CANAL CONTROL ALTERNATIVES IN THE IRRIGATION DISTRICT 'SECTOR BXII DEL BAJO GUADALQUIVIR,' SPAIN

David Lozano[1]
Carina Arranja[2]
Manuel Rijo[3]
Luciano Mateos[4]

ABSTRACT

Improved water management and efficient investment on the modernization of the irrigation districts in most countries are imperative to satisfy the increasing demand of water. The automation and control of their main canals is one mean to increase the efficiency and flexibility of the irrigation systems.

In 2005, we monitored one canal in the irrigation district 'Sector BXII del Bajo Guadalquivir'. This is a representative irrigation canal of the irrigation districts in Southern Spain. This canal is divided into four pools and supplies an area of 5,150 ha. We used ultrasonic sensors and pressure transducers to record water levels upstream and downstream each canal pool. With the measured data and the hydraulic model SIC (Simulation of Irrigation Canals), we evaluated two canal control alternatives (local upstream control and distant downstream control) using a Proportional-Integral (PI) control algorithm. First, we calibrated and validated SIC under steady-state conditions. Then, we calibrated the proportional and integral gains of the PI algorithm. The obtained results show that only the distant downstream controller can quickly and automatically adjust the canal dynamics to unexpected water demands, with efficiency and no spills at the canal tail, even for sudden and significant flow variations.

Keywords: irrigation canal, local upstream control, distant downstream control, PI controller, water saving.

INTRODUCTION

Irrigation is the largest water user in the World. In Spain, irrigation uses about 75% of the available water. In addition, irrigation is now competing for water with the industrial, urban, recreational, and environmental sectors. Therefore, in order to save water and to provide better water delivery services, the irrigation sector must implement intelligent management and operation of the irrigation systems.

[1]Early Stage Researcher; Instituto de Agricultura Sostenible-C.S.I.C.; Alameda del obispo s/n, 14080, Córdoba, Spain; l52loped@uco.es
[2]Early Stage Researcher; Departamento de Engenharia Rural, Universidade de Évora/ICAM; Apartado 94, 7002-554 Évora, Portugal; carinaarranja@hotmail.com
[3]Hydraulic Professor; Departamento de Engenharia Rural, Universidade de Évora/ICAM; Apartado 94, 7002-554 Évora, Portugal; rijo@uevora.pt
[4]Research Scientist; Instituto de Agricultura Sostenible-C.S.I.C.; Alameda del obispo s/n, 14080, Córdoba, Spain; ag1mainl@uco.es

Due to technical and financial reasons, large water conveyance and delivery systems are usually open-channel systems. Water dynamics in open-channel canals are very complex and difficult to control, especially under a demand-oriented operation (Clemmens, 1987).

In Spain, the investment in the modernization of irrigation systems is notable. However, the interventions are focused mainly on the on-farm irrigation systems and on the transformation of the distribution systems from open canal networks to on-demand pressurized-pipe networks. In most cases, the modernization of the conveyance canals has been ignored or treated with little technical attention, and these canals remain the same as they were when first constructed decades ago.

Irrigation canal automation started with the use of self-controlled hydraulic gates -AVIS, AVIO y AMIL- (Kraatz and Mahajan, 1975). Later, electro-mechanical controllers emerged in the market and with them the first applications of control theory to the operation of irrigation canals (Shand, 1971). The introduction of personal computers allowed coupling canal flow simulation models with control algorithms (Clemmens et al., 2005), which has allowed significant advances on the engineering of canal control and automation.

Canal control algorithms can be heuristic, classical, predictive, or optimal (Clemmens and Schuurmans, 2004a). The most recent studies have returned to classical algorithms of the Proportional-Integral (PI) type, using new techniques for tuning the gains of the algorithms (Clemmens and Schuurmans, 2004b; Overloop et al., 2005; Guenova et al., 2005; Litrico et al., 2005; Piao and Burt, 2005). Their robustness, accuracy and easiness to implement on the field have favoured this new trend. However, there is not single solution or recipe applicable to all problems (Burt and Piao, 2004).

The goals of this study are: 1) to calibrate and validate a hydraulic model that allows simulation of the actual operation and resulting water flow regime in a real canal, and 2) the simulation and evaluation of alternative automatic control methods that may help to shift the operation of irrigation canals in Spain from supply-oriented to demand-oriented operation.

For the study, we chose the hydraulic model Simulation Irrigation Canal (SIC) (Malaterre and Baume, 1999) and a representative canal of the irrigation districts in Southern Spain as a case study.

