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Improved Real-Time Control of Water Deliveries Through Decoupling

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Abstract
Real-time control of water level regulators allows for flexible and reliable water deliveries. Rigid control systems are still found due to both non-recognition of the need for flexibility and to the lack of technology for implementation. The technical problems are addressed in this paper. Two existing control algorithms, ELFLO and CARDD, were evaluated, using scale model and computer simulation performance tests. It turned out that both controllers have to be tuned with a tedious "trial and error" procedure. A new controller, a combination of ELFLO and a decoupler, which eliminates interactions, was designed and tested on the scale model canal. It is concluded that the new controller performs better than existing ones and is more easily tuned.

1 Introduction

Irrigation canal systems are very often designed for *upstream control* with the effect that gates along the canal must be continually adjusted to maintain desired water levels. Moreover, careful scheduling of water releases is needed to avoid water spillage or shortage downstream. Automation of the water level regulators along the canal solves the problem of continually adjusting these gates, but careful scheduling of water releases is still needed.

To solve this latter problem *downstream control* can be effective. The advantage of this control method is that the parent canal system becomes *self-regulating* concerning water demands. Self-regulation of the parent canal implies that the inflow is automatically adjusted to match the demand of the offtakes plus leakage losses. Needless to say that control of the offtake demands is still required, especially in periods of water shortage.

Several real-time canal control methods have been developed to make irrigation canals self-regulating. One of them is *regional* downstream control: the water levels at the downstream end of every pool, (also called: canal reach), are controlled by manipulating its upstream gate. The desired or target water

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level is called the setpoint. Regional downstream control has an important advantage. By using regional downstream control the embankments can be kept parallel along the canal bottom, in contrast to *local* downstream control. This feature makes regional downstream control an attractive control method, especially to convert upstream controlled canals into self-regulating canals, because no major canal-hardware modifications are required.

Little experience is available on the performance of regional downstream controllers. In January 1991 a study was formulated in which the Delft University of Technology, department of Civil Engineering and the department of Mechanical Engineering and Marine Engineering, cooperated with the California Poly Technical University. The aim of the study was to investigate the performance of regional downstream control algorithms and, if possible, to develop an improved control algorithm. For this study a mathematical simulation model and a physical scale model were jused in conjunction. This paper describes the findings of the study.

2 Dynamic properties of flow in the Cal Poly Canal and their impact on real-time control

For this research the Cal Poly canal scale model was used. The Cal Poly canal consists of 6 pools in cascade, all equal in length (≈ 30 meter) and shape (trapezoidal with a bottom width of 0.07 m and a side slope of 1 horizontal : 6 vertical), (Fig. 1). At the downstream end of each pool an offtake is present. The connection between the pools is fitted with operable sluice gates.

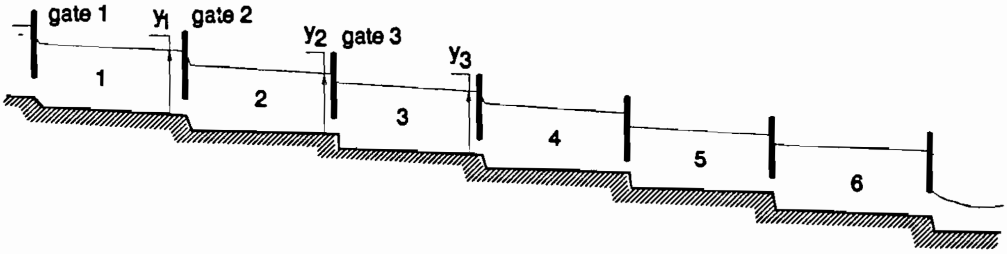

Fig. 1 *Schematic side view of the Cal Poly Canal.*

Figure 2 shows the response of the water levels on a sudden change of gate 2 under respectively low flow rate and high flow rate conditions. From these two tests several conclusions can be drawn.

