TUNING OF PI CONTROLLERS FOR AN IRRIGATION CANAL USING OPTIMIZATION TOOLS

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ABSTRACT

Existing methods for the automatic control of water levels in irrigation canals are based on single input, single output linear feedback PI type controllers. Examples of such control systems are EL-FLO and BIVAL, where local PI controllers are used in series to adjust the position of upstream/downstream control gates.

Linear control theory provides many tools for tuning a PI controller (Astrom and Hagglund 95). But when the system consists of many interconnected non-linear subsystems such as irrigation canals, tuning is challenging. In such cases, control parameters are usually tuned by trial and error during operation or with the help of a simulation model.

This paper proposes a global approach for tuning local PI controllers for a series of interconnected canal pools using optimization tools. The approach couples a hydraulic model based on full Saint Venant equations and a minimization algorithm. This complex non-linear optimization problem is solved by an evolutionary approach where a problem with a smaller number of independent variables is solved first and used as starting point for the higher level problem. Control test results are shown for two kinds of canals, one with short reaches and exhibiting wave propagation and the other with long reaches and exhibiting delays and damped wave motion.

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INTRODUCTION

Control algorithms used to regulate irrigation canals can be classified according to different criteria (Malaterre 98). One of these criteria is the design technique, monovariable or multivariable.

Local control with monovariable design technique is often used because it is easy to implement and tune. The controlled pool gates are operated using local information and there is no need for a supervisory system. The disadvantage of this design is that several interconnected local optimal controllers do not guarantee a globally optimal one. A procedure is needed for tuning local controllers so that the global performance of the system is optimal.

An optimization method is proposed to determine the globally best tuning of the local controllers for a given set of perturbations at offtakes. Optimal parameters are found by minimizing a performance criteria. An algorithm derived from non-linear programming (the simplex method) is used to find the global minimum (Nelder 65). To compute the criteria a hydrodynamic model for irrigation canals is used, that makes possible to simulate flows in a canal regulated by controllers (SIC 92). This procedure is used to tune five distant downstream PI controllers that operate five consecutive gates for two types of canal test.

LOCAL AUTOMATIC FEEDBACK CONTROLLERS

Local automatic control is accomplished with control equipment located at the gate using water levels from adjacent pools (Rogers 98). Various types of algorithms and equipment, like EL-FLO (Buyalski 79), have been used for local control in a canal. The Proportional, Integral and Derivative (PID) control algorithm is by far the most commonly used in control engineering and its philosophy has been integrated to a number of canal control methods. With a PID controller, the command is proportional to the deviation of the controlled variable, the cumulative deviation and the changing speed of the controlled variable. The behavior of the "textbook" version of the PID algorithm can be written as:

$$u(t) = kp\, e(t) + kd \frac{de(t)}{dt} + ki \int e(t)dt \qquad (1)$$

where u = control action, e(t) deviation of the controlled variable from its target at time t and kp, ki, kd = proportional, integral and derivative gains. The integral term is used to eliminate the static error and the derivative to anticipate the response. The PID is very often reduced to a PI controller because it is difficult to tune it properly (Astrom 95). The PI controller comes in many different ways, and can also be written in incremental form (Burt 98). Many different methods have been developed to tune PI controllers, like the well-known Ziegler Nichols method (Ziegler 42) for analog PI, or the Takahashi method (Takahashi 72) for digital implementation. All these techniques are very useful for SISO systems. For a canal with many interconnected pools in series, use of these tuning techniques is difficult because of the interaction between them.

GLOBAL OPTIMIZATION OF LOCAL CONTROLLERS

Principle

Optimization is a powerful tool for tuning controllers with few parameters (Astrom 95). This technique has been successfully applied to tune PI controllers. The optimization problem is posed as the minimization of a performance criteria. There are several problems when using optimization methods. The main one is that for a non-convex problem, the function to be minimized may have local minima and it is impossible to guarantee that the obtained solution is an absolute minimum.

It is proposed to use optimization technique to tune local PI controllers in series. The opening of the upstream gate of the pool is computed by the PI controller to maintain the target water level at the downstream end of the pool. It is chosen to use five pools to have an interesting system to control.

The problem to solve is how to optimize the five kp and ki parameters acting on the five gates to maintain the target levels at the downstream end of the five pools. The methodology proposed can be summarized in three steps:

- define a criteria ξ function of the error level at the downstream end of the pools,

- choose a scenario of perturbations at offtakes,

- simulate the behavior of the five-pool canal with an unsteady flow model to compute the criteria for the set of parameters and scenario tested.

At this stage, the problem is to minimize the performance criteria which is a nonlinear multivariable function of the parameters. The value of this function at one point is known by numerical simulation. The simplex method (Nelder 65) is well suited for this kind of problem, as it uses a geometric approach that does not need gradient computation. A constrained modified version of the simplex method was used to avoid negative values of kp and ki (SAU 95).