MATERIAL AND METHODS

Description of the Study Canal

The case study involves Canal B in the Irrigation District "Sector BXII del Bajo Guadalquivir", located in Lebrija, province of Seville, Spain (Figure 1). This is a branch canal 7.8 km long, with a bottom slope of 0.0002 and a trapezoidal cross section. It consists of four pools separated by check sluice gates (Figure 2). In the transition between of the pools, the trapezoidal cross sections become rectangular. Also, the first 89 m of the first pool is rectangular with a bottom slope of 0.00058. An inverted siphon is located in the fourth pool to cross a drainage ditch.

Pumping stations located just upstream the gates (labeled PS in Figure 2) deliver the irrigation water to the farms through pressurized pipe networks. The design flow for the canal pools are 5.4, 4.5, 3.35, and 1.98 m^3/s, respectively.

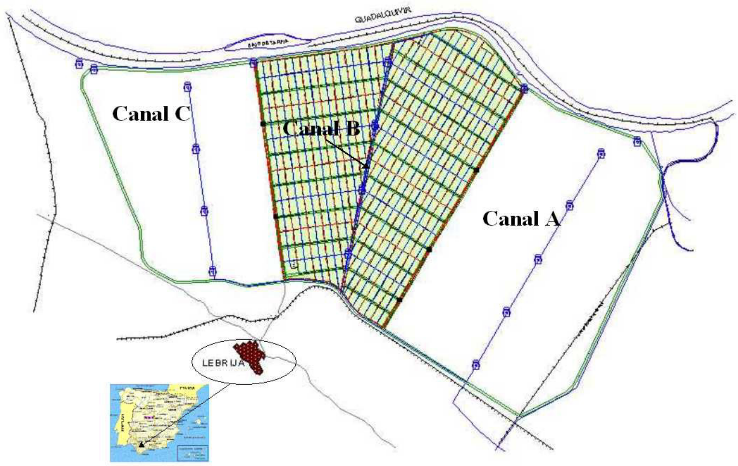

Figure 1. Localization of Canal B of the "Sector BXII del Bajo Guadalquivir"

The canal geometry was established with great detail using an electronic total station (GTS-210, TOPCON).

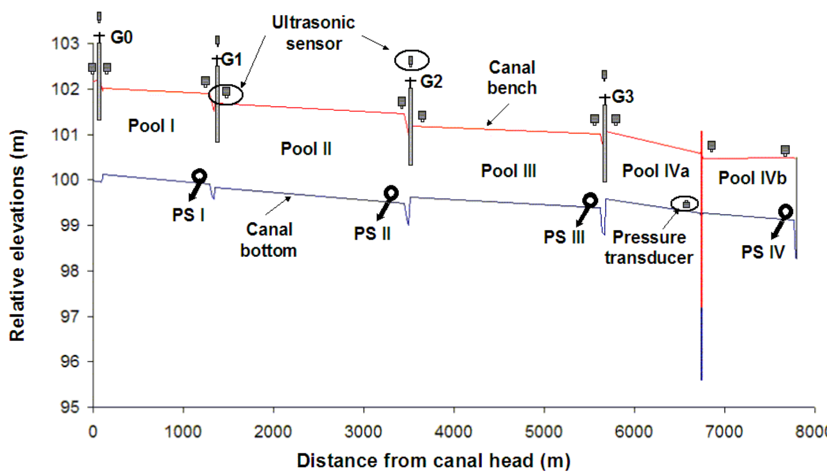

Figure 2. Longitudinal Sketch of Canal B of the "Sector BXII del Bajo Guadalquivir"

Water levels upstream and downstream of each check gate and downstream of the inverted siphon were measured by means of ultrasonic sensors; water level upstream the inverted siphon was measured with a pressure transducer. Gates openings were measured using ultrasonic sensors. All the information was recorded in data loggers.

Description of the Hydraulic Model (SIC)

SIC (Malaterre and Baume, 1999), the hydraulic model used in this study, simulates the water dynamics in canals based on the well known Saint-Venant equations. These equations are nonlinear hyperbolic partial differential equations dealing with the mass and momentum conservation:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \tag{1}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial Q^2/A}{\partial x}+gA\frac{\partial Z}{\partial x}=gA(i-J) \tag{2}$$

where x (m) and t (s) are the distance and time dimensions, respectively, A (m^2) is the area of the flow cross section, Q (m^3/s) is the discharge, Z (m) is the elevation of the water surface, i (m/m) is the canal bottom slope, g (m/s^2) is the acceleration due to gravity, and J (m/m) is the friction slope. J is calculated in SIC based on Manning's formula.