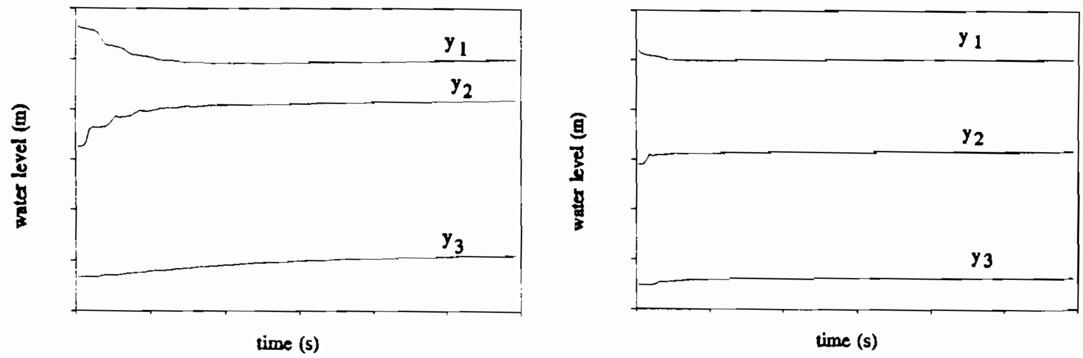

Fig. 2 *Simulated response of the downstream water levels y_1, y_2 and y_3 on a sudden opening of gate 2 of 1.0 cm. To the left: initial flow rate: 0.01 m3/s; to the right: initial flow rate: 0.07 m3/s.*

The responses differ considerable under different flow conditions. This shows that the system is very *non-linear*. In control theory linearity is often assumed. The control theories for non-linear systems are quite under-developed and thus designing a control algorithm for a non-linear system is a more difficult task than designing one for a linear system. A control algorithm, designed with the aid of linear system theory must be evaluated carefully.

In spite of the non-linearities a general describtion about the response can be given. As soon as the gate is opened two steep *surge waves* arise, a positive one travelling downstream, end a negative one travelling upstream. After some time the surge waves reach the upstream, respectively downstream end of the pool, reflect against the gate and start to travel back and forth. This causes the staircase forms in the responses. Eventually the surge waves dampen out and fade away, the rate of damping and reflection of the wave depending on flow conditions. The problems caused by the steep waves and possible solutions have been analyzed in (Shand 1971), (Buyalski 1976) and (Schuurmans 1991). Briefly stated, the steep wave limits the gain factor of the controller considerably, causing sluggish control. One solution to this problem is to apply filtering on the measured signals, so that the controller does not "see" the steep waves anymore.

Another important dynamic property is the so called *interaction*. The sudden opening of gate 2 does not only affect the water level downstream of that gate, but also other water levels. Therefore, it is said that the system shows interaction. A system showing interactions, can often not be controlled satisfactory with local feedback controllers, (i.e. completely decentralised controllers). As it turned out that this was also the case for the Cal Poly Canal, extra attention to this phenomena will be given here.

Theory about interaction and decoupling

First it will be explained why application of local controllers on a system, showing interactions, causes problems. Then, a solution to this problem, known from control theory, will be presented.

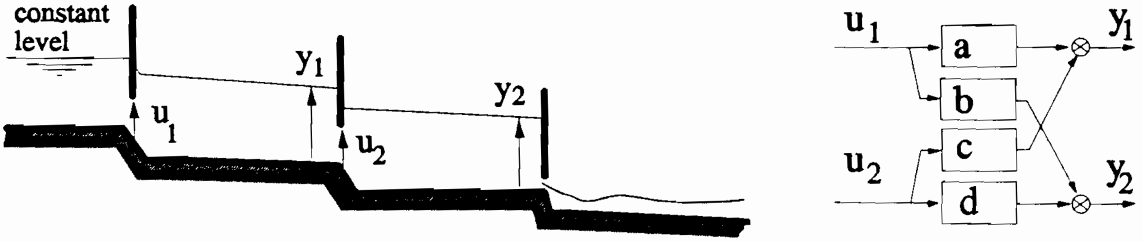

Fig. 3 Canal with two gates and a blockdiagram of that canal.