Performance criteria

For water levels in an irrigation canal, large deviations from the target value and oscillations are dangerous. So a performance criteria based on ISE (Integral of the Squared Error) is better than a performance criteria based on IAE (Integral of the Absolute Error) because it gives more weight to large errors. The idea is to build a criteria of the following form:

$$\xi = \sum_{i=1}^{5} \int_{0}^{T} [(Z_i(t)-Z_{Ti})^2+\delta u_i^2]dt \qquad (2)$$

where T is the length of the scenario, Z_i the water level and Z_{Ti} the target level at the downstream end of pool i, δu is the gate opening variation. The variation of gate opening is introduced in the performance criteria, in order to avoid large variations of gate opening. It is possible to give different weight to the water level error and to the gate opening variation as in the LQG technique (Malaterre 94). In our case, each term of the criteria was given the same weight.

Scenario at offtakes

The global optimization of the five PI controllers needs the choice of a scenario of perturbations. The optimal parameters depend obviously of the chosen perturbation scenario. Very often, in process control, a step perturbation or a Pseudo Random Binary Signal is used. For an irrigation canal, it seems more useful to choose a realistic scenario. A scenario was constructed with discharges measured at pumping stations on an on-demand system. It is observed two peaks of demand per day, one around 10 a.m. and the other around 8 p.m. The scenario is seven days long and the peaks of discharge of each day are generated randomly around the mean value. A typical scenario of discharge at offtake is shown (Figure 1)

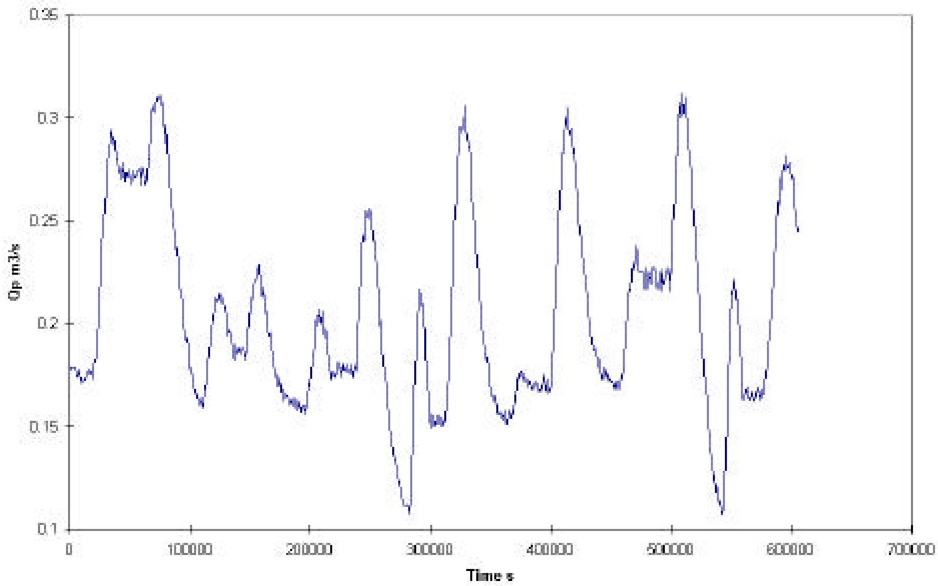

Figure 1 : scenario at offtake

As the dynamics of a canal is nonlinear, it is very important to chose different discharges released at the head end to have a controller with some robustness.

Otherwise parameters will be tuned for a specific discharge and the regulation may have some problems to handle perturbations for another discharge. The scenario at offtake is built from three different flows, one around the maximum discharge, the other near the medium discharge and the last at the minimum discharge. Therefore, the scenarios last for 21 days. With this choice, mean parameters are found for the PI and it is more robust to non linearity at gates and pools dynamic.

Optimization procedure

As the criteria depends on ten parameters and the function is not linear, it is difficult to find a good minimum value. The idea is not to use the simplex method once with ten parameters, but to solve first a problem with less parameters and then progressively to give more degrees of freedom. This approach is set up from downstream to upstream pools. First, the same kp and ki are used for all 5 pools (2 parameters) and the solution is used as starting value for the next optimization step. Then, kp5 and ki5 for the last downstream pool and the same kp and ki for the four upstream pools are optimized (4 parameters) and so on until the ten parameters are optimized for all the canal. The initial set of parameters used to start the next step is the one obtained as the solution of the previous one. This procedure is the one that gives the lowest value for the performance criteria. An approach of the same type from upstream to downstream pools has always given a higher criteria. This seems due to the fact that the PI coefficients are decreasing from upstream to downstream near the solution.

