Simple Water Level Controller for Irrigation and Drainage Canals

By J. Schuurmans,[1] A. Hof,[2] S. Dijkstra,[3] O. H. Bosgra,[4] and R. Brouwer[5]

Abstract: A simple water level controller for irrigation and drainage canals is proposed; the proposed controller has a master-slave structure where the slaves control the flow rates through the control structures. The master controller consists of PI-based controllers for feedback, and a decoupler and feedforward controller that are based on the inversion of a simple dynamic model of the canal system. The applicability of the controller is demonstrated in field experiments.

INTRODUCTION

For the design of reliable control systems, systematic tuning, design, and analysis methods have been developed in linear control theory. In most cases, the controllers, resulting from these techniques, are linear. Roughly speaking, in a linear controller, the control signal is computed by executing linear operations (such as additions and multiplications with constants) on a set of measured variables.

One of these systematic controller design methods is the linear quadratic (LQ) control design method. There is a wide range of articles in which this method was used to design water level controllers for irrigation canals; see, for instance, Corriga et al. (1983), Balogun et al. (1988), Reddy (1990), Rodellar et al. (1995), Garcia et al. (1992), and Malaterre (1994). Roughly speaking, the LQ design method is based on the minimization of water level deviations from target levels in a quadratic cost function, constrained by a linear model. With LQ, it is possible to design reliable controllers that show good performance (i.e., small water level deviations). However, the design and application of an LQ controller are relatively complicated. For instance, the LQ methods assume that the dynamics can be described by a linear model, while it is well known that open-channel flow behaves in a nonlinear way. Therefore, an iterative ''tuning'' method is required in order to obtain a controller that is stable under all operating conditions.

It is questionable whether such complicated control algorithms and controller design techniques are actually necessary for canal automation. Complicated controllers may perform better than simple ones (i.e., they may achieve smaller water level deviations); however, often the issue is not to minimize water level deviations, but to keep the deviations small. We believe that in many cases, simple water level controllers can be used for that purpose.

The current paper presents a method to design and tune a simple water level controller for irrigation and drainage canals. The design and tuning method is mostly based on a simplified model of a canal, as presented in Schuurmans et al. (1995) and Schuurmans et al. (unpublished paper, 1998). The paper is structured as follows. First, we briefly discuss our findings presented in Schuurmans et al. (1995) and Schuurmans et al. (unpublished paper, 1998), and we define variables and concepts that we shall be using in the present article. Next, we present the structure of the controller to justify our choices. We then present our controller design and tuning method. Finally, the effectiveness of the method is demonstrated by experiments on a laboratory canal.

PRELIMINARIES

For controller design purposes, a simplified canal model was presented in Schuurmans et al. (1995) and Schuurmans et al. (unpublished paper, 1998). The dynamics in a canal reach, schematically shown in Fig. 1, are described in these articles by the following model, which we denote as the integrator delay (ID) model:

$$A\,\frac{dh(x,t)}{dt} = q_{in}(t - T) - q_{out}(t) \quad (1)$$

Here, A = surface of the backwater area in the canal; h = water level in the backwater part; x = location somewhere in the backwater part; T = delay time; t = time; q_{in} = upstream inflow; and q_{out} = downstream outflow. The variables h, q_{in}, and q_{out} denote variations around their steady-state value.

If the shape of the cross section does not change in the longitudinal direction (the channel is said to be prismatic), the following expression applies for the delay (T):

$$T = \frac{2L_u}{(1 + \kappa)V_0} \quad (2)$$

where L_u = length of the part with uniform flow (Fig. 1); V_0 = mean velocity; and parameter κ is given by

$$\kappa = 1 + \frac{4P_0}{3B_0}\left(\frac{dR}{dY}\right)_0 \quad (3)$$

where B_0 = width of cross section at surface level; P_0 = wetted perimeter; R = hydraulic radius; and Y = depth of flow. The subscript zero refers to steady-state conditions. If the canal reach is not prismatic, but its shape is well defined, then (3)

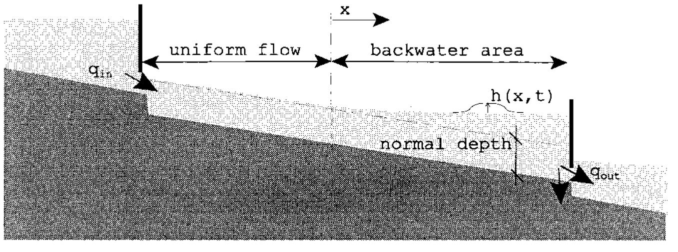

FIG. 1. Definition for Integrator-Delay Model

[1] Dept. of Math. Sci., Loughb. Univ., U.K.; formerly, PhD Candidate, Delft Univ. of Technol., Dept. of Civ. Engrg., P.O. Box 5048, 2600 GA Delft, The Netherlands.
[2] PhD Candidate, Delft Univ. of Technol., Dept. of Civ. Engrg., P.O. Box 5048, 2600 GA Delft, The Netherlands.
[3] Sci. Ofcr., Delft Univ. of Technol., Dept. of Mech. Engrg., P.O. Box 5048, 2600 GA Delft, The Netherlands.
[4] Prof., Delft Univ. of Technol., Dept. of Mech. Engrg., P.O. Box 5048, 2600 GA Delft, The Netherlands.
[5] Prof., Delft Univ. of Technol., Dept. of Civ. Engrg., P.O. Box 5048, 2600 GA Delft, The Netherlands.