Figure 3 shows a canal with two gates and a blockdiagram of this canal. The letters in the blocks represent transfer functions. The inputs of the model are the openings under the gates and the outputs of the model are the water levels at the downstream ends of the pools. When applying one local feedback controller on gate 1, (Fig. 4 A]), the loop transfer function in loop 1 equals, (eq.1):

$$a \cdot co_1 \tag{1}$$

The loop transfer function completely determines the degree of stability of the closed loop system. If also gate 2 is controlled by a local feedback controller, Fig. 4 B], the loop transfer function of loop 1 changes to, (eq. 2):

$$\left[a - \frac{b\ c}{d+1/co_2}\right] \cdot co_1 \tag{2}$$

The change in loop transfer function is caused by the, so called, "hidden" feedback loop formed by

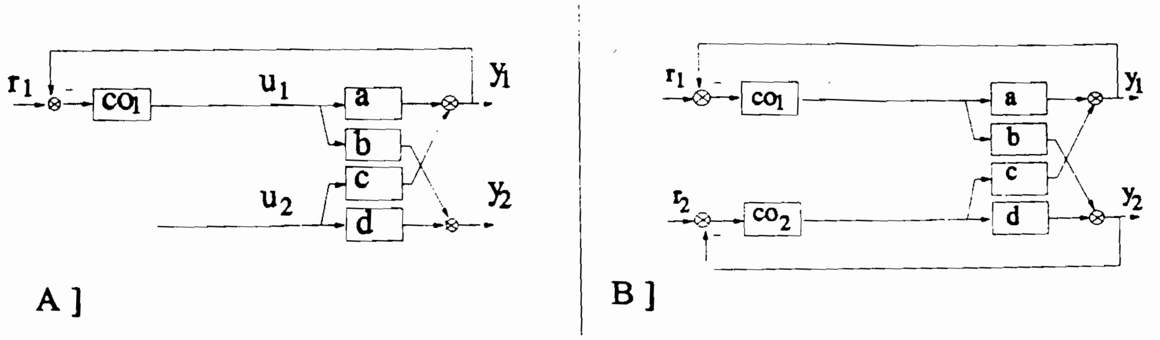

Fig. 4 *Local feedback on gate 1 only, A], and local feedback on both gate 1 and 2, B]. By closing the second loop the closed loop properties in loop 1 change, see text.*

the two feedback controllers. Depending on the system dynamics, the hidden feedback loop can cause extra phase lag, making it necessary to change the control parameters; in particular the proportional gain, which must be decreased. This results in sluggish control, (i.e. slow behaviour). Furthermore, little help is available in adjusting the control parameters.
The effects of interaction have been analysed, among others, by (Shinskey 1979).

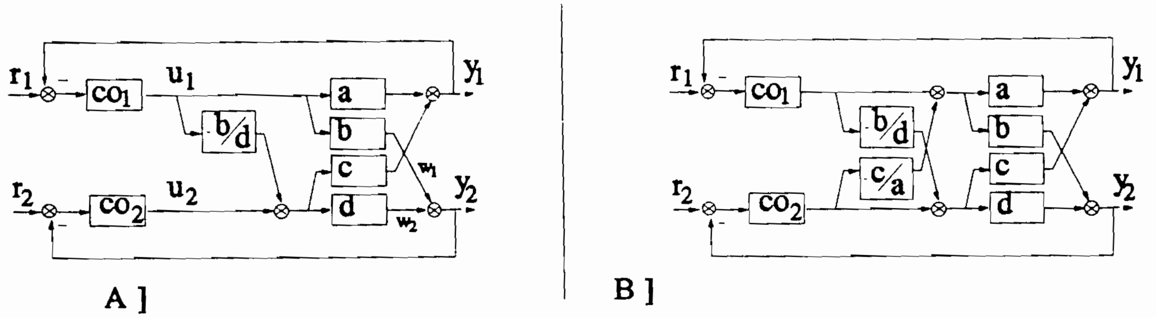

Fig. 5 *Partial decoupling, (A), and complete decoupling, (B). Both methods avoid the interaction problem.*

One way to compensate for interactions is to extend the local feedback controllers with a decoupler. Basically two kinds of decouplers exist: the partial decoupler and the complete decoupler. Figure 5 A] shows the principle of the partial decoupler. The interaction from loop one to loop two has been eliminated, which can be understood by considering the signals w_1 and w_2. Because $w_1 = b \cdot u_1$ and $w_2 = d \cdot -\frac{b}{d} \cdot u_1$, the sum of w_1 and w_2 equals zero.

