Automatic control of pollutant on a shallow river using surface water systems: application to the Ebro River

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ABSTRACT

In this paper, the problem of automatic control of pollutant on a shallow river using surface water systems is addressed using a benchmark test case based in the Ebro River. The Ebro River presents flooding episodes in the city of Zaragoza in Spring when snow melts in the Pyrenees. To avoid flooding and high pollutant levels in living areas, some lands outside the city are prepared to be flooded. Going one step further, this paper is focused on the pollutant level control at a certain point downstream of the river under flooding episodes, and several control strategies for that purpose are presented and tested.

Key words | pollution control, rivers, simulation, telecontrol systems, water systems

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INTRODUCTION

Flooding and pollution prevention and control in rivers are important topics in the river management. However, so far, most of the research has focused on river flooding events: see, for example, van Overloop *et al.* (2008) or Blanco *et al.* (2011) , where they have addressed the problem of mitigating the river flooding effects using model predictive control (MPC). Recently, different real-time control methods have started to be applied to water quality management in canal systems. For example, Litrico *et al.* (2011) used an adaptive control method to control canal discharges by adjusting hydraulic structures to restrict algae development. Augustijn *et al.* (2011) applied dynamic control to prevent salt intrusion in a lake that was modelled as open channel flow. Xu *et al.* (2010) applied a model predictive control technique to generate an optimal flushing strategy and maintain both water quantity and quality in a polder system.

This paper presents the case of the basin of the Ebro River in Spain. In the past, the Ebro basin experienced several floods and pollutant discharges. In order to reduce the flood hazard in a given area, the local water administration decided to set-up several flood-controlled areas to store the excessive water volume during periods of extreme rainfall. In order to control the flows to and from the flooding zones, hydraulic control structures have been put in place. Through these actions, it is planned to have a significant reduction of the flood risk in the basin. In Romera *et al.* (2013), the application of MPC has shown that flooding could have been significantly reduced and even avoided by properly controlling the hydraulic structures. This paper goes one step further, focusing no longer on the flow control problem but on the pollutant control. The pollutant scenarios considered are those that could appear in flooding scenarios when upstream of the river some contaminant is introduced. Then, the pollutant level is required to be controlled at a certain point downstream of the river. In this case, the flooding areas are assumed to store clean water, before the pollutant has arrived, such that they provide the capacity of reducing the contamination downstream by releasing it. To achieve such a goal several control strategies are considered in the paper:

- Indirect flow PID (proportional–integral–derivative) control based on controlling the pollution concentration by means of controlling the flow entering/exiting from the flooding areas.
- Local direct pollution control based on directly controlling the pollutant concentration by means of a set of local PIDs.
- Global direct pollution control based on directly controlling the pollutant concentration by means of a set of local

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PIDs that are supervised using a PID or MPC-based scheme.

These control structures have been tested on a piece of the Ebro River using a high-fidelity simulator that considers not only the flow but also the pollutant propagation. This paper presents a theoretical study regarding the future possible application to the real river.

The structure of the remainder of the paper is the following. In the 'Problem description and modelling' section, the problem addressed in this paper is described as well as the control-oriented modelling approach used. In the next section, the strategies for the automatic pollution control are introduced. Results of their application to a piece of the Ebro River using a simulator are then presented in the 'Results' section. Finally, the main conclusions are presented.

PROBLEM DESCRIPTION AND MODELLING

Description

The Ebro River presents flooding episodes in the city of Zaragoza in Spring when snow melts in the Pyrenees. To avoid flooding in living areas, some lands outside the city are prepared to be flooded. Figure 1 presents the sketch of a benchmark test case with three of the inundation areas located along a canal representing a river reach. The flood going in and out to these areas can be controlled using gates. The management of those flooding areas using MPC has been presented in detail in Romera et al. (2013).

As discussed in the 'Introduction', this paper considers how these flooding areas can also be used in pollutant events that could appear in flooding scenarios when upstream of the river some contaminant is introduced. In this situation, the pollutant level is required to be controlled at a certain point downstream of the river. Thus, the idea to control the pollutant level at the control points is the following: when a combined pollutant/flooding episode starts, the gates should be open to start filling the flooding zones with clean water and closed when they are full. On the other hand, when the pollutant level in the control point downstream exceeds some pre-established safety value, the gates should be opened again to start emptying the flooding zones in order to dissolve the incoming pollutant thanks to the lower pollutant concentration of the stored water in the flooding areas.

In order to test the proposed control strategies to avoid flooding and high pollutant levels at the outlet of the river reach, a finite volume simulation model, based on the well-known Saint-Venant equations that describe subcritical, critical and super-critical flow, has been used. Additionally, these equations allow reproduction of effects such as inertial phenomena, backwater effects and the attenuation of wave flow through time and space. The implemented hydraulic model is based on the 2-D Saint-Venant equation for the description of continuity and momentum conservation (Abbott & Minns 1998; Murillo et al. 2006).

The numerical method implemented is based on an upwind explicit finite volume scheme, designed to work with triangular unstructured grids, that requires a control over the size of the time step. It can deal with inundation over irregular beds and wet/dry fronts.

Modelling

The system presented in Figure 1 can be represented by the block diagram presented in Figure 2.

