Water-resource Optimization Problem of Inland Waterways based on Network Flows with Flow Transition Time and Time Varying Characteristics

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Abstract: Water-resource allocation planning is a well studied problem that aims at sharing water-resource to answer to multi-objective management. For inland waterways, water-resource has to be balanced among the networks to guaranty navigation conditions as a priority. Hydraulic devices such as locks and gates are used to transfer volumes of water between the interconnected navigation reaches that composed the network. By considering a large spatial scale with a low control time scale, transport delays have to be considered. Hence, network flows with flow transition time and time varying characteristics is proposed to deal with transport delays and modifications of the operating conditions over time. Network flows are then used for the optimization step. The proposed model and optimization approach are illustrated by considering an inland waterway that is composed of two navigation reaches.

1 INTRODUCTION

Hydrographical networks are large scale systems that carry volumes of water. These systems have been developed over the time to meet human' needs. They have been equipped with dams to store the water, expansion areas to reduce flood impacts, gates to control water dispatching, and locks to allow navigation. Whatever the hydrographical networks, the water-resource has to be shared between usages. Hence multi-objective management has to be performed (Tchangani, 2017; Amigoni et al., 2015; Xiong et al., 2018; He et al., 2018). This management requires the definition and the solving of water-resource optimization problems. In (Duviella et al., 2018), water-resource allocation planing based on quadratic optimization technique is proposed to guaranty the navigation conditions and to study the resilience of the waterways against extreme events. The requirement of good extreme event prediction based on accurate rainfall/runoff model is discussed in (Hadid and Duviella, 2018). Rainfall/runoff models are based on offline and recursive/online parameter estimation of data-driven linear and nonlinear models (Hadid et al., 2018). In addition, a predictive optimization approach is proposed in (Alves et al., 2018) to improve again the water management. These approaches are based on an integrated model of inland waterways and on a weighted *dynamic generative network flow* that is introduced in (Fathabadi and Hosseini, 2010). The management time corresponds to half of a day implying that no transfer delays have been considered. Moreover, the arcs capacities and node supplies/demands are functions of time. Based on these assumptions, it is assumed that the transfer of water-resource between two reaches is immediate between two time steps. When the transfer delays have to be considered in the optimization, the method requires temporized flow networks or *flow over time* networks. In (Ladeveze et al., 2010), a transportation network is proposed to implement an algorithm leading to optimal trajectories of a multi-objective short-term management of a dam-river system. A time expanded flow network formalism is used in (Ayoub et al., 2018) to consider available hydraulic data. A similar extended flow network is used in (Bencheikh et al., 2017) to decrease the flood impacts thanks to the use of flood expansion area with a real case-study located in the south of France. The proposed transportation networks are based on those described in (Kotnyek, 2003) that aim at considering the time for the flow to pass the arcs, the storage capability for each node, the time varying characteristics of the nodes and arcs, and the concept of throughput in the dynamics of the flow

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networks. The main objective is a well understanding and representing of the dynamics of hydrographical systems.

Flow network modeling is more dedicated to optimization applications. To this aim, a decomposition of the hydrographical networks in conceptual models is required. In (Ladeveze et al., 2010; Ayoub et al., 2018; Bencheikh et al., 2017; Duviella et al., 2018), the nodes of the flow networks correspond to reaches or parts of reach between hydraulic devices such as gates, locks, hydraulic inputs, etc. A systematically decomposition approach has been proposed in (Wolfs et al., 2015). It allows considering conceptual models based on virtual reservoirs. In this paper, the decomposition of inland navigation reaches is based on the Integrator Delay (ID) model (Schuurmans et al., 1999) to take into account the backwater effect that characterizes these systems. Indeed, navigation reaches, depending of their size, can be considered as tanks due to the presence of locks. Moreover, most of them are characterized by a very small slope or no slope that increases the backwater effect and some resonance phenomena (Segovia et al., 2017; Horvàth et al., 2015; Horváth et al., 2014). These three contributions are dedicated to predictive control of water level and not on water resource dispatching. By considering a large spatial scale and a low control time scale, the modelling of inland waterways with flow networks requires *a priori* flow transition time, storage capability, time varying characteristics and throughput dynamics. Based on these concepts, a network flow with flow transition time and time varying characteristics is proposed. It is well suited to inland waterways and optimal water-resource allocation planning.

The paper is organized as follows: Section II describes the inland waterways and the modelling approach based on ID model. The network flows with flow transition time and time varying characteristics are detailed in Section III. Section IV deals with the optimization approach. Finally, a case-study is given in Section V to illustrate the modeling and optimal water-resource allocation steps.

2 INLAND WATERWAYS

2.1 Description and Management Objectives

Inland waterways are large scale and complex systems that are used principally for navigation. They are usually composed with interconnected Navigation Reaches, denoted NR, and equipped with locks that allow guaranteeing the navigation condition whatever is the landform. Artificial canals have been built to connect natural rivers and to permit navigation transport.

