FIELD TESTING OF SACMAN AUTOMATED CANAL CONTROL SYSTEM

A. J. Clemmens[1]
R. J. Strand[2]
E. Bautista[3]

ABSTRACT

Many irrigation districts currently operate their main canals, pumping plants, etc. remotely with Supervisory Control and Data Acquisition (SCADA) software. This is usually manual operation with perhaps a few local automatic control features. SacMan (software for automated canal management) is a software package that adds canal automation logic to commercially-available, windows-based SCADA packages. It allows the user to implement a variety of automatic control features, including complete automatic control, where feasible. It was developed through research at the U.S. Water Conservation Laboratory in Phoenix, AZ. SacMan has several levels of implementation ranging from manual control to full automatic control, including upstream level control, flow rate control, routing of known demand changes, and full (distant) downstream level control. SacMan interfaces with commercial Supervisory Control and Data Acquisition (SCADA) software, currently *iFix* by GE Fanuc (formerly Intellution, Inc.), but potentially applicable to other SCADA packages. SacMan was field tested on the WM lateral canal at the Maricopa Stanfield Irrigation and Drainage District (MSIDD) in central Arizona. In July/August 2004, SacMan successfully operated the WM canal for a period of 30 days, nearly continuously. This paper describes the features of this canal automation software and some results from this long-term testing.

THE SACMAN CANAL AUTOMATION SYSTEM

The SacMan canal automation system includes three main components: hardware at each check structure, a Supervisory Control and Data Acquisition (SCADA) system, and SacMan. The hardware includes the Automata *Mini* that serves as the RTU, spread-spectrum radios, water level sensors, gate position sensors, gate motors, and relays to drive the gate motors. SacMan is currently configured to work with SCADA package *iFix* by GE Fanuc. We expect SacMan to work equally well with other PC-based SCADA packages, but this needs to be

---

[1] Laboratory Director, U.S. Water Conservation Laboratory, USDA-ARS, 4331 E. Broadway Rd., Phoenix, AZ 85040 bclemmens@uswcl.ars.ag.gov
[2] Electrical Engineer, U.S. Water Conservation Laboratory, USDA-ARS, 4331 E. Broadway Rd., Phoenix, AZ 85040 bstrand@uswcl.ars.ag.gov
[3] Research Hydraulic Engineer, U.S. Water Conservation Laboratory, USDA-ARS, 4331 E. Broadway Rd., Phoenix, AZ 85040 ebautista@uswcl.ars.ag.gov

demonstrated. The *Mini* and *iFix* communicate with the MODBUS communication protocol. SacMan (Software for Automated Canal Management) provides value-added features to standard SCADA systems by allowing users to implement various canal automation features. Further details about this system can be found in Clemmens et al. (2003).

SCADA Software

iFix by GE Fanuc (previously Intellution, Inc.) is the SCADA package currently being used. The canal is set up for supervisory control in a standard manner. The *iFix* communication drivers are used to communicate with the field sites through ModBus protocol over the spread-spectrum radios. Information from field sites is processed through a series of calculation blocks to yield information that is directly useful to the operator – for example, transducer voltage is converted to a depth and then this depth is adjusted for the location of the sensor to yield canal water depth.

iFix monitors canal water levels every minute and stores these values in a database. Standard *iFix* displays are used to graph the current water levels, flow rates, and gate positions for each check structure. In addition, the water level and flow setpoints are added to the display. These displays can be customized to suit the users' needs. The canal operator can always manipulate gates manually, even when various automatic features are active. Database information and control actions taken are automatically archived for future evaluation.

The above functions are generally available with most commercial SCADA packages. However, not all are capable of the interface required for this canal automation system. SacMan and its interface to *iFix* are described next.

SacMan Software

SacMan monitors the canal by reading the *iFix* database through proprietary database calls. Based on this information, it determines whether control actions are needed. If a change in gate position is needed, SacMan writes a command to the *iFix* database. This "write" command prompts *iFix* to take action. *iFix* interprets the information that was written by SacMan and sends a command to one or more gates through the ModBus driver. These actions are archived for future evaluation.

