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Real-Time Control of Estuarial Gate by the Self-Tuning Controller During Flood Periods

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Synopsis

The self-tuning controller (STC) of Clark and Gawthrop (1975) is used to do a real-time control of the estuarial weir gate openings during flood periods to maintain a certain water level in the reservoir dammed by the weir gates for domestic, agricultural and industrial water supplies. The Kalman filter is used to estimate, in real-time, the parameters needed to compute the optimal control strategy. Using data of the actual operation of the weir gates during flood periods at Onga River, Kyusyu Island, Japan, the real-time flood control performance of STC is compared with that of the existing control strategy. Some interesting characteristics of the use of STC to the control of weir gate openings during flood periods are presented and discussed.

1. Introduction

In Japan, many weir gate structures are constructed in tidal inlets (river mouths) because feasible sites for reservoir construction in the upperstreams are limited. The water of an estuarial reservoir dammed by weir gates is extracted for domestic, agricultural and industrial water supplies. Water level variations are expected especially during flood periods, therefore water is released to maintain a certain water level. Maintaining a certain water level is required to prevent sea water from entering the reservoir and to avoid drainage problems due to the hydraulic connection between reservoir and aquifer in agricultural lands beside the reservoir. Automatic feedback control can greatly enhance the efficiency of operation of gates and increase the benefits associated with their use, as well as not allowing the water upstream rise above a certain height. With automatic controllers, gate openings are optimally determined so that the energy consumed in operating the gates is minimized and unnecessary depletion of the reservoir is avoided.

Automatic controllers presently in operation employ readily available, inexpensive computer systems, and on-line observation systems using telemeters. An existing automatic controller uses the on-line data from upstream and downstream water levels, present gate openings, and river discharge at a nearby upstream station. Then, these data are entered into the computer system where the gate openings are decided according to a control strategy; computer commands are then carried out to operate the gates. However, the control strategy is not very efficient in treating the stochastic nature of the system. It requires that the inflow be accurately measured or forecasted and that the system be accurately modelled, because the deviation between reservoir water surface level and the required one is not used to correct any modelling errors. Also, it is not adaptive, i.e., if there are changes in the system, the control strategy will be incorrect. Failure to take into account the stochastic and dynamic properties of the system in designing the control strategies has resulted in largely unsatisfactory and sometimes even unstable control. An alternate procedure for designing control strategies is therefore needed.

Adaptive control systems automatically adjust controller parameters on-line in response to changes in the system dynamics, or noise characteristics, or both. This study demonstrates the application of a stochastic adaptive controller, the self-tuning controller (STC) of Clarke and Gawthrop (1975), for the real-time control of weir gate openings during flood periods.

The same gate opening control problem for lock and dam has been discussed by Duong, *et al.* (1978) using one type of self-tuning regulator reported by Wieslander and Wittenmark (1971). The summary of self-tuning regulator is given by Astrom and Wittenmark (1973). Though the application of STC to the optimal control of groundwater abstraction for river flow augmentation has already been discussed by O'Connell (1980), as far as we know, its availability to flood control problems has not yet been investigated.

The Onga River weir system is chosen to demonstrate the effectiveness of the technique during flood periods. Specifically, a comparison is made between the existing control strategy and the STC-designed control strategy. Results indicate that the STC design technique can be more effective and more stable.

2. Self-Tuning Controller

STC consists of an on-line recursive system identification algorithm and a feedback control law whose parameters depend on the currently estimated system model. In this report, the system to be controlled is represented by an ARMAX-type model. The system input, which is the control variable, is the total release under the gates, while the system output is the reservoir water surface level; the uncontrollable but observable inflow and abstractions are the exogenous variables. The total release under the gates is determined by the feedback control law so that the difference between the resulting reservoir water surface level and the required one is minimized.

This section outlines the derivation of an STC algorithm for a system (see Figs.1 and 2) described by an ARMAX-type model.

$$A(z^{-1})y(k) = B'(z^{-1})Q(k-s) + C'(z^{-1})I(k-s) + D'(z^{-1})L(k-s) + F(z^{-1})v(k) \qquad (1)$$

where $y(k)$ is the system output (reservoir water surface level), $Q(k)$ is the system input or control variable (total gate release), $I(k)$ (inflow) and $L(k)$ (abstractions) are uncontrollable but observable inputs, $v(k)$ is the uncorrelated zero-mean random sequence, and k and s denote the sampling instant and the pure time delay between input and output respectively. $A(z^{-1})$, $B'(z^{-1})$, $C'(z^{-1})$, $D'(z^{-1})$ and $F(z^{-1})$ are the coefficients polynomials expressed in teams of the backward shift operator, z^{-1}. For example, $A(z^{-1})$ is denoted as

