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Transportation network model with time delay for flood lamination strategy

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Abstract— **Flooding due to rivers overflowing have affected this year many countries in the world. The engendered problems, due to their intensity, are relative to goods and persons safety, and often cause a sharp increase of the insurance costs, which is no more tolerable in the actual economic context. To prevent these problems, it is necessary to limit water heights downstream the streams. In the literature, numerous described works were done on flows modelling and management. The work presented in this paper, is interested in the quantitative management by means of floods diversion areas placed along the river and for which location and sizing are known. A management method computing the height of gates opening at each time step is proposed. The strategy is based on a transportation network model of the flood diversion area system including the time transfer delays. It allows the computation of the water volumes to be stored in time. Simulation results for different flood episode are discussed.**

Keywords—transportation networks; time delay; flood lamination; network modelling.

I. INTRODUCTION

The last decades violent natural phenomena have been observed on both sides of the planet, which according to experts are largely due to climate change [1]. Among these phenomena, we are interested in floods due to river overflowing, whose severity and magnitude are increasingly significant. Today, this is particularly manifest as attested by the floods in all Europe and particularly in central Europe where flooding of the Elbe and Danube were deadly and exceeded the record level of 2002. In fact, flooding due to excessive rainfall and surface runoff can cause significant damages, properties loss and injuries around the world. 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, given rapidity climatic phenomena at origin of the most of these floods, and difficulty of accurately assess their magnitude; managers must take important decisions quickly in an uncertain context. The integration of adapted digital tools to these crises is relevant and necessary to improve the decision-making [2], [3]. 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 [4], nonlinear programming [5], [6], multiobjective optimization [7] or genetic algorithms [8]. Some heuristics are also used to deal with this management, notably algorithms for flows maximizing [9], [10], [11]. 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 of volume displaced in expansion areas, which are available along of a watercourse in a river system. The proposed method is based on the transport networks with time delay. The paper is organized as follows. Section II describes the flood-diversion area system. Section III gives the main definitions of network flow modeling with time delay. A three-flood-diversion-area system modeling is detailed. In section IV, 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.

II. FLOOD DIVERSION AREA SYSTEM

A flood-diversion-area (FDA) system consists of a series of FDAs distributed along the river. A FDA is a floodplain area equipped with n_G 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 Fig.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 [12], [13]. We assume that T_r is the transfer time from the gate G_r to the following gate $G_{r+1}, r = 1, 2$.

III. TRANSPORTATION NETWORK DESIGN INCLUDING TIME DELAY

In previous work [14], 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
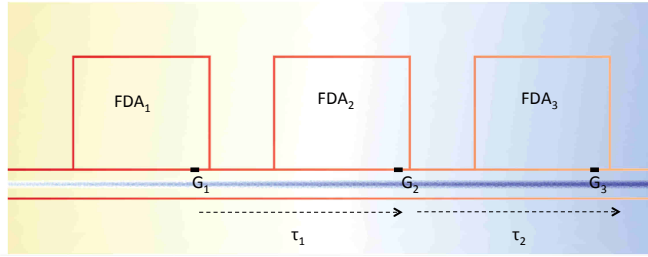

Fig. 1. River with three lateral floodplain.

and the optimization method management parameters. However, the transfer time delays were not taken into account. Therefore, herein, in order to improve the management method, we propose to introduce time delay in the system through the use of a temporized transportation network. Thus, we will see some aspects of the impact of time delay on the studied river system.

For this purpose, we study the evolution of the state of our flood-diversion area system at each kT_c, $k = 0, \cdots, n$ 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 Fig. 2. It can be seen as a dynamic flow network [15], [16] composed by interconnected static sub-networks. These connections allow for model temporization.

