

**Study of Global Change Impacts on the Inland Navigation Management
Application on the Nord-Pas de Calais Network**

Nouasse, Houda; Horv  th, Klaudia; Rajaoarisoa, Lala; Doniec, Arnaud; Duviella, Eric; Chuquet, Karine

DOI

[10.1016/j.trpro.2016.05.023](https://doi.org/10.1016/j.trpro.2016.05.023)

Publication date

2016

Document Version

Final published version

Published in

Transportation Research Procedia

Citation (APA)

Nouasse, H., Horv  th, K., Rajaoarisoa, L., Doniec, A., Duviella, E., & Chuquet, K. (2016). Study of Global Change Impacts on the Inland Navigation Management: Application on the Nord-Pas de Calais Network. *Transportation Research Procedia*, 14, 4-13. <https://doi.org/10.1016/j.trpro.2016.05.023>

Important note

To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

6th Transport Research Arena April 18-21, 2016



Study of global change impacts on the inland navigation management: application on the Nord-Pas de Calais network

Houda Nouasse ^{a,b}, Klaudia Horvath ^c, Lala Rajaoarisoa ^{a,b}, Arnaud Doniec ^{a,b},
Eric Duviella ^{a,b,*}, Karine Chuquet ^d

^aMines Douai, IA, F-59508 Douai, France

^bUniversité de Lille

^cDeltares - TU Delft, Faculty of Civil Engineering and Geosciences, Department of Water management Delft, The Netherlands

^dVoies Navigables de France, Service de la navigation du nord, Lille, France

Abstract

In a global change context, governments in Europe want to promote alternative transports as inland navigation or railway instead of road transport. As example, in north of France, a shift of 20% from road transport to these alternative transport solutions is expected by 2050. Reaching this goal requires not only the delivery of new infrastructures and equipment, but also the design of efficient management strategies. By focusing on waterborne transport, it is thus necessary to improve the management of the inland navigation networks particularly the water resource. Indeed, the waterborne transport accommodation is strongly linked to the available water resource. This will be a challenging point in a global change context.

The paper deals with the global change impacts on inland navigation networks. It aims at proposing new contributions as compared to past and current results of European projects on climate change and inland navigation. It appeared that the multi-scale modeling approach for inland navigation networks that was proposed during the last TRA Conference in Paris in 2014 is useful to determine the resilience of these networks and their ability to guarantee the navigation conditions during drought and flood periods. The proposed tools are developed to consider two space and time scales. The first approach is used to determine the water quantity that is necessary to accommodate the navigation during half a day, and the second allows the efficient control of the gates to keep the water level of each navigation reach close to its setpoint by rejecting disturbances and compensating the waves due to the lock operations. One example based on the real inland navigation network of the north of France is used to highlight the contributions of the multi-scale modeling approach.

* Corresponding author. Tel.: +0-000-000-0000 ; fax: +0-000-000-0000 .
E-mail address: eric.duviella@mines-douai.fr

© 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)

Keywords: Inland navigation network; global change; water management, transport

1. Introduction

The last report of the IPCC (*Intergovernmental Panel on Climate Change*) (IPCC, 2014) *confirms that human influence on the climate system is clear and growing*. Between 2000 and 2010, the increase of total annual anthropogenic GHG emissions came by 11% from transport. However, human have still the *means to limit climate change and its risks*. In the transport sector, *technical and behavioral mitigation measures could reduce final energy demand significantly below baseline levels*. Consistent with this report, a shift of 20% from road transport to alternative transport solutions is expected by 2050 in north of France¹. Indeed, inland navigation transport provides economic and environmental benefits (Mihic, 2011; Mallidis, 2012), with safer transport of goods (Brand, 2012).

Inland navigation development requires the delivery of new infrastructures following the Trans-European network program (TEN-T²), but also the design of adaptive management strategies. Hence, it is necessary to better understand the dynamics of the inland navigation networks and what could be the impacts of climate change. The report of the PIANC (Permanent International Association of Navigation Congresses) lists the main impacts of climate change on navigation by considering also water quality (EnviCom, 2008). An exhaustive state of the art of European project reports and an analysis of the climate change effects on inland waterway transport are proposed in (ECCONET, 2012). Also in this report, policy guidelines have been developed to adapt the management of inland navigation channels. By focalizing on water quantity the GEPET-Eau project³ aims at better understanding the impacts of climate change on inland navigation networks and at designing adaptive management strategies. To reach this objective multi scale modeling approaches and an adaptive and predictive control architecture have been proposed in (Duviella, 2014a). The first model consists in modeling the inland navigation network with a sample time of several hours. It is used to identify the main water intakes, the operating modes of the locks and gates, and finally the uncontrolled water supplies. Based on this model, a flow-based network is designed to represent the constraints on the flows and then to generate an optimization problem under constraints. Solving this problem allows determining volumes of water that are required for navigation on the horizon of several hours. These tools are used to design the *volume management* approach. Then according to these required water volumes, it is still necessary to control the gates with a sample time of several minutes to guarantee that setpoints are applied by rejecting disturbances. A first approach based on Model Predictive Control (MPC) with an Integral Delay Zero (IDZ) and Integral Resonance (IR) models have been designed respectively in (Horvath, 2014a) and in (Horvath, 2014b). More recently a MPC-IDZ is used to deal with several operating modes of a navigation reach in (Horvath, 2015). These tools are used to design the *discharge management* approach.

