PERFORMANCE MONITORING OF CONTROL LOOPS IN IRRIGATION CHANNELS USING REFERENCE MODELS [1]

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Abstract: In this paper a new approach for detection of oscillatory and sluggish controllers is developed. It is specifically aimed at control systems where rejection of load disturbances is the main control objective, and it is based on comparing the actual system output with the output of a reference model. A number of performance measures are defined, and the user can also define additional tailor made performance measures. The developed method has been successfully applied to real data from an irrigation channel. The method correctly detected the control loops which need retuning, and it provided useful information about several aspects of the control performance such as speed of response, oscillations and interactions between control loops.

Keywords: Performance monitoring, Reference model, Performance measures, Irrigation channels, Environmental systems

1. INTRODUCTION

Performance monitoring of control loops is widely recognized as an important issue in process control. In industrial applications, sluggish and oscillatory controllers may be present for a long time without being noticed. This has undesirable consequences such as low product quality, waste of raw material and increased energy consumption. A modern control system may consist of hundreds of control loops, and manual evaluation of all the loops is time consuming and requires huge human efforts. An automatic monitoring tool to assist engineers and operators is therefore in high demand.

A network of irrigation channels is a typical example of where monitoring tools would be very useful. The water levels in irrigation channels are controlled by gates located along the channel. Usually a decentralised control strategy is adopted. In a medium sized channel there might be between 20 and 30 control loops, and in a network of channels there can be several hundred loops. The objectives of the controllers are to keep the water levels on setpoint, and to reject disturbances due to offtakes of water to farms. The presence of badly tuned controllers leads to water losses and reduced level of service to the farmers, and it is therefore important to detect such controllers. In this paper we develop a method for performance monitoring of control loops where rejection of load disturbances is the main control objective.

Early works on performance monitoring such as (Desborough and Harris, 1992), (Lynch and Dumont, 1996) and (Huang and Shah, 1999) were based on the Harris index (Harris, 1989). It was originally derived from minimum variance control (MVC) theory to evaluate the performance of systems with stochastic disturbances. However, it was realised that this approach had several shortcomings when applied to

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systems with deterministic disturbances or when the control objective was different from MVC. Several works have extended the MVC based techniques to systems with deterministic disturbances e.g. (Eriksson and Isaksson, 1994) and (Horch and Isaksson, 1999). These works compare the achieved response with a response which is optimal with respect to some modified MV criterion. Due to reasons such as robustness or lack of integral action, these optimal responses may be very far from the response any reliable practical controller can achieve, and such comparisons will in many cases only give very limited information about the actual control performance. Moveover, in most of the above approaches the performance of the controller has been summarized in one single number. This is in most cases an over-simplification since many factors have to be taken into account when evaluating the performance of a control loop.

The relative performance monitor introduced in (Li *et al.*, 2003) represents a departure from the traditional MV approaches. In that paper, a reference model is customized to represent a user defined acceptably tuned control loop. Like (Li *et al.*, 2003) the method developed in this paper compares the achieved response with the response of a reference model. However, due to the nature of the control problem for irrigation channels we focus on load rejection instead of setpoint tracking. A number of performance indicators are defined based on a typical load rejection response, and several performance measures are created. The method also takes coupling effects between control loops into account. Moreover, the user can easily specify additional measures tailor made to the particular application at hand. The developed method is applied to real data from the Haughton Main Channel (HMC), and it successfully detects the control loops with unsatisfactory performance.

This work is part of a collaborative research project between the University of Melbourne and Rubicon Systems on modelling and control of irrigation channels.

The paper is organized as follows. A brief description of an irrigation channel is given in section 2. The developed reference model approach is presented in Section 3. Section 4 elaborates on how reference models can be constructed for irrigation channels. In section 5, we apply the method to real data from controller tests at the HMC and discuss the results. Finally, conclusions are given in section 6.

2. IRRIGATION CHANNELS

Large amounts of water are wasted in irrigation channels. These water losses can be greatly reduced by employing efficient control systems. It is important that the control systems maintain their performance over time in order to keep the water losses small and to provide a satisfactory level of service to the farmers.

