Contribution to a flood situation management: a supervisory control scheme to reduce disaster impact

H. Nouasse, P. Chiron and B. Archimède

ABSTRACT

Inundations due to river overflows are becoming more frequent; management of flood is thus an important task belonging to the set of preventive measures allowing the protection of people and goods downstream. The flood situation management method proposed in this paper was designed to reduce the flood impact at its early arising stage. The river is supposed to be equipped with reservoirs in which water excesses are stored and then released only when the flood episode ends. The supervisory control scheme allows calculation of the water volumes through the use of a network flow. Management objectives, such as the maximum discharge level allowed in the river, the order of priority for the reservoir storage or release, the measured levels and discharge in the river and in the reservoirs, and the assessed parameters such as time delays, are combined to configure the network flow. Then, the optimal flow in the network is computed and supplies the reservoirs' gate opening setpoints. Finally, the method was applied to a simulated case for which the time delay during the flood varied and remained efficient for flood attenuation compared with the case when the gates were always open, thanks to the network configuration.

Key words | flood control, network flows, time delay, water systems management

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NOMENCLATURE

Q_{out}	The output river discharge
Q_{lam}	The attenuation threshold
n_G	The number of flood control reservoirs and gates
FCR_r	The r^{th} flood control reservoir
G_r	The gate controlling the r^{th} flood control reservoir
τ_r	The time delay from the gate G_r to the following gate G_{r+1}
Q_{do}	The release threshold
T_c	The control period
H_f	The time horizon
n	The number of control periods in the time horizon
Q_{G_r}	The discharge measured at the r^{th} gate
S	The wetted cross section
$d_{G_r,G_{r+1}}$	The distance between the r^{th} gate and the $(r+1)^{th}$ gate
$AR(\%)$	The attenuation rate
$AWR(\%)$	The attenuation wave rate
Q_{mea}	The mean effective attenuation flow
$Q_{out}(k)$	The output river discharge measured at the date kT_c
$Q_{cg}(k)$	The output river discharge measured at the date kT_c when the gates are closed
$Q_{\max}$	The maximum value of the output river discharge during the time horizon

doi: 10.2166/ws.2015.160

INTRODUCTION

Flooding due to excessive rains can cause important human and material damages around the world. The frequency of these events and their scale is increasing, as well as the importance of the human and material damages caused (Wagenknecht & Rueppel 2013). In this context, the term 'crisis' is generally used for floods leading to an actual inundation in a limited geographical zone and for which numerous assistance interventions are needed in order to help the inhabitants either to protect residential areas or to proceed to evacuation. It is essential to consider that the crisis began at the early occurrence of the flood phenomenon. It permits the study and implementation of the means leading to a fast recovery and to inform the inhabitants, to prepare and dispense protection, even in high-risk areas (Plate 2002; Merz *et al.* 2010).

Crisis management is the set of organizational methods, techniques, and means that enable an organization to prepare for and to effectively manage the occurrence of a crisis; and, in a prospective vision, to capitalize upon the lessons of the event to improve procedures and structures. In order to set up an effective management of crisis, three principal phases must be considered (see Figure 1): (1) before the flood, where it is necessary to plan, to prevent, to prepare, to protect, and to anticipate crisis situations; (2) during the flood, where the effective management of crisis is performed; and (3) after the flood, where relevant feedback of the learning experience should be performed in order to improve the first phase and to implement the means for resilience (Hooijer *et al.* 2004; Thieken *et al.* 2007).

Forecast and prevention programs are provided by states in order to face flood events in the world. Thus, the European Commission supports and finances projects in order to develop forecasting and alerting systems to warn communities of impending floods. The various projects described in the literature focus on different aspects of crisis management, and numerous software has been developed (Alfieri *et al.* 2013; Liechti *et al.* 2013; Pengel *et al.* 2013).

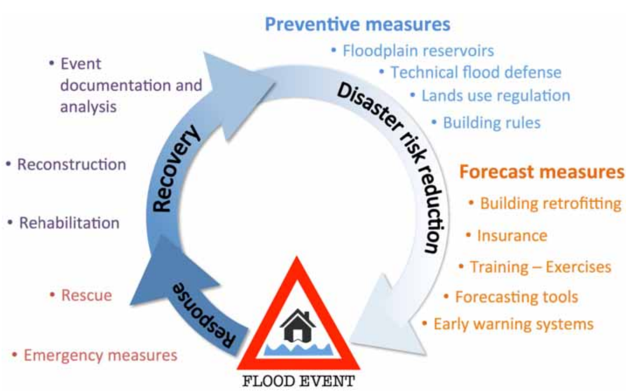

Figure 1 | Management crisis cycle, adapted from Thieken *et al.* (2007).

The present paper focuses on the phase preceding the inundation event. The potential flood is detected and the peak flow is reduced in order to limit the downstream flood impact, and if possible, to avoid the inundation. For this purpose, flood control areas existing along the river are used as reservoirs. In order to reduce the water velocity in the river, the reservoirs are filled with water and thus the flood wave is attenuated.

Various research works have been proposed to reduce flood peaks and volumes, involving linear programming (Needham *et al.* 2000) or hybrid analytic/rule-based approaches (Karbowski *et al.* 2005), for example. Most of these methods do not allow control of the duration of water storage in the reservoir, the storage, release dates, etc. In order to improve managers' decisions during these abrupt climatic phenomena, optimization techniques have been proposed, such as linear programming (Karamouz *et al.* 2003), fuzzy optimization (Fu 2008), and multi-objective optimization (Chuntian & Chau 2002).

Herein, a supervisory control scheme is proposed to handle the water volumes. This scheme, including the variation of time delay with discharge, is described in the next section. Different flood situations are then compared for a simulated river system in the following section, showing the effectiveness of the scheme.

SUPERVISORY CONTROL SCHEME

Supervisory control methods allow combining optimization, regulation, and simulation techniques. In order to help the decision-making process, the supervision, detection, and diagnosis tools are integrated, and diverse schemes and architectures have been proposed in the literature (Isermann 1997). The supervision step consists of the detection, the estimation, the prognosis of the system state, the diagnosis of this state, the computation of the setpoints and, if necessary, the control law reconfiguration.

