Soc. Civ. Eng., Seattle, Wash., 1: 284-299.

Hanes, D. M., and D. A. Huntley, 1986. Continuous measurements of suspended sand concentration in a wave dominated nearshore environment. Continental Shelf Research 6 : 585–596

Hatcher A., P. Hill, J. Grant, and P. Macpherson, 2000. Spectral optical backscatter of sand in suspension: effects of particle size, composition and colour. Marine Geology, 168: 115-128.

Imperial County (2003) Agricultural Crop and Livestock Report. Office of Agricultural Commissioner. El Centro, California.

Jaffe, B.E., R.W. Sternberg, and A. H. Sallenger, 1984. The role of suspended sediment in shore-normal beach profile changes. 19th Coastal Eng. Conf. Proc. Am. Soc. Civ. Eng., Houston, Tex., pp. 1983-1996.

Jansson, M. D., 1992. Turbidimeter measurements in a tropical river, Costa Rica. In: Erosion and Sediment Transport Programmes in River Basins, Proceedings of the Oslo Symposium, August, 1992, IAHS Publ. No. 210: 71-78.

Kineke, G.C., and R.W. Sternberg, 1992. Measurements of high concentration suspended sediments using the optical backscatterance sensor, Marine Geology, 108: 253-258.

Lewis, J., 1996. Turbidity-controlled suspended sampling for runoff-event load estimation. Water Resources Research, 32: 2299-2310.

Ludwig, K. A., and Hanes, D. M., 1990. A laboratory evaluation of optical backscatterance suspended solids sensors exposed to sand-mud mixtures. Marine Geology, 94: 173–179.

Meister, H, K. M. Bali, E. T. Natwick, T. Turini, and J. N. Guerrero. 2004. Guidelines to production costs and practices for Imperial County-Field crops. UCCE_Imperial County Circular 104-F. http://ceimperial.ucdavis.edu.

Sadar M., 2002. Turbidity instrumentation - an overview of today's available technology. Turbidity and Other Sediment Surrogates Workshop, April 30 – May 2, 2002, Reno, NV.

Schoellhamer, D. H., and S. A. Wright, 2003. Continuous measurement of suspended-sediment discharge in rivers by use of optical backscatterance sensors. In: Erosion and Sediment Transport in Rivers: Technological and Methological Advances (Proceedings of the Osol Workshop, June 2002), IAHS Publ. 283: 28-36.

Sternberg, R.W., 1989. Instrumentation for estuarine research: Journal of Geophysical Research. v. 94, no. C10, p. 14289-14301.

Sutherland, T. F., P. M. Lane, C. L. Amos, and J. Downing, 2000. The calibration of optical backscatter sensors for suspended sediment of varying darkness levels Marine Geology, 162: 587- 597.

Wren, D. G., B. D. Barkdoll, R. A. Kuhnle, and R. W. Derrow. 2000. Field techniques for suspended-sediment measurement, Journal of Hydraulic Engineering, 126: 97-104.

Wright, L. D., J. P. Xu, and O. S. Madsen, 1994. Across-shelf benthic transports on the inner shelf of the Middle Atlantic Bight during the ''Halloween storm'' of 1991. Marine Geology 118 : 61–77

ACKNOWLEDGEMENT

WEB-BASED GIS DECISION SUPPORT SYSTEM FOR IRRIGATION DISTRICTS

Brian Fischer[1]
Mark Deutschman, PhD., P.E.[2]

ABSTRACT

Water management can be a complicated effort, especially when there is a lack of supporting information for making a decision. Often information is sparse or located in multiple locations. This presentation will demonstrate an affordable web-based tool developed with Open Source software. The purpose of the tool is to bring information into a single user interface for supporting water management functions and decisions. This presentation will focus on a decision support application created for the Sun River watershed in west-central Montana. The application is not intended to compete with existing SCADA applications, but compliment them by integrating and using some of the SCADA system data.

INTRODUCTION

The Sun River Watershed is located in west-central Montana covering 1.4 million acres of land. The Sun River meanders 110 miles until it flows into the Missouri River at Great Falls, MT. Over the past 10 years water right disputes have arisen because of drought conditions. Making decisions on how to settle water right disputes or even how to prevent them are often difficult because of the sparse nature of water rights information. Another factor that complicates decision making is the lack of accessible information to forecast water demands within the watershed.

The Sun River Watershed Decision Support System was developed as a tool to aid decision makers in preventing water rights disputes and give them easier access to the information they need to manage the watershed. The Sun River Watershed Decision Support System's user interface is shown in Figure 1.

The decision support system has integrated a number of functions and tools making water management decisions easier than previous methods. The purpose of this application is to provide real-time access to environmental and monitoring data (both telemetered from the Irrigation Districts system and from other sources on the web; i.e., NWIS) along with water rights / land use / cropping information, to operate the river system (and thereby conserve water). The tools are capable of computing water demand at specific diversion locations and evaluating upstream

---

[1] GIS Specialist/Programmer, Houston Engineering, Inc. (HEI), 10900 73rd AVE N, Suite 106, Maple Grove, MN 55369; bfischer@houstonengineeringinc.com.
[2] Vice President, HEI; mdeutschman@houstonengineeringinc.com.

shortages (both existing flows in the river and in storage). The demands and storages are computed using GIS information about crop type, and historic meteorological and climate data, and hydromet data. The information is presented using an interactive map with links to various State, Federal and Local databases. The tools are also accessed through this Internet GIS interface for estimating water demands. The tool is not meant to be the only pieces of information watershed and irrigation managers use to make their decisions, but rather another piece of information they can use.
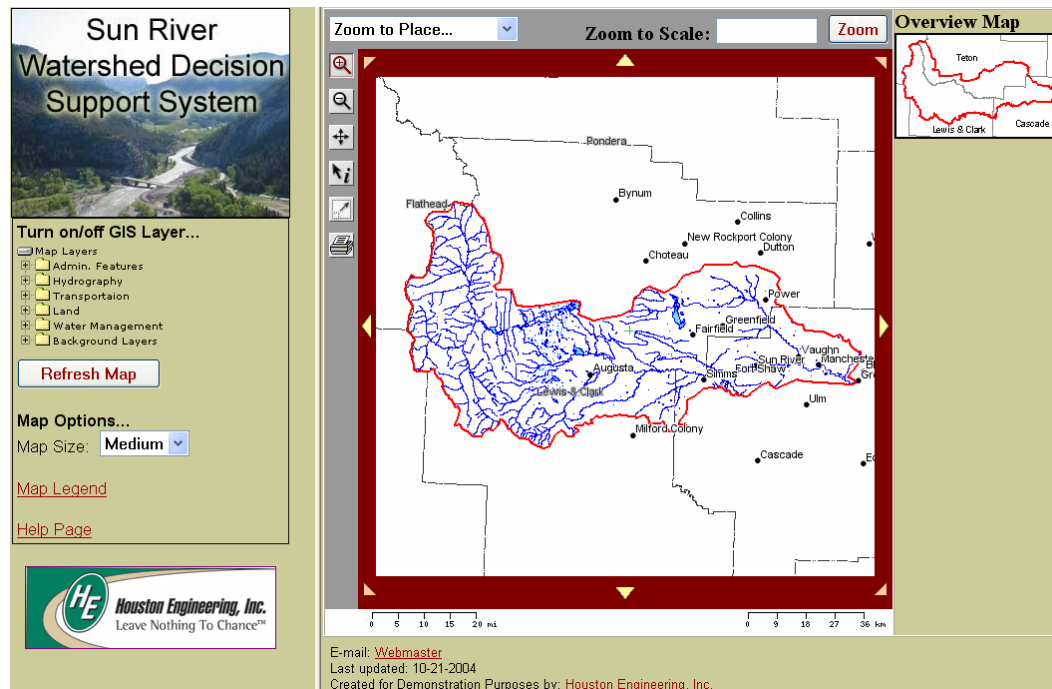

Figure1. Sun River Watershed Decision Support System User Interface.

COMPILING AND LINKING DATA

Data used by the Sun River Watershed Decision Support System includes a variety of basemap information, such as roads, hydrography, and cities, allowing users to orient themselves. Other data includes specific water management data such as water use, diversions, dams, stream flow, and reservoir operations. Most of the water management layers have an associated database allowing users to query for water rights, river discharges and reservoir conditions. Figure 2 shows a map zoomed in around Vaughn, MT with diversion and gaging station GIS layers turned on.
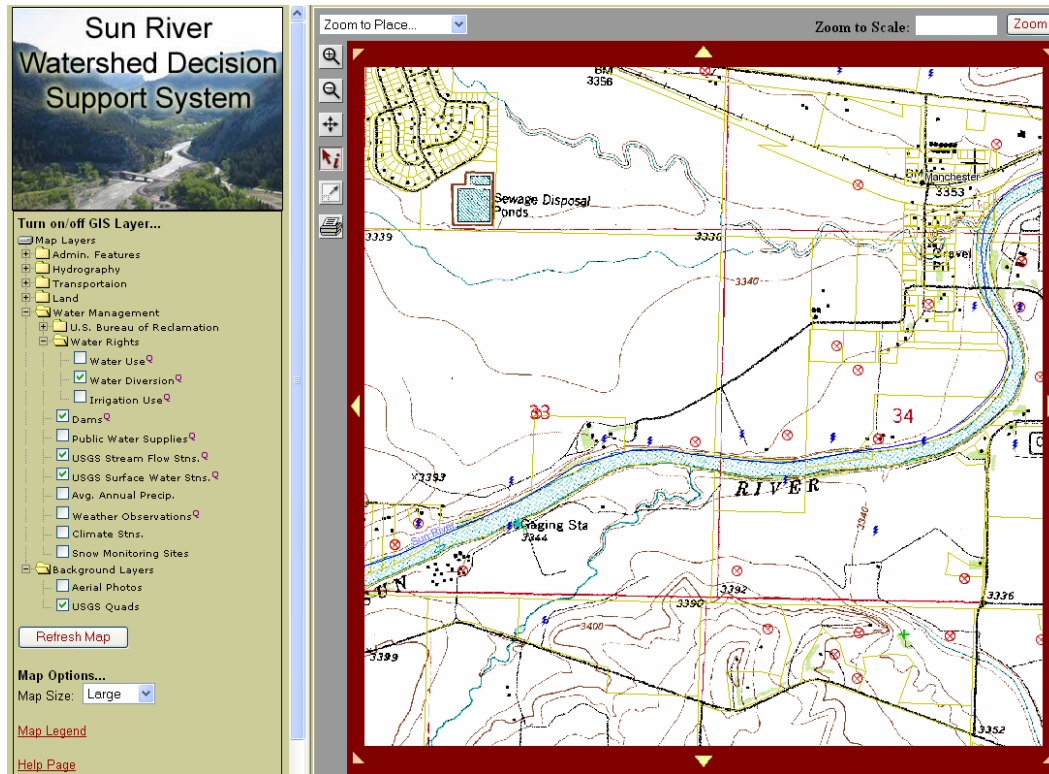
Figure 2. Web Application Zoomed in Around Vaughn, MT.

OPEN SOURCE SOFTWARE

The Sun River Watershed is made up of a watershed management organization and a few irrigation districts. Each organization is small and has limited operating budgets. In order to provide an affordable tool for staff to use in day-to-day decision making, it had to have low maintenance costs.

The logical choice to provide sophisticated functionality at a low cost was to turn to Open Source Software. Two primary Open Source GIS packages were used to develop the application. They included the University of Minnesota MapServer (http://mapserver.umn.edu) and PostGIS (http://postgis.refractions.net/). MapServer is the mapping engine and PostGIS is a spatial database that stores the data and provides querying functionality that is used to drive the web application. This allowed us to develop the application with no software costs and relies on no software maintenance costs into the future. This allows the organizations to focus maintenance costs on ensuring the data is up to date, hosting the web application and developing new tools as needs arise.

CONCLUSION

The Sun River Watershed Decision Support System is simply an Internet GIS tool developed to aid decision makers in the watershed on day-to-day water management decisions. The tool was developed with Open Source software in order to make the web application an affordable solution for local organizations with small operating budgets. The web-based tool is not meant to replace existing decision making processes, but provide additional information in an easy to use interface. Often much of the data exists to make decisions, but can be difficult to find and access. The web-based tool was developed to provide a cost-effective means of accessing the distributed information.

USING RIVERWARE AS A REAL TIME
RIVER SYSTEMS MANAGEMENT TOOL

Donald Frevert [1]
David King [2]

ABSTRACT

RiverWare has been used as a reservoir operation and river systems management tool by the Bureau of Reclamation, Tennessee Valley Authority and a number of other water resources management agencies and organizations for nearly 10 years. Development, maintenance and enhancement of RiverWare's capabilities is handled by the University of Colorado's Center for Advanced Decision Support for Water and Environmental Systems (CADSWES). Basins where RiverWare is presently utilized include the Colorado, Rio Grande, Truckee, Yakima and Tennessee Valley.
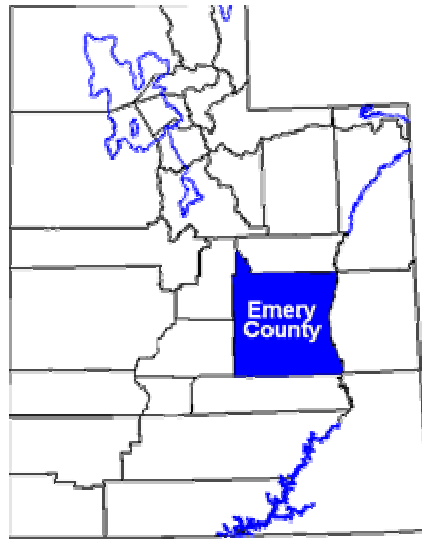
Figure 1. Location of Emery County, Utah.

RiverWare is currently being implemented on Cottonwood and Huntington Creek drainages located in Emery County in central Utah (see Figure 1). An effort is planned to operate a RiverWare model on a near real-time basis. The Emery

[1] Hydraulic Engineer, Water Resources Division, Bureau of Reclamation, Technical Service Center, PO Box 25007, Lakewood, CO 80225, dfrevert@do.usbr.gov
[2] Hydraulic Engineer, Water Resources Division, Bureau of Reclamation, Technical Service Center, PO Box 25007, Lakewood, CO 80225, dking@do.usbr.gov

County Project, a Federal water project operated by the Emery Water Conservancy District, includes a transbasin diversion from Cottonwood Creek to Huntington Creek. Recently, a non-Federal reservoir basin in the Huntington Creek watershed has started to leak, exporting water to drainage outside the county. This situation has put pressure on all the water users and threatens water rights. The implementation of RiverWare will hopefully help to determine the magnitude of the loss and provide a mechanism to improve river operations and ameliorate the situation.

INTRODUCTION TO RIVERWARE

RiverWare is a general purpose, object oriented modeling framework which can be used to develop multi-purpose simulation and optimization models of river and reservoir systems. Additional information about the general capabilities of RiverWare can be found in Zagona et al. (2001). RiverWare has been developed over the past ten years by the University of Colorado – CADSWES with substantial financial support from the Bureau of Reclamation, the Tennessee Valley Authority, the US Army Corps of Engineers and several other partners. Maintenance, technical improvements and distribution for RiverWare are handled by CADSWES.

RiverWare based models offer the capability to address short-term operations and scheduling, mid-term operational forecasting and planning, and long-term policy and planning issues. Computational time steps can range between one hour and one year, subject to the availability of data.   Daily and monthly time steps are most commonly used.

A model constructed in RiverWare consists of a network of linked "objects" such as reservoirs, river reaches, canals and other diversions and water users. The objects hold data and algorithms that tailor it to the site in the river basin it represents. Information passes between objects by way of links e.g., the outflow of a reservoir is linked to the inflow of a downstream river reach. In this way, the modeler has flexibility to completely describe a river and reservoir system.

A key feature of RiverWare is a rulebased simulation solver, through which operating policy is introduced into the simulation by operating "rules" that determine operational decisions such as reservoir releases and diversions. These rules are prioritized, and conflicts are resolved by giving higher priority rules precedence.   Another feature of RiverWare is the capability to do linear goal programming as a means of finding an optimal solution over the entire network and time interval. Another RiverWare capability allows the user to model the economics of hydropower through either simulation or optimization. More details of RiverWare's hydropower modeling capabilities, are found in Zagona and Magee (1999).

In many river basins in the western United States, it is necessary, not only to model water storage and deliveries, but also the ownership of that water. To address the issue of modeling water ownership and water type, RiverWare includes a Water Accounting module that represents the "paper water" as account objects that reside on the simulation objects. Legal accounts and "pass-through" accounts are two very useful features of RiverWare in addressing these issues.

HUNTINGTON AND COTTONWOOD CREEK DRAINAGES

Huntington and Cottonwood Creeks are tributaries of the San Rafael River, which drains a portion of the eastern slope of the Wasatch Plateau. The San Rafael is a tributary to the Green/Colorado River basin system. Stream flows in the San Rafael system are dominated by snowmelt runoff – with occasional runoff from spring and summer rainfall events.

The Emery Water Conservancy District (District) is the overarching water institution in Emery County and is interested in using real-time technologies and decision-support tools to improve river system operations. The flow of Huntington Creek is partially controlled by four non-Federal high mountain reservoirs which have a combined capacity of 17,400 acre-feet. Electric Lake, constructed by a regional electric utility to serve one of its coal-fired power plants, is located on a tributary of Huntington Creek (see Table 1).

Table 1. Statistics for Major Water Storage Reservoir.

Reservoir	Creek	Capacity (AF)	Elevation (ft above S.L.)	Surface (acres)	Max. Depth (feet)
Electric Lake	Huntington	32,000	8,575	425	217
Huntington North	Huntington (off stream)	5,690	5,839	225	56
Joe's Valley	Cottonwood	62,450	6,990	1,183	169

Huntington North Reservoir is an off-stream Federal reservoir located fairly low in the river basin. Joes Valley Reservoir is a Federal reservoir on Cottonwood Creek.

Most water rights in the District's service area are held by the Cottonwood Creek Consolidated Irrigation Company (CCCIC), Huntington Creek Irrigation Company (HCIC), PacifiCorp (the regional power company), and the Federal government. However, several other entities and water rights also exist. The water rights consist of direct flow rights (non-storage water) and storage rights of Federal and non-Federal entities. The Emery County Project provides water from Joes Valley reservoir to CCCIC and HCIC canals and Huntington North

Reservoir via a transbasin diversion. Exchanges can also occur whereby water is used in a location without being physically moved from another location.

In 1993, the District and Reclamation designed and installed the first step in a comprehensive real-time hydrologic and weather monitoring system. This real-time network was designed to improve the responsiveness of the county's water delivery systems. Data from the field sites was telemetered back to District's office by line-of-sight radio. In this initial effort, 17 water and 3 weather monitoring sites were upgraded by adding telemetry equipment.

This initial effort was expanded in subsequent years. The District's now has a monitoring system covering all of western Emery County that includes over 100 field sites, 5 repeaters, and a base station. The system also includes 10 control sites, an early warning system on Joes Valley Dam and Reservoir, and 3 fully automated cloud-seeding sites. The real-time and historic data (for the water year) is displayed on the District's website (www.ewcd.org), which is updated hourly.

Since 1993, the base station for the District's automated data collection system has evolved. It started out with a PC running DOS and the RTU (remote terminal unit) vendor's software, and has over time become far more complex. The current base station includes: (1) a router/firewall which secures the real-time network; (2) a switch which routes network communications; (3) an ADSL modem which connects to the upstream Internet provider; (4) a data collection server running Windows 2000 Professional, which polls the RTUs and stores the real-time data to disk; (5) dual web servers running Redhat 7.3 Linux which provide web/e-mail/DNS hosting for www.ewcd.org; (6) a mirror system residing in an adjacent building; (7) a healthy UPS with web-based management; and (8) a diesel-powered emergency generator.