As in Romera et al. (2013), each river reach has been identified experimentally using the IDZ (integrator delay zero) linear model structure proposed by Litrico & Fromion (2004). Two parallel models are used: one to characterize flow transport and the other to characterize pollutant transport. Those models can be represented by the following transfer functions in discrete-time whose parameters have been adjusted using data and the System

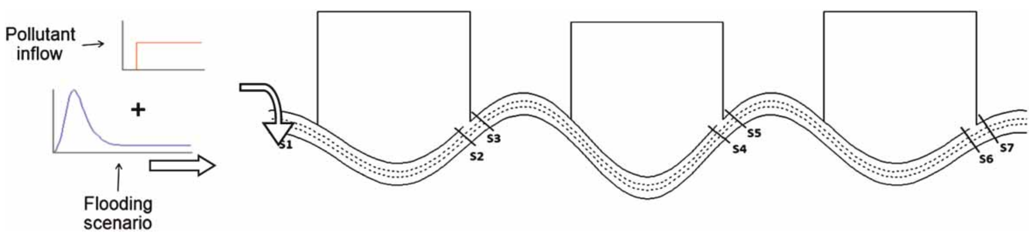

Figure 1 | Ebro River and three of the flooding zones.

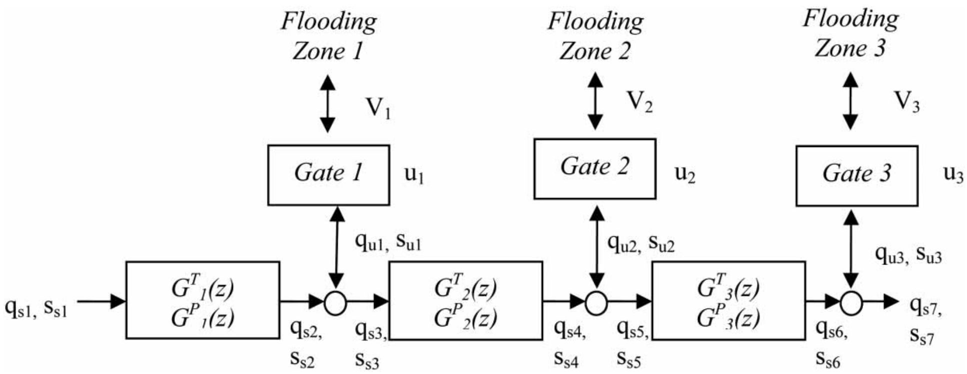

Figure 2 | Block diagram of the Ebro system.

Identification Toolbox from MATLAB (see Figure 3 for model fitting performance) (Weyer 2001):

- Flow transport models

$$G_1^{\mathrm{T}}(z) = \frac{0.9334z^{-1}}{z - 0.09794}; \quad G_2^{\mathrm{T}}(z) = \frac{1.3260z^{-1}}{z - 0.3277}; \quad G_3^{\mathrm{T}}(z) = \frac{1.5510z^{-1}}{z - 0.5527}$$

- Pollutant transport models

$$G_1^{\mathrm{P}}(z) = 1; \quad G_2^{\mathrm{P}}(z) = \frac{0.7864z^{-1}}{z - 0.1816}; \quad G_3^{P}(z) = \frac{0.8627z^{-1}}{z - 0.1033}$$

where the inputs are, respectively, the inflows and the pollutant concentrations upstream each river reach while the outputs are the outflows and the pollutant concentrations downstream each river reach.

Every model uses a different sampling time: $T_{s1} = 22T_s$, $T_{s2} = 11T_s$ and $T_{s3} = 1T_s$, where $T_s = 100$ s, that is related to the different transport delays.

The flow through the gate can be described by the following piece-wise function

$$q_{ui} = \begin{cases} u_i K_i \sqrt{h_{\mathrm{zone},i} - h_{\mathrm{river},i}} & \text{if} \quad h_{\mathrm{zone},i} > h_{\mathrm{river},i} \\ -u_i K_i \sqrt{h_{\mathrm{river},i} - h_{\mathrm{zone},i}} & \text{if} \quad h_{\mathrm{river},i} > h_{\mathrm{zone},i} \end{cases}$$
$$i = 1, 2, 3$$

$$q_{S_{2i+1}} = q_{S_{2i}} + q_{u_i} \quad i = 1, 2, 3$$

where u_i is the gate opening, K_i is a constant that takes into account the gate geometry, $h_{\mathrm{river},i}$ and $h_{\mathrm{zone},i}$ are the water levels at the river and flooding zone side of the gate, q_{ui} is the flow through the gates, $q_{S_{2i}}$ is the flow before the gates and $q_{S_{2i+1}}$ is the flow after the gates.

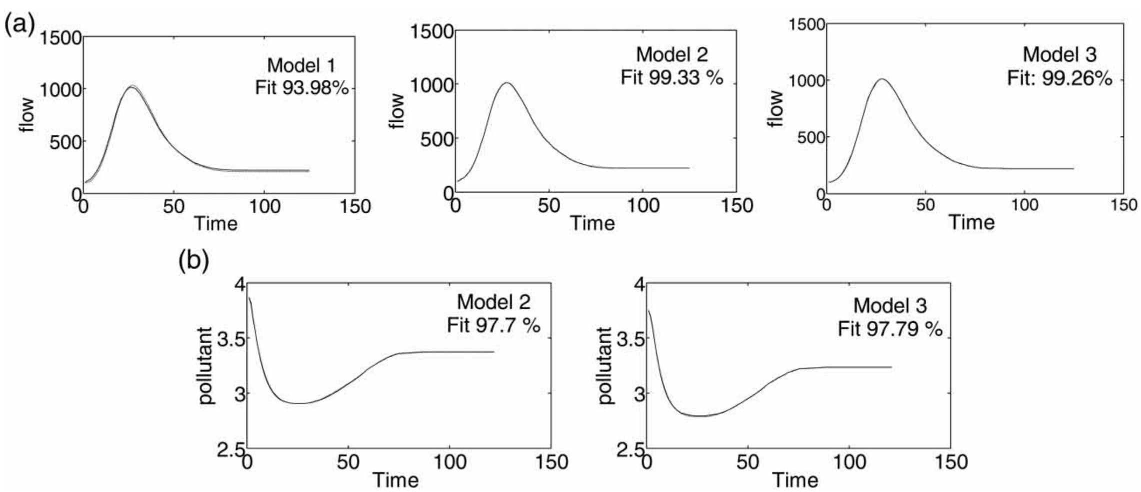

Figure 3 | Fitting of (a) flow models and (b) pollutant models.

