APPLICATION OF CANAL AUTOMATION AT THE CENTRAL ARIZONA IRRIGATION AND DRAINAGE DISTRICT

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ABSTRACT

The Central Arizona Irrigation and Drainage District (CAIDD) began delivering water to users in 1989. Although designed for automatic control, the system was run manually until a homemade SCADA (Supervisory Control and Data Acquisition) system was developed by district employees. In 2002, problems with radio communication and limitations of the homemade SCADA system prompted CAIDD to begin the process of modernization. New spread-spectrum radios and RTUs (Remote Terminal Units) were purchased along with a commercial SCADA package (iFix by GE-IP). In 2005, CAIDD decided to pursue implementation of full automated control of a majority of district check gates. Currently, 125 gates are under remote manual supervisory control and 129 water levels are remotely monitored. CAIDD chose to implement SacMan (Software for Automated Canal Management) under development by the U.S. Arid Land Agricultural Research Center, Maricopa, AZ. The decision was made to only apply full automation at gates that had gate position sensors. Thus purchase and installation of gate position sensors have slowed implementation. To date, five lateral canals have been set up for full automatic control, where SacMan routes flow changes through the canal and uses downstream water level feedback control to correct for any errors that occur. The ditchrider only makes changes at the farm turnouts and district-operated wells. Automation of the Central Main canal has been tested in simulation. Control of this canal requires special treatment, as described in a companion paper. The district is waiting until enough of the canal is ready for automation before it turns automatic controls on 24/7, since this will require some operator training and remote oversight when problems occur. We hope this occurs in the summer of 2010.

INTRODUCTION AND BACKGROUND

CAIDD is headquartered in Eloy, Arizona and services approximately 87,000 acres of agricultural land in south-central Arizona. The district was originally formed in 1964 as part of the Central Arizona Project Association's (CAPA) efforts to bring water from the Colorado River to the Phoenix and Tucson areas. CAPA had been raising money and lobbying since 1946. While the urban populations in the Phoenix and Tucson areas were growing steadily, CAPA needed to show demand for additional water supplies. Dropping ground water levels and problems with recession cracking made the area around Eloy a worthwhile customer for the proposed project. CAPA's efforts were culminated by the signing of the Colorado River Basin Project Act of 1968 by President Lyndon B.

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Johnson. This act provided for the construction of the Central Arizona Project (CAP).
Construction of CAIDD canals began in the mid 1980's and the initial water deliveries
commenced in 1987. By 1990, CAP water was available throughout the district. At that
time, all groundwater wells within the district boundaries were leased to CAIDD for a
period of 40 years.

CAIDD consists of three major regions, each supplied by a main canal off of the CAP
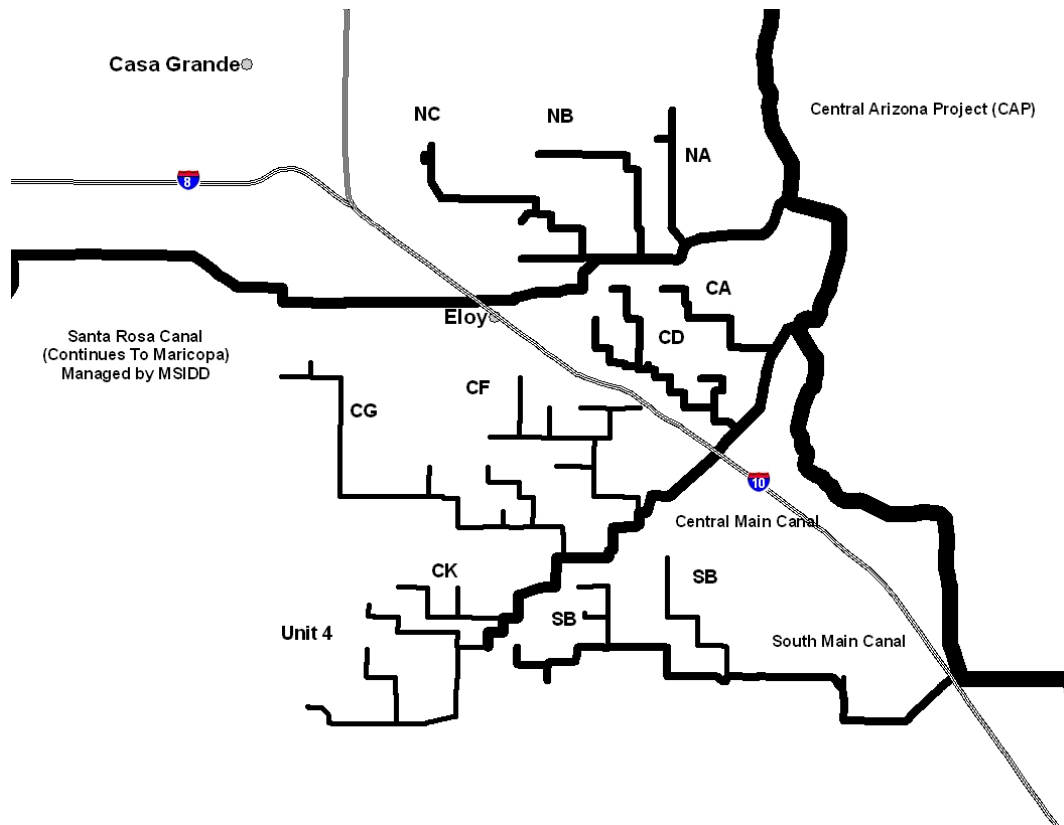(Figure 1).