The main management objective consists in guaranteeing the navigation conditions at each time all along the year. An objective that is denoted Normal Navigation Level (NNL) and a navigation rectangle are defined for each NR. The navigation rectangle is an interval around the NNL that is composed of a low limit, the Low Navigation Level (LNL) and a high limit, the High Navigation Level (HNL). The water-resource management consists in allocating the available resource among the interconnected NR to keep their water levels inside the defined navigation rectangle and closest as possible to the NNL. The main disturbances are from the navigation demand *i.e.* the ships crossing the locks. At each lock operation, a big water volume goes from the upstream NR to the downstream one. Moreover, because inland waterways are strongly connected with other natural rivers, and inside watersheds, they are also affected by climatic events.

The water-resource allocation is performed thanks to the controlled gates by taking into account the configuration of the waterways. Depending on the control time scale, the transfer delay, *i.e.* the required time a volume of water travels from an upstream to a downstream point, must be considered. Otherwise, an order can be sent to a controlled gate before that the water volume arrives this gate leading to deficit of water.

2.2 Integrated Model

A first model entitled integrated model is proposed to well represent the waterways configuration and the possible interactions with naturals rivers or other hydraulic systems that are not considered by the water-resource allocation planning (Duviella et al., 2018). Fig. 1.a shows an example of a waterway composed with five NR and the two elementary configurations; a tributary and a distributary. The corresponding integrated model is depicted in Fig.1.b, with:

- $V_i^{s,c}$ and respectively $V_i^{e,c}$, the controlled volumes from one or several upstream NR that supply and (resp.) empty the NR_i (s: supply, e: empty, c: controlled),
- V_i^c the controlled volumes from water intakes that can supply or empty NR_i. These volumes are signed; positive if NR_i is supplied, negative otherwise,
- $V_i^{s,p}$ and (resp.) $V_i^{e,p}$ the controlled volumes from

pump that can supply and (resp.) empty the NR_i, denoted (p: pumped),

- V_i^u the uncontrolled volumes from natural rivers, rainfall-runoff, Human uses (u: uncontrolled). These volumes are signed depending on their contribution to the volume $V_i(k)$ in NR_i.
- $V_i^{g,u}$ the uncontrolled volumes from exchanges with groundwater (g: groundwater), that can be associated to V_i^u.

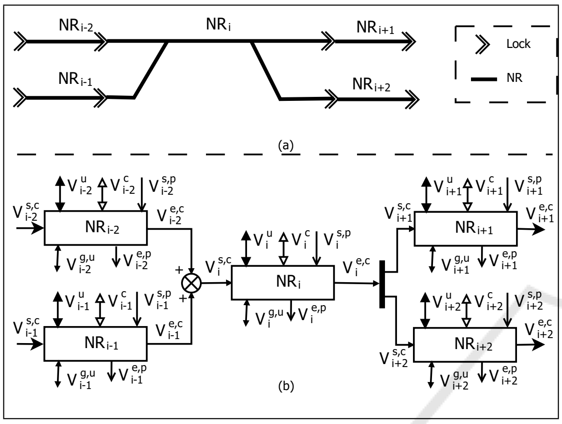

Figure 1: a. Inland waterways, b. corresponding integrated model.

The dynamics of the reach NR_i with a discrete sample time T_s is given by:

$$\begin{aligned} V_i(k) = \quad & V_i(k-1) + V_i^{s,c}(k) - V_i^{e,c}(k) + V_i^c(k) \\ & + V_i^{s,p}(k) - V_i^{e,p}(k) + V_i^u(k) + V_i^{g,u}(k), \end{aligned} \tag{1}$$

where k corresponds to the current period of time and $k-1$ the last one.

This model is well suited for the representation of waterways where no transfer delay has to be taken into account. Otherwise, it is necessary to decompose the NR in conceptual NR according to the transfer delays and the control sample time.

2.3 Conceptual Navigation Reach Model

The conceptual navigation reach model is designed based on the Integrator Delay model (Schuurmans et al., 1999). The ID model aims at linking the discharges that supply/empty a reach to water levels of the reach, at least on the two points that correspond to the boundaries of the reach. It can be expressed as:

$$\begin{bmatrix} y(1,s) \\ \dots \\ y(j,s) \\ \dots \\ y(n,s) \end{bmatrix} = \begin{bmatrix} p_{11}(s) & p_{12}(s) & \dots & p_{1m}(s) \\ \dots & \dots & \dots & \dots \\ p_{j1}(s) & p_{j2}(s) & \dots & p_{jm}(s) \\ \dots & \dots & \dots & \dots \\ p_{n1}(s) & p_{n2}(s) & \dots & p_{nm}(s) \end{bmatrix} \begin{bmatrix} q(1,s) \\ \dots \\ q(i,s) \\ \dots \\ q(m,s) \end{bmatrix} \tag{2}$$

where $y(j,s)$ is the j^{th} water level, $j \in 1:n$, $q(i,s)$ the i^{th} discharge input/output, $i \in 1:m$, with n the number of measurement points and m the number of discharge points. $p_{ji}(s)$ is a term of the ID model that is expressed as:

$$p_{ji}(s) = \frac{1}{A_{ji}.s} e^{-\tau_{ji}.s} \tag{3}$$

with A_{ji} the integrator gain that corresponds to the area of the reach $A = L * W$, with L the length and W the width of the reach. The transfer time delays τ_{ji}, (resp.) τ_{ij}, between the points j and i that are L_{ji} meters apart, with j upstream to i, are expressed by:

$$\begin{cases} \tau_{ji} = \frac{L_{ji}}{C_0 - V_0}, \\ \tau_{ij} = \frac{L_{ji}}{C_0 + V_0} \end{cases} \tag{4}$$

with $C_0 = \sqrt{g.D}$ and $V_0 = \frac{Q_0}{W.D}$, where g is the gravity and D the depth of the reach for the nominal discharge Q_0.