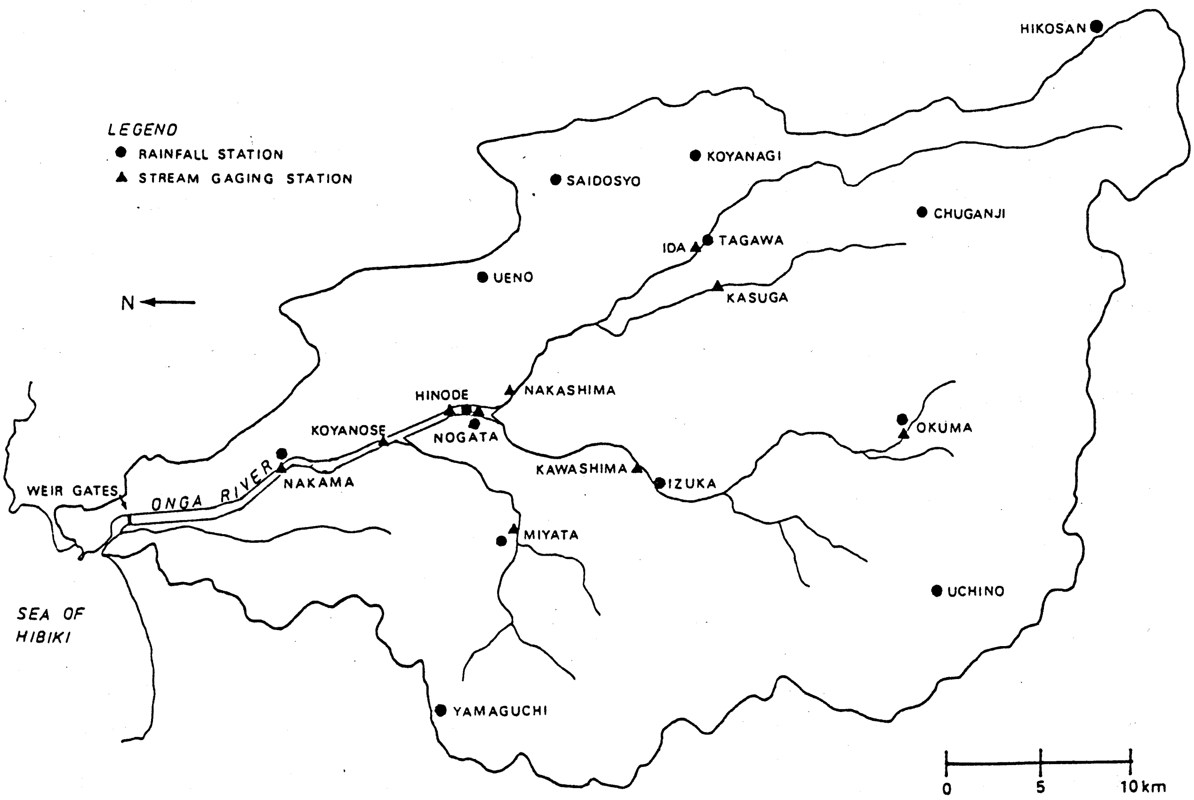

Fig.1 Onga River Basin.

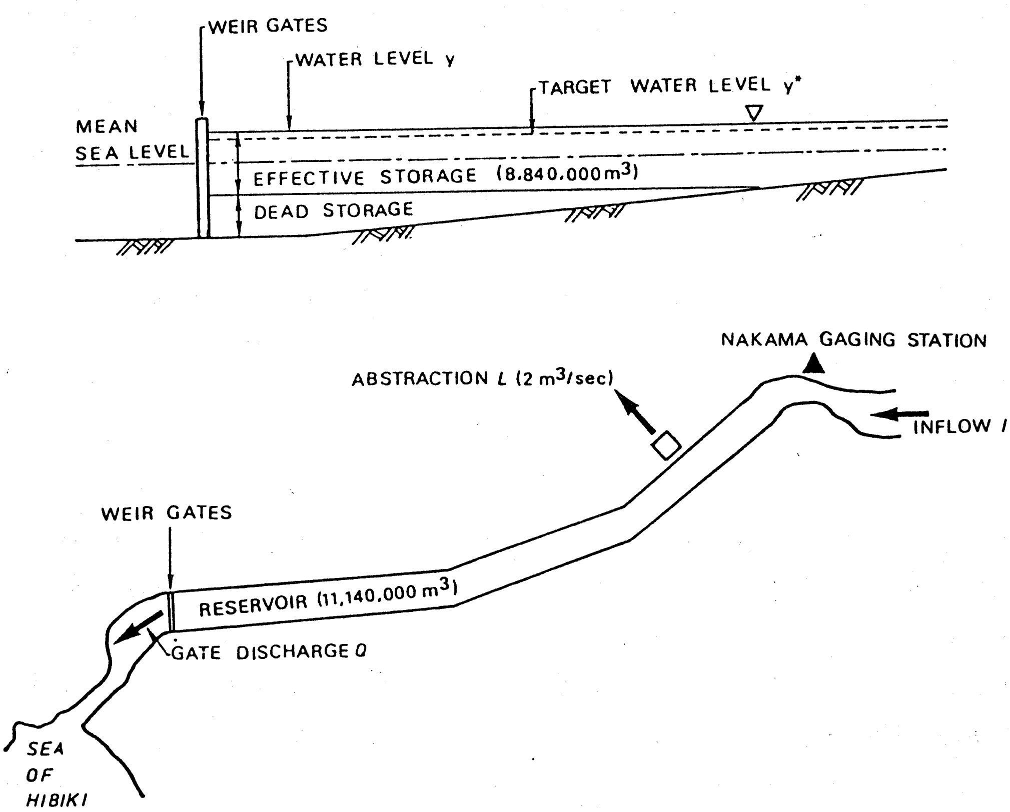

Fig.2 Weir gate openings control problem in Onga River.