Figure 1. CAIDD Topology

The north region of the system is supplied by the Santa Rosa Canal. This 1200 cfs canal
continues past the CAIDD boundaries and services the Maricopa Stanfield Irrigation and
Drainage District (MSIDD) and the Ak-Chin Indian Community. Both are located near
Maricopa Arizona. MSIDD manages the entire length of the Santa Rosa Canal while
CAIDD manages 4 laterals and 5 direct turnouts from the canal. Additionally, there are
46 groundwater wells which either dump directly into the lateral canals, or combine with
delivery flows in the grower's canals.

CAP water is delivered to the central region via the Central Main Canal (CMC). The
CMC has a capacity of 900 cfs in its upper reaches and supplies 7 lateral/sub-lateral
groups. The district also manages 151 wells that either pump into canals or directly into
farm ditches.

The South Main Canal (SMC) serves the south region of the system. It has a capacity of 370 cfs and supplies 3 lateral canals. The south region is also supplied by 42 wells.

The canal system was designed with automatic control in mind. Most check structures were originally equipped with three-phase Limitorque motors, and RTU's & pressure transducers manufactured by Automata Inc., Nevada City, CA. The Limitorque motors included positioning circuitry intended to position the gate based on an analog voltage output from the RTU. Communication was over a licensed narrow-band FM radio system.

There are some regulating structures that were designed to be operated manually. Generally, these sites were either located at the end of lateral canals or in areas where power was not readily available. Others are direct turnouts from the main canals. Some of these sites were outfitted with telemetry equipment to allow water level monitoring. All turnouts were equipped with manual gates and solar-powered single-path ultrasonic flow meters.

In 1989, automatic control tests were conducted on the NB lateral, but were unsuccessful due to hardware incompatibilities and the use of a heuristic control method that did not account for pool dynamics.

CAIDD abandoned the original control software supplied with the construction contract and ran the system manually. Eventually, a district employee developed a home-grown SCADA system that implemented the Automata communications protocol. This DOS-based software could control 45 sites. Additionally, CAIDD abandoned the use of the gate positioning circuitry and developed field hardware utilizing electronic timers. These circuit boards, named "KT Boards" after the developer, used two timers to move the gate for either a "Large Bump" or "Small Bump". The time allocated for each size of movement was adjusted with 2 variable resistors on the board.

A single gate movement was implemented using multiple instructions to the RTU. First, the SCADA system sent a signal to the RTU to set the appropriate analog voltage output to full scale to select the movement direction (up or down). Then a signal was sent to move the gate for one of the two increments. On the main canals, a big bump represented a 5 cfs movement, and a small bump was a 1 cfs movement. In order to get a +7 cfs movement, the SCADA system would send a +5 cfs movement and two +1 cfs movements. While this method required many communication exchanges with the field hardware, it did function well within the existing operations.

Recent Modernization

In 2002, the district lost the license for its narrow-band FM radio frequency due to an administrative error. Faced with varying options, CAIDD chose to use serial frequency-hopping spread spectrum radios; avoiding FCC licensing issues for the foreseeable future. With the radio change, the aging RTUs were also replaced. This new equipment was

provided by Automata. Additionally, CAIDD replaced their home-grown SCADA system with a commercial package; iFix by GE-IP.

The new RTU was custom programmed with a time-based gate movement routine. The movement time & direction are transmitted from SCADA software as a signed (twos-complement) 16-bit integer value. The magnitude of the transmitted value represents the movement time in 0.1 second increments and the sign determines the direction of the movement. This allowed for the removal of the KT Boards from the actuator system.

In 2004, CAIDD started installing Automata gate position sensors on gates in the northern segment of the district. These sensors house two output devices. The first is a 10-turn potentiometer which gives an absolute gate position. The second sensor is an incremental encoder, which gives a 0/+5 volt square wave output based on gate travel. Both devices are connected to a gear which is driven by a gear rack attached to the gate. For the gear ratio giving a 4 ft full scale absolute position range, the incremental sensor has a pulse width of 0.95 mm.

In order to accommodate the gate position sensor, the firmware on the RTU was upgraded to allow an incremental gate movement by counting each rising edge of the pulsed output. The transmission from the SCADA system is similar to the time-based movement implemented earlier, except that the magnitude of the value represents the number of gate position sensor pulses.

Some of the manually operated check structures were upgraded with electric motors and telemetry. Finally, 14 turnout meters in the North region were replaced with meters from Mace-USA, Kansas City, MO that report to the SCADA system.

To date, 129 sites are outfitted with Automata RTU's, 125 of which control check gates. Thirty three of these gate structures are equipped with the Automata gate position sensor.

Current District Operations — Manual & Supervisory

Constraints CAIDD is a closed, demand-driven system. There are a number of constraints that come into play in the management of the district. CAP requires that demand changes for the Santa Rosa, Central Main, and South Main canals be reported by 9:00 a.m. the day prior. Additionally, CAP only allows two flow changes per day at each of the canal headings. There are occasional exceptions in case of an emergency.