The main objective of this paper is to present the several management tools that have been developed in the framework of the GEPET-Eau project and to show their complementarities to study the impacts of global change on inland navigation networks. The paper is structured as the following: section 2 is dedicated to the *volume management* approach. The *discharge management* approach is presented in section 3. In section 4, a part of the inland navigation network in north of France is presented to highlight the advantages of the proposed approaches. Finally, the summary and perspectives of this contribution are given in section 5.

2. Volume management approach

Inland navigation networks cover large territories in Europe. They are composed with interconnected rivers, channels and canalized rivers. They are equipped with controlled locks and gates, and with sensor networks (water flow meters, water level meters). The managers of inland navigation networks have to guarantee all the conditions for navigation, *i.e.* the navigation rectangle (*see* Fig. 1). Hence, the water levels have to be close to the Normal

¹ https://www.nordpasdecals.fr/upload/docs/application/pdf/2014-09/schema_climat-web-170914.pdf

² <http://ec.europa.eu/transport/themes/infrastructure/ten-t-guidelines/index/en.html>

³ <https://gepeteau.wordpress.com/enversion/>

Navigation Level (NNL) and under two boundaries, *i.e.* High Navigation Level and Low Navigation Level. To keep the navigation conditions, it is necessary to control the supply of the networks by considering large scales of space and time. Indeed, it consists in dispatching the available water volumes on the network, *i.e.* to manage the volumes of water. To achieve this task, an integrated model of inland navigation is proposed firstly. Then, a flow-based network is design to represent the links between the rivers and channels and to compute the water flow capacities of these links. Finally, an optimization problem is finally proposed to determine the water volumes that are necessary to accommodate the navigation and how they are dispatched on the network.

2.1. Integrated model

The integrated model is built by considering elementary parts of inland navigation networks: the Navigation Reach (NR). A NR is defined as a part of a navigation river or channel between two locks. The decomposition of the network in elementary NR allows representing its configuration. Moreover, the equipment of the NR (gates and locks), the water intakes and the possible exchanges with groundwater or unknown water contributions can be represented.

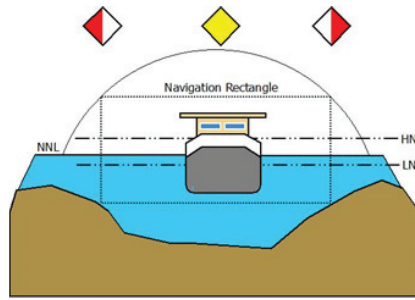


Fig. 1. Navigation rectangle with the NNL and the boundaries HNL and LNL.

Fig. 2.a presents a scheme of an inland navigation network composed of five NR, from NR_{i-2} to NR_{i+2} . The NR are connected themselves by locks. The corresponding integrated model is given in Fig. 2.b. Each NR_i is modeled as a tank with a dynamical volume $V_i(k)$ that has to be close to the volume objective V_i^{NNL} , where i is the index of the NR_i . This volume has to respect the constraint:

$$V_i^{LNL} \leq V_i(k) \leq V_i^{HNL} \quad (1)$$

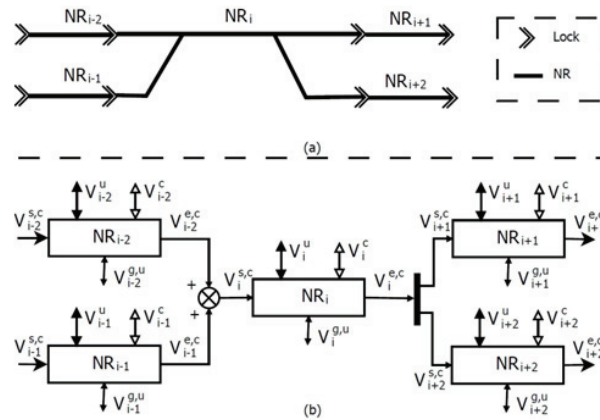


Fig. 2 (a) Inland navigation network, (b) corresponding integrated model.