$$A(z^{-1}) = a_0 + a_1 z^{-1} + \cdots + a_n z^{-n} \tag{2}$$

where n is the order of the system, and coefficient a_0 for $A(z^{-1})$, f_0 for $F(z^{-1})$ are set without losing generality as $a_0=1$, $f_0=1$. The use of the backward shift operator, z^{-1}, is illustrated as

$$A(z^{-1})y(k) = a_0 y(k) + a_1 z^{-1} y(k) + \cdots + a_n z^{-n} y(k)$$

$$= y(k) + a_1 y(k-1) + \cdots + a_n y(k-n) \tag{3}$$

In the following part, A, B', C', D', F denote $A(z^{-1})$, $B'(z^{-1})$, $C'(z^{-1})$, $D'(z^{-1})$, $F(z^{-1})$ respectively for brevity.

In order to derive the optimal s-step predictor $\hat{y}(k+s|k)$ for the system equation (1), first of all, by transforming equation (1), $y(k+s)$ is given as

$$y(k+s) = \frac{B'}{A}Q(k) + \frac{C'}{A}I(k) + \frac{D'}{A}L(k) + \frac{F}{A}v(k+s) \tag{4}$$

The last term of Eq.(4), the noise term is considered as the sum of two terms as

$$\frac{F}{A}v(k+s) = Gv(k+s) + \frac{H}{A}v(k) \tag{5}$$

where G and H are the coefficients polynomials of order $s-1$ and $n-1$ respectively,

$$G = G(z^{-1}) = g_0 + g_1 z^{-1} + \cdots + g_{s-1} z^{-(s-1)} \tag{6}$$

$$H = H(z^{-1}) = h_0 + h_1 z^{-1} + \cdots + h_{n-1} z^{-(n-1)} \tag{7}$$

The first term of Eq.(5) represents future noises, which has nothing to do with control vauable $Q(k)$, and the second term of Eq.(5) is noises that have occured up to and including time step k. From Eq.(5) polynomial H is given as

$$H = (F-AG)z^s \tag{8}$$

On the other hand, $v(k)$ is expressed from Eq.(1) as follows:

$$v(k) = \frac{A}{F}y(k) - [\frac{B'}{F}z^{-s}Q(k) - \frac{C'}{F}z^{-s}I(k) + \frac{D'}{F}z^{-s}L(k)] \tag{9}$$

By substituting Eq.(9) into Eq.(5), and Eq.(5) into Eq.(4), and considering Eq.(9), Eq.(4) is transformed as follows:

$$y(k+s) = \frac{H}{F}y(k) + \frac{GB'}{F}Q(k) + \frac{GC'}{F}I(k) + \frac{GD'}{F}L(k) + Gv(k+s) \tag{10}$$

Then, the optimal s-step predictor $\hat{y}(k+s|k)$ is derived as the minimum square error predictor of Eq.(11) (Astrom (1970)).

$$E[\ y(k+s) - \hat{y}(k+s|k)\ ]^2 \tag{11}$$

By substituting Eq.(10) into Eq.(11), and as the minimum square error predictor, $\hat{y}(k+s|k)$ is given as follows:

$$\hat{y}(k+s|k) = \frac{H}{F}y(k) + \frac{GB'}{F}Q(k) + \frac{GC'}{F}I(k) + \frac{GD'}{F}L(k) \tag{12}$$

The prediction error $\varepsilon(k+s)$ is given by

$$\varepsilon(k+s) = Gv(k+s) \tag{13}$$

The objective of STC is to control the input $Q(k)$ such that the cost function given by Eq.(14) is minimized. The cost function consists of expectation of the sum of square for the deviation of reservoir water surface level from a target value or 'set point' and the chage in the control variable from one time step to the next.

$$J(k) = \mathrm{E}\ [\ \{\ y(k+s) - y^*(k+s)\}^2 + \lambda'\{Q(k) - Q(k-1)\}^2] \tag{14}$$

Here E is the expectation operator, $y^*(k+s)$ is the set point which is the target reservoir water surface level, and the factor λ' is the weight for the change in the control variable from one time step to the next, and is used to stabilize the controller by penalizing the control effort(O'Connell, 1980).