These gates are controlled using PID controllers according to the different strategies described in the next section.

The flooding areas have been modelled as a height–volume relation obtained from the simulator as shown in Figure 4.

STRATEGIES FOR AUTOMATIC POLLUTANT CONTROL

Several strategies will be presented in this section in order to control the maximum concentration of the solute in the outlet of the river using the discharge of the floodplain areas to the river for the pollutant dilution.

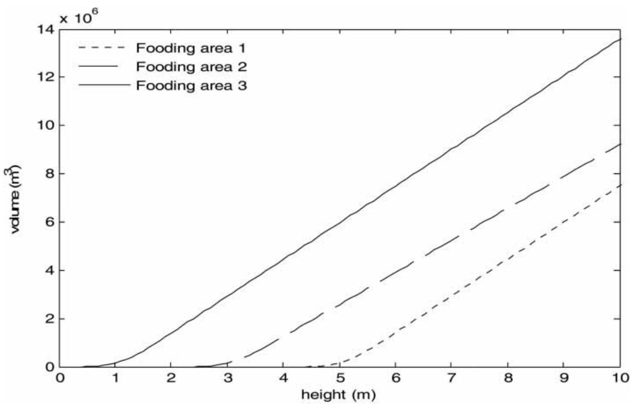

Figure 4 | Flooding areas modelling: relation between height and volume.

Indirect flow PID control

Figure 5 shows the relation between the flow in the river and the concentration of the solute in a specific point of the river. For a constant discharge of solute in the river, if a minimum water flow can be guaranteed, the pollutant concentration can reach the maximum allowable value at this point of the river.

For example, a concentration of 3.1 mg/l of NH_4 is obtained if the flow in the river is around 240 m^3/s. And then, the first strategy indirectly tries to control the concentration of the solute by controlling the minimum flow in the river. Consequently, this first approach involves using the same flow control strategy proposed in Romera *et al.* (2013) to avoid flooding in living areas. The set-point in this case (see Figure 6) is the minimum flow in a point of the river, which generally is the river outlet (S_7). This set-point is compared with the real flow at S_7, and the output of the controller opens or closes the gates of the flooding areas to maintain as much as possible a minimum flow at the river outlet.

Pollutant local control using PIDs

The second approach is based on implementing a PID controller at the output of each tank to control the pollutant concentration at that point (see Figure 7). Knowing the evolution of the pollutant concentration along the river up to the final control point, it is possible to define the set-point of each controller. In this approach, the set-points have to be

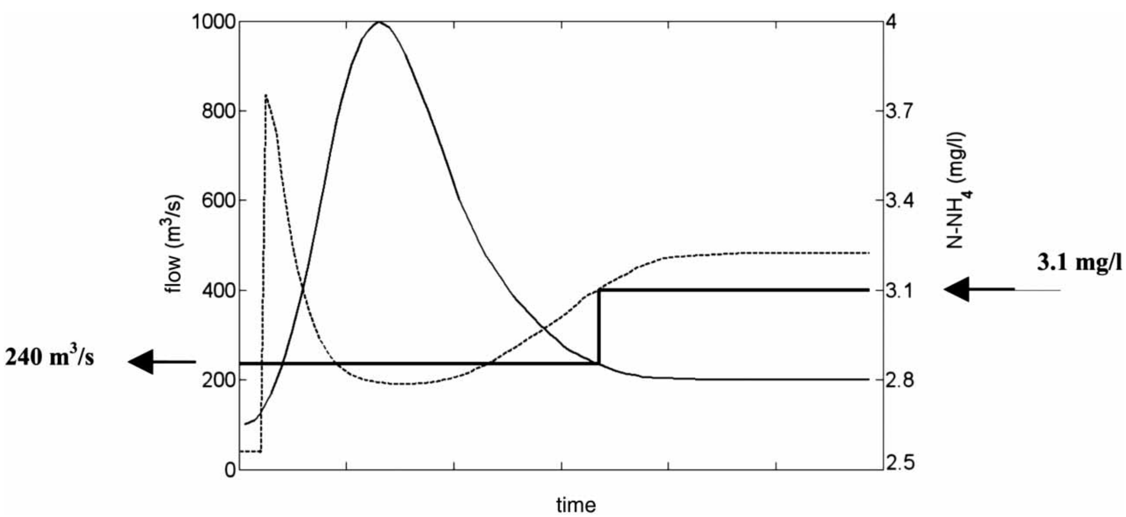

Figure 5 | Relation between pollution and flow.

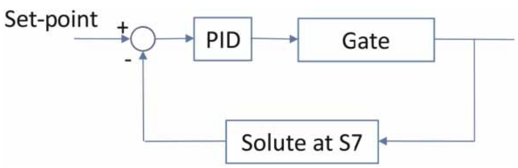

Figure 6 | Indirect flow control strategy.

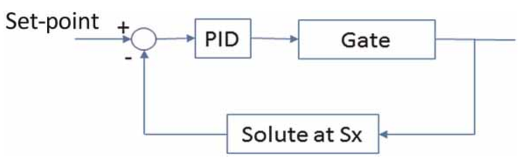

Figure 7 | PID local pollutant control.

prefixed by the maximum pollutant concentration allowed in the river near the gates of the flooding areas. These set-points will be compared with the real concentration of the solute at these points (S_3, S_5 and S_7 in our example), and the controller outputs will move the gates of the flooding areas accordingly.

This strategy presents the problem that the set-points in the intermediate points of the rivers should be fixed by trial and error in order to assure a certain quality of the water in the river outlet.

