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Canal Control Challenge

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Abstract
The operation of a relatively new irrigation canal system in central Arizona, USA is described. Water is relatively expensive and thus farmers pressure the irrigation district to improve delivery service and keep water losses to a minimum. The system was designed and constructed to function with supervisory (manual, remote) control, with the potential for automatic (remote, computer) control. Experiences with hardware and software difficulties are described. While currently, water control and delivery service are very good, further improvements through automation are possible. Real world operating conditions are described which are somewhat different from the assumptions made for the development of canal control algorithms. Field data collection and canal flow computer simulation were used to develop a test case for developers of automatic control algorithms. Desirable canal control performance measures are suggested.

Introduction to MSIDD

The Maricopa Stanfield Irrigation and Drainage District (MSIDD) is located in central Arizona about 50 km south of Phoenix. The irrigation district was formed to receive Colorado River water from the Central Arizona Project. The irrigated area of about 35,000 ha had previously received water from groundwater wells. The irrigation district took over the wells during 1989 and delivers a mix of groundwater and surface water. Many of the wells discharge into the district canals and then the mixed surface and well water is delivered back to the farm. About half of the water delivered currently comes from groundwater.

Construction of the canal system was completed in 1989. The system was designed so that all canal check gates (cross-regulators), including laterals and sublaterals, could be controlled by motorized gates remotely through radio communication. Engineers designed the entire system to be operated by supervisory control (remote, manual control). The design engineers also provided an option for automatic downstream control (remote, computer control) (Kishel, 1986). Farm offtake gates were to remain manually operated. The district began delivering water in 1987, prior to installation of canal gate remote control equipment, through manual operation (see Table 1).

Each farm offtake includes a single-path ultrasonic flow meter that is solar/battery powered. The meters provide both flow rate and accumulated volume readings. Water is relatively expensive in the district (35 to 40 US$ per Megaliter). The district employs personnel who continually check and verify meter calibration. Inflow to the district is measured with a series of multiple-path ultrasonic meters. The system is operated with very little spill (< 1%) and deliveries to the farm match inflow to the district within about 2% (after accounting for seepage and evaporation). Thus there is very precise accounting for where the water goes.

During 1990, district staff attempted to implement automatic downstream control. Initial tests were

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made on the WM lateral canal, which resulted in extremely unstable performance, even when starting from near steady flow. Similar tests were run on the Santa Rosa main canal, but the tests were aborted due to unstable behavior. After several months of efforts by district staff and the design engineering firm, automatic control remained nonfunctional. Only one algorithm for automatic downstream control was tried, and it may have not been the best available downstream control algorithm. Also, significant hardware problems existed (e.g., gear lash or hysteresis, radio interference) which may have kept the control algorithm from providing the proper control. These hardware problems have been fixed (see Table 1), but no further automatic downstream control experiments have been conducted.

Supervisory control on the Santa Rosa canal was implemented during 1991 and 1992. A few lateral canal gates are also operated remotely, where difficulties with local, manual control exist. The district is currently working toward implementing some supervisory control on their lateral canals, though not all the needed hardware modifications have been made. Additional difficulties were faced in starting operations on a system designed for such controls, but not equipped with them for several years of operations, as described in Table 1. Lack of success in attempts at implementing automatic downstream control have made the district staff more cautious in modifying current operating procedures.

The majority of the operating staff is on duty during daylight hours. Farmers can request turn on, changes in flow rate, or turn off any time between about 7 am and 3 pm (operators working hours), referred to as the service window. Official policy requires farmers to give the district 24 hours notice for these changes; however the operating staff is capable of making minor changes on very short notice. A small shift works during the night to make minor adjustments in the system, to handle major problems or hardware failure, and to handle special requests for changes. Farmers can request changes in flow outside the service window, but are charged an extra fee (US$100). Because of long wave travel times on some of the longer laterals, the service window for some farmers effectively becomes shorter since the operator must be on duty to route the changes through the canal. Some farmers have complained about this inequity in service, which can be important since water costs represent a large part of their operating expenses.