The NR is supplied and emptied by:

- a set of controlled volumes that gather the water that is coming from controlled gates and from the lock operations:
 - controlled volumes from all the upstream NR that supply the NR_i , denoted $V_i^{s,c}$ (s: supply, c: controlled),
 - controlled volumes from the NR_i that empty it, denoted $V_i^{e,c}$ (e: empty),
 - controlled volumes from water intakes that can supply or empty the NR_i , denoted V_i^c . These volumes are signed; positive if the NR_i is supplied, negative otherwise.
- a set of uncontrolled volumes that correspond to the withdrawals and supplies from water intakes located along the NR_i , and also exchanges with groundwater when they are considered:
 - uncontrolled volumes from natural rivers, rainfall-runoff, Human uses, denoted V_i^u (u: uncontrolled). These volumes are signed depending of their contribution,
 - uncontrolled volumes from exchanges with groundwater, denoted $V_i^{g,u}$ (g: groundwater). These volumes are also signed.

Based on these water volumes, the volume $V_i(k)$ can be expressed as:

$$V_i(k) = V_i(k-1) + V_i^{s,c}(k) - V_i^{e,c}(k) + V_i^c(k) + V_i^u(k) + V_i^{g,u}(k) \quad (2)$$

with k the sample time.

This model aims at gathering information about identified controlled volumes and estimated uncontrolled volumes. This information is from the managers' knowledge.

2.2. Flow-based network

Network flow models have been proposed in the literature to solve problems of transportation (Silver, 2007; Jonkeren, 2011), optimization of drinking water networks (Grosso, 2014) and flood attenuation (Nouasse, 2013). A flow-based network is defined as a connected directed graph $G = (G_x, G_a, C)$, where G_x is the set of nodes, G_a is the set of arcs and C a set of dynamical attributes of the graph such as capacities or transit times. Each NR_i of the navigation network is representing by a node. The number of the node corresponds to the index of the NR_i , $i \in G_x$. Two additional nodes are also considered to represent the source O and sink N , $\{O, N\} \in G_x$. A directed arc between two nodes is defined as a couple $a = (i, j) \in G_a$, with i the node that is leaving and j the node that is entering. On every arc $a \in G_a$, it is associated a flow variable ϕ_a that can also be expressed by ϕ_{ij} . This flow has to respect capacities constraints $\{l_a, u_a\} \in C$, with l_a the lower and u_a the upper bound capacities of the arc a . Finally, on every node, it is associated the current volume $V_i(k)$ that has to respect the navigation constraints $\{V_i^{LNL}, V_i^{HNL}\} \in C$. The navigation network in Fig. 2 is used to illustrate the design of flow-based network that is showing in Fig. 3.

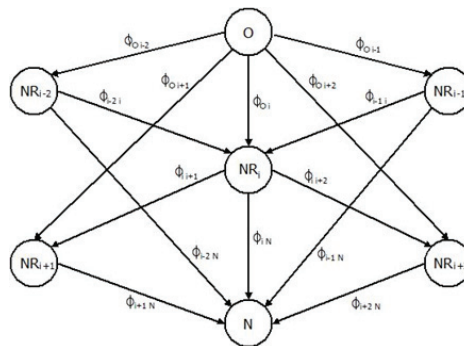


Fig. 3. Flow-based network model.

The nodes correspond to each NR, and the arcs are directed according to the configuration of the navigation network. The node O gathers all the volumes of water that supply the navigation network from upstream and natural rivers. The node N retrieves all the volumes of water from the navigation network. The capacities, i.e. $\{l_a, u_a\}$, are determined

according to the identified controlled volumes and the estimated uncontrolled volumes of the integrated model; the navigation constraints, *i.e.* $\{V_i^{LNL}, V_i^{HNL}\}$, according to the navigation rectangles.

2.3. Optimization problem under constraints

The navigation requires lock operations and therefore water consumption. In the same time, the water exchanges with natural rivers have to be limited and the volume of each NR has to be kept close to its objective value V_i^{NNL} . Thus, it is necessary to determine the flow exchanges between the NR for the navigation and for guaranteeing the navigation conditions. This objective is reached thanks to the solving of an optimization problem under constraints. It leads to the determination of the flow of each arc considering a management horizon T_M . Moreover, this approach allows considering drought and flood situations. It is just necessary to estimate the capacities and navigation constraints during these periods.