Unknown at time k, $y(k+s)$ must be set equal to $\hat{y}(k+s|k)$ (Eq.(12)) with prediction error $\varepsilon(k+s)$ (Eq.(13)), as

$$y(k+s) = \hat{y}(k+s|k) + \varepsilon(k+s) \tag{15}$$

Substituting Eq.(15) into Eq.(14), and taking the mathematical expectation and setting the derivative of $J(k)$ with respect to $Q(k)$ equal to zero to obtain the minimum cost:

$$\{\hat{y}(k+s|k) - y^*(k+s)\}\frac{\partial\hat{y}(k+s|k)}{\partial Q(k)} + \lambda'\{Q(k) - Q(k-1)\} = 0 \tag{16}$$

Using $\partial\hat{y}(k+s|k)/\partial Q(k) = b_0'$ (from Eq.(12)), the control law is given by:

$$\hat{y}(k+s|k) - y^*(k+s) + \lambda\{Q(k) - Q(k-1)\} = 0 \tag{17}$$

where $\lambda = \lambda'/\ b_0'$ (18)

Define a generalized output function ψ such that

$$\psi(k+s) = y(k+s) - y^*(k+s) + \lambda\{Q(k) - Q(k-1)\} \tag{19}$$

In order to predict $\psi(k+s)$, $y(k+s)$, unknown at time k, must be set equal to $\hat{y}(k+s|k)$ so that

$$\hat{\psi}(k+s|k) = \hat{y}(k+s|k) - y^*(k+s) + \lambda\{Q(k) - Q(k-1)\} \tag{20}$$

Then the output prediction error for $\hat{\psi}(k+s|k)$ is equal to $\varepsilon(k+s)$ (Eq. (8)), i.e.,

$$\psi(k+s) = \hat{\psi}(k+s|k) + \varepsilon(k+s) \tag{21}$$

Therefore the minimization of J is the same as setting the prediction of ψ equal to zero at every time step so that the control law (Eq.(17)) is satisfied. In order to implement the self-tuning scheme, Eq.(12) is substituted into Eq.(20) to obtain

$$F\hat{\psi}(k+s|k) = Hy(k) + BQ(k) + CI(k) + DL(k) - Fy^*(k+s) \tag{22}$$

where $$B = GB' + \lambda F(1 - z^{-1}) \tag{23}$$

$$C = GC' \text{ and } D = GD' \tag{24}$$

If $\hat{\psi}(k+s|k)$ is forced to zero at every time step, then rearrangement of Eq.(22) yields the feedback control law that minimizes the variance of $\psi(k)$

$$Q(k) = -\frac{1}{B}\{Hy(k) + CI(k) + DL(k) - Fy^*(k+s)\} \tag{25}$$

Unlike the control law used by Duong, *et al.* (1978), the self-tuning controller (Eq.(25)) considers a variable set-point which is incorporated directly in the cost function.

The substitution of Eq.(22) into Eq.(21)

$$\psi(k+s) = Hy(k) + BQ(k) + CI(k) + DL(k) - Fy^*(k+s) - F\hat{\psi}(k+s|k)$$

$$+ \hat{\psi}(k+s|k) + \varepsilon(k+s) \tag{26}$$

results in

$$\psi(k+s) = M(k+s)x(k+s) - y^*(k+s) - \{F - 1\}\hat{\psi}(k+s|k) + \varepsilon(k+s) \tag{27}$$

In order to implement the feedback control law (Eq.(25), the coefficients of the polynomials H,B,C,D and F should be estimated (The coefficient f_0 of F is excluded, because of $f_0=1$). This study considers an on-line recursive system identification algorithm within a Kalman filter framework. The Kalman filter for the process is formulated as

$$x(k+1) = x(k) + u(k) \tag{28}$$

$$\psi(k) = M(k)x(k) - y^*(k) + \varepsilon(k) \tag{29}$$

where the state and observation vectors are

$$x(k)= [h_0,\cdots,h_{i-1},\ b_0,\cdots,b_{j-1},\ c_0,\cdots,c_{p-1},\ d_0,\cdots,d_{q-1},\ f_1,\cdots,f_{r-1}]^T \quad (30)$$

$$M(k)= [y(k-s),\cdots,y(k-s-i+1),\ Q(k-s),\cdots,Q(k-s-j+1),\ I(k-s),\cdots,$$

$$I(k-s-p+1),\ L(k-s),\cdots,L(j-s-q+1),\ -y^*(k-1),\cdots,-y^*(k-r-1)] \quad (31)$$

The parameters i,j,p,q and r are the number of terms in the respective polynomials H, B, C, D and F. The measurement equation (29) is given by Eq.(27) with $\hat{\psi}(k+s|k)$ assumed to be zero at every time step k. In order to update the parameters, ψ must be measured at every time step k. This quantity $\psi(k)$, which is defined as replacing $k+s$ by k in Eq.(19), is considered as the measured value of ψ at time step k.

The control law (25) uses the estimated parameters $\hat{x}(k|k)$ at each sample instant k as if they had the true values.

3. Example System

The two examples discussed below illustrate the behaviour of STC and compare its performance with that of the existing control strategy during flood periods. Both existing and STC-designed control strategies involve the estimation of a target gate release which is the basis for calculating the opening heights of the gates.

