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A flood lamination strategy based on transportation network with time delay

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ABSTRACT

Over the last few years, the frequency and intensity of floods has become more marked due to the influence of climate change. The engendered problems are related to the safety of goods and persons. These considerations require predictive management that will limit water height downstream. In the literature, numerous works have described flow modeling and management. The work presented in this paper is interested in quantitative management by means of flood expansion areas placed along the river and for which we have size and location. The performance of the management system depends on the time and height of gate opening, which will influence wave mitigation. The proposed management method is based on use of a transportation network with time delay from which the volume of water to be stored is calculated.

Key words | flood lamination, network modeling, time delay, transportation networks

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INTRODUCTION

On October 20, 2012, heavy rains fell on the Pyrenean foothills. The flood of the Gave de Pau river overwhelmed the bottom of Lourdes city and the sanctuary. In the night, the Gave overflowed and the Grotto was flooded. The altar of the Grotto was actually submerged by water. Flooding due to excessive rainfall and surface runoff can cause significant damage, loss of property and injuries around the world. To prevent these problems, river systems are increasingly equipped with means for detecting floods, and floodplains are 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 important decisions quickly in an uncertain context, because most of these floods are induced by abrupt climatic phenomena, and their magnitude is difficult to accurately assess. Recent studies on climatic changes indicate the impact of this phenomenon on flood magnitude and severity (Knox 1993; Molnar 2001; Booij 2005). Other studies focus on the inclusion of this factor in the methods of assessment and management of floods (Burrel *et al.* 2007; Morita 2011; Gilroy & McCuen 2012). The integration of adapted digital tools to these crises is relevant and necessary to improve decision-making (Kracman *et al.* 2006; Wang *et al.* 2011). The difficulty is related to the choice of the optimization model associated with the 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: linear programming (Needham *et al.* 2000), nonlinear programming (Floudas *et al.* 1989; Bemporad *et al.* 1997), multiobjective optimization (Fu 2008) or genetic algorithms (Cai *et al.* 2001). Some heuristics are also used to deal with this management, notably algorithms for flow maximizing (Ahuja *et al.* 1993; Gondran & Minoux 1995; Bertsekas 1998). Unfortunately, the management methods based on algorithms for flow 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 of volume displaced in expansion areas, which are available along a watercourse in a river system. The proposed method is based on the transport networks with delay. The paper is organized as follows. The second section describes the flood-diversion-area (FDA) system. The third section gives the main definitions of network flow modeling with time delay. A three-flood-diversion-area

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system modeling is detailed. In the fourth section, 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 one-dimensional (1D) simulator and suggests some future work.

FLOOD-DIVERSION-AREA SYSTEM

A FDA system consists of a series of n_G FDAs distributed along the river. A FDA is a floodplain area equipped with a 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 with three lateral floodplain areas (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, $r = 1,2,3$. These vertical levees are high enough for avoiding overflow. For simulation purposes, this river is modeled using 1D shallow water equations (Garcia-Navarro *et al.* 2008).

The equations of unsteady open channel flow can be derived, for instance, from mass and momentum control volume analysis and modeled under the St Venant hypotheses. The 1D unsteady shallow water flow can be written in the form:

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

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A} + gI_1\right) = gI_2 + gA\left(S_0 - S_f\right) \tag{2}$$

which emphasizes the conservative character of the system in the absence of source terms. The effects of the wind as well as those of the Coriolis force have been neglected and no lateral inflow/outflow is considered. In (1), A is the wetted cross sectional area, Q is the discharge, g is the acceleration due to gravity, S_0 is the bed slope and S_f is the friction slope. I_1 and I_2 represent hydrostatic pressure force integrals.

We assume that τ_r is the transfer time from the gate G_r to the following gate G_{r+1}.

TRANSPORTATION NETWORK DESIGN INCLUDING TIME DELAY

In previous work (Nouasse *et al.* 2012), in order to model our benchmark, we proposed the use of a static transportation network, where we assume that $\tau_1 = 0$ and $\tau_2 = 0$. 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 the management method, we propose to study the impact of time delay on a temporized transportation network.

We study the evolution of the state of our flood-diversion-area system at each $k\mathrm{T_c}$, $k = 0,\ldots,n$ in the horizon H_f with $H_f = n \times T_c$, $n \in \mathbb{N}^+$, using the temporized transportation network $\mathbb{G}$ given in Figure 2. It can be seen as a dynamic flow network (Köhler *et al.* 2002; Melkonian 2007) composed by interconnected static sub-networks. These connections allow for model temporization.