General scheme

The supervisory control scheme proposed in this paper is depicted in Figure 2. It is composed of three interconnected

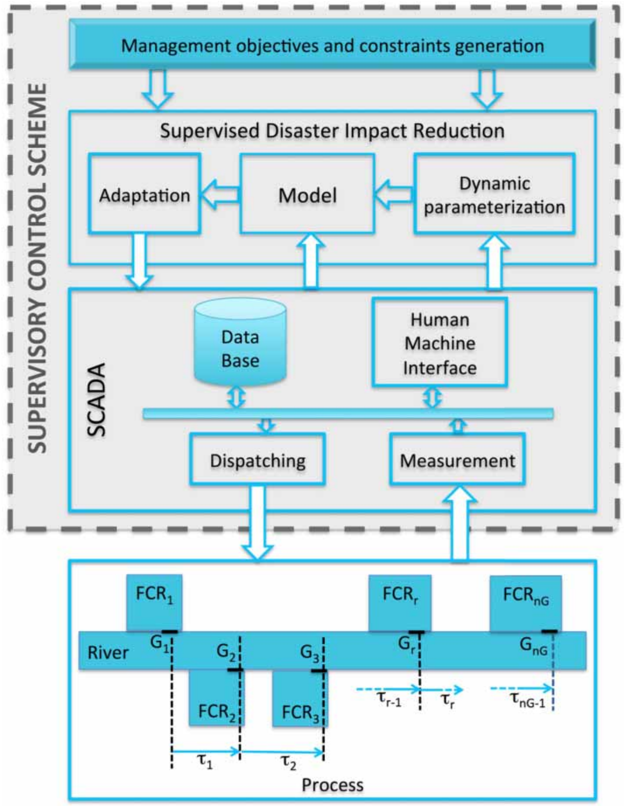

Figure 2 | The river process and the supervisory control scheme.

blocks: the supervisory control and data acquisition (SCADA) system, the management objectives and constraints generation (MOCG), and the supervised disaster impact reduction (SDIR) blocks. This scheme was designed in order to reduce the impact of a flood downstream a river. For this purpose, the river is equipped with n_G flood control reservoirs located along the river, denoted FCR_r.

The reservoirs are used to store the excess of water such that the output river discharge, Q_{out}, remains under a predefined flow value, Q_{lam}: the attenuation threshold. Each reservoir is provided with a controlled gate G_r, $r = 1, \ldots, n_G$. The opening value of each gate is computed by the proposed scheme.

When the reservoirs are not empty, the stored water can be released if the discharge level in the river is lower than the attenuation threshold Q_{lam}. In order to detect when the water can be released from the reservoirs, a threshold, Q_{do}, is defined.

The storage and release phases are exemplified in Figure 3, where Q_{input} is the input discharge in the river.

Moreover, the threshold Q_{do} can be defined in order to include the protection of farming usually present in the reservoirs in the release objective, and to be able to control flood episodes that occur close in time.

Based on the network flow model of the system composed by the river and its reservoirs, the functioning of the scheme is sequenced with eight steps. After defining the management objectives and constraints, the process follows an infinite closed loop including the activities shown in Figure 4.

SCADA system block

The SCADA block is connected to the river process. It permits the collection of data from sensors and to send control values to actuators. Measured and setpoint values can be sent to or given by an operator through a human machine interface. Such a SCADA system can be found in various kinds of systems, such as irrigation canals (Pfitscher *et al.* 2012; Figueiredo *et al.* 2013), inland navigation networks (Duviella *et al.* 2013), or energy management (Mora *et al.* 2012). In our scheme, it transmits the sensors' values to the SDIR block, and receives the gate opening setpoint values in order to send them to the process. The measurements considered herein are levels and discharges.

MOCG block

The MOCG block supplies the SDIR block with management constraints and rules such as threshold values, Q_{lam}, Q_{do}, and the priority parameters allowing, for example, to favor one of the reservoirs, or to define a reservoir assignment order. Some of these values are defined depending on the government organization directives. Moreover, in the network modeling the system, the arc can be weighted with costs in order to evaluate the strategies and take decisions improving the management. The cost values defined in the MOCG block depend on cost–benefit analysis, including an estimation of the costs of the various water usages and risks (Karamouz *et al.* 2003; Loucks *et al.* 2005). The costs definition in the objective function relies on:

- the need to avoid, reduce, or delay as long as possible the inundation downstream the river;

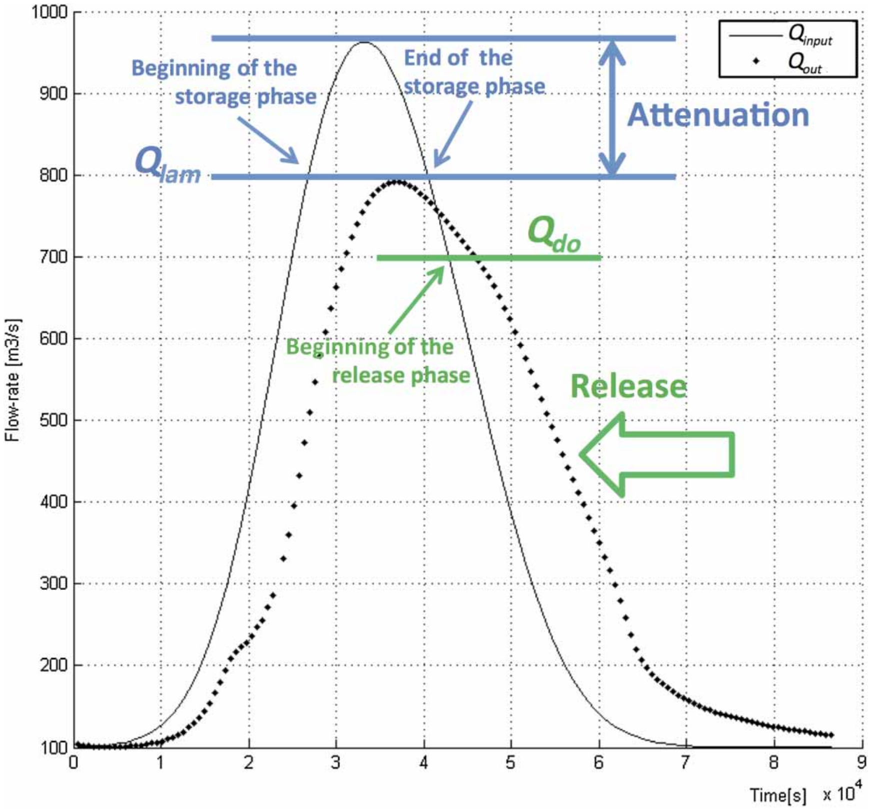

Figure 3 | Storage and release phases.