There is also an electric power threshold for the groundwater wells. Should the cumulative power consumption of the wells exceed this threshold at any time in a billing period, the district-wide billing rate essentially doubles for that billing period. Groundwater is less expensive than CAP water, so the district generally uses as much groundwater as possible while still leaving an error margin to avoid the higher charges. Generally the total district delivery is roughly 50% ground water and 50% CAP water.

Finally, there are manpower constraints. The first shift in the dispatch office arrives at 5:00/6:00 a.m. (peak-flow months/remainder of the year). The office is manned until 4:30 p.m. throughout the year. The SCADA controls are generally unmanned through the night. Dispatch personnel and the senior ditchrider rotate weekly in an emergency on-call capacity and carry a cell phone with a published number.

Ditchriders arrive at 6:00/7:00 a.m. During busy times, there is one ditchrider available to make delivery changes until 9:00 p.m. Otherwise, delivery changes are generally completed by 2:30/3:30 p.m. On weekends, there is one dispatcher, and delivery changes are generally concentrated earlier in the day so that ditchriders can minimize their overtime hours.

Manual Control From the start of water deliveries in 1989, district personnel began to develop a knowledge base for manually operating the system. Vertical staffs were attached to all check gates and operators, equipped with tape measures marked in 0.01 ft increments, began developing gate calibrations for each check structure in the system. Today, the operators still carry notebooks with these calibrations to make manual adjustments. Turnout adjustments are generally based on the reading from the turnout meters.

Supervisory Control Through the SCADA system, dispatchers are able to route flow changes through much of the system. Flow adjustments are input to the SCADA system. Based on the availability of a gate position sensor, the flow changes is either converted to a number of pulses, or seconds of gate movement (both based on field calibrations), and then sent to the RTU. Water levels are automatically polled every 20 minutes. Through the SCADA interface, operators can manually force an RTU to poll the water level.

Demand Management Outside of managing the canals through the SCADA system, one of the major tasks of the dispatchers is to take demand orders from the customers and place supply orders with CAP. This is generally a 6 step process:

1) District customers place their orders over the phone or in person by 9:00 a.m. the day before the changes are needed. Dispatch office personnel write these orders on a large whiteboard in the dispatch office and also enter the information into water accounting software.
2) At 9:00, dispatchers accumulate the orders for the North region of the system and phone the totals to MSIDD staff so that they can include those changes in their order for the Santa Rosa Canal.
3) CAIDD personnel determine any changes to groundwater wells for the following day, write these changes on the whiteboard, and enter them into the computer.
4) They then determine preliminary total inflows required for the CMC and SMC systems at two different times in the following day. The time of day varies based on how the order times for a particular part of the system are grouped, but generally the first time is at the start of the dispatcher's morning shift and the other is sometime in the afternoon. Sometimes, there is some data wrangling as entries wind up missing from either the whiteboard or the computer, or both.

5) Next, they examine the behavior of each system (CMC & SMC) to determine an overall overage/shortage for the prior day. If a system has been slowly dropping over the prior day they will add extra flow to their order for the next day to compensate, or vice versa. Based on the magnitude of the drift in the main canals, the times may be adjusted. These changes and the timing of the orders are based on experience.
6) Finally, they call CAP and place the order for the next day.

The bulk of the dispatcher's day is spent taking orders & payments from the customers, entering meter reads, and managing the canal levels & routing flow changes down canals through the SCADA system. During the spring and summer, the ditchriders are kept busy making delivery changes and reading well, pump, and turnout meters, cleaning trash racks and removing weeds. In the off-peak times of the year, they assist with maintenance on the canals.

AUTOMATIC CONTROL

Overview of the ALARC Approach

Feedforward Control Various methods have been developed to calculate a schedule for routing known flow changes through an open channel system. One of the problems with routing flow changes in an open channel is wave dispersion. A flow change that originates as a square wave at the upstream end of a pool will arrive gradually at the downstream end. Wiley (1969) developed a methodology, called gate stroking, which addressed this problem. However, depending on hydraulic properties of the pool, gate stroking can result in unrealistic changes in inflow.

Bautista and Clemmens (2005) proposed the use of a simple volume compensation method based on the change in pool volume from one steady state to another. As shown in Figure 2, for a given Manning n and downstream water level, the pool volume increases as the steady-state flow rate increases.
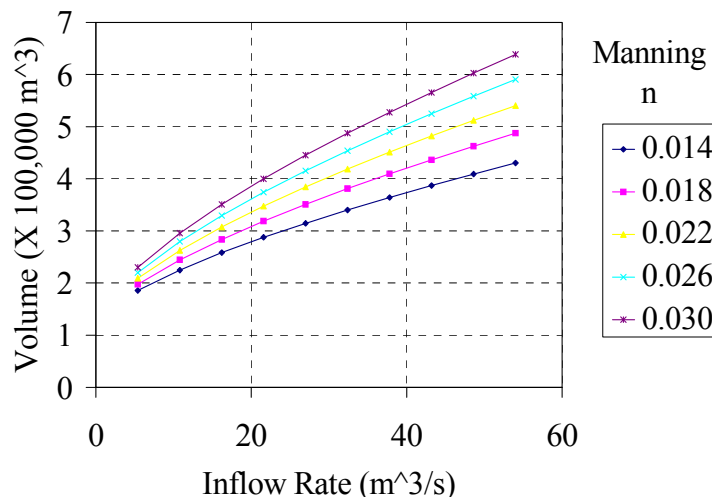