SacMan has three different levels of implementation: Manual control, local upstream water-level control, and centralized control, including downstream water-level control. Currently all control functions are performed at the central computer, except actual gate position changes, even though some of the control functions use local control logic. Centralized operations allow operators to monitor these processes and to provide archived data on control actions, which is useful in diagnosing the cause of problems. If communication is lost or the central computer goes down, gates simply remain in their current positions.

Within these three main categories, there are various features that can be implemented. For standard manual control or upstream level control, no other features are required. Operators can implement various features as they become familiar with SacMan. The first useful feature is the ability to increment or decrement the flow by an operator specified discharge (based on head and site specific gate information). The second is the ability to set and maintain the flow rate at a particular structure, particularly canal headgates.

A series of alarms are available to alert the operator to any unusual circumstances, particularly when the canal is under automatic control. An out-of-bounds controller is available for sensing excessively high or low canal water levels. When such a condition exists, an alarm is given and control reverts to automatic-upstream level control to protect the canal from failure. This mode is available even for manual control.

SacMan Orders provides the operator with the ability to route water orders through the canal system automatically. The operator specifies the location, time, date and flow change (start, stop, or change). SacMan keeps track of the water being delivered throughout the system and computes the timing of check gate flow changes to accommodate the changes in demand. This can either be implemented manually by the operator or automatically by SacMan.

With multiple changes taking place, it is sometimes difficult for operators to keep track of flows within the system. If water orders are entered into the SacMan demand scheduler, SacMan will display the sum of the demands downstream from any check structure. This can then be compared to the actual flow rates. The operator can then get a quick sense of whether or not canal flows are in balance, even when under automatic control.

Pool volume is an important pool property and is used directly in many control schemes. The rate of change of pool volume is related to the mismatch between inflow and outflow, and thus is a measure of flow rate errors. This flow-rate error is computed and displayed so the operator can use it to adjust canal flows.

Our experience through simulation studies, applications, and control engineering literature suggest that automatic control methods can become unstable if started suddenly. To avoid such problems, SacMan has a smooth start-up procedure. It assumes that the initial water levels are the water level setpoints and gradually adjusts them to the real set points. This ability to vary setpoints also allows the operator to schedule in the volume needed to raise canal water levels.

APPLICATION AT MSIDD

The SacMan control system was implemented on the WM canal at the Maricopa Stanfield Irrigation and Drainage District (MSIDD). The WM canal is a lateral canal with a capacity of 90 cfs (2.5 m^3/s). It was originally supplied with motorized gates. Relay boards, built by Automata, were installed in each gate motor. Automata water level sensors were installed in existing stilling wells along the upstream side of the gate frame. Automata's new gate position sensors were also installed.

The feedback control logic used in this application is described by Clemmens and Schuurmans (2003). Application to ASCE test canal 1, which is based on the WM canal, is described in Clemmens and Wahlin (2003). The control logic converts water level errors into flow rate changes at each gate. SacMan determines the gate position change needed to achieve that flow rate change and sends a gate position change to *iFIX*. The feedback portion of the control system determines new flow setpoints for each check structure every 10 minutes. Feedforward changes in the flow setpoint at each check structure, and associated gate position changes, are performed every 2 minutes. If a large number of sites are being controlled, the flow control function may best be accomplished locally, depending on the complexity of the flow calculations.

Field Testing

Field testing of this system has taken place off and on since 1999, with each set of tests suggesting requirements for improving the software and control implementation. The WM canal was operated nearly continuously for a period of 30 days, from July 14, 2004 to August 13, 2004. During this period of time, the MSIDD Watermaster allowed us to have complete control of the canal. Each day we obtained water orders for the day from the watermaster, scheduled them with SacMan order, provided feedback on when deliveries would arrive at the turnout, and actually made the deliveries to the irrigators in the field. During a majority of this time, the canal was under (distant) downstream water-level feedback control, with scheduled deliveries implemented as feedforward commands.