The interaction from loop two to loop one still exists and signals can enter loop one, but they cannot return. Therefore, it can be stated that partial decoupling avoids the hidden feedback loops, which are formed by the two feedback controllers.

If the interaction from loop two to loop one is also eliminated, the decoupler is said to be complete, Fig. 5 B].

By taking into account the dead times of the dynamics, some interesting conclusions about the application of decouplers in canals can be posed. Decomposing the transfer functions a, b, c and d in dead times and remaining dynamics, (the latter characterised with '.' subscripts), the transfer functions, written in the Laplace variable s, become, (eq. 3):

$$\begin{aligned} a &= e^{-\tau_u s} \cdot a_* \\ b &= e^{-(\tau_u + \tau_d)s} \cdot b_* \\ c &= c_* \\ d &= e^{-\tau_d s} \cdot d_* \end{aligned} \tag{3}$$

The dead times τ_v are approximately equal to $\dfrac{L}{Q/A + \sqrt{g \cdot a}}$, in which L is the distance between the water level and the gate, Q is the flow rate, A is the mean surface of the wetted cross section and a is the mean depth of flow. This formula follows immidiately from the fact that the head of a wave, travelling in direction of flow, travels with the critical celerity plus the mean velocity of flow.
The transfer functions of the decouplers, as depicted in Figure 5, become, (eq. 4 and 5):

$$-\frac{b}{d} = -\frac{e^{-(\tau_u + \tau_d)s} \cdot b_*}{e^{-\tau_d s} \cdot d_*} = e^{-\tau_u s} \cdot \frac{b_*}{d_*} \tag{4}$$

which is a causal relation and thus implementable, and:

$$-\frac{c}{a} = -\frac{c_*}{e^{-\tau_u s} \cdot a_*} = e^{+\tau_u s} \cdot \frac{b_*}{d_*} \tag{5}$$

which is not implementable in this dynamical form, because of its non-causality. It can however be implemented in a static form, but, in that case, sufficient elimination of interactions can not be quaranteed anymore.

Decoupling for canals with more than two pools

In general the design of decouplers for a multivariable system with more than two in- and outputs becomes quite complex. However, for canals, it is not necessary to take all interactions into account. This is due to the particular structure of interactions in a canal. The interactions in a canal go via one pool to another. If the interaction between a pool and both its upstream and downstream neighbour pool is eliminated, the interactions between that pool and *all* other pools are eliminated. Thus, if for *each* pool the interactions between both its upstream and downstream neighbour pools are eliminated, the whole canal system is decoupled completely.

If, for each pool, the interaction with its downstream neighbour is eliminated, the whole canal is partially decoupled, and interactions in only one direction are left. As discussed before, decouplers eliminating interactions in the downstream direction are realisable dynamically. In this article experimental results with this manner of decoupling will be presented.

Summarized, three dynamic properties of the flow in the Cal Poly Canal complicate real-time control: non-linearities, steep waves and interactions. In literature it can be found how to deal with the steep (reflecting) waves. However, about non-linearities and interactions, little can be found in literature. As it turned out during the investigations, that interactions limited the performance of local feedback controllers considerably, a simple solution to the interaction problem, known from control theory, was applied.

3 Experimental results with CARDD, ELFLO and ELFLO plus Decoupler

Two control algorithms, known from literature were tested on the Cal Poly Canal, those were CARDD and ELFLO. Both controllers were developed in the USA. First, they will be briefly discussed here.

