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A water storage and release strategy for flood management based on transportation network with time delay

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Abstract

Today, with frequency and severity of extreme weather, flood management became in the world a major concern for governments. The engendered problems are relative to goods and persons safety. Their considerations require a predictive management involving storage and draw-off strategy with several flood areas in order to limit water heights to the downstream of streams. A good flood management requires a control not only of storage to avoid downstream problems but also of water release to protect the fertility of flood expansion areas which are most often based on growing areas. In the literature, numerous described works were done on flows modeling and management. The work presented in this paper, is interested in the quantitative management by means of floods expansion areas placed along the river and for which we have their location as well as their sizing. The performances of management depend on moment and on height of gates opening which influence on wave mitigation. The proposed management method is based on a dynamic mechanism from which the water volumes to be stored or draw-off in time are calculated.

1. Introduction

Flooding due to excessive rainfall and surface runoff can cause significant damages, properties loss and injuries around the world. October 20, 2012, heavy rains fell on the Pyrenean foothills. The flood of the Gave de Pau overwhelmed the bottom of Lourdes city and the sanctuary. In the night, Gave came out of his bed and the Grotto was flooded. The altar of the Grotto was literally submerged by water. To prevent these problems, river systems are increasingly equipped with means for detecting floods and floodplains sized and positioned according to the topography. Flood management requires increased reactivity as compared to other management methods based on planning where the necessary data are known *a priori*. Indeed, managers must take impor-

tant decisions quickly in an uncertain context, because most of these floods are induced by abrupt climatic phenomena, and their magnitude are difficult to accurately assess. The integration of adapted digital tools to these crises is relevant and necessary to improve the decision-making [10], [15]. The difficulty is related to the choice of the optimization model associated to management method, which depends on device characteristics, data availability, goals to achieve and constraints to be satisfied. In the literature, different optimization techniques are proposed to help flood management among which we can mention: the linear programming [12], nonlinear programming [2], [5], multiobjective optimization [6] or genetic algorithms [4]. Some heuristics are also used to deal with this management, notably algorithms for flows maximizing [1], [3], [8]. Unfortunately, the management methods based on algorithms for flows maximizing do not take into account the transfer time of water volumes. Thus, the objective of this paper is to describe a method for managing storage and draw-off of volume dispatched in expansion areas, which are available along of a watercourse in a river system. The proposed method is based on transportation networks with time delay. The paper is organized as follows. Section 2 describes the flood-diversion area system. Section 3 describes the proposed approach to manage the flood. In section 4, the simulation results during a flooding period are displayed and discussed. Finally, the conclusion summarizes the interest of the proposed flood lamination strategy combined to the 1D simulator and suggests some future works.

2 Flood diversion area system

A flood-diversion-area (FDA) system consists of a series of n_G FDAs distributed along the river. A FDA is a floodplain area equipped with controlled gate. The gate opening creates depression waves that interfere with the flood wave to reduce peak flood discharges. To illustrate our approach we use a simplified example, with $n_G = 3$, of a river as a benchmark. A river reach provide with three lateral floodplain area (FDA_1, FDA_2, FDA_3) is assumed (see Figure 1).

The river and the floodplains are separated by levees everywhere except at certain points where they are connected through a gate, G_r , $r = 1, \dots, n_G$. These vertical levees are high enough for avoiding overflow. For simulation purposes, this river is modelled using 1D Shallow water equations [7]. We assume that τ_r ($r = 1, \dots, n_G - 1$) is the transfer time from the gate G_r to the following gate G_{r+1} .

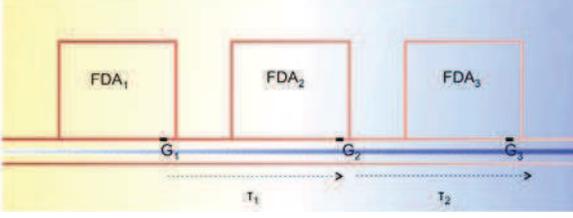


Figure 1. River with three lateral floodplain.