Two boundary conditions are necessary for solving this system of differential equations. Typically, $Q(0,t) = Q_0(t)$ is the upstream boundary condition, where $Q_0(t)$ is a known inflow hydrograph and $Q(L,t)=Q_L(t)$ is the downstream boundary condition, with L the length of the canal and $Q_L(t)$ the discharge hydrograph at the canal tail (usually determined using a discharge equation function of the water level at $x = L$). The initial condition is given by the water level profile at $t = 0$: $Z(x,0)$.

Equations (1) and (2) are not valid to model water flow across hydraulic structures. Therefore, in the case of gates we resort to discharge equations of the form $Q = Q(Z_{us}, Z_{ds}, W)$, with Z_{us} (m) and Z_{ds} (m) the water surface elevations upstream and downstream the gates, respectively, and W (m^2) the area of the flow cross section under the gates. In the case of a weir, the general form of the discharge equation is $Q = Q(Z_{us})$, with Z_{us} referred to the weir crest (Malaterre and Baume, 1999).

In SIC, equations (1) and (2) are linearized and discretized in time (Δt, time step) and space (Δx, space step) using the Preissmann implicit scheme (Cunge et al., 1980).

Control Logics

The main purpose of the canal control is matching the water supply with the water demand at the canal offtakes. Basically, there are two canal control logics (Burt, 1987; Buyalski et al., 1991): upstream control (Figure 3a) and downstream control (Figures 3b and 3c), each referring to the location of where information is needed by the control logic; downstream control is also called distant or local, respectively, when the sensor is located at the downstream section or the upstream section of the canal pool.

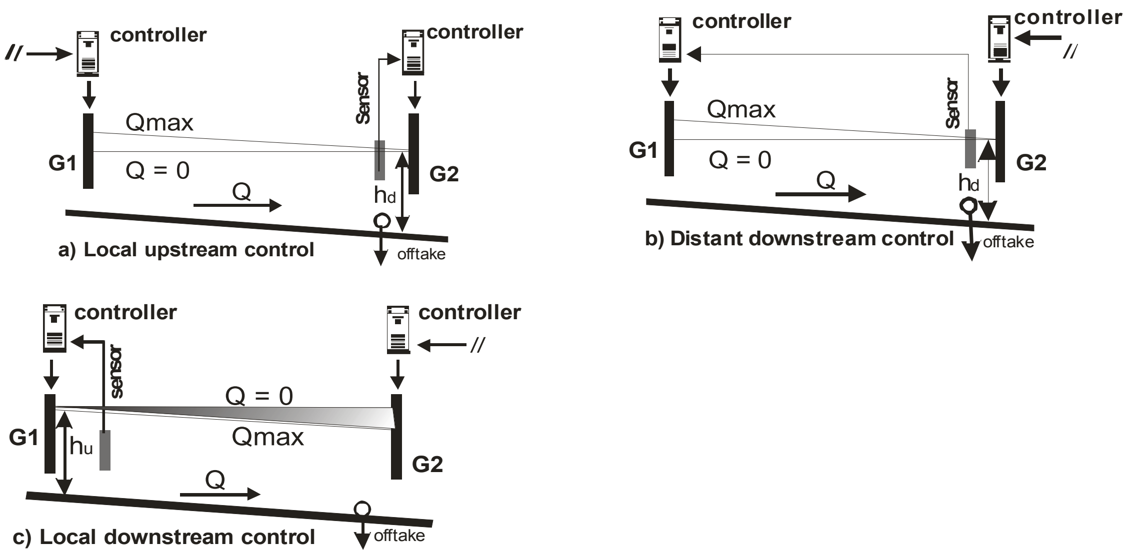

Figure 3. Canal Control Modes (Rijo and Arranja, 2005)

For local upstream control and distant downstream control, the water depth at the downstream end of each canal pool is the controlled variable and the control goal is to guarantee its fast convergence to a predefined set point. These are the two most commonly used control methods because with them, especially the first one, canals can be sized to convey the maximum flow and water depths in steady flow conditions never exceed the normal depth for the design flow (Rijo and Arranja, 2005). As it is shown in Figures 3a and 3b, the water surface profile pivots around the established downstream set point (h_d). A storage wedge is created between different steady-state flows profiles (Figures 3a and 3b represent the surface profiles for maximum and null flow). When the flow changes, the water surface and the storage volume within the pool changes in the same way (increasing or decreasing).