Pollutant global control using supervisory PIDs

The third approach solves the previous problem by adding a cascade structure of PID controllers (see Figure 8). Supervising the local PID controllers, a PID controller layer is implemented that computes the set-points for the local ones. In this case, the global set-point is the concentration of the solute at the river outlet that will be compared with the solute concentration of S_7. The output of the primary controller gives the local set-points of solute concentrations in the intermediate points in the river (S_3, S_5 and S_7).

This method presents two different main problems. The first one is the initial value. The farthest from the optimal point is the set-point, the more difficult is the control, and thus its performance will degrade.

The second problem is due to the fact that it is not possible to apply the same set-point to different local controllers, since the set-point controller layer is referenced to the final control point sharing the same control error.

Pollutant global control using supervisory model predictive control

MPC has shown to be a suitable control strategy to implement global real-time control of water systems since it has some features to deal with complex behaviors such as big delays compensation, the use of physical constraints, relatively simple for people without deep knowledge of control, and multi-variable systems handling (see, for example, Overloop et al. (2008), Blanco et al. (2011)). MPC, as the global control law, determines the set-points for local controllers of the whole closed-loop system. A management level is used to provide MPC with the operational objectives, which is reflected in the controller design as the performance indexes to be minimized.

The optimal control goals in transport water systems are generally concerned with environmental protection: in particular, ecological flow in all the points of the river avoiding flooding. The objective of applying optimal control is to compute, ahead of time, feasible strategies for the

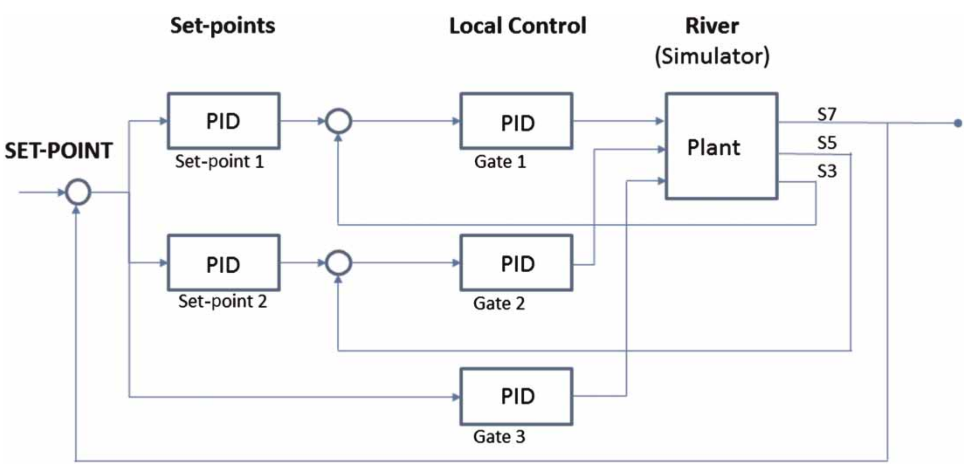

Figure 8 | Cascade PID control strategy.

actuators in the network which produce the best admissible states of the network, in terms of these objectives, during a certain time horizon. The control period must be defined taking into account the telemetry system sampling time and the time constants of the actuators of the network. The optimization horizon must be selected considering the hydraulic time constants of the water transport system. Optimal predictive control has already been applied in water systems by Gelormino & Ricker (1994), Gómez *et al.* (2002), and Cembrano *et al.* (2000; 2005), among others. The computation of the optimal predictive control set-points to be applied at the actuators is based on MPC (Camacho & Bordons 1999; Maciejowski 2001). In MPC, at each sampling time, starting at the current state, the following open-loop optimal control problem over a finite horizon H_p is solved on-line:

$$\min_{u(0|k),\ldots,u(H_u|k)} \sum_{i=0}^{H_p-1} \|y(k+i|k)-r(k+i|k)\|^2_{W_y(i)} + \sum_{i=1}^{H_u} \|\Delta u(k+i|k)\|^2_{W_{\Delta u}(i)}$$

subject to:

$$x(i+1|k) = Ax(i|k) + Bu(i|k), \quad i = 0, \ldots, H_p - 1$$
$$y(i|k) = Cx(i|k), \quad i = 0, \ldots, H_p$$
$$u_{\min} \le u(i|k) \le u_{\max}, \quad i = 0, \ldots, H_p - 1$$
$$y_{\min} \le y(i+1|k) \le y_{\max}, \quad i = 0, \ldots, H_p - 1$$
$$\Delta u_{\min} \le \Delta u(i|k) \le \Delta u_{\max}, \quad i = 0, \ldots, H_p - 1$$
$$\Delta u(i|k) = 0, \quad i = m, \ldots, H_p - 1$$

where m is a prefixed value within the prediction horizon. As a result, a virtual control input sequence $(u(0|k), \ldots, u(H_u|k))$ of present and future values which optimize an open-loop performance function, using a prediction of the system evolution over the horizon H_p, is obtained. This prediction is performed assuming that disturbances and model parameters will keep constant during the horizon. Then, the *receding horizon control strategy* is applied: only the first control input of the sequence $(u(0|k))$ is actually applied to the system, before another sequence based on more recent data is computed. The same procedure is restarted at time $k+1$, using the new measurements obtained from sensors. The resulting controller belongs to the class called open-loop optimal-feedback control. As the name suggests, it is assumed that feedback is used, but it is computed only on the basis of the information available at the present time.

An MPC controller has been applied in order to solve the problems encountered with the previous strategies (see Figure 9). It replaces the previous PID set-point controller layer, presented in Figure 8, computing the pollutant set-points for the local PID controllers trying to control a global set-point of maximum pollutant at the end of the considered stretch of the river, which is in section S_7.