3 Dynamic RGTM mechanism

In previous work [13], in order to model our benchmark, we proposed the use of a static transportation network, where we assumed that $\tau_r = 0$, $r = 1, \dots, n_G - 1$. The problem was formulated as a *Min-Cost-Max-Flow* problem that minimizes a linear cost function subject to the constraints of flow conservation and minimal and maximal capacities. In this formulation we tried to determine an optimal lamination flow that satisfies physical constraints required by a flood scenario and the optimization method management parameters. In order to improve this management method, we have studied the impact of time delay on an expanded temporized transportation network model [9], [11]. In this study [14], we focused on the evolution of the state of our flood-diversion area system at each kT_c , $k = 0, \dots, n$, in the horizon H_f , with $H_f = n \times T_c$, $n \in \mathbb{N}^+$.

The use of such a model requires that transfer times are static between two view points on the river while they depend on the flow-rate, which changes over time. Moreover, this kind of model, depending on the size of the time horizon H_f and the period T_c , can lead to an oversize transportation network. Herein, in order to overcome these two points we propose a dynamic RGTM mechanism (see Figure 2), which allows enhancing the temporized network: more dynamic and suitable for various river sections with variable transfer time.

This mechanism is composed of a reduced transportation network \mathbb{RG} and a Temporization Matrix (TM). The transportation network \mathbb{RG} enables water storage and draw-off and communicates with this matrix in order to store and to get the values of delayed flow. TM is a $n \times 2n_G$ matrix where each column represents the evolution of the gate or FDA discharges, and each line represents an instant of the

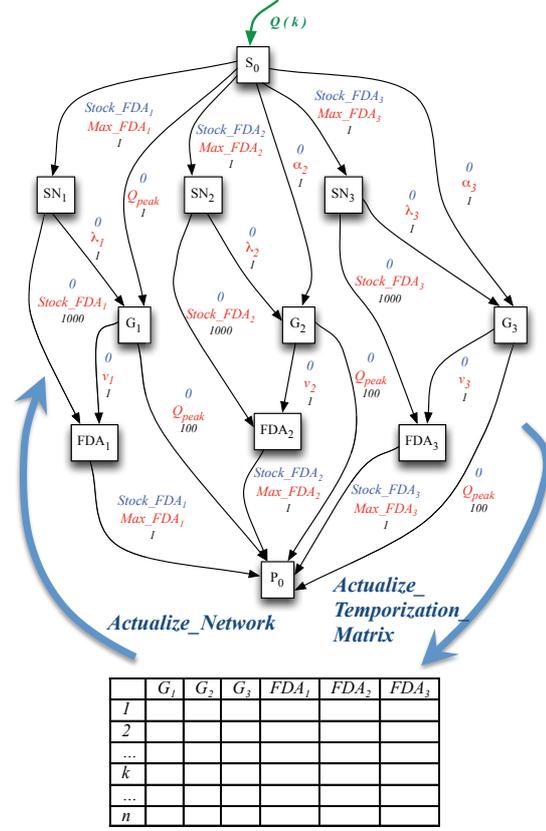


Figure 2. Dynamic RGTM mechanism

evolution of the state of our flood-diversion area system. $\mathbb{RG} = \{\mathcal{RN}, \mathcal{RA}\}$ where \mathcal{RN} is a set of $3n_G + 2$ nodes defined as follows:

- G_r represents the gate, with $r = 1, \dots, n_G$;
- SN_r is a bifurcation node, with $r = 1, \dots, n_G$;
- FDA_r represents the flood lamination area with $r = 1, \dots, n_G$;
- S_0 is a source node corresponding to the fictive entry point of our FDAs system;
- P_0 is a sink node corresponding to the fictive exit point of our FDAs system.