The condition linked to the objective value V_i^{NNL} of each NR can be expressed as a demand $d_i(k)$:

$$d_i(k) = \phi_{a^+} - \phi_{a^-} = V_i^{NNL} - V_i(k), \quad i \in G_x - \{O, N\} \quad (3)$$

with a^+ the arcs leaving the node i and a^- those entering, under the constraints:

$$V_i^{NNL} - V_i^{HNL} \leq d_i(k) \leq V_i^{NNL} - V_i^{LNL}, \quad i \in G_x - \{O, N\} \quad (4)$$

The capacities constraints $\{l_a, u_a\}$ are determined according to the integrated model. It is firstly necessary to define Ψ the set of the index of the upstream NR that are not supplied by another NR, and Ξ the set of the index of the downstream NR that not supply another NR. Considering the example in Fig. 2 and 3, $\Psi = \{i-2, i-1\}$ and $\Xi = \{i+1, i+2\}$, and the capacities constraints are:

- upper capacity for arcs between two NR, *i.e.* $\{(i-2, i), (i-1, i), (i, i+1), (i, i+2)\}$, between O and NR_j , $j \in \Psi$, *i.e.* $\{(O, i-2), (O, i-1)\}$, and between N and NR_l , $l \in \Xi$, *i.e.* $\{(i+1, N), (i+2, N)\}$, are computed as the sum of the maximum available water volumes from water intakes and the required water volumes for the navigation, *i.e.* $b \in \mathbb{N}$, the number of the required lock operations,
- upper capacity for arcs between O and NR_j , $j \notin \Psi$, *i.e.* $\{(O, i), (O, i+1), (O, i+2)\}$, correspond to the sum of the maximum available water volumes from water intakes,
- upper capacity for arcs between N and NR_j , $j \notin \Xi$, *i.e.* $\{(i-2, N), (i-1, N), (i, N)\}$, correspond to the sum of the maximum water volumes that can empty the NR,
- lower capacity for arcs between two NR, between O and NR_j , $j \in \Psi$, and between N and NR_l , $l \in \Xi$, are only the required water volumes for the $b \in \mathbb{N}$ lock operations,
- lower capacity for arcs between O and the NR_j , $j \notin \Psi$, and between N and NR_j , $j \notin \Xi$, are equal to 0.

Then, a constraint programming (CP) approach is proposed to determine the water volumes that are required. Constraint programming is a powerful tool to deal with difficult problems especially in areas of planning and scheduling. It combines the use of a natural and elegant declarative formulation of problem with effective solving algorithm (Dechter, 2003). The formulation in CP consists in constraint satisfaction problems (CSP), *i.e.* a set of variables taking their value in a finite domain and subject to a finite set of constraints. Solving a CSP requires to find for each variable a value in its domain which is consistent with all constraints (*i.e.* which does not violate any constraint of the problem).

For each period T_M , we formulate and solve a constraint satisfaction problem:

- variables are the ϕ_a , $a = (i, j) \in G_a$,
- each ϕ_a has a finite domain expressed as a discrete interval whose bound are calculated according to b ,
- these values are constrained by relations between entering and leaving flow on each node of G_x .

The following algorithm show how constraint programming is integrated to calculate the optimal flow, using *Choco Open Source Java* library (Jussien, 2008).

The *volume management* approach is based on these tools. It allows determining the water volumes that are required for navigation on a management horizon T_M by considering several scenarios (normal, drought and flood). Discharge setpoint on T_M of each gate of the inland navigation networks are then computed. However, determining these setpoint is not sufficient to keep the level of the NR close to the NNL. The water level of the NR is disturbed by lock operations and uncontrolled water intakes. Hence, it is necessary to control the water levels. It is the objective of the *discharge management* approach.

Volume management approach algorithm	
Input: b , Integrated Model, G Output: ϕ , d Local: CSP for $\phi_a, a \in G_a$ do compute l_a and u_a ; end $l_{max} = \max_{a \in G_a} l_a$; $\phi_a \leftarrow \frac{l_{max}}{l_a} l_{max}$;	for $\phi_a, a \in G_a$ do declare ϕ_a as variable of the CSP, with $[l_a; u_a]$ as domain; set $d_i(k) = \phi_{a^+} - \phi_{a^-}$, $i \in G_x - \{O, N\}$ as constraint of the CSP; set $V_i^{NNL} - V_i^{HNL} \leq d_i(k) \leq V_i^{NNL} - V_i^{LNL}$ as constraint of the CSP; end solve the CSP to obtain the value of the $\phi_a, a \in G_a$; return ϕ flow vector and d demand vector