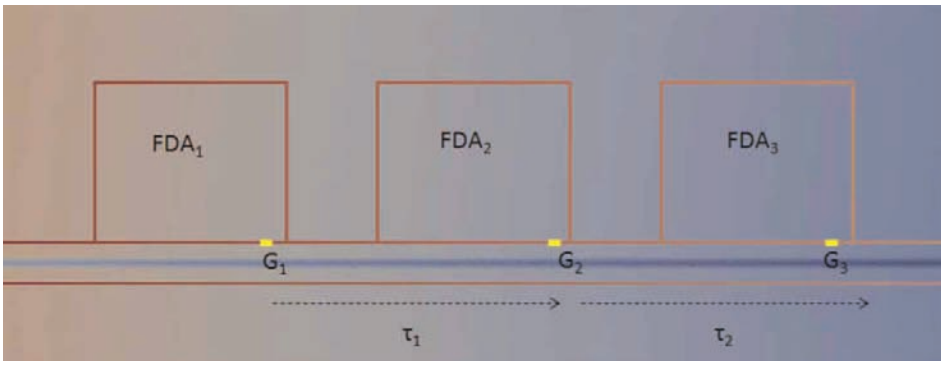


Figure 1 River with three lateral floodplains.

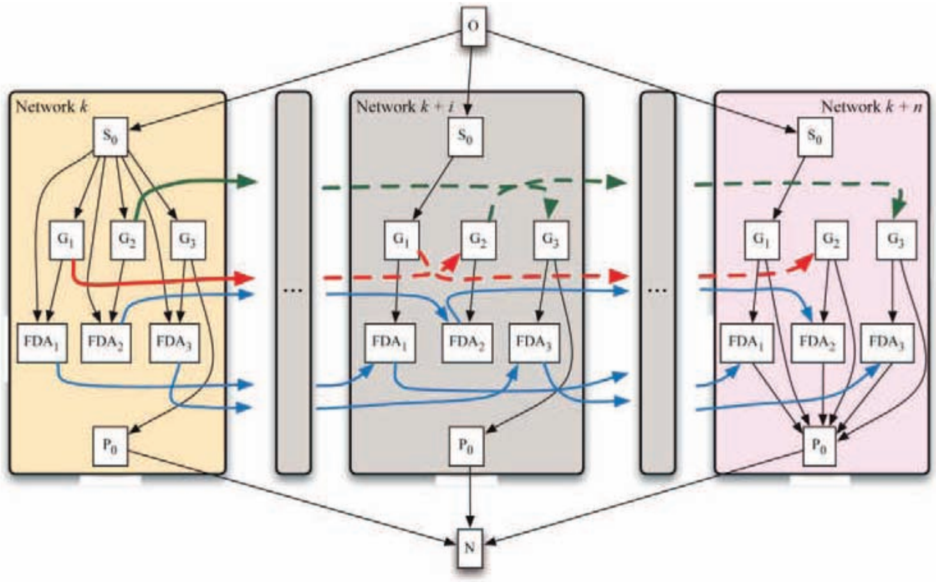


Figure 2 Temporized network model with static sub-networks.

The network $\mathbb{G} = \{\mathcal{N}, \mathcal{A}\}$ where $\mathcal{N}$ is a set of $8 \times (n + 1) + 2$ nodes defined as follows:

- G_r^k represents the gate G_r at k, with $r = 1,\ldots,n_G$;
- FDA_r^k is the FDA_r at k;
- S_0^k is a source node corresponding to the fictive entry point of our FDAs system at k;
- P_0^k is a sink node corresponding to the fictive exit point of our FDAs system at k;
- O is an extra source node corresponding to the fictive entry point of our transportation network whatever the period is;
- P is an extra sink node corresponding to the fictive exit point of our transportation network whatever the period is.

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

- Between the nodes G_r^k and $G_{r+1}^{k+k_r}$ such as $k = 0,\ldots,n-k_r$ with $\tau_r = k_r T_c$ and $r = 1,\ldots,n_G-1$. It carries the delayed discharge that passes by between the gate G_r and the gate G_{r+1}. This kind of arc is designed as type 1 arcs in the following.
- Between G_r^k and P_0^k, with $r = 1,\ldots,n_G-1$, and $k = n-k_r+1,\ldots,n$, it represents the flow-rate downstream the exit point of our FDAs system when this discharge is not stored in the FDA_r^k.
- Between G_{nG}^k and P_0^k, with $k = 0, \ldots, n$, it represents the flow-rate downstream the exit point of our FDAs system when this discharge is not stored in the FDA_{nG}^k.
- Between nodes S_0^k and G_1^k is the flow $Q_{\mathrm{input}}(k)$ at the entry point that is always transferred towards the gate G_1.
- Between nodes S_0^k and G_r^k, with $k = 0,\ldots k_r$ and $r = 2,\ldots,n_G$, takes into account at initialization the flow upstream the gate G_r in the FDAs system.
- Between nodes S_0^0 and FDA_r^0, it takes into account the water volume already stored in the FDA_r at the initialization.
- Between nodes G_r^k and FDA_r^k, 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 nodes FDA_r^k and FDA_r^{k+1}, with $k = 0,\ldots,n-1$ indicates that the water stored in the FDA_r at the end of the period k is available at the beginning of period $k + 1$. This kind of arc is designed as type 2 arcs in the following.
- Between nodes FDA_r^n and P_0^n, respects transportation network conservation flow rules.

