PROGRESS ON CANAL AUTOMATION FOR WATER DELIVERY MODERNIZATION

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ABSTRACT

Modernization implies not just rebuilding but rather improving to meet new performance criteria. For irrigation water delivery systems, better customer service is high on the list of priorities. Agricultural customers are facing increasing competition, increasing water costs, and increasing production costs. Improvements in water deliveries can facilitate improved farm irrigation systems management. Canal automation is potentially one piece of the puzzle in trying to modernize and improve overall project performance. Canal automation theory has advanced substantially over the last decade. However, few of these advances have been implemented on operating projects because the theory has not been easy to apply. This paper presents the results of ongoing research to make canal automation more affordable and to integrate it with water delivery operations.

INTRODUCTION

The need to modernize irrigation water delivery systems is well recognized. Modernization is often justified to reduce maintenance costs, but more importantly, modernization is needed to improve water delivery flexibility and delivery service. Burt et al. (1997) report that many districts in the Mid-Pacific Region of the Bureau of Reclamation already have high levels of flexibility. However, there are many systems throughout the world where both flexibility and delivery service are very poor. Yet, the level of service required is relative to the perceived needs of users. So even systems at a relatively high level of service may still need some form of modernization to meet the current needs, particularly where water supplies are limited.

Modernization suggests improvements in the measurement and control of water supplied to and delivered by a project. Increasing the level of control implies the ability to provide more flexible and better service. The level of control that can be achieved for a given project is dictated by physical constraints (e.g., canal properties, structures, etc.), water supply constraints (e.g., storage and

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availability), and operating procedures and methods. Some of these constraints can be minimized with improvements in hardware and operating procedures. In this paper, we discuss the potential role of canal automation in the modernization of irrigation water delivery systems.

WATER CONTROL

In simple terms, ***the control of water within a delivery system centers on control of flow rate and control of volume*** at various points within the system, particularly at delivery points. For any part of the system, inflow equals outflow plus change in storage volume over time. Most canal operating schemes focus on these two concepts of flow and volume balances in one form or another. While these concepts are simple in theory, they are often difficult to apply in practice.

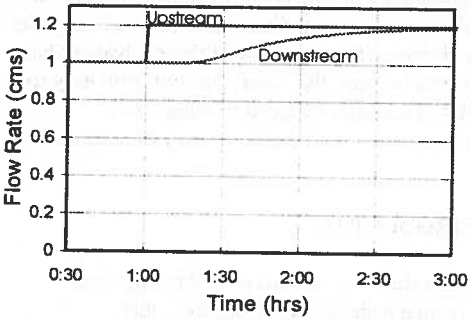

Fig. 1. Flow rate at downstream control structure for a step change in canal inflow rate.

For open-channel systems, application of flow-volume concepts is complicated by lag times — the time required for changes in flow to travel through the system. Further, sudden flow changes made upstream tend to arrive gradually at downstream locations due to wave dispersion, as shown in Figure 1 and described in detail by Strelkoff et al. (1998).

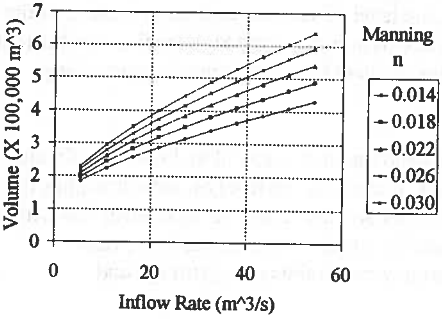

Fig. 2. Pool volume variation with inflow rate, setpoint depth, and Manning *n*.

For sloping canals, changes in flow rate and/or resistance to flow result in changes in pool volume that may not be considered by operators (Figure 2). Changes in pool water levels upstream from control structures also change pool volumes. ***Operators are easily fooled by the time delays, wave dispersion, and pool volume changes that occur within a system.***

While many operators have a heuristic understanding of these concepts and operate to take these into account, canal automation provides a more systematic way of dealing with these issues.

Flow rates set at check and offtake structures are never exactly correct. These errors may be large or small depending on the sophistication of the technology and operating staff. But these ***flow-rate errors will tend to accumulate within the system***. For effective, modern operations, some form of feedback, either manual or automatic, is needed to remove these errors. If inflow is inaccurately set for a given canal (or pipeline) and storage changes are not taken into account, outflow (i.e., deliveries) will never be as intended.