Irrigation channels are open water channels with offtakes to farms and secondary channels, see Fig. 1. Along the channels, there are gates which are used to regulate the flows and water levels. Fig. 2 shows a part of the HMC with a decentralized control scheme, see section 2.2. The reach between two consecutive gates is referred to as a pool. The measurements we have available are the water levels and the gate positions which are denoted by y_i and p_i respectively, $i = 8, \ldots, 11$. The height of water above a gate is called the head over gate, and it is given by $h_i = y_i - p_i$. By convention the pool is named after upstream gate, so Fig. 2 shows pool 8, 9 and 10. According to this convention y_{i+1} is the water level in pool i.

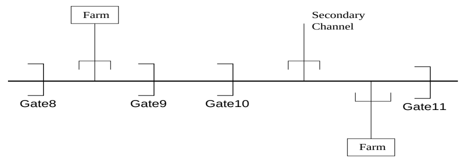

Fig. 1. Top view of Haughton Main Channel

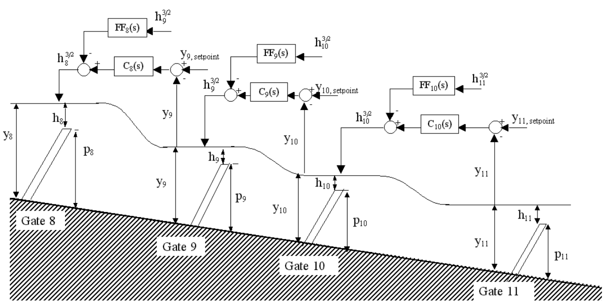

Fig. 2. Side view of the HMC with a decentralized control system

2.1 System Identification Models

The mathematical model used for control design is taken from (Weyer, 2001). For Pool i, the model is given by

$$\dot{y}_i(t) = c_{i,\mathrm{in}} h_i^{\frac{3}{2}}(t - \tau_i) + c_{i+1,\mathrm{out}} h_{i+1}^{\frac{3}{2}}(t) + d(t) \quad (1)$$

The equation is a simplified mass balance which says that the rate of change in the water level is proportional to the flow over the upstream gate (first term on the right hand side) minus the flow over the downstream gate (second term, where $c_{i+1,\mathrm{out}} < 0$) minus the flows at the offtakes ($d(t) \leqslant 0$). The delay τ_i is included in order to account for the travel time from the upstream gate to the downstream gate. $c_{i,\mathrm{in}}$and $c_{i+1,\mathrm{out}}$ are unknown parameters which are found from system identification experiments (Weyer, 2001). These models have successfully been used for control design in (Weyer, 2002) and (Ooi and Weyer, 2003).

2.2 Controllers

One of the main control objectives is that the water levels should be kept at set points and load disturbances due to offtakes should be rejected. In order to achieve this, a distant downstream controller configuration is often used. In this configuration the water level in a pool is controlled by the upstream gate, see Fig. 2. The controller is a PI controller augmented with a 1st-order lowpass filter

$$C(s) = \frac{K_c(1+T_i s)}{T_i s} \cdot \frac{1}{(1+T_f s)} \tag{2}$$

and the total controller is given by

$$u_{10}(s) = C_{10}(s)(y_{11,setpoint} - y_{11}(s)) \tag{3}$$

$$h_{10}^{\frac{3}{2}}(s) = u_{10}(s) - \frac{c_{11}}{c_{10}} K_{ff} F_{10}(s) h_{11}^{\frac{3}{2}}(s) \tag{4}$$

where K_{ff} is a feedforward gain, and $F_{10}(s)$ is a lowpass filter. $h_{10}^{\frac{3}{2}}(s)$ and $h_{11}^{\frac{3}{2}}(s)$ are the Laplace transform of $h_{10}^{\frac{3}{2}}(t)$ and $h_{11}^{\frac{3}{2}}(t)$ respectively. For details see (Weyer, 2002) and (Ooi and Weyer, 2003). Other controllers can also be used, and the one above is only used as a starting point for deriving sensible reference models, see section 4.

3. REFERENCE MODEL APPROACH

This section introduces the new reference model approach, which is developed specifically for controllers whose main objective is load disturbance rejection. The idea is to base the performance assessment on a comparison between the real system response and a reference model response as shown in Fig. 3. The reference model is a low order model which represents a user-defined acceptable response.