Note. Discussion open until January 1, 2000. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on October 29, 1997. This paper is part of the ***Journal of Irrigation and Drainage Engineering***, Vol. 125, No. 4, July/August, 1999. ©ASCE, ISSN 0733-9437/99/0004-0189–0195/$8.00 + $.50 per page. Paper No. 16854.

J. Irrig. Drain Eng. 1999.125:189-195.

can be applied to small parts of the reach and summed thereafter; i.e.

$$T = \sum_{i=1}^{N} \frac{2(\Delta L_u)_i}{(1 + \kappa_i)(V_0)_i} \quad (4)$$

Here, $\Sigma_{i=1}^{N} (\Delta L_u)_i = L_u$; and subscript i refers to the ith part of the reach. The backwater surface can be computed once the steady-state profile is known.

The delay time (T) and backwater surface (A) of the model in (1) can vary considerably with the operation conditions. For instance, at low flow (i.e., if the flow rate running through the canal is low), the delay is usually considerably longer than at high flow. For controller design and tuning, it is wise to take these variations into account if the controller is guaranteed to be able to stabilize under all operation conditions. In the present paper, we shall denote the smallest and largest of the parameter values by the subscripts min and max, respectively. For instance, by $A_{\min}$ we mean the smallest value of the backwater surface.

If the backwater part stretches fully over the length of the canal reach, resonance may occur. Gravity waves, caused by inflow changes of either q_{in} or q_{out}, travel up and down the reach several times before they damp out. This phenomenon is not modeled by (1). However, if the controller is to be guaranteed to be able to stabilize under all operating conditions, resonance should be taken into account in controller design and tuning. We therefore define the following resonance parameters: ω_r, the lowest resonance frequency, and R_p, the resonance peak gain. The meaning of these parameters is as follows: If either q_{in} or q_{out} would vary in a sinusoidal fashion with frequency ω_r and amplitude α, the water level would vary with amplitude $\alpha \cdot R_p$. Hence, the amplification is R_p at ω_r. At multiples of ω_r, i.e., at $k\omega_r$, $k = 1, 2, 3, \ldots$, the amplification is also R_p, but at any other frequency larger than ω_r, the amplification is smaller. Since the resonance phenomenon is caused by gravity waves traveling up and down the reach, the lowest resonance frequency (ω_r) is exactly equal to $2\pi/T_r$, with T_r being the time a gravity wave needs to travel up and down a reach; i.e.

$$T_r = \frac{L}{v_0 + c_0} + \frac{L}{v_0 - c_0} \quad (5)$$

where L = length of the reach; and c_0 = celerity of a gravity wave, given by

$$c_0 = \sqrt{\frac{gA_{c,0}}{B_0}} \quad (6)$$

where g = gravitational acceleration; and $A_{c,0}$ = cross-sectional area in steady-state conditions.

In the present article, we shall be using digital controllers. To design these, we shall use a discretization of the model as described by (1). Using a Euler backward difference scheme, or a zero-order hold sampling method (Åström and Wittenmark (1984), the ID model can be approximated with reasonable accuracy by

$$\Delta h_i(k) = \frac{T_s}{A_i} [q_{\text{in}}(k - \tau) - q_{\text{out}}(k)] \quad (7)$$

Here, $\Delta h(k) = h(k) - h(k - 1)$; k = discrete-time level (0, 1, 2, . . .); T_s = sample period; τ = round (T/T_s) = delay (in sample units); and round (x) rounds x to the nearest integer.

The inflow q_{in} and outflow q_{out} can be specified in a slightly more detailed way; doing so will be useful to clarify the structure of the controller we propose. Assume we are dealing with an irrigation canal where reach number i is sandwiched between two other reaches $i - 1$ and $i + 1$. Then, the outflow ($q_{\text{out},i}$) of reach i consists of flow that passes on to the next reach, which we denote by q_{i+1}, and flow that is consumed by an offtake is lost by seepage, evaporation, etc., which we denote by d_i. Part of the flow d_i is often known in advance, or can be measured at the time of occurrence. Offtake flows are often determined according to some delivery schedule. We denote the part of the flow d_i that is known in advance or that can be measured by $d_{\text{m},i}$. The rest of the flow d_i, i.e., $d_i - d_{m,i}$, is denoted by $d_{u,i}$. It follows that the inflow to reach i, $q_{m,i}$ is equal to q_i. With these definitions, (7) becomes

$$\Delta h_i(k) = \frac{T_s}{A} [q_i(k - \tau_i) - q_{i+1}(k) - d_{m,i}(k) - d_{u,i}(k)] \quad (8)$$

The subscript i refers to the ith reach. For drainage canals, the variables q_{out} and q_{in} can be split up in a similar way. For clarity, we shall only use (8) in the present article.

STRUCTURE OF CONTROLLER

The controller, proposed in the present article, can be written mathematically as follows:

$$q_i(k) = K_{FB,i}(z)h_i(k) + K_{D,i+1}(z)q_{i+1}(k) + K_{FF,i}(z)d_{m,i}(k) \quad (9)$$

Here, $K_{FB,i}(z)$ describes the feedback controller; $K_{D,i}(z)$, the decoupler; and $K_{FF,i}(z)$, the feedforward controller. With the variable z we denote the shift operator: $z^m h(k) = h(k + m)$, with m as an integer (not necessarily positive). The variable z is to be treated algebraically. For instance, if $K_{FB,i} = 1/(3z + 2)$, $K_{D,i} = K_{FF,i} = 0$, then $3q_i(k + 1) + 2q_i(k) = h_i(k)$. We only use the variable z to define the controller equations more easily.