One problem with the above-described procedure is choosing the two initial values for ki and kp. It was found that it is better to choose parameters of a very slow regulator. If initial values are too high, the procedure can be trapped in a local minimum due to water oscillations in the canal. One possibility is to compute parameters for one reach by a classical tuning method like Ziegler Nichols and to lower the parameters until no oscillation occurs.

APPLICATIONS

Presentation of canal tests

To illustrate the performance of this global optimization of local controllers, two test canals are used.

Fluctuations in discharge and water depth in a canal pool are due to two physical phenomena, wave propagation and mass transport. A dimensionless analysis has shown that two numbers characterize the dynamic of a pool (Baume 97), the Froude number Fr and a dimensionless length $\chi = \frac{Sb\ Xr}{yn}$, where Sb is the bed slope, Xr the reach length and yn the normal depth. The study showed that χ

characterizes discharge propagation and $\eta = \frac{\chi}{Fr\,(1-Fr)}$ downstream level perturbations.

For each dimensionless number, values were determined that characterize different kinds of behavior (Baume 98). The study of upstream to downstream discharge transfer function, for a wide rectangular channel, shows that 3 classes can be built. If $\chi < 3/5$ a first order model is able to model the discharge dynamic. For $3/5 < \chi < 27/20$ a second order model is needed and for $\chi > 27/20$ a second order with delay.

The study of downstream level to upstream level transfer function shows that if $\eta > 3$ there is no influence of the downstream perturbation on the upstream part of the reach (the wave is completely damped). Using classes for χ and η five kinds of behavior can be found for a reach dynamic as χ and η are linked. It was shown that these limits are still valid for non-rectangular channel.

Table 1: Reach characteristics

	Type 1	Type 5
η_m	1.038	6.578
η_M	2.432	14.339
χ_m	0.141	1.642
χ_M	0.308	3.535
B	7 m	8 m
m	1.5	1.5
S_b	0.0001	0.0008
X	3000 m	6000 m
K	50	50
Q_m	3.5 m^3/s	20 m^3/s
Q_M	14 m^3/s	80 m^3/s
y_m	0.97 m	1.36 m
y_M	2.12 m	2.92 m

Reaches characteristics are described in Table 1, where Type 1 is a short reach with wave propagation and Type 5 is a long reach with damped motion and delay.

Where B is the bed width, m the side slope, y the uniform depth, K is the Strickler coefficient used to compute the friction slope. Subscripts m and M are for minimum and maximum discharge.

An example of Bode response for the discharge transfer function is shown (Figure 2) and (Figure 3) to illustrate the difference of dynamics between the two reaches. Some amplitude peaks are obtained for high frequencies for type1 due to wave propagation.