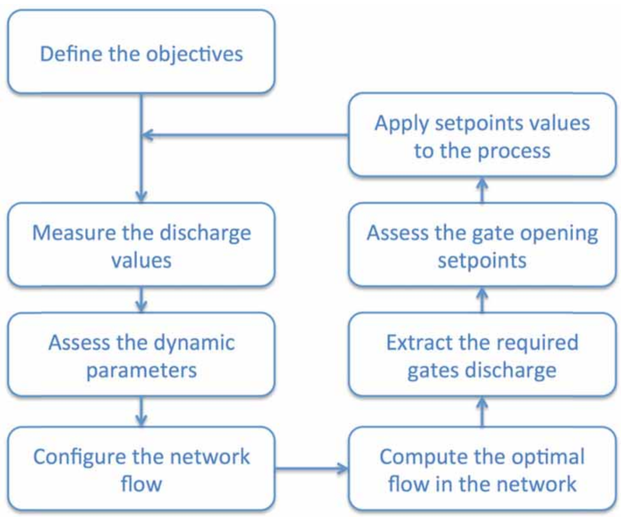

Figure 4 | Supervisory process.

- the reservoir nature (agricultural zone, fallow, etc.);
- the reservoir capacity;
- the reservoir usability;
- the protection of the farming existing in the reservoir;
- the maximal duration of the water retention;
- the necessity of preserving the water quality in the reservoir.

SDIR block

The management constraints are taken into account, according to the measured values, thanks to the SDIR block, which is detailed in the upper part of Figure 5. In order to manage the flood episode, the control method must be associated with a scheduling method (Baldea & Harjunkoski 2014). Indeed, while tracking the overflow of the discharge in case of floods, we need to establish a diagnosis of the process state, to optimize the storage and the release of the water volumes in the flooding reservoirs and to control the opening of their gates. We choose to implement a management method based on the network flow described in detail in Nouasse *et al.* (2013a, 2013b, 2013c). This SDIR block includes the following:

- The dynamic parameterization (DP) block allowing the supply of the SDIR with all the necessary dynamic parameters, such as the costs and the time delays obtained by the use of estimation techniques, for example.
- The model block producing the setpoint values for each reservoir. The model involved in this block is based on a network flow modeling the network, the reservoirs, and their management. For each kT_c, $k = 0, \cdots, n$, in the horizon H_f, with $H_f = nT_c$, $n \in N^+$. This model is first configured according to the measures and to the dynamic parameters' values: maximum and minimum arc capacities are set depending on the delayed flow and on the reservoirs' dimensions; the release or storage functioning mode is defined on the basis of the diagnosed state of the flow. Then, in the data exploitation phase, the optimal flow is computed by applying a Min cost Max flow problem resolution for this network, producing the setpoint discharge values. The proposed implementation of the network flow includes time delays. If the time delays vary, the network structure is not impacted; thus it is not necessary to add node or arc, and only network parameters are modified (Nouasse *et al.* 2013b).
- The adaptation block converting the setpoint values supplied by the model into values adapted with the process actuators controller and thus understood by the SCADA system. In fact, the water crosses the gravitational reservoir gates thanks to the difference between the levels inside the reservoir and in the river. Thus, discharge setpoint values need to be converted into level values. The Bernoulli equation is applied to the flow between the river and the reservoir to derive the non-linear static equation representing the dynamic behavior of this structure.

Using the measured flow values, the reservoir's configuration, the time delays, and the objectives, the SDIR block computes the gate opening setpoint values allowing the output flow to remain under the attenuation threshold.

IMPLEMENTATION AND RESULTS

In order to evaluate the efficiency of the proposed model, a simulation for several cases of flood was done. More often, the dimensioning of the reservoirs is done such that they can attenuate a potential flood; thereby the gates are not regulated. Thus, in each simulated flood case, the method was compared with the case when the gates are always open, which is often the case.

Implementation

The process and SCADA systems were replaced by the implementation of a test case river performed by using a 1D–2D coupled numerical model, according to the description given in Morales-Hernandez *et al.* (2013), as illustrated in Figure 5.

In this simulator, each gravitational gate is modeled considering that the flow discharge that crosses the gate is governed by the difference between the water levels on both sides of the gate. The 1D–2D coupled simulator entries are the values of the gate opening; thus, the adaptation block consists of the computation of the gate opening values from the optimal flow, by means of a static inversion of the free flow open channel equations. The DP block was used in order to compute the time delays at each $kT_c (k = 1, \ldots, n)$. The time delay, τ_r, from the gate G_r to the following gate G_{r+1} $(r = 1, \ldots, n_G)$ depends on the flow discharge. It was approximated by the following equation (see Karamouz *et al.* (2003) for example):

$$\tau_r = \frac{Q_{G_r}}{S.d_{G_r,G_{r+1}}} \quad (1)$$

where Q_{G_r} is the discharge measured at gate G_r, S is the wetted cross section, and $d_{G_r,G_{r+1}}$ is the distance traveled from G_r to G_{r+1}. In order to evaluate time delays, methods such as the ones developed in Romera *et al.* (2013) can also be used.

