Accelerated Irrigation Canal Flow Change Routing

Charles M. Burt, Ph.D., P.E., M. ASCE
Kyle E Feist, P.E.
Xianshu Piao, Ph.D.

Abstract

In a traditional automated upstream controlled canal with a downstream buffer reservoir, the process to fill the buffer reservoir requires one step: the inflow to the canal is increased, and the flow change eventually arrives at the buffer reservoir. This paper explains an attempt to shorten the time necessary to stabilize the new flow rate at the buffer reservoir. The method requires calculated, remote manual adjustments to all the canal check structure gate positions in addition to two flow rate changes made at the head of the canal, followed by a return to automated upstream control. The method was tested in the Upper Main Canal of Central California Irrigation District both through simulation and in the field. With a canal flow of about twenty percent of the maximum, simulation modeling predicted a flow rate change arrival at the reservoir would be about 5.5 hours in a typical operation, with final stabilization in about 16 hours. Simulation of an improved procedure indicated an almost instantaneous increase in flow at the reservoir of half the flow change, with final flow stabilization at 11 hours. The field test resulted in almost the full flow change arriving at the reservoir after about 20 minutes, with gradual stabilization occurring over the next 11 hours. Important differences between simulation and actual are discussed.

Subject Headings: Irrigation Canals, Canal Automation, Model Predictive Control, Hierarchical Control, Canal Flow Routing

Literature Review – Rapid Transmission of Scheduled Flow Changes
Chapter 6 of Wahlin and Zimbelman (2014) contains a discussion of flow routing in irrigation canals. Few of the control options proposed in the literature have been successfully applied in irrigation districts over long periods of time, and under multiple conditions. All involve some type of feedforward or predictive approach, and generally require knowledge of water orders and the present hydraulic status throughout a canal – as opposed to simple automated upstream control in which all actions by a gate are only dependent upon feedback of the water level status at that gate.

A challenge is to not only move the proper flow change down a canal for the proper duration, but to simultaneously maintain fairly constant water levels in the canal pools.
Feedforward (Bruggers 2004) and feedforward/decoupling (Li et al. 2005) strategies adjust target water level set points and/or flow set point changes to speed up the delivery of a flow rate change from the head of the canal, down to the end of the canal.

A volume compensation method of feedforward control in conjunction with feedback control was presented by Clemmens et al. (2010) to handle multiple flow changes simultaneously for downstream water level. Linear Quadratic Regulator control (LQR) requires a model of the entire canal consisting of all water level deviations and control interactions (Clemmens et al. 2005). It includes the development of a matrix, with an objective function that allows the user to minimize negative effects of large flow or water level changes. Implementation of LQR requires an excellent knowledge of instantaneous flow rates in/out of a canal, and water levels, all combined into a model that properly relates those interactions.

Others have proposed a distributed model predictive control of irrigation canals, focusing on the model predictive control (MPC) usage in a distributed control system, in which each controller employs MPC to determine the control actions that maintain water levels after disturbances to obtain the system-wide multiple-variable optimum performance. Negenborn et al. (2009) described the use of a serial, iteration-based, distributed MPC scheme for a seven-pool open irrigation canal system and presented the simulated graphs of water level set points and water level deviations. MPC has a special feature that accounts for limitations in check structure flows.

Event-driven hierarchy control, as examined by Sadowska et al. (2014) for the CCID Main Canal as part of this research that was not implemented, explored a more theoretical approach on rapid flow change delivery. A higher-level, centralized controller was introduced. Other approaches to rapid routing have included that of Kang (2014) that views an irrigation canal as a multivariable system and uses optimal control. Diamantis et al. (2011) proposed a form of adaptive control, and van Overloop et al. (2005) proposed a multiple-model optimization method.