The network $\mathbb{G} = \{\mathcal{N}, \mathcal{A}\}$ where $\mathcal{N}$ is a set of $3n_G + 2$ nodes defined as follows. The network layers are indexed through the use of exponent k.
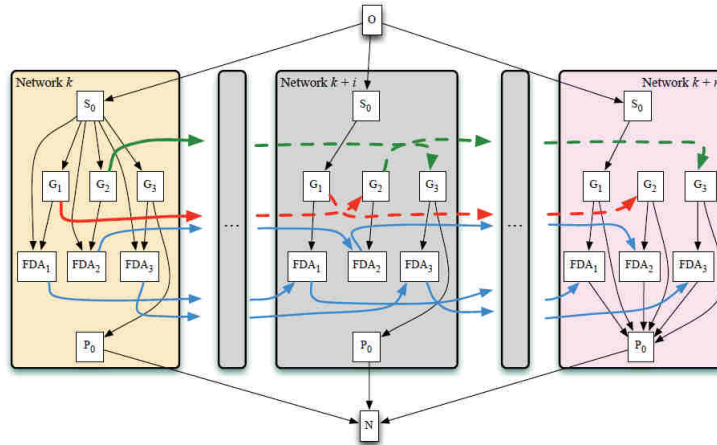
- G_r^k represents the gate G_r at k, with $r = 1, \cdots, n_G$; FDA_r^k is the FDA_r at k;

- 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 $k = 0, \cdots, n - k_r$ with $\tau_r = k_r T_c$ and $r = 1, \cdots, n_G - 1$. 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 $r = 1, \cdots, n_G - 1$ and $k = n - k_r + 1, \cdots, n$, it represents the flow downstream the exit point of our FDAs system when this discharge is not stored in the FDA_r^k.

- Between $G_{n_G}^k$ and P_0^k, with $k = 0, \cdots, n$, it represents the flow downstream the exit point of our FDAs system when this discharge is not stored in the $FDA_{n_G}^k$.

- Between nodes S_0^k and G_1^k, is the flow $Q_{input}(k)$ at the entry point that is always transferred towards the gate G_1.

- Between nodes S_0^k and G_r^k, with $k = 0, \cdots, k_r$ and $r = 2, \cdots, n_G$, it takes into account at initialization the flow upstream the gate G_r in the FDAs system.

Fig. 2. Temporized network model with static sub-networks.

- 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, the arc 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 $k = 0, \cdots, n-1$, the arc 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, the arc 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 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 Fig. 3), which allows enhancing the temporized network: more dynamic and suitable for various river sections with variable transfer time.
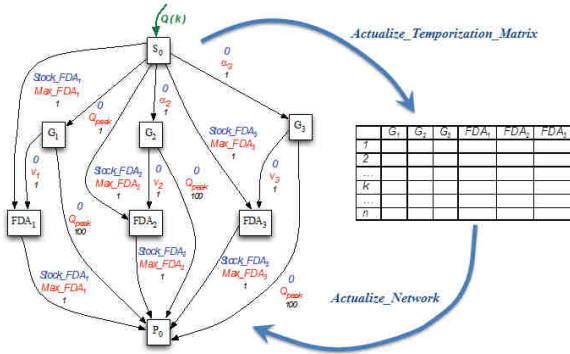

Fig. 3. Dynamic reduced size network.

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 Fig. 3, for each arc, its maximum capacity is written in blue, its minimum capacity is written in red and its cost is written in black.

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 τ_r from gate G_r

to gate G_{r+1} is $\tau_r = k_r T_c$, $r = 1, \cdots, n_G - 1$

γ_r indicator for using or not FDA_r

$Q_{input}(k)$ the flow of flood scenario at

kT_c for $k = 1 \cdots n$

$Q_{lam}(k)$ the lamination flow 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 $k = 1$ **to** k_r
        for $r = 2$ **to** n_G
            $TM(k, r) \leftarrow min(Q_{input}(k), Q_{lam})$
        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

Fig. 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

γ_r indicator for using or not FDA_r

$Q_{lam}(k)$ the lamination flow 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

        $\nu_r \leftarrow min[max(0, TM(k,r) - Q_{lam}(k)), max(0, Max\_FDA_r - TM(k, n_G + r))] \times \gamma_r$

    end

End

Fig. 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 τ_r from gate G_r to gate G_{r+1} is $\tau_r = k_r T_c$

$\mathbb{G}$ the network

Output

    TM the $n \times 2n_G$ temporization matrix

Begin

    for $r = 1$ **to** $n_G - 1$

        $TM(k + k_r, r + 1) \leftarrow$

        $TM(k + k_r - 1, r + 1) + \phi_{(G_r, P0)}(k)$

    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

Fig. 6. Actualization temporization matrix algorithm.