Performance criteria

The flood wave attenuation can be defined as the decrease in the downstream peak flow due to the attenuation of the flood (Bedient *et al.* 2013). In order to evaluate the performances of the proposed flood attenuation method, two indicators were defined: the attenuation rate (AR) and the attenuation wave rate (AWR). These indicators allow us to

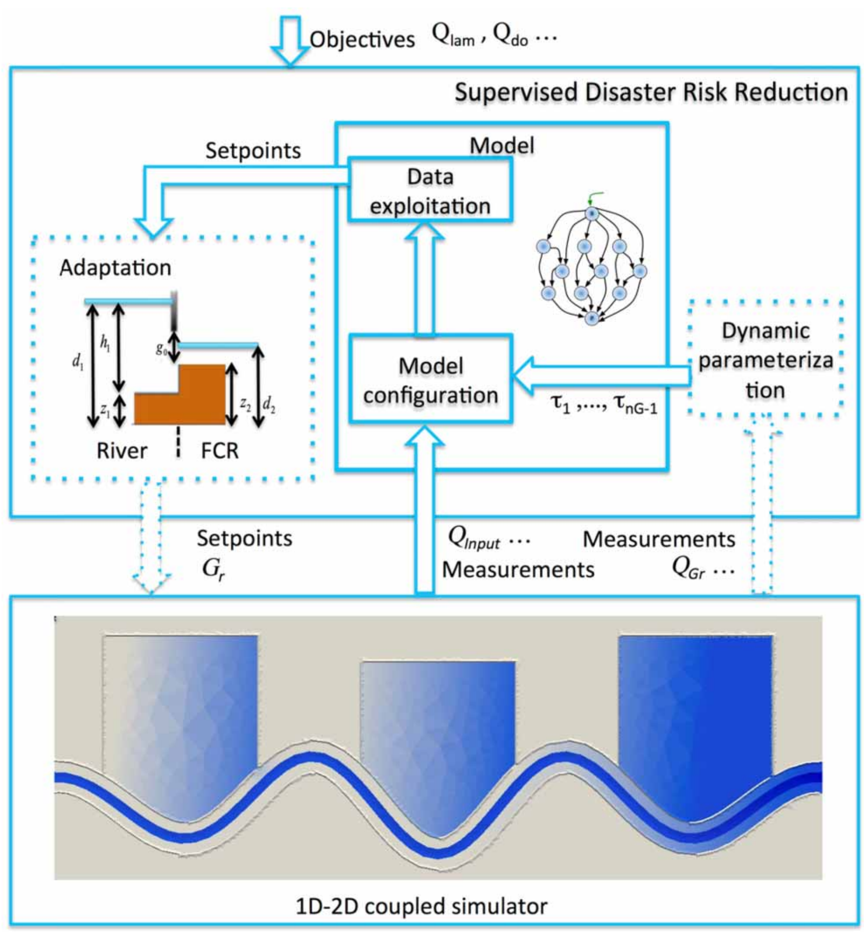

Figure 5 | Simulator and supervisory control scheme.

evaluate how we prevent downstream flood by using the proposed method. All these indicators are computed over the time horizon H_f, i.e., for $k = 0, \ldots, n$; and we denote Q_{out} the downstream flow. The AR allows measurement of the difference between the attenuation threshold objective and the obtained attenuation threshold. It is defined as the ratio between the mean effective attenuation flow, Q_{mea}, and the predefined attenuation flow Q_{lam}, as given in Equations (2) and (3):

$$AR = \frac{Q_{mea}}{Q_{lam}} \tag{2}$$

$$\begin{cases} if\ \exists k |\ Q_{out}(k) > Q_{lam} & Q_{mea} = \underset{Q_{out}(k) > Q_{lam}}{\text{mean}}\ Q_{out}(k) \\ \text{else} & Q_{mea} = \max\limits_{k=1\cdots n} Q_{out}(k) \end{cases} \tag{3}$$

Q_{mea} is the mean of all the Q_{out} whose value is greater than Q_{lam}. In case of flood: $Q_{input} > Q_{lam}$, if $AR > 1$, the attenuation is not complete and if $AR < 1$, too much water is stored.

Another estimator of the attenuation capacity is the AWR, which compares the case where the gates are always closed (indexed cg) to the case in which a

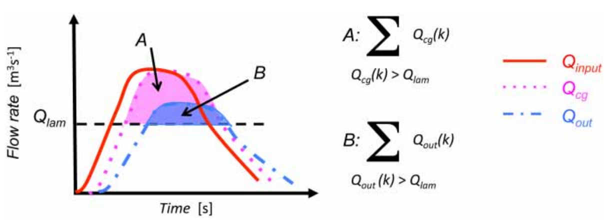

Figure 6 | *AWR* computation.

strategy is involved. It is illustrated in Figure 6 and is expressed by Equation (4).

$$AWR = \frac{\sum_{Q_{cg}(k)>Q_{lam}} Q_{cg}(k) - \sum_{Q_{out}(k)>Q_{lam}} Q_{out}(k)}{\sum_{Q_{cg}(k)>Q_{lam}} Q_{cg}(k)} \quad (4)$$

The downstream flow when the gates are closed is denoted Q_{cg}. The AWR value is a relative estimation of the not attenuated volumes.

RESULTS

Simulations were done within the horizon $H_f = 86{,}400$ s, corresponding to 24 h, $T_c = 100$s, thus $n = 864$. The simulated river was equipped with $n_G = 3$ flood control reservoirs, each one controlled by a gravitational gate.

The first case studied is a flood episode, Q_{input}, with one peak flow of 790 m^3s^{-1} occurring at $k = 330$, i.e., around 9 h after the beginning of the simulation. The values of attenuation and draw-off flows were set to $Q_{lam} = 675\ m^3s^{-1}$ and $Q_{do} = 600\ m^3s^{-1} \approx 90\%\ Q_{lam}$. For this one peak flood, the measured time delays varied between 11 T_c and 16 T_c, as illustrated in Figure 7. Thus, in order to compare the results obtained when the strategy

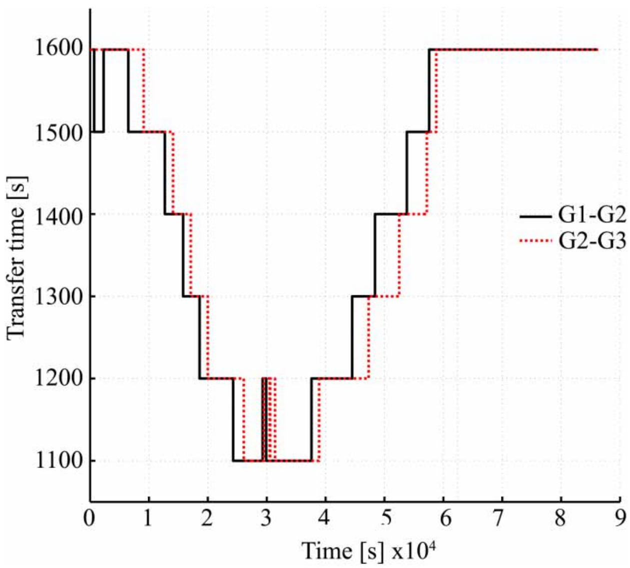

Figure 7 | τ_1 and τ_2 evolution for a one peak simulation with $Q_{lam} = 675 m^3s^{-1}$ and $Q_{do} = 600 m^3s^{-1}$.