These nodes are associated to the set of valued arcs \mathcal{RA} , describing the following connections:

- Between nodes S_0 and SN_r , $r = 1, \dots, n_G$, it represents the water volume already stored in the FDA_r linked to it.
- Between nodes SN_r and G_r , $r = 1, \dots, n_G$, it represents the draw-off flow leaving the FDA_r towards the gate G_r at the concerned period.
- Between nodes SN_r and FDA_r , $r = 1, \dots, n_G$, it represents the water volume remaining in the FDA_r at the end of the concerned period.

- Between nodes S_0 and G_r , with $r = 2, \dots, n_G$, takes into account at initialization the discharge upstream the gate G_r in the FDAs system.
- Between nodes G_r and FDA_r , connects each gate with its FDA, and represents the flow crossing the gate G_r towards the FDA_r at the end of each period k .
- Between G_r and P_0 , with $r = 1, \dots, n_G - 1$, it represents the flow transferred to following gate G_{r+1} . This discharge is stored in the column associated to gate G_{r+1} at line $k + k_r$ with $\tau_r = k_r T_c$
- Between G_{n_G} and P_0 , the flow-rate downstream the exit point of our FDAs system when this discharge is not stored in the FDA_{n_G}
- Between nodes FDA_r and P_0 , it takes into account the available water volume stored in the FDA_r at the end of the concerned period

In Figure 2, for each arc, its maximum capacity is written in blue, its minimum capacity is written in red and its cost is written in black. All these arc values are used by the Flood-Lamination algorithm described in algorithm 1 in order to derive the gate opening set-point values. In the Flood-Lamination algorithm, after an initialization phase, at each k , the network is actualized (see algorithm 2), the optimal flow is computed and the temporization matrix is actualized (see algorithm 3). In order to compute the optimal flow, the Min cost Max flow problem resolution for this reduced size temporized network is done, using a Linear Programming formulation (as described in [13]), according to our management objectives. In the algorithms:

- $Q(k)$ is the flow-rate entering the network at kT_c . At k , it corresponds to the sum of flows entering the gates added to the sum of the water volumes stocked in all FDAs turned into discharges.
- Q_{peak} is the maximum peak flow-rate of flood scenario.
- Max_FDA_r is the maximum storage capacity of FDA_r , it depends on Q_{peak} .
- ν_r is the maximal capacity on the arc between the gate G_r and the FDA_r .
- λ_r is the maximal capacity on the arc between the node SN_r and the gate G_r .
- The storage phase and release phase cannot occur at the same time for one gate. This is govern

by the use of μ_r and γ_r coefficients with

$$\begin{cases} \gamma_r = 1, \mu_r = 0 & \text{storage in } FDA_r \\ \mu_r = 1, \gamma_r = 0 & \text{release from } FDA_r \\ \gamma_r = 0 & \text{no storage in } FDA_r \\ \mu_r = 0 & \text{no release from } FDA_r \end{cases}$$

- Q_{lam} is the lamination flow-rate chosen by the river system manager and defined as the flow level at which the river flow-rate must be laminar, i.e. the hydraulic set point over the foreseen horizon H_f .
- Q_{do} is the discharge level under which the FDA draw-off is done.
- $Stock_FDA_r$ is the minimum capacity on the arc between the source S_0 and the FDA_r . It corresponds to the amount of water already present in the FDA_r .