Based on this model and considering a discrete sample time T_s, it is possible to represent the dynamics of each part of the reach with a virtual tank of area A that is supplied and emptied with the delayed discharges. Thus:

$$y_j(k) = y_j(k-1) + \frac{\sum_{i=1}^{m} q_i(k - T_{ji}).T_s}{A} \tag{5}$$

with $q_i(k)$ a signed discharge and $T_{ji} = \lfloor \tau_{ji}/T_s \rfloor$, where $\lfloor\ \rfloor$ provides the floor integer number.

Fig.2.a depicts a schematic view of a NR with multiple inputs/outputs (discharges Q_i) and measurement points (levels Y_j), and the corresponding delays between these points. Note that the delays T_{ji} when i is located in the same place than j are not shown because they are equal to 0. The corresponding conceptual model is shown in Fig.2.b, where a tank is associated to each measurement point. The area of the tanks is the same. These tanks are supplied/emptied with delayed discharges according to the configuration of the waterway. This conceptual model is then used to design the network flows.

3 NETWORK FLOWS

The definition and the description of static network flows are proposed in (Ahuja et al., 1993). In (Kotnyek, 2003), a state of the art of dynamic network flows is given. It aims at describing a formalism of dynamic network flows able to take into account flow time, storage capability, time varying characteristics, and the concept of throughput. All these properties are required to model inland waterways thanks to network flows. Hence, the proposed network flow is defined on a direct graph $G = (N, E, B, T, \Omega, \Phi)$, with:

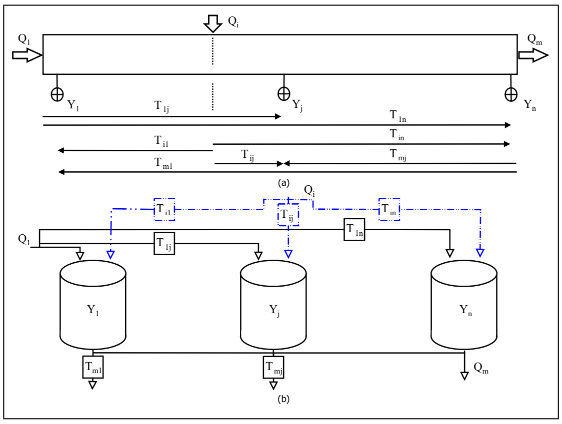

Figure 2: a. schematic view of a NR with transfer delays, b. corresponding conceptual model.

- the nodes $N = N_i \cup N_c \cup N_T \cup O \cup S$, with O the supersource, S the supersink that gather respectively all the sources and all the sinks, N_i the set of nodes that corresponds to the NR or parts of NR, N_c the set of conceptual nodes, and N_T the set of temporized nodes,
- the arcs $E = E_i \cup E_c \cup E_T \cup E_d$, with E_i the set of arcs between NR, source O and sink S, E_c the set of conceptual arcs, E_T the set of temporized arcs, and E_d the set of arcs starting from and entering in the same NR allowing the modelling of the capacity of the nodes N_i,
- the boundaries $B = B_e \cup B_d$ are composed of a lower and a higher limits, $l_{ij}(k)$ and $u_{ij}(k)$ respectively , with B_e the set of boundaries associated to arcs E_i, and B_d the set of boundaries associated to arcs E_d,
- the transfer delays T that are associated to the set of arcs E_T,
- the weights $\Omega = \Omega_i \cup \Omega_d$ that are associated to the set of arcs $E_i \cup E_d$, respectively,
- the flows $\Phi = \Phi_i \cup \Phi_c \cup \Phi_T \cup \Phi_d$ that are transferred by the set of arcs E.

The limits and weights can change over the time. They are expressed according to time k. Hence, the network flow has time varying characteristics.