involved constant time delay or varying time delay, we realized simulation for constant time delays underestimated or overvalued: $\tau_1 = \tau_2 = 10\ T_c$, $\tau_1 = \tau_2 = 11\ T_c$, $\tau_1 = \tau_2 = 14\ T_c$, $\tau_1 = \tau_2 = 16\ T_c$, $\tau_1 = \tau_2 = 18\ T_c$. In Figure 8, the Q_{input} value is shown by the dotted line, and results obtained for the four following cases are compared. Case one, when the gates are always open (unregulated reservoirs), is shown by the solid line. Case two, when the proposed strategy is applied with constant time delays: $\tau_1 = \tau_2 = 11\ T_c$, is shown by the dotted–dashed line. Case three, when the proposed strategy is applied with constant time delays: $\tau_1 = \tau_2 = 16\ T_c$, is shown by the dashed line. Case four, when the proposed strategy is applied with varying time delays expressed as function of flow and computed thanks to the DP block, is shown in black. When the gates are always open, the peak flood is reduced; however, the discharge exceeds the Q_{lam} value. When time delays are computed, the Q_{out} curve is between the Q_{out} curves obtained for the time delays set to their variation interval bounds. In all these cases, the Q_{out} maximum value is given, and is denoted Q_{max} in the second column of Table 1. Without the use of flood control reservoirs, the peak flow reaches 777 m^3s^{-1}; when the gates are always open, the peak flow reaches 690 m^3s^{-1}. When the proposed strategy is applied, the peak flow decreases and it is lower than the Q_{lam} value when the time delays are computed. When time delays are set to constant values, performance decreases, and we can conclude that it is preferable to overestimate the time delays.

The values of the performance criteria obtained in the studied cases are given in Table 1. Whatever the method used for the time delays' computation, the ability to absorb the flood is increased when using the network flow. Indeed, $AWR = 65\%$ when the time delays are underestimated, and $AWR = 90\%$ when the time delays are overvalued. When the time delays are set to the minimum value of their variation interval, $AWR = 91\%$. When the time delays are computed or set to high enough values, $AWR = 100\%$, the peak flow is under the Q_{lam} value. Finally, $AWR = 37\%$ when the gates are not regulated. The AR value is better if it is as close as possible to 100%, which is the case for computed time delays. Finally, in all cases, the water volume stored in the reservoir is higher than the estimated needed volume.

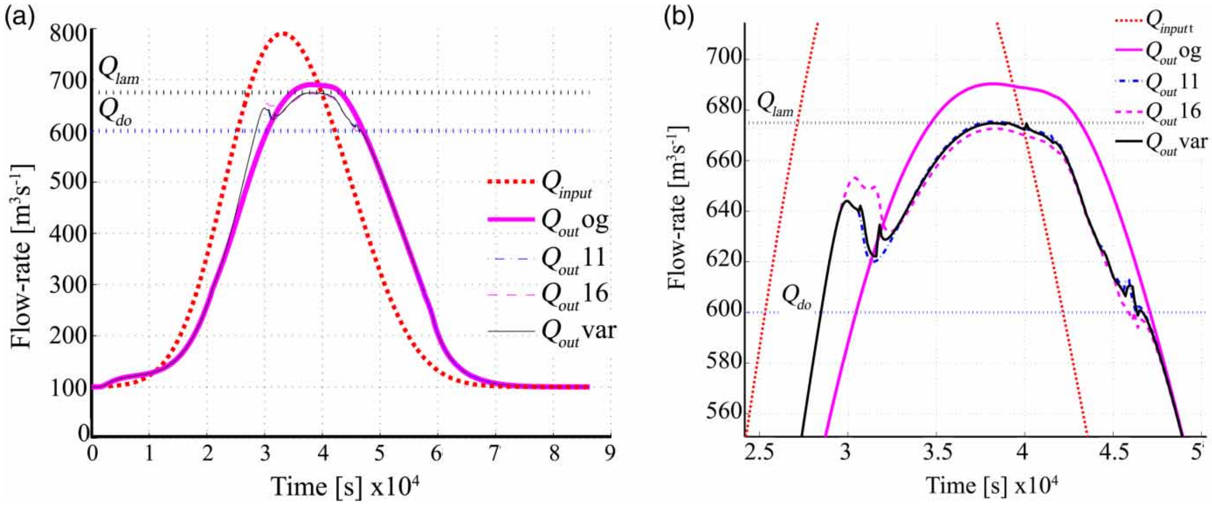

Figure 8 | Q_{input} and Q_{out} for a one peak simulation with $Q_{lam} = 675\text{m}^3\text{s}^{-1}$ and $Q_{do} = 600\text{m}^3\text{s}^{-1}$. (a) Original scale, (b) zoom.

Table 1 | *AR* and *AWR* values for the one peak scenario

Case	Q_{max} (m^3s^{-1})	*AR* (%)	*AWR* (%)
Open gates	690	102	37
$\tau_r = 10\ T_c$	679	100	65
$\tau_r = 11\ T_c$	675	100	91
$\tau_r = 14\ T_c$	674	100	100
$\tau_r = 16\ T_c$	673	100	100
$\tau_r = 18\ T_c$	675	100	90
Varying τ_r	675	100	100

The gates' opening height computed by the algorithm with varying time delays is shown by the dotted-dashed line in Figure 9(a) for the gate G_1, in Figure 9(c) for the gate G_2, and in Figure 9(e) for the gate G_3. The water level inside the reservoir is represented in black and the water level in the river in front of the gates in the dashed line. The water levels are measured with regard to the riverbed. In each figure, the gate is first opened in order to store water; thereafter, during the phase when the discharge is between Q_{lam} and Q_{do}, the gate is closed, and finally, the gate is opened in order to empty the reservoir.

