Flooding Management using Hybrid Model Predictive Control at the Ebro River in Spain

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Abstract:

In this paper, the problem of flooding management at the Ebro River in Spain is presented. 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. This paper presents a hybrid model predictive control approach to determine and fix the level of flooding in pre-established zones by controlling the gates that controls the water input to the land to be flooded. Finally, several scenarios are used to validate the performance of the proposed approach.

Keywords

Water systems, rivers, simulation, predictive control, tele-control systems

1. INTRODUCTION

Flooding prevention and control in rivers is a important topic in the river management. This is also the case in the basin of the river Ebro in Spain. In the past, the Ebro basin experienced several floods. In order to reduce the flood hazard in a given area, the local water administration usually sets up several flood-controlled areas for being able 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. Recent simulations of these past events in a hydrodynamic river model showed that flooding could have been significantly reduced and even avoided if the hydraulic structures would have been controlled in a different way. Therefore, the main interest of this paper is to test a different control strategy than the one currently adopted.

Due to the specific nature of the flooding problem, a model predictive control (MPC) strategy (Maciejowski, 2001) seems to be the most suitable option. In this paper, the problem of flooding control at the Ebro River in Spain is addressed using MPC. Finally, several scenarios are used to validate the performance of the proposed approach.

In Section 2, the problem addressed in this paper is described. In Section 3, a control oriented model is proposed. In Section 4, the control approach based on an MPC is described. Results of the application of the proposed control approach using a virtual reality simulator are presented in Section 5. Finally, in Section 6, the main conclusions are presented.

2. PROBLEM 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 three of the inundation areas located along the river. The flood going in and out to these areas can be controlled using gates. The idea is the following: when a flooding episode starts, the gates should be open to start filling the flooding zones and closed when they are full. On the other hand, when the flow in the control point downstream is going down below some pre-established safety flow, the gates should be opened again to start emptying the flooding zones.

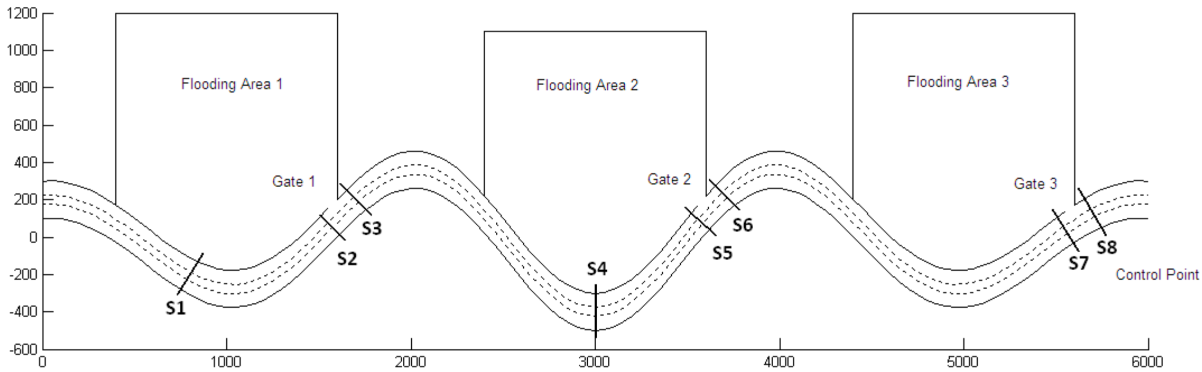

Figure 1. Ebro River and three of the flooding zones

In order to test the proposed optimal predictive controller to avoid floodings in Ebro river, a high-fidelity simulator, based on the well-known Saint-Venant equations that describe sub-critical, critical and super-critical flow, has been developed. Additionally, these equations allow reproducing 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 (Abbot and Minns, 1998; Martin et al, 2006)
The numerical method implemented is based on a four-point implicit finite difference scheme, where the partial differential equations are replaced by the evaluation of functions at the discrete points. For each interaction step a sparse matrix is computed.