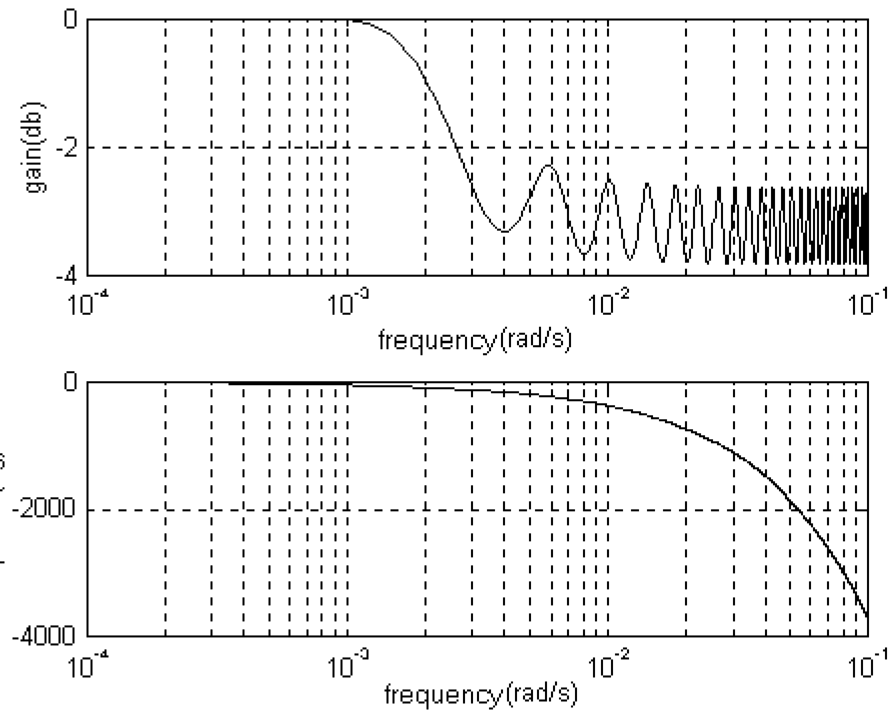

Figure 2 : Type 1, Bode response for discharge

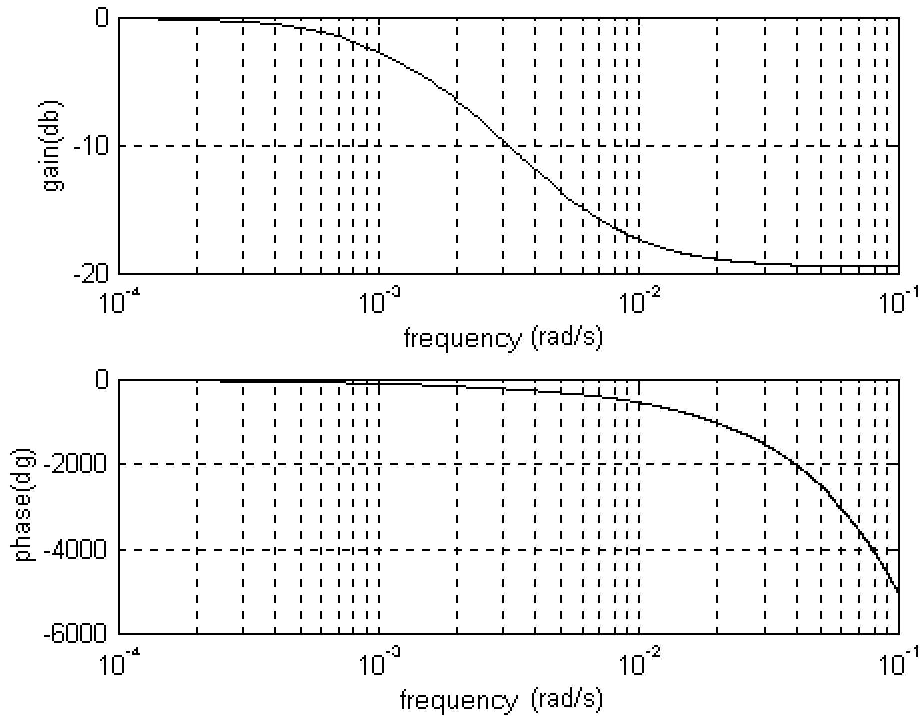

Figure 3 : Type 5, Bode response for discharge

Gate characteristics for the two types are described in Table 2. These values are chosen to have the same dimensionless discharge coefficient.

Table 2: Gate characteristics

	Type 1	Type 5
L	10.18 m	12.38 m
cd	0.824	0.807
d	0.04 m	0.48 m

Where L is the width, cd the discharge coefficient and d the drop. The target level upstream the gate is taken at y_M .

Results for Type 1

To use the optimization procedure described above, the chosen scenario was the following. The discharge released at the upstream pool was 10.5 m3/s for high flows, 7 m3/s for medium flows, and 3.5 m3/s for low flows. The mean peak of discharge at each offtake is taken at 5% of the corresponding initial flow at the head of the system. Table 3 shows the resulting set of parameters for all the reaches at each step of the optimization process.

Table 3: Optimization Type1

step	iter	ξ	kp					$ki10^4$				
			1	2	3	4	5	1	2	3	4	5
ini.			0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
1	24	385	2.65	2.65	2.65	2.65	2.65	3.11	3.11	3.11	3.11	3.11
2	67	277	2.62	2.62	2.62	2.62	2.63	8.88	8.88	8.88	8.88	0.14
3	127	140	2.72	2.72	2.72	1.83	0.29	11.80	11.80	11.80	1.38	0.01
4	138	115	2.59	2.59	1.91	0.40	0.20	17.44	17.44	9.23	2.00	0.04
5	207	105	2.87	2.43	2.09	2.16	0.32	17.79	16.72	3.25	1.77	0.51

The minimun of the performance criteria is ξ = 105 m^2s or in dimensionless ξ^* = 5.05 10^{-3}. If the upstream to downstream approach is used the criteria is not so good, ξ = 141 m^2s .

The parameters tuned with our procedure give an interesting solution because the criteria is very low compared with local optimization. The Ziegler Nichols method was applied to one reach and gives: kp = 2.2 and ki = 6.7 10^{-4}. These values do not take into account all the interactions between reaches. If these parameters are used, the criteria ξ is equal to 807 m^2s, far from the minimum.

(Figure 4) shows the upstream discharge and (Figure 5) shows the water levels at the downstream end of each pool (water level is modified for visibility) for a simulation using the optimized parameters and the scenario at offtakes described above.