In the fourth illustrated case, the water level inside the reservoir is superimposed in Figure 9(b) for the gate G_1, in Figure 9(d) for the gate G_2, and in Figure 9(e) for the gate G_3. The always open gate case is shown by the solid line. The proposed strategy applied with constant time delays: $\tau_1 = \tau_2 = 11\ T_c$ is represented by the dotted–dashed line, with $\tau_1 = \tau_2 = 16\ T_c$ by the dashed line, and with varying time delays in black. For each one of the three gates, the curve for the always open gate case is always above the other ones, which indicates that the necessary reservoir capacity is lower when using the regulation scheme. Moreover, the reservoirs are filled later in that case and the water remains for less time in the reservoirs; thus the agricultural zones are better preserved. The water level curve in the case of computed time delays is between the curves obtained for the time delays set to their variation interval bounds.

The second case studied is a flood episode with two peak flows: the first one is of 839 $\text{m}^3\ \text{s}^{-1}$ occurring at $k = 324$, i.e., around 9 h after the beginning of the simulation, and the second is 754 $\text{m}^3\ \text{s}^{-1}$ and occurs at $k = 570$, i.e. around 16 h after the beginning of the simulation. The values of attenuation and draw-off flows were set to $Q_{lam} = 710\ \text{m}^3\ \text{s}^{-1}$ and $Q_{do} = 680\ \text{m}^3\ \text{s}^{-1} \approx 95\%\ Q_{lam}$. That case was proposed in order to evaluate the ability of the method to attenuate a second flood episode. Moreover, Q_{do} was set high enough to allow for a water draw-off from the reservoir after the first peak and before the second one and so that the ability to absorb the second flood exists. Since results obtained in the one peak flood episode show that results were better in the computed time delay case, we

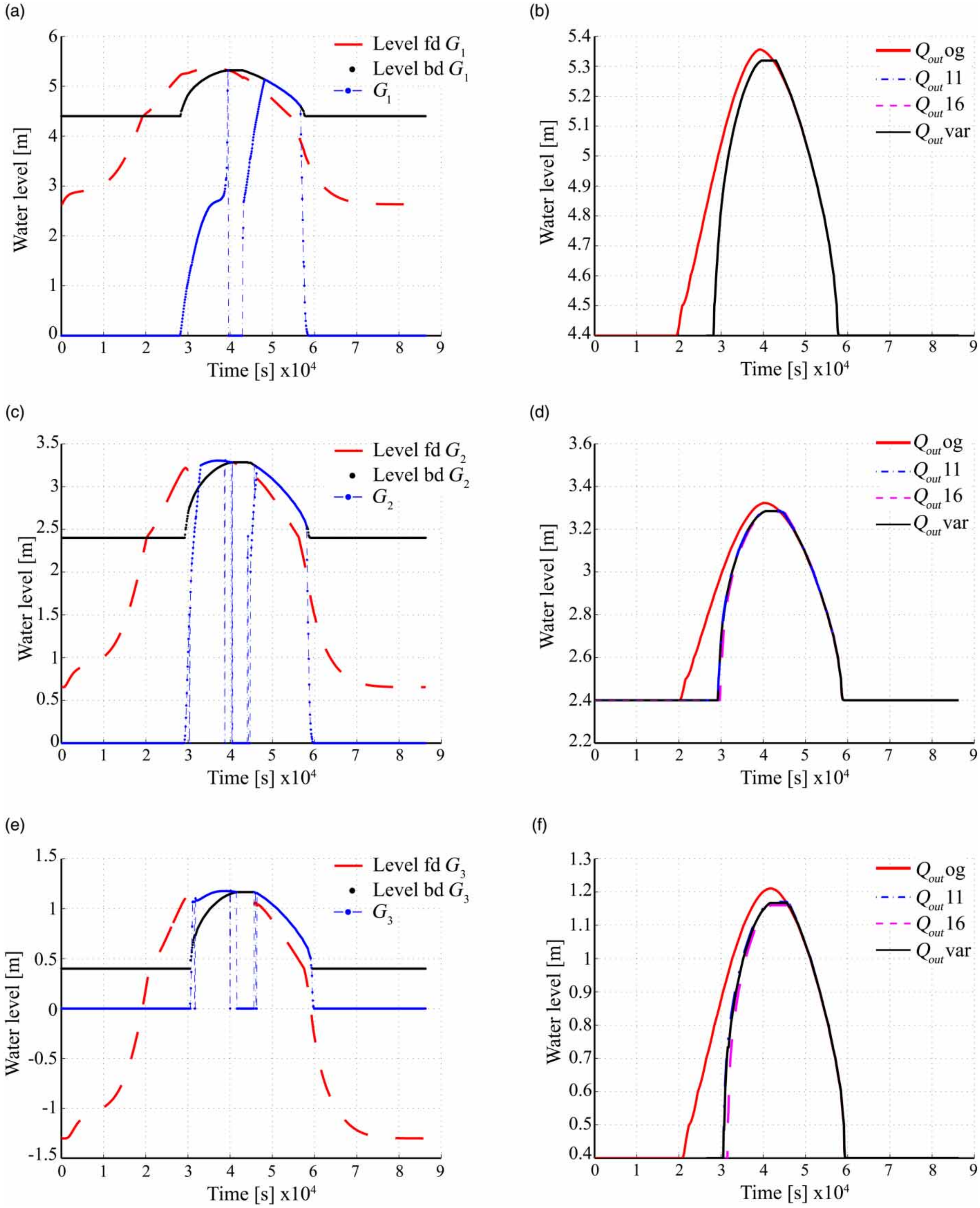

Figure 9 | Gate opening and water levels for a one peak simulation with $Q_{lam} = 675\ m^3\ s^{-1}$ and $Q_{do} = 600\ m^3\ s^{-1}$. The water levels inside (outside) the reservoirs are denoted bd (fd), respectively. (a) G_1 gate opening and water levels inside and outside FCR_1, (b) comparison of water levels inside FCR_1, (c) G_2 gate opening and water levels inside and outside FCR_2, (d) comparison of water levels inside FCR_2, (e) G_3 gate opening and water levels inside and outside FCR_3, (f) comparison of water levels inside FCR_3.