The Onga River is located in Fukuoka Prefecture, Kyushu Island, Japan (see Fig.1). It has a drainage area of 938.6 km^2 at the weir gate structure and a length of 61 km. The average annual rainfall in the basin is 1500 to 1700 mm in the plains and 2500 to 2700 mm in the mountains. The weir gate structure (see Fig.2) is located at 2.0 km from the Sea of Hibiki. The reservoir dammed by the weir has a total capacity of 11,140,000 m^3 and 8,840,000 m^3 of which is the effective volume. It has a surface area of 2.94 km^2 and a length of 9.39 km. At 6.85 km from the weir, 172,800 m^3 of water is being abstracted daily for municipal and industrial water supplies. The weir gate structure has a total length of 517 m and is composed of seven main gates and two auxiliary gates for small flows and fishway.

During flood periods, operation of the gate is far more critical than during periods of low inflows, because of the very fast variations of water levels, and higher-than-required water levels would cause severe flooding to areas at the upper end of the reservoir. Hence the control of the weir gate openings has to be done every 10 min during these periods. Considering the shortness of the period between adjustments, an automatic controller is justifiably important.

The existing control strategy deterministically estimates the target gate release as

$$Q(k) = \alpha\,[y(k) - y^*(k)] + I(k) - L(k) \tag{32}$$

where

$$\alpha = [aI(k) + b][\frac{c|I(k) - I(k-3)|}{I(k)} + 1] \tag{33}$$

For $I(k) \leqq 24$ m^3/s, $a = 0$, $b = 200$ and $c = 0$; for 24 m^3/s $\leqq I(k) \leqq 300$ m^3/s, $a = 4.71$, $b = 87$, and $c = 3$; and for $I(k) > 300$ m^3/s, $a = 3.57$, $b = 428.6$ and $c = 3$. The target reservoir water surface level $y^*(k)$ is at El. 1.45 m for $I(k) > 24$ m^3/s and at El. 1.485 m for $I(k) \leqq 24$ m^3/s. If $I(k) \geqq 1200$ m^3/s, there is no target reservoir water surface level, that means the control is terminated, and the gates are fully opened.

In applying STC to Onga River weir gates operation, the system model considered is

$$y(k) = -a_1 y(k-1) + b_0' Q(k-s) + c_0' I(k-s) + d_0' L(k-s) + v(k) \tag{34}$$

based on the reservoir continuity equation. One time step equals 10 minutes, and the time delay $s = 1$ step. The feedback control law for the system described by Eq.(34) will be derived as follows. The coefficents polynomials $A(z^{-1})$, $B'(z^{-1})$, $C'(z^{-1})$ and $F(z^{-1})$ are expressed as follows:

$$A(z^{-1}) = a_0 + a_1 z^{-1} = 1 + a_1 z^{-1} \tag{35}$$

$$B'(z^{-1}) = b_0', \qquad C'(z^{-1}) = c_0' \quad \text{and} \quad D'(z^{-1}) = d_0' \tag{36}$$

$$F(z^{-1}) = f_0 = 1 \quad \text{and} \quad G(z^{-1}) = g_0 = 1 \tag{37}$$

Applying Eq.(8):

$$H(z^{-1}) = -a_1 \tag{38}$$

Recalling Eq.(23) and Eq.(24):

$$B(z^{-1}) = b_0' + \lambda(1 - z^{-1}) \tag{39}$$

$$C(z^{-1}) = c_0' \quad \text{and} \quad D(z^{-1}) = d_0' \tag{40}$$

Using Eq.(22):

$$\hat{\psi}(k+s|k) = -a_1 y(k) + (b_0'+\lambda)Q(k) - \lambda Q(k-1) + c_0' I(k) + d_0' L(k)$$

$$- y^*(k+s) \tag{41}$$

Hence, the feedback control law is

$$Q(k) = -\frac{1}{b_0}\{h_0 y(k) + b_1 Q(k-1) + c_0 I(k) + d_0 L(k) - y^*(k+s)\} \tag{42}$$

where $h_0 = -a_1$, $b_0 = b_0' + \lambda$, $b_1 = -\lambda$, $c_0 = c_0'$ and $d_0 = d_0'$ (43)

In Eq.(42) or Eq.(30), the number of parameters to be estimated is five, $x = [h_0, b_0, b_1, c_0, d_0]^T$, and in Eq.(31), $M(k) = [y(k-s), Q(k-s), Q(k-s-1), I(k-s), L(k-s)]$. In this study the weight value λ in Eq.(19) is set to -0.0001, and in executing the Kalman filter algorithm, the initial estimates are $h_0 = 1$, $b_0 = -0.0002$, $b_1 = 0.0001$, and $c_0 = d_0 = 0.0001$; the diagonal elements of the initial error covariance matrix of $\hat{x}(0|0)$ equal 1.0 for h_0 element and 10^{-8} for other elements, and off-diagonal elements equal 10^{-10}, the covaricance matrix U of system noise u in Eq.(28) equals zero, the variance V of measurement noise ε in Eq.(29) equals 0.01.