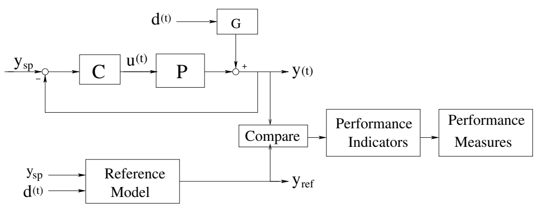

Fig. 3. The principle behind the reference model approach. C - controller, P - plant, G - disturbance transfer function

3.1 Performance Indicators

For a load rejection response, see Fig. 4, five performance indicators are defined corresponding to important aspects of the control performance.

1. Maximum Deviation y_{max}: the maximum difference between the setpoint y_{sp} and $y(t)$.

2. Peak Time t_p: the time the response reach the maximum deviation y_{max} from the set point.

3. Rise Time t_r: the time it takes to go from the maximum deviation back to $y_{sp} - 0.1(y_{sp} - y(t_p))$, that is, the time it takes for the response to cover 90% of the distance between $y(t_p)$ and y_{sp}. We denote the

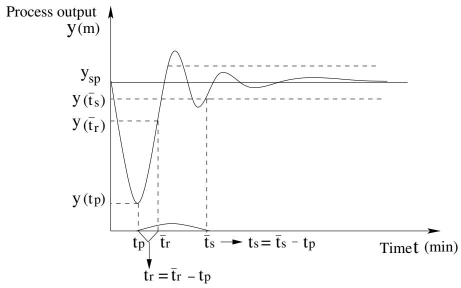

Fig. 4. A typical load rejection response

time instant when the response reach the 90% mark by $\bar{t}_r$, (i.e. $y(\bar{t}_r) = y_{sp} - 0.1(y_{sp} - y(t_p))$), and hence $t_r = \bar{t}_r - t_p$, see Fig. 4.

The rise time measures the response speed, and it is an important factor in the assessment of control performance. The main benefit of measuring the time from t_p is that it can be easily determined from experimental data, while it may be difficult to determine accurately when a load disturbance took place.

4. Settling Time t_s: the time it takes from the maximum deviation until $y(t)$ reaches and stays within $y_{sp} \pm 0.05(y_{sp} - y(t_p))$, that is, within 5% relative to the maximum deviation. Denote by $\bar{t}_s$ the last time the response hits the 5% mark (i.e. $y(\bar{t}_s) = y_{sp} - 0.05(y_{sp} - y(t_p))$), then $t_s = \bar{t}_s - t_p$.

5. Oscillation Indicator I: the number of times the response goes outside $y_{sp} \pm 0.05(y_{sp} - y(\bar{t}_p))$. A large I is indicative of an oscillatory response.

3.2 Reference Models

The reference model is used to represent the behavior of a user defined acceptable performance. A second-order model

$$y(s) = \frac{b\omega_n^2 s}{s^2 + 2\xi\omega_n s + \omega_n^2} d(s) \tag{5}$$

will usually be able to approximate most load disturbance responses. Here b is a scaling parameter, ξ is the damping ratio, ω_n is the undamped natural frequency and $d(s) = \frac{d_0}{s}$ is a load disturbance of size $d_0 \leqslant 0$. A different low order model can of course also be used if it suits the purpose better.

3.3 Performance Measures

Making use of the performance indicators in section 3.1, five performance assessment criteria are defined in (6)-(10).

$$D_{ymax} = \frac{y_{max,ref} - y_{max}}{y_{max,ref}} \tag{6}$$

$$T_R = \frac{t_{r,ref} - t_r}{t_{r,ref}} \tag{7}$$

$$T_S = \frac{t_{s,ref} - t_s}{t_{s,ref}} \tag{8}$$

$$I_{yact} - \text{ the number of times that } y(t) \text{ goes outside } y_{sp} \pm (y_{sp} - y(\bar{t}_s)) \tag{9}$$

$$D_I = I_{yact} - I_{yref} \tag{10}$$

(6)-(8) measure the relative difference between the actual response and the reference response. By using the relative difference, the thresholds are independent of the disturbance size and physical characteristics of the plants. (9) is used for oscillation detection, and (10) is used to differentiate whether an oscillation is caused by the controller for the loop under consideration or by disturbances from interacting control loops.