Calibration, Validation, and Application of SIC to the Study Canal

First, we calibrated discharge coefficients for each gate of the canal using a discharge equation of the type mentioned above:

$$Q = C_d W \sqrt{2g(Z_{us} - Z_{ds})} \tag{3}$$

where all the variables have been defined above except C_d, that is the discharge coefficient. C_d showed variations from gate to gate and in some cases also varied with the gate opening. For the purpose of the simulation with SIC, we used mean adjusted discharge coefficients: 0.87 for G0, 0.70 for G1, 0.66 for G2 and 0.64 for G3. The analysis of the variations of the discharge coefficients and of the errors in the determination of discharges will be the subject of a separate study.

The calibration and validation of SIC under unsteady flow conditions would require knowing the hydrographs at the offtakes. Unfortunately, this information was not available at the time of this evaluation. However, we considered that the Manning's roughness coefficient *n*, the parameter to be calibrated, would be rather similar under unsteady and steady regimes. Therefore, for calibrating *n*, we selected along the 2005 irrigation season 35 days and corresponding periods of steady state conditions (during which the outflows in the canal could be calculated by difference between the discharges under consecutive gates) with similar canal flow, and we did this calibration for each pool. Then SIC, using the flow and water levels measured in each pool, calculated *n*. We observed variations of *n* along the irrigation season, mainly due to the development of algae during springtime. The analysis of this variation of *n* and its effect on the outputs of the model and control gains will be matter of a separate article. Herein we will use the average *n* resulting of the *n* values obtained for the 35 steady state regimes used for the calibration. These average values were 0.016, 0.019, 0.019, and 0.022 for the first four canal pools, respectively.

Next, we proceeded to the validation of SIC. For this purpose, we used data sets independent of that used for the model calibration. As in the case of the calibration, we had to restrict the validation to steady state conditions, but we did so in two conditions. First, we validated the simulated water levels and gate openings by comparing the field measurements with the model outputs in 7 steady state regimes corresponding to 7 days along the 2005 irrigation season, with canal inflow varying from 1.82 to 3.2 m^3/s. Second, we simulated 2 steady regimes observed in the canal, entering in the model the actual inflow hydrograph, the actual gate movements, and outflows at the offtakes (estimated by difference between flows in consecutive gates). Third, we continued simulation until reaching a new steady regime. Finally, we compared the resulting water levels with those observed in the canal under the new steady conditions.

Once the model was validated, we proceeded to evaluate two automatic control methods: distant downstream (Figure 3b) and local upstream (3a). We fixed the outflow at offtakes PSI (0.597 m^3/s), PSII (0.686 m^3/s) and PSIII (0.717 m^3/s), and we increased instantaneously by 25% and decreased instantaneously by 50% a typical outflow at PSIV (1.2 m^3 s^{-1}). For the distant downstream method this resulted in two tests: DSdistant-In and DSdistant-De, respectively. For the local upstream method, we tested six hypothetical operations of gate G0, three concerning the outflow increase at PSIV, and the other three concerning the decrease of outflow at PSIV:

- USlocal-In1, the operator increased inflow at G0 the same amount of the outflow increased at PSIV at the same time that the variation occurred at PSIV;
- USlocal-In2, as in the first test, but increasing during one hour the inflow at G0 an amount 150% of the outflow increase at PSIV in the same instant;
- USlocal-In3, as in test 2, but delaying the increase of flow at G0 75 minutes with respect to the time of variation at PSIV;
- USlocal-De1, as USlocal-In1 but decreasing the outflow at G0;
- USlocal-De2, as USlocal-In2 but decreasing the outflow at G0;
- USlocal-De3, as USlocal-In3 but decreasing the outflow at G0.

Then, for both control methods and all tests, we observed the resulting inflow hydrograph, gate G3 movement, water level and spills at the canal tail.

Control Algorithm. PI Controllers Tuning

In this study, we have used the Proportional-Integral (PI) control algorithm, a simplification of the Proportional, Integral and Derivative algorithm (PID) better adapted to canal control (Åström and Hagglund, 1995). This advantage has lead to many implementations of PI algorithms, as reported in recent publications (Clemmens and Schuurmans, 2004b; Piao and Burt, 2005; Litrico et al., 2005).