In each sub-network there is no transfer time between the different nodes. Transfer times are introduced by connecting the different sub-networks with type 1 and type 2 arcs.

The use of such a model requires that transfer times are static from a layer to another in the set H_f while they depend on the flow-rate, which changes over time. Moreover, this kind of model, depending on the size of the time horizon

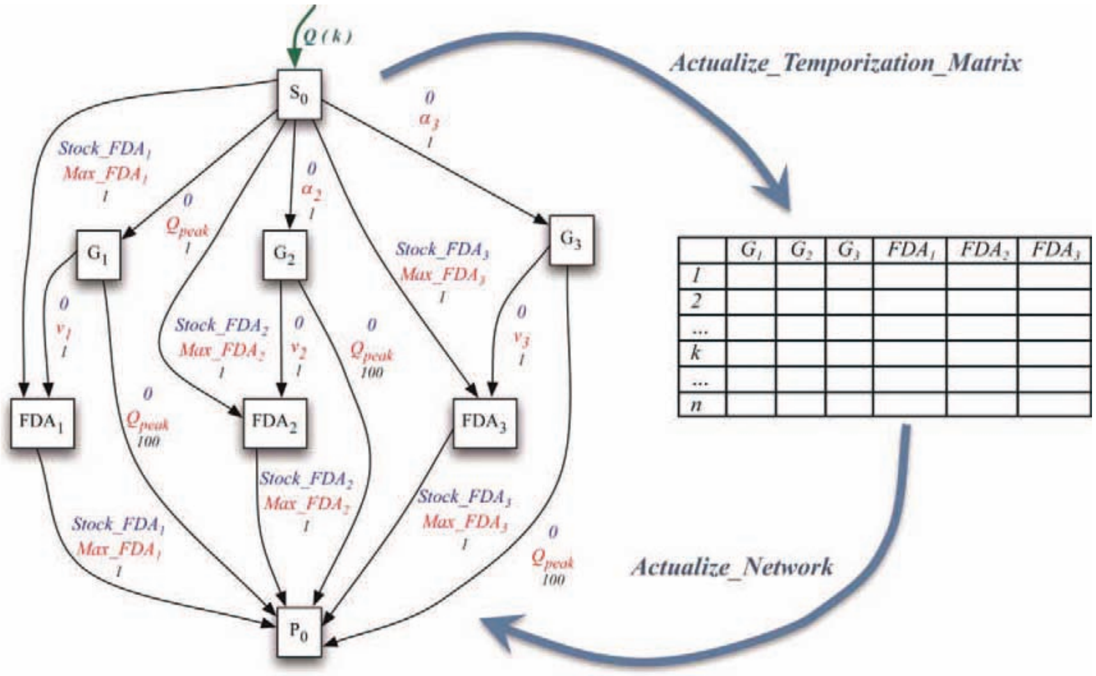


Figure 3 Dynamic reduced size network.

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 reduced size model (see Figure 3), which allows enhancing the temporized network: more dynamic and suitable for various river sections with variable transfer time.

This reduced transportation network is obtained by the conservation of nodes number of a sub-network, by the fusion of all the different sub-networks of our previous model and by eliminating arcs between sub-networks. In this reduced size model, link between layers are represented through a matrix and thus the transportation network communicates with this matrix where the values of delayed flow are stored. In Figure 3, for each arc, its maximum capacity is written beneath its minimum capacity, and its cost is written lowermost. The flood-lamination algorithm described in Figure 4 uses all these arc values in order to derive the gate opening set-point values. In the flood-lamination algorithm, after an initialization phase, at each kT_c, the network is actualized (see Figure 5), the optimal flow is computed and the temporization matrix is actualized (see Figure 6).

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 Nouasse *et al.* (2012)), according to our management objectives. In the algorithms:

$Q(k)$ is the discharge entering the network at kT_c.

Q_{peak} is the maximum peak flow-rate of flood scenario.

Max_FDA$_r$ is the maximum FDA$_r$ storage capacity, depending on Q_{peak}.

v_r is the maximal capacity on the arc between the gate G_r and the FDA$_r$.