Changes to lateral canal inflows are made primarily in the morning. Operators change flows at the canal heading and work their way down the canal adjusting check gates and farm offtakes. Several trips up and down the canal are then required to stabilize the canal so that inflow matches outflow and each farmer has the proper flow rate. With manual operations and the time needed by the operator to move up and down the canal, some delivery flow fluctuations do occur. From farmer interviews, flow fluctuations i) appear to be more of a problem toward the tail end of laterals and ii) influence some types of irrigation system more than others (several different types of surface irrigation systems are in use), as shown in Table 2.

The district is interested in improving delivery service and reducing operating costs so that farms can maintain economic viability. Poor yields and increasing operating costs threaten the economic viability of farmers within the district (Dedrick et al 1992). Some Board of Directors members once viewed canal automation as a white elephant (i.e., a large expense with no apparent value). Some success with supervisory control on the main canal has changed this negative view. The operating staff continue to work toward full implementation of supervisory control as a means of lowering operating costs and improving service. The district staff is still interested in implementing automatic controls, but only if it can be demonstrated that such controls are effective and have appropriate safeguards against failure. MSIDD is a potentially good testing ground for canal automation algorithms because of the existing hardware on canals with widely varying properties (e.g., different slopes, flow rates and storage volumes) and the staff's interest in improving controls. The purpose of this paper is to provide details on real world operating conditions in MSIDD so that canal control experts can develop improved methods, which ultimately could be applied to MSIDD and other irrigation district canals.

Introduction to canal controls

Improvements and/or automation of canal control can be justified by improved service to clients, improved efficiency of operations, reduced overall operating costs, and safety. The type of automation used on canal delivery systems depends upon such things as the type of canal structures, the rules for delivery service, the types of water delivery, the availability of communication between the control center and automatic structures, the expectations of water users and operating staff, and economic considerations. Canal control methods in use and their conditions of applicability are briefly described below. Many of these methods are summarized by the U.S. Bureau of Reclamation (Buyalski, 1991). The needs for improved control are discussed in Zimbelman (1987), along with methods not covered in Buyalski (1991).

Most open channel delivery systems operate with upstream control. Downstream demand is determined, and that amount is released into the head of the canal. Offtake gates are manually operated. Upstream control attempts to keep the water level immediately upstream from each canal check gate (usually associated with an offtake) constant, so that associated offtake flows become constant once they are set. With upstream control, if the water level at a check gate drops below the target level, that gate is closed to release less water downstream. Any errors in matching canal inflow to outflow are moved to the tail end of the canal. Canal check gates can be adjusted individually by field operators, remote operators, local automatic gates (e.g., Littleman controller), or by central computer. Canal response to a change in inflow can be modeled and gate positions determined to provide nearly constant water level (e.g., Gate Stroking). Upstream control methods are usually not conducive to flexible, efficient water delivery service.

For large main canals, controlled volume methods are often used. Here, an attempt is made to maintain a near constant volume in a pool between check structures. The target pool volumes can be varied as needed to adjust for an imbalance between inflow and outflow. Water levels thus can vary within each pool. Maintaining constant deliveries usually requires offtakes to be automated. Controlled volume control requires centralized control logic, that is, check gates are not adjusted independently. Controlled volume can be viewed as intermediate between upstream and downstream control (i.e., flow rate errors are accumulated at the tail, middle and head for upstream, controlled-volume and downstream control, respectively).

A variety of downstream control methods have been proposed. With downstream control, a gate is adjusted on the basis of water level conditions at a point or points downstream. Here, differences between inflow and outflow are moved upstream to the canal source, where canal inflow must be adjustable. Some methods use the water level immediately downstream from the gate to determine needed gate adjustments. This scheme is frequently not practical, since it requires canals with nearly level tops and offtakes at the upstream end of a canal reach where minimum head is available relative to the land surface. A number of local downstream control schemes have been proposed, where each gate is adjusted based on the water level either at the downstream end of a pool or at a series of points along the pool (CARRD, BIVAL, ELFLOW, Zimbelman, see Zimbelman 1987). While there are conditions under which these local downstream control methods have been effective, there are also cases where they respond poorly (Schuurmans 1992). Centralized downstream control methods have also been proposed (e.g., Balogun, 1988), but few such systems have been implemented.