CCID Canal Description
The Central California Irrigation District (CCID) service area encompasses approximately 56,700 hectares (140,000 acres) with an irrigated area of 48,600 hectares (120,000 acres) in the central San Joaquin Valley, with the district headquarters in Los Banos, California. The CCID Main Canal is 104.6 km (65 miles) long with a capacity of 45.3 m³/s (1600 CFS). The Main Canal is split into two control systems: the Upper Main Canal is approximately 64.4 km (40 miles) long with nine check structures, controlled by automatic upstream water level control; the Lower Main Canal is 40.2 km (25 miles) long with eight check structures, controlled by an automatic downstream water level control system (see Fig. 1). An additional 9.3 km (5.8 mile) canal segment (pool) links the Upper and Lower Main Canal systems. At km 73.8 (MP 45.8), a 0.25 Mm³ (200 acre-feet) regulating reservoir (Ingomar Reservoir) was constructed. It utilizes automated gravity-inlet gates and VFD-controlled outlet pumps.
The types of gates and the gate dimensions for the check structures in the CCID Upper Main Canal are listed in Table 1. Each automated gate site is equipped with a district-standard Remote Terminal Unit (RTU) that runs modified PIF (Proportional-Integral-Filter) control algorithms, designed by the Irrigation Training & Research Center (ITRC) at Cal Poly San Luis Obispo, in a SCADAPack controller. The specific PIF control algorithm and optimized control constants for each gate were determined via ITRC’s optimization program, which takes into account resonance and storage, and tunes the constants for all pools simultaneously.
Table 1. Gate types and dimensions in CCID Upper Main Canal

<table>
<thead>
<tr>
<th>Check #</th>
<th>Check Name</th>
<th>Station, km</th>
<th>Type of Gate(s)</th>
<th>Function</th>
<th>Approx. Freeboard, m</th>
<th>Design Flow, m³/s</th>
<th>Test Initial Flow³, m³/s</th>
<th>Average Velocity During Test, m/s</th>
<th>Bottom Slope</th>
<th>Average of Wetted Perimeter, m</th>
<th>Top Width, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Three Mile</td>
<td>5.28</td>
<td>Radial</td>
<td>USA¹</td>
<td>1.0</td>
<td>43.0</td>
<td>5.78</td>
<td>0.2</td>
<td>-0.00010</td>
<td>26.23</td>
<td>25.6</td>
</tr>
<tr>
<td>2</td>
<td>Firebaugh</td>
<td>12.09</td>
<td>Radial</td>
<td>USA²</td>
<td>0.8</td>
<td>40.8</td>
<td>4.42</td>
<td>0.2</td>
<td>0.00023</td>
<td>20.3</td>
<td>18.6</td>
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<tr>
<td>3</td>
<td>Parsons</td>
<td>17.97</td>
<td>Radial</td>
<td>USA²</td>
<td>1.0</td>
<td>38.5</td>
<td>2.97</td>
<td>0.2</td>
<td>0.00015</td>
<td>19.5</td>
<td>17.9</td>
</tr>
<tr>
<td>4</td>
<td>China</td>
<td>24.37</td>
<td>Langemann</td>
<td>USA²</td>
<td>0.3</td>
<td>36.2</td>
<td>1.10</td>
<td>0.1</td>
<td>0.00005</td>
<td>27.1</td>
<td>26.0</td>
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<tr>
<td>5</td>
<td>Redfern</td>
<td>27.77</td>
<td>Langemann</td>
<td>USA²</td>
<td>0.7</td>
<td>34.0</td>
<td>0</td>
<td>0.1</td>
<td>0.00009</td>
<td>22.1</td>
<td>21.3</td>
</tr>
<tr>
<td>6</td>
<td>Oro Loma</td>
<td>30.70</td>
<td>Langemann</td>
<td>USA²</td>
<td>0.3</td>
<td>31.7</td>
<td>0</td>
<td>0.1</td>
<td>0.00017</td>
<td>21.5</td>
<td>20.5</td>
</tr>
<tr>
<td>7</td>
<td>Camp 13</td>
<td>40.66</td>
<td>Langemann</td>
<td>USA²</td>
<td>1.0</td>
<td>29.5</td>
<td>1.21</td>
<td>0.2</td>
<td>0.00001</td>
<td>16.7</td>
<td>16.0</td>
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<tr>
<td>8</td>
<td>Mason</td>
<td>53.81</td>
<td>Langemann</td>
<td>USA²</td>
<td>0.3</td>
<td>27.2</td>
<td>0</td>
<td>0.1</td>
<td>-0.00001</td>
<td>21.5</td>
<td>20.9</td>
</tr>
<tr>
<td>9</td>
<td>Town</td>
<td>57.33</td>
<td>Langemann</td>
<td>USA²</td>
<td>0.3</td>
<td>24.9</td>
<td>0</td>
<td>0.1</td>
<td>0.00025</td>
<td>21.7</td>
<td>21.0</td>
</tr>
<tr>
<td>10</td>
<td>Volta</td>
<td>65.25</td>
<td>Langemann</td>
<td>USA²</td>
<td>0.3</td>
<td>22.7</td>
<td>0</td>
<td>0.1</td>
<td>0.00011</td>
<td>25.4</td>
<td>24.8</td>
</tr>
</tbody>
</table>