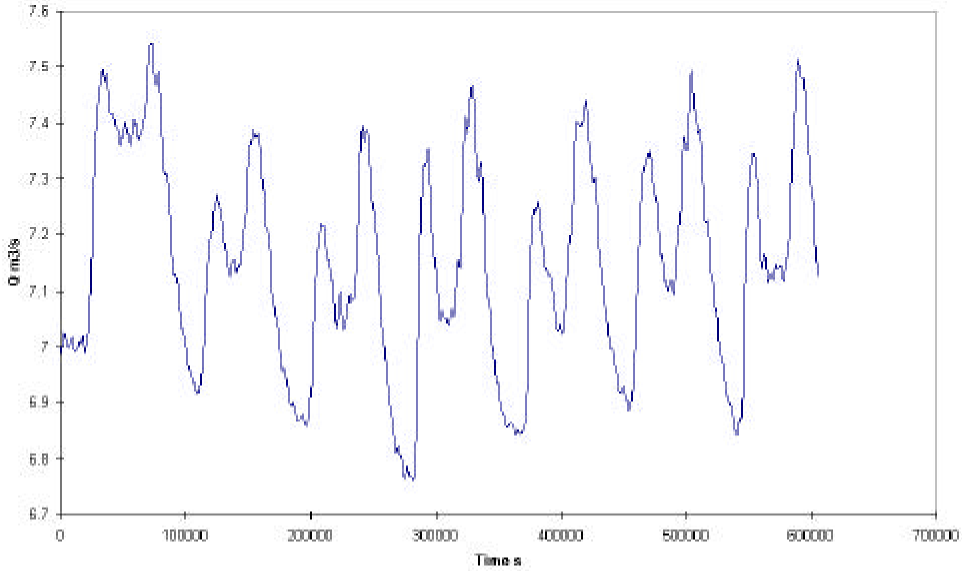

Figure 4: Upstream discharge

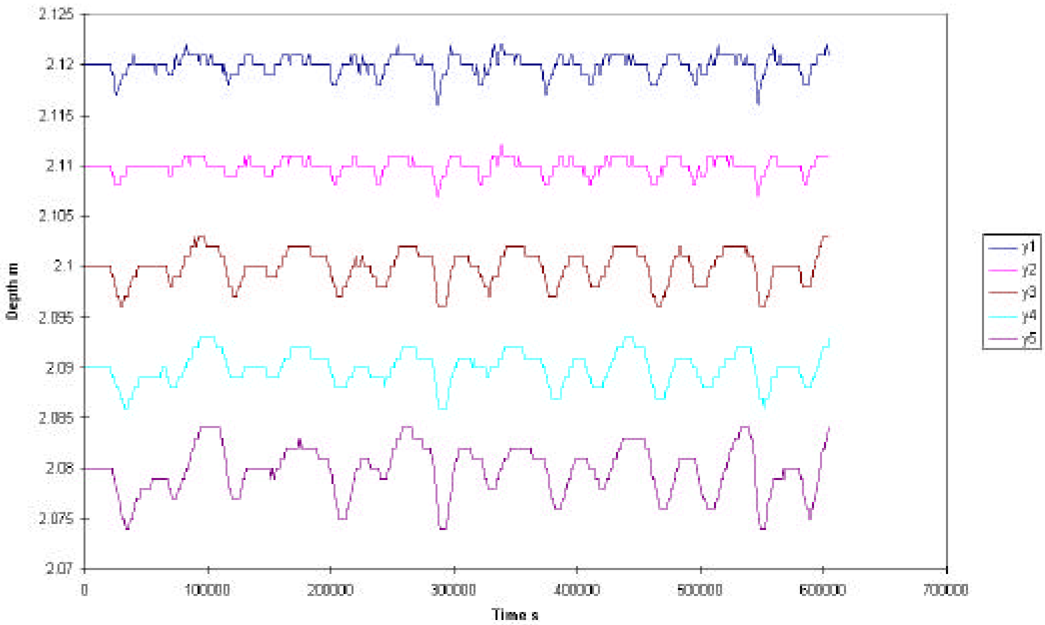

Figure 5: Water levels

The downstream water level of the last pool is not regulated as well as the others. So it seems that the optimization takes into account interactions between subsystems and the water level is controlled by the discharge upstream of the pool but also by the modifications at the downstream gate, which is not the case for the last reach. Anyway, even with this optimization procedure downstream reaches are not regulated as well as upstream reaches.

The response to a step perturbation of 1m^3/s at the offtake of the downstream end of the first reach is shown (Figure 6) and (Figure 7). (Figure 6) shows the upstream discharge and (Figure 7) shows the water levels at the downstream end of each pool (water level is modified for visibility).