Upstream control has the limitation that flow rate errors, inflow minus outflow, end up at the tail end of the canal resulting in either shorting the last outlet or spill. Controlled volume methods are limited to canals with automated offtakes. Downstream control methods on some canals are unable to respond quickly enough to needed flow increases downstream. What is needed is a mix of these different control methods. Observation of supervisory control operators indicate that they use a form of upstream control to route flow increases through the canal (i.e., feedforward); they use downstream control to back flow decreases out of the canal (some use upstream control); they use downstream

downstream seems to work if there is storage enough → Granite canal (USA) Heinchenctt (of chirnam) avec 1 PID sur côté aval control (feedback control) and in some cases volume control to adjust for mismatches in inflow and outflow. Some use the concept of active and inactive pools. Active pools have ongoing water deliveries and thus must maintain constant water levels. Inactive pools have no active offtakes. The volume in inactive pools can be used to help balance the system. Manual canal operators follow similar practices. As a result, many canals are well controlled manually, and attempts at implementing one or more of the simplified automatic control methods have been unsatisfactory. (It is also interesting to note that on most automated canal systems, the automation was retrofitted to an existing manually operated system).

Most applications of automatic (or even supervisory) control have been on large main canals. However, water distribution problems in irrigation systems often occur on smaller lateral or branch canals, where few automatic controls exist. Automatic control for these smaller canals is more difficult since they tend to be steeper, have less relative storage, and have larger percentage flow changes. However, if appropriate control schemes can be developed for these smaller canals, control of larger canals can also become more effective, even though existing scheme may be satisfactory.

Canal details

The canal chosen for study, MSIDD canal WM, is very steep with fast response and very little storage. This is the canal on which automatic downstream control was tried and failed. A standard check gate arrangement is used, in which overflow weirs are provided on both sides of vertical sluice gates. These overflow weirs are placed at the same elevation as the top of the gate. Thus a closed gate serves as a weir. The W-M canal is 9.5 km long and drops 40 m in elevation. It has 7 check structures and delivers water to 11 offtakes, including 2 short sublaterals (1 offtake each). Because of the steepness of the terrain, the upper parts of some canal reaches are on mildly supercritical slopes. Supercritical flow also occurs within some culverts. All gates are unsubmerged (i.e., downstream water level has no influence on discharge). The canal is broken into pools which are divided by check gates. Each pool contains a series of canal reaches and culverts (pipe sections).

Canal simulation

In order to test any canal control method, it is necessary to simulate unsteady flow in the canal. There are a variety of unsteady flow models available with differing capabilities. We used the CARIMA model developed by SOGREAH (LHF, 1988), which has been demonstrated to be useful for irrigation canal simulations (Holly and Parrish, 1991).

One of the first steps in using unsteady flow simulation models is the calibration of gates, weirs, channel roughness, etc. Calibrations of the necessary parameters are often done under steady flow conditions. Field measurements were collected on the WM canal for a 24 hour period over July 1 and 2, 1992. The canal was initially at essentially steady flow, as no changes had been made to any gates for at least 16 hours. This condition was observed for several hours.

At about 8:43am, the ditchrider began making changes to add 264 l/s to canal flow to start water deliveries at offtakes WM-7 and WM-7P (Table 3). He began at the head of the canal, opened the offtake gate from the main canal and then worked his way down the canal, opening check gates as the change in flow arrived, and finally opening the outlet to WM-7 and starting the pump to WM-7P. This flow change took several hours to reach the offtakes, and during that time and for some time after, the ditchrider traveled up and down the canal several times and readjusted gates as necessary. After about 10:43am, no further changes were made until the following morning.