To minimize the effort of the CPU computation, the control models, presented in the 'Modelling's section, have been defined as simply as possible taking into account the delays of the water transport from each tank to the final control point as well as the delays of pollutant transport to the same control point. Thus, the system is divided into two different problems according to its two different sampling times and has been solved sequentially from the farthest away to the closest to the control point. It is important to mention that since the third tank is nearly located at the control point, it has been optimized out of the MPC controller, directly through its local PID controller.

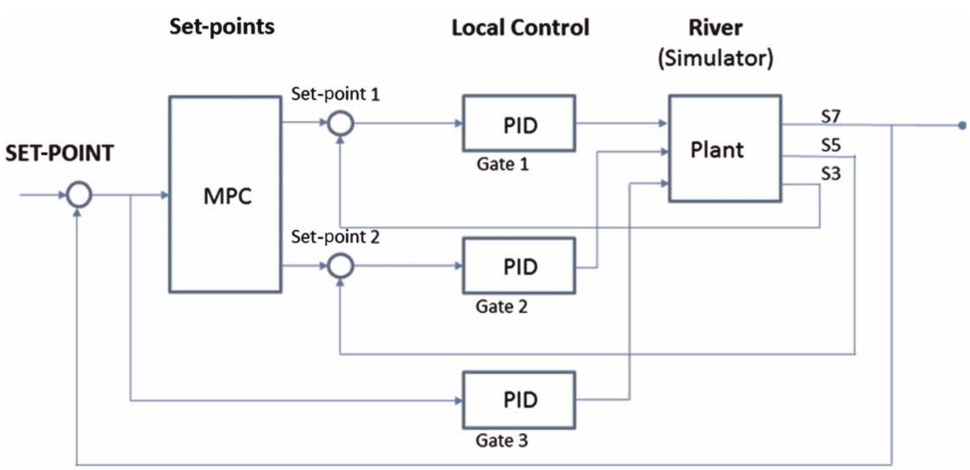

Figure 9 | Model predictive control strategy.

RESULTS

In order to show the results obtained applying these procedures, a single input scenario is used to test and compare the different control strategies. The scenario is defined with two different inputs at the beginning of the considered stretch of river. A flooding episode with a 1,000 m^3/s of a maximum flow peak and a constant 20 m^3/s of pollutant input has been considered.

Indirect flow PID control

Figure 10 shows the flow control around a set-point of 400 m^3/s when the indirect flow PID control, presented in Figure 6, is used. In this case, this set-point is selected to achieve the desired pollutant concentration based on the results presented in Figure 5. From Figure 10, it can be noticed that this control strategy succeeded in fixing the desired flow in the control point, guaranteeing the desired pollutant dilution.

Pollutant PID local control

Figure 11 presents the results that correspond to a direct pollutant PID local control (see Figure 7) when fixing the set-points as in the figure. The results on this strategy are good for constant set-points. However, the determination of set-points for the PID controllers upstream the outlet of the river (where the desired concentration should be achieved) is not easy.

Pollutant global PID control

The results presented in Figure 12 correspond to using the control strategy presented in Figure 8. They look quite good without the need for manually pre-setting the set-points of the different PIDs as in the case of the previous strategy presented in the 'Pollutant PID local control's section. Although Figure 12 shows that the set-point of 2.8 g/m^3 is reached at the end of the river after a transient period, notice the difficulties of the controller to reach the desired set-point, as discussed in the section 'Pollutant global control using supervisory PIDs'.

Pollutant model predictive control

In Figure 13, the computed set-points from the MPC controller are shown in the top plot. In the middle plot, the outputs of the local PID controllers (the opening gates) are

