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

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Keywords: Model Graph, Large Scale Systems, Optimization, Modelling, Water System.

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...
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; Duvieilla 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 hydraulic effect and some resonance phenomena (Segovia et al., 2017; Horváth 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 (Duvieilla 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:

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

- \(V_u^i\) 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.
- \(V_e^{s,c}\) 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, with a discrete sample time \(T_s\), is given by:

\[
V_i(k) = V_i(k-1) + V_{i,e}^c(k) - V_{i,c}^e(k) + V_{i,g}^c(k) - V_{i,g}^e(k) + V_{i,u}^e(k),
\]

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:

\[
\begin{bmatrix}
y(1,s) \\
y(j,s) \\
y(n,s)
\end{bmatrix} =
\begin{bmatrix}
p_{11}(s) & p_{12}(s) & \cdots & p_{1m}(s) \\
p_{j1}(s) & p_{j2}(s) & \cdots & p_{jm}(s) \\
p_{n1}(s) & p_{n2}(s) & \cdots & p_{nm}(s)
\end{bmatrix}
\begin{bmatrix}
q(1,s) \\
q(j,s) \\
q(n,s)
\end{bmatrix}
\]

where \(y(j,s)\) is the \(j^{th}\) water level, \(j \in \{1 \ldots n\}\), \(q(i,s)\) the \(i^{th}\) discharge input/output, \(i \in \{1 \ldots m\}\), 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:

\[
p_{ji}(s) = \frac{1}{A_{ji,s}} e^{-\tau_{ji,s}}
\]

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

\[
\begin{bmatrix}
\tau_{ji} = \frac{L_{ji}}{L_{ji} - D_{ji}} \\
\tau_{ji} = \frac{L_{ji}}{L_{ji} + D_{ji}}
\end{bmatrix}
\]

with \(C_0 = \sqrt{g \cdot D}\) and \(V_0 = \frac{Q_0}{W^2}\), 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:

\[
y_j(k) = y_j(k-1) + \sum_{i=1}^{m} q_i(k-T_{ji})/A
\]

with \(q_i(k)\) a signed discharge and \(T_{ji} = \lfloor \tau_{ji}/T_s \rfloor\), where \(\lfloor \cdot \rfloor\) 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:
- the nodes $N = N_I \cup N_O \cup N_T \cup O \cup S$, 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 $N_T$,

- the boundaries $B = B_e \cup B_d$, $B_{e}$ the set of boundaries associated to arcs $E_I$, and $B_d$ the set of boundaries associated to arcs $E_d$, respectively,

- 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. $\max[i/j[T_s] = 0$, (see Fig.3.a), the corresponding network flow (see Fig.3.b) is defined as:

- $E = E_{i} \cup E_{d}$, with $E_{i} = \{e_{O1}, e_{1S}\}$, $E_{d} = \{e_{11}\}$ where $e_{ij}$ is the arc between nodes $i$ and $j$, $E_{C} = \emptyset$

- $B = B_{e} \cup B_{d}$, 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 $e_{ij}$,

- $T = \emptyset$,

- $\Omega = \Omega_I \cup \Omega_d$, with $\Omega_I = \{w_{O1}(k), w_{1S}(k)\}$, $\Omega_d = \{w_{11}(k)\}$,

- $\Phi = \Phi_I \cup \Phi_C \cup \Phi_T \cup \Phi_d$, with $\Phi_I = \{\phi_{O1}(k), \phi_{1S}(k)\}$ and $\Phi_C = \{\phi_{11}(k)\}$,

- $B_T = \emptyset$.

When the maximum transfer delays is higher than the sample time (see Fig.3.c), i.e. $\max[i/j[T_s] \geq 1$, the corresponding network flow (see Fig.3.d) is defined as:

- $N = N_I \cup N_O \cup N_T \cup O \cup S$, 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 $E_I = \{e_{O1}, e_{1S}\}$, $E_{d} = \{e_{11}\}$ and $E_{C} = \{e_{1C}\}$, $E_{T} = \{e_{T_1}, e_{T_2}, e_{T_3}, e_{T_4}\}$,

- $B = B_{e} \cup B_{d}$, with $B_{e} = \{[l_{O1}(k), u_{O1}(k)], [l_{1S}(k), u_{1S}(k)]\}$ and $B_{d} = \{[l_{11}(k), u_{11}(k)]\}$, $[l_{1S}(k), u_{1S}(k)]\}$, 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 $\Omega_I = \{w_{O1}(k), w_{1S}(k)\}$, $\Omega_d = \{w_{11}(k)\}$,

- $\Phi = \Phi_I \cup \Phi_C \cup \Phi_T \cup \Phi_d$, with $\Phi_I = \{\phi_{O1}(k), \phi_{1S}(k)\}$ and $\Phi_C = \{\phi_{11}(k)\}$,
Φ_d = \{φ_{1a1a}(k), φ_{1b1b}(k)\} and Φ_T = \{φ_{O1a}(k), φ_{1bS}(k), φ_{O1a}(k-T_{12}), φ_{1bS}(k-T_{21})\}.