A crew of technicians recorded canal water levels at the check gates, check gate openings, offtake delivered volumes, and offtake gate openings. All readings were taken manually. Staff gauges were installed on the side of each check gate to record water levels there. Gate opening were measured with a ruler from the top of the gate to the upper frame. (The distance from the upper frame to the bottom of the gate was known). Offtake flow meter volumes were read to determine flow rate from volume and time. Volumes were a more reliable indicator of average flow rate than individual flow rate readings for these meters. However, this causes some damping of the real fluctuations in flow rate experienced at the turnout. Offtake gate opening were also difficult to determine. Gates were well below the water surface and not visible. Gate stems were encased in steel pipe for protection. A radial dial was available on the gate gear box, but the indicator was not very precise.

Calibration is important in determining response of canal and offtake flow rates and canal water levels to changes in canal inflow and gate positions. However, calibration parameters are not necessarily constant over the full range of possible conditions, making calibration valid only near the range of conditions observed. Further, canal and gate response can change over time, and field measurements contain inaccuracies. Thus calibration will never be exact. For this example, some assumptions were made regarding actual conditions so that an inexact, although useful, solution could be attained.

The initial steady conditions on July 1, 1992, were used to determine check gate coefficients. Under the initial conditions, flow passing each check structure was through the gates with no flow over the weirs. A head-discharge relationship was developed for each offtake. These were used to determine the influence of unsteady flow on offtake flow rates (i.e. a head-discharge relationship as a function of gate opening). During steady flow simulations, a fixed discharge was used for the offtakes.

Performance criteria

Canal control can have several possible performance measures. Often, water level fluctuations are used as a measure of performance. However, fluctuations in delivery rates is a better service-oriented measure of performance. While delivery fluctuations are dependent upon the specific structures in place, for a specific case, they are a more direct measure of performance. Changes in canal levels can alter offtake flows, this in turn can change canal flow rates which can alter other offtake flow rates. Thus using water level fluctuations as a performance measure to evaluate automatic canal control algorithms with assumed constant outflows can be misleading.

Palmer, et al (1989) used the coefficient of variation of flow rate (standard deviation of individual readings divided by mean) as a measure of delivery performance. Palmer, et al (1991) used the ability to deliver the desired flow as another measure of performance. Within MSIDD, most growers were more interested in stable flows even if the desired flow was not exactly provided (Dedrick et al 1992). For this study, we did not know the desired or ordered flow rate, or whether this rate was renegotiated in the field.

Table 3 gives the initial and final flow rates for each offtake. Also provided are field estimates of the minimum and maximum flows, the coefficient of variation, and the maximum percent deviation from the target flow rate (final or {initial + final}/2). Fluctuations in flow meter readings made exact determination of field values of these variables difficult, and make the coefficient of variation and maximum percent difference subject to some interpretation.

The challenge to developers of canal control algorithms is to develop a control algorithm which will provide the needed changes in delivery while causing less than 10% change in any offtake flow rate (difference between initial {or new target flow} and either maximum or minimum flow of less than 10%) and providing a coefficient of variation for each delivery of less than 3%. Details of the MSIDD WM canal and the test conditions can be obtained from the senior author on request. Control algorithms should be tested on canal simulation software to demonstrate the degree of control attained. A task committee is being formed by the American Society of Civil Engineers (ASCE) to develop evaluation criteria for canal control algorithms and to define limits of applicability. This proposed committee would be interested in results obtained with this example for various control schemes. Experiences and results can be communicated to the senior author.

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Table 1. Milestone events in the development of the MSIDD automated control system. (Extracted from Dedrick, et al 1992).