In practice, water levels can only be controlled by adjusting the check structures in the canal, such as gates, pumps, and likewise. We shall assume that q_i is controlled by a separate controller that adjusts the check structures for this purpose, which we shall refer to as the ‘‘slave controller.’’ The inflow signal q_i is adjusted by the ‘‘master controller,’’ defined by (9). We will clarify this in the next section.

Hence, the proposed controller has a master-slave structure, is decentralized (for each reach there is a different master controller), and uses feedback, decoupling, and feedforward. In the next section, we justify our choice for this structure.

Master-Slave Structure

Linear controllers offer the advantages of reliability and practical applicability. However, the more nonlinear a system behaves (as flow in a canal clearly does), the more the performance of a linear controller usually degrades. By applying local feedback loops to parts of the system that contribute to nonlinearities, the source of the performance degradation is tackled.

This principle can be effectively applied to the control of water levels in irrigation and drainage canals (Fig. 2). For simplicity, only one water level is controlled. The actuator is the device that provides motive power to the check structure— a control gate, in this case. The water level controller (the

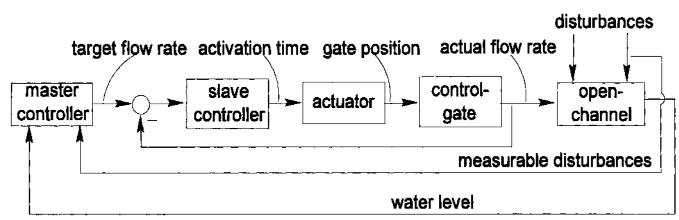

FIG. 2. Master-Slave Structure; Master Controls Water Level by Generating Target Flow Rate; Slave Adjusts Actuator of Control Gate to Control Flow

J. Irrig. Drain Eng. 1999.125:189-195.

master controller) produces a control signal in the form of a target flow rate [q_i in (9)]. A second controller, the flow rate controller (slave controller), attempts to track the target flow rate by adjusting the actuator.

Ideally, the actual flow is precisely equal to the target flow rate. Then, the (nonlinear) behavior of the actuators and check structures plays no role in the water level control problem anymore. To achieve this, it is essential that the slave controller is designed correctly and that the flow rate is measured as accurately as possible. The feedback controller will compensate errors in the flow measurements, but the performance of the system will improve if the measurements are more accurate.

If the flow rate is measured using a discharge relation of the check structure, it is possible to ''invert'' the discharge relation; i.e., given a target flow rate, the adjustable variable of the check structure, such as an activation time of the actuator, is computed. Inversion algorithms are described in Schuurmans (1997) and Rogers et al. (1995). If the flow rate cannot be measured accurately from the discharge relation of the control structure, it may be possible to measure the flow rate from a separate, more accurate flow rate sensor, such as a flume or an acoustic flow rate sensor; then, more accurate flow control is possible. In Papageorgiou and Messmer (1985) and Shinskey (1979), it is discussed how the slave controller can be realized in such a case.

Decentralization

We now discuss why we chose a decentralized structure for our master controller, defined by (9). As far as practical applicability is concerned, decentralized controllers offer important advantages over centralized controllers. First, the control system is simpler, and thus easier to understand. Second, the impact of a communication failure or breakdown of electrical power [failures and breakdowns due to lightning, vandalism, and rodent bites are common (Rogers et al. 1995)] is more limited if the control system is implemented locally. Third, the communication systems and other electronic devices can be cheaper (as compared to the systems needed for a fully centralized control system).

A well-known problem with decentralized feedback controllers is the interaction problem. In this phenomenon, the control actions of one feedback controller (say, $K_{FB,1}$) influence the control actions of another feedback controller (say, $K_{FB,2}$) in such a way that controller $K_{FB,1}$ is affected in return. Experiments on a laboratory canal, described in Schuurmans (1992), and simulations, described in Liem (1995), have shown that this problem can occur if local feedback controllers adjust gate positions upstream of the controlled water levels, such as in ELFLO. It was demonstrated that, due to the interactions, the design of controllers becomes complicated: To tune the local feedback controllers, the global system (including all interacting controllers) has to be taken into account. Furthermore, it was demonstrated that the performance of interacting feedback controllers degrades.

Now, consider a canal controlled by the following structure of the controller: On each control structure a flow rate controller is used; the target flow rates are generated by decentralized master controllers, of which each master controls a single reach. Then, if perfect flow controllers are used, the master controllers cannot interact. One controller can only perturb the other. To clarify this, cosider Fig. 3. Here, each feedback controller ($K_{FB,1}$ and $K_{FB,2}$) adjusts the target flow rate through one control structure. Strictly speaking, the variables h and q denote variations of the water level and flow rate around steady-state values. For brevity, we speak of ''water level h'' and ''flow rate q.'' The structure of this controller satisfies the description above. When the flow rate through

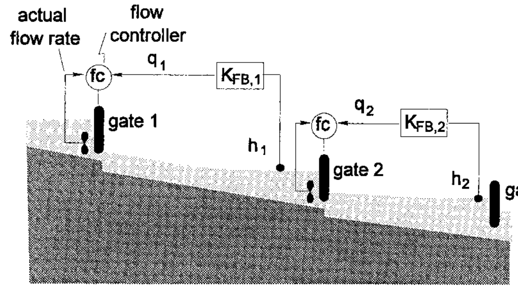

FIG. 3. Controller with Master-Slave Structure; h_i Is Water Level (Deviation from Target Level) in Reach i; q_i Is Target Flow Rate for Gate i

gate two is changed by controller $K_{FB,2}$, the water level h_1 will be disturbed; i.e., it will deviate from the target level. However, the control actions of controller $K_{FB,1}$ cannot affect h_2, since the flow rate through gate two depends exclusively on the controller $K_{FB,2}$ (assuming flow control is ''perfect''). Hence, by using flow rate controllers, interactions can be avoided.