3. CONTROL ORIENTED MODEL

One of the most important stages on the design of real-time control (RTC) schemes for open-flow channels, in the case of using a model-based control technique as MPC, lies on the modelling task. This is because performance of model-based control techniques relies on model quality. So, in order to design an MPC-based RTC scheme with a proper performance, a system model with accuracy enough should be used but keeping complexity manageable.

Water flow in rivers is open channel, which corresponds to the flow of a certain fluid in a channel in which the fluid shares a free surface with an empty space above. The Saint–Venant equations, based on physical principles of mass conservation and energy, allow the accurate description of the open-channel flow and therefore also allow having a detailed nonlinear description of the system behaviour. Associated to this concept is the volumetric flow rate, which can be thought of as the mean velocity of the flow through a given cross-section, multiplied by its cross-sectional area. Mean velocity can be approximated through the use of the Law of the Wall (Abbot and Minns, 1998; Martin et al, 2006). In general, velocity increases with the depth (or hydraulic radius) and slope of the river channel, while the cross-sectional area scales with the depth and the width: the double counting of depth shows the importance of this variable in determining the discharge through the channel.

Notice that models based on Saint-Vennant's equations describe the system behaviour in high detail. However, such a level of detail is not useful for RTC implementation because of the complexity and the high computational cost of combining those equations with the MPC strategy. Alternatively, several conceptual modelling techniques that deal with RTC of rivers have been proposed: Hayami model (Litrico, 1999a, b), Muskingum model (Gómez, 2002), IDZ model (Litrico, 2004) or black-box models identified using parameter estimation (Weyer, 2001).

Rivers, seen as water transport channels, present several inherent hybrid behaviours that cannot be modelled using a pure linear model. In this paper, the hybrid modelling framework based on piece-wise linear functions (PWLF) is used to model such behaviours. More precisely, the PWLF-based modelling methodology, proposed in (Ocampo-Martinez, 2010), consists in using continuous and monotonic functions to represent expressions that contain logical conditions, which describe the nonlinear discontinuous behaviours. The PWLF approach is thought as an alternative to the use of a pure hybrid modelling approach, already proposed for the RTC of related dynamical systems (Ocampo-Martinez, 2010).

The PWL functions used to model the discontinuous behaviours of such systems are defined as "saturation" of a variable x in a value m (i.e. $sat(x, m)$), and "dead zone" of the same variable x starting in a value M (i.e. $dzn(x, M)$). Those functions are monotonic and continuous and might lead to a quasi-convex optimisation problem when formulating the MPC problem. According to (Ocampo-Martinez, 2010), the global optimal solution of quasi-convex optimisation problems can be obtained by using a bisection method, which is logarithmic in time. This fact represents an advantage with respect to the mixed-integer linear problems resultant when using a pure hybrid approach based on mixed logical dynamic (MLD) forms or piece-wise affine (PWA) approaches. This type of models induces an exponential complexity given by the handling of Boolean variables and the discrete optimization required.

4. CONTROLLER DESIGN

In most water systems, the regulated elements (pumps, gates and retention devices) are typically controlled locally, that is, they are controlled by a remote station according to the measurements of sensors connected only to that station. However, a global RTC system requires the use of an operational model of the system dynamics in order to compute, ahead of time, optimal control strategies for the actuators based on the current state of the system provided by supervisory control and data acquisition (SCADA) sensors, the current disturbance measurements and appropriate disturbance predictions. The computation procedure of an optimal global control law should take into account all the physical and operational constraints of the dynamical system, producing set-points though which given control objectives are achieved.

MPC has shown to be a suitable control strategy to implement global RTC of water systems since it has some features to deal with complex behaviours and features such as big delays compensation, the use of physical constraints, relatively simple for people without deep knowledge of control, multi-variable systems handling etc. 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, what is reflected in the controller design as the performance indexes to be minimised.