During the phase one of the initialization of the Flood-Lamination algorithm, the first column of TM matrix is set to the value of the flow-rate upstream the river at each kT_c ($k = 1, \dots, n$), which is the flow-rate upstream the first gate G_1 . The initialization phase two allows to introduce discharge values upstream all the gates G_r ($r = 2, \dots, n_G$) during the non stationary phase i. e. before $k = k_{n_G-1}$, with $\tau_{n_G-1} = k_{n_G-1} T_c$. We choose in this case to set these upstream discharges to the flow-rate upstream the river except when it is higher than the lamination flow-rate. In the Actualization Network algorithm described in algorithm 2, the network \mathbb{RG} is updated at each kT_c ($k = 1, \dots, n$). The network parameters values at $k - 1$ such as adjacency matrix, costs and constraint vector (arc minimum and maximum values) are provided as input parameters. The strategy parameters, γ_r and μ_r are set depending on the discharge values in the matrix TM . The flow entering the network is updated with the sum of the line k of the TM matrix. In order to take into account the transfer time between gates, the maximum flow-rate upstream each gate G_r ($r = 2, \dots, n_G$), α_r , is set to the TM matrix stored value at previous time. The maximum capacity of the arc (G_r, FDA_r) , ν_r , is set to the amount of flow-rate overtaking $Q_{lam}(k)$ lower than the remaining FDA_r capacity (only if the FDA_r can be used i. e. $\gamma_r = 1$). The value of $Stock_FDA_r$ is set to its previous value stored in the TM matrix. Finally, the maximum capacity of the arc (SN_r, G_r) , λ_r , is set to the amount of flow-rate overtaking $Q_{lam}(k)$ lower than the remaining FDA_r capacity (only if the FDA_r can be used i. e. $\gamma_r = 1$). In the Actualization Temporization Matrix algorithm described in algorithm 3, the matrix TM is updated at each kT_c ($k = 1, \dots, n$). In this matrix, the temporized flow values are stored and actualized such that transfer times can be introduced in the network. In order to

Algorithm 1: Flood lamination

input :

$\mathbb{R}\mathbb{G}$ the reduced transportation network
 $n = E(\frac{H_f}{T_c}) + 1$ the number of samples
 n_G the numbers of gates and FDA in the river system
 k_r such that $\tau_r = k_r T_c$, $r = 1, \dots, n_G - 1$
 $Q_{input}(k)$ the flow of flood scenario at kT_c for $k = 1 \dots n$
 Q_{lam} the lamination flow

output:

$\mathbb{R}\mathbb{G}$ the reduced transportation network
 TM the $n \times 2n_G$ temporization matrix
 φ the optimal flow for each arc in the network
 $\mathbb{R}\mathbb{G}$

begin

```
% Initialization phase one
for  $k = 1$  to  $n$  do
  |  $TM(k, 1) \leftarrow Q_{input}(k)$ 
  | for  $r = 2$  to  $2n_G$  do
  | |  $TM(k, r) \leftarrow 0$ 
  | end
end
% Initialization phase two
for  $r = 1$  to  $n_G - 1$  do
  | for  $k = 1$  to  $k_r$  do
  | |  $TM(k, r + 1) \leftarrow$ 
  | |  $\min(Q_{input}(1), Q_{lam})$ 
  | end
end
 $k \leftarrow 1$ 
while ( $k \leq n$ ) do
  |  $Actualize\_Network(\mathbb{R}\mathbb{G}, k, TM)$ 
  |  $\varphi(k) \leftarrow$ 
  |  $Compute\_Optimal\_Flow(\mathbb{R}\mathbb{G}, k)$ 
  |  $Actualize\_Temporization\_Matrix(\varphi(k), k, TM)$ 
  |  $k \leftarrow k + 1$ 
end
```

end

take into account the transfer time between gates, the optimal flow from each gate G_r ($r = 1, \dots, n_G - 1$) to the sink P_0 , $\varphi_{(G_r, P_0)}(k)$, is stored in the TM matrix as the future discharge upstream the following gate G_{r+1} at $k + k_r$. The flow feeding each FDA_r ($r = 1, \dots, n_G$) at k , $\varphi_{(FDA_r, P_0)}(k)$, is added to the flow already stored in order to obtain the new stored value. This value is written in the TM matrix as the future FDA_r stored value i. e. at $k+1$. A co-

Algorithm 2: Actualization network

input :

TM the $n \times 2n_G$ temporization matrix
 $\mathbb{R}\mathbb{G}$ the reduced transportation network
 n_G the numbers of gates and FDA in the river system
 k the iteration number
 γ_r the indicator for using or not FDA_r
 μ_r the indicator for release water or not from FDA_r
 $Q_{lam}(k)$ the lamination flow at kT_c

output:

$\mathbb{R}\mathbb{G}$ the reduced transportation network

begin

```
 $Q(k) \leftarrow 0$ 
for  $r = 1$  to  $n_G$  do
  | if  $TM(k, r) \geq Q_{lam}(k)$  then
  | |  $\gamma_r \leftarrow 1$ ;  $\mu_r \leftarrow 0$ 
  | else
  | | if ( $TM(k, r) < Q_{do}(k)$ ) then
  | | |  $\mu_r \leftarrow 1$ ;  $\gamma_r \leftarrow 0$ 
  | | | else
  | | | |  $\mu_r \leftarrow 0$ ;  $\gamma_1 \leftarrow 0$ 
  | | | end
  | end
end
for  $r = 1$  to  $2n_G$  do
  |  $Q(k) \leftarrow Q(k) + TM(k, r)$ 
end
for  $r = 2$  to  $n_G$  do
  |  $\alpha_r \leftarrow TM(k, r)$ 
end
for  $r = 1$  to  $n_G$  do
  |  $\nu_r \leftarrow \gamma_r \times \min[\max(0, TM(k, r) -$ 
  |  $Q_{lam}(k)), \max(0, Max\_FDA_r -$ 
  |  $TM(k, n_G + r))]$ 
  |  $Stock\_FDA_r \leftarrow TM(k, n_G + r)$ 
  |  $\lambda_r \leftarrow$ 
  |  $\min[Stock\_FDA_r, \max(0, Q_{lam} -$ 
  |  $TM(k, r))] \times \mu_r$ 
end
```

end

operation has been established between the dynamic RGTm mechanism and the 1D simulator (developed by [7]), in order to update flow and water quantity stocked with measured values. The scheme used is given in Figure 3 and the algorithm for actualization of temporized matrix is modified as given in algorithm 4.

Algorithm 3: Actualization temporization matrix

input :

- TM the $n \times 2n_G$ temporization matrix
- n_G the numbers of gates and FDA in the river system
- k the iteration number
- k_r such that $\tau_r = k_r T_c$, $r = 1, \dots, n_G - 1$
- $\varphi(k)$ the optimal flow in the network $\mathbb{R}G$ at kT_c

output:

TM the $n \times 2n_G$ temporization matrix

```

begin
  for  $r = 1$  to  $n_G - 1$  do
     $TM(k + k_r, r + 1) \leftarrow$ 
     $TM(k + k_r - 1, r + 1) + \varphi_{(G_r, P_0)}(k)$ 
  end
  for  $r = 1$  to  $n_G$  do
     $TM(k + 1, n_G + r) \leftarrow$ 
     $TM(k, n_G + r) + \varphi_{(FDA_r, P_0)}(k)$ 
  end
end
  
```

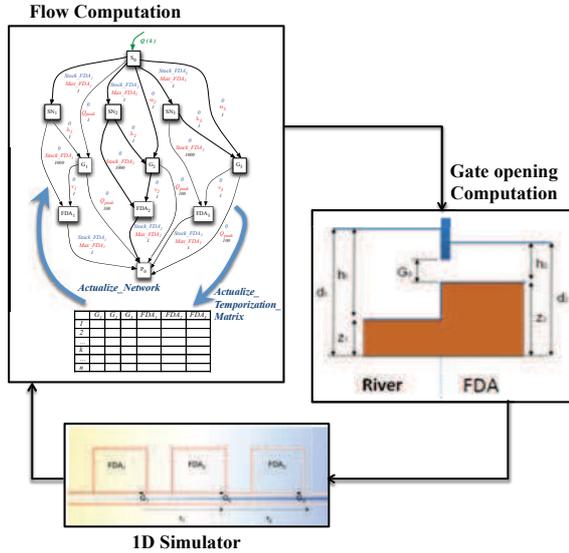


Figure 3. Dynamic RGTM mechanism and 1D simulator cooperation

4 COMPUTATIONAL RESULTS

We present some results obtained using the dynamic RGTM mechanism cooperating with the 1D