Figure 2. Pool Volume as a function of Inflow & Manning n at a given downstream depth

The delay time, τ, for routing a flow change through the pool is given by

$$\tau = \frac{V_{Q_2} - V_{Q_1}}{Q_2 - Q_1} \qquad (1)$$

Figure 3 shows an example of a 25 cfs change being routed through a pool with an initial inflow of 35 cfs and a turnout delivery of 10 cfs. If the volume change required to go from an initial steady-state flow of 35 cfs to a final flow of 60 cfs is 45000 ft^3, then the delay time, τ, is 45000/(60-35)/60 = 30 minutes. If the upstream gate is opened at 3:30, then the required volume will have accumulated in the pool at 4:00 at which time the downstream gate is then opened.
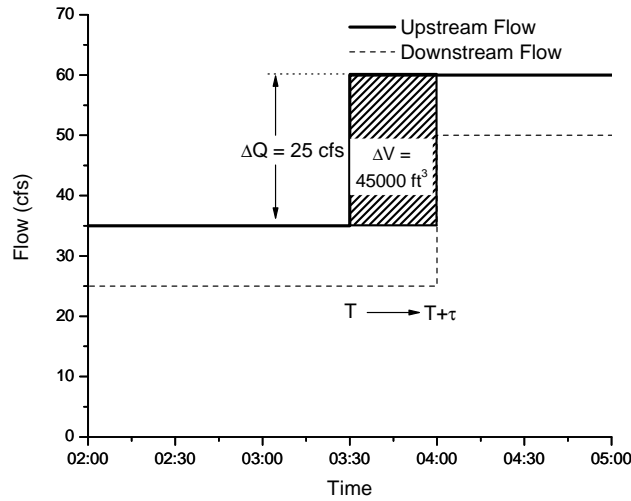
Figure 3. Feedforward Control Example

Local Upstream Level Control Local upstream level control (LULC) is a single-input, single-output (SISO) type of feedback control that adjusts the local gate at regular intervals to bring the upstream water level to the setpoint (Figure 4). This type of level control does not manipulate the inflow at the upstream end of the pool.
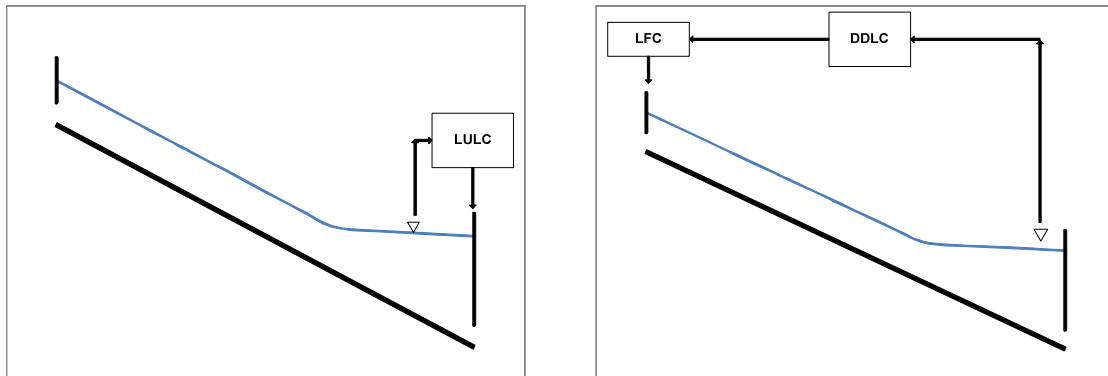
Figure 4. Local Upstream & Distant Downstream Water Level Control

Should the flow coming from immediately upstream drop, the gate will close to maintain the local upstream depth and vice versa. This means that any errors in pool inflow are passed downstream. Since the controller is matching local inflow and outflow, the response of this type of control is generally quite fast. However, in a situation where multiple pools are controlled by individual local upstream level controllers, any error between upstream inflows and the combined outflows in the controlled polls will be concentrated in the last pool. Additionally, flow disturbances caused by controllers at upstream pools can be amplified by the controllers further downstream, possibly causing instabilities.

Distant Downstream Level Control In its elementary form, distant downstream level (DDLC) moves the downstream water level to setpoint by modifying the flow through the upstream gate at regular intervals (Figure 4).

The ALARC formulation of DDLC adjusts the flow setpoint for a local flow controller (LFC) at the next upstream gate. By separating the feedback control from the local flow control, the hydraulic properties of the regulating structure are removed from feedback formulation. This makes the determination of the feedback parameters much less arduous as the parameters are determined from a linearized hydraulic response of the pool.

In DDLC, flow errors are moved upstream, eventually matching the upstream inflows with total pool outflow. One downside is that this type of control can be quite slow. This is due to the long delay time between a change at the upstream end and the response at the downstream end.