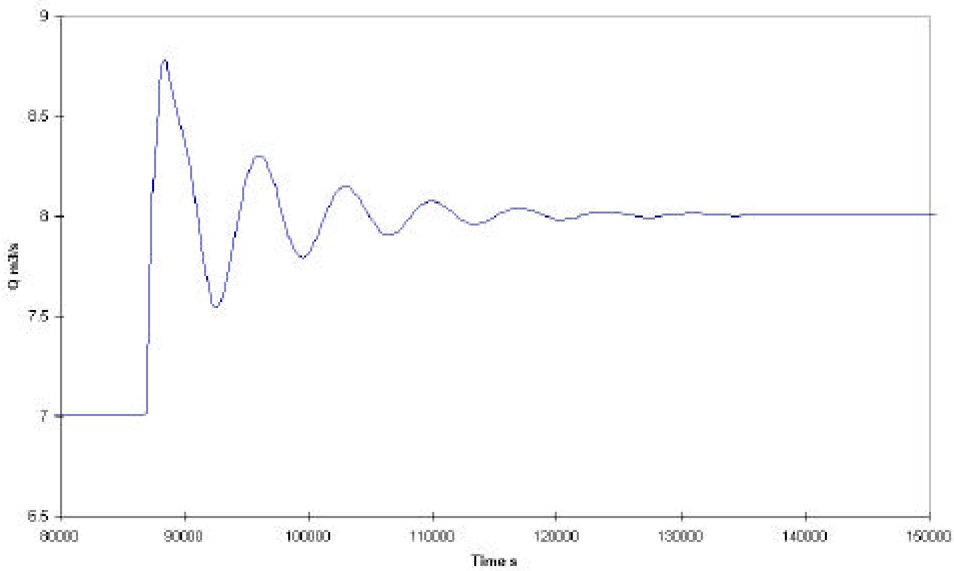

Figure 6 : Upstream discharge for step perturbation

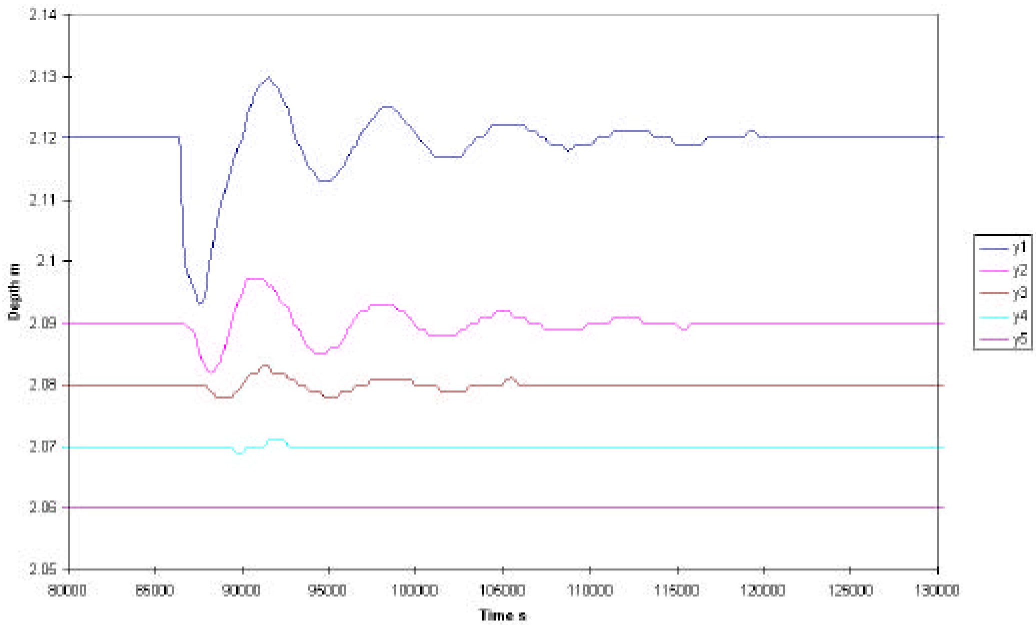

Figure 7 : Water levels for step perturbation

These figures show that the response to a load disturbance is poorly damped. This can be explained by the type of scenarios chosen for the optimization. Notice that the gains obtained with the optimization process are lower than with Ziegler Nichols method and that the gains are lower from upstream to downstream gate controllers.

Results for Type 5

The perturbation scenario at offtake was the following. The discharge released at the upstream pool was 60 m^3/s for high flows, 40 m^3/s for medium flows, and 20 m^3/s for low flows. The mean peak of discharge at each offtake is taken at 5% of the corresponding initial flow at the head of the system.

With the global optimization the criteria is = 14008 m^2s or in dimensionless $\xi^* = 0.605$. Table 4 shows the different steps of the optimization process.