Check and offtake structure properties influence how flow changes are divided at a bifurcation. They can also influence pool volume (e.g., if the downstream level changes) and the speed at which upstream changes are felt downstream (see Strelkoff et al. 1998 for examples). Thus, ***structure hydraulics also influence the response of the system*** and have an influence on the effectiveness of both manual and automatic controls.

Modernization may also include better accounting for water diverted. Improved measurement and control can also help provide better estimates of water delivered, or help determine where in the system losses are occurring. Developing the hardware and operational procedures for good internal auditing of water volumes over time can provide a good impetus for further modernization efforts. If you don't know where the inefficiencies of the system are, it is hard to prioritize potential improvements. ***"To Measure is to Know!"***

MANUAL OPERATIONS

Gate Settings

A vast majority of canal systems are operated manually, with varying degrees of success. A common concept for local-manual control is to divide the flow at bifurcations by establishing a target water level. Gates are set so that if the water level is "close" to the target, the proper flow will go to each offtake or continuing canal. Because the zanjero (ditch rider or canal operator) cannot see all control structures at once, control actions must be made based on judgment and observations from traveling up and down the canal. (See Johnston and Robertson 1990 for further details). Errors in gate settings can increase the amount of time required by the operator to stabilize flow in the canal. Changes in gate hydraulics can cause the relationship between flow, level, and gate opening to change over time. Without separate flow measuring devices, additional zanjero judgment is required.

Scheduling Deliveries

There are a variety of water delivery schedules that determine when an offtake will receive water. The main ones being categorized as rotation, arranged or demand schedules (See Johnston and Robertson 1990 for further details). For all but pure demand systems, the schedule of water delivery changes can be established each day at all points within the system. For manually operated systems, there are several different methods for determining the timing of gate actions. Often, the changes are made at the head of the canal at some point in time (e.g., at the start of the morning shift). Then changes to downstream offtakes are made as the wave travels downstream. Based on experience, the zanjeros can estimate the time of the change at a particular offtake downstream based on when the heading was changed and the travel time for the wave to reach that offtake. Alternatively, a new delivery is made to correspond to the completion of another delivery, and the heading flow is not changed (e.g., delivery is rotated based on demand). For more flexible schedules, the change at the canal head is made to correspond to the requested time of change at the offtake. For example, if the offtake flow is to start at 10 am and the travel time is 3 hours, then the change at the heading must be scheduled for 7 am. The scheduling of deliveries thus depends upon the rules of delivery service and the amount of delivery flexibility provided to the water users. Generally, increased flexibility requires a better control system, both in terms of personnel (e.g., skills, number of employees, etc.) and hardware.

Manual Routing of Flow Changes

The main job of zanjeros is to route flow changes through the canal system. This is a time-consuming, tedious task. Water in open canals flows according to the laws of physics and not the desire of zanjeros. The work involves considerable judgment and experience. This judgment can be improved with a better understanding of canal hydraulics — i.e., “training”.

For manually operated systems with gates (or combined weirs and gates) as control structures, increases in flow are nearly always routed from the canal head to the offtake being changed. The operator starts flow into the canal and travels to the next gate downstream. There, (s)he waits for the change in flow to arrive. Since the wave arrives gradually, (s)he must wait until a sufficient portion of the flow increase arrives before transmitting it downstream by opening the gate. Here the gate opening is judged by making the same change in flow as at the previous upstream gate (less seepage losses if significant) for the target water level. The water level at the time of the change may be different from the target level, but should eventually return to it. Figure 3 shows what happens to the flow rate to the offtake and downstream canal while the water level stabilizes. This type of offtake hydrograph is not uncommon (Palmer et al 1991).

The operator proceeds downstream changing each gate in turn until the offtake is finally opened. Now the operator must return to the canal head and repeat the setting of gates with the assumption that flows have stabilized. Now adjustments are made to correct for errors made during the first pass. If the errors in the first pass are large, then the second pass may not be sufficient to bring the canal into balance. In particular, if inflow to the canal is set wrong, the actual canal inflow and the desired outflow cannot balance. To achieve a balance, the headgate must be adjusted and the process starts over.