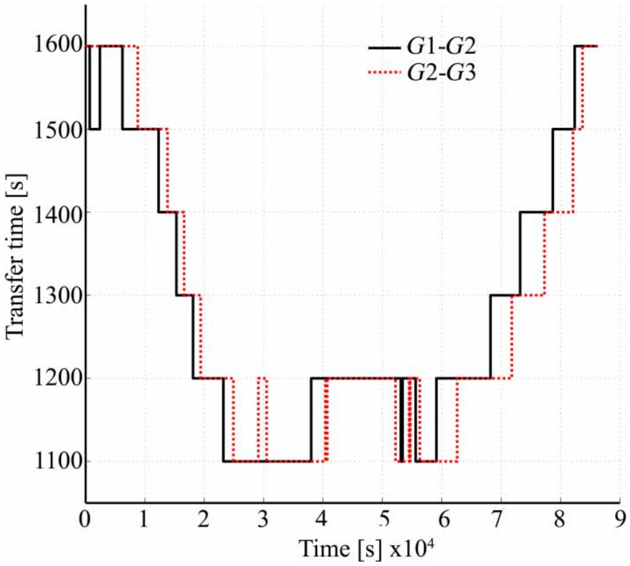

Figure 10 | τ_1 and τ_2 evolution for a two peak simulation with $Q_{lam} = 710\ m^3\ s^{-1}$ and $Q_{do} = 680\ m^3\ s^{-1}$.

compared for the two peaks flood episode only this case and the case when gates are always open. For this two peaks flood, the measured time delays varied between 11 T_c and 16 T_c, as illustrated in Figure 10.

In Figure 11, the Q_{input} value is shown by the dotted line, and the always open gates case by the solid line. The proposed strategy applied with varying time delays is represented by the dotted–dashed line. When the gates are always open, the peak flood is reduced; however, the discharge exceeds the Q_{lam} value. When time delays are computed, the Q_{out} curve is between the Q_{out} curves obtained for the time delays set to their variation interval bounds. Without the use of flood control reservoirs, the peak flow reaches $823\ m^3\ s^{-1}$ for the first wave and $746\ m^3\ s^{-1}$ for the second one. When applying the strategy, the peak flow reaches $704\ m^3\ s^{-1}$ for the first wave and $713\ m^3\ s^{-1}$ for the second one. Applying the strategy allows the discharge to remain under the Q_{lam} value for the first wave and very close to it for the second wave.

The values of the performance criteria computed for each case are given in Table 2. As in the first test, the ability to absorb both flood waves is increased when using the proposed method. Indeed, for the first wave, $AWR = 100\%$ when gates are regulated, whereas $AWR = 64\%$ when gates are not regulated. For the second wave, $AWR = 92\%$ when the strategy is used whereas $AWR = 77\%$ when the gates remain open. Before the arrival of the second flood, we take advantage of the decrease of the water level in the river to release a certain amount of water from the reservoirs into the river. This enables us to better accommodate the second wave of flooding.

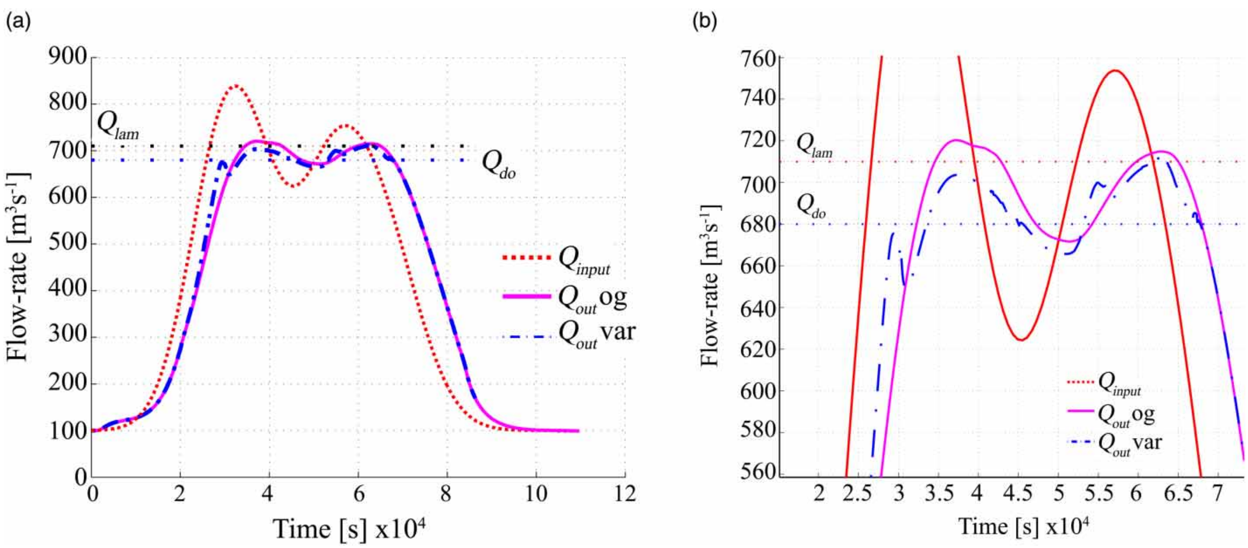

Figure 11 | Q_{input} and Q_{out} for a two peak simulation with $Q_{lam} = 710\ m^3\ s^{-1}$ and $Q_{do} = 680\ m^3\ s^{-1}$. (a) Original scale, (b) zoom.

Table 2 | *AR* and *AWR* values for the two peak scenario in the two different cases

		AWR (%)	
Case	***AR*** **(%)**	**1st peak**	**2nd peak**
Open gates	101	64	77
Varying τ_r	100	100	92

CONCLUSION

In this paper, a crisis management method included in a supervisory control scheme has been proposed.

- It consists of three blocks connected to a river process using reservoirs allowing the management of the flood situation.
- It allows calculating the water volumes to be stored or released through the use of a network flow.
- The variation of the time delays does not impact the network structure.
- Simulation results, for the case of a river with three reservoirs, showing the effectiveness of the proposed method.
- The proposed simulated case has attested to the feasibility of including varying time delays in the network.
- Future research will study the case of an extended catchment; thus, the proposed scheme will consider a river network with longer delays, bifurcations, and confluences.

ACKNOWLEDGEMENTS

The authors want to thank Confederación Hidrográfica del Ebro for providing the case study used in this paper as well as for sharing their hydrological management expertise and Fluid Mechanics, LIFTEC-EINA, University of Zaragoza for providing the 1D-2D coupled simulator.