The Flood-Lamination algorithm described in Fig.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 Fig. 5), the optimal flow is computed and the temporization matrix is actualized (see Fig. 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 flow entering the network at kT_c.

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

- Max_FDA_r is the maximum FDA_r storage capacity, depending on Q_{peak}.

- ν_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 flow chosen by the river system manager and defined as the flow level at which the river flow 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 [12], [13]), in order to update flow and water quantity stocked with measured values. The scheme used is given in Fig. 7 and the algorithm for actualization of temporized matrix is modified as given in Fig. 8.
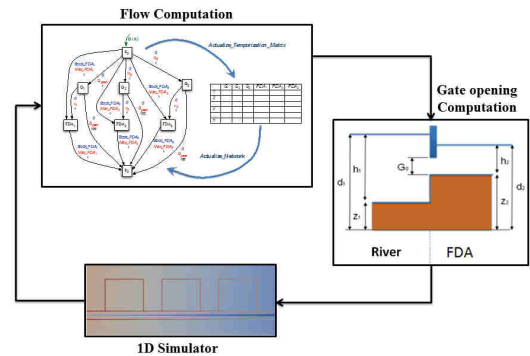

Fig. 7. Dynamic reduced size network connected with 1D simulator

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
gate G_r to gate G_{r+1} is $\tau_r = k_r T_c$
$\mathbb{G}$ the network

Output

TM the $n \times 2n_G$ temporization matrix

Begin

  for $r = 1$ **to** $n_G - 1$
    $TM(k + k_r, r + 1) \leftarrow$
    $TM(k + k_r - 1, r + 1) + \phi_{(G_r, P0)}(k)$
  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

Fig. 8.   Actualization temporization matrix algorithm

IV.   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 calculating the optimal flow-rate. This flow-rate value will be used for computing the opening height of each FDA gate. The computation algorithm involves a static inversion of the free flow open channel equations [17].

In Fig. 9 (a) Q_{input} is the inlet discharge. The Q_{output} is the outlet measured discharge when the flood lamination strategy is applied. The parameters of the network delay model are $\tau_1 = 11T_c$, $\tau_2 = 15T_c$ and $Q_{lam} = 650 m^3/s$.

The sum of the stored water volume in each FDA is plotted in Fig. 9 (b). The water volume to store in the FDAs is the volume such as Q_{input} is over Q_{lam}. This volume is denoted $V_{theoretical}$ in Fig. 9 (b), and approximated with the trapezoidal numerical integration of the flow-rate function above Q_{lam}.
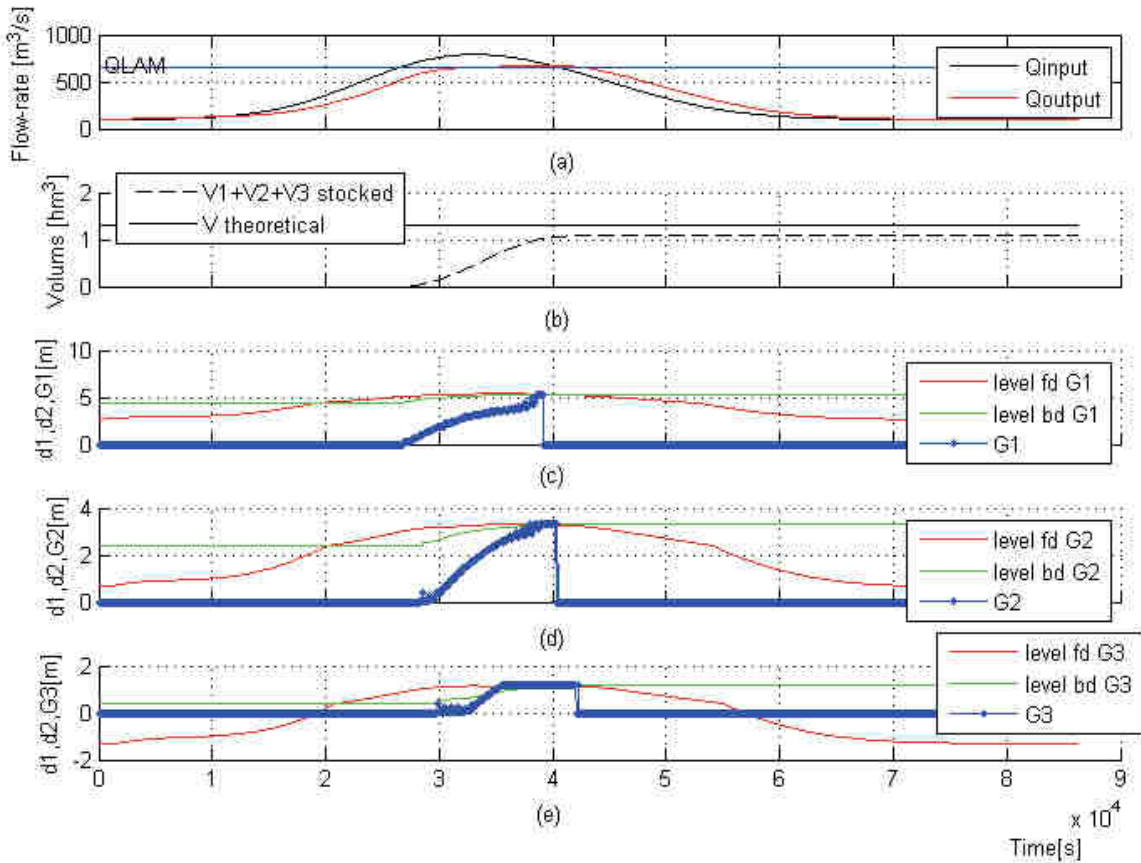
Fig. 9.   Simulation results for $\tau_1 = 11T_c$, $\tau_2 = 15T_c$, water levels forward the gates (d1, fd) and backward the gates (d2, bd)