Referring to Fig. 2, if both I_{yact} and I_{yref} for Pool 9 are larger than a certain value, say 3 or 4, it is taken as an indication that the controller for Pool 10 is too aggressive and introduces oscillations in pool 9. Instead of adjusting controller 9, we should retune controller 10. In addition to the above measures, the user can define other measures suitable for different control objectives and applications.

4. REFERENCE MODELS FOR IRRIGATION POOLS

In this section we briefly describe the reference models for pool 8, 9 and 10 at the HMC. For a single pool such as Pool 9, there are two kinds of "disturbance" signals, the offtake $d(s)$ and $h_{10}^{3/2}(s)$, the head over the downstream gate. $h_{10}^{3/2}(s)$ is controlled by the controller for pool 10, and this causes interactions between the two pools.

In order to establish reference models, it is necessary that the user has a fair idea of what constitutes an acceptable performance. This may at first seem unrealistic, but in fact, the user only need to have this knowledge for a single pool since all other reference models can be obtained by scaling according to pool lengths (or surface area if the width changes), for details see (Zhang, 2004). The above requirement is therefore a very mild one since we can reasonably expect that the control engineers have made an effort to obtain well tuned controllers for at least some of the pools. Moreover, experience from other irrigation channels can also be drawn upon.

4.1 Reference Models for Pool 8, 9 and 10

The reference model structures are

$$y_{i+1}(s) = \frac{b_i \omega_{ni}^2 s}{s^2 + 2\xi_i \omega_{ni} s + \omega_{ni}^2} \cdot d(s) \tag{11}$$

$$y_{i+1}(s) = \frac{b_i \omega_{ni}^2 s}{(s^2 + 2\xi_i \omega_{ni} s + \omega_{ni}^2)} \cdot \frac{c_{i+1\text{out}}(1 - K_{ff} + (0.5 + 0.5K_{ff})\tau_i s)}{(1 + 0.5\tau_i s)} h_{i+1}^{\frac{3}{2}} \tag{12}$$

$K_{ff} = 0.75$ and $\xi = 0.9$ for all pools and the other parameters are given in Table 1. The additional term in the second transfer function is due to that the controller employs feedforward from the downstream head . If there were no feedforward action, we would use the same transfer function as in (11).

Table 1. Reference model parameters

Pool	$b(\times 10^3)$	ω_n	$c_{i+1\text{out}}$	τ_i
8 (1600m)	3.25	0.0256	-0.0312	8
9 (860m)	0.8126	0.0512	-0.0624	4
10 (3200m)	13	0.0128	-0.0156	16

The reference models were obtained by first using the above transfer functions to approximate the simulated response in pool 10 when pool 10 was controlled by a well tuned controller. Then the responses were slowed down by a factor two in order to create an acceptable performance (as opposed to a very good one). The reference models for Pool 8 and 9 were obtained by scaling the reference model for Pool 10 according to pool lengths.

Notice that once a reference model has been established for one pool, all other reference models follows by scaling. That we have used a particular controller for derivation of the reference models guarantees that the reference responses are realistic. However, the actual controllers being monitored do not need to be of the type (3) - (4), since the evaluation is based on comparisons of responses only.

5. APPLICATIONS ON REAL DATA FROM HMC

The results from two controller tests at the HMC are reported in this section. Using the reference models from Section 4 and the measurements of the water levels and the head over gates, the controllers for pool 8, 9 and 10 are evaluated.

5.1 Modifications of Performance Indicators

In order to be able to supply water to farmers, the water levels in an irrigation channel are required to be kept within a range around the setpoints rather than precisely at the setpoints. Also, a dead band on the gate positions is used to reduce the wear and tear on the gates. That is, the gates do not move until the difference between the new gate position from the controller and the current gate position is more than a certain value. This motivates us to redefine $y(\bar{t}_r)$ and $y(\bar{t}_s)$ as

$$y(\bar{t}_r) = y_{sp} - \triangle_y - 0.1(y_{sp} - y(t_p) - \triangle_y) \tag{13}$$

$$y(\bar{t}_s) = y_{sp} \pm \triangle_y \pm 0.05(y_{sp} - y(t_p) - \triangle_y) \tag{14}$$

where $\triangle_y = 0.01$ is a tolerable offset. Accordingly, we redefine t_r and t_s as $t_r = \bar{t}_r - t_p$ and $t_s = \bar{t}_s - t_p$ using the new definitions of $\bar{t}_r$ and $\bar{t}_s$.