Decoupling

We use a decoupler ($K_{D,i}$) in (9) to reduce the disturbing effects of control actions of ''adjacent' controllers. To see this, let us first consider Fig. 3, where local feedback controllers are used. The feedback controllers can reduce the effect of any disturbances—even the unmeasured ones. However, when using local feedback controllers only, the control inputs of one master controller act as disturbances on the adjacent controller. Again, consider Fig. 3: Control input q_2 can affect h_1, but controller $K_{FB,1}$ cannot adjust q_2. Hence, the signal q_2 acts as a disturbance on water level h_1.

The disturbing effect of control actions can lead to large transients if the disturbances are amplified from one reach to another. In the present article, this phenomenon is denoted as disturbance amplification. Disturbance amplification was observed, among other things, in the control of water levels in the Rhine River, as described in Nestmann and Theobald (1994). Disturbance amplification has also been observed during experiments on a laboratory canal (see the Example section of the present paper).

The disturbing effects of control actions of neighbor controllers can be reduced by a decoupler. The decoupler measures the disturbing control input to determine a control action. Fig. 4 shows how a decoupler (denoted by $K_{D,1}$) could be fit into the control configuration as shown in Fig. 3. The input to the decoupler is the feedback control signal q_2, and its output is added to the control signal of $K_{FB,1}$. As soon as the control signal q_2 increases (and thus the outflow of reach one increases), the decoupler should increase the inflow of reach one so as to reduce the water level drop of h_1. Hence, the decoupler

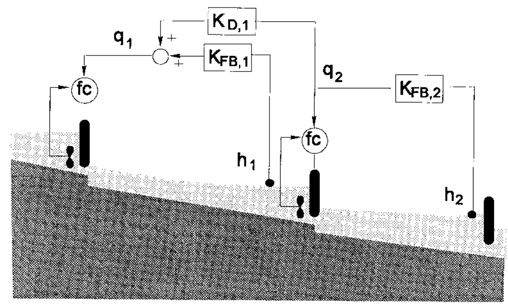

FIG. 4. Control Configuration with Decoupler; Decoupler Measures Control Signal of Controller $K_{FB,2}$ and Uses That Information to Reduce Water Level Deviations That Would Be due to Disturbing Control Actions of Controller $K_{FB,2}$

J. Irrig. Drain Eng. 1999.125:189-195.

should try to eliminate the disturbing effect of the signal q_2 on the control error h_1.

If the decoupler completely eliminates the effect of the signal q_2 on the control error h_1, disturbance amplification cannot occur. We shall refer to such a decoupler as a ''perfect decoupler.'' If perfect decoupling is not possible, disturbance amplification is unavoidable. However, the amplifications are not necessarily unacceptably large; if they are too large, though, the control parameters can be adjusted such that they become acceptably small. For this, one can apply either a trial-and-error method or parametric optimization (Schuurmans 1997).

Feedforward

We finalize this section with a justification for using feedforward ($K_{FF,i}$) in (9). A control system that uses local feedback controllers with decouplers may be sufficiently accurate (that is, it may be able to maintain small water level deviations); if not, the accuracy can be improved considerably by ''adding'' feedforward. The feedforward controller measures the disturbances, such as offtake flows, and uses that information to generate a control signal. In combination with feedback control, the feedforward controller can be very accurate.

DESIGN AND TUNING OF MASTER CONTROLLER

In this section, we consider the tuning and design of the master controller defined by (9).

Feedback Controller

One of the most simple and widely applied feedback controllers is the PI controller. The digital PI controller could be described as (Åström and Wittenmark 1984)

$$K_{FB} = \frac{K_p T_i}{T_s} z^{-1} + K_p(1 - z^{-1}) = K_{PI}(z) \tag{10}$$

Here, k = discrete time (k = 0, 1, 2, . . .); K_p = proportional gain (m^2/s); T_i = integration time constant(s); T_s = sample period (s); and z = time shift operator.

To simplify tuning, expressions for the control parameters have been derived in Schuurmans (1997). Using a 45° phase margin criterion (Franklin et al. 1986), the ID model, and the resonance parameters R_p and ω_r, the following settings were obtained for the PI controller for leveled reaches (we refer to a leveled reach when the backwater effect extends over the entire reach over all operation conditions; otherwise, the reach is referred to as a sloping reach) (Schuurmans 1997):

$$K_p < \frac{1}{2R_p}; \quad T_i = \frac{1}{\sqrt{2}}\frac{A}{K_p}; \quad \omega_c = \frac{1}{T_i} \tag{11}$$

Here ω_c = so-called cross-over frequency (rad/s). The cross-over frequency is a useful parameter for selecting the sample period.