1) Manual Upstream Control. No changes during the test.
2) Automated Upstream Control
3) "Test Initial Q" varies at some sites from 5.78 to zero during the one-hour period before the test

Discrepancies between inflows and outflows of the Lower Main Canal System are buffered by the Ingomar Reservoir, which sits between the Upper and Lower systems and is used for two purposes: to buffer the excess flow coming from the Upper Main Canal system, and to temporarily provide the necessary extra flow for the Lower Main Canal system when there is not enough flow coming directly from the Upper Main Canal system. When the water level in the Ingomar Reservoir drops below a certain level (or increases above another target level), the operator will release more flow (or reduce the flow) at the headworks of the Main Canal in order to adjust the reservoir volume. Ideally, the flow changes made at the headworks should reach the reservoir as quickly as possible.

Simulated Typical Flow Rate Adjustment
In CCID, when a flow rate increase is made at the head of the Main Canal, the flow rate change typically moves gradually down the canal through the Upper Main Canal system via automated check structures (upstream control) until it reaches the Ingomar Reservoir at Mile Post (MP) 45.8. Automated upstream control is type of a local feedback control, although in the case of CCID the actual control is distributed because although the individual check structure PLCs operate independently, they can be remotely monitored and operated, and target water levels can be changed remotely.

The simulations described in this paper were conducted with ITRC’s modified CanalCAD unsteady flow simulation program. ITRC used that program/model, plus a proprietary program to characterize resonance and storage, and another program to determine the original check structure PIF control constants in 2006. Those original PIF control constants, plus various heuristic logic, have been used on the complete Main Canal since then. The PIF control constants, and gate types and dimensions, are different for each check structure in the upstream and downstream controlled sections of the canal.

As a note of technical interest - ITRC’s field experiences have shown that simulation timesteps of as little as 3 seconds, but typically 10 seconds, are necessary to accurately identify resonance problems when testing new controls on canals. Conversations by the senior author with various canal modelers indicate that others use much longer timesteps for simulations.
Graphs showing the simulated results for this current mode of operation, under low flow conditions, are provided in Figs. 2 and 3 simply to provide readers more familiarization with the canal. Fig. 2 shows the total flow at the head of the canal (left) and the changes in flow at the head and end of the Upper Main Canal system (right). As is evident in Fig. 2, a change made at the head first appears at the end of the canal five hours after the change was made; it takes another eleven hours for the flow rate change to completely arrive at the end of canal and stabilize. A low flow condition is used as a simulation example here because the actual field verification of the new control logic was conducted in a low flow condition. Fig. 3 shows the simulated water level and gate positions at all check structure sites. Table 2 lists the headworks inflow and turnout outflow used in the simulations and field test.