The first few days of testing was a shake-down period where we periodically shut down the automatic control to fix the SacMan software. There were times when these bugs caused control of the canal to be unacceptable, and we would have to take over and run the canal manually. Gradually, all the bugs disappeared. As testing continued, however, we added features to help us run tests which occasionally introduced new bugs.

During this 30-day period there were 60 scheduled delivery changes. Of those 48 were successfully routed through the canal automatically with SacMan. During the first few days of the debugging, nine deliveries were routed through the canal manually. Human errors later in the testing caused the remaining 3 deliveries to be routed manually.

Example Results

To date, we have not fully analyzed all of the data from this 30-day period. Example results are shown for two types of testing: 1) the ability of the control system to handle routine water delivery changes and 2) the ability of the control system to handle significant disturbances.

Routing scheduled flow changes: The first example consists of 3 scheduled flow changes on July 17, 2004. This was three days into the testing period. Requested flow changes consisted of: 1) a turn on for the pump offtake in pool 7 (WM-7PA) at 8:00 (+3.2 cfs); 2) a turn off of the delivery (gravity offtake) at WM-6 (-8 cfs) at 11:00; and 3) a turn off of WM-7PA at 14:00. Total demand for the canal prior to these changes was 35.5 cfs, with 28.2 cfs supplied from the main canal and 7.3 cfs supplied from wells. WM-3-well-1 adds 3.6 cfs to the canal just upstream from check WM-3, and WM-5-well-1 adds 3.7 cfs to the canal just downstream from check WM-4. These wells remained on during this entire day.

During this test, the canal was under automatic downstream level control. A PI^{+}_{-1} controller was used during this test, as defined by Clemmens and Schuurmans (2004). A simple PI controller would change the flow rate (or gate position) of the gate at the upstream end of the pool. With this controller, an error in water level in a given pool results in a change in flow to all upstream gates (+) and a change in flow to the gate immediately downstream (-1). This controller was designed at 80% of capacity, while the inflow was only about 30% of capacity. In addition, because of previous difficulties in controlling the level at pool WM-5, this controller did not include water level errors from this pool and did not adjust the gate at WM-5. Instead, the water level at WM-5 was controlled by the gate at WM-5 with local upstream-level control.

The requested demand changes were scheduled with the SacMan Order software, which passed the schedule of flow changes to the SacMan control program when posted by the operator. The feedforward schedules for these delivery changes caused the flow to be changed at the headgate at 7:05 (55 minute delay to WM-7PA), 10:11 (49 minute delay to WM-6), and 13:03 (57 minute delay to WM-7PA). The change in delay time for the on and off for WM-7PA results from a change in the initial conditions (i.e., less flow in the canal).

Figure 1 shows the inflow rate at the canal head and the water levels in each pool from 6:00 am to 6:00 pm (18:00). **Neither manual control nor operator intervention occurred during this test period. The canal was under complete control by the combination of iFix SCADA and SacMan.** The flow rate shown at the head (WM-0) is not necessarily an accurate flow rate since we do not have an upstream water-level sensor at this site (i.e., it is based only on gate position). The downstream demand was 28.2 cfs, while the graph shows 31.8 cfs, and the actual flow is likely somewhere in-between. Since control deals with flow changes, this is a minor inconvenience.