IMPLEMENTATION OF RIVERWARE

Recently, Electric Lake started to leak and the end result is that water is being unintentionally exported to an adjacent drainage. This has put pressure on all the water users and threatened the water rights associated with the Emery County Project and others. Plans are to make RiverWare operate on a near real time basis on Huntington Creek.   Before that can be done, however, a water rights and accounting analysis using historical data must be completed. Although the basin is not hydrologically complex, the water rights, transbasin diversions, and exchanges make the water accounting problem complex.

Using a combination of mass-balance, water accounting features, and rules, the District's RiverWare model will enable after the fact detailed water accounting of the basins. The implementation of RiverWare will hopefully help to quantify the magnitude of the loss, account for all real and paper water, and enhance

operations. Researchers believe that the Huntington Creek implementation will pave the way for additional real time applications of RiverWare by local government entities and stakeholder organizations in Utah as well as other locations.

REFERENCES

Zagona, E. and T. Magee (1999) "Modeling Hydropower in RiverWare", American Society of Civil Engineers, Waterpower '99, Proceedings of the International Conference on Hydropower, Las Vegas, NV, July, 1999.

Zagona, E., T. Fulp, T. Magee and H.Goranflo (2001) "RiverWare: A Generalized Tool for Complex Reservoir Systems Modeling", Journal of the American Water Resources Association, Volume 37, Number 4, pages 913-929.

SUBMERGED VENTURI FLUME

Tom Gill[1]
Robert Einhellig[2]

ABSTRACT

Improvement in canal operating efficiency begins with establishing the ability to measure flow at key points in the delivery system. The lack of available head has been a constraint limiting the ability to measure flow using traditional critical-flow measurement structures at many locations. Engineers at Reclamation's Water Resources Research Laboratory (WRRL) have been investigating the viability of measuring flow where limited head is available using a submerged venturi flume.

The term "venturi flume" is used in flow measurement literature to describe a broad range of measurement structures. The geometry being referred to as a venturi flume in this paper is a flat bottomed-structure with prismatic upstream and downstream sections, a gradual contraction leading to a prismatic throat of narrowed width, followed by a gradual expansion to the downstream section. Sidewalls may be either sloped or vertical. Flumes of this geometry with sloped sides have commonly been called trapezoidal flumes. Venturi flumes have been used for many years as a critical-flow measurement device that will perform with greater tolerance for submergence than Parshall flumes. When functioning as a critical flow device, discharge through a venturi flume is a function of only the upstream water level. For submerged-flow measurement, water levels both upstream and at the throat section must be known.

Laboratory tests were performed using a long-throated flume installed in series with, but downstream from a venturi flume. The long-throated flume both created submergence on the venturi flume and provided a means of comparative flow measurement. In initial laboratory testing, agreement between flows measured with the long-throated flume and the submerged venturi flume was within 4% over a discharge range from 0.5 ft^3/s to 5.0 ft^3/s.

Key to practical field use of the submerged venturi is identification of an affordable means of obtaining accurate measurement of small head differential in an efficient manner. WRRL engineers are working to develop an affordable,

---

[1] Hydraulic Engineer, Bureau of Reclamation, PO Box 25007, Denver CO 80225-0007; Phone 303 445 2201; e-mail tgill@do.usbr.gov
[2] Hydraulic Engineer, Bureau of Reclamation, PO Box 25007, Denver CO 80225-0007; Phone 303 445 2201; e-mail reinhellig@do.usbr.gov

robust differential-head sensing system to field test with the submerged venturi flume during the 2005 irrigation season.

INTRODUCTION

The degree to which utilization of modernized control technology such as Supervisory Control and Data Acquisition (SCADA) systems can provide improved delivery system efficiency is directly related to the ability to measure flow rates at points throughout the delivery system. Until recently, flow measurement in an open channel has almost exclusively been performed by passing flow through a critical-flow measurement structure. If critical flow is developed, then there will be a unique relationship between an upstream flow depth and the discharge. Where sufficient head is available, critical flow devices remain an excellent choice for flow measurement accuracy and, in most cases, for flow measurement affordability.

When limited water-surface drops can be tolerated in a system, critical-flow measurement structures often experience conditions of downstream submergence. Submergence of a critical-flow measurement structure occurs whenever the downstream water-surface elevation exceeds the control elevation of the structure (e.g., the crest of a weir). The amount of submergence on a flow-measurement structure is commonly defined as the ratio of the height of the downstream water surface to the height of the upstream water surface, where each is measured relative to the control elevation.

Many flumes can tolerate varying degrees of submergence while maintaining the critical-flow conditions necessary for accurate measurement. This is a distinct advantage over weirs which require more head drop and are unable to maintain critical-flow conditions if any submergence is present. The Parshall flume—long the open channel measurement standard—will continue to provide accurate flow measurement with submergence levels of up to 70 percent (U.S. Bureau of Reclamation, 1997).

With the widespread availability of personal computers, rating and calibration procedures have been incorporated into software for designing and calibrating long-throated flumes (Wahl et al, 2000). These structures continue to provide accurate flow measurement with downstream flow depths above the flume crest approaching 90 percent of the upstream flow depth. When it is recognized that these flumes often feature a raised crest, the minimum differential (or head loss) between the upstream and downstream water surfaces at which accurate measurements can be made with a long-throated flume is considerably smaller that the minimum elevation differential required for accurate measurements with the Parshall flume.

Despite the improved performance characteristics offered by the long-throated flume, many districts have the need to measure flows at sites where the limited head available is insufficient for even a long-throated flume. Recently developed acoustic doppler profiling instruments are often able to measure open-channel flow under such conditions with essentially no resulting head loss. With the cost of these instruments varying from a few thousand up to about twenty thousand dollars and the lower-end units providing varying degrees of accuracy and performance consistency, these devices are not yet widely deployed for irrigation turnout applications. This paper examines a structural alternative (the venturi flume) for measuring flows under any degree of submergence.

VENTURI FLUMES

The term venturi flume can be found in literature referring to a class of structures in which the flow cross-sectional area is gradually reduced to accelerate flow velocity. Under this broad definition, Parshall, cutthroat and broad crested flumes would all be subsets of the venturi flume class. A narrower, more concise use of the term venturi flume is a flat-bottomed structure with prismatic approach, throat and discharge sections. A gradual contraction section joins the approach and throat, while the throat and discharge sections are joined by a gradual expansion section. A popular geometry for these flumes uses trapezoidal cross sections at all locations, however vertical-walled structures would also meet the criteria for venturi geometry.

Work funded by the US Department of Agriculture (USDA) was performed at Colorado State University to assess the suitability of venturi flumes as critical flow structures. In this effort, Robinson and Chamberlain (1960) developed laboratory-calibrated rating curves for two trapezoidal venturi flume sizes based on empirically-developed data. Their studies showed that as a critical-flow measurement device, venturi flumes continue to provide accurate flow measurements up to a submergence level of eighty percent. This represents approximately a ten percent increase in submergence tolerance over the Parshall flume.

SUBMERGED VENTURI FLUMES

It has long been recognized that if water levels (and hence cross-sectional flow areas) can be accurately determined at both the prismatic approach section and the prismatic throat section, flow can be calculated analytically by combining and solving the energy and continuity equations. This methodology could be utilized both when critical flow is present or under highly submerged conditions. Unfortunately, the degree of accuracy in depth measurement needed—particularly at low flow conditions—requires a significantly greater resolution than the 0.01 ft. least reading of common staff gages used to measure depth in critical-flow devices.

A series of tests was performed at Reclamation's Water Resources Research Laboratory (WRRL) in 2003 with a submerged venturi flume to evaluate the viability of measuring approach section and throat depths with sufficient accuracy to provide acceptable measurement accuracy. The test model featured a trapezoidal channel with a 0.860-ft bottom width and 1:1 side slopes. The throat section has a 0.333-ft bottom width with 1:1 side slopes and a length in the direction of flow of 3 ft. Gradual contraction and expansion sections in either direction from the throat are each 3 ft long in the direction of flow and maintain a 1:1 side slope. A long-throated flume was constructed at the downstream end of the channel, both for obtaining a control flow measurement and to create submerged conditions on the venturi flume. The invert of the test flume was horizontal throughout.

Taps were placed in the channel wall just above the channel invert at four locations. The first tap was located in the approach section 1.5 ft upstream of the upper end of the converging section. The second tap was placed at mid-reach of the venturi throat. A third tap was placed 1.5 ft downstream of the lower end of the expansion section. The fourth tap was placed upstream of the long-throated flume at the design location called for by the WinFlume software. Valves were placed in all tap lines, beyond which all taps were connected into a manifold plumbed to a common stilling well equipped with a hook-type point gage with a reading increment of 0.001 ft.

Figures 1 & 2 show the laboratory venturi flume model. Figure 1 is a view looking in the direction of flow. Submergence of the venturi flume (seen in the foreground) is caused by presence of the long-throated flume at the downstream end of the channel (upper middle of photo). Discharges measured with the long-throated flume served as the control measurements for the study. The stilling well equipment is seen at the right of the venturi flume in Figure 2 which is shown which a discharge in excess of 5 ft^3/s.

Figure 1.

Figure 2.

LABORATORY TEST RESULTS

In the 2003 tests, eight flows over a targeted discharge range of 0.5 to 5 ft^3/s were delivered to the model. Flow depths at each of the three venturi tap locations were measured as was the flow depth over the long-throated flume. Each time the tap connection to the stilling well was changed, the stilling well was given 5 minutes to stabilize before a reading was taken. After another 5 minutes, a second reading was taken to confirm the level in the stilling well had reach equilibrium. If a differential in readings was observed, a reading would be taken after a third five minute interval. For all measurements taken, consecutive equivalent level readings were obtained in 15 minutes or less using this methodology. As previously mentioned, discharge through a submerged venturi flume may be determined analytically by combining the Energy and Continuity equations. The formula derived from this combination is:

$$Q = C_d * \frac{A_1 * A_T}{(A_1^2 - A_T^2)^{0.5}} * \left(\frac{2g}{\alpha} * (H_1 - H_T)\right)^{0.5} \qquad \text{Equation 1}$$

Where: Q = discharge in ft^3/s
C_d = discharge coefficient (dimensionless) to account for losses between the upstream and mid-throat flow cross sections. (This value is empirically determined – typically near 0.95)
A_1 = upstream flow cross section area in ft^2 (at location of upper tap)

A_T = throat flow cross section area in ft^2

α = velocity correction term (dimensionless) to account for the fact that flow velocity near the taps will be less than the mean cross section velocity. (α is commonly assigned a value of 1.02)

H_1 = depth of flow (ft) at the upstream tap

H_T = depth of flow (ft) in the flume throat

A_1 & A_T of Equation 1 are calculated from measured values for H_1 & H_T and from known geometry of respective channel cross sections. Table 1 shows the respective flow level readings obtained at the taps for each of the flow rates observed. As shown in the lower right of the table, discharges measured in the submerged venturi flume varied by less than four percent from flows measured in the long-throated flume for all observed flow rates.

Table 1.

	Submerged Venturi Meter				
	Depth of Flow			Calculated	Flume
Run #	up stream ft	throat ft	down stream ft	Discharge ft^3/s	Submergence %
1	0.632	0.623	0.628	0.549	99.4
2	0.731	0.710	0.725	1.049	99.2
3	0.821	0.788	0.812	1.575	98.9
4	0.902	0.854	0.891	2.177	98.8
5	0.937	0.881	0.923	2.474	98.5
6	1.021	0.945	1.002	3.249	98.1
7	1.148	1.033	1.123	4.568	97.8
8	1.214	1.052	1.184	5.428	97.5

	Long-Throated Flume			
	Depth of Flow		Calculated	Deviation in
	Above	Above	Discharge	Calculated
Run #	Invert ft	Flume Crest ft	ft^3/s	Discharge %
1	0.628	0.203	0.53	3.95
2	0.725	0.300	1.01	3.99
3	0.812	0.387	1.57	0.24
4	0.891	0.466	2.19	0.55
5	0.923	0.498	2.47	0.23
6	1.002	0.577	3.23	0.60
7	1.123	0.698	4.59	0.55
8	1.184	0.759	5.37	1.05

Flow for the long-throated flume was calculated from flow levels at tap 4 using the following rating equation (developed using the WinFlume software):

$$Q = 0.05684 * (H/12 + 0.6134)^2$$
Equation 2

Where: Q = discharge in ft3/s
  H = depth of upstream flow above flume crest (ft)

Discharge rates calculated for both flumes are plotted in Figure 3. In this plot, discharges from both flumes are plotted against the discharge for the long-throated flume which served as the control for this study. This graphic representation of the discharge data from Table 1 shows the high degree of agreement in discharge measurements obtained from the two structures during the laboratory tests.
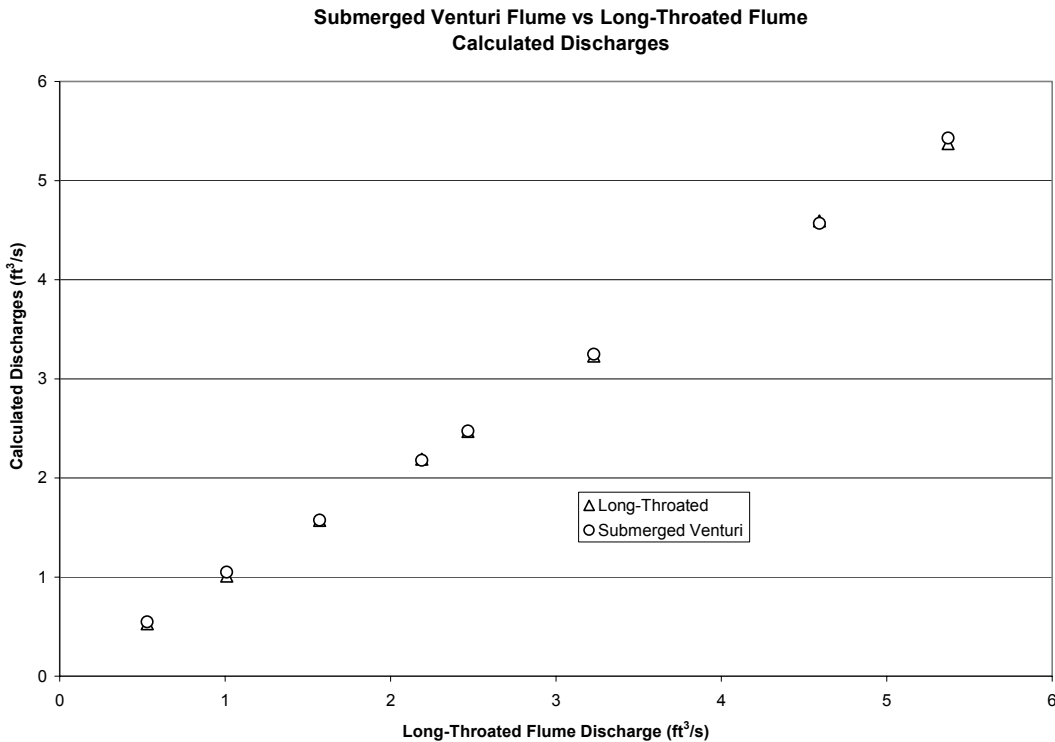
Figure 3.

CONCLUSIONS FROM INITIAL LABORATORY TESTING

The laboratory test results presented above indicate discharge rates measured using a submerged venturi flume can approach the flow measurement accuracy of a long-throated flume. This suggests field use of submerged venturi flumes could be viable for measuring discharge under conditions of limited head availability in the field. The methodology used to measure flow depths in the laboratory study (requiring up to 30 minutes per discharge reading) would not be practical for many canal applications.

The issue of time require per discharge reading could be greatly diminished if two level measurements could be obtained with suitable measurement accuracy without using a single stilling well. One option would be installation of two independent water-level sensors—one measuring level at the upstream cross section and the other measuring level at the throat. This would introduce uncertainties into the measurement process both from the accuracy of calibration of each sensor and in terms of the measurement resolution limits of the sensors.

For an example, consider only the resolution limits of a candidate submersible pressure transducer sensor. A selected product has been identified that can operate over a 3.3 ft depth range and provide a 0.2% of full scale accuracy. Based on this information, each sensor would have a resolution limit of 0.007 ft. Utilizing the combined information from two such sensors to calculate flow in the submerged venturi the resolution limits alone would result in an uncertainty of twice the resolution limit or 0.014 ft. This value exceeds the 0.009 elevation differential shown in Table 1 by which a discharge of approximately 0.55 ft^3/s was calculated. When uncertainties related to sensor calibration plus drift away from calibration that is commonly observed over time with various sensor technologies are added to resolution limit uncertainties, use of two independent water-level sensors to determine flow rates in a submerged venturi flume would not appear to provide promising prospects for attaining an acceptable level of measurement accuracy.

A second approach considered is the use of two sensors that do not function independently. One sensor could be used to measure upstream level, while the second sensor would measure level differential. With this configuration, accounting for resolution limitation and calibration uncertainties would present a diminished impact compared with using two independent sensors. Two candidate technologies for measuring level differential that were considered are 1) a differential pressure transducer plumbed between two stilling wells and 2) a "balance beam" system that measures differential buoyant forces on non-buoyant plummets partially submerged in two stilling wells. Either of these differential level sensors could be coupled with any of the range of available level sensors which could be used to measure upstream level.

A third approach for obtaining water levels at the two submerged venturi flume cross sections would be to utilize a single level sensor that remotely senses pressure at a given point, such as a bubbler sensor. A configuration using a bubbler sensor and a two-way solenoid valve installed in the bubbler line could alternately sense flow depth in each of two stilling wells. Signal from the sensor would be coupled with feedback indicating valve position by a controller that would process the information to determine both flow depths, and from flow depth values, calculate discharge. This approach would appear to introduce the least degree of uncertainty into the discharge calculation with a submerged venturi flume, and would represent a more simplistic installation over the other level measurement alternatives identified above.

PLANNED CONTINUATION OF RESEARCH

A proposal has been submitted for fiscal year 2006 funding through Reclamation's Science and Technology Program to investigate water-level measuring methods that will provide the required degree of measurement accuracy for both upstream and throat water levels in a submerged Venturi flume, and that will be practical from a required time duration standpoint. One of the measurement methods outlined in the research proposal includes using a single bubbler sensor to measure both the upstream and throat section levels. A second method proposed would feature use of plummets in two stilling wells suspended from a balance beam to measure differential head. Proposed work with the balance beam would include development of both manual and electronic methods for making differential level measurements.

SUMMARY AND CONCLUSIONS

The initial phase of this study focused on determining whether discharge rates could be determined in a submerged venturi flume with a useful degree of accuracy. Results of the WRRL's 2003 tests indicate that a level of measurement accuracy can be achieved suitable for open-channel measurement applications. From that point, the focus of the study has turned to identifying technologies for both manual and electronic measurement methods that would make the use of submerged venturi flumes practical for measuring flow in agricultural water-delivery systems.

Looking forward, as practical water-level sensing and measurement calculating capabilities are identified for submerged venturi flumes, field demonstrations of the technology will be the next stage of the study. Based on what has been shown in the tests concluded to date, submerged venturi flumes offer promise as an affordable means of measuring open-channel discharge at sites where limited head availability makes use of critical-flow devices unfeasible. This expanded flow measurement capability could play a pivotal role in enhancing the level of

sophistication of SCADA operations which a water delivery system is able to develop and adopt.