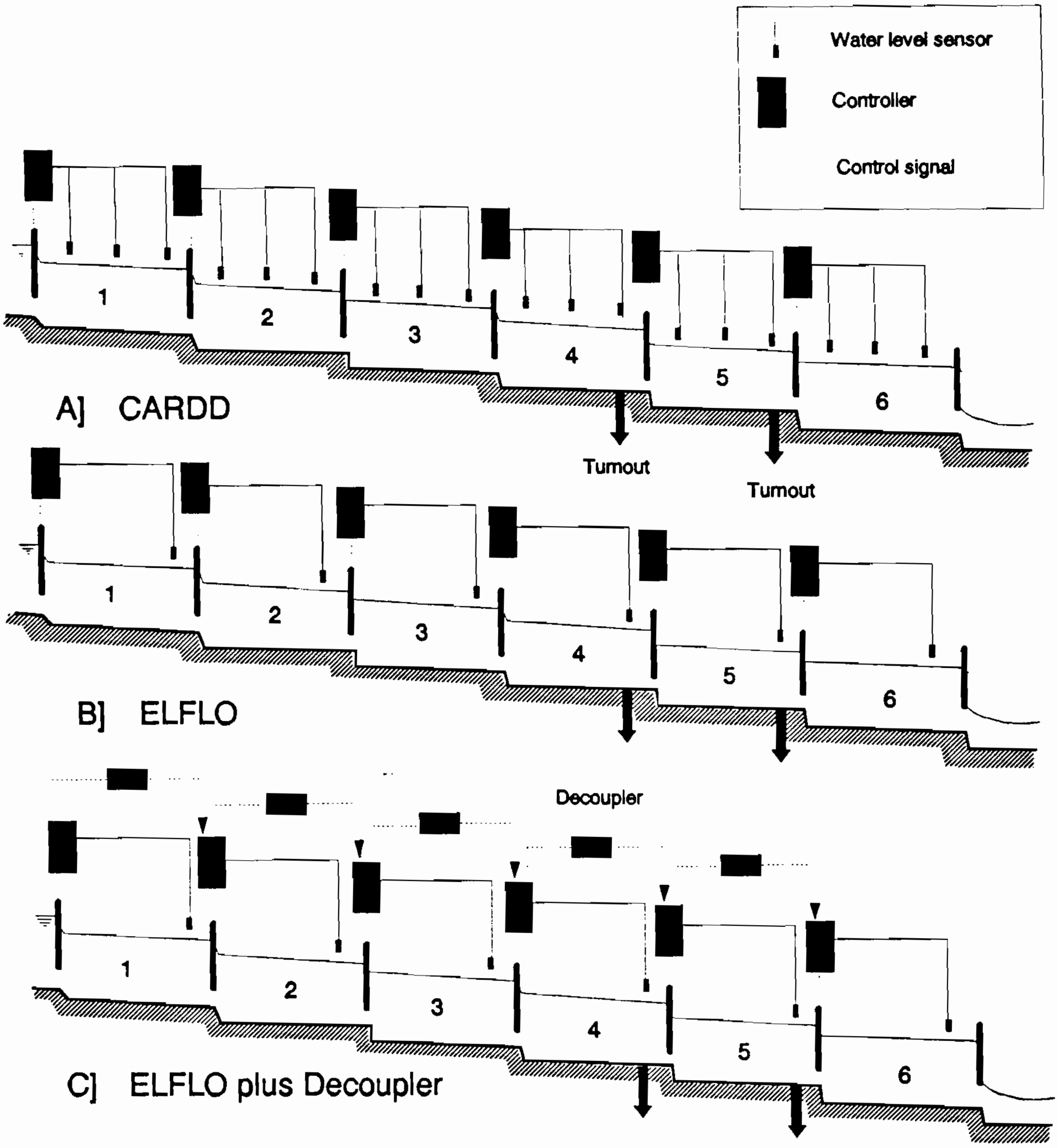

Fig. 6 Schematic representation of three regional downstream controllers

The Canal Automation for Rapid Demand Deliveries (CARDD) controller was developed by Burt (Burt, 1989) and is heuristic. It is based on "physical interpretation" of changing water level slopes. The controller needs three water level sensors per pool (Fig. 6A). Out of these levels the variations of the mean and downstream water level are calculated. Depending on these variables five cases are distinguished with different gate actions for positive and negative deviations from the target water level. If, for example, the deviation is negative (water level is above setpoint) and both the mean and downstream water level are rising, CARDD commands the upstream gate to close rapidly to reset the water level on setpoint. The CARDD control algorithm includes 11 control parameters, all of which have been tuned by "trial and error" using a computer simulation programme. It is claimed that all of them, but one, can be kept constant for any canal system, provided that the canal bottom is not too steep. To test the CARDD controller the Cal Poly Canal was built in California, USA. So far, CARDD control has not been applied on full scale irrigation canals.