For an inland waterway that is composed of one NR where the maximum transfer delay is lower than the sample time, *i.e.* $max\lfloor \tau_{ji}/T_s \rfloor = 0$, (*see* Fig.3.a), the corresponding network flow (*see* Fig.3.b) is defined as:

- $N = N_i \cup O \cup S$, with $N_i = \{1\}$, $N_T = \varnothing$ and $N_c = \varnothing$,
- $E = E_i \cup E_d$, with $E_i = \{e_{O1}, e_{1S}\}$, $E_d = \{e_{11}\}$ where e_{ij} is the arc between nodes i and j, $E_c = \varnothing$ and $E_T = \varnothing$,
- $B = B_e \cup B_d$, with $B_e = \{[l_{O1}(k),\ u_{O1}(k)],\ [l_{1S}(k),\ u_{1S}(k)]\}$ and $B_d = \{[l_{11}(k),\ u_{11}(k)]\}$, where $l_{ij}(k)$ (resp. $u_{ij}(k)$) is the lower (higher) limit of the flow that passes trough the arc e_{ij},
- $T = \varnothing$,
- $\Omega = \Omega_i \cup \Omega_d$, with $\Omega_i = \{w_{O1}(k), w_{1S}(k)\}$, $\Omega_d = \{w_{11}(k)\}$,
- $\Phi = \Phi_i \cup \Phi_d$, with $\Phi = \{\phi_{O1}(k), \phi_{1S}(k)\}$, $\Phi_d = \{\phi_{11}(k)\}$, where $\phi_{ij}(k)$ is the flow that passes through the arc e_{ij} at time k, $\Phi_c = \varnothing$ and $\Phi_T = \varnothing$.

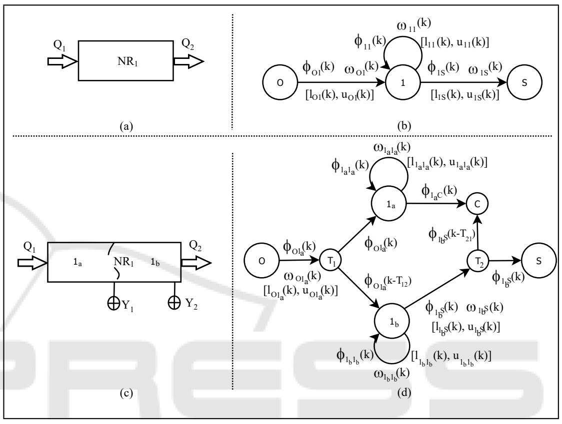

Figure 3: a. NR without consideration of time delay, b. corresponding network flows, c) NR with consideration of time delay, d) corresponding network flows.

When the maximum transfer delays is higher than the sample time (*see* Fig.3.c), *i.e.* $max\lfloor \tau_{ji}/T_s \rfloor \geq 1$, the corresponding network flow (*see* Fig.3.d) is defined as:

- $N = N_i \cup N_c \cup N_T \cup O \cup S$, with $N_i = \{1a, 1b\}$, $N_c = \{C\}$, $N_T = \{T_1, T_2\}$,
- $E = E_i \cup E_c \cup E_T \cup E_d$, with $E_i = \{e_{OT_1}, e_{1_bT_2}\}$, $E_d = \{e_{1_a1_a}, e_{1_b1_b}\}$ and $E_c = \{e_{1_aC}\}$, $E_T = \{e_{T_11_a}, e_{T_11_b}, e_{T_2C}, e_{T_2S}\}$,
- $B = B_e \cup B_d$, with $B_e = \{[l_{O1_a}(k),\ u_{O1_a}(k)],\ [l_{1_bS}(k),\ u_{1_bS}(k)]\}$ and $B_d = \{[l_{1_a1_a}(k),\ u_{1_a1_a}(k)],\ [l_{1_b1_b}(k),\ u_{1_b1_b}(k)]\}$, where $l_{ij}(k)$ (resp. $u_{ij}(k)$) is the lower (higher) limit of the flow that passes trough the arc e_{ij}, at time k,
- $T = \{T_{12}, T_{21}\}$,
- $\Omega = \Omega_i \cup \Omega_d$, with $\Omega_i = \{w_{O1_a}(k), w_{1_bS}(k)\}$, $\Omega_d = \{w_{1_a1_a}(k), w_{1_b1_b}(k)\}$,
- $\Phi = \Phi_i \cup \Phi_C \cup \Phi_T \cup \Phi_d$, with $\Phi_i = \{\phi_{O1_a}(k),\ \phi_{1_bS}(k)\}$ and $\Phi_C = \{\phi_{1_aC}(k)\}$,

$\Phi_d = \{\phi_{1_a1_a}(k),\ \phi_{1_b1_b}(k)\}$ and $\Phi_T = \{\phi_{O1_a}(k), \phi_{1_bS}(k), \phi_{O1_a}(k-T_{12}), \phi_{1_bS}(k-T_{21})\}$.

The set of nodes N_i verifies the Kirchhoff's law such as:

$$\sum_{j\in E^+_{N_i}} \phi_{e_j}(k) - \sum_{j\in E^-_{N_i}} \phi_{e_j}(k) = 0 \qquad (6)$$

with $E^+_{N_i}$ and $E^-_{N_i}$ (resp.), the set of arcs entering, outgoing (resp.) the node N_i, and ϕ_{e_j} the flow associated to the arc e_j.