For sloping reaches, the following settings for the PI controller were derived by Schuurmans (1997):

$$K_p = \frac{A_{\min}}{3T_{\max}}; \quad T_i = \frac{2A_{\min}}{K_p}; \quad \omega_c = \frac{2.2}{T_i} \tag{12}$$

Other Feedback Controllers

In leveled reaches with resonance, the performance is limited by resonance. The gain of the PI controller must be limited at the resonance frequency to avoid instabilities. Harder et al. (1971) suggested extending the PI controller with a low pass filter; for the digital controller, the PI controller in series with a low pass filter can be realized by using (Schuurmans 1997)

$$K_{FB}(z) = K_{PI}(z)\,\frac{1 - a}{1 - az^{-1}} \tag{13}$$

where $a = \exp(-T_s/T_f)$; T_f = filter time constant (s); and z = time shift operator.

The feedback controller given by (13) is used in ELFLO [Harder called his controller the hydraulic filter level offset controller (HYFLO). HYFLO used a hydraulic tube to realize the low pass filter]. Here, the PI controller with a low pass filter is applied in a somewhat different manner: It adjusts the flow rate through a control structure instead of through the gate position (as is done in ELFLO). To avoid confusion, we shall therefore use the term ''PIF'' controller to denote the controller according to (13). Using a phase margin criterion, the ID model, and the resonance parameters, the following settings were derived for the PIF controller (Schuurmans 1997):

$$T_f = \frac{AR_p}{\omega_r}; \quad K_p = \frac{A}{2T_f}; \quad T_i = 6T_f; \quad \omega_c = \frac{1}{2T_f} \tag{14}$$

If the filter time, computed from this equation, is higher than $1/\omega_r$, the filter can be expected to be useful, in that it decreases the gain at the resonance frequency. In that case, it can be expected that by applying a PIF controller, the control error will be smaller than the control error that would be obtained with a PI controller.

Selection of Sample Time

The settings derived for the feedback controllers may be used if the sample period is sufficiently small. To decide on this matter, the following rule-of-thumb condition (Åström and Wittenmark 1984) on the sample period can be used:

$$T_s\omega_c \le 0.15 \tag{15}$$

If the sample period is limited to a larger value than the outcome of (15), the control parameters may have to be adjusted.

Remarks on Tuning

For tuning the feedback controllers, according to the rules described above, certain parameters are needed (for a sloping reach, $A_{\min}$ and $T_{\max}$, and for a leveled reach with resonance, A, R_p, and ω_r). These parameters can only be determined after the operation range of the controller has been chosen (which is usually determined by the minimum and maximum flow rate that runs through the reach). When implementing the controller, the controller may not be stabilizing outside the operation range.

It is worthwhile to discuss how the resonance peak gain R_p can be found. One way is to determine the peak gain from an accurate hydraulic model, as mentioned in the companion paper (Schuurmans et al., unpublished paper, 1998). Another method to determine R_p is to perform a closed-loop experiment at low flow conditions (where the resonance gain is usually highest). If a proportional feedback controller with gain K_p is used, the closed loop will show undamped oscillations if the proportional gain is varied until $K_p = 1/R_p$, for the phase lag of the loop at the resonance frequency is exactly $-\pi$ rad if steady oscillations occur (Shinskey 1979).

In (11), the gain of the PI controller is limited to $1/2R_p$. This is consistent with the closed-loop method of finding the resonance peak gain, as described above. For values of the proportional gain K_p higher than $1/R_p$, instability can be expected.

Decoupler

Consider the ID model for a canal reach given by (8). To achieve perfect decoupling (i.e., to nullify the disturbing effect

J. Irrig. Drain Eng. 1999.125:189-195.

of q_{i+1} on the water level deviation), the decoupler (K_D) should be chosen according to

$$K_{D,i} = z^{\tau_i} \tag{16}$$

This is followed by substitution for $K_{D,i} = z^{r_i}$ in (9), which leads to

$$\Delta h_i(k) = \frac{T_s}{A} [K_{FB,i}(z)h_i(k - \tau) + z^{\tau} q_{i+1}(k - \tau) + K_{FF,i}(z)d_{m,i}(k - \tau) - q_{i+1}(k) - d_{m,i}(k) - d_{u,i}(k)]$$
$$= \frac{T_s}{A} [K_{FB,i}(z)h_i(k - \tau) + K_{FF,i}(z)d_{m,i}(k - \tau) - d_{m,i}(k) - d_{u,i}(k)] \tag{17}$$

Clearly, the control error $\Delta h_i(k)$ is independent from q_{i+1}, since $z^{\tau_i} q_{i+1}(k - \tau) - q_{i+1}(k) = 0$. If the delay τ_i is not zero, the perfect decoupler needs the values of the control signal q_{i+1} at a future time level. However, as these values are not known in advance (they contain feedback control signals), perfect decoupling is only possible if the delay time τ_i is zero. However, even if $\tau_i \neq 0$, a simple decoupler according to

$$K_{D,i} = 1 \tag{18}$$

can still be useful in reducing water level deviations.