3. Discharge management approach

A lock operation consists in emptying a lock chamber in order to allow ships to cross the lock. In general, several thousand of meter cubic are emptying in some minutes. That can lead to waves along the NR with sometimes resonance phenomenon. These waves according to their magnitude can disturb the navigation, because the water level can cross the boundaries of the navigation rectangle. Moreover water intakes or uncontrolled discharges can also disturb the navigation. Control algorithms have to be designed to keep the water levels close to their setpoint. Model Predictive Control approaches have been proposed in the literature for irrigation canals (Puig, 2009; wahli, 2004; van Overloop, 2010). In (Ocampo-Martinez, 2015), the MPC for navigation reach is dealt. In this paper, the MPC approach that is proposed in (Horvath, 2014a; Horvath, 2015), is used to perform the *discharge management* approach. The control algorithms lead to reduce the magnitudes of the waves and the impacts of disturbances. Thus, the risk that the water level crosses the boundaries of the navigation rectangle is reduced. Hence, navigation constraints, *i.e.* $\{V_i^{LNL}, V_i^{HNL}\}$, can be considered and the NR can be used as storage during flood periods and can be emptied during drought periods.

3.1. Navigation reach modeling

The proposed modeling approach consists in using the Integrator Delay Zero (IDZ) model (Litrico, 2004a). It is a linear model that captures the low and the high frequency behavior of a canal reach. On low frequencies, the water level of the NR is increasing like the dynamics of a tank. The integral value of the discharge can lead to the determination of the water increase. The value of the integrator is the reciprocal of the NR surface, *i.e.* the backwater area $A_s = BL$ that can be approximated by the product of the width B and the length L of the NR. The time that a wave travels from one end to the other end of the NR corresponds to the delay. The delay depends on the direction of the wave: from upstream,

$$\tau_u = \frac{L}{c-v} \quad (5)$$

from downstream,

$$\tau_d = \frac{L}{c+v} \quad (6)$$

with the velocity V and the celerity $C = \sqrt{gH}$, with g the acceleration of gravity and H the water level.

The fast response of a NR is clearly seen during lock operations. It is modeled by the zero which calculation can be found in (Litrico, 2004b).

The obtained transfer function is given by:

$$\frac{H(s)}{q(s)} = \frac{p_1 s + 1}{A_s s} e^{-\tau_s} \quad (7)$$

where q is the discharge, p_1 accounts for the zero and τ_s is selected according to the direction of the wave.

3.2. Model Predictive Control

Based on the discretization of the transfer function (7) at the sample time k , it is possible to transform the model to a minimal state-space model (for details see (Horvath, 2014a)):

$$\begin{cases} x(k+1) = Ax(k) + Bu(k) \\ y(k) = Cx(k) \end{cases} \quad (8)$$

with matrices $A \in \mathbb{R}^{n \times n}$, $B \in \mathbb{R}^{n \times m}$ and $C \in \mathbb{R}^{p \times n}$, n the number of states, m the number of inputs and p the number of measured variables, $x(k)$ the state variable, $u(k)$ the change of the discharge and $y(k)$ the water level error.

Then, the state variable is extended as $z(k) = [x^T(k), Q^d(k)]^T$ to be able to formulate constraints on the input discharges $Q^d(k)$. The obtained model is given by:

$$\begin{cases} z(k+1) = \hat{A}z(k) + \hat{B}u(k) \\ e(k) = \hat{C}z(k) \end{cases} \quad (9)$$

with

$$\hat{A} = \begin{bmatrix} A & 0 \\ 0 & I_m \end{bmatrix}, \hat{B} = \begin{bmatrix} B \\ I_m \end{bmatrix}, \hat{C} = [C \quad 0] \quad (10)$$

where $I_m \in \mathbb{R}^{m \times m}$ is the identity matrix.

The proposed control approach is expressed as a quadratic programming problem. It consists in minimizing the following objective function on the future control horizon λ :

$$\min_{u=(u(k|k), u(k+1|k), \dots, u(k+\lambda-1|k)) \in \mathbb{R}^{m\lambda}} J(z, u) = \sum_{j=1}^{\lambda} z(k+j|k)^T P z(k+j|k) + \sum_{j=0}^{\lambda-1} u(k+j|k)^T R u(k+j|k) \quad (11)$$

with $z(k|k) = z$ and $\forall j = 1, \dots, \lambda$:

$$z(k+j+1|k) = \hat{A}z(k+j|k) + \hat{B}u(k+j|k),$$

$$e(k+j|k) = \hat{C}z(k+j|k),$$

subjected to the following constraints:

$$z_{\min} \leq z(k+j|k) \leq z_{\max},$$

where P and R are weighing matrices, z_{\min} and z_{\max} the boundaries of the variable z .