The set of temporized nodes N_T do not verify the conservation rule as it is specified in (Kotnyek, 2003). It allows associating a transfer delay to each of the flow outgoing the temporized node:

$$\phi_{e_j}(k) = \phi_{e_{N_T}}(k - T_j) \qquad (7)$$

with $j \in E^-_{N_T}$, the set of arcs outgoing the node N_T, e_{N_T} the arc that enters the node N_T, and T_j the transfer delay that is associated to the outgoing arc e_j.

The set of conceptual node N_C verifies a conservation law between the flow on the arc outgoing the nodes N_i ($e^-_{N_i}$) and the flow on the arc outgoing the nodes N_T ($e^-_{N_T}$), defined as:

$$\phi_{e^-_{N_i}}(k) = \phi_{e^-_{N_T}}(k - T_j) \qquad (8)$$

The optimization of dynamic network flows leads to NP-hard problem as it is stated in (Skutella, 2009). To overcome this problem, a formalism of extended network flow has been proposed in (Fulkerson, 1966) and used in (Ladeveze et al., 2010; Bencheikh et al., 2017). The network flows in Fig. 3.d is represented in Fig.4 by considering $T_{12} = T_{21} = 1$ and two step times from $k = 1$ to $k = 2$. The dashed red arcs represent the temporized flows. Depending of the value of $max\lfloor \tau_{ji}/T_s \rfloor$, a throughput is defined and the optimization can be done for each of it. In this example, this throughput is equal to 2. Finally, some optimization approaches can be applied.

4 WATER-RESOURCE ALLOCATION PLANNING

The allocation planning consists in dispatching the water-resource among the waterways by keeping the volume inside each NR close to their objective (Duviella et al., 2018). These objectives are defined in relative value with the volumes that correspond to the NNL. Thus, a capacity of a NR equal to 0 corresponds to the NNL. The capacity boundaries are defined with the LNL and HNL, with negative and positive boundaries. They are associated with the boundaries B_d.

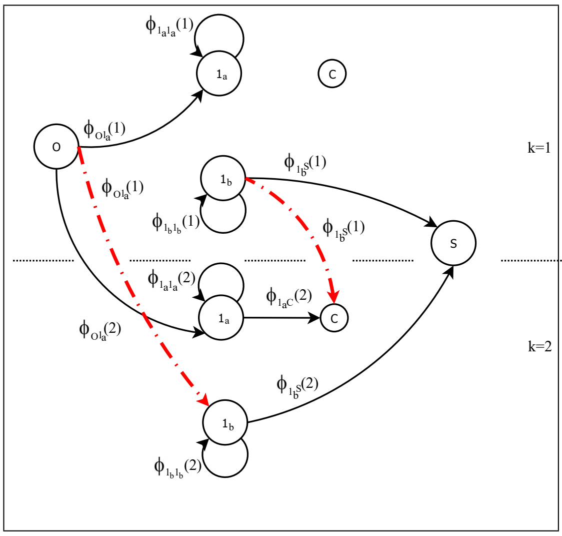

Figure 4: Time representation of the network flows depicted in Fig.3.d.

The dynamics for inland waterways are defined according the relations (7-9) following the configuration of the network.

The water-resource allocation planning is performed according to an optimization approach that consists in minimizing the absolute value of the NR's capacity by exchanging water through the arcs between the source and the sink. In order to minimize the water volume inside the NR, the weights Ω_d that are associated to the arcs E_d have to be big. Other weights Ω_i that are associated to the arcs E_i are tuned according to the priority of the paths from a part of the network to another one. Thus, the objective function can be defined as:

$$J_V = \sum_{N_i \in E_i} \Big| \sum_{j\in E^+_{N_i}} \omega_j(k)\phi_{e_j}(k) - \sum_{j\in E^-_{N_i}} \omega_j(k)\phi_{e_j}(k) \Big| \qquad (9)$$

by considering the constraints given by relation (6), the boundaries B, and the transfer delays T. That means that the exchanges of water volumes between each NR or part of NR have to be balanced between the entering and outgoing flows at each step time k.

For the waterway where the maximum transfer delays is lower than the sample time (*see* Fig. 3.a), the objective function to minimize is defined as:

$$J_V = |\omega_{O1}(k)\phi_{O1}(k) + \omega_{11}(k)\phi_{11}(k) - \omega_{1S}(k)\phi_{1S}(k)| \qquad (10)$$

with:

$$\begin{cases} \phi_{O1}(k) + \phi_{11}(k) - \phi_{1S}(k) = 0, \\ \phi_{O1}(k) \in [l_{O1}(k), u_{O1}(k)], \\ \phi_{1S}(k) \in [l_{1S}(k), u_{1S}(k)], \\ \phi_{11}(k) \in [l_{11}(k), u_{11}(k)], \end{cases} \qquad (11)$$

where $\omega_{11}(k) \gg \omega_{O1}(k)$ and $\omega_{11}(k) \gg \omega_{1S}(k)$.