Feedforward Controller

In contrast to perfect decoupling, perfect feedforward control is often possible. To see that, consider the ID model, (8). To nullify the effect of the disturbance $d_{m,i}$ on the control error, the feedforward controller should be chosen according to

$$K_{FF,i} = z^{\tau_i} \tag{19}$$

Apparently, the perfect feedforward controller ''needs to know'' the disturbance τ_i time levels before the disturbance actually takes place; this is due to the delay from the inflow to the controlled water level. Hence, for perfect feedforward control, the disturbance must be known in advance if the delay τ_i is not zero.

In principle, a fixed prediction time τ_i can be used. However, one often knows how the time τ_i varies over the operation conditions. The performance of the feedforward controller (in the sense of keeping the water level deviations small) can be expected to improve considerably by taking those variations of the delay time into account.

Accurate predictions of disturbances are often available. For instance, most U.S. water users need to request water 24 h in advance. However, there may be reasons to avoid the use of predicted disturbances. For instance, if one wants to increase the flexibility of water deliveries, it is desirable to use feedforward controllers that do not need predicted disturbances. In those cases, a simple static feedforward controller according to

$$K_{FF,i} = 1 \tag{20}$$

can be useful, in that it reduces the water level deviations.

EXAMPLE

In this section, we show experimental results of the controller proposed in the present paper applied to a laboratory canal.

Control of Water Levels in Laboratory Canal

The applicability of the simple controller and the tuning rules, as presented in the current article, have been verified experimentally on a laboratory canal, located at the Irrigation Training and Research Center at the California Polytechnic State University in San Luis Obispo, California. The canal is a physical scale model of an existing irrigation canal; it consists of six reaches, which are more or less of equal length. The most important physical data are shown in Table 1.

TABLE 1. Parameter Values of California Polytechnic State University Canal

Parameter (1)	Value (2)
Length of reaches	33 m
Manning's resistance coefficient	0.016 s/m$^{1/3}$
Bed slope	0.0043 rad
Bottom width	0.076 m
Side slope	0.159 rad

Note: Cross sections are trapezoidal.

There are six control gates and offtake structures (the seventh gate at the downstream end cannot be operated from the control computer). The control gate is a flat sliding orifice; it can be moved in the vertical direction. The offtake structure consists of a pipe outlet of the canal; the flow through the offtake can be varied by a butterfly valve. The following variables can be measured:

- The water levels at the upstream end, in the middle, and at the downstream end of each reach
- The opening height of each control gate

These variables are sampled by a digital microprocessor, which can perform basic operations such as scalar multiplication, addition, and logic operations. Before sampling, the water levels are filtered hydraulically with a filter time constant that is sufficiently small to avoid aliasing effects (Schuurmans 1992). The computer generates pulses, which are sent to the electromotors of the gate actuators. If the electromotor is activated, the gate opening changes in proportion to the amount of pulses.

Control-Oriented Model

The reaches of the laboratory canal are clearly leveled under normal operation conditions, i.e., the reaches are completely affected by backwater. Furthermore, all reaches are more or less the same. Therefore, we use $T_i = 0$ for $i = 1 \ldots 6$.

The backwater surface in each reach varies, depending on the shape of the water profile. However, for this canal, the variations are relatively small; at a target depth (at the downstream end of each reach) of 0.7 m, the value is approximately 9 m^2 in each reach, with a variation of less than 10% in the operational conditions. The parameters R_p and ω_r were determined as $R_p = 17$ s/m^2 and $\omega_r = 0.2$ rad/s (for each reach, the same values were found).

Controller

The flow controllers were realized as follows. Each sample time, the flow controllers computed the desired gate openings by using an inversion algorithm and a ''standard'' discharge relation. That is, the discharge relation was inverted each sample time. Once the desired gate openings were known, the slave controllers computed the amount of pulses to get the gates at the right opening heights.

For the (master) water level controller, we used the controller structure of (9) with the tuning rules as described in the present article. Using these parameters and the tuning rules described in the current paper, it appeared that the filter time contrast T_f of the PIF controller was higher than $1/\omega_r$. Hence, the filter allows higher gains of the PI controller; therefore, the PIF controller was used. The settings of the PIF controller were computed to be $K_p = 0.15$ s/m^2, $T_i = 150$ s, and $T_f = 27$ s.

J. Irrig. Drain Eng. 1999.125:189-195.

Four seconds was chosen as the sample period for the controller. By this choice, (6) is satisfied, so that the initial settings can be used for the digital PIF controller.

Experiment with Local Feedback Controllers Only

In one experiment, the initial flow rate was 14 L/s in all reaches; this flow rate is relatively low (approximately 20% of the maximum flow rate). Then, the offtake in reach six was opened for 50% at t = 0, resulting in an offtake flow rate change of approximately 10 L/s. During this test, local discrete-time PIF controllers were used, while the decoupler and feedforward controller were switched off. Hence, $q_{D,i} = q_{FF,i} = 0$.

Fig. 5 shows the water levels during this experiment. As can be seen, the control errors increase in the upstream direction; i.e., the control error of h_i is larger than that of h_{i+1}. This was expected to be the result of disturbance amplification in the upstream direction, as discussed in the Structure of the Controller section. If so, extension with a decoupler should ''cure'' the problem.

The effectiveness of this measure highly depends on the correctness of our modeling assumptions. Therefore, the effect of the aforementioned disturbance was simulated on the closed-loop model, consisting of the ID model [(8)], and the feedback controller [(9), with $K_{FF,i} = K_{D,i} = 0$)]. The simulated response is shown in Fig. 5 as well. It can be seen that the simulated water levels match the measured levels rather closely.