REFERENCES

Robinson A.R., and A.R. Chamberlain. "Trapezoidal Flumes for Open Channel Flow Measurements." *Transactions, American Society of Agricultural Engineers*, vol. 3 (No. 2):120-124,128, 1960

U.S. Bureau of Reclamation, 1997, Water Meaurement Manual, 3rd ed., U.S. Government Printing Office, Washington, DC 20402.

Wahl, T.L., A.J. Clemmens, J.A. Replogle, and M.G. Bos, 2000, "Winflume—Windows-based Software for the Design and Calibration of Long-Throated Measuring Flumes," 4th Decennial National Irrigation Symposium, Phoenix, Arizona, November 14-16, 2000.

OCHOCO IRRIGATION DISTRICT TELEMETRY CASE STUDY

Kathy Kihara[1]
Shane Livingston[2]

ABSTRACT

Ochoco Irrigation District with help from Reclamation's Water Conservation Field Services Program installed three water measurement stations with cell phone telemetry at the tail end of three of their main delivery canals in the spring of 2001. The project was funded to improve the district's water management so they could cope with reduced supplies. In the past the district would send a ditchrider to these locations at the end of the day to record and report the amount of water being spilled each day. This information was then used to calculate the releases needed for delivery the next day along with the incoming water orders. The installation of the water measurement structures and cell phone telemetry enabled the district manager and ditchriders to check on the amount of tailwater at any time during the day. This allowed them to then tweak the deliveries to reduce the amount of tailwater. The implementation of the project was done with a combination of technical and financial assistance from Reclamation and in-kind labor by the district. The timeline was: the idea was explored during the fall of 2000, a grant for financial assistance was done in early winter 2001, the designs for the ramp flumes was done at the same time along with the procuring the telemetry equipment, installation of the flumes and telemetry was done in the spring of 2001. The results of the project were that the district was able to make deliveries for the entire irrigation season in spite of the drought water year and have carryover storage in both Ochoco and Prineville Reservoirs.

INTRODUCTION

The Ochoco Irrigation District (OID) serves 23,840 acres in an area which lies north and west of Prineville Oregon. The water resources of Ochoco Creek and Crooked River furnish irrigation water to OID. The district was organized in 1916 to build a dam on Ochoco Creek. Ochoco Dam was constructed with private capital in 1917-1918, with a usable capacity of 46,500 acre-feet. In 1948 Ochoco Dam rehabilitation was authorized by Congress. The Crooked River Project was authorized by Congress in 1956 for construction of Arthur R. Bowman Dam to provide a supplemental irrigation supply to the district of 70,282 acre-feet. The OID has approximately 97 miles of distribution facilities.

[1] Water Conservation Coordinator, Bureau of Reclamation (USBR), 1375 SE Wilson Avenue, Suite 200, Bend Oregon 97702; kkihara@pn.usbr.gov
[2] Automation Technician, Bureau of Reclamation (USBR), Pacific Northwest Region, 1150 North Curtis Road, Suite 100, Boise ID 83706: slivingston@pn.usbr.gov

Before installation of the water measurement stations and telemetry, the district manager would send a ditchrider out to the last measuring stations on the delivery canals at the end of each day to record and report the amount of water being spilled. This information was then used to calculate reservoir releases needed for delivery the next day along with the incoming water orders. This method worked but resulted in a lot of excess water being released and was labor intensive.

DESCRIPTION OF THE PROJECT

The District approached Reclamation as part of the Water Conservation Field Services Program about installing some improved water measurement structures with telemetry. Reclamation personnel visited the District in the fall of 2000 to determine the locations for the water measurement structures and negotiate a cost share agreement. Three tail-end stations were chosen, as these would give the District the largest benefit in terms of water savings and labor. The stations chosen were "the Gap" at the end of the Ochoco Main Canal, "Lytle Creek", and "Crooked River" at the end of the Crooked River Distribution Canal. Ramp flumes were chosen for the measuring device and cell phones were chosen for the telemetry.

The project was funded to improve the District's water management. The District wanted to be able to stretch their supply.

IMPLEMENTATION PROCEDURE

Reclamation designed the ramp flumes and specified the telemetry equipment. The District fabricated the ramp flumes and installed them. Once the measurement structures were installed, Reclamation personnel installed the telemetry equipment. The telemetry equipment was programmed and calibrated and OID was instructed in the use of the equipment so they could operate it independently.

Figure 1. Installing pre-fabricated ramp flume at "The Gap."

Figure 2. "The Gap" Stilling well installed. Box and stand for the telemetry
equipment installed.

Figure 3. Completed installation of the station at "The Gap."

Figure 4. Ochoco Irrigation District Manager Russ Rhoden
checking the installation at "Lytle Creek."

Figure 5. Typical installation of telemetry equipment.

POST-PROJECT EVALUATION AND RESULTS

District patrons had a full season of irrigation (if not a full allotment) and there was carryover storage in Ochoco Reservoir. In previous drought years, the content of Ochoco Reservoir was down to less that 500 acre-feet by September 30. In 2001, the content of Ochoco Reservoir was 8448 acre-feet on September 30.

In comparing pre and post project Ochoco Reservoir hydrographs, there is an approximate 26% reduction of the drawdown rate. For pre-project conditions the overall drawdown rate was 155.94 ac-ft/day from May 21 to September 30. For post-project conditions the overall drawdown rate was 115.38 ac-ft/day from May 8 to September 30.

SUMMARY

Installation of this low-cost water measurement and telemetry equipment has improved OID's water management and resulted in time, cost, labor, and water savings.
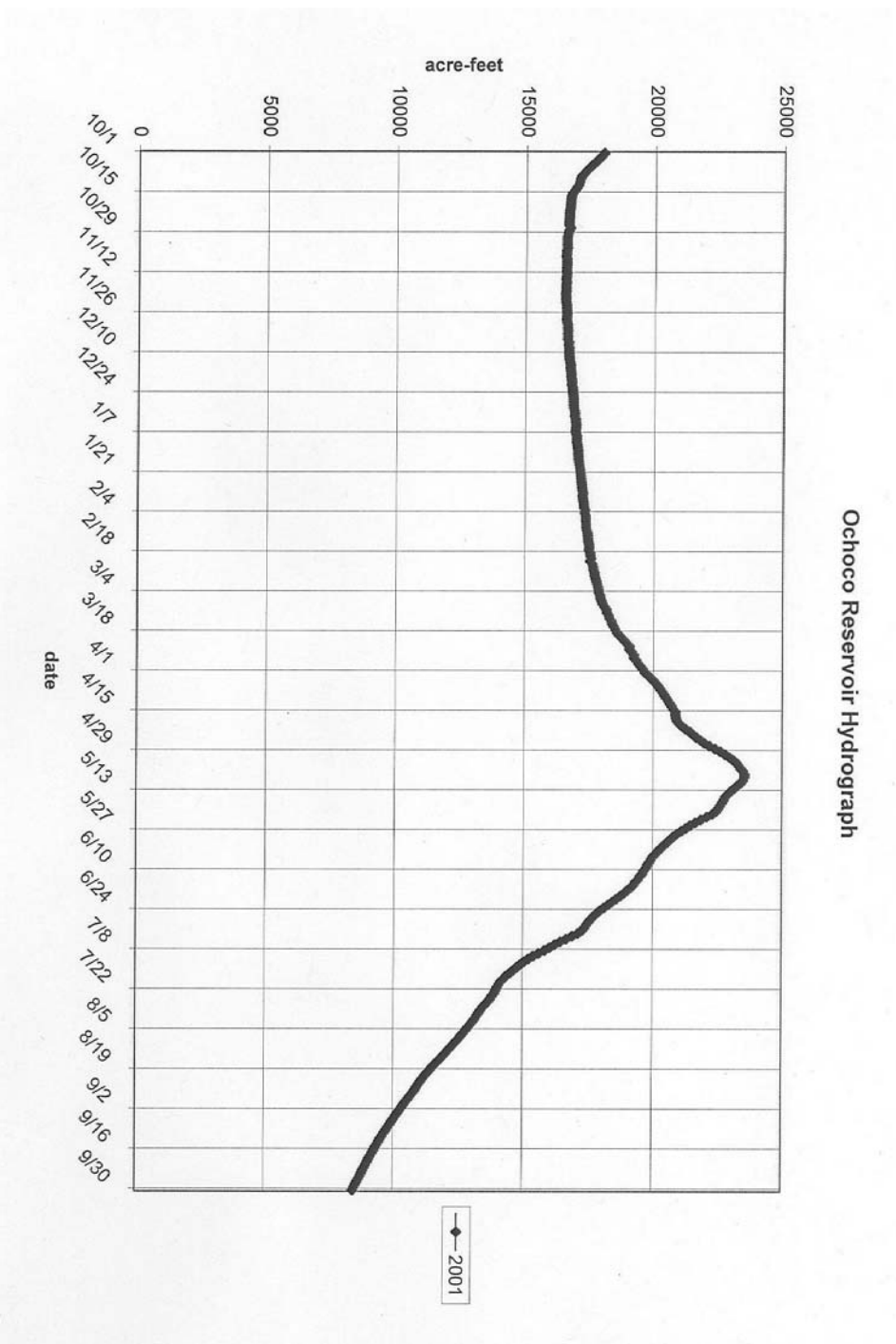
Figure 6. Ochoco Reservoir Hydrograph for water year 2001. The project was installed prior to the irrigation season.
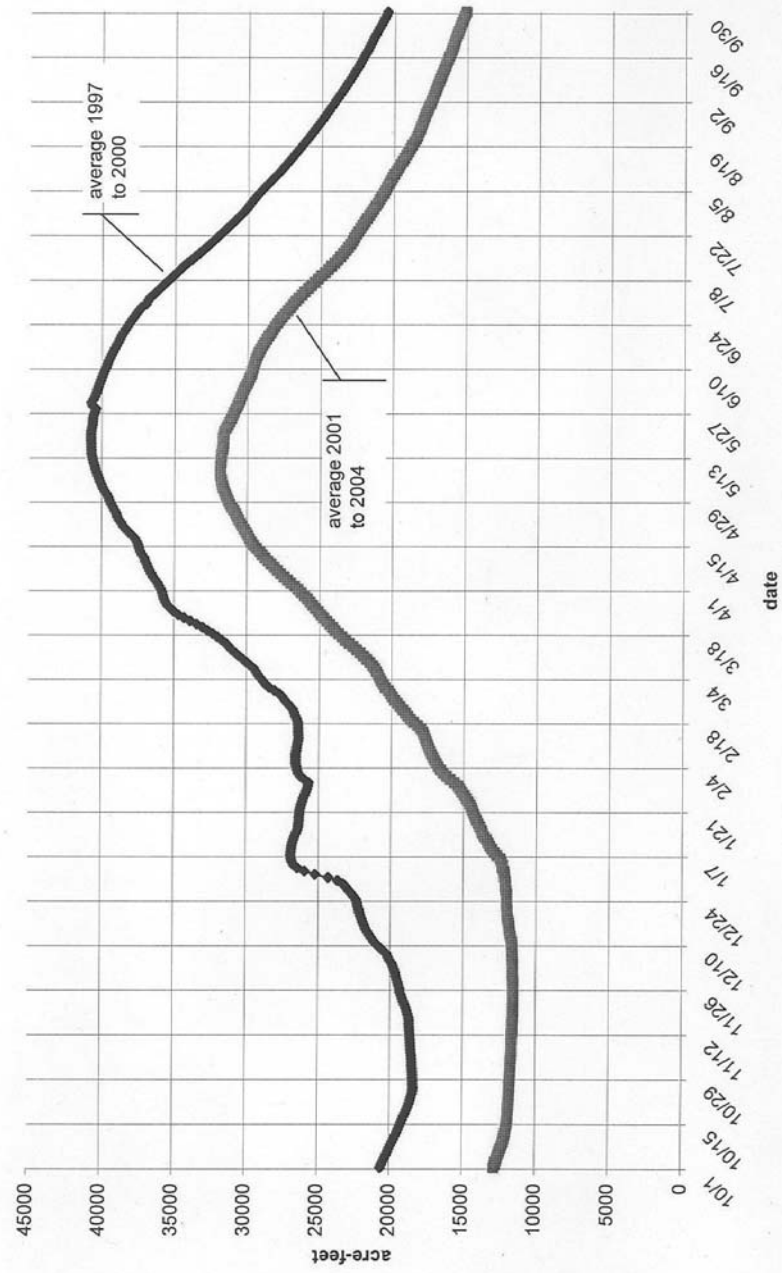
Figure 7. Hydrographs of the averages of water years 1997 to 2000 (pre-project) and of water years 2001 to 2004 (post-project).

UINTA BASIN REPLACEMENT PROJECT:
A SCADA CASE STUDY IN MANAGING MULTIPLE INTERESTS AND ADAPTING TO LOSS OF STORAGE

Wayne Pullan[1]

ABSTRACT

Section 203(a) of the Central Utah Project Completion Act authorized a replacement project--the Uinta Basin Replacement Project (UBRP)—to replace the Uinta and Upalco Units of the Central Utah Project (CUP) which were not constructed. The UBRP will provide: 2,000 acre-feet of irrigation water; 3,000 acre-feet of municipal and industrial water; reduced wilderness impacts; increased instream flows; and improved recreation.

On the Lake Fork River, UBRP must be integrated into a complex water environment. The SCADA information generated by UBRP will play a key role in reducing uncertainty for water users—which is expected to have an economic impact.

Construction delays in enlarging Big Sand Wash Dam and Reservoir eliminated the ability of the Moon Lake Water Users Association (Association) to store any substantial amount of water behind the old dam during the 2005 irrigation season. In response to this crisis, the partners in the project expanded the planned installation of SCADA monitoring and automation at key sites and required the installation to be completed over a period of weeks instead of years. The objective was to mitigate the effect of the lost storage by increasing flexibility and fine-tuning operations. The effort was largely successful.

DESCRIPTION OF THE UINTA BASIN

Any fourth-grader in Utah can tell you that the Uinta Mountains are the only major mountain range running east to west in North America. The Uinta Basin lies to the south of the Uinta Mountains and is fed by creeks and rivers flowing south from those mountains. Many of the principal rivers (Strawberry River, Currant Creek, Rock Creek, Lake Fork River, and Uinta River) flow into the Duchesne River which feeds the Green River.

The Basin is the location of the Ute Tribe of the Uinta and Ouray Reservation (Tribe) which is commonly referred to as the Northern Ute Tribe, as well as the

---

[1]Program Coordinator, Central Utah Project Completion Act Office, Department of the Interior, 302 East 1860 South, Provo, Utah 84606, (801) 379-1194, wpullan@uc.usbr.gov

cities of Duchesne, Roosevelt, and Vernal. When oil prices are sufficiently high to overcome the cost of transportation to areas outside the Basin, the area's oil industry roars to life (as it has in the past two years). Ordinarily, agriculture (chiefly cattle operations) is the lifeblood of the Basin economy; and, in the Basin, irrigation is the lifeblood of agriculture. It is important to note also that wilderness designation protects much of the Uinta Mountains. The mountains and associated steams are an important ecological resource.

This summary establishes the competing interests in Uinta Basin Water: non-Indian irrigators, the Tribe, the cities, the oil industry, and the natural environment. All water development in the Basin has been intended to serve one or more of these interests.

WATER DEVELOPMENT IN THE UINTA BASIN

The current incarnation of UBRP is founded on and entwined with other water development in the Basin. Key stages in that development are: the establishment of the Northern Ute Reservation, homesteading and early water development, the Uinta Indian Irrigation Project, the Moon Lake Project, the CUP as originally planned (with the Uinta and Upalco Units), and the current UBRP.

The Northern Ute Reservation

The Northern Ute Reservation was established in 1861 and tribal water rights associated with the creation of the reservation share that filing date. To date, the Tribe has not fully asserted its water right claims. An adjudication of Uinta Basin water rights begun by the Utah State Engineer in 1956 was placed in abeyance while the Tribe, the State of Utah, and the Secretary of the Interior negotiated a water rights compact. These negotiations, in one form or another, have continued for over forty years, although promising progress has occurred within the past year.

Homesteading and Early Water Development

The reservation was opened for homesteading by non-Indians in 1905. During the early decades of the twentieth century, both Indian and non-Indian irrigation systems were constructed, including the construction of the High Mountain Lakes.

The Uinta Indian Irrigation Project

The principal Indian irrigation project in the Basin is the Uinta Indian Irrigation Project. The Bureau of Indian Affairs (BIA) designed and constructed this project. By 1935, it was irrigating over 77,000 acres of Indian land. Today, the UIIP continues to serve Indian and non-Indian irrigators in the Lake Fork drainage and elsewhere in the Basin. It continues to be owned and operated by BIA.

The Moon Lake Project

In the 1930's, the Bureau of Reclamation (Reclamation) designed and constructed the Moon Lake Project on the Lake Fork River. The Association operates and maintains the Moon Lake Project on behalf of Reclamation and will operate and maintain the enlarged Big Sand Wash Dam and Reservoir.

The Central Utah Project

In 1956, the Colorado River Storage Project Act became law. The Act authorized the CUP (as well as other Reclamation projects). The CUP provided for the trans-basin diversion of Uinta Basin water to the Wasatch Front. The Wasatch Front is the most populous area of Utah and includes Provo City and Salt Lake City. The project mitigated for the trans-basin diversion by creating the Uinta and Upalco Units. These units would have provided new storage in the Uinta Basin--on the Uinta and Lake Fork Rivers respectively.

For a variety of reasons, the Uinta and Upalco Units were never constructed. Section 203 (a) of the Central Utah Project Completion Act authorized funding for UBRP—a project intended to provide similar benefits, in some measure, to those that were promised by the units that were not constructed. Originally, the UBRP project planned under the authority of Section 203 (a) was to serve both Indian and non-Indian needs using Indian and non-Indian water. Although planning continued for several years, the Tribe withdrew its support at the eleventh hour--as contracts were being executed. The departure of the Tribe made a reformulation of the plan necessary. Eventually, a scaled-down version was developed. The scaled-down project intentionally avoided interference with tribal water rights, lands, and interests.

The Central Utah Water Conservancy District (District) is the sponsor and entity responsible for repayment of the federal obligation associated with the Bonneville Unit of the CUP and UBRP. One example of the complications involved in layering the UBRP on top of pre-Moon-Lake-Project irrigation facilities and the Moon Lake Project involves SCADA; the Association and the District have established different SCADA platforms. To ensure that both entities have equal access to UBRP information, the UBRP SCADA system has been designed so that the SCADA information can be displayed on both the Association's system and the District's system.

THE UINTA BASIN REPLACEMENT PROJECT

In the paragraphs above, five separate stages in the development of Uinta Basin water were discussed. Each of these stages brought with it new water development facilities. Each stage served a different bundle of water right interests and a different set of constituents. The result is a complex layering of

economic interests, water rights, land ownership, management objectives, and politics.

Perhaps nowhere in the Basin is this layering and the accompanying actual and potential conflict more focused than the Lake Fork River. The river begins in the High Uintas wilderness area and feeds thirteen small, high-elevation lakes-turned-reservoirs (High Mountain Lakes). It then provides early-priority Tribe flow rights though a portion of the UIIP, feeds Reclamation's Moon Lake Project (serving non-Indian irrigators), and provides additional irrigation water by exchange with Starvation Reservoir (a CUP feature). Because it diverts Lake Fork River water, integrating UBRP into this already complex and contentious water environment has been difficult and problematic.

The Feasibility Study and Environmental Assessment for UBRP were published in 2001. As a partial replacement for the Uinta and Upalco Units, UBRP is intended to serve the following purposes: stabilizing the aging and unsafe High Mountain Lakes on the Lake Fork River drainage and restoring ecological values compatible with the High Uintas Wilderness; providing replacement water for the late season irrigation water stored in the High Mountain Lakes; providing 3,000 acre-feet of water per year to Roosevelt City for municipal and industrial (M&I) purposes; providing 2,000 acre-feet of water per year to Lake Fork River irrigators; facilitating improved water resources management and water conservation in the Uinta Basin by increasing water efficiency, enhancing beneficial use, and developing water storage; and enhancing environmental, fish, wildlife, and recreation resources.