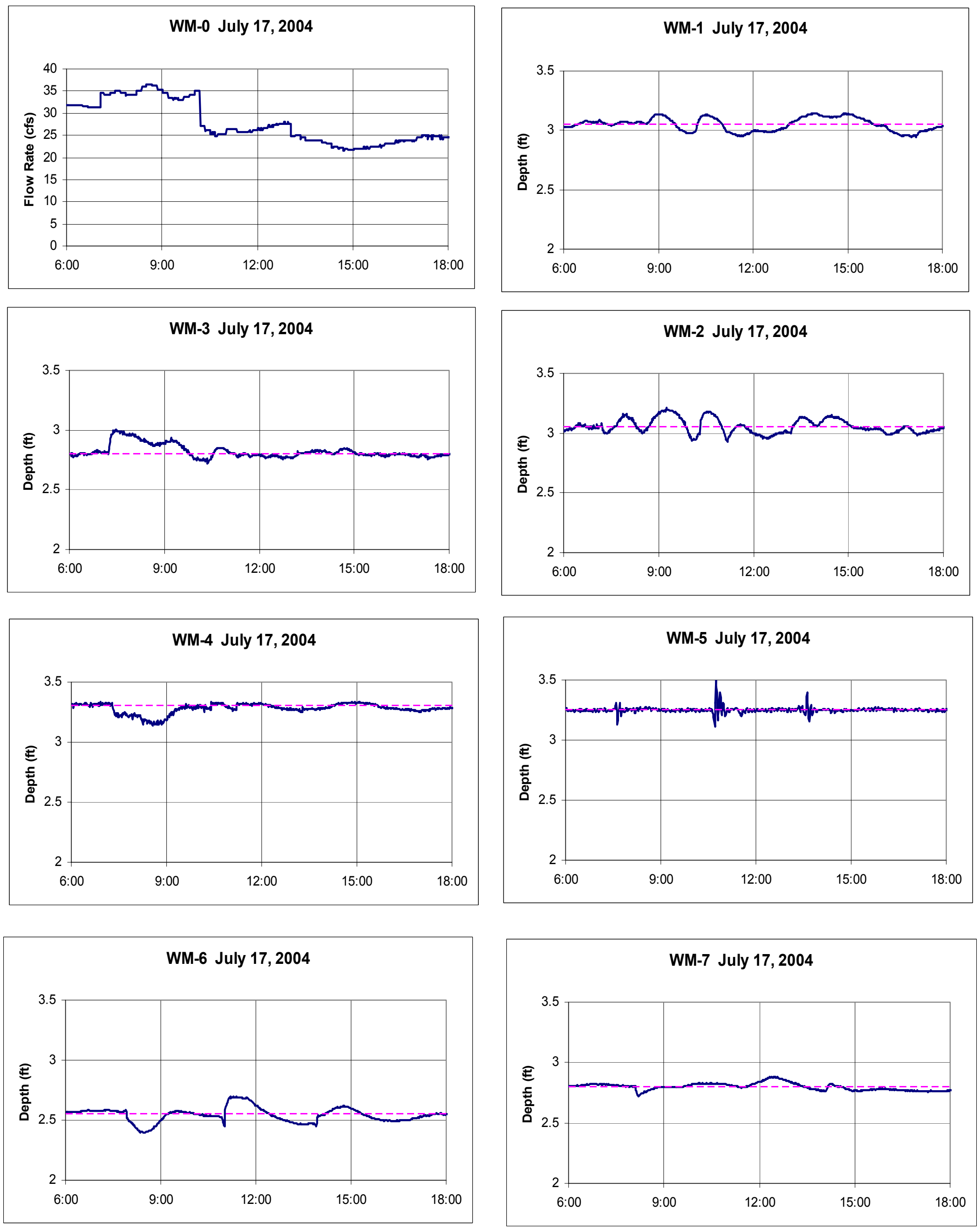

Figure 1. Canal inflow and canal water levels for routine routing or delivery changes on MSIDD's WM canal.

At roughly 7:05, one can see the step increase in inflow corresponding to the 3.2 cfs delivery change. This is followed by 1) some minor oscillations in flow caused by the feedback controller, 2) the step decrease in inflow at 10:11 because offtake WM-6 was to go off at 11:00, 3) additional feedback oscillations, and 4) the step decrease at 13:03. The inflow eventually stabilized at around 18:00.