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 actuators in the network which produce the best admissible states of the network, in terms of these objectives, during a certain 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 water transport system. Optimal predictive control has already been applied previously in water systems by (Gelormino, 1994; Gómez, 2002; Cembrano, 2000; 2005), among others. The computation of the optimal predictive control set-points to be applied at the actuators is based on model predictive control (MPC) (Camacho, 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:

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

$$\begin{aligned}
&subject\ to:\\
&x(i+1|k) = Ax(i|k) + Bu(i|k), \quad i = 0,\cdots,H_p - 1\\
&y(i|k) = Cx(i|k), \quad i = 0,\cdots,H_p\\
&u_{min} \le u(i|k) \le u_{max}, \quad i = 0,\cdots,H_p - 1\\
&y_{min} \le y(i+1|k) \le y_{max}, \quad i = 0,\cdots,H_p - 1\\
&\Delta u_{min} \le \Delta u(i|k) \le \Delta u_{max}, \quad i = 0,\cdots,H_p - 1\\
&\Delta u(i|k) = 0, \quad i = m,\cdots,H_p - 1
\end{aligned}$$

where *m* is a prefixed value within the prediction horizon. As a result, a virtual control input sequence ($u(0|k),\cdots,u(H_u|k)$) 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 strategy* is applied: only the first control input of sequence ($u(0|k)$) is actually applied to the system, until 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.

5. RESULTS

5.1 Modelling

Using the modelling methodology presented in Section 3, the Ebro system presented in Figure 1 can be represented by the block diagram presented in Figure 2.

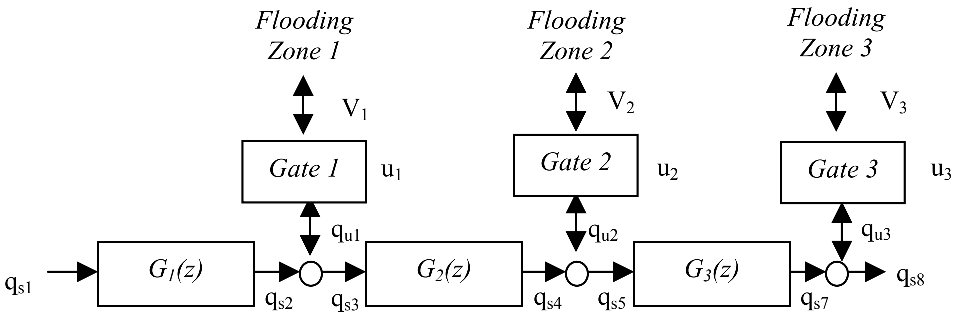

Figure 2. Block diagram of the Ebro system

Each river reach has been identified experimentally using the IDZ model structure proposed by Litrico (2004) leading to the following transfer functions

$$G_1(z)=\frac{0.1432z^{-6}}{z-0.8547} \quad ; \quad G_2(z)=\frac{0.09515z^{-6}}{z-0.9049} \quad ; \quad G_3(z)=\frac{0.1247z^{-6}}{z-0.8761}$$

The flow through the gate can be described by the following PWL function

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

where u_i is the gate opening of the gate, K_i is a constant that takes into account the gate geometry and $h_{river,i}$ and $h_{zone,i}$ are the levels of water at the river and flooding zone side of the gate.

5.2 Control results

The control objective is to avoid that flow goes over certain maximum value at the section S8 (the end of Ebro reach shown in Figure 1). In the simulations, this maximum value is set to 600 m^3/s.