In this study, the control strategies are applied in the flood periods since it is the most critical period in the control of gate openings. Both existing and STC-designed control strategies are applied to the data resulting from the actual operation of the weir gates during the floods on June 23-29, 1985 (Flood 1) and July 2-4, 1985 (Flood 2). It must be emphasized that the actual gate operation was based on the target gate release by the existing control strategy (Eq(32)). The two examples discussed in this chapter involve the determination of the target gate release.

Example 1 (Fig.3 and Fig.4) demonstrates the use of the existing control strategy (Eq.(32)) during these floods. Example 2 (Fig.5 and Fig.6) shows the use of the STC-designed control strategy (Eq.(42)), where the data used in estimating the parameters of this feedback control law are those values of Q and y obtained from the simulation of the gate operation based on STC target gate release. In this case, the STC-simulated gate operation assumes that the discharge under the gates equals the STC target gate release. Two examples use the same values of $I(t)$ and $L(t)$ observed during the floods. Fig.3 to Fig.6 contain the plots of observed and target $Q(k)$ and observed and expected $y(k+s)$ for each flood; observed values are in solid line and target and expected values associated with the control strategy are in circled line. In all figures, the expected $y(k+s)$, the reservoir water level at time step $k+s$, is calculated using the reservoir continuity equation, assuming that the actual Q equals the target Q, and the

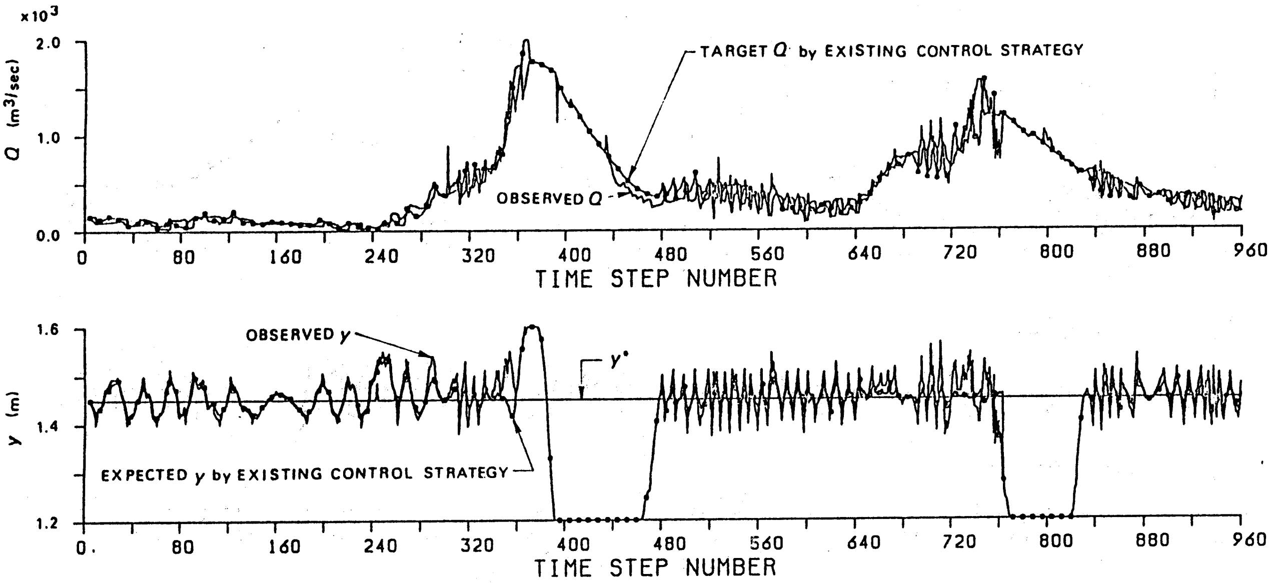

Fig.3 Performance of the existing control strategy for Flood 1.