4. Inland navigation network in the north of France



Fig. 4. Inland navigation network in the north of France with the studied NR.

4.1. Description

The inland navigation network in the north of France is managed by Voies Navigables de France (VNF). It allows the navigation from north of Paris to Belgium and the Netherlands. It is composed of more than fifty NR connected by locks and gates. The main objective of VNF is to gather all the conditions for the navigation, *i.e.* control the water levels to be close to the NNL. To illustrate the proposed management approaches by keeping clarity on the obtained results, a short part of this network is considered: the NR_2 called Cuinchy-Fontinettes and the NR_1 upstream between the towns of Douai and Cuinchy (*see* Fig. 4). The Cuinchy-Fontinettes reach is very well known because its dynamics has been studied since several years. It is also very well equipped with flow and level meters. It is particularly interesting because it is subjected to strong wave phenomena during lock operations. Moreover, it can be used to dispatch water volumes between several rivers or navigation paths.

4.2. Volume management

A schematic view of the studied system is given in Fig. 5.a. The NR_1 is supplied by operations of the lock L_1 ; NR_2 by the lock L_2 . The gate G_1 is controlled to supply the NR_2 . The water volume from NR_1 to NR_2 is equal to the sum of volumes from the L_2 and G_1 . The lock L_4 and the gate G_3 are considered as a global reserved water volume. The NR_2 is emptied by the lock L_3 . It can be supplied or emptied by the gate G_2 .

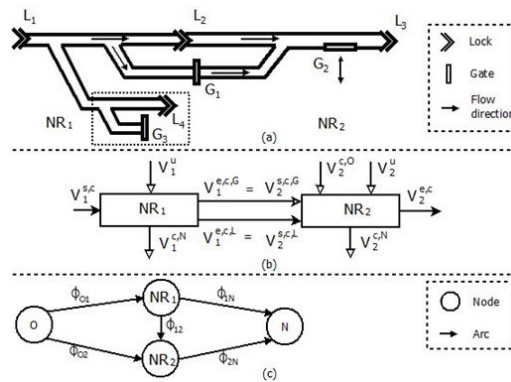


Fig. 5 (a) Inland navigation network composed of 2 NR, (b) integrated model, (c) flow graph.

The integrated model of the system is given in Fig. 5.b. The characteristics of the NR are given in Table 1, with volumes from gate $V_i^{s,c,g}$ and from lock $V_i^{s,c,l}$. Exchange with groundwater is not considered. The corresponding flow graph is depicted in Fig. 5.c. The constraints of the flow graph are determined thanks to these data:

$$\begin{aligned} -\phi_{O1} &= [9T_M; 9T_M + 5b_1], & -\phi_{O2} &= [2.7T_M; 2.7T_M + 25.2T_M], & -\phi_{12} &= [3.7b_2; 3.7b_2 + 36T_M], \\ -\phi_{1N} &= 5b_4 + 0.9TM, & -\phi_{2N} &= [25b_3; 25b_3 + 25.2T_M]. \end{aligned}$$

Table 1. Characteristics of the NR, with volumes in thousand of m³, TM in hour, volumes as $V_i^{s,c,g}$ computed according to available discharges that are expressed in m³/h, bj the operation number of lock Lj.

NR	V_i^{NNL}	$[V_i^{LNL}, V_i^{HNL}]$	$V_i^{s,c,L}$	$V_i^{e,c,L}$	$V_i^{s,c,G}$	$V_i^{c,O}$	$V_i^{c,N}$	V_i^u	$V_i^{g,u}$
NR_1	11,250	[10,750;12,000]	$5b_1$	$3.7b_2$	X	X	$5b_4 + 0.9T_M$	$9T_M$	X
NR_2	8,946	[8,526;9576]	$3.7b_2$	$25b_3$	$[0;36T_M]$	$[0;25.2T_M]$	$[0;25.2T_M]$	$2.7T_M$	X

The first scenario consists in two periods of $T_M = 12$ hours; one during night, *i.e.* $b_j = 0$, one during days with $b_1 = 50$, $b_2 = b_3 = 10$ and $b_4 = 40$, in a normal situation. During night, flows between NR are depicted in Fig. 6.a. NR_1 and NR_2 are supplied with $48,600 \text{ m}^3$. This volume is used during the day for navigation as it is shown in Fig. 6.b.