Algorithm 4: Actualization temporization matrix linked to simulator

input :

- n_G the numbers of gates and FDA in the river system, herein $n_G = 3$
- TM the $n \times 2n_G$ temporization matrix
- k the iteration number
- k_r such that the transfer time τ_r from G_r to G_{r+1} is $\tau_r = k_r T_c$, $r = 1, \dots, n_G - 1$
- $V_{FDA_r}^{mes}(k)$ the measured amount of water stored in the FDA_r at kT_c
- $Q_{(G_r, FDA_r)}^{mes}(k)$ the measured discharge from gate G_r to FDA_r at kT_c
- \mathbb{G} the network

output:

TM the $n \times 2n_G$ temporization matrix

```

begin
  for  $r = 1$  to  $n_G - 1$  do
     $TM(k + k_r, r + 1) \leftarrow$ 
     $TM(k + k_r - 1, r + 1) + \varphi_{(G_r, P_0)}(k) +$ 
     $max(0, \varphi_{(G_r, FDA_r)}(k) -$ 
     $Q_{(G_r, FDA_r)}^{mes}(k))$ 
  end
  for  $r = 1$  to  $n_G - 1$  do
     $TM(k + 1, n_G + r) \leftarrow$ 
     $TM(k, n_G + r) + V_{FDA_r}^{mes}(k)$ 
  end
end
  
```

hydraulic simulator as described in section 2. At each T_c , an input hydrograph representing usual encountered cases is sent to the 1D simulator (see Figure 3). The actual levels along the river and in the FDAs are computed thanks to this hydraulic simulator and sent to the RGTM program. It computes the flow to be sent in each FDA. These values are transformed in height by the gate opening computation block. The gates opening values are then given as input to the 1D simulator. All values are registered and plotted in the figures displayed in this section.

In figure 4 are given in red the Q_{input} value, in green the Q_{output} value with gates always opened (un-regulated reservoirs), in black the Q_{output} value when the strategy is applied with $Q_{lam} = 675m^3/s$ and $Q_{do} = 600.6m^3/s$. The time delay values were set to $\tau_1 = 10T_c$ and $\tau_2 = 9T_c$, with $T_c = 100s$. For these values, the discharge remains under the Q_{lam}

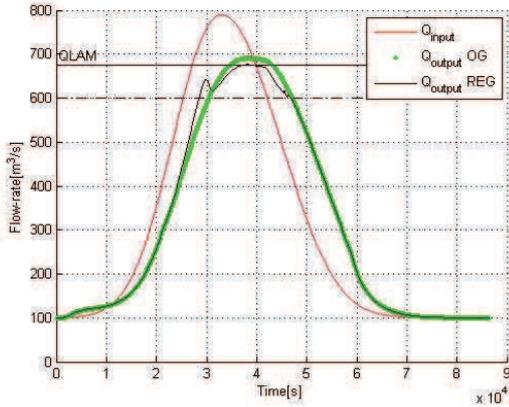


Figure 4. Q_{input} and Q_{output} for $Q_{lam} = 675m^3/s$, $Q_{do} = 600.6m^3/s$ and open gates

value, and the draw-off begins at $k = 432$ when the discharge is under the value of Q_{do} . On the contrary, when gates are always opened it is not possible to avoid flood downstream, in fact the discharge overstep the Q_{lam} value. In figures 5, 6 and 7 are represented in blue the gates opening height computed by the algorithm, in black the water level inside the FDA (backward the gate), and in red the water level in the river forward the gates, for respectively gates 1, 2 and 3. The water levels are measured with regard to the river bed. On each figure, the gate is firstly 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 FDA.