In Fig 9. (c), (d) and (e) the gate opening values are displayed for gate 1, 2 and 3 respectively. In these figures, d_1 stands for the water level forward each gate and d_2 stands for the water level backward each gate.

The values of $\tau_1 = 11T_c$ and $\tau_2 = 15T_c$ were estimated by an empirical method for $T_c = 100s$, however methods like the one developed in [18] can be used.

Simulations were done for the same input scenario (i.e. values of Q_{input} displayed in black) and for $Q_{lam} = 650m^3/s$ for three different regulation strategies. Results are given in Fig. 10, where Q_{output} obtained in case where the gates were always open is displayed in red dotted line ($Q_{output\_}OG$). In the case where the lamination strategy proposed in [14] was applied Q_{output} is displayed in blue crosses line ($Q_{output\_}REG\_oldgraph$). Finally, when the lamination strategy proposed here (with the network delay model) Q_{output} is displayed in red ($Q_{output\_}REG$). The peak flood discharge reduction is better in the latter case.

V. CONCLUSION

A flood lamination strategy based on a transportation network model including time delay was proposed. The strategy allows controlling a river system equipped with flood diversion areas. In order to avoid oversize in the transportation network and to include non-static transfer times, a reduced graph with temporization matrix was proposed. Results obtained with this strategy for water storage purpose were discussed. The strategy can be improved by modeling the release of water from the FDAs to the river. Furthermore, beyond a 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 works.
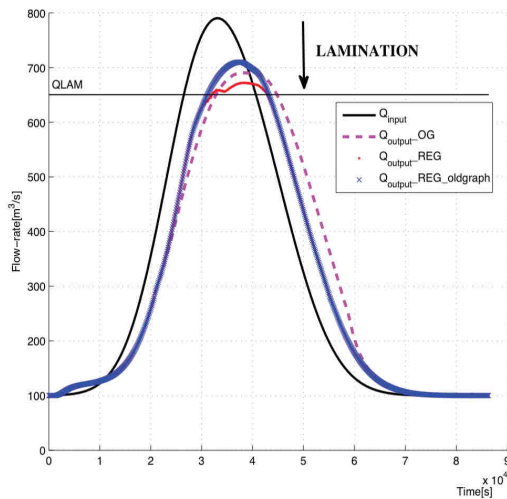

Fig. 10. Comparison of simulation results for $Q_{lam} = 650m^3/s$.

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