5.2 *The Controllers and Thresholds of the Measures*

The controllers which are used at the HMC are of the type (3) - (4), but with h_{10} and h_{11} instead of $h_{10}^{3/2}$ and $h_{11}^{3/2}$ in (4). This means that under low flow conditions, which were the flow conditions during the experiments, these controllers are expected to be slower than the ones in section 2.2.

The measures from section 3.3 are used, and the thresholds are given in Table 2. The same thresholds are used for Pool 9 and 10 since gate 9 and 10 have the same physical dimensions. The threshold $D_{ymax} = -0.5$ means that if y_{max} is more than 1.5 times larger than $y_{max,ref}$, then the control loop should be checked. The lower limits of T_R and T_S are set as to zero, which require the real response to be faster than the reference response in order to be acceptable. This is a reasonable threshold since the reference response is already slowed down with a factor two compared to a fast response. The upper limit is used for the situation when the real response is much faster than the reference model response. The threshold 0.75 means that if the reference response is 4 times slower than the real response, then we should check if the reference model was set up properly. Moreover, the response is deemed oscillatory if I_{act} is larger than 3, and a warning for interactions between pools is raised if in addition D_I is smaller than 2.

The width of gate 8 is only 75% of the width of gate 9 and 10. The requirements for t_r and t_s to Pool 8 should therefore be slowed down with a factor $\frac{1}{0.75} = 1.33$ (Zhang, 2004). Without changing the reference model for Pool 8, this can be achieved by adjusting the thresholds for D_{ymax}, T_R and T_S, see Table 2.

Table 2. Threshold values

Pool	D_{ymax}	T_R/T_S(Low)	T_R/T_S(Up)	I_y	D_I
8	-0.995	-0.33	0.812	3	2
9/10	-0.500	0	0.750	3	2

5.3 *Experiment I*

The water levels in Pool 8, 9 and 10 were steady on the setpoints 26.4, 23.8 and 21.15 mAHD (meters Australian Height Datum which is relative to sea level). At 410 min, the flow over gate 11 was increased from 0.35m^3/sec to 1.5m^3/sec. This corresponds to a step in the head over gate 11 from 0.12m to 0.30m.

The measured head over the downstream gate in each pool (not shown) was used as input to the reference models. The real responses and the reference model responses are shown in Fig. 5

From the plots, we see that the control loop for Pool 8 is much slower than the reference response. The controller for Pool 9 has a faster response than its reference model. In Pool 10, the real response is quite close to the reference response. The values of the performance measures are shown in Table 3.

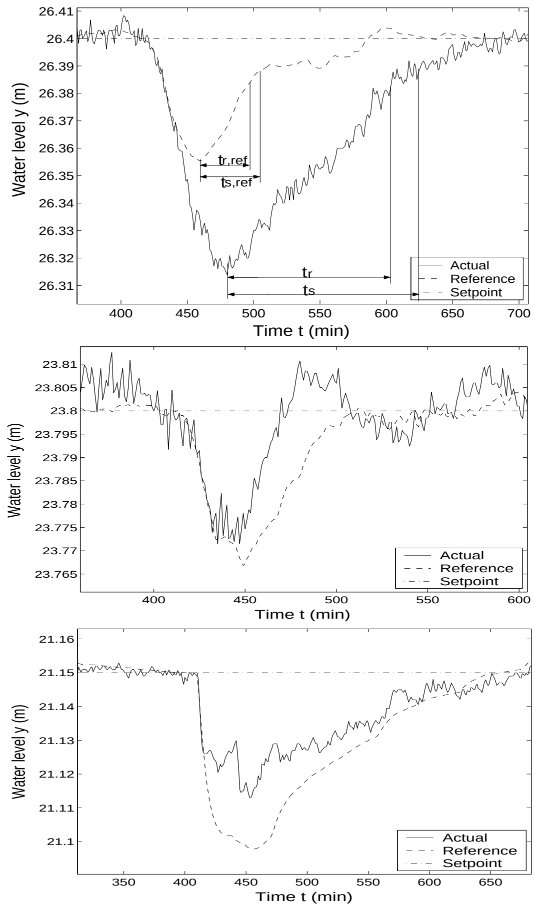

Fig. 5. Measured water level and reference model response of Pool 8 (top), 9 (middle) and 10 (bottom)