The PI algorithm can be written as:

$$U(t) = K_p \cdot e(t) + K_i \int e dt \tag{4}$$

where $U(t)$ is the control action (gate opening in this case), $e(t)$ is the error or deviation of the controlled variable (water level in this case) from its target value at time t, and K_p and K_i are the proportional and integral gains, respectively.

In irrigation canals, oscillations and large deviations of the water levels from the target values and frequent variations of gate opening are undesirable. Thus, the performance criterion used herein was based on the integral of the water level errors and the integral of the gate opening variations (Baume et al., 1999). Therefore, optimal values of K_p and K_i were found by minimizing the function:

$$\xi = \sum_{i=1}^{n} \int_{0}^{T} \left[\left| Z_i(t) - Zr_i \right| + \delta w_i \right] \cdot dt \tag{5}$$

where T (s) is the duration of the optimization period, Z_i (m) and Zr_i (m) are the measured and target water levels at pool i, respectively, and δw (m) is the gate opening variation. Function ξ (equation 5) was minimized using the simplex method (Nelder and Mead, 1965), the optimization algorithm implemented in SIC (Malaterre and Baume, 1999).

The resulting adjusted values of K_p and K_i are in Table 1.

Table 1. Optimized Controllers Gains

Gate	**Local upstream control**		**Distant downstream control**	
	K_p (-)	**K_i (s)**	**K_p (-)**	**K_i (s)**
G0			3.33	66.6
G1	-2.29	-803.5	4.50	23.3
G2	-3.14	-336.2	3.84	7.1
G3	-2.12	-716.2	2.20	2.6

RESULTS

Model Validation

Figure 4a compares measured and simulated water level values upstream and downstream check gates G0, G1, G2 and G3, inverted siphon, and at the end of the canal, for the selected seven independent steady state periods. The agreement is excellent. Also, the observed and measured gate openings (Figure 4b) agreed very well.

Considering two observed and validated initial steady-states, Figure 5 shows the water levels of the two correspondent final steady states, achieved after unsteady flow regimes. As shown, also in these cases the measured and simulated water levels agreed very well.

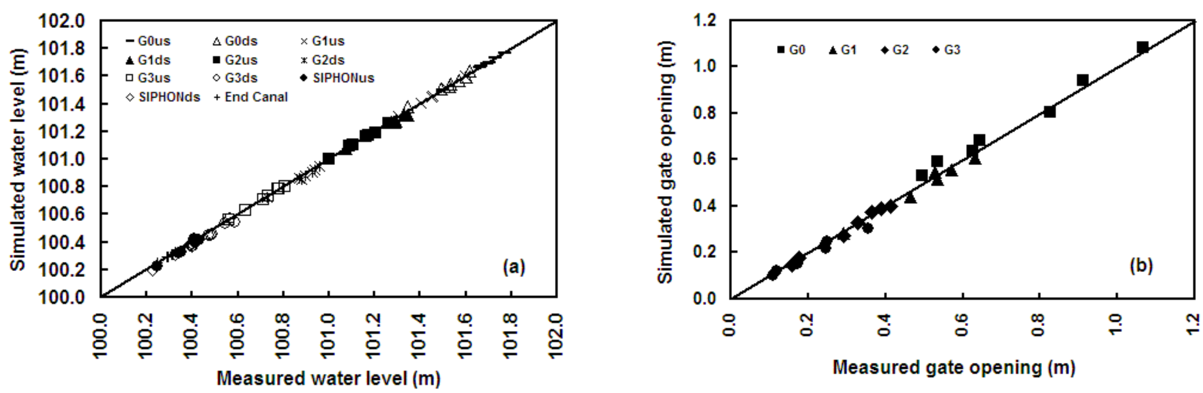

Figure 4. Measured and Simulated Values for Seven Independent Steady Flow Periods: a) Water Levels; b) Gate Openings.

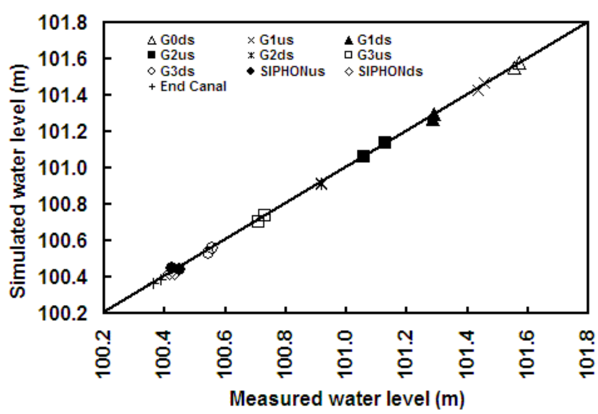

Figure 5. Measured and Simulated Water Levels for Two Real Steady Flow, Achieved After Unsteady Flow Periods.