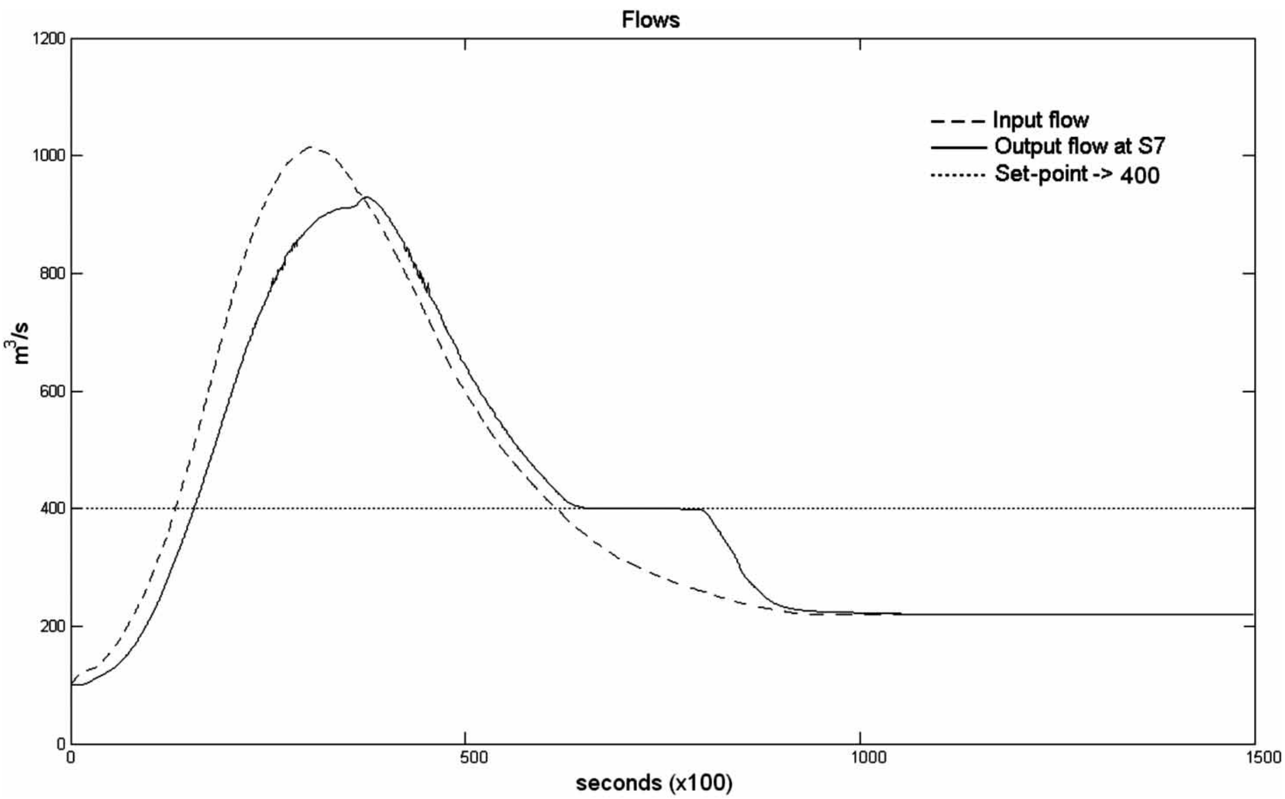

Figure 10 | Results of the indirect flow PID control strategy.

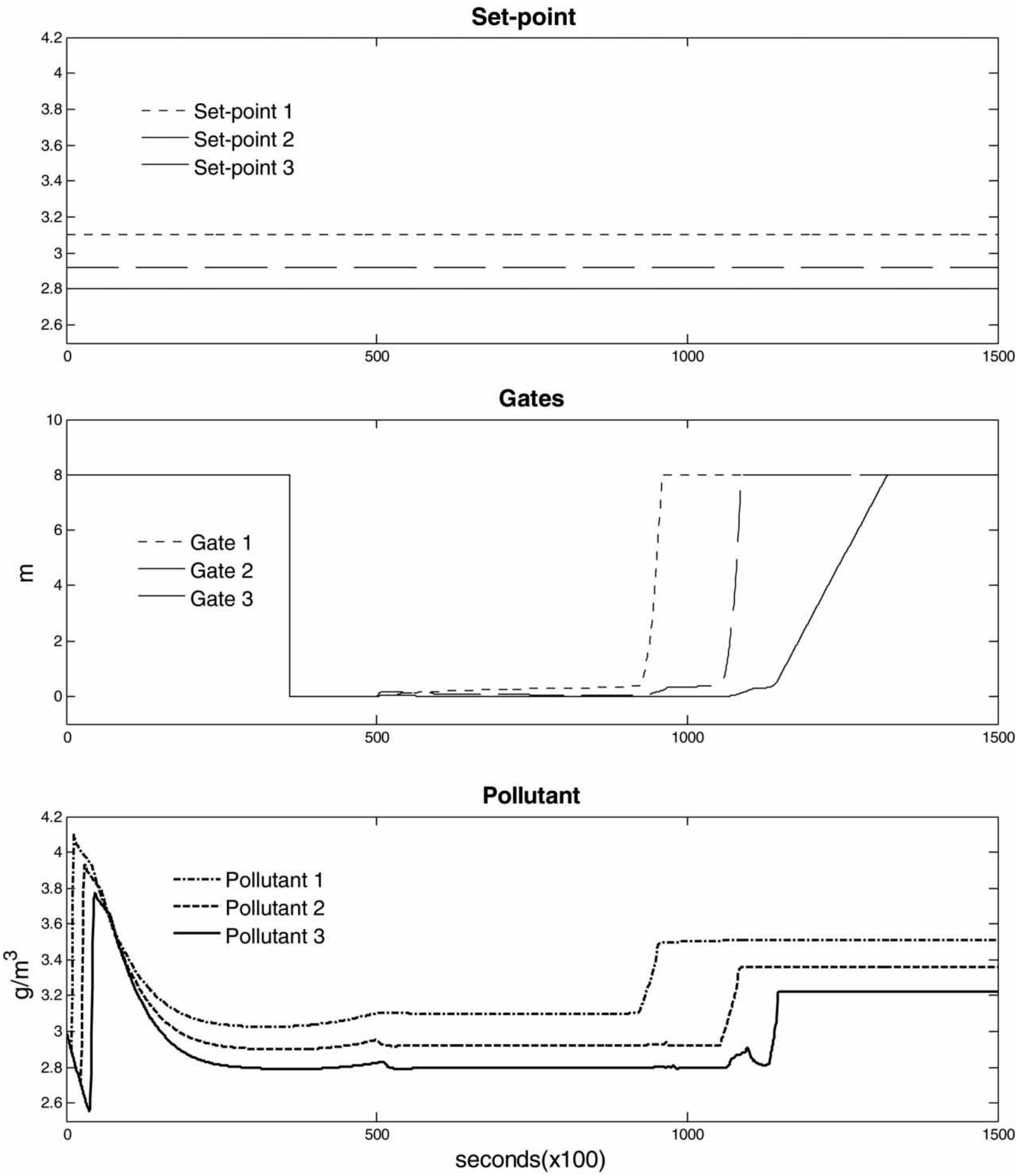

Figure 11 | Results of the local pollutant PID control strategy.

presented, which are sent to the simulator. Finally, in the bottom plot, the pollutant concentration at the local control points that correspond to the output of the tanks is presented. The concentration at section S_7 corresponds as well with the river control point, which is controlled around its set-point of 2.8 g/m^3. These results show that this strategy satisfactorily achieves the desired control specifications, without the problems of the previous strategies. Thus, this is the preferred one to solve the combined pollutant/flooding problem presented in 'Problem description and modelling'.