The project purposes are to be accomplished by construction (or upgrade) of the following facilities.

High Mountain Lakes

The stabilization of the thirteen High Mountain Lakes will eliminate the reservoir storage and will return the lakes to their natural levels. As a result, flows originating in the High Mountain Lakes' watersheds will return to natural hydraulic runoff patterns and thereby restore fishery and recreational resources in the High Mountain Lakes. In addition, the wilderness impacts associated with operation and maintenance of the High Mountain Lakes will be eliminated.

Big Sand Wash Diversion and Feeder Pipeline

Construction of the Big Sand Wash Diversion and Feeder Pipeline has been completed. The Diversion diverts flows from the Lake Fork River into the Feeder Pipeline. The Feeder Pipeline transports the water to Big Sand Wash Reservoir—an existing off-stream reservoir that is being enlarged as part of the project.

Enlarged Big Sand Wash Reservoir

The enlargement of the Big Sand Wash Reservoir (by raising the level of the dam and associated dikes and saddle dams) will provide additional water storage capacity and regulation capability. The enlarged reservoir will allow for the storage of water that had been stored in the High Mountain Lakes. This transfer also results in improved instream flow in certain reaches of the Lake Fork River and its principal tributary—the Yellowstone River. The water stored in the enlarged reservoir will serve irrigation and M&I purposes.

Increasing the height of the new dam is being accomplished by removing about two-thirds of the downstream side of the old dam, excavating a new keyway immediately downstream of the remaining structure, constructing the new dam, and integrating the remnants of the old dam into the upstream fill of the new, taller structure.

Big Sand Wash – Roosevelt Pipeline

The Big Sand Wash – Roosevelt Pipeline will deliver project M&I water to Roosevelt City as well as project irrigation water to the lower portions of Lake Fork drainage systems.

THE ROLE OF SCADA IN UBRP

The commitments to SCADA instrumentation and the monitoring of UBRP operations are contained in the UBRP Environmental Assessment. The obvious purpose for the installation and operation of SCADA instrumentation at UBRP is to ensure that both federal/non-federal water and tribal/non-tribal water are delivered in accordance with law, water rights, water supply contracts, environmental requirements, and delivery commitments. If this most-apparent purpose is met, the secondary purposes will also likely be achieved: improved efficiency in deliveries from Lake Fork facilities; conservation of water; greater confidence that the river is being managed fairly; and assurance that environmental commitments are being met. Of course, the installation of SCADA instrumentation makes eventual automation possible, resulting in reduced operation and maintenance costs, improved conservation, more finely-tuned operation, etc.

SCADA AND UNCERTAINTY

In addition to the achievement of the primary and secondary purposes of SCADA, there is a tertiary economic benefit that should not be ignored; by providing timely and reliable information, the SCADA system will reduce uncertainty and increase efficiency among water-users and associated businesses.

In the paragraphs above, the layering of interests in water and the accompanying complexity was introduced. The Lake Fork River is one site in the Uinta Basin where all of these layers and the associated interests of groups and individuals intersect. The Lake Fork is perhaps the most over-subscribed stream in the Basin. Among those groups or individuals whose interests are served by the Lake Fork, the complexity of the situation has, over decades, led to excessive caution, suspicion, mistrust, and conflict.

This outcome is not unreasonable; the complexity of the Lake Fork milieu creates a level of uncertainty about the operation of facilities, deliveries of water, and priorities for deliveries of water, etc. In situations of uncertainty, individuals and groups take actions to ensure against loss. These actions in response to uncertainty are costly. Basic economics tells us that uncertain processes are less efficient than certain ones. In other words, the measures that Lake Fork water users must take to assure themselves that they are receiving their share of Lake Fork water are a source of inefficiency (if only because these measures distract each water user from his primary focus—farming, ranching, oil, etc.).

The installation of SCADA sites, the collection of data, and moreover the wide dissemination of that date via the Internet has the potential to ease (to some degree) the uncertainty surrounding water deliveries in the Lake Fork Drainage. Certainly, the SCADA system cannot solve the entire problem but for a range of deliveries, the SCADA system will provide an accurate, credible record of some of what is occurring on the system.

The situation of the Tribe provides an excellent example of how SCADA can engender greater certainty. The Lake Fork River commissioner is paid by the Association, the Dry Gulch Irrigation Company, and the BIA—two non-Indian entities and one Indian-related entity. As a result, Tribal members are continually skeptical about accuracy of the printed, after-the-fact data provided to them from the River Commissioner. Many Tribal members suspect that the data has been doctored to hide the theft of Tribal irrigation water. Following the initiation of operation of the UBRP and Moon Lake SCADA sites, the Tribe now has access to current delivery information. This has not answered all of the Tribe's concerns but it has focused them on those areas in which there is a real potential that they may not be receiving their fair share of Lake Fork water.

RESPONSE TO LOSS OF STORAGE: INSTRUMENTATION AND AUTOMATION

The UBRP construction schedule called for SCADA instrumentation to be installed on the diversion structure, pipelines, and dam as each individual feature was completed. Those SCADA sites needed to monitor instream flows would only be installed after work was well underway on the stabilization of the High Mountain Lakes. As a result, only the SCADA site at the diversion structure was

complete and operating by spring of 2005.

Under the construction schedule, a substantial portion of the new dam (integrated into the remains of the old dam that would be left in place) would be constructed by the beginning of the 2005 irrigation season. This would allow the accumulation of about 40 feet of storage behind the partially constructed dam. The limited, interim storage would have eased the situation for irrigators who would not being able to make full use of the reservoir during the 2005 construction season.

By February, slower than anticipated progress on the grouting made it clear that no part of the new dam would be constructed by the beginning of the irrigation season. Any interim storage in Big Sand Wash Reservoir would have to be backed up behind the remnants of the old dam alone because about two-thirds of the old dam structure had been removed. Early results had shown that a well point system or drain-rock embankment could be used to dewater the old dam structure, thereby maintaining slope stability and allowing storage of the full forty feet in the reservoir.

After additional slope-stability studies by the Project Engineer and verification by the Reclamation, it was determined that it would be infeasible (if not impossible) to store any sizable amount of water and stay above Reclamation's stability risk threshold of 1.30. It would only be possible to store perhaps two feet in the reservoir—enough to deliver 190 cubic feet per second (substantially less than could be delivered with over 40 feet of head).

In a meeting held in March, the parties involved in the UBRP project met to discuss the new restriction on storage behind the remainder of the old dam and how the impact on irrigators might be eased. The parties decided that flows would be controlled at the diversion structure (where the SCADA equipment had already been installed). It was also the consensus of the group that accelerated installation of SCADA instrumentation and automation at a number of additional Moon Lake Project and UBRP sites would help fine-tune deliveries and thereby avoid unnecessary loss of water.

The District relied on Roger Hansen (the elder statesman of Reclamation's SCADA automation efforts) and his crew to design and assist in installing SCADA equipment at the new sites. The schedule for design and installation was accelerated to attempt to have the work completed before the beginning of May.

CONCLUSION

The installation was completed largely on time and is regarded by the irrigators as a success. Factors contributing to the success include the following.

1.   Commitment and Cooperation. All parties involved (the District, the Association, Reclamation, and Interior) were committed to easing the plight of the irrigators. They showed that commitment in a willingness to search for solutions, provide funding, and work long hours.

2.   Funding. The District was immediately willing to commit substantial funding to the SCADA solution.

3.   Familiarity with Facilities on the Lake Fork. Because the Reclamation crew had worked with the Association on a number of other sites, it was familiar with the personnel, the SCADA platform, and the system (dams, diversions, and canals).

4.   Adaptable Technology. The SCADA technology used is highly adaptable to a variety of situations and uses. As a result, it was somewhat easier to customize it quickly to a variety of situations.

5.   Advance Solution to Two Platforms. Finally, the effort was successful because the issue of providing data on two platforms had largely been solved before the loss of the irrigation storage problem had arisen.

USE OF SCADA TECHNOLOGY TO CONTROL PM$_{10}$ DUST EMISSIONS ON OWENS DRY LAKE

Greg C. Roland[1]
Richard V. Haapala[2]
Abdul Majid E. Karim[3]

ABSTRACT

This paper will present a case study in the use of a Supervisory Control and Data Acquisition (SCADA) system as an integral part of a unique water delivery system and how it was designed to control and monitor the pumping, filtering, and blending of the Owens Dry Lake Dust Mitigation Project's two water sources, the fresher aqueduct water and the reclaimed saline groundwater. This project is unprecedented for a number reasons, the unique history behind the need for the dust mitigation, the vast size of the area requiring control and an item impacting constructability and material selection, the very extreme soil and environmental conditions on the dry lakebed.

INTRODUCTION

In 1997, the Los Angeles Department of Water and Power (LADWP) entered into a historic agreement with Great Basin Unified Air Pollution Control District. The agreement committed LADWP to control dust emissions from the surface of the Owens Lakebed, which at the time was the leading source of PM$_{10}$ (particulate matter < 10 microns in diameter) dust emissions in the United States.

To accomplish this, LADWP was required to divert water back onto the Lakebed from the Los Angeles Aqueduct (LAA). The aqueduct was built back in the early 20th century to transport Owens Valley water to the growing City of Los Angeles and by 1930, about 110 mi^2 of the Owens Lakebed became the Owens "Dry Lake". The vast, fairly flat, salt-encrusted land surface is underlain by water that is extremely saline with a total dissolved solids (TDS) concentration of about 130,000 mg/L, or roughly 4 times the salinity of seawater.

The dust control measures or DCMs chosen for controlling the dust emissions are called Shallow Flooding (SF) and Managed Vegetation (MV). Because of the shear geographic magnitude of the project and the cost of the water being diverted, a SCADA system was a must in terms of allowing LADWP to manage these two DCMs while optimizing the demand on water and power resources.

---

[1] CH2MHILL, PO Box 105, Keeler, CA 93530, (760) 876-0082 office, email: groland@ch2m.com

[2] CH2MHILL, 8836 W. Gage Boulevard, Suite 202A, Kennewick, WA 99336, (509) 735-9149 office, email: dhaapala@ch2m.com

[3] CH2MHILL, 3 Hutton Centre Drive, Suite 200, Santa Ana, CA 92707, (714) 435-6057 office, email: mkarim@ch2m.com

The SF covers over 26 square miles and has over 10,000 – 2 inch diameter alfalfa type riser valves. There are 18 areas with individual pressure controlled submains and tail-water pump-back stations, as well as nearly 100 riser-valve (or bubblers) laterals with on/off remotely controlled valves. Tail-water and groundwater are blended with aqueduct water to meet the evaporative demand of the shallow flooded areas.

The MV is divided into 60 – 40 acre blocks (nearly 4 sq-miles) and has over 3,500 miles of a subsurface drip irrigation system. There are also nearly 150 miles of subsurface drainage pipes that drain into 13 pump stations. This drain water (EC >100 dS/m) is carefully blended with the fresh aqueduct water to an EC of 9 dS/m for growing the vegetation and for maintaining the soil structure.

The SCADA system is a distributed control system in which remotely located Programmable Logic Controllers (PLCs) are programmed to operate an area independent of the master PLC. The master PLCs are required to download schedules and control all data transfers between the PLCs in the field and the SCADA servers. The system server and main operator stations are located in a facility near the little community of Keeler on the eastern edge of the dry lake-bed. The SCADA server and master PLC are linked to the remote PLCs, Remote Terminal Units (RTU) and Remote Input/Outputs (RIO) via approximately 45 miles of fiber optic cable. RTU was the contractors choice of terminology instead of PLC in the first construction phase and consequently used in tag names and all drawings.

The long distances, highly saline and windy nature of the Owens Lake environment also added many challenges to the SCADA system design and maintenance. The real-time and reliable control of the components in this system is crucial to it's overall success and sustainability for LADWP.

SCADA SYSTEM DESIGN AND CONSTRUCTION CONSIDERATIONS

The engineers on this Project, acknowledging that even though the ultimate intent is to control dust emissions, knew that dust would be a major design consideration. During the six distinct construction phases (2001 – 2006) and through each new areas system startup, before the "dust control" is attained, there would be significant dust events that would impact the sensitive electronic equipment. The dust alone is challenge enough, because of it's 10 micron or smaller size and the perpetual winds on the lakebed, but coupled with the fact that the dust has a salt constituent, added a corrosion concern as well.

All electrical and Instrument & Control (I&C) components are typically housed in 316 stainless steel, NEMA 4X enclosures that have air conditioning systems. These specialized air conditioning units maintain the NEMA rating of the enclosures. These component enclosures are housed inside of a fiber re-enforced plastic (FRP) housing, sealed onto a concrete pad and sized large enough to walk into or access the internal enclosures from the outside through both the panel and housing doors. All system components are made from non-corrosive materials

such as plastics or 316 stainless steel. The wiring is run in PVC-coated Rigid Steel conduit and no below ground splices were allowed.

Below the surface of the lake bed there are known pockets of methane and hydrogen sulfide gas pockets. Therefore all electrical conduit runs and circuits to the below grade pumps, in the drainage system wet wells, are intrinsically safe and explosion proof.

Extra component and panel grounding was supplied because of the high electrical conductivity of the dust particles and the local soils. Being an alkaline lakebed, the systems are exposed to a higher than normal risk from lightning strikes and built up static electricity. All below ground metallic system components are provided with corrosion protection anodes or they are connected to a current induced corrosion protection system.

Also, due to the magnitude and scope of the project, it was constructed over six years and under six separate contracts. This fact has lead to a system that has been built by three different construction companies and although it was designed and specified by one design firm, the end product varies somewhat from phase to phase. The SCADA system was faced with concerns over consistency of Tag naming nomenclature, similar graphics and consistent internal programming documentation to name just a few issues.

SCADA SYSTEM NETWORKS

Office Complex Central Computer Network

The Owens Lake Dust Control SCADA system is a stand-alone system that has limited connection to the facility's broader computer network that links all project offices to various internal servers and to the outside world via the Internet. This network is located in the various buildings comprising the Owens Lake Dust Mitigation Program office complex in Keeler. Access to the SCADA system from the facility network is intentionally limited to maintain the security and integrity of the SCADA system.

Figure 1 diagrams the configuration of this computer network system and its link to the SCADA system network.

Operations Building Central SCADA System Network

The Owens Lake Dust Control Facility is operated by two separate SCADA systems, one for the North Sand Sheet (NSS) and one for the South Sand Sheet (SSS). Together, the two SCADA systems monitor and control all water system operations on the Lake. The software used for the SCADA system is GE's Proficy iFix (previously known as Intellution iFix). The full client-server version of the software is used for the SSS.

The SSS and NSS SCADA systems work independently. Each system has its own dedicated SCADA server. These SCADA servers are connected to the Operations Server that is used to back up the data from both systems.

The key SCADA system components, in addition to the two system servers, are the master PLCs, Operator Workstations (OWS) and peripherals (also shown in Fig. 1).

NSS and SSS SCADA Servers

The NSS computer system consists of a single Dell Optiplex GX280 PC. The system runs Windows XP Service Pack 2. The computer has a CDRW drive. In future development phases, this server will be upgraded with a twin to the SSS server and both will be configured to run the entire operation as redundant backups to each other.

The SSS SCADA system consists of a Dell Server PowerEdge 4600 using Windows 2000 Professional Server software configured as a 'Domain Controller'. Two operator workstations run iFix 3.0 software. They are assigned as Client 1 and Client 2 on the iFix Server/Client network. The server has four 2GHz processors and three 36GB hard disk drives in a RAID-5 configuration. The server and switch are housed in a rack enclosure.

Each server is the primary source of input/output (I/O) data for its own area and the clients access the database residing on the server. The SCADA Servers communicate over an Ethernet communications link with their associated Allen-Bradley SLC 5/05 Master PLC that polls the I/O data at a refresh rate configured in the A-B Driver.

A UPS provides power to the servers and the two workstations are located about 20 feet from the rack. The two independent networks are connected to the many field PLCs or RTUs via fiber optic cables using a DH-485 protocol.

Operations Server

This is the main Keeler Operations building administrative server and it is also used to back up data from both NSS and SSS SCADA servers. See Figure 1.

NSS and SSS Operator Workstations

The SCADA server for the NSS is currently used as the Operator Workstation. When the NSS server is upgraded this OWS will also be upgraded to match the one in the SSS described below.

The SSS OWS is a Dell Precision 530 with an Intel Xeon, 2.2GHz processor, 1GB RAM and a 36GB hard drive. This station runs on Windows 2000 Pro with SP2. The computer has a DVD+RW+R+CD ROM.

Two laptops are available in place of the workstation if the PCs fail.

SCADA System Field Network

Each of the SCADA servers is connected to a series of RTU (NSS PLC designation), PLCs and RIOs in the field. These various field units and the SCADA servers communicate through fiber optics or two-way radios using the Data Highway 485 (DH-485) protocol. The RTUs in the NSS are configured for peer-to-peer communication and the PLCs and RIOs in the SSS are configured for master-slave communication. The SCADA servers communicate with the Master PLCs via a 10 megabyte per second (Mbps) Ethernet connection.

The RTUs and PLCs provide the control logic and collect monitoring information for pumping and flow control. In the SSS, the PLC control and monitoring functions are extended through RIO modules. These components are configured hierarchically; the RIO modules report to the PLCs (RIO slave to PLC) and the PLCs report to the Master PLC and Server. Figures 2 shows a map of the dry lake and the project site, the detail is limited because of the project size, but this map will offer a good perspective. The shaded areas in the north have 13associated RTUs and the smaller gridded area in the south has 24 associated PLCs, or RIOs. The other irregular shaped areas throughout the project site are areas slated for future development and will have scores of additional PLCs.

RTUs, PLCs and RIOs

The LADWP standard hardware manufacturer for PLCs is Allen-Bradley. The RTUs and PLCs contain the A-B SLC-5/03 processor, analog input, analog output, digital input and digital output cards, chassis, power supply, memory and cards for fiber optic communication. The RIOs use Allen-Bradley's Flex I/O systems that provide an I/O system that is expandable.

Communication Links between Office and Field Systems

The various field units (RTUs, PLCs, and RIOs) and the SCADA servers in the Keeler Operations building communicate through fiber optics or two-way radios, with the associated fiber optic or radio transceivers located at each of the field locations. Additionally, there is a stand-alone fiber optic repeater located approximately midpoint between the Keeler Operations building and the PLC at turnout location T8 (approximately 22,000 ft). Each field units have fiber optic modules for receiving and transmitting analog and digital signals via the fiber optic cables.

In addition to the fiber optic link, the PLC at T8 also has a two-way radio link to the Keeler Operations building. This radio access is through a repeater located on the Cerro Gordo mountain peak to the east of Keeler. The radio link for this site is used as the primary mode of communication and will automatically switch to the fiber optic mode if there is a radio communication problem.

The PLC at the Lubkin Spillgate structure is also linked via this radio system, but does not have a fiber optic link as a backup. These two locations with radio links

are a test for the possible future use of radio communication on the Owens Lake project.