The set of nodes Ni verifies the Kirchhoff’s law such as:

\[ \sum_{j \in E_{N_i}} φ_j(k) - \sum_{j \in E_{N_i}} φ_j(k) = 0 \]  

(6)

with \(E_{N_i}\) (resp.), the set of arcs entering, outgoing (resp.) the node \(N_i\), and \(φ_j\) 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:

\[ φ_{e_j}(k) = φ_{e_j}(k - T_j) \]  

(7)

with \(j \in E_{N_T}\), the set of arcs outgoing the node \(N_T\), \(e_j\) 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 \(N_j\) \(e_j\) and the flow on the arc outgoing the nodes \(N_T\) \(e_{N_T}\), defined as:

\[ φ_{e_{N_T}}(k) = φ_{e_{N_T}}(k - T_j) \]  

(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 flows 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 \(\max[τ_j/T]\), 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 (Duvieilla 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 \(B_2\),

\[ Φ_d = \{φ_{1a1a}(k), φ_{1b1b}(k)\} and Φ_T = \{φ_{O1a}(k), φ_{1bS}(k), φ_{O1a}(k-T_{12}), φ_{1bS}(k-T_{21})\}. \]
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 \( k + \max[\tau_j/T_j] \). In this case, by considering \( T_{21} > T_{12} \), it is defined as:

\[
J_\nu = |\omega_{O1}(k)\phi_{11}(k) + \omega_{O1}(k)\phi_{11}(k) - \\
\omega_{I1}(k-T_{31})\phi_{11}(k-T_{21})| + \\
|\omega_{O1}(k-T_{12})\phi_{11}(k) + \omega_{O1}(k)\phi_{11}(k) - \\
\omega_{I1}(k)\phi_{11}(k)| + \\
\ldots \\
|\omega_{O1}(k+T_{31})\phi_{11}(k+T_{21})| + \\
\omega_{I1}(k+T_{31})\phi_{11}(k+T_{21}) - \\
\omega_{I1}(k+T_{21}-1)\phi_{11}(k+T_{21}-1)| + \\
|\omega_{O1}(k+T_{21}-1)\phi_{11}(k+T_{21}) + \\
\omega_{I1}(k+T_{21})\phi_{11}(k+T_{21}) - \\
\omega_{I1}(k+T_{21})\phi_{11}(k+T_{21})| \\
\tag{12}
\]

with, for \( k' \in \{ k : k + T_{31}\} \):

\[
\left\{ \begin{array}{l}
\phi_{O1}(k) + \phi_{11}(k') - \phi_{I1}(k') = 0, \\
\phi_{O1}(k) + \phi_{11}(k') + \phi_{I1}(k') = 0, \\
\phi_{I1}(k') \in [L_{11}(k'), u_{I1}(k')], \\
\phi_{I1}(k') \in [L_{11}(k'), u_{I1}(k')], \\
\omega_{O1}(k) > \omega_{O1}(k'), \omega_{O1}(k') > \omega_{I1}(k'), \\
\omega_{I1}(k') > \omega_{O1}(k'), \omega_{I1}(k') > \omega_{I1}(k').
\end{array} \right. \\
\tag{13}
\]

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 \( L_{NR1} = 5 \text{ km}, L_{NR2} = 20 \text{ km} \), with the same width \( W = 20 \text{ m} \), nominal discharge \( Q_0 = 1 \text{ m}^3/\text{s} \), and depth \( D = 2.2 \text{ m} \). The parameters of the ID models for both NR are identified (see Table 1). The sample time is \( T_s = 30 \text{ min} \). Thus, according to the transfer delays, only NR2 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: during 6 hours it can be controlled on the operating range \([0;5]\) and inside the proposed intervals. Two periods of management are considered for the gate downstream NR: during 6 hours it can be controlled on the operating range \([0;5] \text{ m}^3/\text{s}\), the next 6 hours between \([0;10] \text{ m}^3/\text{s}\).

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\(^1\)https://www.mathworks.com/help/optim/ug/linprog.html

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**Table 1**: ID model parameters - \( \tau [\text{min}] \).

<table>
<thead>
<tr>
<th>( P_{11} )</th>
<th>( P_{12} )</th>
<th>( P_{21} )</th>
<th>( P_{22} )</th>
<th>( P_{31} )</th>
<th>( P_{32} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( NR_1 )</td>
<td>( \tau_{ij} )</td>
<td>0</td>
<td>18</td>
<td>17</td>
<td>0</td>
</tr>
<tr>
<td>( A )</td>
<td>100,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( NR_2 )</td>
<td>( \tau_{ij} )</td>
<td>0</td>
<td>-71</td>
<td>35</td>
<td>-36</td>
</tr>
<tr>
<td>( A )</td>
<td>400,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Lock during 15 min</th>
<th>Gate ([\text{m}^3/\text{s}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_1 )</td>
<td>15,000 \text{ m}^3 \rightarrow 16.66 \text{ m}^3/\text{s}</td>
</tr>
<tr>
<td>( Q_2 )</td>
<td>6,000 \text{ m}^3 \rightarrow 6.66 \text{ m}^3/\text{s}</td>
</tr>
<tr>
<td>( Q_3 )</td>
<td>7,000 \text{ m}^3 \rightarrow 7.78 \text{ m}^3/\text{s}</td>
</tr>
</tbody>
</table>

The weights are tune such as \( \omega_{11}(k) = \omega_{22},(k) = 1 \) and \( \omega_{11}(k) = \omega_{12}(k) = \omega_{22}(k) = 1 \), 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 \( Q_2^* \) and \( Q_3^* \) come from the lock operations upstream and downstream \( NR_2 \) (\( L \) for lock). This knowledge allows the optimization of the crite-
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. $Q_G^2$ and $Q_G^3$ 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.

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.

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