AUTOMATED SCHEDULING OF OPEN-CHANNEL DELIVERIES: POTENTIAL AND LIMITATIONS

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ABSTRACT

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

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

BACKGROUND

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

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

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

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

CURRENT SRP CANAL OPERATIONS

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

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

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

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

SACMAN SCHEDULER

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

$$\Delta V = V(Q_0 + \Delta q) - V(Q_0) \quad (1)$$

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

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

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

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

COMPARISON OF RESULTS

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

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

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

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

* "AZ" indicates Arizona Canal; "GR" indicates Grand Canal

** "CHK" indicates check structure; "otk" indicates offtake

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

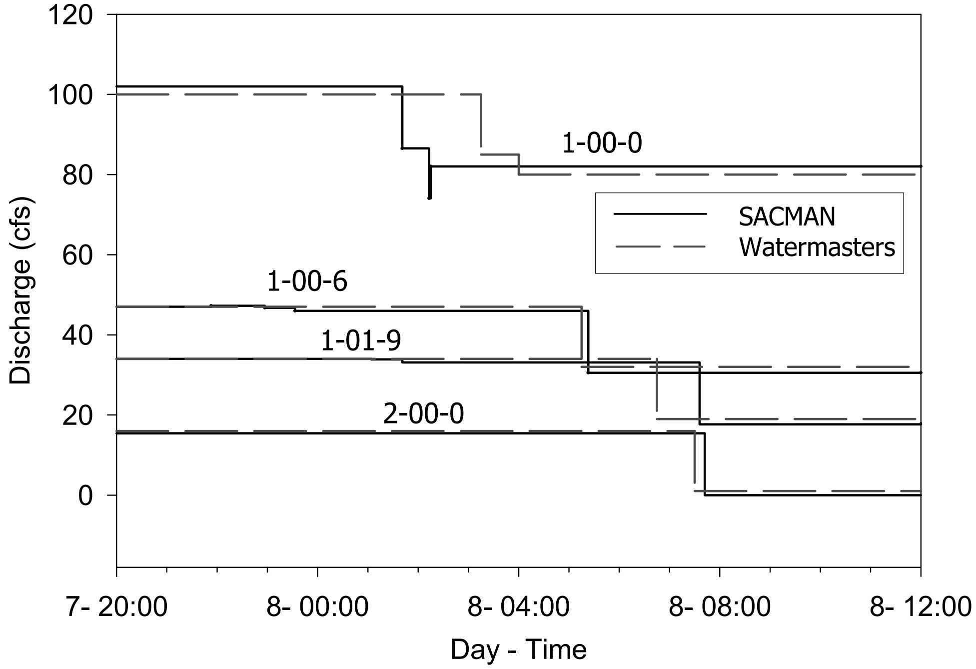

Figure 1. Flow Schedule Comparison

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

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

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

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

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

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

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

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

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

CONCLUSIONS AND WORK TO BE DONE

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

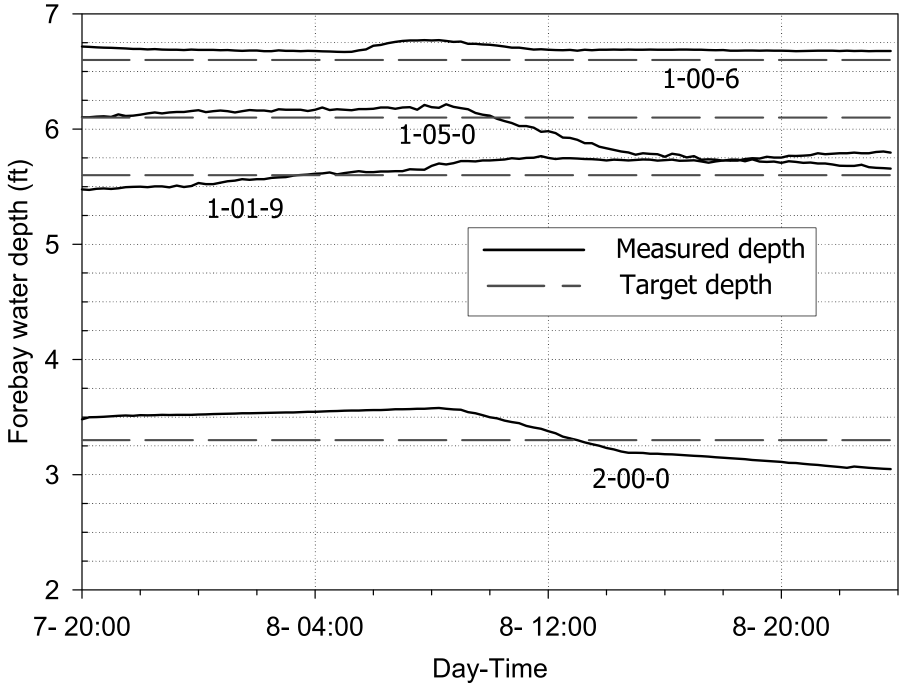

Figure 2. Variation in water depths with time at selected forebays, using the watermasters' schedule

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

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

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