-	MSIDD accepted control of first pools of the Santa Rosa Canal and received delivery on the first CAP water.	FEB 1987
-	First water delivery to a District grower.	MAY 1987
-	First water delivered to Ak Chin Indians, Santa Rosa A & B Canals completed.	JUN 1987
-	Automated Control Contract awarded to Sierra Misco[2].	NOV 1987
-	Automated Control Software contract awarded to Sierra Misco.	MAR 1988
-	Sierra Misco begins testing of control equipment.	NOV 1988
-	Control system found to be inoperable due to gate operation electronics losing calibration. The problem was traced by district personnel to a latent defect discovered in the Limitorque MOD-100 boards.	JAN 1989
-	Limitorque Corporation replaced the MOD-100 board at each gate control site.	APR 1989
-	Automated Control System largely completed and Pre-transfer Inspection of the system was conducted.	MAY 1989
-	Automated control testing unsuccessful due to signal interference on our radio frequency.	AUG 1989
-	District staff under the guidance of Bookman Edmonston Engineering contacted the Utilities Tele-Communications Council to request assistance in exploring an alternative frequency. Application was made for Frequency Coordination.	OCT 1989
-	A trip to Coachella Valley Water District was undertaken by MSIDD personnel to investigate their telemetry control system, with emphasis on Little-Man-Controller technology.	NOV 1989
-	Radio frequency successfully changed through the FCC.	DEC 1989
-	MSIDD personnel designed and constructed Little-Man-Controllers as recommended by Bookman Edmonston to be used as a backup to our automated control system. The controllers were installed on most check structures on the E-10 and E-12 laterals. (Only 4 still in use).	JAN 1990
-	Installation of new radio crystals by Protec Radio Communications assisted by district personnel	FEB 1990
-	Scheduled completion of Control Software by Sierra Misco.	MAR 1990

[2] Trade names, company names and names of individuals are provided for the convenience of the user and do not imply endorsement or preferential treatment.

Table 1. (Continued)

-	Control system testing and system debugging continued through the summer season 90.	APR/JUL 1990
-	Trip to Oakland, CA, to the manufacturers of our automated control system was undertaken for the purpose of a hardware training seminar. In attendance was Marshall Davert of B.E., Jack Kilgore and George Wall of MSIDD, Henry Parales of CAIDD, and a system installer from Sierra Misco.	AUG 1990
-	Marshall Davert of B.E. along with district staff conducted the first comprehensive test of the fully functional Automated Control System. Although all systems were operable it caused wide fluctuations in water levels in all 6 pools included in the WM lateral test.	SEP 1990
-	Jerry Schmidt of B.E. informed MSIDD that all construction of our Automated Control System was completed by 11/15/90.	NOV 1990
-	District personnel designed and constructed a remote control switch that was added to each control site on the Santa Rosa Canal. This switch was needed due to the canal being operated in manual mode by field operators, coupled with the need for the office dispatcher to be able to switch the gate site into remote control from the office to give us the ability to move the gate remotely in case of flood events.	NOV 1990
-	District staff determined that the gear lash problem in the gate opening report mechanism at the radial gate sites was unacceptable for smooth water level regulation. In early January Limitorque Corporation agreed to manufacture a special gear set that would remove most of the gear lash. This prototype kit was provided to us at Limitorque's expense for experimental purposes. Though installation of this kit greatly improved the gear lash problem, we found that the resulting improvement was still not enough and the cost of additional kits was prohibitive at $450 each. At this point district staff designed and constructed a direct drive gear lash kit for a cost of $100 each that gave us the improvement that we were seeking. After testing of the improved gate site, we then found that the built-in dead band in the electronic MOD-100 board tended to give negative results for smooth water level regulation.	MAY 1991
-	On June 18th, district staff designed and constructed the first Radial Gate Stroker by converting one of the Little-Man-Controllers and installed it at pool B5 for remote control testing. The test was a success.	JUN 1991
-	Begin design of gate stroker software patterned after our Manual Canal Operation Method which had long been used by our field canal operators, by district staff and Ken Taylor of CAIDD.	JUN 1991
-	District staff was authorized to order parts needed for construction of strokers for the lower Santa Rosa B section from pools B5 through B12.	JUL 1991
-	Stroker hardware and software of the lower Santa Rosa B section completed and canal regulation testing started.	AUG 1991
-	First successful supervisory control of the entire lower Santa Rosa B	