The basic form of distant downstream control is SISO. When DDLC is applied to consecutive pools with robust flow control at each site, this formulation can reduce the propagation of errors in the downstream direction.   However, like upstream level control, instabilities can occur due to pool interactions and resonance. To address these issues, the ALARC control formulation utilizes a state-space approach to develop multiple-input multiple-output (MIMO) controllers for both LULC and DDLC. Refer to Clemmens and Strand (2010b) for details on the development of controllers based on the state-space approach.

The LFC maintains the flow through the local regulating structure at a specified flow setpoint. This setpoint can be modified by flow changes prescribed by the feedforward control as well as those generated by the DDLC.

The ALARC approach allows the flexibility of combining both types of level control. Consider the profile view of the NB lateral at CAIDD (Figure 5). The pool upstream of NB-13 has little storage and the turnout at that site is very sensitive to changes to the water level in that pool. Additionally, the pool between NB-14 and NB-16 has two inverted siphons that greatly increase the time for a flow change to reach NB-16. Finally, the gates at both NB-16 and NB-17 are manually operated.
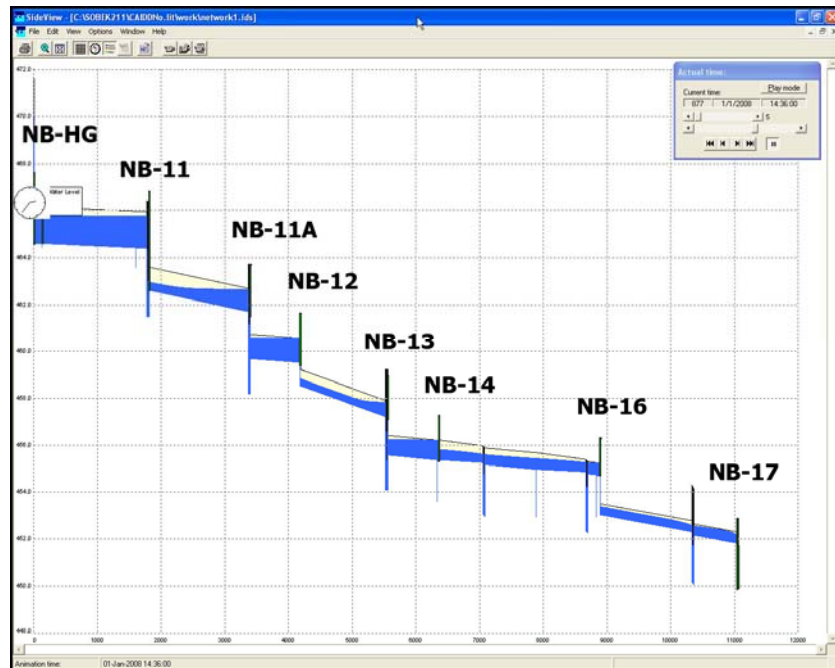
Figure 5. Side View of NB Lateral

As shown in Figure 6, utilizing the fast response of LULC at NB-13 avoids large fluctuations caused by the lack of storage at the site and maintains the turnout flow. The state-space feedback essentially skips that pool. During daytime operation, it is best to avoid controlling water levels at sites with manually operated gates. With no flow control at such a site, improper or poorly timed gate adjustments can have a large impact on the controller response for the whole lateral. Nonetheless, it is advantageous to enable control at such a site during long periods with no delivery changes in order to drive the level to setpoint. Given the long delays in the NB-16 pool, creating a separate, highly damped state-space feedback loop allows the level to be controlled without the large fluctuations in the pool directly impacting the loop that controls the upstream portion of the lateral.
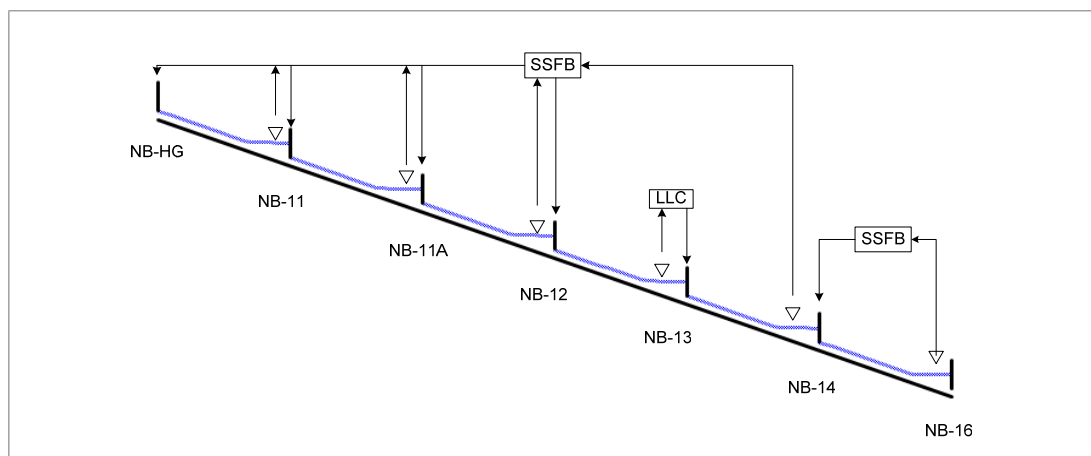

Figure 6. Combining LULC and SSFB

Control Software

SacMan (Software for Automated Canal Management) is a research tool developed by the ALARC to test control methodologies (Clemmens and Strand 2010a). SacMan consists of two programs. SacMan Order (Figure 7) provides an interface for entering orders and calculating a feedworward schedule.