In view of these results and despite the impossibility of validate the model under unsteady state conditions, we considered that the model had been sufficiently tested and validated to proceed to explore (under unsteady state conditions) with SIC alternative control methods in the study canal.

Control Simulation Results

Figures 6 and 7 show the simulation results for the irrigation canal under study, using the two implemented and tuned PI controllers, the local upstream and the distant downstream controllers.

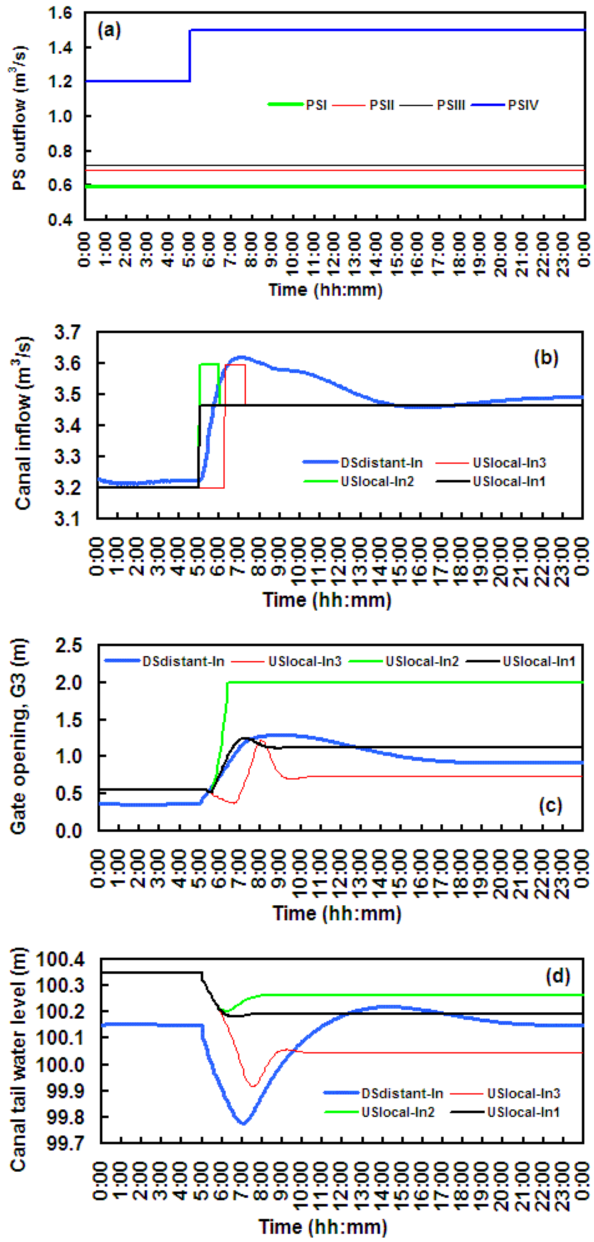

Figure 6. Local Upstream and Distant Downstream Controllers Responses to an Unexpected Outflow Increment at the Pumping Station PSIV. (a) Pumping Station Outflow,(b) Canal Inflow, (c) G3 Gate Opening, (d) Canal Tail Water Level