Water level deviations were on the order of ±0.1 ft. This is acceptable control for this canal. Yet, these results show some interesting feature of automatic canal control. The timing of delivery changes can be seen by the water level deviations that occurred. Because waves disperse as they move down the canal, one cannot obtain perfect control in all pools, without passing oscillating flow changes downstream. For this canal, no spills were allowed, so we could not use this to mitigate the effect of wave dispersion. The timing of the arrival of the wave can be seen by the variations in water levels in pool 7 at 8:00 and 14:00 when the pump was turned on and then off. One can see that the water level quickly returned to the setpoint. At 8:00 the water level was stable, dropped for a short time when the pump came on, then very quickly stabilized, indicating good volume compensation (i.e., we put the right volume into the canal pool, even if the timing of the wave was imperfect). At 14:00, the pool was not stable, but was responding to the shut off in pool 6. The timing there was not as good, as shown by the rise in water level at roughly 11:00 when the turnout was shut. Some of that error in water level resulted in extra water being sent downstream, resulting in a small rise in the water level in pool 7. When the change arrived at 14:00, the water level was dropping, which actually helped to stabilize this pool faster.

As the wave for the flow changes needed in pool 7 passed through pool 6, one sees that the timing was not very good, resulting in deviation in the water level in pool 6. These were not very severe and they stabilized fairly quickly. Some of this deviation is caused solely by wave dispersion and is not entirely due to poor timing.

Pool 5 shows the response of the upstream water level controller. This controller was operated remotely on a two minute time interval. The changes in gate position were determined from a simple PI controller in incremental discrete form

$$\Delta w(k) = 0.668\ \Delta e(k) + 0.198\ e(k-1)$$

where $\Delta w(k)$ is the change in gate position at time step k, $\Delta e(k)$ is the change in water level error between time steps k-1 and k, $e(k$-1) is the previous water level error, and 0.688 and 0.198 are the proportional and integral constants, respectively. While overall control of this water level was reasonably good, there were significant spikes when the flow changes passed through. We discovered that the timing of water level measurement was significantly delayed such that the controller might be working on a measured water level that was a minute old. This actually caused the controller to perform poorly. For later tests, we added filtering to the water level values, upped the scan rate for this site so that we had more recent water level data, changed the control time step to one minute, and retuned the control constants through both simulation and real-time testing (not reported here). This canal pool is a bit extreme in that the pool is extremely short (e.g., backwater extending roughly 100 ft upstream). In this case, we would recommend that such control be implemented at the local site, as opposed to local logic at the central site. For larger canal pools, we did not experience these problems.

On first examination, we were concerned about the large deviation in water level in pool 3. This seemed like more than a timing mismatch. When we examined the data, we discovered that the 3.2 cfs feedforward flow change did not occur at this gate. Thus the flow change was not passed on to pool 4, causing its level to drop, while the level in pool 3 rose. This error was entirely removed with the feedback controller. The problem was caused by operator interaction. Such interaction should not have caused this change to be missed. We have since found the problem in the software and corrected it. This flow setting error also caused the oscillations in pools 1 and 2 as they tried to adjust their flows to compensate through feedback control. We have noted the tendency for pool 2 to oscillate and are working on ways to minimize this. Overall however, the feedback controller did a good job of correcting the problem.

Correcting unknown disturbances: The presence of a well pumping into the canal just upstream from gate WM-3 provided us with a good test scenario for studying the performance of the feedback controllers. Twice during the 30-day test period, this well was turned off by lightning strikes during thunder storms. In both cases, the controller was able to maintain control of water levels, bringing additional water in from the canal headgate to overcome the resulting flow shortage. We found it convenient to simulate this event by just routing a negative flow change down to pool WM-3, and then not implementing any changes there. On July 30 and 31, we performed this routine with two different controllers. Demand from the main canal was 27.0 cfs and no changes in demand occurred during this test period. The first controller was a PI^{+}_{-1}, as described above. The second controller was a fully-centralized controller PIL^{+}_{-}, where water level errors in all pools influence the flow to all gates (a so-called optimal controller). These controllers were designed at 40% of capacity, reasonably close to the test conditions. All pools were under feedback control. There was no demand in pools 7 or 8, so water level data there are meaningless. The results are shown in Figure 2.