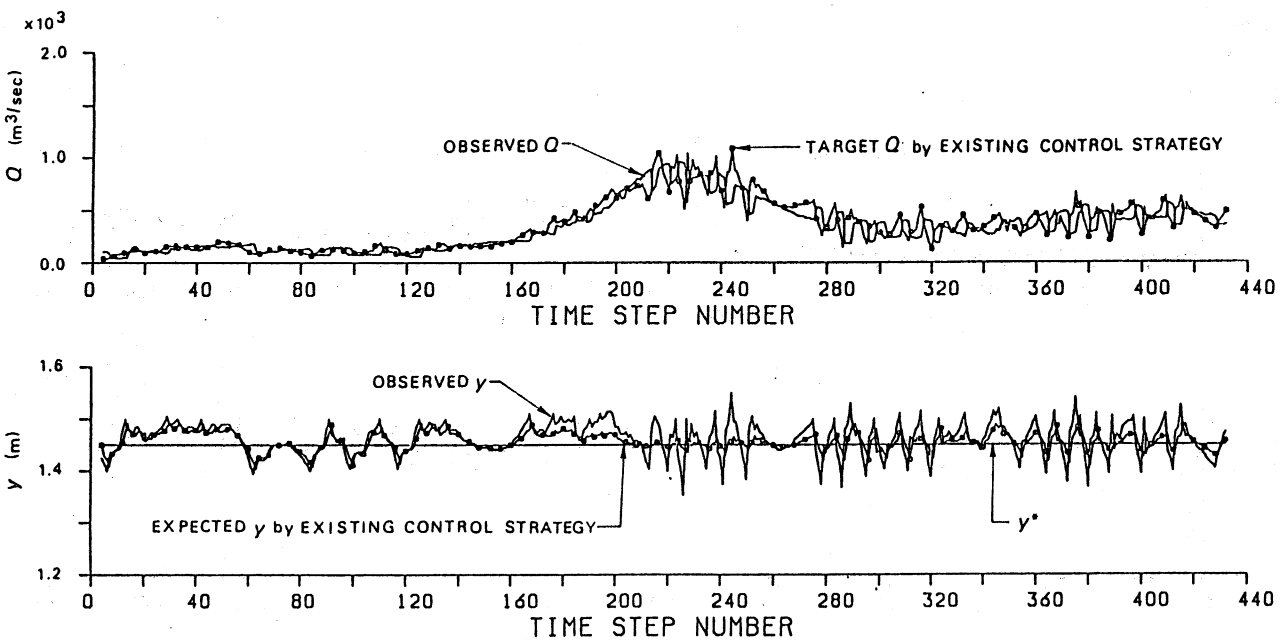

Fig.4 Performance of the existing control strategy for Flood 2.

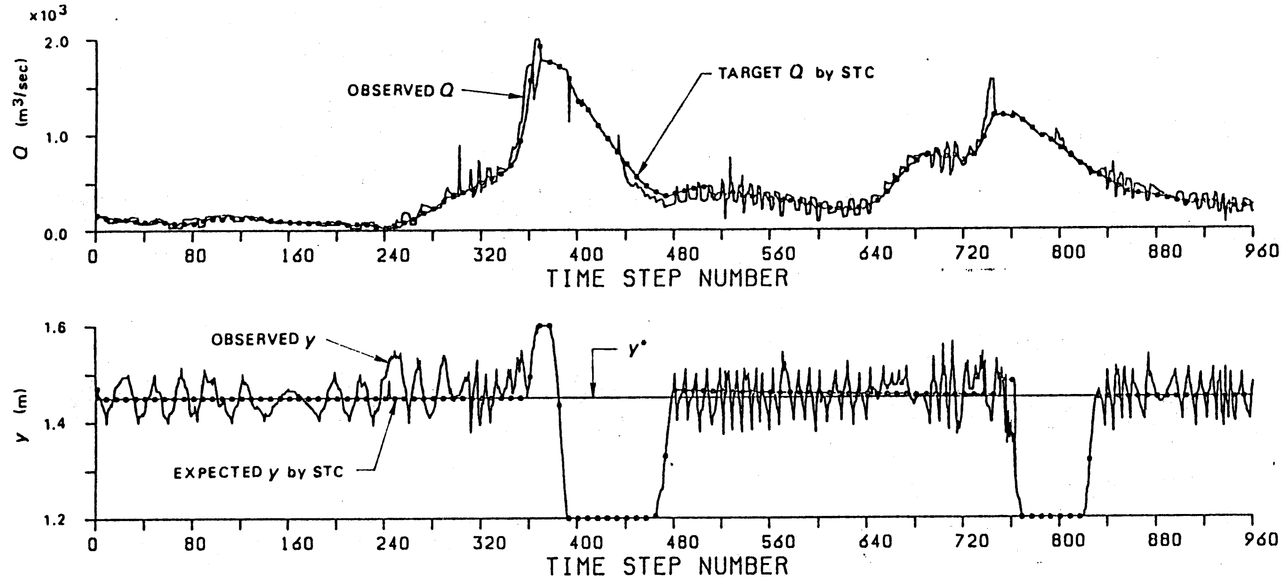

Fig.5 Performance of STC for Flood 1.