PROCESS CONTROL SYSTEMS

North Sand Sheet

The NSS is subdivided into ten recycling shallow flood areas designated T23, T24, T25, T26, T27, T28, T29, T30, T35, and T36. Each of these areas operates similarly using an RTU within a local control panel (LCP). Control features are provided to irrigate each shallow flood area using freshwater from the freshwater mainline, recycled tailwater from the deep portion of the shallow flood area, and subsurface drainage water from the perimeter of the shallow flood area. The control equipment consists of:

- Tailwater pump
- Drainwater pump
- Submain control valves
- Tailwater pump control valve
- Drainwater pump control valve
- Lateral control valves

The monitoring instruments consist of:

- Limit switches on control valves
- Pressure transmitter in main line
- Flow transmitter in main line
- Flow transmitter in tailwater pump line
- Flow transmitter in drainwater pump line
- Level switches on tailwater pump
- Level switches on drainwater pump

Each RTU controls a large submersible tailwater pump (75 to 100 hp) and a smaller, submersible drainwater pump (25 to 30 hp). The RTU includes LOCAL/OFF/REMOTE switches for the pumps. When set to REMOTE, the normal setting, the pumps are operated from the operator workstation in the Keeler Operations facility.

The protective features for the tailwater pump motor include overload, over temperature, high moisture, and LOW-LOW level cutout. Other features include an interlock to make sure the control valves pilot tubing flush valve is OPEN and a power failure RESTART time delay to stagger the tailwater pumps on power failure recovery. Additional features include HIGH-HIGH and LOW-LOW wet well level alarms sent over the RTU/SCADA system.

The protective features for the drainwater pump motor include overload, over temperature, and high moisture. Other features include HIGH-HIGH and LOW-LOW wet well level alarms sent over the RTU/SCADA system.

The pumps operate remotely from the RTU/SCADA system based on wet well level, water demand schedules, and other factors as selected via the OWS at the Keeler Operations facility.

The system also provides control for the submain valves and lateral valves and automatic mixing of tailwater, drainwater, and aqueduct freshwater. The valves can be controlled locally or remotely from the OWS. Irrigation schedules are entered at the operator's workstation in the Keeler Operations facility. The submain valves and lateral valves are opened and closed based on an operator downloaded schedule to apply water through the systems laterals and bubblers to the shallow flood areas.

South Sand Sheet

The South Sand Sheet water delivery system consists of four distinct systems, interconnected to provide an overall system:

- **Freshwater Mainline**. The freshwater mainline system supplies water from the aqueduct onto the lake and it connects with the Los Angeles Department of Water and Power (LADWP) aqueduct at the Cartago Spillgate. This connection includes flow measurement, differential level, and trash screen rake failure alarms from the LADWP Rugid PLC. Data gathered at the aqueduct are sent to the OWS via a PLC and the fiber optic communications link.

- **Drainage / Brinewater**. The drainage collection and pumping system gathers the subsurface ground water and pumps it into a pressurized "brinewater" mainline. The PLC process control maintains a maximum ground water level and a constant mainline pressure. The system includes pumping stations, pressure control systems, and flow control systems. This system provides brinewater for blending with fresh water to irrigate the managed vegetation at the T5-T8 turnouts and for shallow flooding the T3 and T4 areas of the SSS.

- **Turnout Facilities**. The turnout facility controls the blending rate, chemical feed, and filtering of the water for the irrigation system at the turnouts from the mainline. The PLC-based process control system blends the water between two lines, the freshwater mainline and the drain system brinewater mainline. The system consists of flow control valves, chemical feed pumps, filters, and associated controls and monitoring systems.

- **Irrigation**. The irrigation system consists of RIO-controlled irrigation control valves to provide the blended irrigation water to the salt grass fields and field flushing valves for flushing out the drip lines and submains.

All four of these systems and their associated processes are connected through a network of PLCs, RIOs, and field instrumentation and integrated into one process control system. The individual systems are locally controlled as independent subsystems sharing information as required.

Freshwater Mainline Process Control System

The freshwater mainline process control system consists of interconnected logic between each of the four MV turnout's associated distribution manifolds in order to balance the total system flow. This process control is time and interval-based. It consists of an irrigation schedule manually entered in the SCADA OWS for weekly timing and interval values for each field, supplemented by rainfall, evaporation, and moisture data, which may impact the irrigation schedule. The source of the freshwater is the LADWP aqueduct connection at the Cartago spillgate. This connection consists of a turnout structure that contains a brush cleaning mechanism, which operates based on a differential level signal across the trash screens. The facility also contains a flowmeter for measurement of the flow to the SSS managed vegetation and shallow flood zones. Flow rate, level, and screen cleaning alarm information are monitored by a PLC at the aqueduct facility. This PLC is tied to the SCADA/OWS via the fiber optic communication link.

Drainage Collection and Tailwater Pumping Process Control System

The drainage collection and pumping process control system is provided with multiple pumping stations. The pumping stations consist of drainage or brinewater collection pumps and tailwater recycling pumps that discharge into the common brinewater mainline. The brinewater mainline is controlled to maintain constant pressure and to provide the required brine flow to each of the MV turnout blending locations based on the scheduled irrigation water demand.

A drainage collection pumping station is located at the lowest elevation point within the associated Drainage Management Unit (DMU). These pump stations are controlled through the use of float switches in the drainage collection wet wells. When the wet well water surface reaches a certain level and the pump has not run six times or more in the last 1 hour, the pump is called to turn on. The number of pump starts in an hour is limited to protect the pump and is locally programmed on the reduced voltage soft starters (RVSS). The pump will run until the wet well water surface reaches a LOW level, at which time the pump is called to stop. The pump stations are provided as packaged systems and connect to a local RIO for interfacing RUN, HIGH-HIGH, and FAIL alarm signals with the overall control system. A pressure controlled tailwater pumping station is provided at the T4 shallow flood ponds and a pond level control pumping station is provided at T3NE shallow food pond. The variable speed pumps at T4 turn on at a low brinewater mainline pressure value and vary the pump speed to control the pressure in the mainline. The pumps turn off if a high pressure value is reached. The wet wells intake tailwater from the shallow flood ponds via screened inlet structures. The tailwater pump station pumps this water into the brinewater mainline or it recirculates the water into the T4 shallow flooding area.

The variable speed pumps at T3NE, are also located in a wet well, but they turn on at a designated pond level value and vary the pump speed to control the level in the tailwater pond. The pumps turn off if a low level is reached. The wet wells

receive tailwater from the shallow flooding area via a screened inlet structure. The tailwater pump station at T3NE only pumps or recirculates the water back into the associated T3 shallow flooding areas.

High pressure in the brinewater line is controlled through the use of pressure control valves at T4 and T9. If the pressure in the line exceeds a preset value, the valves open and discharge into either of the shallow flood areas, reducing the pressure to a preset value. When a low pressure set point is reached, the valve closes. These two valves are set at slightly different low pressure set points, so that they sequentially open and close based on the brinewater mainline pressure fluctuations.

Turnout Facility Process Control System

The turnout facility process control system is provided to control the flow to the MV fields associated with turnouts T5 to T8. Each turnout has a PLC for process control of the system. Each turnout is connected to both the freshwater mainline and the brinewater mainline. The pressure in the brinewater mainline is maintained higher than the pressure in the freshwater mainline. This allows for the blending process to take place without the use of pumping systems on the larger-volume, freshwater side of the system which has a static head of approximately 75 psi. The salinity of the irrigation water is controlled through the blending of these two lines. The blending rate is controlled through the use of an electrical conductivity (EC) transmitter and flow control valve. The flow control valve is located in the brine line, and the EC analyzer is located downstream of the mixing point of the two lines. The freshwater line pressure at the blending point is maintained at a constant set point through the use of a pressure transmitter and control valve. Proportional/integral/Derivative (PID) process control is used for both of these control loops to adjust the valves based on the transmitters processed values and OWS setpoints.

Instantaneous flow is monitored in both the drainwater line and in the blended irrigation water distribution manifold line. The total flow is also obtained through these flowmeters.

Pressure indication is provided for the connection to the brinewater system and the freshwater zonal mainline. Differential pressure monitoring is provided for the filtering system.

The chemical feed system at the turnout facilities consists of chemical pumps that are controlled to feed proportional to the irrigation flow rate.

Sand media filtration is provided at each of the 4 MV turnout facilities. The filters and their control are provided as a packaged system. The control consists of backwash control based on differential pressure or time. The packaged system also provides IN BACKWASH and ALARM signal interfaces to the local PLC. The packaged system is provided with local indication and controls.

Irrigation Process Control System

The irrigation system is controlled to provide the required flow to the drip irrigated fields and the drip tube/submain flushing systems. Each of the fields consists of solenoid-controlled, pilot actuated valves for irrigation and for flushing. Secondary filters and water distribution valve manifolds are provided for each group of four fields. Because of the extensive distance from the mainline turnout facilities to the distribution manifolds, controls are provided through the use of RIO modules. These RIO devices connect via a fiber optic communications link to the associated mainline turnout facility PLC. The fields connected to the turnout facility PLC are configured as multidrop communication links. This method eliminates large quantities and sizes of conductors routed to each distribution manifold from the turnout facilities and allows for fields to be added to the same link in the future.

Control of the valves is provided through a timer-based rolling irrigation schedule. The values for this schedule of operation are sent from the OWS to the distribution manifold control valves through the PLC and RIOs. The durations and intervals are controlled to provide the necessary irrigation flow to each field. The flushing control is also based on a timer and duration control system. The flow between the fields is balanced through the use of a user-entered irrigation schedule. Control of the duration and interval of irrigation is also tuned by an operator in the form of a field irrigation schedule, taking into account rainfall, evaporation, and moisture monitoring. The rainfall, evaporation, and atmospheric moisture data are gathered from an automated monitoring system connected to a Web-based server which a system operator downloads. Field monitoring personnel also gather information about the saltgrass health, soil moisture, and the water table depth. These data, in conjunction with the above evaporation data, are used by the system operators to adjust irrigation schedules on a routine weekly basis.

IN SUMMARY

The Los Angeles Department of Water and Power has been required to invest a very large sum of money into an irrigation system to control dust on the Owens Dry Lake. A significant part of that investment was devoted to a central computerized SCADA system that will help minimize the systems long term operations costs by reducing field labor time and water use. The extensive control and monitoring features of the SCADA system will eliminate many man hours of travel and field time across the projects hundreds of miles of roads and 30 square miles of area. The automated operation and remote control will also enable LADWP to meet all the requirements for controlling dust emissions from the dry lake bed in an efficient manner while optimizing the use of fresh water and power. The robust engineering and construction of the system will protect it from the Lakes very harsh environment, insuring the Projects success well into the future.
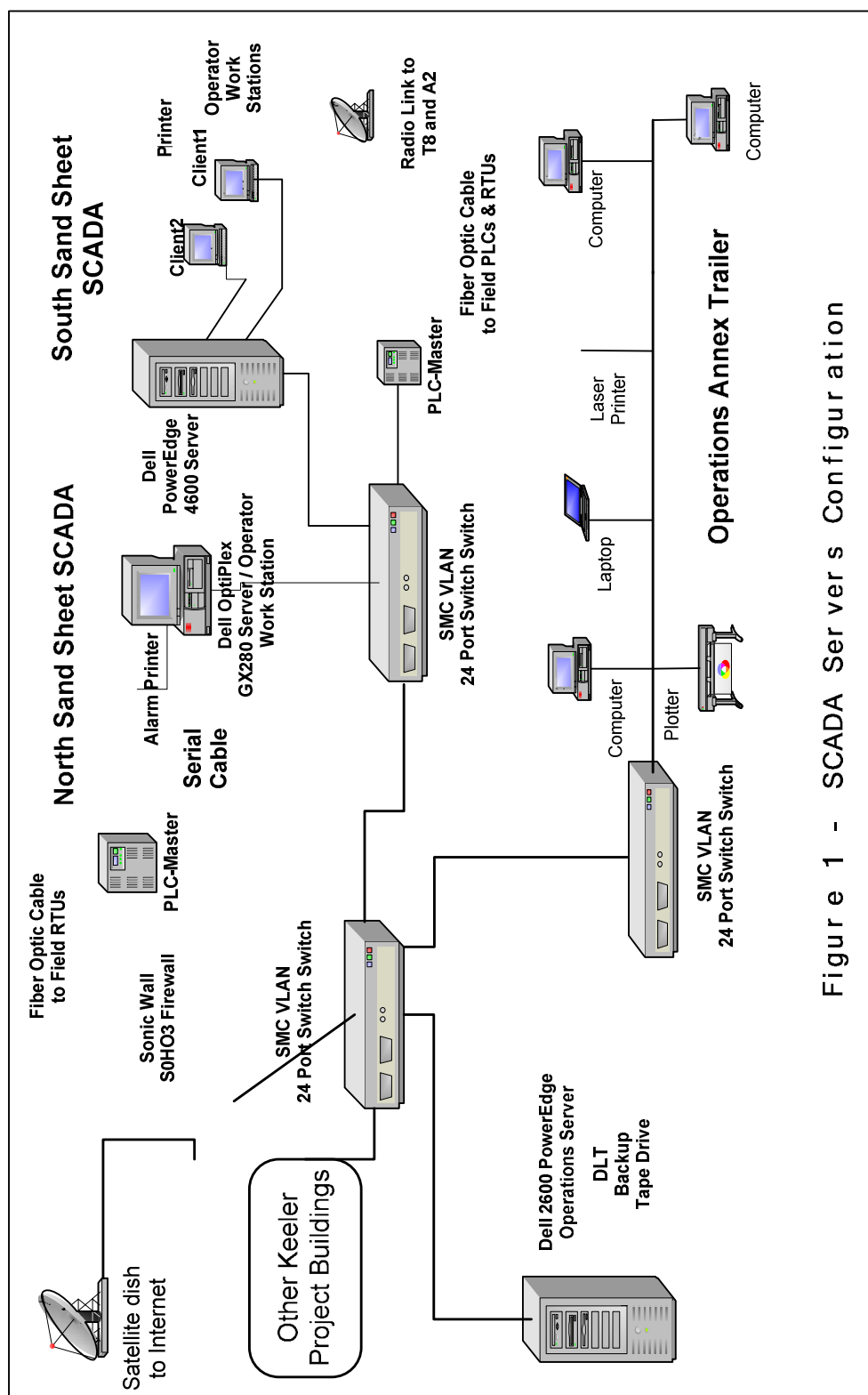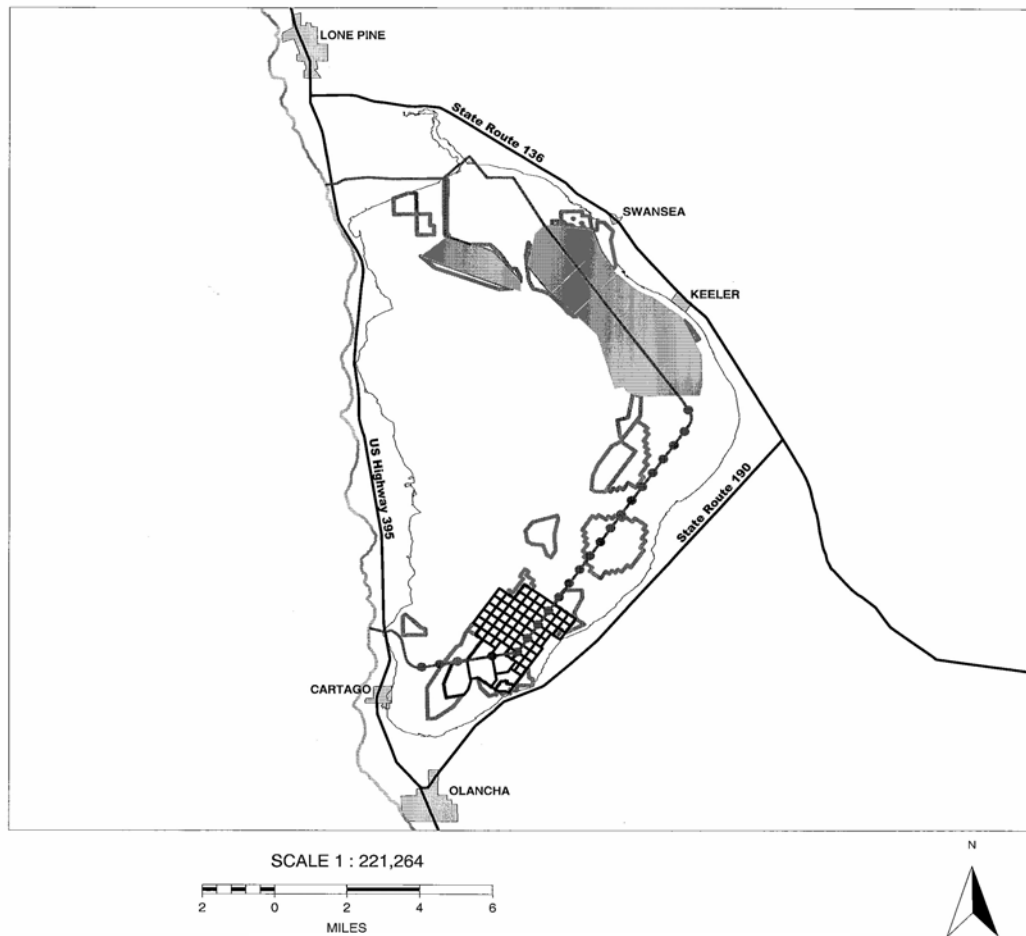
Figure 1. SCADA System Network.

Figure 2. Owens Dry Lake Project Map.

TRAINING SCADA OPERATORS WITH REAL-TIME SIMULATION

R.J. Strand[1]
A.J. Clemmens[2]
N.T. Denny[3]

ABSTRACT

Many irrigation districts use SCADA software to manage their canal systems. Whether homegrown or commercial, these programs require a significant amount of training for new operators. While some SCADA operators are hired with extensive field experience, others are hired with no field experience at all and require extended training to gain an understanding of the behavior of open-channel systems. Additionally, many new operators have little or no experience with general computer use. Regardless of experience, these operators usually receive SCADA training while managing the actual canal system and their training is driven by the day-to-day operation of the system. Similar to the training needs of human operators, canal automation systems need to be tested for situations, such as hardware vandalism, a large storm event, or a canal breach, that cannot be created easily in an actual canal without wasting water, causing significant fluctuations in adjoining pools, or potentially causing severe damage. Additionally, the SCADA software itself needs to be tested for proper response to various alarm conditions. Currently, there are no practical methods to simulate emergency conditions for SCADA systems. The U.S. Water Conservation Laboratory (USWCL) has created a method for replacing the real canal with a simulation model without making any changes to the SCADA software. The connection from the SCADA computer to the radio is replaced with a connection to another computer that performs the canal simulation. If the simulation model were a good representation of the canal, gates, etc., the SCADA operators would not be able to tell the difference. This additional computer also runs software modeling the telemetry system, including communications, sensors and remote terminal units (RTU's) or programmable logic controllers (PLC's), as well as the physical components of the canal sites such as gate positions and battery voltages. Through the simulation system, situations such as a noisy transducer, a stuck gate, an electrical failure, or an unexpected supply or demand change can be simulated. If needed, these situations can be easily repeated. This paper describes this prototype system and potential uses for training and for validation of SCADA and automatic control functions.

---

[1] Electrical Engineer, USDA-ARS, U.S. Water Conservation Laboratory., 4331 E. Broadway Rd., Phoenix, AZ, 85040; bstrand@uswcl.ars.ag.gov
[2] Director, USDA-ARS, U.S. Water Conservation Laboratory., 4331 E. Broadway Rd., Phoenix, AZ, 85040; bclemmens@uswcl.ars.ag.gov
[3] Computer Programmer Senior, Maricopa Agricultural Center, University of Arizona, 37860 Smith-Enke Rd., Maricopa, AZ, 85239; denny@ece.arizona.edu

INTRODUCTION

USWCL Canal Automation Research Activities

The USWCL has been involved in canal automation research since 1991. Early research was focused on the use of canal simulation models to evaluate various canal automation methods. Since 1995, USWCL research has turned to the application of canal automation on existing systems and development of feedback and feedforward control methodologies.