The first flow change was routed from the headgate at 20:50, for arrival at 21:04. This flow change caused slight disturbance around 21:00 at WM-1 and WM-2. However, the larger disturbance during the next few hours was caused by the feedback controller trying to bring more water into the canal. As can be seen from the flow at WM-0, the flow had to increase above the steady-state value to provide the extra water needed to make up for the time when the flow was lower.

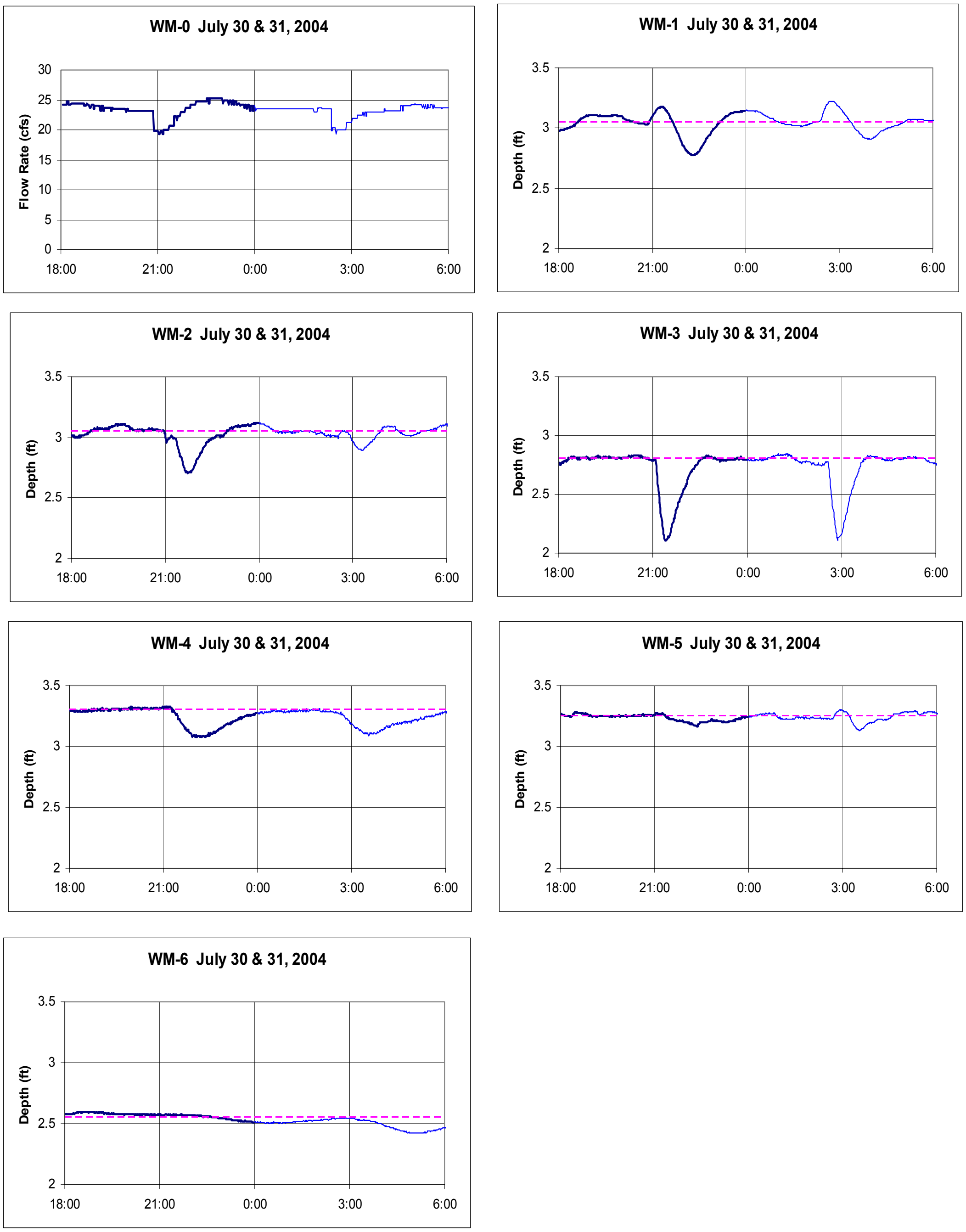

Figure 2. Canal inflow and canal water levels for simulated pump outage on MSIDD's WM canal.