CONCLUSIONS

This paper has presented the case of combined pollutant/flooding control in the basin of the Ebro River in Spain. Several strategies to address this problem have been presented

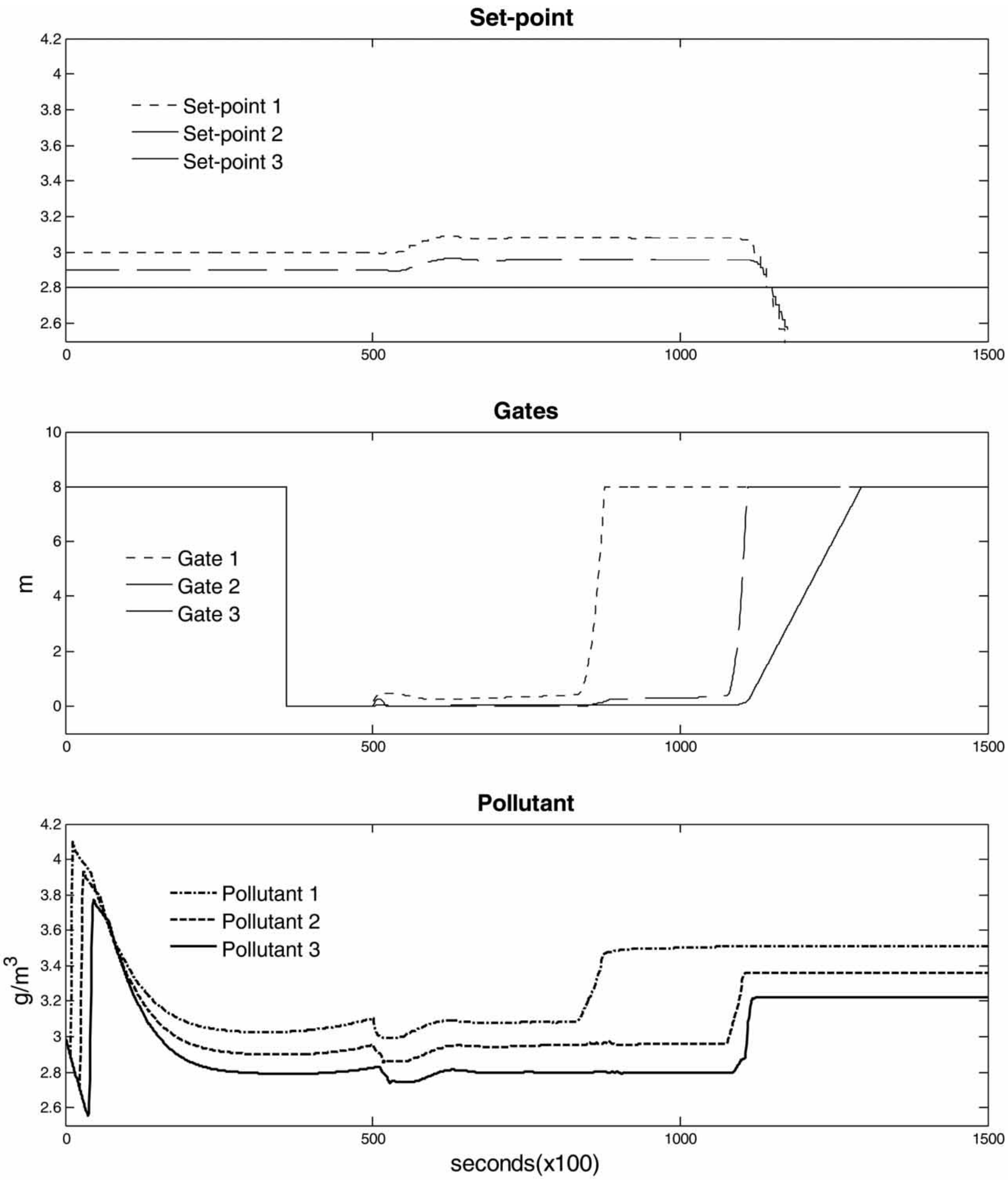

Figure 12 | Results of the global pollutant PID control strategy.

and tested when applied to flooding scenarios. From the simplest to the most complex, all of them are quite good for certain cases but present as well some problems.

The main problem of indirect flow PID control is the fact that the pollutant solute concentration is time and flow dependent. So, controlling only the flow does not guarantee that the pollutant concentration at the river outlet will be achieved.

The PID local control is a good solution only when set-points of the local controllers are constant over time. Pollutant global PID controller is intended to solve the static set-point problem. It also works well enough, but in case of a critical value for the control variable it should not be chosen due to the bad performance when switching between the different controllers. However, the transient response until the desired set-point is