**Fig. 2.** Simulation graphs of flow (left) and change in flow (right) at the head and most downstream check (Check 10) of the Upper Main Canal using a typical approach.
Fig. 3. Simulation results for all check structure sites along the Main Canal using a typical approach
Table 2. Headworks inflow and turnout outflow used in the simulations and field test

<table>
<thead>
<tr>
<th>Time</th>
<th>Simulation Flow Rate</th>
<th>Field Test Flow Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Headworks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>5.95 m^3/s 210 CFS</td>
<td>5.80 m^3/s 205 CFS</td>
</tr>
<tr>
<td>Hour 0</td>
<td>10.19 m^3/s 360 CFS</td>
<td>10.05 m^3/s 355 CFS</td>
</tr>
<tr>
<td>Hour 3</td>
<td>8.78 m^3/s 310 CFS</td>
<td>8.64 m^3/s 305 CFS</td>
</tr>
<tr>
<td>Total flow rate of all turnouts</td>
<td>Unchanged</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.83 m^3/s 100 CFS</td>
<td>7.36 m^3/s 260 CFS</td>
</tr>
<tr>
<td>Flow increase at Check 10 when stabilized</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.83 m^3/s 100 CFS</td>
<td>2.83 m^3/s 100 CFS</td>
</tr>
</tbody>
</table>

1) The flow rate at Headworks was estimated using the rated cross section.
2) The total of turnout flow rates was based on farmer orders; it was not verified at each of the turnouts.
3) The flow rate through Check 10 when stabilized was calculated using the weir equation; the flow increase at Check 10 was calculated using the weir flow minus the initial flow at Check 10.

Simplified Rapid Flow Rate Routing Procedure

General
A simplified rapid flow rate routing was developed using a flow rate control approach to expedite the flow rate change delivery. This process needs no modeling of the canal prior to each implementation event, assuming that the real-time conditions of each check structure (width, opening, and head difference) are known. Turnout (offtake) flow rates do not need to be known. The check structure gate widths, openings, and head differences are commonly monitored SCADA parameters with automated upstream control systems.

The rules for implementing this technique, for various flow rate conditions and flow rate changes, should be determined through advance simulation. That simulation does not need to be repeated once the rules have been established. The nature of the simplified rapid routing procedure is such that it is unnecessary to be precise with the changes that are made.

The flow rate control was implemented by switching all gates to remote manual mode and adjusting the gate positions to make one desired flow rate change. The gates were left in remote manual mode for the flow control period of three hours, which is about three times as long as it takes the delay for the wave (van Overloop et al. 2010) to travel in the longest pool. This dampens the wave, allowing it to travel down and up and down again within a CCID pool.

During this flow control period, the desired initial flow rate change can be obtained in each pool. Extra flow (greater than the desired steady-state increase in flow) was introduced at the head for several hours to compensate for increased wedge storage.

Simulation
Simulations were conducted to obtain estimates of the extra flow needed (and for how long) to compensate for the water level dropping in each pool when making a 2.83 m^3/s (100 CFS) increase in flow rate control through the canal. Simulations showed that an extra 1.47 m^3/s (50 CFS) for three hours was sufficient. After the three hour flow control period in remote manual mode at all sites, the flow into the head of the canal was reduced by the extra 1.47 m^3/s (50 CFS).
and all check structures were returned to automation mode to maintain local upstream water level control.

Simulation results showed that once the automation mode was reinstated, several of the most downstream gates moved so much that almost no flow was allowed to pass those gates. To solve this, the simulated control added movement limits on all gates for a period of time after automation was reinstated. Gate movement was restricted to no more than 0.061 m (0.2 foot) above (note that these are Langemann gates, which move upwards to raise the upstream water level) the position just before automation was reinstated. There were no limits to the downward movement after the automation was turned back on. The movement limits were removed at 18 hours.

Simulation results are seen in Figs. 4 and 5. Fig. 4 shows that almost immediately after the flow rate change is made at the head and the adjustments are made to the last check, the end of the canal obtains approximately 60% of the expected flow change, and the full flow rate change completely arrives in about eleven hours. Fig. 5 shows that all the upstream water levels are maintained within an acceptable range during this period.

**Fig. 4.** Simulation graphs of flow (left) and change in flow (right) at the head and most downstream check (Check 10) of the Upper Main Canal using the accelerated routing procedure
Fig. 5. Simulation results for all check structure sites along the Main Canal using the accelerated routing procedure.
Field Test
For the rapid flow rate change field test, the intent was to deliver the entire flow rate change all the way to Ingomar Reservoir, rather than diverting portions of the change to the lateral canals along the Upper Main Canal. Operators were asked to not make any changes to the lateral canal inlet flow rates between the Mendota Pool and Ingomar Reservoir during the test.