Local Feedback Controllers with Decouplers

We expected that by extending the feedback controllers with decouplers, the performance would improve and disturbance amplification would not occur. To test this, we repeated the test as described above. Fig. 6 shows the water levels during this experiment (solid lines). Due to the decoupler, the control errors are small everywhere, except in reaches one and six. In reach six, where the disturbance is created, control errors can be expected, but not in reach one. These appeared to be caused by fluctuations in the small reservoir upstream of gate one. The water level in this reservoir could not be measured; thus, the flow controller on the upstream gate could not function properly. In spite of that, the control error h_1 is relatively small. To test the robustness of the controller, the test was repeated under different initial conditions as well (i.e., starting from an initial flow of 50 L/s in all reaches; 50 L/s is approximately 80% of the maximum flow rate).

The dashed-dotted lines in Fig. 6 show the water levels during this experiment. Notice the similarity in responses (except in reach one, due to the aforementioned reasons) for the two different initial conditions. This confirms that the relation between the flow rates q_i and control errors h_i is rather linear, as expected from the closed-loop model (taking into account that the value of the backwater surface varies less than 10%).

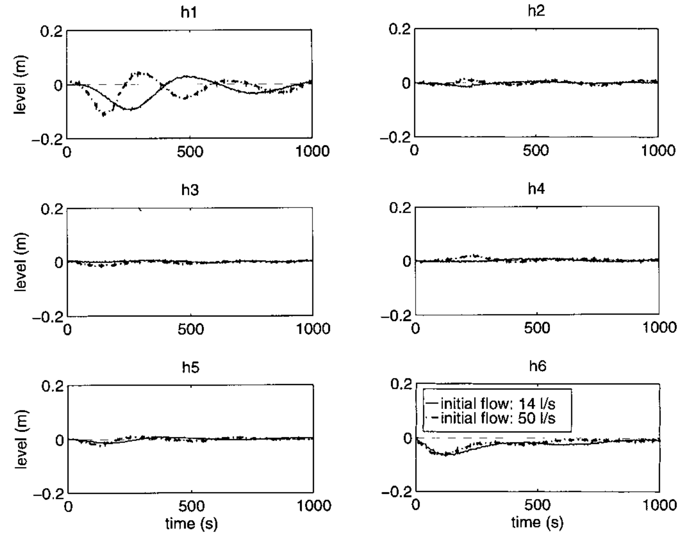

FIG. 6. Water Level Deviations during Two Tests When Using PIF Controllers with Decouplers; in Both Tests Flow through Offtake Six Increased 10 L/s at *t* = 0 s

Local Feedback Controllers with Decouplers and Feedforward Controllers

Since the decoupler appeared to be successful, it was expected that good results would be achieved by adding feedforward control. To test this, the initial flow rate was first set up to 14 L/s in all reaches; then, offtake six was opened completely at t = 0 s, such that the offtake flow rate changed from zero to approximately 24 L/s. The test results are shown in Fig. 7. Indeed, the control errors are almost neglectably small compared with the control errors during the other experiments—in spite of the fact that the disturbance was twice as large as in the other experiments.

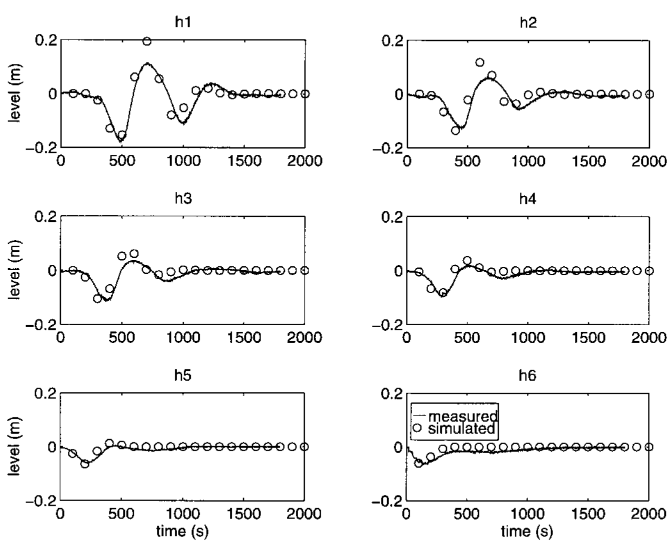

FIG. 5. Simulated and Measured Deviations of Water Levels When Local PIF Controllers Are Used; at *t* = 0 s Flow through Offtake Six Increased 10 L/s

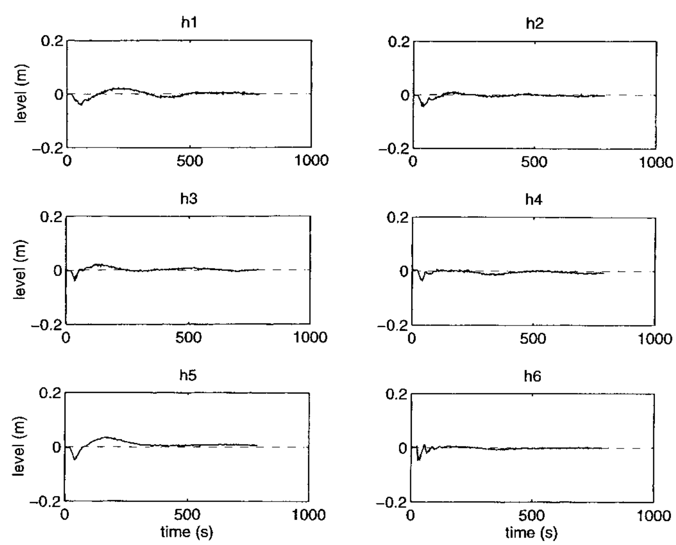

FIG. 7. Water Level Deviations during Two Tests When Using PIF Controllers with Decouplers and Feedforward Controllers; at *t* = 0 s Flow through Offtake Six Increased 24 L/s