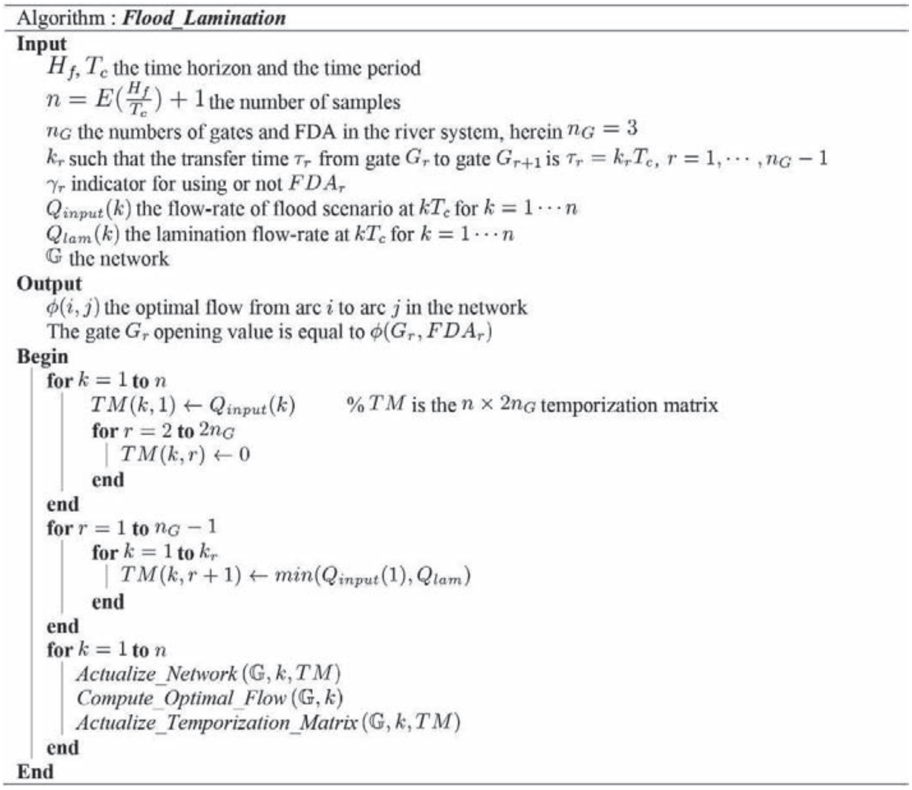
γ_r is a strategy parameter with

$$\gamma_r = \begin{cases} 0 & \text{if decision is not to stock water in FDA}_r \\ 1 & \text{if decision is to stock water in FDA}_r \end{cases}$$

Q_{lam} is the lamination discharge chosen by the river system manager and defined as the discharge level at which the river flow-rate must be laminate, i.e. the hydraulic set point over the foreseen horizon H_f.

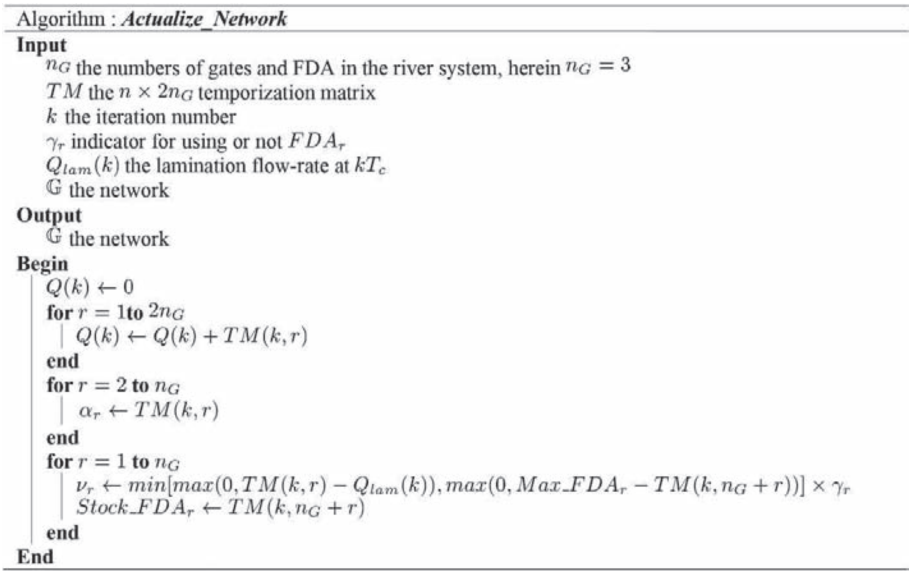
Stock_FDA$_r$ is the minimum capacity on the arc between the source S_0 and the FDA$_r$. It corresponds to the amount of water already present in the FDA$_r$.