Table 3. Values of performance measures

Pool	D_{ymax}	T_R	T_S	I_{yact}	D_I
8	-0.928	-2.04	-2.14	1	0
9	0.145	0.2604	0.2568	1	0
10	0.293	0.0054	0.0544	1	0

Comparing the results in Table 3 with the thresholds for T_R and T_S, we draw the conclusion that the controller for Pool 8 should be retuned. The controller for Pool 10 is just acceptable, and there is room for improvement. None of the three controllers give oscillatory responses. Accordingly, for the second experiment, the gain in controller 8 is increased and the integral actions in both controller 8 and 10 are increased to improve the response speed.

5.4 *Experiment II*

Using the new control parameters, a repeat experiment was carried out and the performance of controller 8 and 10 was re-assessed. The real responses and the reference responses are shown in Fig. 6.

From the plots, we see that the response in Pool 8 is similar to the reference response. The response in Pool

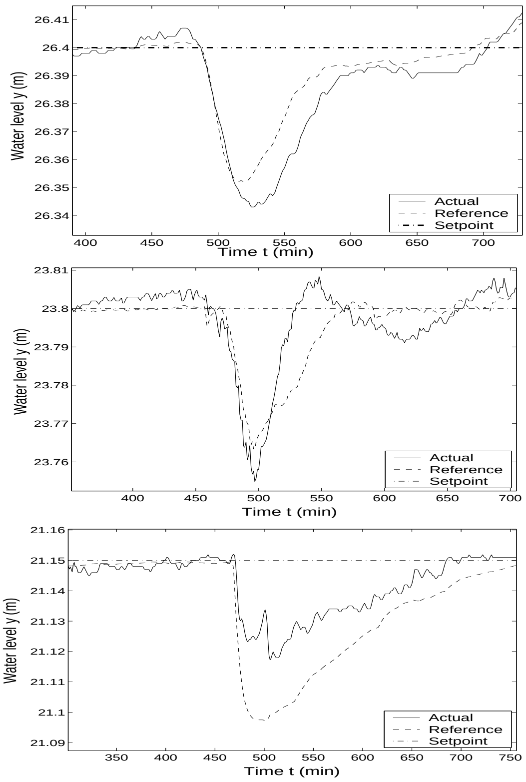

Fig. 6. Measured water level and reference model response of Pool 8 (top), 9 (middle) and 10

Table 4. Values of performance measures

Pool	D_{ymax}	T_R	T_S	I_{yact}	D_I
8	-0.185	-0.326	-0.329	1	0
9	-0.23	0.519	0.523	1	0
10	0.378	0.181	0.304	1	0

10 is now faster than the reference response, and the controller for Pool 9 continues to work well. The values of the performance measures are shown in Table 4. Comparing the results with the thresholds, we find that all controllers achieve acceptable performance. As expected, the values of T_R and T_S have increased for Pool 8 and 10 since the new controllers have higher gain (Pool 8) and more integral action.

5.5 Discussions

In the experiments, it is demonstrated that the developed method can efficiently detect the under performing controllers. There were no false alarms where a well performing controller is judged to give an unsatisfactory response.

The user can easily define new performance measures. For irrigation channels, such additional measures could be the absolute difference in rise time and settling time $t_{r,ref} - t_r$ and $t_{s,ref} - t_s$. These measures with suitable thresholds are more robust against false alarms in short pools with fast dynamics. Hence one way to robustify the monitoring algorithm is to require that both T_R and $t_{r,ref} - t_r$ should exceed the thresholds.

6. CONCLUSIONS

In this paper we have developed a novel approach to performance monitoring of control systems where the main objective is to reject load disturbances. The approach is based on comparisons between the actual system response and the response of a user defined reference model. The user can specify any number of performance criteria measuring different aspects of the control performance. With sensibly specified reference models, the developed approach avoids the problems associated with performance monitoring schemes which use a theoretically optimal response as a benchmark.

The developed method gives very good results when applied to real data from controller tests at the HMC. It detects the controllers which need retuning without giving any false alarms. Since it is easy to establish reference models for irrigation channels and the assessment of the control loops can be carried out on routine operational data, the developed method bears promise of becoming a valuable tool for management of irrigation channels.

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