The rapid flow rate change field test required the ability to accurately change the flow through each check structure along the Upper Main Canal. Therefore, the following items were verified before the field test:

- The values of the gate position, upstream and downstream water levels shown on the ClearSCADA HMI were verified as corresponding to the actual gate openings and staff gauge readings.
- The flashboard heights at the sides of each automated gate in the check structures between Mendota and Volta were checked to ensure that there was no flow over the flashboards during the test.

The preparations before the start of the field test included the following:

- The flows at the turnouts along the Upper Main Canal were obtained from the district, for later simulation runs.
- The flows into and out of the Upper Main Canal were obtained from the district.
- The instantaneous values for checks between Firebaugh and Volta were obtained via SCADA:
  - Gate UP/DOWN soft limits
  - Upstream and downstream water levels
  - Gate positions
- With a spreadsheet program the following were computed:
  - The flows through each check structure
  - The new gate positions to net an increase in flow of 2.83 m³/s (100 CFS) through each check structure
- All automated checks from Firebaugh to Volta were switched to remote manual mode via SCADA.
- At time zero,
  - The flow rate at the canal entrance was increased by 4.25 m³/s (150 CFS).
  - All gates were given their new target positions to pass an additional 2.83 m³/sec, which was accomplished within about 12 minutes.
- The gate soft UP limits (to be used in the control code once automatic upstream control was reinstated) were temporarily increased to +0.061 m (+0.2 ft) above the new position.
- Three hours after the start of the test, the flow rate into the canal was reduced by 1.42 m³/s (50 CFS), to 2.83 m³/sec.
- All check structures were then switched back into automation mode.
- When the test was over (about 18 hours after the first flow rate change was made at the head of the canal) the gate movement limits for all check structures were returned to their original settings.

After the field test, the data was collected from the office SCADA server. Results are presented in graphs in Figs. 6 and 7. Fig. 6 shows that the end of the canal obtained 70% of the expected
flow change right after the flow rate change was made at the head of the Main Canal, and the full flow rate change arrived about seven hours later.

Fig. 6. Field test data of flow (left) and change in flow (right) at the head and most downstream check (Check 10) of the Upper Main Canal using the accelerated routing procedure.
Fig. 7. Field test results for all check structure sites along the Main Canal using the accelerated routing procedure.
Results and Discussion

The simulations showed a fast routing of a flow change from the beginning of the canal to the regulating reservoir. The water levels were also controlled well. We know that the simulation program provides relatively accurate results, based on previous work.

One small note is that according to the simulation graphs, when the new method was implemented, the flow rate changes at all check structures were almost immediate after the flow rate change was made at the head gates. In the field, a delay was caused by the time it took to make manual adjustments to the gate positions via the SCADA system in the trial.

The major observation, however, is that there are substantial differences between the field test results and the simulation results. Upon examining the field data, two things become evident:

1. The Upper Main Canal was in a deficit flow condition when the test was started. The total turnout flow rates were about 1.6 m³/s (55 CFS) more than the inflow rate. A re-creation of the initial condition showed that the field test started from a deficit flow condition with a headworks flow of 5.8 m³/s (205 CFS) and total of turnout flow of 7.36 m³/s (260 CFS) at the start of the test. The impact can be seen in Fig. 7 at time zero: five overshot check structures were out of water with no flow going by, and the water level at Check 8 (Mason) was already about 0.15 m (0.5 feet) below the target.

2. The canal was in an unsteady state; gate positions had been continually changing for at least a half-day before the test was started. This was in spite of discussions before the test regarding an attempt to achieve a steady state condition before the field trial. The reality in the field is that the irrigation district cannot easily manipulate a canal and stop regular operations to meet ideal conditions for a test.