The same conditions are kept in the second scenario considering a drought situation. The available resource from water intakes are reduced to 25% as it is expected by the project Explore2070⁴: $\phi_{O1}=[6.75T_M; 6.75T_M+5b_1]$ and $\phi_{O2}=[2T_M; 2T_M+18.9T_M]$. Fig 6.c shows flows between NR during night with an increase of water volume in NR_1 and NR_2 of 35,100 m^3 . During day, flows are depicted in Fig 6.d. Thus, NR_2 has to be supplied by water intake (59.6 instead of 24), that corresponds to a mean discharge at G_2 of 0.82 m^3/s . The discharge of gate G_1 has to be tune to 2.78 m^3/s . According to these setpoints, the discharge management aims at rejecting disturbances.

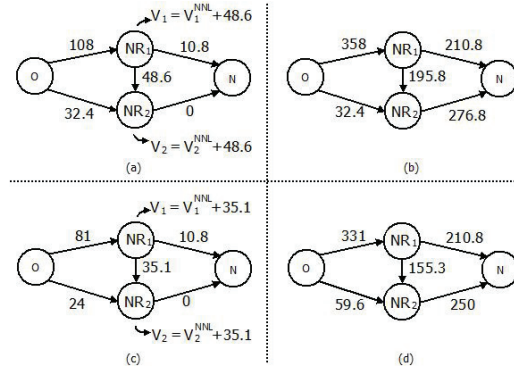


Fig. 6 (a) flows exchanges in normal situation (a) during night, (b) during day, in drought situation (c) during night, (d) during day.

4.3. Discharge management

NR_2 is used to highlight the performances of the designed MPC by considering the drought scenario. During navigation schedules, this NR is strongly disturbed by L_3 lock operations (see Fig. 7.a) that can lead to resonance phenomenon with waves of magnitude close to 20 cm. The MPC is tuned considering the characteristics of NR_2 (for details, see Horvath, 2014a). It allows reducing the magnitude of the waves guaranteeing the navigation conditions. The water levels of NR_2 are keeping close to V_2^{NHL} as it is show in Fig. 7.b, even if during night (first 12th hours) levels are increasing. The designed MPC leads to discharges that are in average close to the decided setpoint 2.78 m^3/s for G_1 and 0.82 m^3/s for G_2 (see Fig. 7.c). It allows following the decisions coming from the volume management layer.

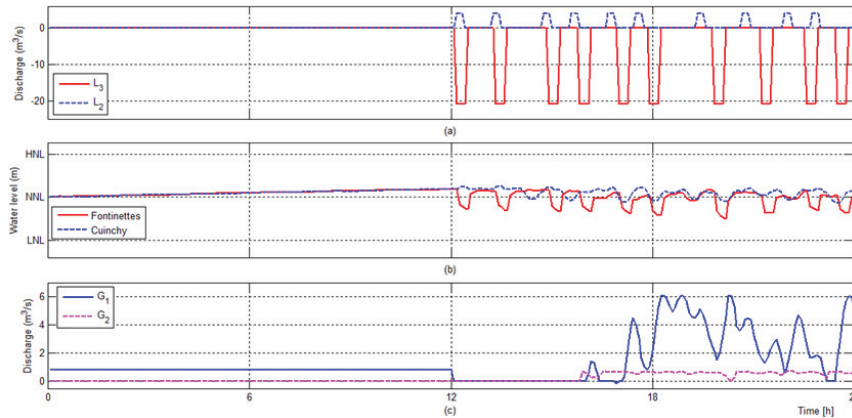


Fig. 7 (a) Discharges due to the lock operations, (b) water levels in the NR_2 , (c) controlled discharges G_1 and G_2 .

⁴ <http://www.developpement-durable.gouv.fr/Evaluation-des-strategies-d.html>

5. Conclusion

The paper presents the tools that are developed to design adaptive management strategies dealing with global change impacts. These tools are gathering in a management strategy architecture allowing the modeling and the water resource control considering two space and time scales. They can be viewed as two management strategy layers. The first one is used to dispatch the water volume on the networks to supply it with enough water during drought periods, and emptying it during flood periods. The second consists in controlling the gates to control the water levels of each navigation reaches in order to guaranty the navigation conditions. The designed tools have been tested considering the central part of the inland navigation network in the north of France. It highlights the contributions of this multi-scale management approach. Future works will consist in considering large part of this inland navigation network.