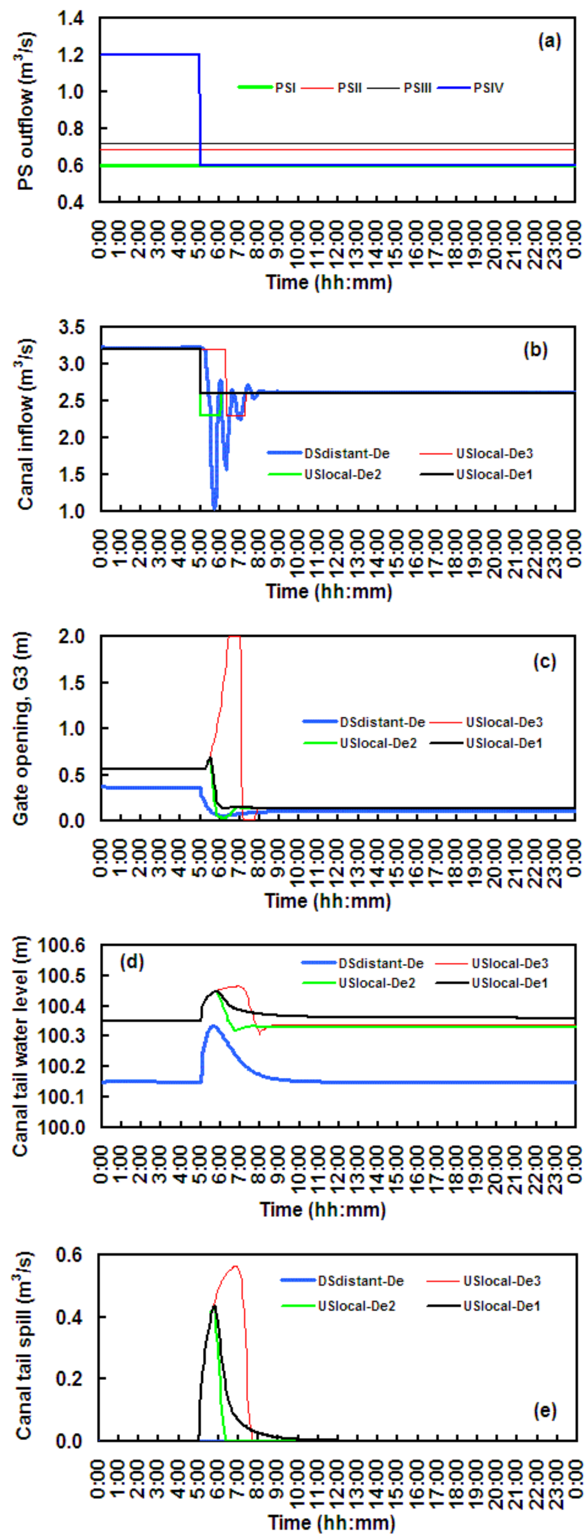

Figure 7. Local Upstream and Distant Downstream Controllers Responses to an Unexpected Outflow Decrement at the Pumping Station PSIV. (a) Pumping Station Outflow,(b) Canal Inflow, (c) G3 Gate Opening, (d) Canal Tail Water Level, (e) Canal Tail spill.

Figure 6 presents the response of the canal, under the operation of the two controllers, to the unexpected outflow increment at PSIV (from 1.2 m^3/s to 1.5 m^3/s) represented in Figure 6a; and Figure 7 presents that response to the unexpected outflow decrement (from 1.2 m^3/s to 0.6 m^3/s) at the same pumping station (Figure 7a). As stated under Calibration, Validation, and Application of SIC to the Study Canal (and shown in Figures 6a and 7a), the outflows for the other pumping stations (PSI, PSII, PSIII) remained constant for both scenarios.

Usually, the local upstream control guarantees an automatic water level control inside the canal, but it needs a complementary manual flow control at the canal intake (Rijo and Arranja, 2005). The canal intake is always operated according to the experience and personal judgements of the canal manager, which is one of the disadvantages of upstream control. For this reason, spills are common, especially when there is a demand-oriented operation. This situation is simulated here considering three attempts presented in Figures 6 and 7.

Figure 6b presents the canal inflow variations (USlocal-In1, USlocal-In2, USlocal-In3) imposed by the canal manager under upstream local control in order to adjust the canal dynamics to the unexpected increment of water demand. For the three attempts, the PSIV outflow increment was satisfied, with no spills at the canal end; but, as shown in Figure 6d, using a part of the water volume inside the canal pool IV. In other words, the water level did not return to the initial value for any of the three attempts. Moreover, Figure 6c shows that the controller stabilized the position of gate G3, but also shows that, for the USlocal-In2 attempt, gate G3 reached its maximum opening (2.0 m).

On the other hand, the distant downstream control response of the canal was better than that of the local upstream control. Now, the inflow canal hydrograph is a control output, the entire canal operates totally automatic (Rijo and Arranja, 2005), the gates operation is stable (Figure 6c), and the canal pool IV water level returns to its target value in a very stable way (Figure 6d).

Regarding the second group of scenarios (those considering outflow decrements at PSIV), Figure 7b presents attempts of manual regulation of the canal inflow similar to those presented in Figure 6b for the local upstream control, but now for the outflow decrement. The controlled water level inside canal pool IV is quickly regained, but the spills at the canal end became important for the three attempts. The excess of water inside the canal is well illustrated in Figure 7c for the USlocal-De 3, where it is shown that, during nearly one hour, gate G3 was completely open.

Also for the unexpected outflow decrement the canal responded to the distant downstream control mode better than to the local upstream control. The gates operation is stable (Figure 7c), the controlled water level regained its target value, and there are no spills at the canal end.