There are currently three types of orders available. The first is "Start of Day". This order type is used to specify orders already starting. It is used to establish the initial conditions if the software has not been used for some time. The second is a typical future order specifying the time that a change is to arrive at its destination. Using Eq. (1), the feedforward calculation for this type of order starts at the destination point and delay times are then computed working in the upstream direction. The third type is an "ASAP" order to handle the routine question of "How soon can you get water to me?" This order type calculates the feedforward schedule starting at the top of the system, summing the delays computed from Eq. (1) in the downstream direction, and computes the arrival time if the schedule were initiated five minutes from the time of the date entry.
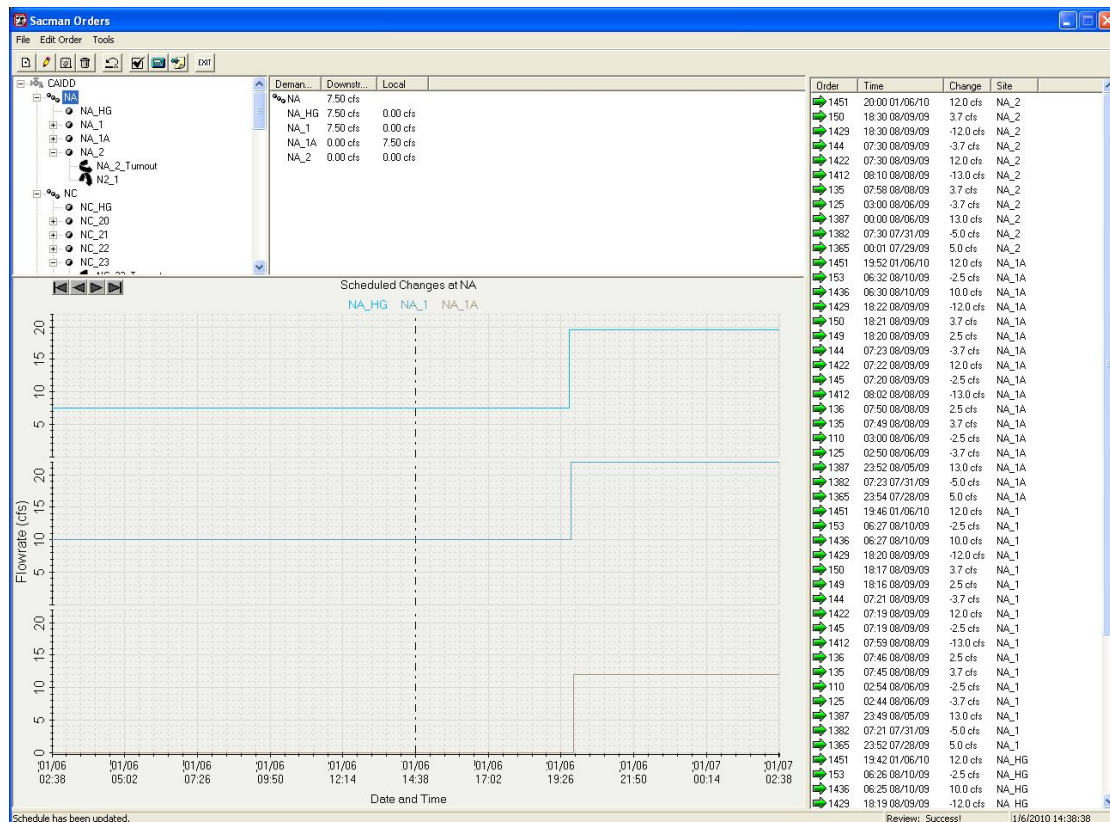

Figure 7. SacMan Order

Once the schedule is reviewed, the operator can post the schedule to the SacMan Control Program (CP)

SacMan CP (Figure 8) provides a user interface to configure the control implementation. It allows the operator to determine which canals or individual sites are under automatic control and the type of control applied. Additionally, it maintains a real-time event queue consisting of 5 types of events (in priority order):

1) System Diagnostics (Observers)
2) SCADA data reads
3) Central feedback control calculations – DDLC
4) Feedforward modifications to flow setpoints (Usually from SacMan Order)
5) Local control calculations – LULC, LFC

The queue uses a multi-threaded approach to minimize impact on computer resources while waiting for the time to execute the next event.