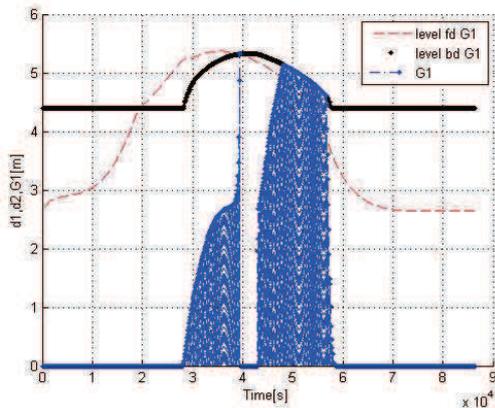


Figure 5. First gate opening and water levels inside and outside $FDA1$

In order to show the benefits of our strategy compared to strategy where all gates are always opened during the concerned horizon, the water level inside the FDA are superimposed in figures 8, 9 and 10

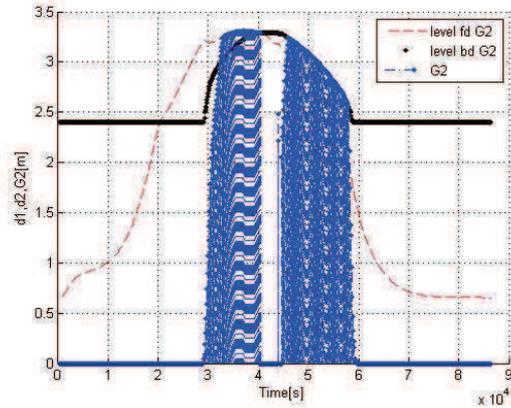


Figure 6. Second gate opening and water levels inside and outside $FDA2$

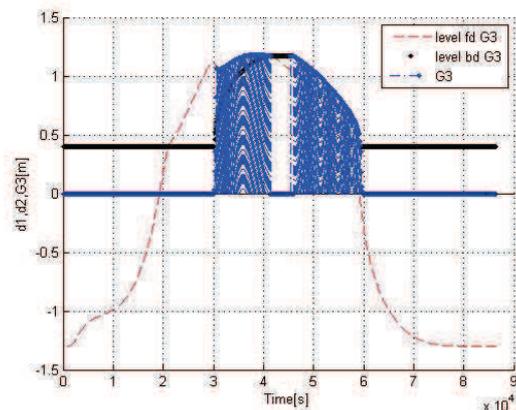


Figure 7. Third gate opening and water levels inside and outside $FDA3$

where our strategy is in black and the gates always opened are in green. For the three gates, the green curve is always upper the black one, that means that the reservoirs capacity should be more important in the always open gates cases. Furthermore the FDA are filled earlier in the always open gates strategy. The proposed RGTM strategy allows to better preserved the agricultural zones used as flood diversion areas. If the slope of the water level is found to be too important so that it can affect the fertility of the flood diversion area, it should be considered as a new decision criterion to include in the dynamic RGTM method.

In figure 11 are compared results obtained with two different Q_{do} values: in black $Q_{do} = 600.6m^3/s$ and in blue $Q_{do} = 500m^3/s$. In the case where $Q_{do} = 600.6m^3/s$, the FDA is emptied earlier. The choice of the Q_{do} can be driven by the nature of the cultivation done in the FDA. Moreover, it is possible to decide to empty the FDA as soon as possible in order to be able to absorb a further flood.

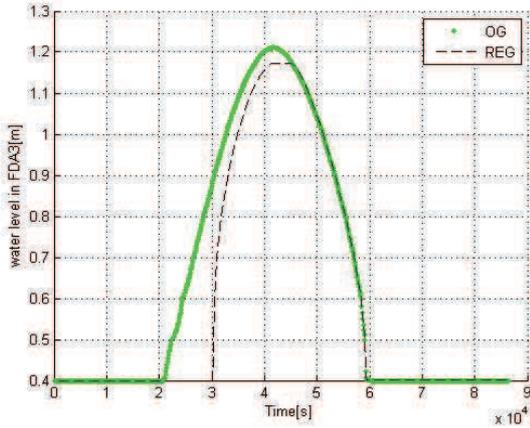


Figure 8. Water levels inside the FDA_1 for open and regulated gates. $Q_{lam} = 675m^3/s$, $Q_{do} = 600.6m^3/s$, $\tau_1 = 10T_c$, $\tau_2 = 9T_c$