J. Irrig. Drain Eng. 1999.125:189-195.

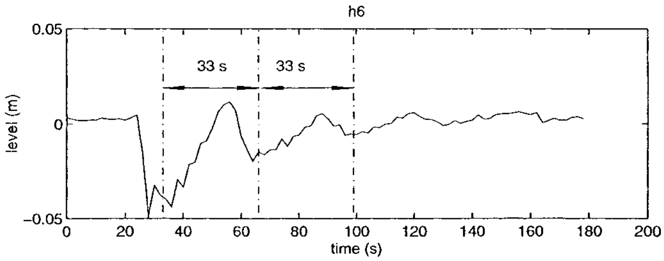

FIG. 8. Detailed View of Water Level Deviation in Reach Six

The small oscillations in Fig. 7 are the result of resonance (gravity waves that travel up and down the reach). To make this plausible, Fig. 8 shows a more detailed view of the control error h_6 in reach six. The oscillations show a period of approximately 33 s, which corresponds to the resonance period $\omega_r = 0.2$ rad/s $\approx 2\pi/33$.

CONCLUSIONS

The current article presented a water level controller for irrigation and drainage canals. The proposed controller has a master-slave structure, is decentralized, and uses feedback, feedforward, and decoupling. The choice for this structure of the controller was justified, and detailed tuning and design rules for the controller were presented. The applicability of the controllers was demonstrated in a laboratory test.

ACKNOWLEDGMENTS

We would like to thank C. M. Burt and M. Lehnkuhl for their assistance during the experiments on the laboratory canal in California. Furthermore, we would like to thank the following organizations for their support: the NWO, the Universiteitsfonds Delft, Dr. Hendrik M.'s Vaderlandsch Fonds, the College van Bestuur of the Delft University of Technology, and the KIvI.

APPENDIX. REFERENCES

Åström, K. J., and Wittenmark, B. (1984). *Computer controlled systems; Theory and design*. Prentice-Hall, Englewood Cliffs, N.J.

Balogun, D., Hubbard, O. S., and de Vries, J. J. (1988). ''Automatic control of canal flow using linear quadratic regulator theory.'' *J. Hydr. Engrg.*, ASCE, 114(1), 75–102.

Corriga, G., Sanna, S., and Usai, G. (1983). ''Sub-optimal constant-volume control for open-channel networks.'' *Appl. Math. Modelling*, 7, 262–267.

Franklin, G. F., Powell, J. D., and Emami-Naeini, A. (1986). *Feedback control of dynamic systems*. Addison-Wesley, Reading, Mass.

Garcia, A., Hubbard, M., and de Vries, J. J. (1992). ''Open-channel transient flow control by discrete time LQR methods.'' *Automatica*, 28(2), 255–264.

Harder, J. A., Shand, M. J., and Buyalski, C. P. (1971). ''Automatic downstream control of canal control gates by the hydraulic filter level offset (HYFLO) method.'' *Proc., 5th Tech. Conf.*

Malaterre, P. O. (1994). ''Modélisation: Analyse et commande optimale LQR d'un canal d'irrigation,'' PhD thesis, Ecole Nationale du Génie Rural des Eaux et des Forêts (ENGREF), Paris (in French).

Nestmann, F., and Theobald, S. (1994). ''Numerisches Modell zur Steuerung and Regelung einer Staustufenkette am Beispiel von Rhein und Neckar.'' *Wasserwirtschaft 84*, 2, 72–79 (in German).

Papageorgiou, M., and Messmer. (1985). ''A continuous-time and discrete-time design of water flow and water level regulators.'' *Automatica*, 21(6), 649–661.

Reddy, J. M. (1990). ''Local optimal control of irrigation canals.'' *J. Irrig. and Drain. Engrg.*, ASCE, 116(5), 616–631.

Rodellar, J., Gómez, M., and Vide, J. P. M. (1995). ''Stable predictive control of open-channel flow.'' *J. Irrig. and Drain. Engrg.*, ASCE, 115(4), 701–713.

Rogers, D. C., et al. (1995). *Canal systems automation manual: Volume 2*, 1st Ed., U.S. Department of the Interior, Bureau of Reclamation, Denver.

Schuurmans, J. (1992). ''Controller design for a regional downstream controlled canal,'' MS thesis, Delft University of Technology, Laboratory for Measurement and Control, Delft, The Netherlands.

Schuurmans, J. (1997). ''Control of water levels in open channels,'' PhD thesis, Delft University of Technology, Faculty of Civil Engineering, Delft, The Netherlands.

Schuurmans, J., Bosgra, O. H., and Brouwer, R. (1995). ''Open-channel flow model approximation for controller design.'' *Appl. Math. Modelling*, 91, 525–530.

Shinskey, F. G. (1979). *Process control systems; Application, design, and tuning*. McGraw-Hill, New York.

J. Irrig. Drain Eng. 1999.125:189-195.