Both SacMan CP and SacMan Order utilize proprietary iFix libraries to communicate directly with the iFix process database. Both programs have been developed with the flexibility to connect to other data sources.
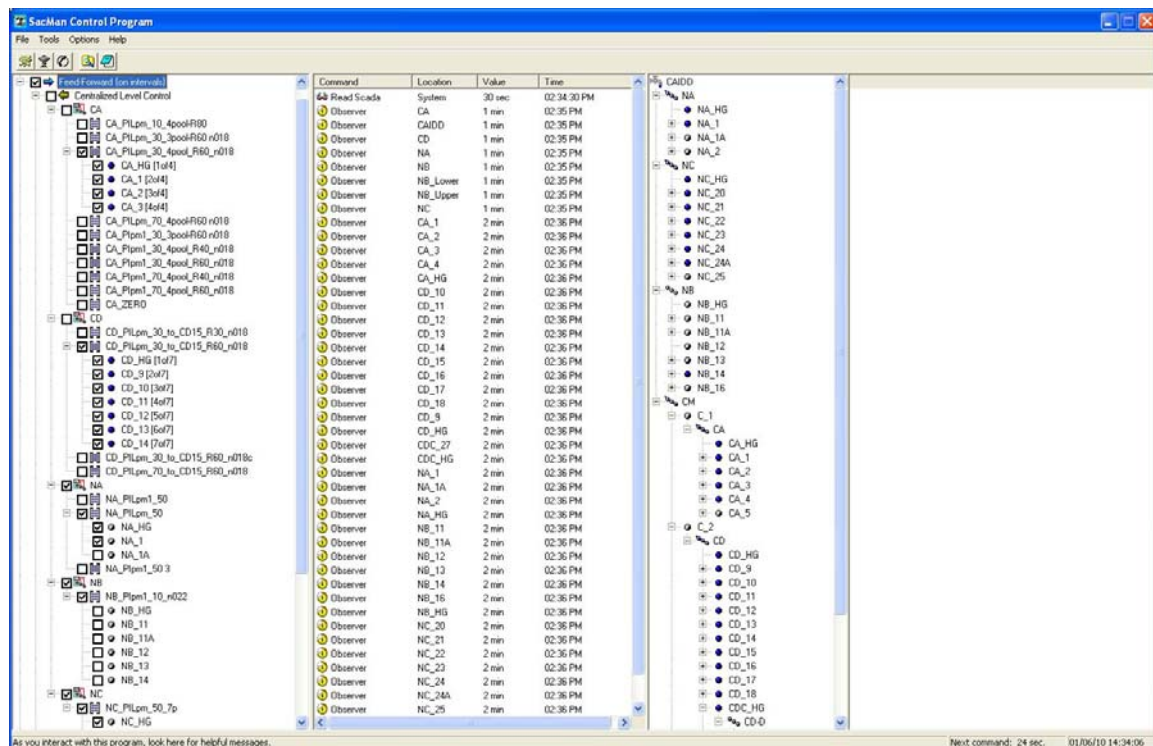

Figure 8. SacMan CP

The program provides the option of allowing the operator to approve both flow setpoint changes prescribed by the downstream level control as well as gate movements calculated from the local level & flow control events. After a set delay, the changes are

automatically approved. Additionally, SacMan CP provides an option for sound cues to the operator to warn of large flow changes and gate movements.

Implementation at CAIDD

The North region of CAIDD presents an interesting management scenario. CAIDD controls the lateral canals, while the Santa Rosa Canal, which supplies the CAIDD canals, is managed by MSIDD. The first two pools of the Santa Rosa Canal are very large, and provide a great storage buffer. At times, MSIDD takes advantage of this situation, disrupting the flows into the NA, NB, and NC laterals of CAIDD by either quickly raising or lowering the water levels in the Santa Rosa pools. With the installation of gate position sensors, it was possible to begin automatic control implementation on the North side of the district with the hopes of providing constant flow to the laterals and better customer service to the growers. Automatic control has also been implemented on the CA and CD laterals of the Central region of CAIDD.

For routine use at CAIDD, SacMan is installed on an iFix SCADA View node (Figure 9). This allows automatic control to be implemented without competing with dispatch personnel for the SCADA computer. While some laterals are being controlled automatically by SacMan, CAIDD dispatchers can continue supervisory control on the rest of the district. The iFix View node automatically routes data exchange between SacMan and the iFix process database on the SCADA node over the district LAN using proprietary TCP/IP-based communication. From SacMan's point of view, this interaction is seamless.
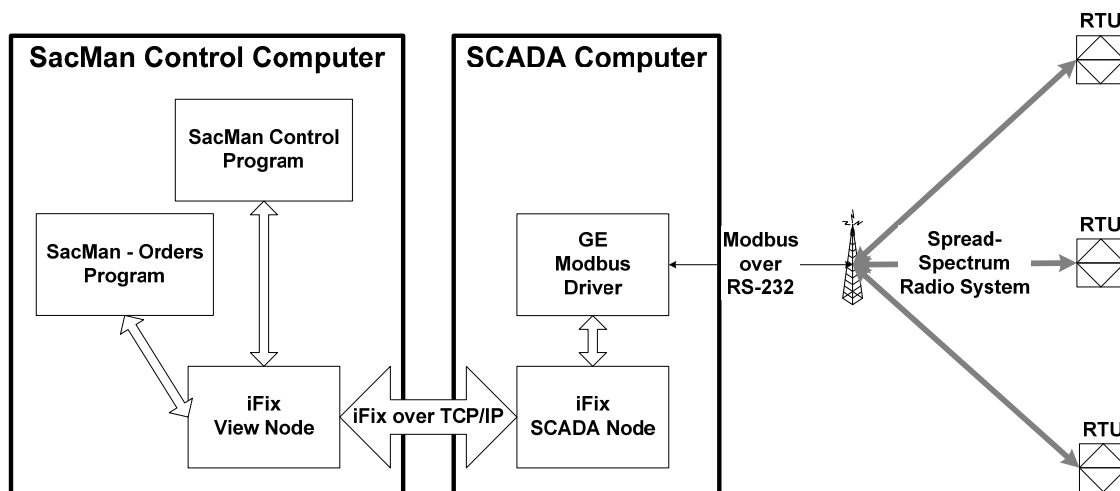