For the waterway where the maximum transfer delays is higher than the sample time (*see* Fig. 3.c), the objective function to minimize has to be defined by considering a throughput that is computed according to the maximum transfer delay, *i.e.* from k to $k+max\lfloor\tau_{ji}/T_s\rfloor$. In this case, by considering $T_{21} \geq T_{12}$, it is defined as:

$$\begin{aligned} J_V = {} & |\omega_{O1_a}(k)\phi_{O1_a}(k)+\omega_{1_a1_a}(k)\phi_{1_a1_a}(k)- \\ & \omega_{1_bS}(k-T_{21})\phi_{1_bS}(k-T_{21})|+ \\ & |\omega_{O1_a}(k-T_{12})\phi_{O1_a}(k)+\omega_{1_b1_b}(k)\phi_{1_b1_b}(k)- \\ & \omega_{1_bS}(k)\phi_{1_bS}(k)|+ \\ & \dots \\ & |\omega_{O1_a}(k+T_{21})\phi_{O1_a}(k+T_{21})+ \\ & \omega_{1_a1_a}(k+T_{21})\phi_{1_a1_a}(k+T_{21})- \\ & \omega_{1_bS}(k+T_{21}-1)\phi_{1_bS}(k+T_{21}-1)|+ \\ & |\omega_{O1_a}(k+T_{21}-1)\phi_{O1_a}(k+T_{21})+ \\ & \omega_{1_b1_b}(k+T_{21})\phi_{1_b1_b}(k+T_{21})- \\ & \omega_{1_bS}(k+T_{21})\phi_{1_bS}(k+T_{21})| \end{aligned} \qquad (12)$$

with, for $k' \in \{k : k+T_{21}\}$:

$$\begin{cases} \phi_{O1_a}(k')+\phi_{1_a1_a}(k')-\phi_{1_bS}(k'-T_{21})=0, \\ \phi_{O1_a}(k'-T_{12})+\phi_{1_b1_b}(k')-\phi_{1_bS}(k')=0, \\ \phi_{O1_a}(k') \in [l_{O1_a}(k'), u_{O1_a}(k')], \\ \phi_{1_bS}(k') \in [l_{1_bS}(k'), u_{1_bS}(k')], \\ \phi_{1_a1_a}(k') \in [l_{1_a1_a}(k'), u_{1_a1_a}(k')], \end{cases} \qquad (13)$$

where $\omega_{1_a1_a}(k') \gg \omega_{O1_a}(k')$, $\omega_{1_a1_a}(k') \gg \omega_{1_bS}(k')$, $\omega_{1_b1_b}(k') \gg \omega_{O1_a}(k')$, $\omega_{1_b1_b}(k') \gg \omega_{1_bS}(k')$.

The optimization approach can be based on Constraints Satisfaction Problems (CSP) (Nouasse et al., 2016b), on *minimum cost problem* (Kotnyek, 2003), on linear programming (Nouasse et al., 2016a) or on quadratic programming (Duviella et al., 2018). In this paper, a linear programming approach based on the Matlab function *linprog*[1] is used.

5 CASE-STUDY

The considered inland waterways is composed with two NR as it is schematized in Fig. 5.a. The lengths of the NR are $L_{NR_1} = 5\ km$, $L_{NR_2} = 20\ km$, with the same width $W = 20\ m$, nominal discharge $Q_0 = 1\ m^3/s$, and depth $D = 2.2\ [m]$. The parameters of the ID models for both NR are identified (*see* Table 1). The sample time is $T_s = 30\ min$. Thus, according to the transfer delays, only NR_2 is decomposed in two parts. Fig. 5.b depicts the network flows associated to the case-study. Hydraulic devices like locks and gates supply and empty the NR. Their characteristics are given in Table 2. The locks are activated for navigation and a lock operation corresponds to a transfer of water volume between two NR. The duration of a lock operation is equal to 15 *min*. The gates can be controlled inside the proposed intervals. Two periods of management are considered for the gate downstream NR_2: during 6 hours it can be controlled on the operating range $[0;5]$, the next 6 hours between $[0;10]$ $[m^3/s]$.

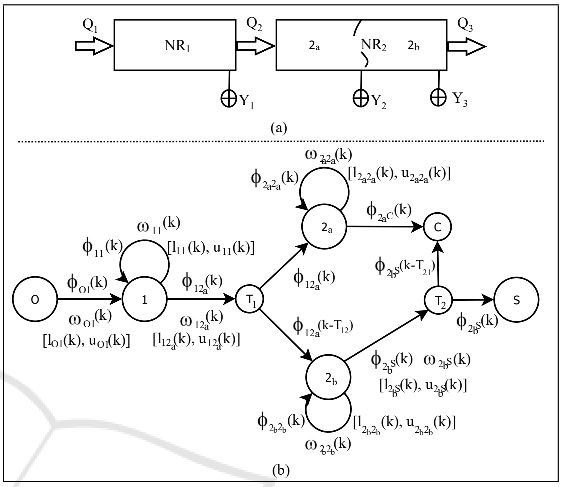

Figure 5: a. Inland waterways composed with two NR, b. network flows model.

Table 1: ID model parameters - τ [min].

		P_{11}	P_{12}	P_{21}	P_{22}	P_{31}	P_{32}
NR_1	τ_{ij}	0	-18	17	0		
	A	100,000					
NR_2	τ_{ij}	0	-71	35	-36	70	0
	A	400,000					

Table 2: Characteristics of the inputs/outputs of the *NR*.