The Electronic Filter Level Offset plus Reset (ELFLO) controller was developed by the University of California at Berkeley, (Harder et al., 1972), (Fig. 6C). The sensor of each individual controller is located at the downstream end of a pool and the monitored level is transmitted to the gate located upstream of that pool. The controller exists of a combination of a low pass filter, to filter the steep waves, and a conventional Proportional Integral (PI) controller. In California ELFLO control has been applied successfully on the Coalinga canal and the Corning Canal, both situated in California.

The tests

Various closed loop experiments were carried out to investigate the performances of these two control algorithms. The most severe tests are those whereby the closed loop system becomes extra non-linear. This extra non-linearity occurs when the gates reach their limits of opening.

The performance of the controller is expressed by two indicators: the maximum deviation of the water level above setpoint, and the mean offset. The first indicator specifies the embankment height above setpoint and the latter indicates the disturbance in offtake discharge as a result of water level fluctuations in the parent canal.

The most severe experiment carried out on the Cal Poly Canal was the one whereby an initial low flow condition was suddenly disturbed by a relative large flow extraction at the downstream end of the canal. Many gates remained completely opened during the period of active control.

The initial flow conditions were, steady state, discharge of 0.009 m^3/s (= 10 % of Qmax), and all downstream water levels on setpoint. Then, at t = 10 seconds, the turnouts of pool 4 and 5 were suddenly completely opened and, at t = 800 seconds ($\approx$ 13 minutes), the same turnouts were suddenly closed again. The controlled downstream water levels were monitored during the experiment and are depicted in Figure 7 and 8 for CARDD and ELFLO respectively.

General description of the response

The extraction of flow caused the water levels to drop below setpoints. To raise the water level, the controller commanded the upstream gate to open to increase the inflow. This, in turn, caused a drop of the water level in the upstream pool, as water was extracted to correct the downstream water level offset. This process continued for all pools until the most upstream one was reached and additional flow was supplied from the intake reservoir. The closure of the offtakes caused the opposite effect. The water levels raised, and, one by one, the gates closed in an attempt to reduce the offset until the most upstream gate closed and the intake from the reservoir reduced.

CARDD

The results of the experiments, (Fig. 7), show that CARDD functions well in this experiment. The large fluctuations in pool 3 are a result of the CARDD controller which tries to keep the gate in contact with the flow. The small amplitude fluctuations (especially after closing the gates) are caused by the steep waves travelling back and forth with critical celerity.

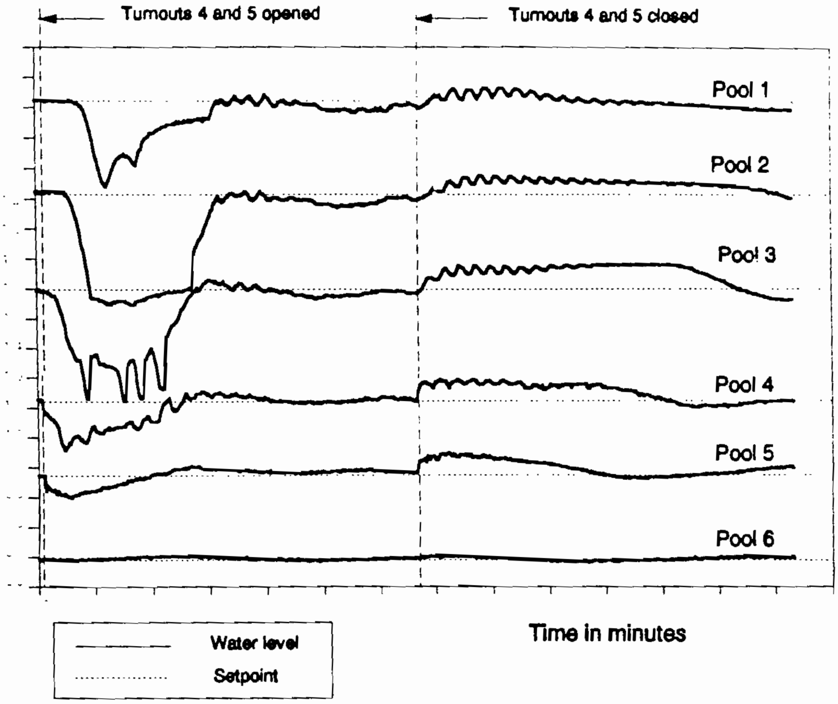

Fig. 7 Test results with CARDD applied to the Cal Poly Canal. $Q_{t=0\,s} = 0.009$ m^3/s.