REFERENCES

Alfieri, L., Burek, P., Dutra, E., Krzeminski, B., Muraro, D., Thielen, J. & Pappenberger, F. 2013 GloFAS–global ensemble streamflow forecasting and flood early warning. *Hydrol. Earth Syst. Sci.* **17**, 1161–1175.

Baldea, M. & Harjunkoski, I. 2014 Integrated production scheduling and process control: a systematic review. *Comput. Chem. Eng.* **71** (4), 377–390.

Bedient, P. B., Huber, W. C. & Vieux, B. E. 2013 *Hydrology and Floodplain Analysis*, 5th edn. Prentice Hall, Upper Saddle River, NJ, USA.

Chuntian, C. & Chau, K. 2002 Three-person multi-objective conflict decision in reservoir flood control. *Eur. J. Oper. Res.* **142** (3), 625–631.

Duviella, E., Rajaoarisoa, L., Blesa, J. & Chuquet, K. 2013 Adaptive and predictive control architecture of inland navigation networks in a global change context: application to the Cuinchy-Fontinettes reach. In: *7th IFAC Conference on Manufacturing Modelling, Management, and Control*. St Petersburg, Russia, pp. 2201–2206.

Figueiredo, J., Ayala Botto, M. & Rijo, M. 2013 SCADA System with predictive controller applied to irrigation canals. *Control Eng. Pract.* **21** (6), 870–886.

Fu, G. 2008 A fuzzy optimization method for multicriteria decision making: an application to reservoir flood control operation. *Exp. Syst. Appl.* **34**, 145–149.

Hooijer, A., Klijn, F., Pedroli, G. B. M. & Van Os, A. G. 2004 Towards sustainable flood risk management in the Rhine and Meuse river basins: synopsis of the findings of IRMA-SPONGE. *River Res. Appl.* **20** (3), 343–357.

Isermann, R. 1997 Supervision, fault-detection and fault-diagnosis methods – an introduction. *Control Eng. Pract.* **5** (5), 639–652.

Karamouz, M., Szidarovszky, F. & Zahraie, B. 2003 *Water Resources Systems Analysis*. Lewis Publishers, New York, USA.

Karbowski, A., Malinowski, K. & Niewiadomska-Szynkiewicz, E. 2005 A hybrid analytic/rule-based approach to reservoir system management during flood. *Decision Support Syst.* **38** (4), 599–610.

Liechti, K., Panziera, L., Germann, U. & Zappa, M. 2013 The potential of radar-based ensemble forecasts for flash-flood early warning in the southern Swiss Alps. *Hydrol. Earth Syst. Sci.* **17** (10), 3853–3869.

Loucks, D., van Beek, E., Stedinger, J., Dijkman, J. & Villars, M. 2005 *Water Resources Systems Planning and Management: An Introduction to Methods, Models and Applications*. United Nations Educational, Scientific and Cultural Organization, Paris, France.

Merz, B., Hall, J., Disse, M. & Schumann, A. 2010 Fluvial flood risk management in a changing world. *Natural Hazard Earth Syst. Sci.* **10**, 509–527.

Mora, D., Taisch, M., Colombo, A. W. & Mendes, J. M. 2012 Service-Oriented Architecture approach for Industrial 'System of Systems': State-of-the-Art for Energy Management. In: *2012 10th IEEE International Conference on Industrial Informatics*, Beijing, China, pp. 1246–1251.

Morales-Hernandez, M., Garcia-Navarro, P., Burguete, J. & Brufau, P. 2013 A conservative strategy to couple 1D and 2D models for shallow water flow simulation. *Comput. Fluid.* **81**, 26–44.

Needham, J. T., Watkins Jr., D. W., Lund, J. R. & Nanda, S. K. 2000 Linear programming for flood control in the Iowa and Des

Moines Rivers. *J. Water Resour. Plann. Manage.* **126** (3), 118–127.

Nouasse, H., Chiron, P. & Archimède, B. 2013a A flood lamination strategy based on transportation network with time delay. *Water Sci. Technol.* **68** (8), 1668–1696.

Nouasse, H., Chiron, P. & Archimède, B. 2013b A water storage and release strategy for flood management based on transportation network with time delay. In: *2013 IEEE 18th Conference on Emerging Technologies Factory Automation*, Cagliari, Italy, pp. 1–8.

Nouasse, H., Chiron, P. & Archimède, B. 2013c Transportation network model with time delay for flood lamination strategy. In: *2013 XXIV International Conference on Information, Communication and Automation Technologies*. Sarajevo, Bosnia and Herzegovina, pp. 1–8.

Pengel, B., Shirshov, G. S., Krzhizhanovskaya, V. V., Melnikova, N. B., Koelewijn, A. R., Pyayt, A. L. & Mokhov, I. I. 2013 Flood early warning system: sensors and Internet. IAHS Red Book N 357. In: *Floods: From Risk to Opportunity* (A. Chavoshian & K. Takeuchi, eds), IAHS Press (International Association of Hydrological Sciences), Oxfordshire, UK, pp. 445–453.

Pfitscher, L. L., Bernardon, D. P., Kopp, L. M., Heckler, M. V. T., Behrens, J., Montani, P. B. & Thome, B. 2012 Automatic control of irrigation systems aiming at high energy efficiency in rice crops. In: *2012 8th International Caribbean Conference on Devices, Circuits and Systems*, Playa del Carmen, Mexico, pp. 1–4.

Plate, E. J. 2002 Flood risk and flood management. *J. Hydrol.* **267** (1–2), 2–11.

Romera, J., Ocampo-Martinez, C., Puig, V. & Quevedo, J. 2013 Flooding management using hybrid model predictive control: application to the Spanish Ebro River. *J. Hydroinform.* **15** (2), 366–380.

Thieken, A. H., Kreibich, H., Müller, M. & Merz, B. 2007 Coping with floods: preparedness, response and recovery of flood-affected residents in Germany in 2002. *Hydrol. Sci. J.* **52** (5), 1016–1037.

Wagenknecht, A. & Rueppel, U. 2013 Process driven emergency management platform for flood response integrating web GIS technologies. *Int. J. Civil Environ. Eng.* **13** (4), 1–8.

First received 3 March 2015; accepted in revised form 21 October 2015. Available online 24 November 2015