There are many additional possible explanations for the differences one could see between actual initial conditions for a field test and the anticipated initial conditions. These include:

1. Turnout flow measurement (possibly ±12%) error.
2. Flow rate measurement error at the headworks. The flow rate is measured at a rated section, which is influenced by canal roughness. The canal pool is also quite long and several hours are required for the water level to stabilize after a change in flow rate.
3. Start and stop times of turnout flow rate changes are likely rounded to the nearest 10 minutes or half hour.
4. Gate position errors (estimated ±10% for radial gates, ±2% for Langemann gates). Radial gate positions in the CCID Upper Main Canal are not calibrated as frequently as the Langemann gates.
5. Seepage and evaporation losses. The uncertainties relating to these are very small.

The five items above are commonly discussed in terms of instantaneous values. The fact is that in this canal, as with most irrigation canals in the western U.S. that provide flexible deliveries, the canal is almost never in a steady state hydraulic condition. In other words, the initial conditions for real-time hydraulic model simulation/control are almost never accurately known throughout the canal.
One might question why the field test proceeded once it became obvious that the initial conditions were very undesirable. The answers are:

1. It is very difficult to arrange for an experiment on a large working canal. The district needs to make deliveries, and actions need to be coordinated with many people. The test was scheduled after waiting almost a year for an opportunity to conduct the test.

2. A fundamental belief of the authors is that a routing technique that requires real-time modeling with an excellent definition of flows and conditions is impractical. Field implementation is completely different from the ease of performing simulations. The routing that was tested here was intended to work reasonably well in spite of not knowing all the instantaneous hydraulic parameters of the canal. We wanted to know if that would prove to be the case.

In the field, the flow rate stabilization time at the end of the canal was less than one hour after the gates were switched from remote manual mode to automation (after 4 hours, total). This is comparable to a total of 16 hours during regular operation. There was a definite improvement.

The water level changes throughout the system were also held to a minimum: less than 0.076 m (0.25 ft) on average. In general, the water levels were maintained very close to their targets throughout the experiment. However, measurable drops in the water level were noted between the Oro Loma, Camp 13, and Mason check structures, caused by insufficient flow at the Redfern, Oro Loma, and Mason check sites. The upstream level had already dropped below the target set points during the start of the test. Table 3 lists the maximum water level deviations recorded during the experiment.

<table>
<thead>
<tr>
<th>Check #</th>
<th>Check Name</th>
<th>Max. drop in pool water level upstream of check (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Firebaugh</td>
<td>0.06 m (0.2 ft)</td>
</tr>
<tr>
<td>3</td>
<td>Parson</td>
<td>0.03 m (0.1 ft)</td>
</tr>
<tr>
<td>4</td>
<td>China</td>
<td>0.09 m (0.3 ft)</td>
</tr>
<tr>
<td>5</td>
<td>Redfern</td>
<td>0.02 m (0.08 ft)</td>
</tr>
<tr>
<td>6</td>
<td>Oro Loma</td>
<td>0.09 m (0.3 ft)</td>
</tr>
<tr>
<td>7</td>
<td>Camp 13</td>
<td>0.15 m (0.5 ft)</td>
</tr>
<tr>
<td>8</td>
<td>Mason</td>
<td>0.20 m (0.66 ft)</td>
</tr>
<tr>
<td>9</td>
<td>Town</td>
<td>0.06 m (0.2 ft)</td>
</tr>
<tr>
<td>10</td>
<td>Volta</td>
<td>0.02 m (0.08 ft)</td>
</tr>
</tbody>
</table>

Certainly, the procedure can be improved beyond what was tested. For example, better results might be obtained if all gates are moved sufficiently to pass the desired flow rate change to reach the end, plus the sum of all downstream wedge storage compensation flow rate changes.

**Conclusions**

1. The simplified rapid flow rate change method can significantly expedite flow rate change delivery.
2. The simplicity of the general principles used was the key to success.
3. Complicated real-time simulation inputs would have been incorrect. The flows within a real system are not accurately measured, there are multiple uncertainties, and the flows are continually in an unsteady state.

4. It is very valuable to use simulation models for the development of rules for rapid routing.

Acknowledgements

Support for this research was provided under CSU ARI Project #47852. The writers gratefully acknowledge CCID staff for their support in planning the field test and the use of their ClearSCADA workstation to operate and monitor the Upper Main Canal system.

References