ELFLO

In comparison with CARDD, ELFLO control performs a little worse, for this particular canal, (Fig. 8). The performance in pools no. 5 and 6, however, is better. In these pools the ELFLO controllers were tuned with higher proportional gains than in the other pools. In the more upstream pools the gains had to be so much lower due to the interaction problem, that CARDD performed better in the upstream pools. Therefore, a control algorithm, in which the local feedback controllers, (ELFLO), were extended with decouplers was implemented and tested.

ELFLO plus Decoupler

Two partial decouplers were tested, one which eliminated the interactions in upstream direction and one which eliminated the interactions in downstream direction. In both cases, the decouplers were combined with local ELFLO controllers. The decoupler, eliminating upstream interactions, in combination with ELFLO controllers appeared not to be robust (Schuurmans J. 1992). The other decoupler however, eliminating downstream interactions, provided good results in combination with ELFLO controllers. The controller was tested over a wide range of flow conditions, and, in spite of the non-linearities, the (linear) controller functioned stable under all flow conditions. This controller will be denoted here as 'ELFLO plus Decoupler'. Figure 6c shows a schematic representation of this controller on the canal.

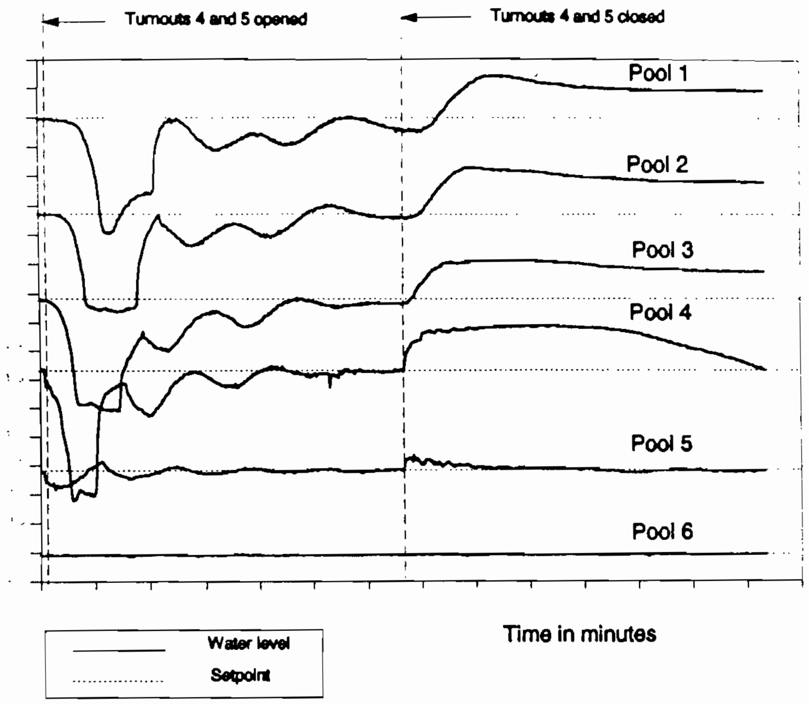

Fig. 8 *Test results with ELFLO applied to the Cal Poly Canal.* $Q_{t=0s}=0.009\ m^3/s$.