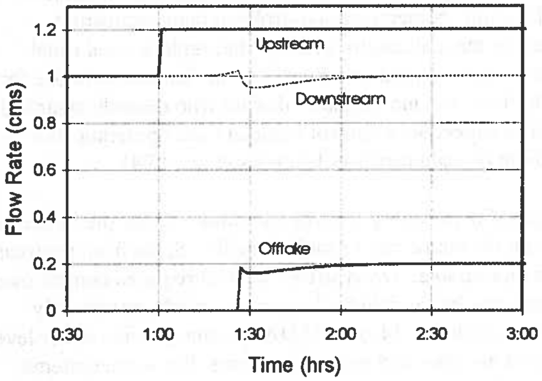

Fig. 3. Typical response in canal outflow for a change in offtake flow resulting from dispersion of step inflow upstream.

This correction of headgate inflow based on mismatches constitutes manual downstream control. Making flow changes on a canal usually requires a minimum of two passes (the second to confirm everything is okay) and a maximum of four or five passes. Flow measurement devices which give an accurate flow rate can help the zanjero minimize trips up and down the canal.

A common practice in some areas is to deliver a greater flow change than needed to satisfy changes in demand. For example, if a 150 lps change is needed, 200 lps more may be added. Experience suggests that this "carriage" water is needed to help move the change through the canal faster. This carriage water is useful for supplying the pool volume changes associated with the change in flow rate. Unfortunately, this carriage water is often left in the canal long after the transients have died out, resulting in wasted water.

We can model these unsteady-flow processes and determine the results of different zanjero operating rules, and the potential improvement of automation. As an example, Lamacq (1997) found through simulation a 10 to 20% variation (standard deviation) in delivery flow rates with respect to their targets using an unsteady flow model and knowledge of zanjero operating rules. Her finding were supported by district records. These variations in flow occurred even though this district has modern equipment and strives to provide excellent service.

Supervisory (Manual-Remote) Control

A single operator has difficulty controlling a canal where changes are taking place at many locations at once. For large canals, it has become practical to control gates from a centralized location. Supervisory control and data acquisition (SCADA) systems are remote manual control systems that replace local canal operators with supervisory control operators. Such systems have been in use for irrigation projects since the 1960's. One irrigation district who recently switched from manual-local control to supervisory control reduced their operating staff by seven people on about 80 km of main canals (Clemmens et al. 1994).

One of the main advantages of supervisory control operations is that the operator can see what is occurring on the entire canal simultaneously. Spills from upstream control of main canals are undesirable. Downstream control requires control over the water source, which may not be feasible for large main canals, particularly where transmission distances are long. Most SCADA systems provide water levels to operators. However, most are operated to adjust volume. For some systems, pool volume errors are actually computed, and flow rate changes needed to compensate for these errors are suggested. Operators may chose to let water levels deviate from the target so that they can use the canals for storage, for example when they do not have complete control of canal inflow.

If one pool is gaining while another is losing volume, gates are adjusted to shift volumes between pools. This method of operation has proven to be effective in many cases. However, most supervisory control operators have difficulty dealing with canal transients. Most control decisions are made after flows have stabilized -- a change and wait approach. Automated systems, discussed below, can be designed to take transients into account so that the operators do not have to wait for the flows to stabilize. They can act continuously. Brouwer (1997) compared an automated control scheme with manual SCADA control for a large main canal, through simulation. The results suggest that automatic control could provide significant improvement. While simulation results of automatic control are encouraging (Clemmens et al. 1997), they have yet to be proven in the field.

Water Accounting

Water accounting methods should determine the destination of all water diverted or pumped into the canal system. One level of water accounting is to compare water delivered to users with that entering the canal. For some districts, records of delivered water are not sufficiently accurate to make these assessments. Water changes tend to reflect ordered volume more than delivered volume. Such water accounting often shows that a significant amount of the diverted water is not accounted for, even when seepage and evaporation are taken into account. Charging for water based on cropped acreage discourages water conservation.

Few districts with canals have volumetric water meters. Mostly, rate is determined from head on a gate or weir. Such measurements may or may not give an accurate picture of water delivery. Careful monitoring of one water district showed that the average flow rate varied by 30% from that based on a one time a day measurement or by 40% from that ordered or intended (Palmer et al. 1991).

Proper water accounting takes this one step further to include water balances on lateral canals. Often, lateral canals near the head of the system receive more water relative to demand than those downstream. Proper water accounting can be used to document and correct this inequity. Good flow rate measurements with sufficient reading frequency or totalizing meters are required to make this water accounting reliable. However, good water accounting should be the first step toward solving water delivery and distribution problems.