The dynamic reduced size network has been connected to the 1D simulator (developed by Garcia-Navarro *et al.* (2008)), in order to update flow and water quantity stocked with measured values. The scheme used is given in Figure 7 and the algorithm for actualization of temporized matrix is modified as given in Figure 8.



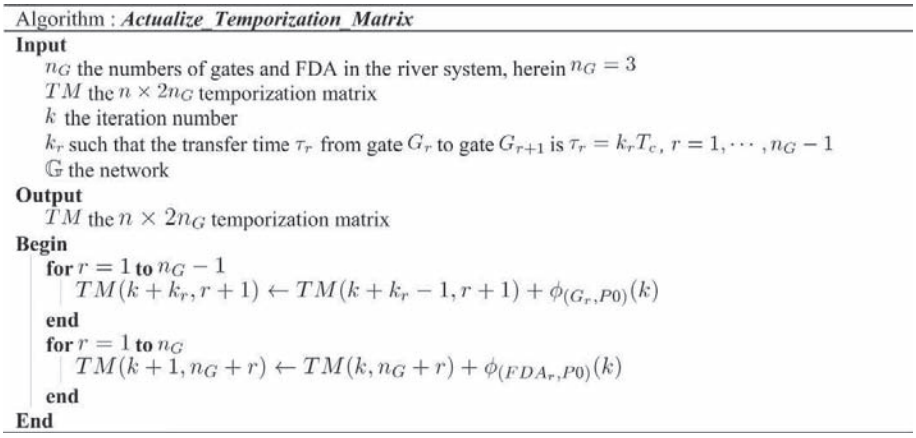
```
Algorithm : Flood_Lamination
Input
    $H_f, T_c$ the time horizon and the time period
    $n = E(\frac{H_f}{T_c}) + 1$ the number of samples
    $n_G$ the numbers of gates and FDA in the river system, herein $n_G = 3$
    $k_r$ such that the transfer time $\tau_r$ from gate $G_r$ to gate $G_{r+1}$ is $\tau_r = k_r T_c,\ r = 1, \cdots, n_G - 1$
    $\gamma_r$ indicator for using or not $FDA_r$
    $Q_{input}(k)$ the flow-rate of flood scenario at $kT_c$ for $k = 1 \cdots n$
    $Q_{lam}(k)$ the lamination flow-rate at $kT_c$ for $k = 1 \cdots n$
    $\mathbb{G}$ the network
Output
    $\phi(i, j)$ the optimal flow from arc $i$ to arc $j$ in the network
    The gate $G_r$ opening value is equal to $\phi(G_r, FDA_r)$
Begin
    for $k = 1$ to $n$
        $TM(k, 1) \leftarrow Q_{input}(k)$        % $TM$ is the $n \times 2n_G$ temporization matrix
        for $r = 2$ to $2n_G$
            $TM(k, r) \leftarrow 0$
        end
    end
    for $r = 1$ to $n_G - 1$
        for $k = 1$ to $k_r$
            $TM(k, r + 1) \leftarrow min(Q_{input}(1), Q_{lam})$
        end
    end
    for $k = 1$ to $n$
        Actualize_Network ($\mathbb{G}, k, TM$)
        Compute_Optimal_Flow ($\mathbb{G}, k$)
        Actualize_Temporization_Matrix ($\mathbb{G}, k, TM$)
    end
End
```

Figure 4 Flood lamination algorithm.



```
Algorithm : Actualize_Network
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
    $\gamma_r$ indicator for using or not $FDA_r$
    $Q_{lam}(k)$ the lamination flow-rate at $kT_c$
    $\mathbb{G}$ the network
Output
    $\mathbb{G}$ the network
Begin
    $Q(k) \leftarrow 0$
    for $r = 1$to $2n_G$
        $Q(k) \leftarrow Q(k) + TM(k, r)$
    end
    for $r = 2$ to $n_G$
        $\alpha_r \leftarrow TM(k, r)$
    end
    for $r = 1$ to $n_G$
        $\nu_r \leftarrow min[max(0, TM(k, r) - Q_{lam}(k)), max(0, Max\_FDA_r - TM(k, n_G + r))] \times \gamma_r$
        $Stock\_FDA_r \leftarrow TM(k, n_G + r)$
    end
End
```

Figure 5 Actualization network algorithm.



```
Algorithm : Actualize_Temporization_Matrix
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 $\tau_r$ from gate $G_r$ to gate $G_{r+1}$ is $\tau_r = k_r T_c$, $r = 1, \cdots, n_G - 1$
    $\mathbb{G}$ the network
Output
    $TM$ the $n \times 2n_G$ temporization matrix
Begin
    for $r = 1$ to $n_G - 1$
        $TM(k + k_r, r + 1) \leftarrow TM(k + k_r - 1, r + 1) + \phi_{(G_r, P0)}(k)$
    end
    for $r = 1$ to $n_G$
        $TM(k + 1, n_G + r) \leftarrow TM(k, n_G + r) + \phi_{(FDA_r, P0)}(k)$
    end
End
```

Figure 6 Actualization temporization matrix algorithm.