Table 4: Optimization Type 5

step	iterations	ξ	kp					$ki10^4$				
			1	2	3	4	5	1	2	3	4	5
ini.			0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
1	29	36737	0.435	0.435	0.435	0.435	0.435	0.021	0.021	0.021	0.021	0.021
2	107	21117	0.458	0.458	0.458	0.458	0.001	0.028	0.028	0.028	0.028	0.001
3	85	17475	0.486	0.486	0.486	0.146	0.001	0.059	0.059	0.059	0.016	0.006
4	313	16303	0.512	0.512	0.363	0.170	0.017	0.017	0.017	0.033	0.031	.0055
5	907	14008	0.595	0.404	0.285	0.130	.0005	1.495	0.437	0.045	0.073	.0045

For this type of reach the optimization process needs more iterations than for the type1 and the criteria in dimensionless form shows that the precision of the regulation is not so good. This confirms that a damped and delayed system is more difficult to control with this kind of controller.

(Figure 8) shows the upstream discharge and (Figure 9) shows the water levels at the downstream end of each pool (the water level is modified for visibility).

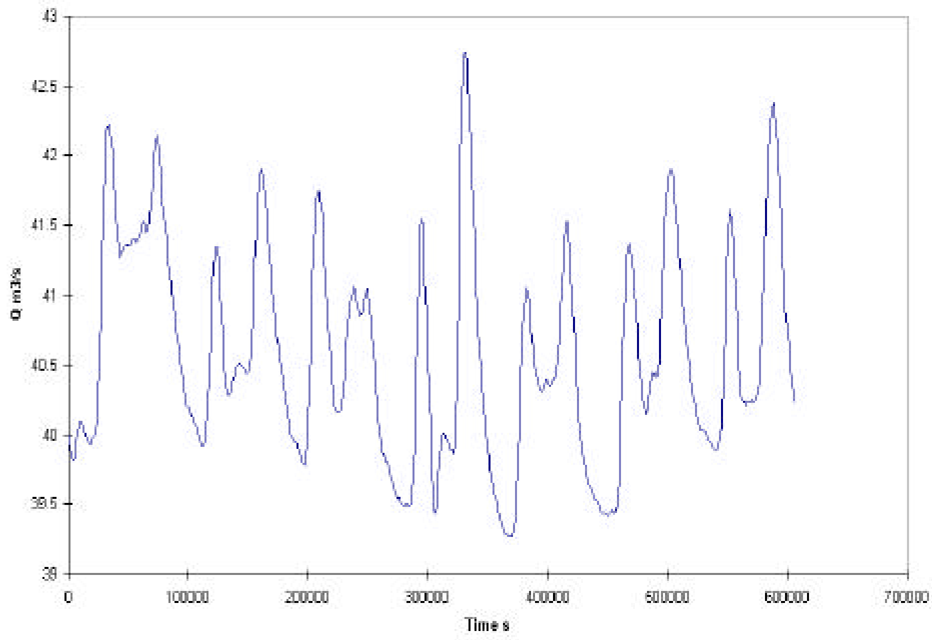

Figure 8 : Upstream discharge

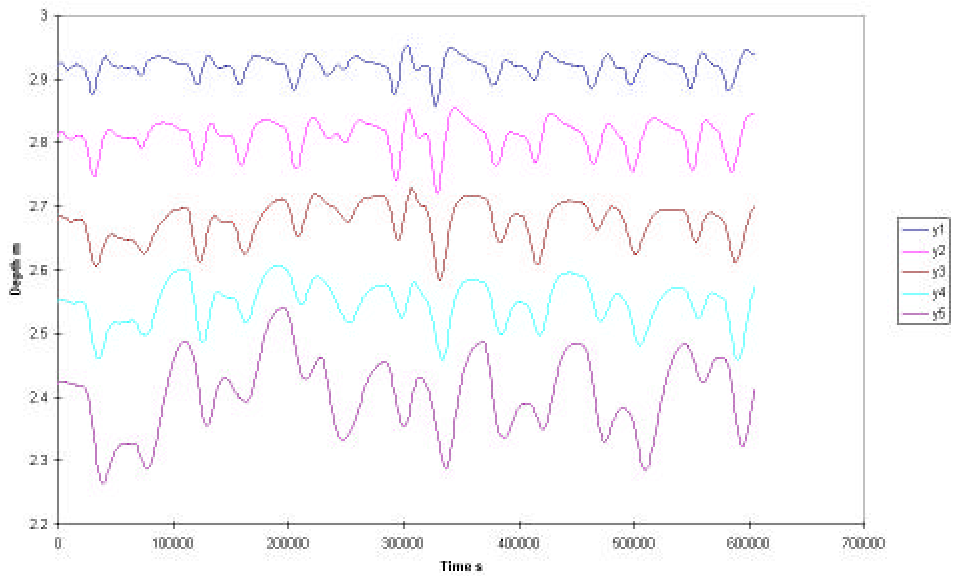

Figure 9 : Water levels

Like for type1 the water level at the downstream end of the last pool is not regulated as well as the others.