Figure 3 shows the results obtained in a first scenario corresponding to a peak of flow of 1000 m^3/s at the entrance of the system (S1). The first picture ("flow") compares the input flow of reach S1 against the flow obtained at the output of the reach S8 allowing to see the performance of the MPC control. It can be noticed that peak flow is only reduced to 800 m^3/s, the minimum achievable in this scenario due to physical limitation. The second picture ("gates") shows the water level of the river and flooding (tank) areas where the gates are located. The levels in the river and flooding zone side of the gate are represented with solid and dashed lines. The gate position (control action) determined by the MPC controller is presented in dash-dot line. From this last plot, it can be noticed that the MPC controller do not open the gate until it predicts the flow will be higher than the maximum desirable flow (600 m^3/s) at S8. At this point (about $2.3\text{x}10^4$ seconds), the MPC controller opens the gates to store water at the flooding zones in order to reduce the flow at the control point S8. The gates have to be closed when the flow level on the riverside is equals or higher than the tank side (about $4\text{x}10^4$ seconds). Once the controller predicts the flow at S8 going under the maximum desirable flow (600 m^3/s), it opens the gates again to empty the flooding zones. Finally, in the last picture, the amount of water stored and released in the three flooding zones is shown. The water stored in the three flooding zones is about 1,5 million of cubic meters (see Figure 3) in the most critical situation of the flooding scenario. This allows to decrease about 20% of the maximum flow (from 1000 m^3/s to 800 m^3/s) at the output of the reach S8. The maximum capacity of the flooding zones is around three million of cubic meters. In this scenario, only about 50% of this maximum capacity is used due to the physical characteristics of the flooding scenario (maximum 1000 m^3/s) and the passive system (gates) used to transfer the river water to the flooding zones. An alternative way to increase the maximum stored water of the flooding zones would imply to install an active system, such as pumping stations, to transfer the water from/to the river to the flooding zones.