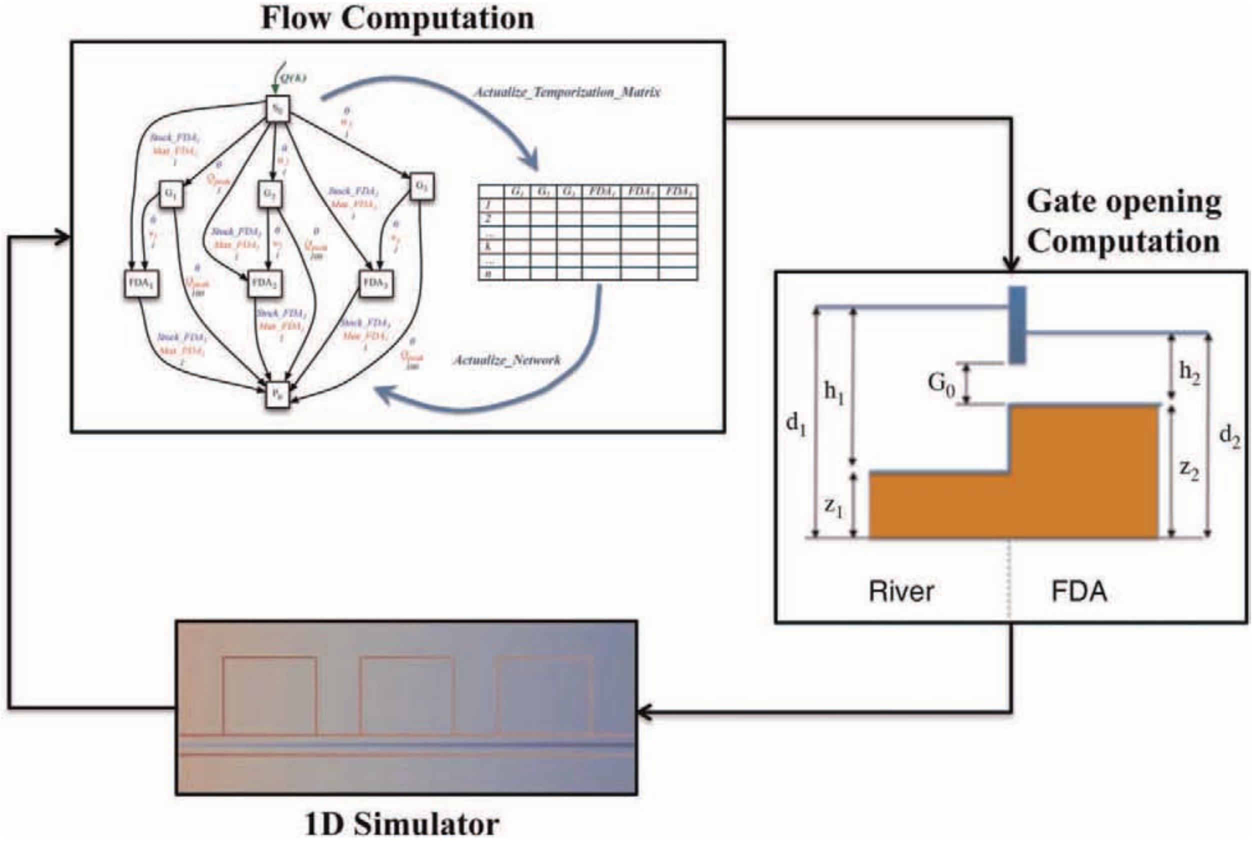
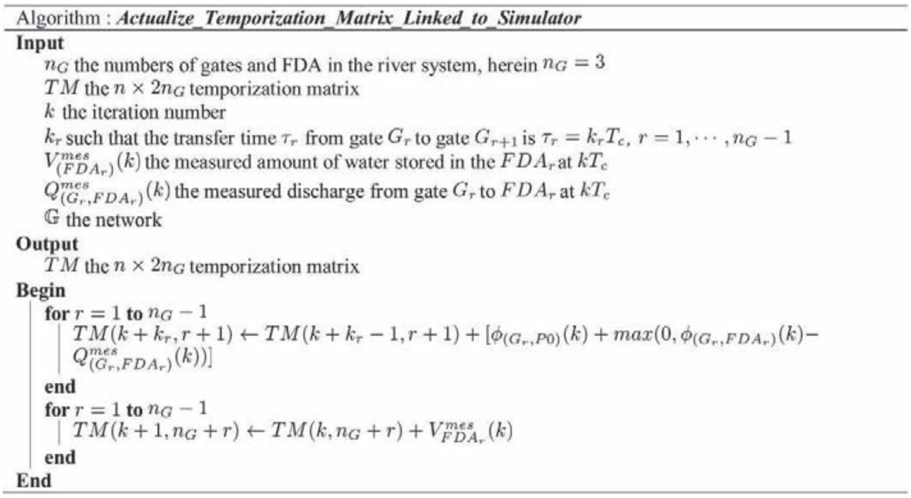