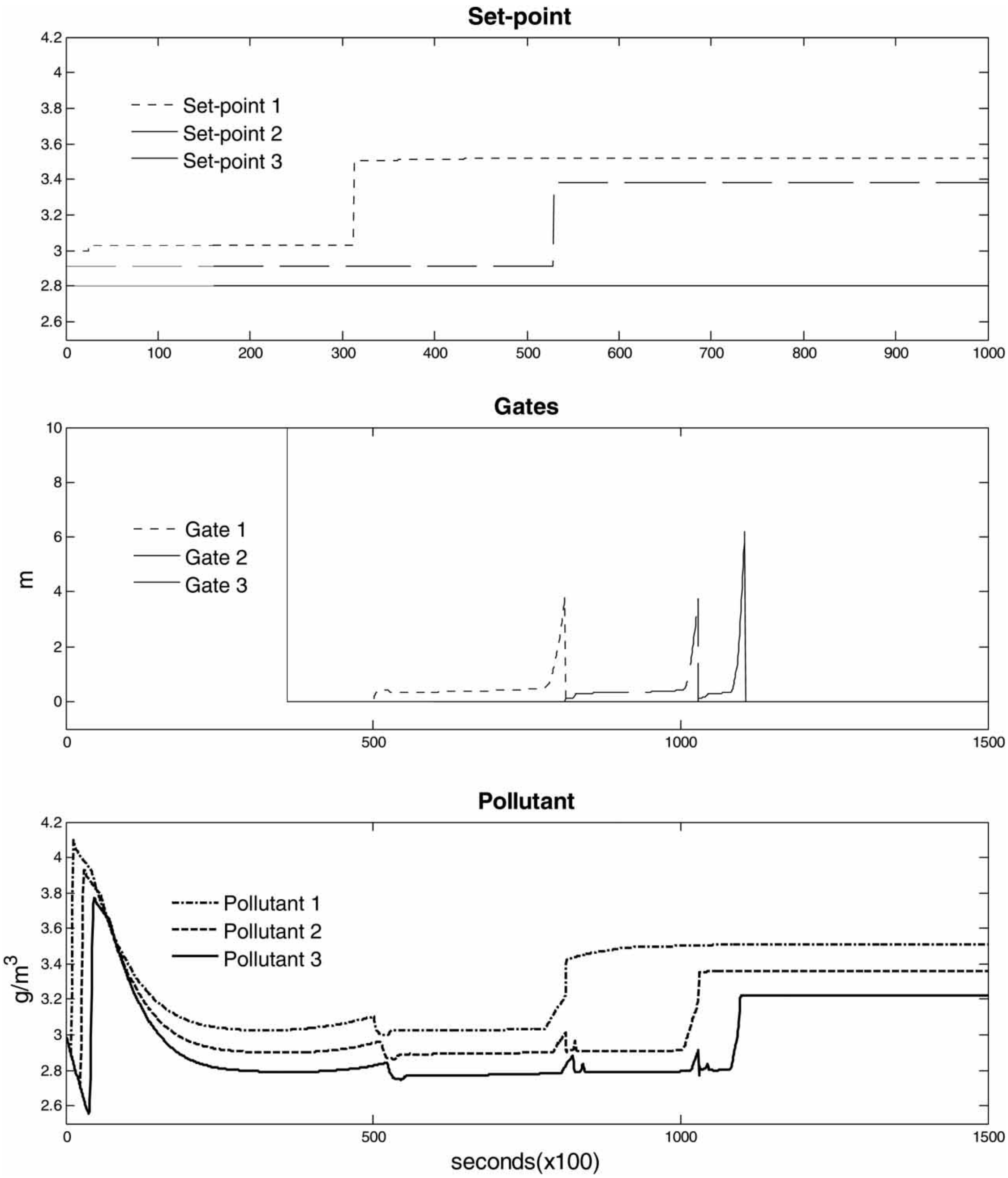

Figure 13 | Results of the model predictive control strategy.

achieved is not good enough because of transport delays that are present.

Finally, the MPC scheme is proposed to solve all the above mentioned problems. This strategy is good for determining the local controller set-points, and is a good option for systems with delays and multiple manipulated variables. The results show that it is the best strategy among the ones considered despite its higher implementation burden.

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REFERENCES

Abbott, M. B. & Minns, A. W. 1998 *Computational Hydraulics*. Ashgate Publishing, Aldershot, UK.

Augustijn, D. C. M., van den Berg, M., de Bruine, E. & Korving, H. 2011 Dynamic control of salt intrusion in the Mark-Vliet river system, The Netherlands. *Water Resources Management* **25** (3), 1005–1020.

Blanco, T. B., Willems, P., Chiang, P., Haverbeke, N., Berlamont, J. & DeMoor, B. 2011 Flood regulation using non-linear model predictive control. *Control Engineering Practice* **18** (10), 1147–1157.

Camacho, E. F. & Bordons, C. 1999 *Model Predictive Control*. Springer, London.

Cembrano, G., Wells, G., Quevedo, J., Pérez, R. & Argelaguet, R. 2000 Optimal control of a water distribution network in a supervisory control system. *Control Engineering Practice* **8** (10), 1177–1188.

Cembrano, G., Quevedo, J., Puig, V., Pérez, R. & Figueras, J. 2005 First results of predictive control application on water supply and distribution in Santiago-Chile. *Proceedings of the IFAC '05 World Congress*, Prague.

Gelormino, M. S. & Ricker, N. L. 1994 Model-predictive control of a combined sewer system. *International Journal of Control* **59**, 793–816.

Gómez, M., Rodellar, J. & Mantecon, J. A. 2002 Predictive control method for decentralized operation of irrigation canals. *Applied Mathematical Modelling* **26**, 1039–1056.

Litrico, X. & Fromion, V. 2004 Simplified modeling of irrigation canals for controller design. *Journal of Irrigation and Drainage Engineering* **130** (5), 373–383.

Litrico, X., Belaud, G. & Fovet, O. 2011 Adaptive control of algae detachment in regulated canal networks. *IEEE International Conference on Networking, Sensing and Control (ICNSC), Delft, The Netherlands, April 11–13*, pp. 179–202.

Maciejowski, J. M. 2001 *Predictive Control with Constraints*. Addison-Wesley, Harlow, UK.

Murillo, J., García-Navarro, P., Burguete, J. & Brufau, P. 2006 A conservative 2D model of inundation flow with solute transport over dry bed. *International Journal for Numerical Methods in Fluids* **52** (10), 1059–1092.

Romera, J., Ocampo-Martínez, C., Puig, V. & Quevedo, J. 2013 Flooding management using hybrid model predictive control at the Ebro river in Spain. *Journal of Hydroinformatics.* **15** (2), 366–380.

van Overloop, P. J., Weijs, S. & Dijkstra, S. 2008 Multiple model predictive control on a drainage canal system. *Control Engineering Practice* **16** (5), 531–540.

Weyer, E. 2001 System identification of an open water channel. *Control Engineering Practice* **9**, 1289–1299.

Xu, M., van Overloop, P. J., van de Giesen, N. C. & Stelling, G. S. 2010 Real-time control of combined surface water quantity and quality: polder flushing. *Water Science and Technology* **61** (4), 869–878.

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