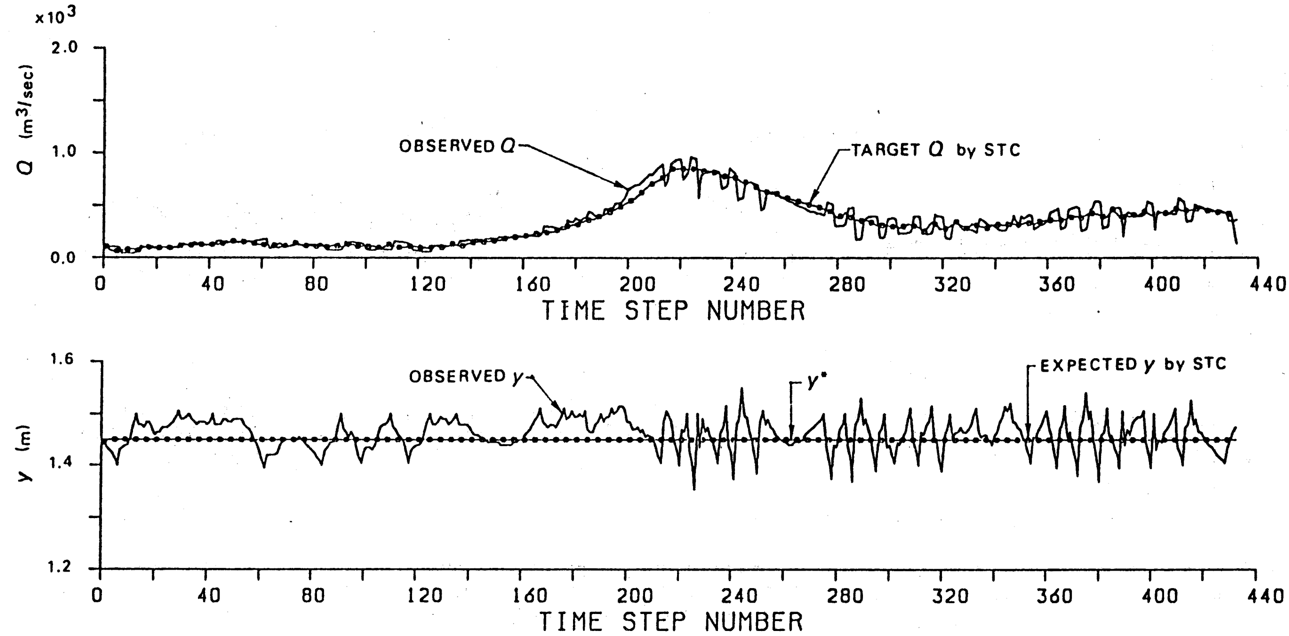

Fig.6 performance of STC for Flood 2.

elevation-storage curve.

4. Discussion

This section presents the discussion of results in the two examples.

In Figs.3 and 4 the target gate release $Q(k)$ is calculated from Eq.(32) given $y^*(k)$ and the observed $y(k)$, $I(k)$ and $L(k)$. The parameter α in Eq.(32) depends only on I and neither on the error between the present and target water levels nor on the present gate discharge. Notice in the figures that, although the opening heights of the gates are calculated using the target gate release, the actual (observed) gate release differs much from the target gate release. This is because, besides the target gate discharge, the actual gate operation is also determined by the predicted tidal water level downstream of the gates, the assumed gate coefficient, the speed at which each gate moves, the present opening heights of the gates, and so on. (Of these factors, the assumed gate coefficient is considered as the most uncertain.) Their effects are also shown by the fluctuating behaviour of the actual reservoir water surface levels about the target water level in Fig.3 and Fig.4.

During periods from about 390 to 460 step and from about 770 to 820 step in Fig.3, the reservoir water surface level lowered quickly. This is because that inflow I is 1200 m^3/s or more during these periods, so that the gates were fully opened. From the circles lines of Figs.3 and 4, the expected reservoir water surface level controlled by existing control strategy is unstable, fluctuate and differs much from target one.

Next, the performance of STC-designed control strategy in Figs.5 and 6 indicate that the target gate release Q behaves very smoothly and more realistic than that by existing strategy in Figs.3 and 4. Moreover it shows that the expected water surface level $y(k+s)$ is very stable and is practically equal to target water level $y^*(k+s)$ especially in Fig.6, if the STC target gate release obtained from Eq.(42) is perfectly followed. Even though the actual gate discharge may differ from the target gate release, better control can still be achieved using STC than employing the existing control strategy.

To obtain a quantitative measure of the performance of the controllers, the root mean square of deviation of reservoir water surface level from the target one is calculated for a period beginning after simulation starting transients have died out. A decision on the quality (goodness) of the controller is related to the lowest value of this index. The value by the exsisting control strategy is 0.019 (m) for Flood 1 and 0.018 (m) for Flood 2. On the other hand, the value by the STC is 0.002 (m) for Flood 1 and 0.001 (m) for Flood 2. These values show that the deviation of reservoir water surface level from the targer one by STC is greatly smaller than that by exsisting control strategy.

From the above results conclude that STC is much more effective than existing control strategy for real-time control of estuarial weir gate during flood periods.

5. Conclusions

The STC control law Eq.(42) has been found to be well suited for the optimal control of weir gate openings. The performance of STC has been found to be superior to that of the existing control strategy Eq.(32). For this system described by an ARMAX-type model, the control variable (gate discharge) depends particularly on the exogenous variables (inflow and abstraction), which is obvious for the reservoir process. The satisfactory results shown in this study could serve as a basis for more applications of STC to water flow and water level control problems arising in flood control systems, water resources systems, water distribution networks and sewer control systems. In general, this study has shown some interesting characteristics of the use of STC to the control of weir gate openings.

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