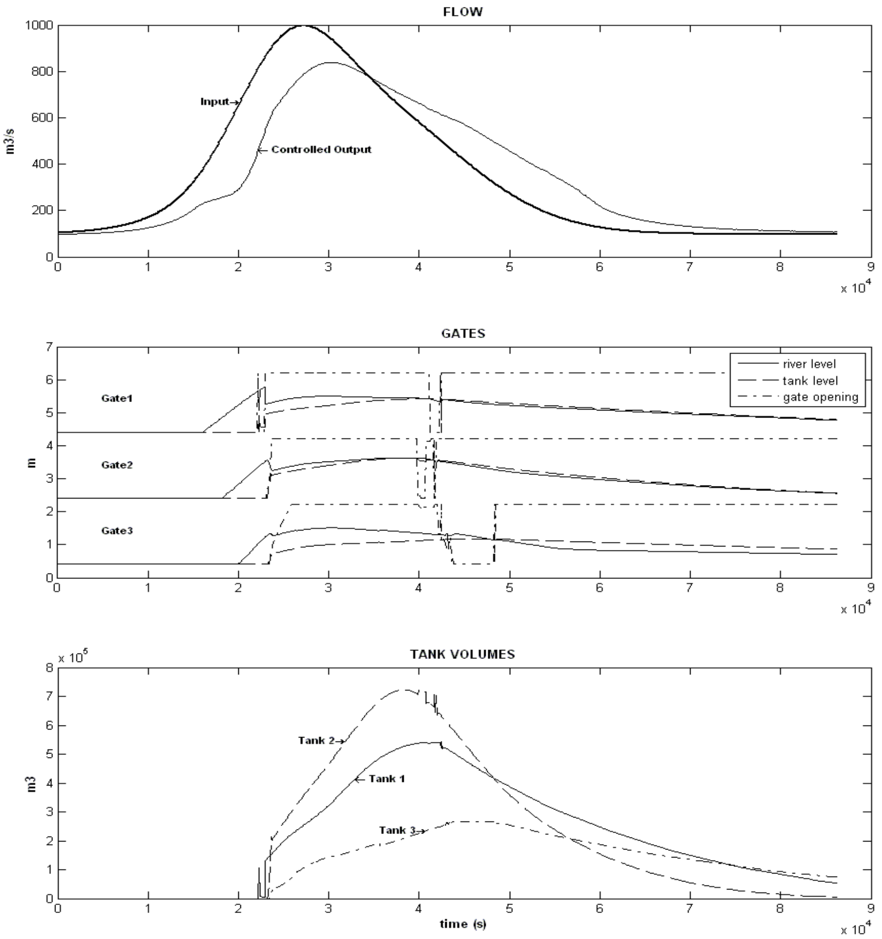

Figure 3. First flooding scenario

Figure 4 presents the results of two-peak flow scenario, each one of 1000 m^3/s. The control objective is the same than in the first scenario. In the *flow* picture, it can be seen that the peak reduction of the controlled flow is more or less the same. The peak is reduced in approximately 800 m^3/s at the output of the reach S8. This is 20% less than the maximum flow in the input of the river. In the *gates* picture, it can be noticed that the controller opens the gates when the first peak arrives, closes the gates between peaks to prevent emptying the tanks and open again when the second flow peak appears. Finally, once the flow goes down to the maximum desirable flow (600 m^3/s), gates are opened to empty the three flooding zones. From the *volume* picture, it can be seen how water is stored during and between peaks in the flooding zones in order to reduce the flow at S8. In this scenario, the flooding zones stored more than 2 million of cubic meters (70% of the maximum capacity) because the second flow peak arrives before the stored water due to the first peak has been released from the flooding zones.

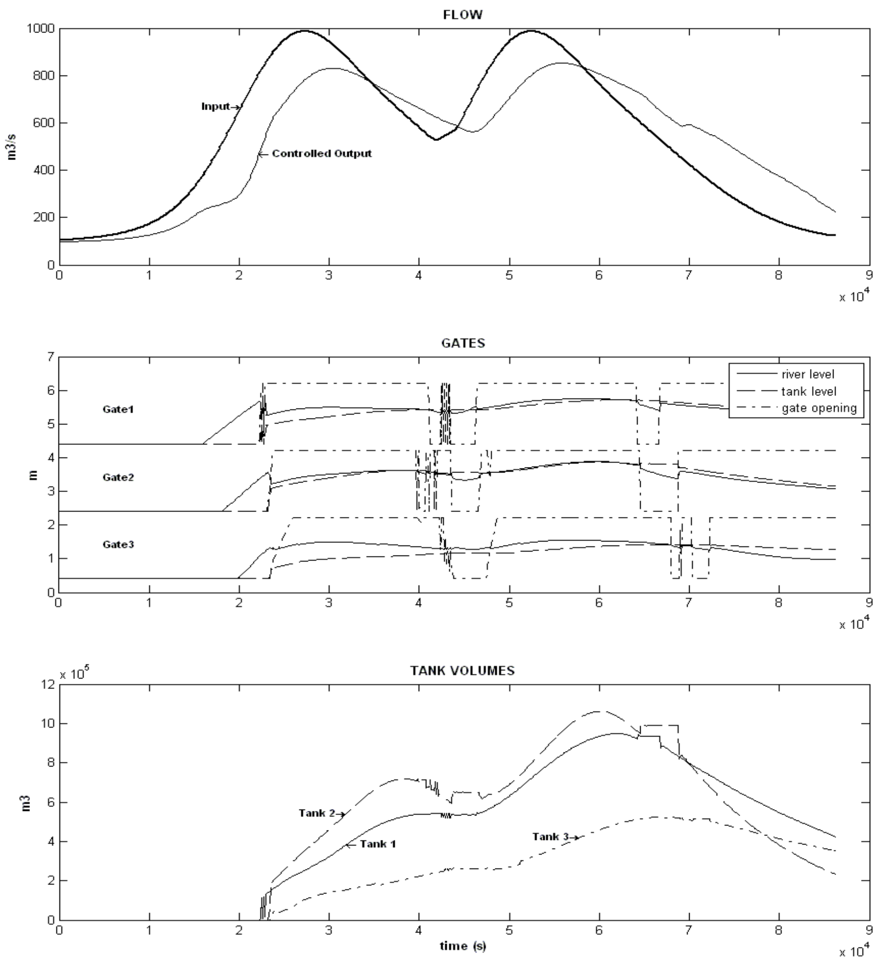

Figure 4. Second flooding scenario

6. CONCLUSIONS

In this paper, the problem of flooding control at the Ebro River in Spain is presented. 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. This paper has presented an hybrid MPC approach to contrrol the level of flooding in pre-established areas by manipulating the gates that regulates the water input to the land to be flooded. Several scenarios have been used to validate the performance of the proposed approach. Obtained results are promising although they could be improved by replacing gates by pumps to fill/empty the flooding zones.