AUTOMATIC CONTROLS

The position taken here is that there is a place for some type of automatic control of various delivery-system operational functions. The type and extent of automatic control that is appropriate depends upon the specifics of the system and its management. However, canal automation has much more potential than is currently being exploited.

There are a wide variety of automatic control systems in the literature. Most of these are classified and discussed by Malaterre et al. (1998). Those in use are summarized by Rogers and Goussard (1998). In reality, effective control, whether manual or automatic, must control the distribution of volume and must control flow rates at bifurcations. Control of water levels is typically secondary in order to control flow rates.

The application of canal automation is really in its infancy. There are basically only two types of automatic controls currently in use;

1. automation of single devices or single functions, with more system-wide functions done manually and
2. automation of some global decisions, with local functions done manually or through simple structures (e.g., where storage volumes are large).

The net result is that automatic controls are primarily implemented in a piecemeal fashion. A more ***systematic approach to the development of control "strategies" is needed***, as opposed to control "devices" or control "algorithms." Local control devices will continue to be one component of canal modernization. But, they can not deal with overall regulation issues and will not be discussed here. Also, I will not attempt to cover all the control methods proposed or in use. Several of the more important ones will be discussed. First, however, it is important to distinguish several different types of control.

Open-loop control occurs when the variable that is being controlled is not measured. For example, routing of flow changes through a canal can be done without regard to existing water levels (e.g., by determining needed changes in gate openings based on assumed conditions). If the controlled variable is water level and you change the upstream flow based on a measured offtake flow change, this is still open-loop control. This is often called feedforward control. Closed loop control exists when the variable to be controlled is measured and control actions are taken (e.g., changes in gate flows or opening) based on that variable. Automatic control of water levels immediately upstream or downstream from a gate is a form of closed-loop (feedback) control.

Centralized Automatic Control

There are only a few canals in the world which use centralized automatic control. Utilizing centralized automatic control logic has become a research project for every canal to which it has been applied. At this point in time, it is not off-the-shelf technology. However, a necessary and important first step in such automation is development of the hardware and communication systems needed for supervisory control (i.e., SCADA).

One of the more significant approaches to canal automation is dynamic regulation, developed for the Canal de Provence in southern France. The scheme estimates future demands, observes water levels within the system and determines changes in flow rate at the head of canal needed to restore volumes if those demands are realized. Pool volumes as a function of flow rate and stage are known. Flows between pools are adjusted by automatic gates that try to maintain a constant differential in water levels between pools. Water is pumped from the canals into water towers for pressurizing sprinkler irrigation systems. Thus the canals really serve as reservoir, and are quite different from gravity flow systems typical of much of the Western U.S. Other systems built by the French and operated in a similar way also tend to have large storage volumes – i.e., canals are not designed as efficient sections for transmission of water, as is typical in most irrigation projects. This is primarily an open-loop control system, with some local feedback components.

Another significant approach is that used to control the Central Arizona Project. Their control approach is to determine the desired conditions for some future time, and then changes the gate settings so that when the transients die down, the system will be at the desired steady state. The system seems to work well, and is useful considering the constraints imposed by lift station pumps. However, it is not responsive to changes in demand and the staff has to continuously calibrate gate coefficients and canal roughness parameters. There is no real feedback. Gate stroking was originally proposed (discussed below), but proved too difficult to implement.

Gate Stroking

Wiley (1969) first proposed a method for numerically computing, with the method of characteristics, the timing and amount of upstream flow changes to satisfy downstream changes in demand. This method has come to be known as gate stroking. It is a form of open-loop feedforward control. The U.S. Bureau of Reclamation (Falvey and Luning 1979) developed software to implement Wiley's method. Several attempts have been made to implement this in practice and they have all been unsuccessful. Several finite-difference approaches (e.g., Preissman scheme) to the gate stroking problem have been attempted. Bautista et al. (1997) summarize these methods and present an improved method. However, further research with this method suggests it will always be difficult to use because of the hydraulic constraints being imposed. With gate-stroking, the downstream water level is fixed exactly, and the desired discharge is forced to make abrupt changes. Because of the dispersive nature of waves, sharp changes in discharge and a constant water level are essentially a physical impossibility. Thus, the numerical procedures often produce upstream inflow hydrographs that oscillate significantly or are not physically possible. This water-level constraint is actually not critical, since water levels can change a small amount with little negative influence on delivery performance. A further complication is that unsteady flow is not linear. As a result, the inflow hydrograph for the sum of several individual changes does not equal the inflow hydrograph for the combined changes. Thus, this technique would require recalculation for every combination of changes – these hydrographs have to be computed essentially in real time. A much simpler and still effective alternative is discussed below.