	Lock during 15 *min*	*Gate* $[m^3/s]$
Q_1	$15,000\ m^3 \rightarrow 16.66\ m^3/s$	-
Q_2	$6,000\ m^3 \rightarrow 6.66\ m^3/s$	$[0;10]$
Q_3	$7,000\ m^3 \rightarrow 7.77\ m^3/s$	$[0;(5-10)^*]$

The weights are tune such as $\omega_{11}(k) = \omega_{2_a2_a}(k) = \omega_{2_b2_b}(k) = 1,000$ and $\omega_{O1}(k) = \omega_{12_a}(k) = \omega_{2_bS}(k) = 1$, with the objective to minimize the water that is stored inside the NR. Finally, according to the ID parameters, $T_{12} = T_{21} = 2\ T_s$.

The lock operations over the future time horizon $2T_s$ are supposed to be known and depicted in Fig. 6. The discharge Q_1 is the equivalent discharge due to the lock operation upstream NR_1 during 15 min. The discharges Q_2^L and Q_3^L come from the lock operations upstream and downstream NR_2 (L for lock). This knowledge allows the optimization of the crite-

[1] https://www.mathworks.com/help/optim/ug/linprog.html

rion J_V on horizon $2T_s$ according to relation (9) and the constraints given by relation (6).

A model of the considered inland waterway has been implemented with Simulink/Matlab. The optimization approach that is based on the *linprog* function is implemented with a matlab function. The simulation results are depicted in Fig. 7 with the controlled discharges at the gates upstream and downstream NR_2, *i.e.* Q_2^G and Q_3^G respectively (G for gate). The resulting levels downstream NR_1 and NR_2 are depicted in Fig. 7.c and Fig. 7.d respectively. When no optimization strategy is used, the simulation results lead to the results depicted in dashed red line in Fig. 7.c and Fig. 7.d. These results are improved when the proposed optimization approach is used as it is shown in continuous blue line in Fig. 7.c and Fig. 7.d. The maximum gap from the objective levels is lower when the proposed approach is used.

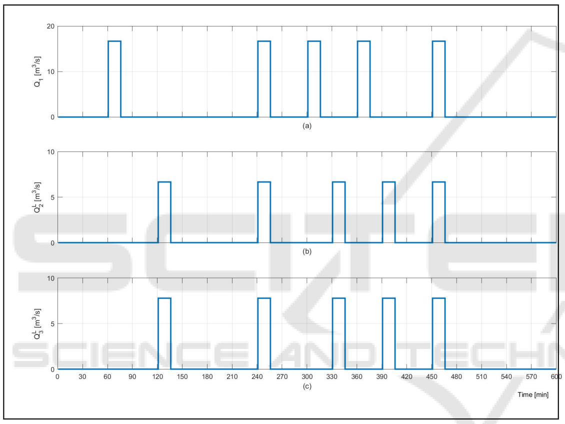

Figure 6: a. The discharge due to the lock operations upstream NR_1, b. the discharge due to the lock operations upstream NR_2, c. the discharge due to the lock operations downstream NR_2.

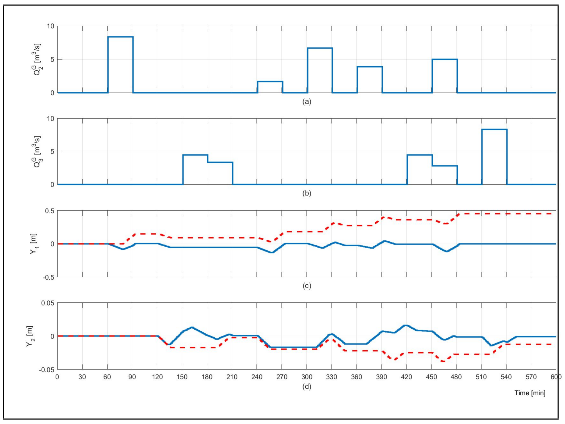

Figure 7: a. The controlled discharge upstream NR_1, b. the controlled discharge downstream NR_2, c. the water level downstream NR_1, d. the water level downstream NR_2.

6 CONCLUSIONS

In this paper a network flows with flow transition time and time varying characteristics formalism is proposed to deal with water-resource optimization of inland waterways. This formalism is based on the graph theory. The design of the network flows is achieved thanks to the ID model allowing the determination of transfer delays. Then, an optimization approach based on a linear programming is used. The proposed approach is illustrated by considering an academical case-study that consists in a two navigation reaches. The main objective is to deal with time delays and time varying characteristics. Future works will aim at adapting and applying this approach on real systems with outlets to the sea that require time varying characteristics to deal with the tide effect. Another perspective will be the comparison of this approach with MPC.

REFERENCES

Ahuja, R.-K., Magnanti, T.-K., and Orlin, J.-B. (1993). *Network flows - Theory, algorithms and applications*. New Jersey.