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REFERENCES

Abbott M.B. and Minns A.W. (1998). *Computational Hydraulics*. Ashgate Publishing Limited, England. ISBN: 0-291-39835-9.

Brdys, M. A. and Ulanicki, B. (1994). *Operational control of water systems: Structures, algorithms and applications*. Prentice Hall International, UK.

Bergez J., Garcia F. and Lapasse L. (2004). A hierarchical partitioning method for optimizing irrigation strategies. *Agricultural Systems*, Vol. 80, pp. 235-253.

Camacho E.F. and Bordons C. (1999). Model Predictive Control in *Advanced Textbooks in Control and Signal Processing*. Ed. Springer, London.

Cembrano, G., Wells, G., Quevedo, J., Pérez, R. and 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. and 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. and Ricker N. L, (1994). Model-Predictive Control of a Combined Sewer System *International Journal of Control*, Vol. 59, pp 793-816.

Gómez M., Rodellar J., and Mantecon J.A. (2002). Predictive control method for decentralized operation of irrigation canals. *Applied Mathematical Modelling*, Vol.26, pp.1039-1056.

Leenhardt D., Trouvat J., Gonzalès G., Pérarnaud V., Prats S. and Bergez J. (2004). Estimating irrigation demand for water management on a regional scale: I. ADEAUMIS, a simulation platform based on bio-decisional modelling and spatial information. *Agricultural Water Management*, Vol. 68, pp. 207-232.

Leenhardt D., Trouvat J., Gonzalès G., Pérarnaud V., Prats S. and Bergez J. (2004). Estimating irrigation demand for water management on a regional scale: II. Validation of ADEAUMIS. *Agricultural Water Management*,Vol. 68, pp. 233-250.

Litrico X. and Georges D. (1999a). Robust continuous-time and discrete-time flow control of a dam-river system: (I) Modelling. *Applied Mathematical Modelling*, Vol. 23, No.11, pp.809-827.

Litrico X. and Georges D. (1999b). Robust continuous-time and discrete-time flow control of a dam-river system. (II) Controller design. *Applied Mathematical Modelling*, Vol. 23, 11, pp.829-846.

Litrico X. and Fromion V. (2004). Simplified modeling of irrigation canals for controller design. *Journal of Irrigation and Drainage Engineering*, Vol. 130, No. 5, pp. 373-383.

Maciejowski J.M. (2001). *Predictive Control with Constraints*. Ed Addison-Wesley. UK.

Martin C., Cardona C. M., San Martin D., Salterain A. and Ayesa E. (2006). Dynamic simulation of the water quality in rivers based on the IWA RWQM1. Application of the new simulator CalHidra 2.0 to the Tajo River. *Water Science and Technology* 54 (11-12), 75-83.

Mouelhi S., Michel C., Perrin C. and Andreassian V. (2002). Rainfall-runoff modeling at three large time-steps. *Proposal to Hydrological Sciences Journal*.

Ocampo-Martinez, C. and V. Puig (2010). Piece-wise linear functions-based model predictive control of large-scale sewage systems", IET Control Theory Appl., Vol. 4, Iss. 9, pp. 1581–1593

Oudin L. (2006). Une formule simple d'évapotranspiration potentielle pour la modélisation pluie-débit à l'échelle du bassin versant. *Houille blanche*, Vol. 6, pp. 113-120.

Popova Z., Eneva S. and Pereira L. (2006). Model Validation, Crop Coefficients and Yield Response Factors for Maize Irrigation Scheduling based on Long-term Experiments. *Biosystems Engineering*, Vol. 95, pp. 139-149.

Smith M. (2000). The application of climatic data for planning and management of sustainable rainfed and irrigated crop production. *Agricultural and Forest Meteorology*, Vol. 103, pp. 99-108.

Wallach D., Goffinet B., Bergez J., Debaeke P., Leenhardt D. & Aubertot J. (2001). Parameter estimation for crop models: a new approach and application to a corn model. *Agronomy journal*, Vol. 93, pp. 757-766.

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