Integrator-Delay Model

Schuurmans et al. (1995) propose an approximate model of canal response (integrator-delay model) based on two simple canal pool properties: the disturbance wave time delay and the water surface area of the pool portion influenced by backwater from the control structure. These two properties, delay time and backwater pool area, can be computed with their model, determined from observation of canal properties, or computed from unsteady-flow simulation. This canal response model assumes that downstream structures use constant flow rate control. Thus a step change in inflow would cause, once the wave arrives, a constant rate of change of backwater pool volume. Assuming that the backwater area is constant for a given set-point depth, the rate of rise of the water level is then related to the mismatch in flow rate (e.g., difference between inflow and outflow), which is used to guide the development of controller constants. The properties of the integrator-delay model can be used to develop both feedforward and feedback control methods.

For pools affected by backwater over their entire length, the above-described model assumes no time delays. The backwater pool area is the only controller design variable. However, reflection waves may be present for these types of pools. Most pools have either a significant time delay, or reflection waves, but seldom will they have both. Examples of the response of downstream water level to a step change in pool inflow and constant pool outflow for two pools of one canal are shown in Figures 4 and 5 (Clemmens et al. 1997).

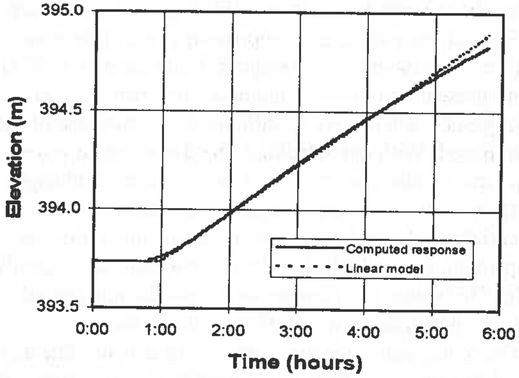

Fig. 4. Response in water level at the downstream end of pool 1 for a step change in inflow from 43 to 47.3 m³/s and no change in outflow (from Clemmens et al., 1997).

Figure 4 shows a linear integrator-delay model fitted to water-level response data for a pool primarily flowing at normal depth. The fit is reasonably good initially, but the actual response deviates from the model at large depths because the actual surface area changes as the depth rises, which is ignored in this approximate model.

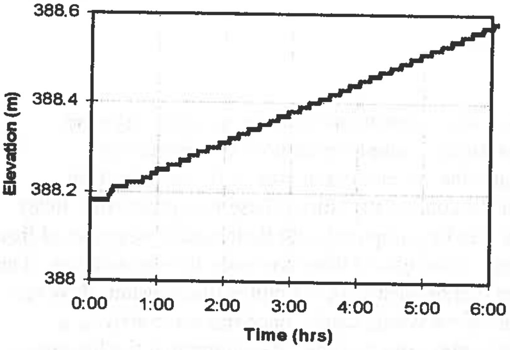

Fig. 5. Response in water level at the downstream end of pool 3 for a step change in inflow from 9 to 10.8 m³/s and no change in outflow (from Clemmens et al, 1997).

Figure 5 shows the response for a pool entirely under backwater. Note that changes in downstream water level occur with several cycles of delays followed by rapid changes. These are the result of oscillation waves within the pool that are reflecting off the boundaries. Wave celerity governs the period of these cycles. The waves dampen quickly, and at long times, the change in water level over time is essentially linear. A straight line fit to the data shown in Figure 5 intersects the initial water level at approximately time zero, suggesting that the approximate model by Schuurmans et al (1995) is reasonable.

Simple Open-Loop Routing Method

Bautista and Clemmens (1998) developed a simplified routing scheme based on required volume changes and kinematic and dynamic wave velocities. The approach is outlined in Figure 6. It starts with determining the change in volume required, ΔV, to go from the initial steady flow rate, Q_i, to the final steady flow rate, Q_f, resulting from a requested flow change, Δq. Next the travel time for a wave to go from the upstream end to the downstream end of the pool is determined, Δτ. The initial change in flow rate upstream, $\Delta Q(t_1)$, is computed as the needed change in volume, ΔV, divided by the travel time, Δτ. This change in flow rate may be different from the requested flow change. In this case, a second flow change, $\Delta Q(t_2)$, is made upstream so that inflow and outflow balance. The assumption behind this method is that if the correct volume is applied and inflow matches outflow, the pool will eventually stabilize itself with the correct volume and flow rates. Simulation studies performed suggest that this is the case.