For the first test, the disturbance primarily moved upstream and to the next pool downstream, as one would expect from this PI^{+}_{-1} (deviations influence all gates upstream and one gate downstream). Very little disturbance occurs in pools WM-5 and WM-6 because the flow is held constant at WM-4 by its flow controller.

For the second test, the flow change at the head occurred at 2:20 for arrival at WM-3 at 2:34. This more centralized controller tries to spread the disturbance out since the performance criteria are based on the sum of the squared values of the water level errors. The disturbance in pool WM-3 is slightly less, but is also of less duration. Deviations in pools WM-1 and WM-2 are less and the canal inflow appears to stabilize more quickly. However, more of a disturbance can be seen in the two downstream pools, with WM-6 showing a significant deviation that took a very long time to be removed. These kinds of tests are useful for understanding the performance and strategies of these various controller and should help in selecting the best type of controller for a particular application.

DISCUSSION

We have demonstrated that the SacMan control system is capable of controlling water levels in an irrigation canal. The basic components are working satisfactorily within a commercial SCADA package. The Automata hardware and firmware in the field is also performing as expected. Refinements are needed to make this system more failsafe so that it can run essentially unsupervised.

The SacMan control logic has been developed in a flexible manner so that a variety of control objectives can be attained. More details on the control approach can be found in Clemmens et al. (2002), Clemmens et al. (1997), and Clemmens and Schuurmans (2003).

At MSIDD, only small infrequent spills are tolerated. Under manual control, this also happens, but with manually controlled check gates, some of the error in flow gets distributed to users all along the canal. SacMan currently provides information on flow and volume errors to assist the manual operator in adjusting canal inflow to minimize these problems.

Downstream water-level feedback control eliminates the problem of excesses and shortages. However it is recognized that sloping canal systems cannot automatically respond to large demand changes regardless of the control logic (i.e., open canals cannot perform like closed pipelines). Major flow changes need to be routed through the canal. With SacMan, this can be done manually by the operator or automatically with SacMan Order.

The downstream control logic moves errors in flow to the upstream end of the canal, adjusting the headgate flow to get the canal flows and volumes into balance. However, on many large canals, the headgate flow is not continuously adjustable. Here, what was downstream control logic has to be adjusted to more central control logic, taking this upstream constraint into account. SacMan's flexible approach to control can make this happen. Further, information on flow and volume mismatches provided by SacMan help a manual-control operator in deciding how much water to order from the upstream supplier.

REFERENCES

Bautista, E., A.J. Clemmens, and T.S. Strelkoff. 2002. Routing demand changes with volume compensation: an update. p. 367-376. In Proceedings, USCID/EWRI Conference on Energy Climate and Water – Issues and Opportunities for Irrigation and Drainage, San Luis Obispo, CA 10-13 July.

Clemmens, A. J. and J. Schuurmans. 2004. Simple optimal downstream feedback canal controllers: Theory. *J. of Irrigation and Drainage Engineering*. 130(1):26-34.

Clemmens, A.J., Strand, R.J., Feuer, L. and Wahlin, B.T. 2002. Canal Automation system demonstration at MSIDD. p. 497-506 In Proceedings, USCID/EWRI Conference on Energy Climate and Water – Issues and Opportunities for Irrigation and Drainage, San Luis Obispo, CA 10-13 July.

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. and B. T. Wahlin. 2004. Simple optimal downstream feedback canal controllers: ASCE test case results. *J. of Irrigation and Drainage Engineering*. 130(1):35-46.