In 1995, the USWCL started long term cooperative efforts with the Salt River Project (SRP) of Phoenix, Arizona. Originally, this work was an SRP pilot project to determine the feasibility of implementing automatic control on the main canals in the SRP delivery system and to test automatic control on a segment of one canal.

From 1995 to 2004, the USWCL was in a cooperative agreement with Automata, Inc. of Nevada City, CA, to develop a plug-and-play automation system using Automata hardware. This system is currently being tested on the WM-Lateral of the Maricopa-Stanfield Irrigation and Drainage District (MSIDD) in Maricopa, Arizona.
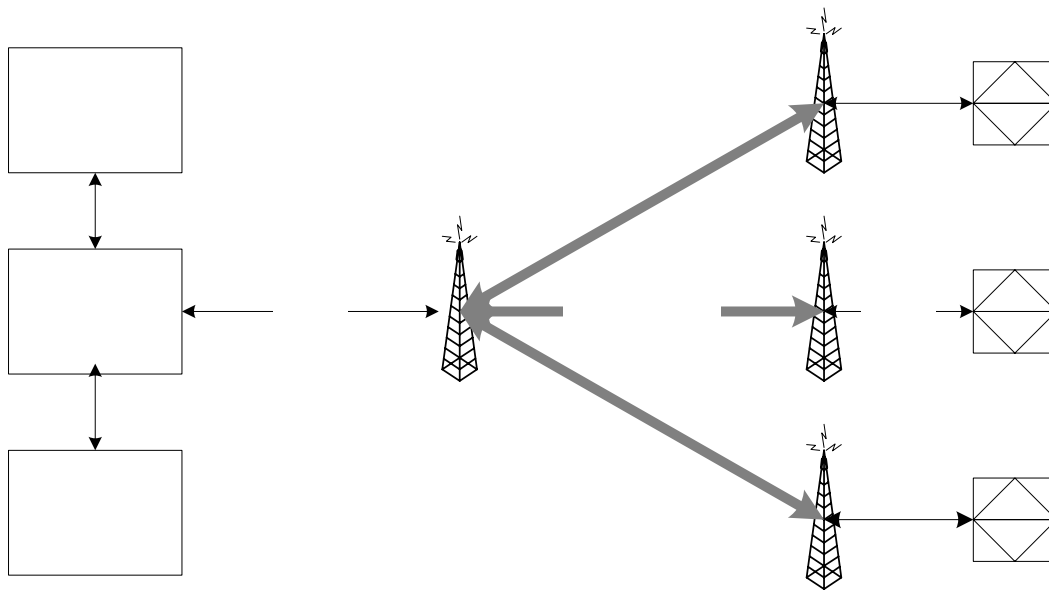
Figure 1. USWCL Canal Control System.

The USWCL canal automation system, shown in Figure 1, consists of various hardware and software components. The SCADA software is iFix by GE Fanuc

(formerly by Intellution). This software functions as a supervisory control interface and provides a data interface for automatic control. The USWCL has developed a suite of accompanying software programs, collectively called SACMan (System for Automating Canal Management) that implements local control, central feedback control, and feedforward control functionality and generates management information for use in the iFix supervisory interface (Clemmens et al. 2003). SACMan communicates with the iFix process database (PDB) through a proprietary library. The field hardware includes Automata pressure transducers, gate position sensors, and Automata's "Mini" RTU's. Communication between the iFix and the field hardware is over spread spectrum radios using the Modbus protocol on a serial RS-232 interface.

As part of the cooperative effort with Automata, the USWCL has assisted the Central Arizona Irrigation and Drainage District (CAIDD) in Eloy, Arizona with implementation of a district-wide hardware replacement and configuration of a new iFix SCADA installation in 2002. To date, 118 main and lateral canal check structures have been equipped with Automata RTU's, pressure transducers, and spread-spectrum radios. All of these devices are monitored and controlled in a supervisory fashion through a single iFix SCADA node.

Training Issues

While the USWCL has been involved with SRP, MSIDD, and CAIDD in canal automation research and implementation, a number of operator training issues have become apparent. First, operators start with varying levels of canal experience. At SRP, a very large organization, operators generally work their way through the hierarchy of the canal operations system. Most start as a zanjero and eventually work their way to the control room. Through this experience, they gain working knowledge of system topology, pool transmission delays, problem check structures, etc. This knowledge is invaluable once they are in the control room. While smaller organizations do promote some field operators to SCADA operator positions, these smaller districts are sometimes forced to hire SCADA operators with little or no canal operation experience.

Second, regardless of the level of applicable canal experience, the learning curve for a SCADA system can be quite steep, especially for an operator with limited computer experience. Some "homegrown" SCADA systems run essentially as embedded systems, meaning that the only software available on the computer is the SCADA software. With modern Windows-based SCADA systems, these computers can allow the operator to use other tools, such as email, databases, billing, and accounting software on the same computer. Many operators require some training to gain familiarity with a networked computer environment as well as managing critical processes in conjunction with other applications.

Finally, operators are trained in a "Live" environment while operating a real canal. At SRP, the environment is generally focused on running the canal system. There are separate departments that handle ordering, billing, and payment receipt. At MSIDD and CAIDD, the canal operators handle all of those financial/clerical tasks in addition to operating the canal. For those with little or no canal experience, the distraction of dealing with the business functions can be overwhelming and can hinder progress in understanding the system from an operational perspective.

Hydraulic Simulation Software

As previously noted, since 1991, the USWCL has made extensive use of hydraulic simulation models as part of ongoing canal automation research (Clemmens et al. 2005). These models have been used to determine canal pool properties and pool response for controller design and for validation of control methodologies. The models are useful because they essentially compress time by simulating hours of canal activity in a matter of minutes. One of these models, Sobek, by Delft Hydraulics, Delft, the Netherlands, has been used at the USWCL since the late 1990's. Originally released in 1993, Sobek uses an interface with the MATLAB computational environment to allow control decisions to be made within that framework (Delft Hydraulics 2004). Water levels are passed to MATLAB and gate positions are passed back to Sobek. The control routines are written as MATLAB "m" files (MathWorks 2005).

Simulators as Training Tools

Digital computer simulations have been used for decades by the military to train fighter jet pilots in flight simulators. Additionally, flight simulator time has become part of required yearly training for commercial airline pilots. Digital simulations have also been employed in medicine. Today, surgeons are able to practice optical and endoscopic surgery with visual feedback generated by digital models. In parallel to these advanced uses of digital simulations, the USWCL has harnessed the capabilities of Sobek to create a simulation based training tool for canal operators.

APPROACH

While conceptualizing the simulation system, a number of requirements became clear. First, the SCADA system configuration had to remain intact. Even in moderately sized implementations, the configuration of SCADA software can be time consuming and complex. To avoid reconfiguring an established system, the simulator had to interface with the SCADA system at the external communication layer – the same layer used to communicate with the RTU's or PLC's. In the case of the USWCL system, this meant that the simulator had to use the Modbus

protocol to exchange sensor information and gate movement commands with the SCADA system.

By moving the communication to this layer, switching from the real canal to the simulator is accomplished by simply unplugging the serial cable leading to the radio and replacing it with a serial connection to another computer. Additionally, use of the external communication layer allows simulation of errant transmissions and transmission delays, as well as the implementation of other serial and network communication protocols. Finally, moving the communication to the external layer allows the simulator to be used with any SCADA system using Modbus, not just iFix.

Second, the simulator had to provide a good representation of the field hardware. This meant that the simulator had to replicate the embedded programming of the Automata RTU, A-D conversion, and sensor types and ranges. This allows testing of various types of problems ranging from sensor noise to gate motor failure.

As shown in Figure 2, the simulator software is implemented as two processes. One process, the physical simulator, maintains physical information about the canal such as gate positions, water levels, battery voltages, and turnout flows. The physical simulator has an interface which allows a user to implement field changes such as adjusting a turnout flow or starting a source well.
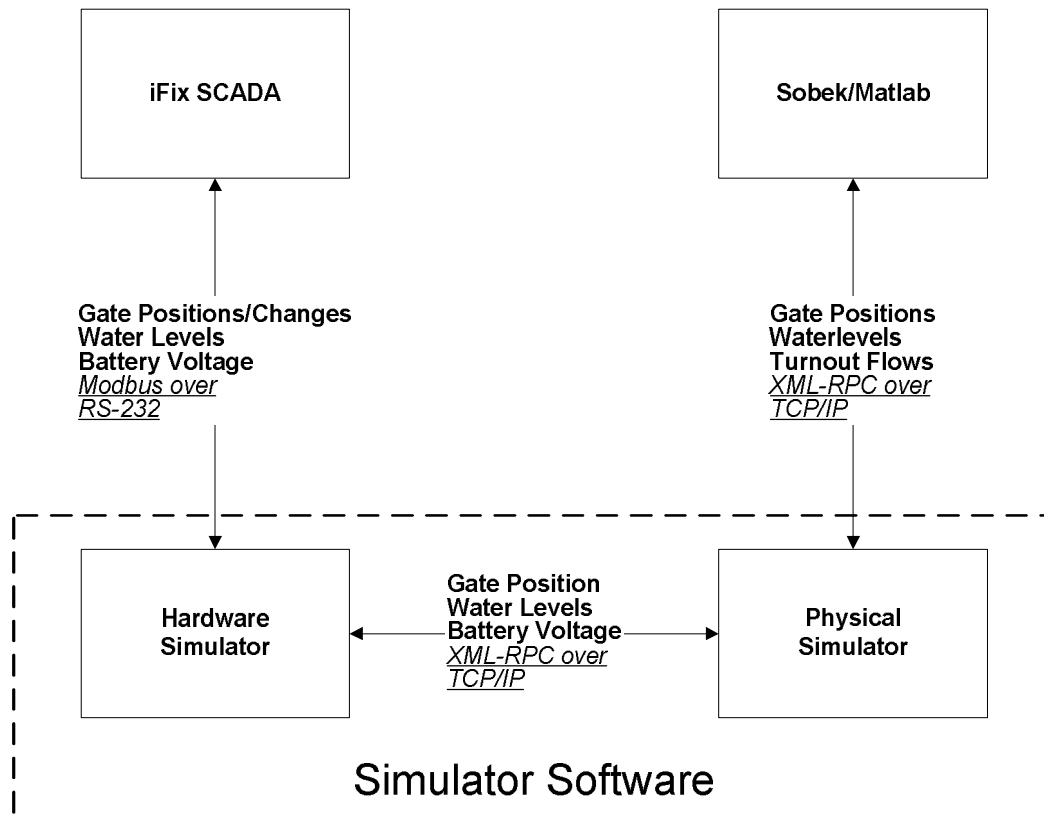
Figure 2. Simulator Components and Communication.

The second process, the hardware simulator, emulates the RTU, its associated sensors and relays, and the gate motor. Perturbations such as noise or a stuck gate are introduced in this process and transmitted to the SCADA system. In order to implement movement delays and sensor warm-up and to accommodate the implementation of real-time embedded process in the field hardware, this process actually creates a separate thread to emulate each RTU. A user interface allows modification of delays and addition of noise to a gate position or water level.

The processes were separated for a number of reasons. First, the properties maintained in the physical simulator are considered to be actual real-world values. To maintain a stable Sobek simulation, these values are not modified by noise or sensor malfunction. Second, separation of the processes also facilitates independent communication rates with MATLAB and the SCADA system.

As previously stated, in normal use, Sobek computes canal responses very quickly. For use in a real-time simulator, each Sobek timestep is delayed until real-time has caught up to the simulation time. This is accomplished by implementing delays in the MATLAB "m" file.

A number of operational sequences take place to move information between the SCADA system and Sobek

Interrogation of a pressure transducer for a water level requires the following steps:
- Whether initiated by a SCADA user query or routine timed polling, the SCADA software sends a Modbus signal over the serial cable to the hardware simulator.
- The hardware simulator parses the Modbus command and initiates a sensor reading by the appropriate RTU thread
- The RTU thread gets the most recent water level from the physical simulator, emulates the A-D conversion and adds any noise prescribed though the hardware simulator interface.
- The result is sent back to the SCADA system in the Modbus reply message.

Moving a gate requires the following steps:
- The SCADA operator implements the gate movement through the SCADA interface.
- The SCADA software sends a Modbus signal over the serial cable to the hardware simulator.
- The hardware simulator queries the physical simulator for the current gate position, calculates the new gate position and then writes the updated gate position to the physical simulator.
- On the next Sobek timestep, the physical simulator passes the new gate position to MATLAB which then sends it to Sobek for future calculations.

In order for Sobek to update a water level, the following steps take place:
- Sobek calls the MATLAB routine
- MATLAB examines the timestamp of the Sobek data. Generally, Sobek is ahead of real time, so MATLAB waits in a delay loop until real time catches up to the Sobek time.
- MATLAB passes the water level to the physical simulator.
- This water level is then available for the hardware simulator.

Field events, such as a turnout change, require interaction with the physical simulator through a user interface.
- The user enters the new turnout flow in the physical simulator user interface.
- On the next Sobek timestep, MATLAB recognizes the flow change and calculates a new gate opening based on either the current water level or a setpoint water level.
- This new turnout gate position is then passed to Sobek for use in subsequent calculations.

The Extensible Markup Language (XML) file format provides a method for combining data and descriptive information for that data in a single text file. XML-RPC (XML Remote Procedure Call), an extension of XML, provides a method for implementing cross-platform distributed computing. XML-RPC processes communicate using standard Internet protocols. Through XML-RPC, a process on one machine can call another process, on the same machine or on another networked computer, and pass XML encrypted data in the function call.

As shown in Figure 2, the two processes making up the simulator use XML-RPC to communicate with each other as well as MATLAB. Each process has a front-end which essentially functions as a web server. This front end processes XML-RPC calls from the other sources. By using a network based communication protocol, the processes can be distributed among multiple networked computers in very large implementations. MATLAB and Sobek can run on one computer, the physical and hardware simulators can each run on separate computers, and the SCADA computer remains untouched. The communication between the hardware simulation and the SCADA system uses the Modbus protocol over an RS-232 serial connection.

USE AS A TRAINING TOOL

As this new functionality was being developed, it became quite clear that while this system was going to be of great benefit for the internal testing of the USWCL control system, the simulator would also be an excellent training tool.

Any irrigation district that uses a computerized control system should maintain a duplicate system as a backup in case of a failure of the primary system. This backup system could also be used as a training system for operators. Sobek, MATLAB, and the simulator software can run on a separate computer representing the "Canal Side" of the system.

One advantage of using the simulator for training is that the trainee can be isolated from the distractions of the control room and can focus on computer skills and canal management. Another advantage is the ability to repeat a given scenario. This is almost impossible to accomplish while training with the real canal.

Training Scenarios

One of the first training sessions could be simply routing ordered deliveries through the simulated system. This could initially be done in a supervised manner and then repeated by the trainee. The results could be compared by reviewing the historical data from the SCADA system.

Alarm situations could be the next scenario. Each organization has allowable tolerances for various measurements and procedures for dealing with related alarms. Scenarios can be created to simulate high, low or quickly changing water levels, sensor failure, communication failure, or intermittent sensor spikes.

One of the most common situations requiring operator intervention is an unexpected offtake change. Whether caused by an unexpected shutdown at a water treatment plant, power malfunction at a supply well, or high winds at a time when grain is tall and headed out, these emergency changes can require intense effort on the part of the supervisory SCADA operator. Again, the ability to replicate and review individual scenarios could be of great use in training a new operator.

Although less frequent, gate malfunctions are a problem situation. Whether due to long-term use or vandalism, these malfunctions can cause huge water level deviations and can require intense effort on the part of the SCADA operator to avoid damage to the canal. In the simulator, it is quite simple to force a gate to close and stop responding to control commands.

This simulator is also valuable for training with SCADA systems utilizing automatic control. Even with field experience, operators face a learning curve associated with operation and configuration of the control system as well as understanding the actions taken by automatic control methods. Additionally, operators need to understand the limits of the automatic control system and learn when to intervene and switch to supervisory control.

FUTURE ENHANCEMENTS

As previously stated, the hardware simulator only supports the Automata "Mini" RTU as it is configured for use in the USWCL canal automation system. It would be desirable to expand this to other hardware. One of the issues is in replication of the embedded functionality of these devices. Assimilation of the various forms of ladder logic, assembly language, and other programming languages combined with hardware specific addressing makes it difficult to simply import the program code for another programmable logic controller (PLC) or RTU. Recent work by the International Electrotechnical Commission (IEC) to develop a PLC programming standard may make this integration feasible in the future.

Similarly, the hardware simulator can be upgraded to handle various publicly available communication protocols in addition to Modbus.

In addition to Sobek, the USWCL also has extensive experience with the MIKE11 simulation model from the Danish Hydraulics Institute (Danish Hydraulics Institute 1995). The user interface for this program is through code modules compiled in Borland Delphi. It would be useful to create an XML-RPC library

for use in Delphi, thereby allowing MIKE11 to be used to generate the canal response for the simulator.

CONCLUSION

For research purposes, this simulator has already been a valuable tool for debugging the USWCL control system in preparation for field trials at MSIDD. In its current form, the simulator is ready to be used as a training tool with Modbus based SCADA systems. With some enhancements, the simulator could be used with other communication protocols and could simulate a wide range of field hardware.

REFERENCES

Clemmens, A. J., Strand, R. J., and Feuer, L. 2003. Application of canal automation in central Arizona. p. 455-464.   In 2nd Int. Conference on Irrig. & Drain, Phoenix, AZ, May 12-15, 2003.

Clemmens, A. J., Bautista, E., Wahlin, B. T., and Strand, R. J. 2005. Simulation of automatic canal control systems.   Journal of Irrigation and Drainage Engineering 131(4):324-335.

Danish Hydraulics Institute (DHI). 1995. Mike11 Version 3.11 user manual, Horsholm, Denmark

Delft Hydraulics 2004. Technical reference for real time control, Version. 2.09.

MathWorks 2005. MATLAB user's guide. Version 7. The Math Works Inc., Natick, MA.

DEMONSTRATION OF GATE CONTROL WITH SCADA SYSTEM IN LOWER RIO GRANDE VALLEY IN TEXAS

Burak Turan[1]
Guy Fipps[2]
Eric Leigh[3]
Azimjon Nazarov[4]

ABSTRACT

The management of canal operations with centralized control provides a powerful way to monitor the existing conditions at the site, regulate water demands and supplies, while minimizing delays and losses. Three control structures on lateral E3-A of Delta Lake Irrigation District (DLID) in the Lower Rio Grande Valley (LRGV) in Texas will be automated and integrated with the Supervisory Control and Data Acquisition (SCADA) system in two Phases. Control of two gate structures, Check 1 and Check 2, at the most upstream of the lateral will be integrated with SCADA system first in Phase 1. The third gate structure, Check 3, at the downstream of Check 2 will be automated in Phase 2 to conduct research on delivering unknown irrigation demands. This system will be utilized as a long-term management and decision support tool for the district. This study focuses on the methodology of integrating the canal automation with the optimal management strategies of turnout structures to meet on-farm delivery demands. The discussion reviews the identification and selection of the SCADA system components for DLID.

INTRODUCTION

Irrigation in the Lower Rio Grande Valley

The Lower Rio Grande Valley (LRGV) (Figure 1) area in Texas experienced two severe droughts in 1996 and 1998. The farmers could not get enough water and were looking for support to optimally manage irrigation. Engineers at Texas Cooperative Extension have been undertaking water conservation projects in LRGV to produce water savings in the region and to improve conveyance efficiency in order to achieve optimal irrigation that will also help in drought conditions.