Figure 7 Dynamic reduced size network connected with 1D simulator.

COMPUTATIONAL RESULTS

We present some results obtained using the method where our network model is connected with the 1D hydraulic simulator. The network model allows calculation of the optimal flow-rate which will be used in the calculation of the opening gate of the FDAs by means of a static inversion of the free flow open channel equations (Litrico *et al.* 2008).



```
Algorithm : Actualize_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 $\tau_r$ from gate $G_r$ to gate $G_{r+1}$ is $\tau_r = k_r T_c,\ r = 1, \cdots, n_G - 1$
    $V^{mes}_{(FDA_r)}(k)$ the measured amount of water stored in the $FDA_r$ at $kT_c$
    $Q^{mes}_{(G_r,FDA_r)}(k)$ 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 $n_G - 1$
        $TM(k + k_r, r + 1) \leftarrow TM(k + k_r - 1, r + 1) + [\phi_{(G_r,P0)}(k) + max(0, \phi_{(G_r,FDA_r)}(k) -$
        $Q^{mes}_{(G_r,FDA_r)}(k))]$
    end
    for $r = 1$ to $n_G - 1$
        $TM(k + 1, n_G + r) \leftarrow TM(k, n_G + r) + V^{mes}_{FDA_r}(k)$
    end
End
```

Figure 8 Actualization temporization matrix algorithm.

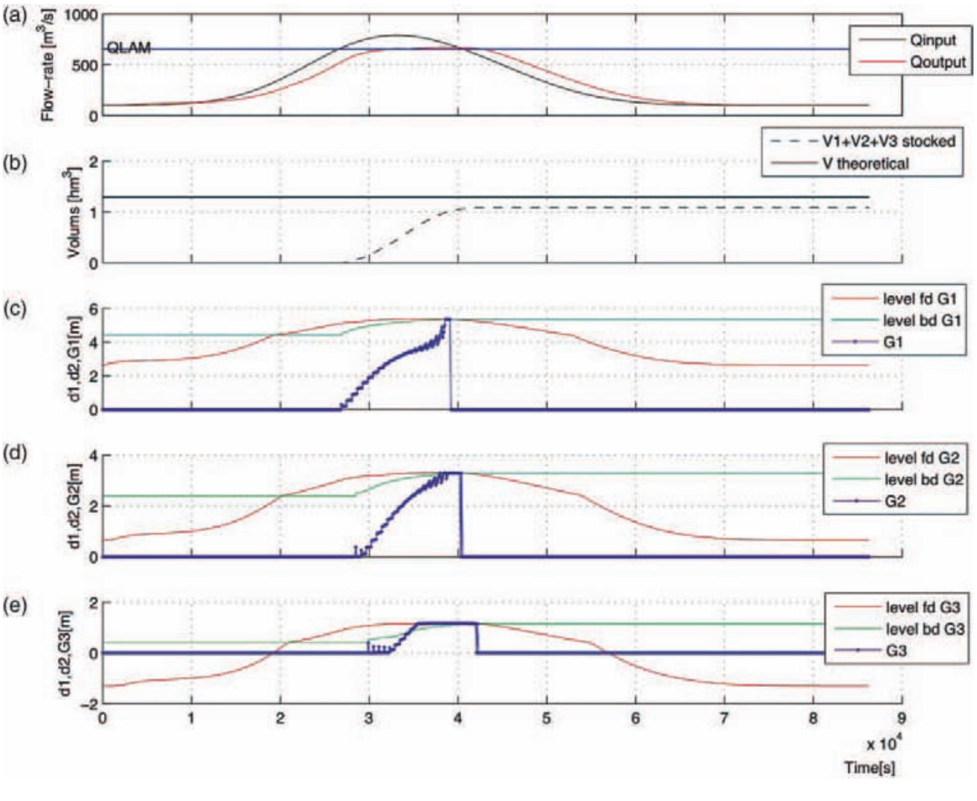


Figure 9 Simulation results for $\tau_1 = 11T_c$, $\tau_2 = 15T_c$. (a) Q_{input} discharge upstream the river, Q_{output} discharge downstream and Q_{lam} lamination set point. (b) Sum of volumes stored in all FDAs and the theoretical volume to laminate. (c), (d), (e) Opening gates, water levels forward (d_1, fd) and backward (d_2, bd) the gates.