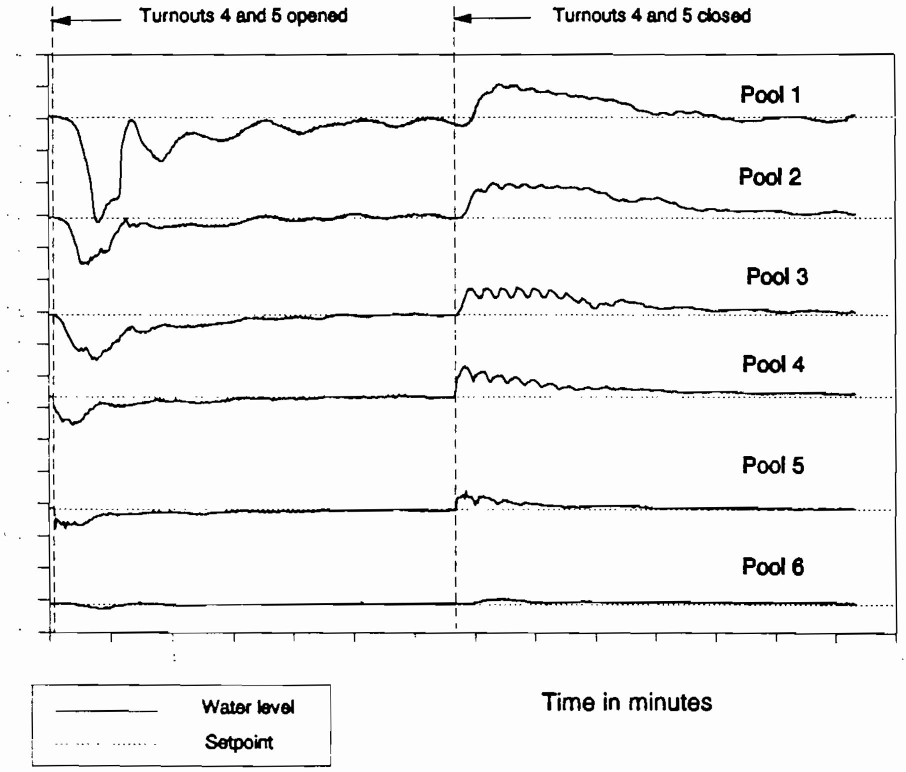

Fig. 9 *Test results with ELFLO plus decoupler applied to the Cal Poly Canal.* $Q_{t=0\,s}=0.009\ m^3/s$.

Figure 9 shows the performance of this controller, in which the same test is applied as on CARDD and ELFLO, under the same conditions.

The performance in all pools is equal, except for the most upstream one. The most upstream pool suffered from interaction with the supplying reservoir. The water level in the reservoir, controlled by a proportional controller, was not kept constant during the experiments.

In Table 1, the maximum deviation of the control algorithms on the Cal Poly canal is presented together with the integrated time offset curve.

Table 1 Performance of three regional controllers on the Cal Poly physical scale model.

Controller	Maximum offset above setpoint (m)	$\int_0^{t=1600s} \lvert e_t \rvert dt \,/\, 1600$ (m)
CARDD	0.10	0.25
ELFLO	0.15	0.42
ELFLO + Decoupler	0.10	0.14

Note: e_t is defined as the offset from setpoint

4 Conclusions and recommendations

Regional downstream control is an attractive control method which allows for flexible and reliable water deliveries. Studies have shown that the continued predominant application of rigid control systems, such as upstream control, is due to both non-recognition of the need for flexibility and to the lack of technology for implementation (Burt et. al., 1981). This latter problem was addressed in this study.

Two existing and one new control algorithm for regional downstream control were tested and compared.

The CARDD controller functions well on the Cal Poly Canal. Three water level sensors are required, which is more than that of the other controllers. CARDD might also function on other canals, but it should be tested in practice. The tuning of the controllers must be done by "trial and error".

The ELFLO controller can be applied on canals with few pools, but for canals with many pools problems might occur due to the interactions. For the Cal Poly canal, consisting of six pools, ELFLO performed worse than CARDD. The proper control parameters can partly be found with tuning rules, known from control theory, but readjustment is necessary if multiple pools are involved.

For canals with multiple pools, having an interaction problem, the ELFLO controller plus decoupler is recommended. The decoupler eliminates interactions between subsequent pools and, hence, avoids tuning problems and improves the performance. Only one water level sensor is required, but additional communication lines are needed to connect subsequent controllers.

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