---

[1] Extension Associate, [2]Professor, [3]Extension Associate, and [4]Extension Associate, respectively, Department of Biological and Agricultural Engineering, Texas A&M University, College Station, TX 77843-2117. [1]bturan@tamu.edu, [2]g-fipps@tamu.edu, [3]e-leigh@tamu.edu , [4]asnazarov@ag.tamu.edu

There are 28 water districts in Hidalgo, Cameron and Willacy Counties in LGRV. These districts (Figure 1) hold combined agricultural water rights totaling 1,468,314 ac-ft. The water right at the smallest district is 625 ac-ft and 174,776 ac-ft at the largest district. The largest eight districts account for 69% of the total and Delta Lake Irrigation District (DLID) holds 174 776 ac-ft. The main distribution networks consist of 790 miles of canals, 124 miles of pipeline, and 76 miles of Resacas. The secondary and tertiary networks ("laterals") consist of about 670 miles of canals and 1690 miles of pipelines. There are 552 miles of lined canals, 614 miles of unlined canals, and about 294 miles of canals with unknown lining status. (Fipps, 2005).
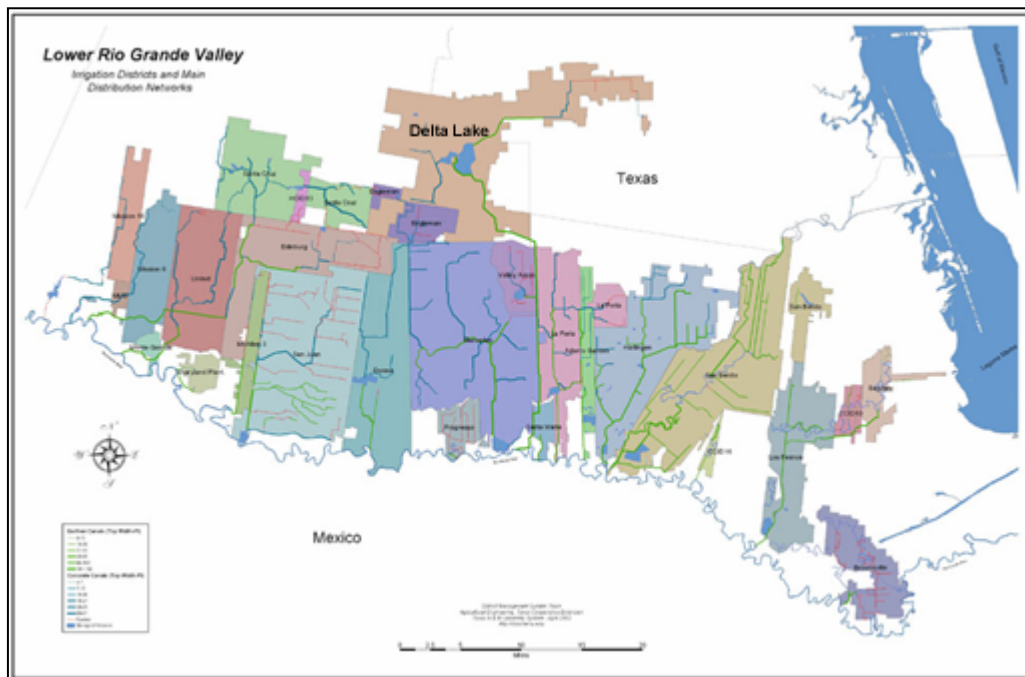
Figure 1. GIS map of distribution network in LRGV.

Project Plan

The canal control combined with SCADA system improves the management of canals and accordingly increases the conveyance efficiency. In addition, these systems can reduce the delays while delivering irrigation demands and maximize the yields while saving water in the area of LRGV. Canal control structures can be controlled by a unit located at the site (local automatic control) or at a monitoring station away from the site (supervisory control). Both the local and supervisory systems can include the SCADA and telemetry systems.

Control of gates from the main office has never been implemented in DLID. A pilot project will start in the near future to control three gate structures on E3-A lateral (Figure 2) of this district's distribution network from office by utilizing SCADA system. The project will be achieved in two phases. In Phase 1, two gate structures, Check 1 (Figure 2 and 3) and Check 2 (Figure 2, 3 and 4), at the point where lateral separates to north and south, will be automated. Phase 2 will be performed soon after Phase 1 is implemented. In Phase 2, Check 3 (Figure 2) which is the first check structure at the downstream of Check 2 will be automated to conduct research on control algorithms and management of flow in case of delivering unknown demands.
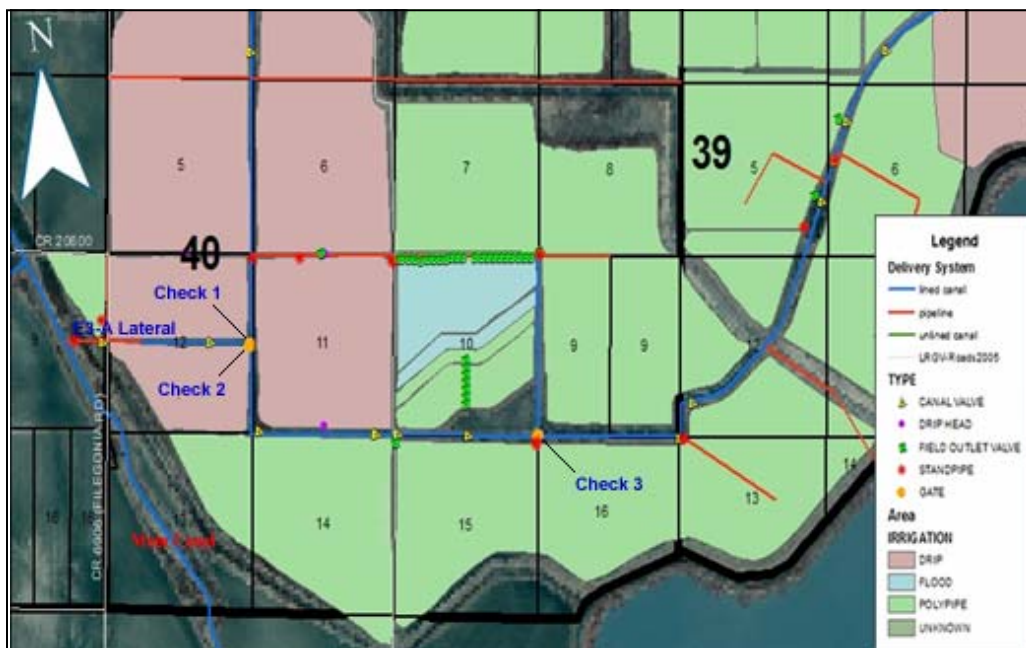
Figure 2. GIS Map of distribution network and irrigated fields of E3-A lateral.
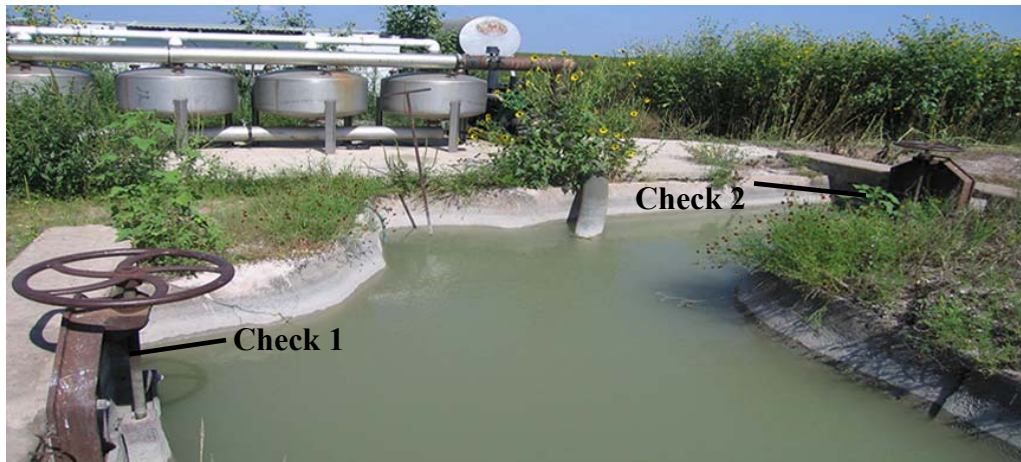
Figure 3. View of Check 1 and Check 2 structures.

Figure 4. View of Check 2 (heading south).

Irrigation Technology Center (ITC) team at Texas A&M University is working on E3-A lateral (Figure 2) to recommend the optimal management methods of turnout structures and on-farm irrigation practices and to increase on-farm efficiency for the fields served by this lateral. The purpose of installing the SCADA system fits to the tasks of this project, so SCADA system will be tied with this project.

Irrigation Flow Delivery In LRGV

Local manual control of gate structures is predominant in LGRV. This creates management problems due to the lack of experience and technical knowledge required to route the flow in complex canal systems (Buyalski et al, 1991). Flow is delivered by rotation, schedule or on demand by operators in canal systems. In scheduled delivery method, the operator knows the flow rate, duration and time of

the irrigation for any turnout in advance and they route the flow to the turnout by changing the settings of the upstream gates. In most of the irrigation districts in LRGV, flow is delivered with scheduled delivery. Under local manual control, this kind of delivery causes head problems at the turnouts and the fields cannot get the required amount of water. In addition to these, there is always delay in the delivery of the ordered flow. However, scheduled flows can be delivered on time with SCADA systems.

INTEGRATION OF ON-FARM MANAGEMENT WITH SCADA SYSTEMS

The check structures can be controlled in a way to satisfy the optimal on-farm management objectives. This will help water users optimally manage the demand, and deliver only the recommended amount of water to each field exactly on scheduled time. ITC team developed on-farm management tool (Figure 5) to find the irrigation requirements at each turnout and irrigation interval for each field composing of furrows. The data coming from weather stations will also be tied to this tool in order to predict the evapotranspiration and crop water requirements that will be used for the determination of irrigation schedules. Within the scope of the project, the developed tool will be utilized as a component of the SCADA system and the check gates will be controlled according to the demand schedule obtained from this tool.

1.	Soil Type	Cameron sic	
2.	Crop Type	Cotton	
3.	Furrow Length	1200	(feet)
	Time of Application	225	(minutes)
	Efficiency	90	(%)
	Total Flow at the Farm Outlet	2771	(gpm)
	Width of each Irrigation Set	183	(feet)
	Number of Irrigation Sets	7	

Figure 5. On-Farm Irrigation Tool.

SCADA SYSTEM COMPONENTS IN DLID PROJECT

Automatic canal control with SCADA systems requires the availability of communications, office and field equipment (Figure 6). The SCADA system

composes of office software, Programmable Logic Controllers (PLC), sensors, gate actuators and the communication system. Combining the software and remote units located at the office SCADA system offers the easiness of monitoring and managing the structures from the office. Most of the companies do not supply all of the SCADA components. Therefore, the users should combine different companies' products and form different sets of components according to their needs.
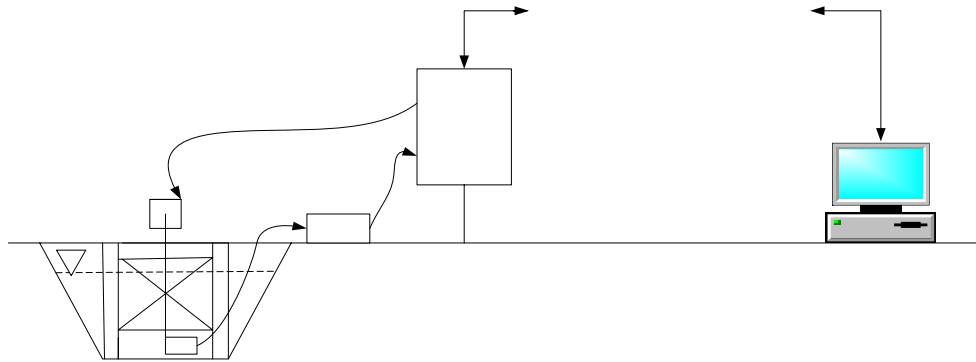

Figure 6. SCADA System Structure.

In Phase 1, these two gates will be controlled manually from the office in order to route the required flow to downstream and maintain constant water level at the upstream according to the known demand schedules. This system will assure monitoring of the water depth and the flow in the canal from the office. So, the operator will not need to go to the site to change the opening of the gate. However, the main task is to change the setting of the gates correct, have reliable flow delivery to the turnouts, collect data, and store it in the database.

To perform this study, the available equipment in the market is investigated. The products of two companies, which have so many applications that fit the tasks of this study, are selected for further investigation. The equipment of these companies with their costs is provided. This information is given in Table 1. The total cost of the set up will be shared between ITC and DLID (Table 2).

THE COST AND METHODOLOGY OF THE SCADA SYSTEM SET UP IN DLID

The Control Microsystems's controller is selected to be used in this study. In the beginning of the study, the gates will be calibrated to derive the H-Q curves and the C coefficient for each structure. These curves will be utilized while estimating

the flow passing through the structures by using the data coming from upstream, downstream water level sensors and gate sensors. The PLC and the software components of the system will control the gates remotely (Xianshu et al, 2001). There will be one water level sensor (pressure transducer) at the upstream and two water level sensors (pressure transducer), each of which will be at the downstream of the each gate. Each gate will be equipped with gate sensors to measure the opening and gate actuator to change the amount of the opening. Water level and gate sensors and gate actuators will be connected to the PLC as analog inputs. The communication will be used to transmit the data collected at the PLC at the field to the central office and send the commands from the computer in the office to the PLC at the field. So, operators at the office will monitor the data transferred and take the necessary actions to establish the constant water level at the upstream and deliver scheduled water to downstream. These actions will be sent to the field PLC as commands. The commands will be transmitted to the gate actuators to change the setting. The operator will also have the capability to check the level when away from the office. Telepace Logic Program (Telepace LLP) software will be used to debug the Ladder Logic control programs for the SCADAPack controllers (Xianshu et al, 2001). The users can also write their own control processes as C code to program the controller.

Table 1. The equipment and cost provided from two companies.

	Company 1	Company 2
Office Equipment		
*SCADA Software		
**Controller Software		
Radio System	$6,130.00	$13,940.00
***Office Computer System		
Antenna		
Site Equipment		
Field Station		
Controller		
Radio Connection		
***Transmission and Cables		
Operator Interface	$5,946.00	$3,520.00
Power Supply		
***Miscellaneous Hardware		
Antenna		
Cable, installation, burying		
***Vandalism Enclosure		
Sensors and actuators		
Water level sensors (3)		
Gate Sensors (2)	$7,000.00	$5,500.00
Gate Actuators and Motors (2)		
Total	**$19,076.00**	**$22,960.00**

*   **:** The SCADA software for Company 2 is provided from another company
** **:** The software for Company 2 is used in order to achieve downstream control.
*** **:** The equipment is provided from another company.
Note: Cable, installation and burying costs are not included.

Table 2. Total cost share between district and ITC.

	Company 1	**Company 2**
Two Gates		
Gate 2 communicates with Gate 1 with radio		
Our Cost	$11,576.00	$16,960.00
District's Cost	$7,500.00	$6,000.00
Total Cost	**$19,076.00**	**$22,960.00**
One Gate		
Our Cost	$9,102.00	$15,450.00
District's Cost	$3,750.00	$3,050.00
Total Cost	**$12,852.00**	**$18,500.00**

Check 3 will be automated in Phase 2 in order to maintain constant water level at the upstream pool and also to work on the controllers to deliver unknown demands. When a disturbance occurs in the pool between Check 2 and Check 3 (Figure 2), the system should handle this automatically by changing the gate settings and bring the system back to the steady state and deliver the ordered flow. According to the water level, the gate opening will be changed automatically. The discussion of current and applied algorithms (Malaterra et al, 1998; Rogers et al, 1998; Buyalski et al , 1991; Goussard, 1993; Rogers et al, 1995) studied in order to come up with the necessary controller formulation for the   E3-A lateral. One of the unsteady hydraulic simulation models available in the market such as MIKE 11 (DHI, 2004), SOBEK (DH, 2004), SIC (Cemegraf, 2004) will be used in order to simulate the flow and estimate the necessary water level and flow set points for the system to deliver the irrigation demand. The feed forward control will be used to route the known demands. The feedback commands will be utilized in order to minimize the differences from the set points and minimize the delays created by the disturbance (Clemmens et al., 2005). The SCADA and communication system along with the proper numerical model and control algorithms must be compatible and set accordingly to the existing canal conditions and operation practices. The canal controller that is selected should be suitable with the irrigation practices in the lateral and the canal geometry (Strelkoff et. al., 1998; Buyalski et al, 1991).

REFERENCES

Buyalski, C. P. , Ehler, D. G.,Falvey,H.T., Rogers, D.C.,and Serfozo, E. A. (1991). *Canal systems automation manual*, Vol. 1, U.S. Bureu of Reclemation, Denver, Colo.

Cemegraf, (2004), *SIC user's Guide and theoretical concepts*, CEMAGREF, Montpellier, France.

Clemmens B, A. J., Strand R. J., Bautista, E. (2005). *Field Testing of SACMAN Automated Canal Control System,* Proceedings of Third International Conference on Irrigation and Drainage , United States Committee on Irrigation and DrainageSCID, San Diego, CA.

Delft Hydraulics. (2004). *SOBEK-flow-module technical reference guide* Delft, the Netherlands

Danish Hydraulic Institute (2004). *MIKE 11 User & Reference Manual*, Danish Hydraulic Institute, Denmark.

Fipps, G., (2005). *Potential Water Savings in Irrigated Agriculture for the Rio Grande Planning Region (Region M)*, Texas Agricultural Experiment Station, College Station, TX.

Goussard, J.(1993). *Automation of canal irrigation systems*. International Commission on Irrigation and Drainage, New Delhi, India.

Malaterre, P. O., D. C. Rigers, and J. Schuurmans. (1998). *Classification of canal control algorithms*. Journal of Irrigation and Drainage Engineering. 124(1): 3-10.

Rogers , D.C., et al. (1995). *Canal systems automation manual*, Vol. 2, U.S Bureau of Reclamation, Denver, Colo.

Rogers, D.C. and Goussard, J. (1998). *Canal control algorithms currently in use*, J. *Irrig. and Drain. Engr.*, ASCE, 124(1), 11-15.

Xianshu P., Burt L., (2001). *Remote Monitoring and Control System Setup, ITRC Report No. R 01-010,* Irrigation Training and Research Center, 2001*Cal Poly State University San Luis Obispo, CA*. www.itrc.org/reports/RemoteMonitoring/remote.pdf

Strelkoff, T.S., Deltour, J. L., Burt, C. M., Clemmens, A. J., and Baume, J. P.(1998). *Influence of canal geometry and dynamics on controllability* J.Irrig and Drain.Engrg., ASCE,124(1),16-22.

INCORPORATING SHARP-CRESTED WEIRS INTO IRRIGATION SCADA SYSTEMS

Tony L. Wahl[1]

ABSTRACT

Real-time flow measurement and monitoring are important components of modern irrigation SCADA systems. Many projects have existing sharp-crested weir structures that have not been incorporated into SCADA systems because they are partially contracted, and thus do not have a simple rating equation relationship. The Kindsvater-Carter procedure for calibrating partially contracted sharp-crested weirs is accurate and straightforward, but also somewhat tedious. Existing computer programs simplify the process but can presently be applied only to individual measurements. This paper presents a Microsoft® Excel spreadsheet model that can compute complete rating tables for sharp-crested weirs with full or partial flow contraction, using the Kindsvater-Carter procedure. Furthermore, through regression analysis, the spreadsheet determines a simplified rating equation that can easily be incorporated into remote terminal units (RTUs) and SCADA systems. The spreadsheet can be applied to fully contracted V-notch weirs with included angles of 25° to 100°, partially or fully contracted 90° V-notch weirs, partially or fully contracted rectangular weirs (including suppressed rectangular weirs), and fully contracted Cipoletti weirs.