Alves, D. C. S., Duviella, E., and Doniec, A. (2018). Improvement of water resource allocation planning of inland waterways based on predictive optimization approach. In *ICINCO, Porto, Portugal*.

Amigoni, F., Castelletti, A., and Giuliani, M. (2015). Modeling the management of water resources systems using multi-objective dcops. In *Proceedings of the 2015 International Conference on Autonomous Agents and Multiagent Systems*, AAMAS '15, pages 821–829, Richland, SC. International Foundation for Autonomous Agents and Multiagent Systems.

Ayoub, T., Ladeveze, D., Chiron, P., and Archimède, B. (2018). Reconstruction of hydrometric data using a network optimization model. *HIC conference, Palermo, July 1st-6th*.

Bencheikh, G., Tahiri, A., Chiron, P., Archimede, B., and Martignac, F. (2017). A flood decrease strategy based on flow network coupled with a hydraulic simulation software 11this work was partially supported by the urban community of le grand tarbes. *IFAC-PapersOnLine*, 50(1):3171 – 3176. 20th IFAC World Congress.

Duviella, E., Doniec, A., and Nouasse, H. (2018). Adaptive water-resource allocation planning of inland waterways in the context of global change. *Journal of Water Resources Planning and Management*, 144(9):04018059.

Fathabadi, H. S. and Hosseini, S. A. (2010). Maximum flow problem on dynamic generative network flows with time-varying bounds. *Applied Mathematical Modelling*, 34(8):2136 – 2147.

Fulkerson, D. (1966). Flow networks and combinatorial operations research. In *American mathematical monthly*, volume 73.

Hadid, B. and Duviella, E. (2018). Water asset management strategy based on predictive rainfall/runoff model to optimize the evacuation of water to the sea. In *ICINCO, Porto, Portugal*.

Hadid, B., Duviella, E., and Lecoeuche, S. (2018). Improvement of a predictive data-driven model for rainfall-runoff global characterization of aa river. cited By 0.

He, Y., Chen, X., Sheng, Z., Lin, K., and Gui, F. (2018). Water allocation under the constraint of total water-use quota: a case from dongjiang river basin, south china. *Hydrological Sciences Journal*, 63(1):154–167.

Horváth, K., Duviella, E., Petreczky, M., Rajaoarisoa, L., and Chuquet, K. (2014). Model predictive control of water levels in a navigation canal affected by resonance waves. In *HIC 2014, 11th International Conference on Hydroinformatics*, New York.

Horvàth, K., Rajaoarisoa, L., Duviella, E., Blesa, J., Petreczky, M., and Chuquet, K. (2015). Enhancing inland navigation by model predictive control of water level – the Cuinchy-Fontinettes case. *Transport of Water versus Transport over Water - Exploring the dynamic interplay between transport and water - Carlos Ocampo-Martinez, Rudy Engenborn (eds)*.

Kotnyek, B. (2003). An annotated overview of dynamic network flows. *INRIA Report n. 4936*.

Ladeveze, D., Charbonnaud, P., and Archimède, B. (2010). Multi-objective management of multi-resource hydrographical systems. *IFAC Proceedings Volumes*, 43(8):585 – 590. 12th IFAC Symposium on Large Scale Systems: Theory and Applications.

Nouasse, H., Doniec, A., Duviella, E., and Chuquet, K. (2016a). Efficient management of inland navigation reaches equipped with lift pumps in a climate change context. *4^{th} IAHR Europe Congress, Liege, Belgium 27-29 July*.

Nouasse, H., Doniec, A., Lozenguez, G., Duviella, E., Chiron, P., Archimède, B., and Chuquet, K. (2016b). Constraint satisfaction problem based on flow transport graph to study the resilience of inland navigation networks in a climate change context. *IFAC Conference MIM, Troyes, France, 28-30 June*.

Schuurmans, J., Clemmens, A. J., Dijkstra, S., Hof, A., and Brouwer, R. (1999). Modeling of irrigation and drainage canals for controller design. *Journal of irrigation and drainage engineering*, 125(6):338–344.

Segovia, P., Rajaoarisoa, L., Nejjari, F., Puig, V., and Duviella, E. (2017). Decentralized control of inland navigation networks with distributaries: application to navigation canals in the north of France. *ACC'17, Seattle, WA, USA, May 24–26*.

Skutella, M. (2009). An introduction to network flows over time. In *Research Trends in Combinatorial Optimization*, pages 451–482. Springer-Verlag.

Tchangani, A. P. (2017). Sustainable management of natural resource using bipolar analysis. application to water resource sharing. *IFAC-PapersOnLine*, 50(1):3177 – 3182. 20th IFAC World Congress.

Wolfs, V., Meert, P., and Willems, P. (2015). Modular conceptual modelling approach and software for river hydraulic simulations. *Environmental Modelling & Software*, 71:60 – 77.

Xiong, W., Li, Y., Zhang, W., Ye, Q., Zhang, S., and Hou, X. (2018). Integrated multi-objective optimization framework for urban water supply systems under alternative climates and future policy. *Journal of Cleaner Production*, 195:640 – 650.