Both controllers guarantee a fast and stable response to the flow variations. The time for the control water depth to converge to the setpoints almost immediately (less than 1cm of water level error) for the local upstream controller and about 2 hours for the distant downstream controller.

SUMMARY

Considering a demand-oriented-canal operation, the main conclusion is that only the distant downstream control can quickly and automatically adjust the studied canal dynamics to unexpected water demands, with efficiency and no spills at the canal tail, even for sudden and significant flow variations. The tested automatic local upstream control improves the actual manual upstream control, saving labor in the canal operation, but only the distant downstream control guarantees a totally automatic canal operation. In the study case, with the last control mode, the actual number of seven canal managers could be reduced to only one, and the water delivery improved.

REFERENCES

Åström, K. J. and Hagglund, T.,. (1995). “PID controllers: theory, design and tuning,” 2nd ed. Instrument Society of America, Research Triangle Park, North Carolina.

Baume J.P., Malaterre P.O. and Sau J. (1999). “Tuning of PI controllers for an irrigation canal using optimization tools”. In Proc. of the USCID Workshop, 483-500, A.J. Clemmens & S.S. Anderson, eds. Phoenix, U.S.A.

Buyalski, C.P., Ehler, D.G., Falvey, H.T., Rogers, D.C. and Serfozo, E.A. (1991). “Canal systems automation manual. Vol I”, U.S.Department of the Interior, Bureau of Reclamation, Denver, E.U.A.

Burt, C. (1987). “Overview of canal control concepts” in ‘Planning, Operation, Rehabilitation and Automation of Irrigation Water Delivery systems’. ASCE. New York.

Burt, C.M. and Piao, X. (2004). "Advances in PLC-based irrigation canal automation". Irrigation and Drainage, 53, 29-37.

Clemmens A.J. (1987). “Delivery system schedules and required capacities”. In Planning, operation, rehabilitation and automation of irrigation water delivery systems, 18-34, ASCE, New-York.

Clemmens, A.J. and Schuurmans, J. (2004a). "Simple optimal downstream feedback canal controllers: theory". Journal of Irrigation and Drainage Engineering, 130(1), 26-34.

Clemmens, A.J. and Schuurmans, J. (2004b). "Simple optimal downstream feedback canal controllers: ASCE Test Case Results". Journal of Irrigation and Drainage Engineering, 130(1), 35-46.

Clemmens, A.J., Bautista, E., Wahlin, B.T. and Strand, R.J. (2005). “Simulation of automatic canal control systems.” Journal of Irrigation and Drainage Engineering, 131(4), 324-335.

Cunge, J.A., Holly, J.F.M. and Verwey, A. (1980). “Practical aspects of computational river hydraulics”. Pitman Publishing Limited, 420 p.

Guenova, I., Litrico, X., Fromion, V., Rijo, M. and Malaterre, P.O. (2005) “Stability analysis of classical decentralized control of irrigation canals”. 16th IFAC World Congress, Prague, July 4-8.

Kraatz, D.B. and Mahajan, I.K. (1975). “Small hydraulic structures”. Irrigation and Drainage Paper no. 26, FAO, Rome, Italy.

Litrico, X., Fromion, V., Baume, J.-P., Arranja, C. and Rijo, M. (2005). “Experimental validation of a methodology to control irrigation canals based on Saint-Venant equations”, Control Engineering Practice, 13/11, 1425-1437.

Malaterre, P.O. and Baume, J-P. (1999). “SIC 3.0, A simulation model for canal automation design”. CEMAGREF, Montpellier, France.

Nelder, J.A., and Mead, R. (1965). “A simplex method for function minimization”, Computer journal, 7, 308-313.

Overloop, van P.J., Schuurmans, J., Brouwer, R. and Burt, C.M. (2005). “Multiple-model optimization of proportional integral controllers on canals”. Journal of Irrigation and Drainage Engineering, (131)2, 190-196.

Piao, X. and Burt, C.M. (2005). “Tuning algorithms for automated canal control.” ITRC Report No. R05-005. September 2005.

Rijo, M. and Arranja, C. (2005). "Hydraulic performance of a downstream controlled irrigation canal equipped with different offtakes types". Agricultural Engineering International: the CIGR Journal of Scientific Research and Development. Vol II. March.

Shand, M.J. (1971). “Automatic downstream control systems for irrigation canals.” PhD thesis, University of California, Berkeley, CA.