The response to a step perturbation of 1m3/s at the offtake of the downstream end of the first reach is shown (Figure 10) and (Figure 11). (Figure 10) shows the upstream discharge and (Figure 11) shows the water levels at the downstream end of each pool (the water level is modified for visibility).

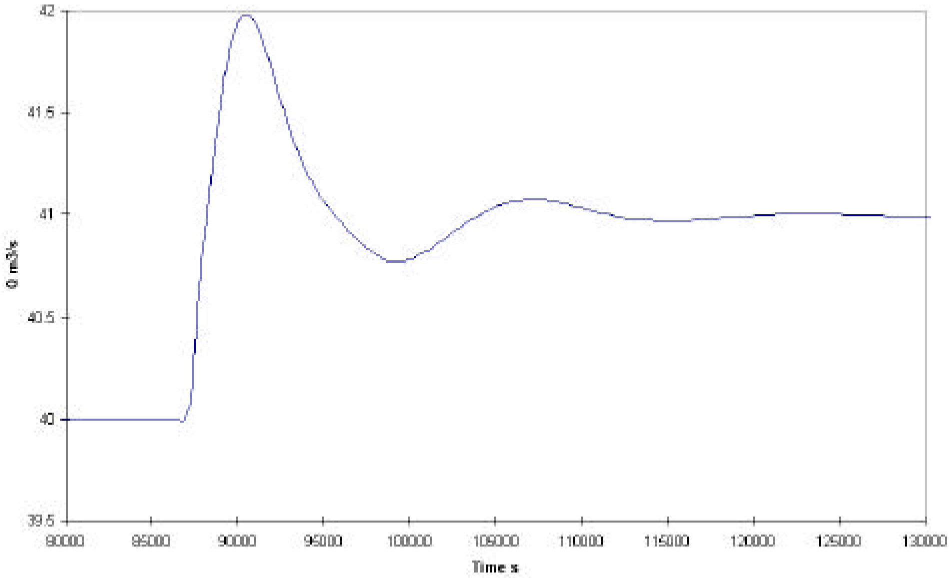

Figure 10 : Upstream discharge for step perturbation

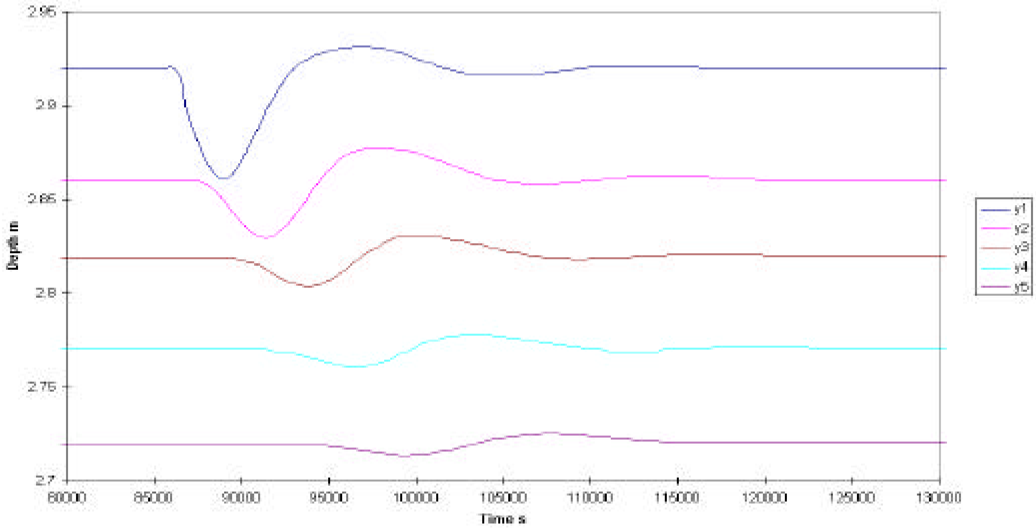

Figure 11 : Water levels for step perturbation

These figures show that the response to a load disturbance is less oscillatory than for type1. Notice that the gains obtained with the optimization process are very low compared to type 1 and that the gains are lower from upstream to downstream gate controllers.

CONCLUSIONS

The optimization procedure proposed is an interesting tool to tune local controllers in series. It is possible to choose a performance criteria and a scenario of perturbations well adapted to the specific problem to solve.

There are several pitfalls when using this global optimization procedure. The method is well suited for local controllers with few parameters, otherwise the computation time may be excessive. For ten parameters the average number of iterations is around 500. Care must be taken to choose properly the starting set of parameters and the scenario of perturbations at offtakes. If the scenario is too long the computation time increases without any benefit for the solution.

Results are shown for local PI controllers but this technique can be useful to tune other local controllers. It can also be used to tune local controllers for a real canal. For this purpose, it is necessary to choose properly the criteria and the type of scenario at offtakes adapted to the context.

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