In Figure 9(a) the Q_{input} and the Q_{output} show the results obtained by applying the flood lamination strategy with the network delay model, for $Q_{\text{lam}} = 650\,\text{m}^3/\text{s}$. The stored water volume in the FDAs is plotted in Figure 9(b). In Figures 9(c), 9(d) and 9(e) the gate opening values and the water levels d_1 (forward the gate) and d_2 (backward the gate) measured with regard to the river bed are displayed for gates 1, 2 and 3 respectively. The values of $\tau_1 = 11T_c$

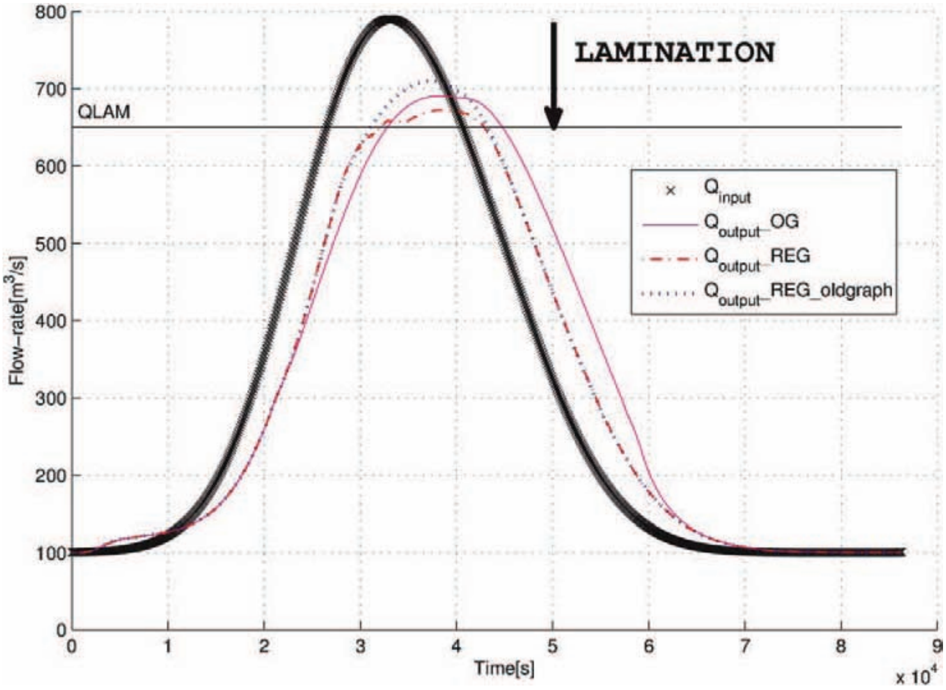


Figure 10 Comparison of simulation results for $Q_{\mathrm{lam}} = 650\,\mathrm{m}^3/\mathrm{s}$.

and $\tau_2 = 15T_c$ were estimated by an empirical method for $T_c = 100\,\mathrm{s}$; however, methods like the one developed in (Romera *et al.* 2013) can be used.

Simulations were done for the same input scenario (i.e. values of Q_{input}) and for $Q_{\mathrm{lam}} = 650\,\mathrm{m}^3/\mathrm{s}$ for three different regulation strategies. Results are given in Figure 10. Q_{input} is the thick line with crosses, and Q_{output} is displayed as:

- thin line ($Q_{\mathrm{output\_OG}}$) in the case where gates were always open;
- vertical dashes ($Q_{\mathrm{output\_REG\_oldgraph}}$) in the case where the lamination strategy proposed in Nouasse *et al.* (2012) was applied;
- horizontal dashes with dots ($Q_{\mathrm{output\_REG}}$) in the case where the lamination strategy with the network delay model proposed here was applied.

The peak flood discharge reduction is better in the latter case.

CONCLUSION AND FUTURE WORK

A transportation network including time delay was presented in order to perform flood lamination strategy to control a river system equipped with flood diversion areas. A reduced graph with temporization matrix mechanism was proposed in order to take into account the discharge dependent transfer times. Results obtained with this strategy including only the water storage were discussed. The strategy can be improved by defining a Q_{lam} value for each gate according to water levels, and by modeling the release of water from the FDAs to the river. Furthermore, beyond quantitative flood management an important problem to address is the quality of water in the river and in the FDAs. These extensions will be studied in future work.

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