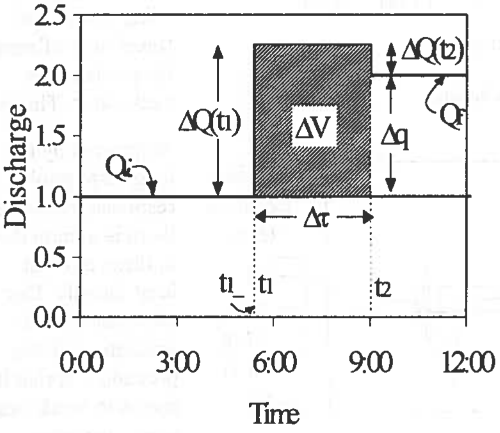

Fig. 6. Check flow change schedule from volume compensation and time delay.

For multiple pools, the volumes and delay times are summed from downstream to upstream. The cumulative volume is divided by the cumulative delay time to arrive at the flow change for each structure. If multiple flow changes are desired, check flow changes are computed for each. These incremental changes are then overlapped. For example, one requested flow change may compute a change of +100 l/s at 12:45 pm and -10 l/s at 3:00 pm. Another requested flow change may compute a change of +200 l/s at 2:00 pm and -40 l/s at 3:30 pm. An example of multiple flow changes is given in Figures 7 and 8.

In order to implement this method, pool volumes must be determined for various combinations of 1) flow rate, 2) downstream set-point level, and 3) Manning n. Volume as a function of these variables can be determined from computed backwater curves and canal geometry, or from simulation with steady hydraulic

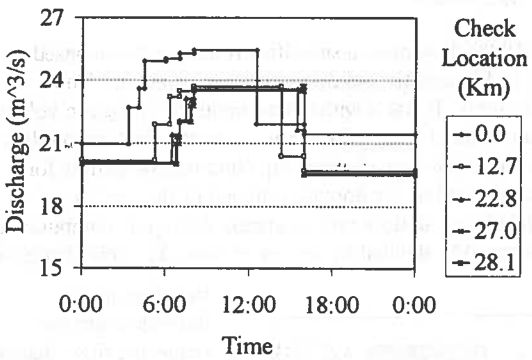

Fig. 7. Computed check flow schedules.

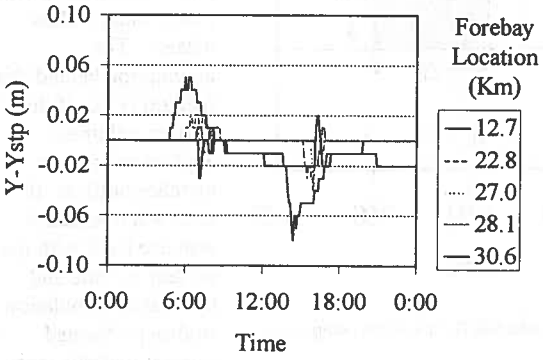

Fig. 8. Simulated forebay water level variations.

models (e.g., HEC-RAS). This scheme can also be used to implement changes in water level set-point.

The integrator-delay model of Schuurmans et al. (1995) suggests using a delay or travel time of zero for pools under backwater. This is supported by the long-term pool response. However, there is a finite delay in these pool, at least initially. Our experience with simulation of this procedure is that it seems to work best when we use a delay time equal to ½ that determined from the speed of a celerity wave for pools or portions of pools under backwater. For these pool sections, celerity should be computed with an "average" depth over the portion under backwater.

Downstream Feedback Control of Water Levels

Without some form of downstream control, there is no way of controlling the water delivery to users. Local manual and supervisory control systems use some form of manual downstream control to make adjustments when the system is "out-of-balance." Automatic downstream control systems serve the same purpose. They adjust the system for mismatches in inflow and outflow. They do this is such a way that the proper volumes are added to the system. Downstream control is useful even if all demand changes are prescheduled.