5 Conclusion

A water storage and release strategy was presented in order to perform flood lamination of a river system equipped with flood diversion areas. The strategy is based on a dynamic mechanism combining a Reduced Graph and a Temporization Matrix. It allows to account for time delay without using expanded graph usually performed in this context. The results of the collaboration between this mechanism and the 1D simulator of river were given, highlighting the benefits of the strategy. Namely, during storage phase, the strategy allows for remaining under the lamination discharge level imposed: the flood is laminated,

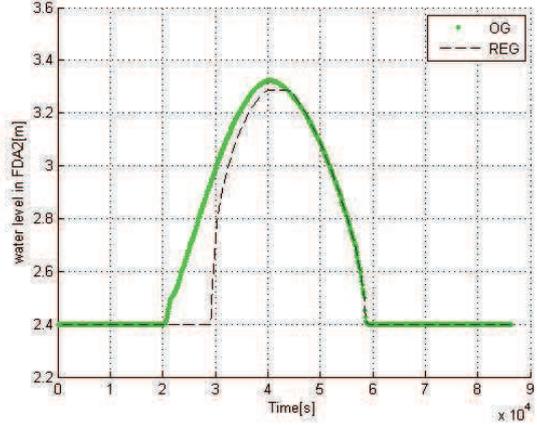


Figure 9. Water levels inside the FDA_2 for open and regulated gates. $Q_{lam} = 675m^3/s$, $Q_{do} = 600.6m^3/s$, $\tau_1 = 10T_c$, $\tau_2 = 9T_c$

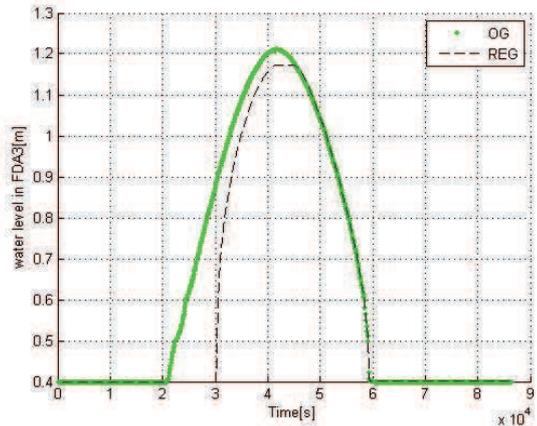


Figure 10. Water levels inside the FDA_3 for open and regulated gates. $Q_{lam} = 675m^3/s$, $Q_{do} = 600.6m^3/s$, $\tau_1 = 10T_c$, $\tau_2 = 9T_c$

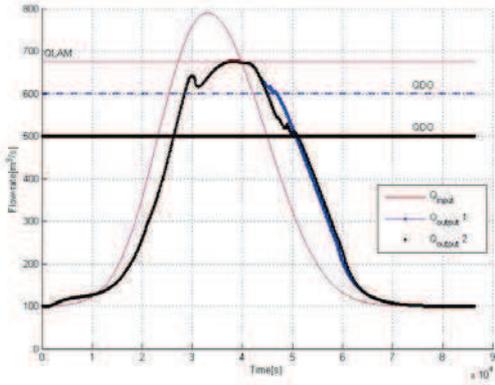


Figure 11. Q_{input} and Q_{output} for $Q_{lam} = 675m^3/s$, $Q_{do} = 600.6m^3/s$ and $Q_{do} = 500m^3/s$

and during the draw-off phase, Flood Diversion Areas are preserved. The strategy can be used in order to estimate the capability of the river system equipped with flood diversion areas to take over floods. Beyond a quantitative flood management an important problem to address is the quality of water in the river and in the FDAs. Future work will focus on the integration of pollution problems in the strategy.

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