Acknowledgements

This work is a contribution to the GEPET-Eau project which is granted by the French ministry MEDDE - GICC, the French institution ORNERC and the DGITM. <https://gepeteau.wordpress.com/enversion/>

References

- Brand C., M. Tran and J. Anable, 2012. The UK transport carbon model: An integrated life cycle apppp.roach to explore low carbon futures, *Energy Policy*, Volume 41, pppp.. 107-124.
- Dechter R., 2003. Constraint processing, Morgan Kaufmann.
- Duviella E., K. Horváth, L. Rajaoarisoa and K. Chuquet, 2014a. Multi-scale modeling apppp.roaches of inland navigation networks for their management in a global change context, *Transport Research Arena*, Paris La Défense, France.
- ECCONET, 2012. Effects of climate change on the inland waterway networks. Final report.
- EnviCom - Task Group 3, 2008. Climate Change and Navigation -Waterborne transport, ports and waterways: A review of climate change drivers, impacts, responses and mitigation. *EnviCom TG 3 issue*.
- Grosso J.M., C. Ocampo-Martínez, V. Puig and B. Joseph, 2014. Chance-constrained model predictive control for drinking water networks, *Journal of Process Control*, Volume 24, Issue 5, pppp. 504-516.
- Horváth K., E. Duviella, L. Rajaoarisoa, R. Negenborn and K. Chuquet, 2015. Improvement of the navigation conditions using a Model Predictive Control - The Cuinchy-Fontinettes case study, *International Conference on Computational Logistics*, Delft, The Netherlands.
- Horváth K., E. Duviella, M. Petreczky, L. Rajaoarisoa and K. Chuquet, 2014b. Model predictive control of water levels in a navigation canal affected by resonance waves, *HIC*, New York, USA.
- Horváth K., M. Petreczky, L. Rajaoarisoa, E. Duviella and K. Chuquet, 2014a. MPC of water level in a navigation canal - The Cuinchy-Fontinettes case study, *European Control Conference*, Strasbourg, France.
- IPCC, 2014. *Climate Change 2014. The Core Writing Team*, R. K. Pachauri and L. Meyer, Synthesis Report, https://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full.pdf.
- Jonkeren O., B. Jourquin and P. Rietveld, 2011. Modal-split effects of climate change: The effect of low water levels on the competitive position of inland waterway transport in the river Rhine area, *Transportation Research Part A: Policy and Practice*, Volume 45, Issue 10, pppp. 1007-1019.
- Jussien N., G. Rochart and X. Lorca, 2008. Choco: an Open Source Java Constraint Programming Library. *CPAIOR'08 Workshop on Open-Source Software for Integer and Constraint Programming (OSSICP'08)*.
- Litrico X. and V. Fromion, 2004a. Frequency modeling of open-channel flow, *Journal of hydraulic engineering*, Volume 130, Issue 8, pppp. 806-815.
- Litrico X. and V. Fromion, 2004b. Simplified modeling of irrigation canals for controller design, *Journal of Irrigation and Drainage Engineering*, Volume 130, Issue 5, pppp. 373-383.
- Mallidis I., R. Dekker and D. Vlachos, 2012. The impact of greening on supppp.ly chain design and cost: a case for a developing region, *Journal of Transport Geography*, Volume 22, pppp. 118-128.
- Mihic S., M. Golusin and M. Mihajlovic, 2011. Policy and promotion of sustainable inland waterway transport in Europe - Danube River, *Renewable and Sustainable Energy Reviews*, Volume 15, Issue 4, pppp. 1801-1809.
- Nouasse H., P. Chiron and B. Archimède, 2013. A flood lamination strategy based on transportation network with time delay, *Water Science Technology*, Volume 68, Issue 8, pppp. 1668-1696.
- Ocampo-Martínez C. and R.R. Negenborn, 2015. *Transport of Water versus Transport over Water*, Springer International Publishing, isbn 978-3-319-16132-7.
- Puig V., J. Romera, J. Quevedo, C. M. Cardona, A. Salterain, E. Ayesa, I. Irizar, A. Castro, M. Lujan, P. Charbonnaud, P. Chiron and J.-L. Trouvat, 2009. Optimal predictive control of water transport systems: Arret-Darre/Arros case study, *Water Science and Technology*, Volume 60, Issue 8, pppp. 2125-2133.
- Silver M. and O. de Weck, 2007. Time-expanded decision networks: A framework for designing evolvable complex systems, *Systems Engineering*, Volume 10, Issue 2, pppp. 167-188.
- van Overloop, P.-J., A. Clemmens, R. Strand, R. Wagemaker and E. Bautista, 2010. Real-time implementation of model predictive control on Maricopa-Stanfield Irrigation and Drainage District's WM Canal, *Journal of Irrigation and Drainage Engineering*, Volume 136, Issue 11, pppp. 747-756.
- Wahlin, B. T., 2004. Performance of model predictive control on ASCE test canal 1, *Journal of Irrigation and Drainage Engineering*, Volume 130, Issue 3, pppp. 227-238.