Figure 9. SacMan Implementation at CAIDD

A typical day starts by verifying the day's orders for the canals that are currently under automatic control. Care must be taken to ensure that the automatic routing will result in a realistic schedule for each operator. Once verified, the feedforward schedule is posted from SacMan Order to SacMan CP. Throughout the day, growers call the dispatch office to slightly modify their orders. Usually, these calls are placed far enough in advance to allow the feedforward schedule to be updated. When in operation, the automatic control

manages the water levels quite well. As an example, Figure 10 shows the water level deviations in the NC lateral for 14 days starting 1 August 2009. The automatic control was engaged from the evening of 6 August through mid-afternoon on 11 August. The canal was under supervisory control for the remainder of the time.
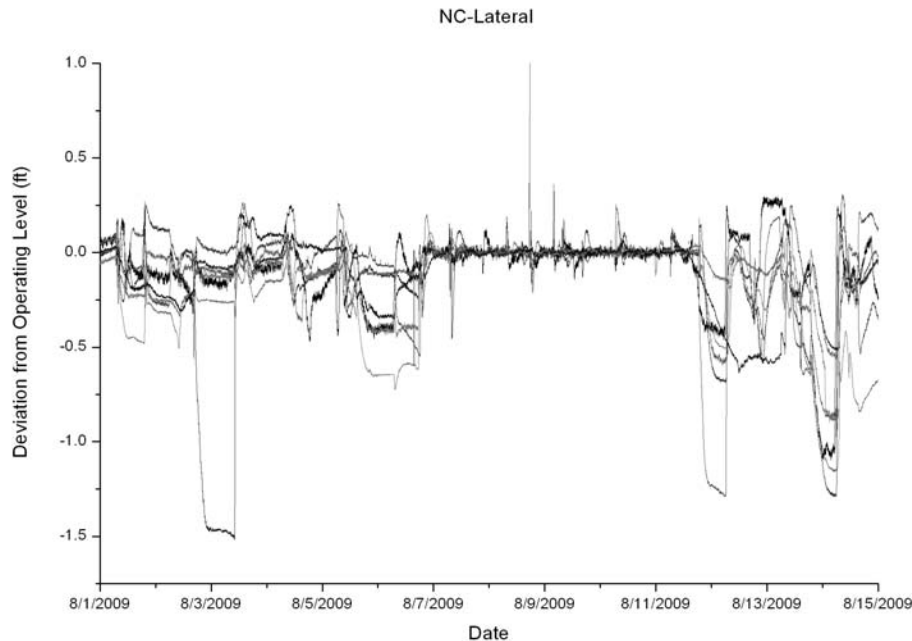

Figure 10. Feedback Control Performance on NC-Lateral

FUTURE WORK

From a supervisory control standpoint, CAIDD has found position sensor based gate movement to be superior to the original time-based movement. This is primarily due to fact that the gate position sensor compensates for the hysteresis in the motor when changing movement direction. They will continue to install gate position sensors as funding is available.

With automatic control implemented on the three north region laterals and CA & CD laterals in the central region, the focus moves to the Central Main Canal. The combined flow capacity of the CF and CG laterals is 450 cfs. The concern is that implementing automatic control on these laterals with the CMC still under supervisory control could result in large unexpected water level deviations in the CMC.

Initially, local flow control will be implemented on the rest of the lateral head gates on the CMC system. Automatic control will be extended down the remaining CMC laterals as funding allows for the installation of gate position sensors.

To this point, the state-space formulation of the feedback control has assumed complete control of the canal inflow. As noted earlier, the inflow to the CMC generally changes only twice each day. A new formulation has been developed that spreads flow mismatches across the pools of the canal. Should inflow not match demand, this control would spread this mismatch across all pools by equalizing the pool water level errors. Details of this control approach are discussed in a companion paper. Preliminary real-time testing will commence in the spring of 2010.

At this point, the automatic control is only in operation while ALARC staff is available. This is partially due to the fact that SacMan is still a research tool and continually being upgraded. The focus of the software development has been on proving the concepts of the ALARC automatic control approach and not on usability. User interface, control configuration, and startup issues will be addressed in the spring of 2010 to facilitate the integration of automatic control into routine district operations during the 2010 irrigation season.

The automatic control is most effective if it is allowed to run continuously. Up to this point, ALARC staff has monitored the automatic control on a 24 hr basis. To conform to current district staffing hours, an alternative "night mode" is under consideration. This would allow control on selected laterals to be limited to local flow control at the head gate, thereby limiting the number of sites running in an unsupervised fashion, but still maintaining some control on the system. Additionally, alarm monitoring software will be evaluated in 2010. This software will notify on-call personnel by phone, email, or text messaging should designated SCADA alarms appear. More robust alarm monitoring will also be added to SacMan.

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