Many of the older automatic downstream control systems have been developed under the assumption that all demanded flow changes downstream control can handled. For most canals, this is simply not possible. Pool delay times preclude large demand changes from being implemented from the downstream end without anticipation and routing. The problem is that many of these older downstream control scheme are not set up to handle simultaneous routing of demand changes. This is a major weakness and has resulted in these systems being shut off frequently, for example when demand changes are large. The ability to combine open-loop routing of flow changes with feedback control of downstream water levels is essential for the effective wide-scale implementation of canal automation.

Feedback control of downstream water levels on canals with many pools and long delay times is usually required to be relatively damped to insure stability, and to reduce unnecessary oscillations in canal inflow and water levels. Disturbances behave differently in normal-depth pools than in backwater pools and must be handled differently in the feedback control system design (just as they are handled differently in open-loop routing). In the normal-depth sections, disturbances essentially travel only in the downstream direction. While in backwater pools, disturbances can travel in both directions and reflect at the boundaries. If improperly designed, the feedback can produce oscillations or even instability.

An important issue for water level feedback on canals with many pools is whether to use local feedback controllers (e.g., ELFLO or BIVAL) or more centralized controllers. Simple, local feedback controllers may have very limited performance for some canals (Schuurmans, 1992). However, centralized controllers are often too complex and too much like a black box, such that controller performance may be somewhat unpredictable. There is a strong reluctance to actually implement some of these controllers because of their complexity. A new downstream-water-level-control method with an intermediate level of complexity has been proposed (Clemmens et al. 1997, based on Schuurmans, 1995). It has been combined with other control features into an overall scheme, discussed below. Research is ongoing in this area.

USWCL AUTOMATIC CONTROL SCHEME

The staff at the U.S. Water Conservation Laboratory (USWCL) has developed a control scheme that is based on the integration of automatic controls with existing, manual operations. It allows one to take a more systematic approach to canal automation. It uses optimization to develop feedback controller components and attempts to maintain simplicity and understandability. It has three components:

1. open-loop control of flow rate and volume based on hydraulic routing,
2. closed-loop control of (distant) downstream water levels, and
3. local closed-loop control of check-structure flow rate based on 1 and 2.

Routing of flow changes is required because many canals have insufficient storage to provide adequate control with downstream feedback control alone. Feedback control of downstream water levels is necessary, even when demand changes are made by routing, since flow rates set at check structures always contain errors and since routing is never perfect. Check structure flow rate control provides some advantages for both open-loop routing and downstream feedback control. It also allows the two to be easily combined. The general scheme for one pool is shown in Figure 9. Manual controls can also be done simultaneously with automatic control — that is, the automatic control does not have to be shut off to make manual changes.

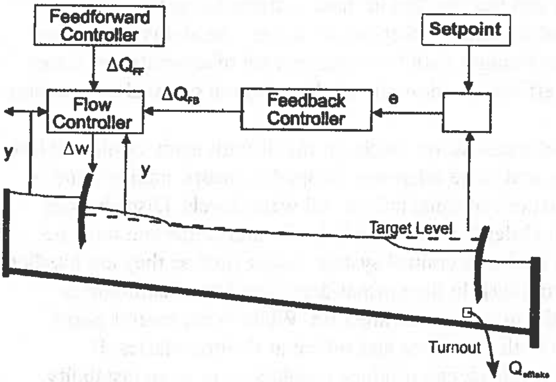

Fig. 9. USWCL canal control scheme.

Implementation

The wide-spread implementation of canal automation depends upon its being integrated with the overall operation of the district. Several research projects are ongoing to provide the needed integration. A pilot project on canal automation was initiated by the Salt River Project (SRP). Under this pilot project, the USWCL canal automation scheme will be tested in real time. During Phase I, completed in March 1997, simulation tests were run to determine whether the automatic control system could handle typical SRP control situations. This phase was very successful and the control system is now being implemented on SRP's SCADA system during Phase II, scheduled for completion in December 1998. Real time testing will begin in 1999 under Phase III. If successful, the system will be expanded.

A cooperative research and development agreement was established with Automata, Inc. to jointly develop a canal automation product line based on the USWCL control scheme. The intent is to try to make this system *Plug-and-Play*. Initial testing of Automata's system is being done on Maricopa Stanfield Irrigation and Drainage District's WM canal. This system should also be ready for real-time testing in late 1998 or early 1999. If these two efforts are successful, canal automation may quickly become a useful and powerful tool for modernization of irrigation water delivery systems.

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