INTRODUCTION

Real-time flow measurement and monitoring are important components of modern SCADA systems used on irrigation delivery and drainage projects. In open-channel applications, critical-depth flumes and weirs are common measurement devices. They are convenient for SCADA application, since discharge can be computed from a single water level measurement.

Long-throated flumes and broad-crested weirs are the recommended structure for most new installations, since they have the lowest head loss requirement of any critical-flow device and can be calibrated by computer analysis (Clemmens et al. 2001), but sharp-crested weirs are still commonly encountered on many irrigation systems. Rating tables and equations for fully contracted weirs are provided in many handbooks and manuals, but many real-world structures are not fully contracted, due to either inadequate flow depth or channel width upstream from the weir. These partially contracted structures have not been easy to incorporate into modern SCADA systems because their rating equations cannot be expressed in a simple form. Replacement of these structures with new devices having more

[1] Hydraulic Engineer, , Bureau of Reclamation, Water Resources Research Laboratory, , P.O. Box 25007, D-8560, Denver, CO 80225,twahl@do.usbr.gov

reliable and accurate ratings and more tractable rating equations is not always practical or economically feasible.

Kindsvater and Carter (1957) produced charts for calibrating both fully and partially contracted sharp-crested weirs. These are recognized as the most accurate approach to sharp-crested weir calibration and have been incorporated into many manuals, guides, and international standards. Simple web-based tools exist for determining the flow corresponding to a single head (e.g., http://www.LMNOeng.com/Weirs/), but there has not been a convenient method for developing a simple and complete rating equation relationship that can be incorporated into a modern SCADA system. This technology gap has limited the integration of sharp-crested weirs into SCADA systems used for flow monitoring.

As a leader in western water management, the Water Resources Research Laboratory of the Bureau of Reclamation (Reclamation) works to develop tools that simplify and improve distribution, measurement and accounting for water on western water projects. This paper presents a Microsoft® Excel spreadsheet model that can be used to compute the rating tables for sharp-crested weirs with full or partial flow contraction. By regression analysis, the spreadsheet produces a simplified power-curve rating equation that can easily be incorporated into remote terminal units (RTUs) and SCADA systems. The spreadsheet can be used to analyze fully contracted V-notch weirs with included angles of 25° to 100°, partially or fully contracted 90° V-notch weirs, partially or fully contracted rectangular weirs (including suppressed rectangular weirs), and fully contracted Cipoletti weirs. Except for Cipoletti weirs, the algorithms used are those developed by Kindsvater and Carter (1957), which are also documented in Reclamation's Water Measurement Manual (2001) and Bos (1989). For Cipoletti weirs, the algorithm used is that described in Bos (1989), which includes an adjustment for velocity of approach at the head measurement location.

SPREADSHEET CONSIDERATIONS

Spreadsheets are widely used for engineering calculations and data analysis. Computational models can be easily created and tested, and spreadsheets facilitate production and presentation of results in table and chart form. Microsoft® Excel also provides a full set of graphical user controls and the ability to write custom macros and subroutines in Visual Basic. The spreadsheet presented here takes advantage of all of these capabilities.

A disadvantage of spreadsheets for distribution of finished applications is the fact that formulas, subroutines, and formatting of output are modifiable by the end-user. This makes it possible (perhaps even probable) that over time a spreadsheet application could be inadvertently modified or damaged by the user or a third party reviewing a particular file. Fortunately, Excel provides tools for protecting spreadsheets so that underlying formulas and routines cannot be modified. The

protection process used for this spreadsheet application will be described and some comparisons made to other forms of engineering software development and distribution.

USE OF THE SPREADSHEET

The spreadsheet was developed in Microsoft® Excel version 2002, but should operate correctly in earlier versions of Excel back to at least that included in Microsoft® Office 97. The file provided to the user is initially named *USBRWeir.xls*. Because the spreadsheet contains macros that must be executed as the user enters and changes data in the sheet, the user should set the macro security setting to Medium or Low, through the Tools|Options menu, prior to loading the spreadsheet file. The macros in the file are not digitally signed. Figure 1 shows a typical view as seen on a portrait-mode screen.

Users should begin by personalizing their copy of the spreadsheet with their name and the location and description of the weir they are analyzing. The date field is automatically filled by the computer.

The weir type is selected from a list box, with five choices offered:

- 90° V-notch weir
- Rectangular suppressed weir
- Rectangular contracted weir
- Cipoletti weir
- V-notch weir (25° to 100°)

The first three weirs can be analyzed in either a partially contracted or fully contracted approach flow condition. The Cipoletti weir and the non-90° V-notch weirs must be fully contracted.

To the right of the weir type list box, the user can select either a manual or automatic recalculation mode. In both modes, whenever the characteristics of the weir and its approach channel are changed, the Dimension Check area of the page will display a new message indicating whether the weir as presently defined can be calibrated, and whether it is fully contracted or partially contracted. If the weir cannot be calibrated or is only partially contracted, suggestions are given for modifying the properties of the weir to enable its calibration, or to make it fully contracted (although many partially contracted weirs can be calibrated). In the automatic recalculation mode, the rating table will be fully recomputed after each change in the weir properties. In the manual mode, the user must click the Recalculate Rating button.

To the left of the Dimension Check area, the user can select preferred units of measurement and enter the dimensions of the weir and approach channel. The

rating table range can also be entered, and the desired head measurement resolution can be selected using a set of spin buttons. Resolution can be either 0.01 or 0.001 ft, or similarly 0.01 or 0.001 m.

The rating table is presented in a compact format that shows discharges at the intersection of head values indicated by the labels in the left-hand column and top row of the table. Below the rating table, a power-curve rating equation is shown

Figure 1. Example of Weir Calculator Spreadsheet.

Figure 2. Example Rating Curve Output.
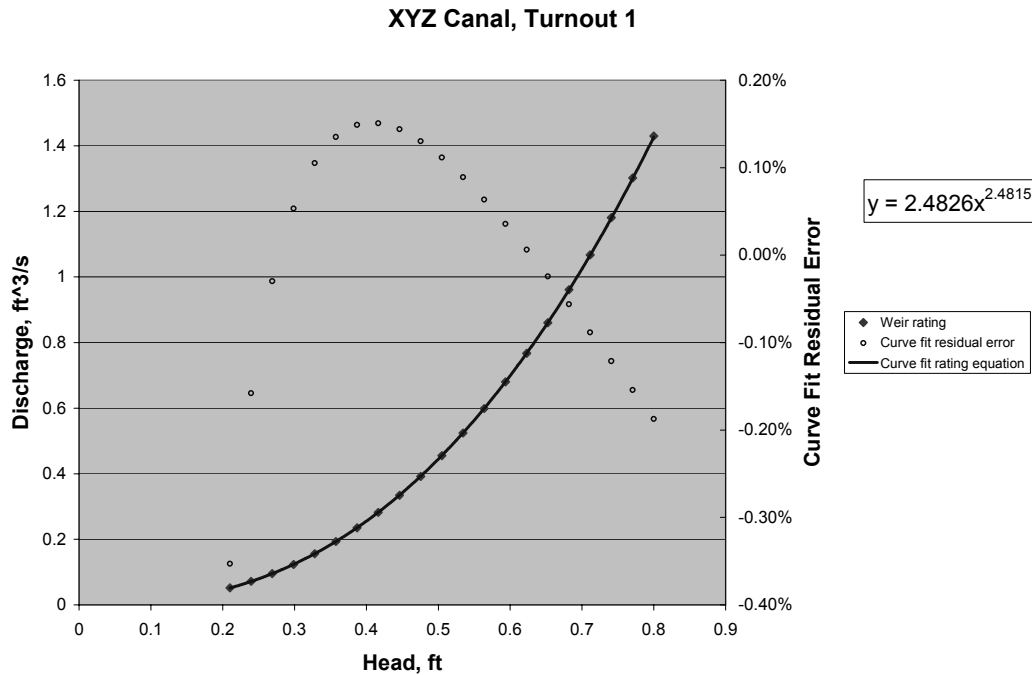
that can be used to compute flow from measured upstream head. Buttons to the right of the Weir Type list box can be used to print the rating table and head-discharge curve (Fig. 2).

SPREADSHEET DESIGN

Although the distributed (protected) version of the spreadsheet shows only one worksheet page to the user, the actual structure of the application is multifaceted. Seven worksheet pages exist in the file, most of them hidden from the user and protected against modification.

- **Input** – Always visible to the user. This sheet contains the graphical interface controls used to process input and display output.
- **Weir Rating** – Essentially a duplicate of the Input sheet without data input controls. The format of this page is optimized for its appearance when printed.
- **Curve** – Contains the head-discharge rating curve that can be printed by the user.
- **Weir Calcs** – Performs weir calculations for a single value of the upstream head.
- **Fit** – Organizes data for regression analysis to determine curve-fit rating equation.

- **Config** – This sheet contains information on configuration choices made by the user, e.g., units system, weir type, etc., and also provides calculations, logic, and temporary storage for results of the dimension check before it gets copied to the Input and Weir Rating sheets.
- **Charts** – This sheet contains the charts that define the Kindsvater-Carter weir formulas and other associated relationships. Regression analyses to convert the charts to computational form are contained on this sheet.

Calculations

The Weir Calcs sheet contains the majority of the actual hydraulic calculations. The sheet is set up so that it actually calculates the flow for all five weir types for a single input head provided in one cell of the worksheet; however, only one of the results is actually relevant at any given time. A Visual Basic subroutine manages the process of performing calculations over a range of heads to generate a complete rating table. The routine iteratively copies different values of upstream head into the input cell and retrieves the appropriate computed discharge from the Weir Calcs sheet. This result is copied into the rating table on the Weir Rating page. Similarly, the routine generates head-discharge pairs that are entered into the Fit sheet, where Excel's LINEST worksheet function is used to determine regression parameters for a linear function fitted to the log-transformed head-discharge data. The iterative copy and paste method of generating head-discharge pairs required a significant amount of Visual Basic programming, but is fast and efficient in operation. Other approaches, such as the use of Excel's two-cell Data Table command, seemed at first to be more elegant and require less programming, but in practice provided much slower performance.

The development and testing of software is always an interactive process, especially during the debugging phase; this is especially true in a spreadsheet application, where calculations and logic can reside in both worksheet cells and Visual Basic code modules. The fact that code modules can easily modify cell contents makes it very easy for errant code to have destructive consequences for the application. Thus, it is crucially important for the developer to save their work often and to archive the application at significant milestones.

Code Documentation

Building this application in a spreadsheet environment made it easy to document some aspects of the code and logic as the application was created. This was especially true on the Charts sheet, where data tables and charts that define the Kindsvater-Carter procedure are displayed, and the regression analyses used to convert the data tables to programmable equations are provided with each chart. The LINEST function was used to generate 3rd and 4th order polynomial regression equations to model most of the charts. In general, the regression equations reproduced the original charts with sufficient accuracy to avoid introducing any significant biases through the modeling process. Many people

use the regression tools in the Excel charting module (i.e., trend lines) for curve fitting, but the LINEST function is convenient because it provides more detailed output and can be replicated into multiple worksheet cells when a number of similar regressions need to be performed on different data sets. An example is the determination of equations for the C_e coefficient for partially contracted 90° V-notch weirs. Regressions were performed to define a family of C_e curves at different values of the ratio p_1/B_1 (crest height to approach channel width). It was then necessary to interpolate between adjacent curves, which was accomplished with formulas entered into worksheet cells.

It should be noted that the Excel LINEST worksheet function occasionally malfunctions when fitting 3rd and 4th order polynomials, a fact that has been previously observed by the author. The condition triggering this bug is not entirely clear, and the problem is not even always repeatable. The problem can be observed by plotting the resulting regression line onto a chart containing the original data. It is interesting to note that when the LINEST function fails, the Excel chart module still seems to draw accurate trend lines using a polynomial of the same order, and if requested to do so, it will print the correct equation coefficients onto the chart. Unfortunately, it does so in a fixed notation that shows only four digits to the right of the decimal, which is insufficient precision in many cases. This problem was encountered on a couple of occasions during the development of this spreadsheet. To solve the problem, data sets that exhibited this problem were manually copied to Lotus 1-2-3 version 5.0 for development of the regression equations. The equation coefficients were then manually transferred back into Excel.

Some aspects of code documentation are quite difficult to achieve in a spreadsheet application. Because formulas entered into worksheet cells often use cell references rather than variable names, deciphering them at a later date can be tedious. This problem can be overcome to some degree by generous use of range names for cells that contain specific data, such as gravitational constants, weir dimensions, etc.

SPREADSHEET PROTECTION

The spreadsheet makes use of four layers of security protection provided in Excel for packaging and protecting spreadsheets for public distribution:

- Hiding worksheets
- Protecting worksheets
- Protecting the workbook structure
- Locking Visual Basic projects

Hiding individual worksheets is accomplished with the Format|Sheet|Hide command on the Excel top menu. A similar Unhide command makes worksheets visible again. Hiding worksheets removes visual distractions that the user does

not need to be aware of, and prevents inadvertent modification of all data and formulas on the hidden sheets. Hidden sheets cannot be accessed by macros or subroutines, so it becomes necessary for the Visual Basic code itself to unhide and hide worksheets whenever access is needed to a hidden sheet. Hidden worksheets are not password protected and can be unhidden by the user unless the complete workbook is protected. Thus, by itself, the hiding of worksheets provides minimal security.

Protecting individual worksheets, using the Tools|Protection command, leaves sheets visible to the user (unless separately hidden as described above), but cell contents cannot be modified except for specific cells that are designated "Unprotected" by the worksheet designer. Again, protection also prevents Visual Basic code access, so macros and subroutines must unprotect worksheets before modifying them, and then protection must be reapplied internally by the code. Passwords can be assigned when protection is applied, but since subroutines in the Visual Basic code must be able to unprotect and protect sheets, the password must be embedded in the code, where it could be seen by the user. Thus, worksheet protection also offers minimal security by itself.

Protecting the entire workbook structure prevents the user from inserting, deleting, hiding, showing, moving, or renaming individual worksheets. The combination of hiding sheets and protecting workbook structure creates an additional layer of protection, but again it is sometimes necessary for the Visual Basic code to have access to hidden sheets. Thus, the code must be able to temporarily remove the workbook structure protection in order to reveal worksheets, and for this purpose the password used to apply and remove workbook structure protection must be embedded in the code.

The final item required to protect the application is to prevent the user from viewing the Visual Basic code, since it contains the passwords for hiding and protecting the worksheets and workbook, as well as the logic of the application. Inadvertent modification of the code could cause the worksheet to stop functioning or produce erroneous results. The Visual Basic code can be hidden and locked from the Visual Basic Editor by choosing the Tools|VBA Project Properties command. On the Protection tab of this dialog box, select Lock Project for Viewing and assign a password.

The protection process is analogous to the compilation of source code to create a stand-alone executable application. An unprotected version of the worksheet (i.e., the source code) should be maintained by the designer in parallel with the protected, distributed version (i.e., the compiled application). This saves one from having to go through the process of unprotecting the distributed version when modifications or improvements need to be made, and also provides insurance against losing or forgetting the critical password for gaining access to the Visual Basic code.

```
Public Sub ProtectApplication()
  Dim s As Object
  For Each s In Application.Sheets
    Call ProtectSheet(s.Name)
    If s.Name <> "Input" Then Call HideSheet(s.Name)
  Next
  Call ProtectWorkbook
End Sub

Public Sub ShowSheet(Sheetname As String)
  Call UnprotectWorkbook
  Sheets(Sheetname).Visible = True
  Call ProtectWorkbook
End Sub

Public Sub UnprotectSheet(Sheetname As String)
  Sheets(Sheetname).Select
  ActiveSheet.Unprotect Password:="sheetpassword"
End Sub

Private Sub UnprotectWorkbook()
  ActiveWorkbook.Unprotect Password:="bookpassword"
End Sub

Public Sub HideSheet(Sheetname As String)
  'Comment out all lines of this subroutine in unprotected version
  'Call UnprotectWorkbook
  'Sheets(Sheetname).Visible = False
  'Call ProtectWorkbook
End Sub

Public Sub ProtectSheet(Sheetname As String)
  'Comment out all lines of this subroutine in unprotected version
  'Sheets(Sheetname).Select
  'ActiveSheet.Protect Password:="sheetpassword", DrawingObjects:=True,
      Contents:=True, Scenarios:=True
End Sub

Private Sub ProtectWorkbook()
  'Comment out all lines of this subroutine in unprotected version
  'ActiveWorkbook.Protect Password:="bookpassword"
End Sub
```

Figure 3. Key Visual Basic Subroutines for Protecting the Spreadsheet.

The protection process is somewhat tedious and must be repeated whenever changes are made to the application. To simplify the work, the subroutines that hide and protect worksheets are collected together in one Visual Basic module, as shown in Figure 3. All lines of code shown in the last three subroutines (HideSheet, ProtectSheet, and ProtectWorkbook) are commented out in the unprotected version. When one wishes to create a new protected version, four steps are required:

1. Remove comment marks (`'`) to enable the code in the last three subroutines in Figure 3 (HideSheet, ProtectSheet, and ProtectWorkbook)
2. From the Visual Basic Editor, choose Tools|VBA Project Properties. Go to the Protection tab and check "Lock Project for Viewing", and assign a password.
3. Run the ProtectApplication macro, which will automatically:
    • Protect each individual worksheet with a first password
    • Hide all worksheets, except the main sheet, named "Input"
    • Protect the entire workbook with a second password
4. Save the protected application under a new name, e.g., *ProtectedFile.xls*

CONCLUSIONS

The spreadsheet application documented here is expected to be a useful tool for incorporating sharp-crested weirs into SCADA systems used on irrigation and other water resources projects. The application will enable users to develop detailed rating tables and simplified rating equations for the most common types of partially and fully contracted weirs. The spreadsheet checks weir and approach channel dimensions to verify that ratings can be determined, and then applies the widely accepted Kindsvater-Carter weir relationships to develop a head-discharge rating table. Regression analysis techniques are then used to obtain a simple power-curve equation relating discharge to measured upstream head.

Although spreadsheet applications are not compiled, the application has been secured through a multi-tiered approach described in this paper, so users can be confident that the distributed spreadsheet has not been modified from its original form. One area that may be worthy of some future investigation is the digital signing of the Visual Basic macros and subroutines that accompany the spreadsheet. This would potentially free the user from the need to enable macros each time the spreadsheet is loaded. However, initial research showed that the steps required to produce digitally signed macros are complex and poorly documented, and at this time, few organizations are making use of this security technology.

The weir calculator spreadsheet is available at this time in a beta-test version from the web site of Reclamation's Water Resources Research Laboratory. The URL is **http://www.usbr.gov/pmts/hydraulics_lab/usbrweir/**.

REFERENCES

Bos, M.G., 1989. *Discharge Measurement Structures*, ILRI Publication 20, International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands, 401 p.

Bureau of Reclamation, 2001. *Water Measurement Manual*, 3rd ed., revised reprint, U.S. Government Printing Office, Washington, DC 20402.

Kindsvater, C.E. and R.W.C. Carter. 1957. Discharge Characteristics of Rectangular Thin-Plate Weirs. *Journal of the Hydraulics Division*, Proceedings of the American Society of Civil Engineers, Vol. 83, No. HY6. Paper 1453.

Clemmens, A.J., T.L. Wahl, M.G. Bos, and J.A. Replogle, 2001. *Water Measurement with Flumes and Weirs*, ILRI Publication 58, International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands, 382 p.