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# Constraint satisfaction problem based on flow graph to study the resilience of inland navigation networks in a climate change context<sup>\*</sup>

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**Abstract:** The T-Ten European program aims at optimizing the transport logistics in Europe by promoting alternative transport modes. Navigation transport offers a competitive and environmentally friendly alternative. Hence, it is foresaw an increase of the navigation transport demand that it will be necessary to accommodate. This will be very challenging particularly in a global change context where less available water resource is expected. A constraint satisfaction problem based on flow graph is proposed in this paper to study the resilience of inland navigation networks against increase of the navigation demand and extreme events. Drought and flood scenarios are simulated considering an network composed of five interconnected navigation reaches. The results show that the designed tools are well adapted to the resilience study of inland navigation networks.

**Keywords:** Resilience, Constraint satisfaction problems, Graphs, Navigation networks, Water management, Global change.

## 1. INTRODUCTION

Inland navigation transport is part of the multimodal transport that is promoted by the Trans-European network program (TEN-T<sup>1</sup>). This program aims at developing new transport infrastructure policy to close the gaps between Member States' transport networks and to guaranty seamless transport chains for passenger and freight. To well integrating the inland navigation transport in this framework, an efficient water management strategy is required. It consists in guaranteeing the navigation conditions even if an increase of navigation demand and extreme events due to climate change is expected Bates et al. (2008). The intergovernmental panels as the IPCC (*Intergovernmental Panel on Climate Change*) has defined RCP scenarios (*Representative Concentration Pathways*) on which future forecasts on temperature and rain can be generated IPCC (2014). Based on these scenarios, the flood and drought events will be more frequent and mode intensive in close future Boé et al. (2009); Ducharne et al. (2010); Wanders and Wada (2015); Li et al. (2015); Park et al. (2015). Thus, constraints on water resource management for navigation will be bigger.

To deal with the navigation demand increase and the climate change effects, adaptive water management strategies have to be designed. An adaptive and predictive control architecture was proposed in Duviella et al. (2013). It is based on the multi-scale modeling approach proposed in Duviella et al. (2014) to

reproduce the dynamics of inland navigation networks during flood and drought events. This architecture is improved in this paper to consider events that can impact large areas on larger periods. It consists in dispatching volumes of water through the network to guarantee enough water in each part of the network. Thus, the designed tools aim at determining the resilience of the inland navigation networks. They are based on an integrated model of inland navigation network that allows locating the navigation reaches, the locks and gates and identifying the main water intakes. Then a flow graph is proposed to determine the possible paths between the navigation reaches and the main constraints on water volume exchanges. Network flow problems have been widely used for the computation of maximum flow or minimum cost flow in several areas such as transportation Silver and de Weck (2007), telecommunication Fekete et al. (2008), job scheduling or flood attenuation Nouasse et al. (2013). Finally, a constraint satisfaction problem is defined to determine the water volumes that have to be exchanged between each navigation reach. Mathematical programming in general Passchyn et al. (2016) and constraint satisfaction in particular Sun et al. (2014) is a major tool to address the problems of transport.

The management objectives of waterways are given in Section 2. Section 3 allows formulating the problem of this management during drought and flood periods. The integrated model is detailed. Then, the constraint satisfaction problem is proposed. All the designed tools allows considering inland navigation networks that are composed of several confluents and diffluents. In Section 4, an academical example of inland navigation networks composed of five interconnected navigation reaches is considered. Its characteristics have been determined

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<sup>1</sup> [http://ec.europa.eu/transport/themes/infrastructure/ten-t-guidelines/index\\_en.htm](http://ec.europa.eu/transport/themes/infrastructure/ten-t-guidelines/index_en.htm)

considering real navigation networks. This case study allows detailing the design step of the proposed tools. Finally, drought and flood events are simulated to highlight the performances of the designed tools.

## 2. WATERWAYS MANAGEMENT

Waterways are equipped and opened to passenger transport, cargo and boating. Their different uses have an economic benefit Mihic et al. (2011); Mallidis et al. (2012); Brand et al. (2012). It is observed that inland navigation network is constituted by a number of hydraulic structures, including locks. A part of an inland navigation network between two locks is defined as a Navigation Reach (NR). It is assumed that in general navigation requirements are the same for each NR. Navigation is maintained in a reach respecting the so called navigation rectangle. The boundaries of the navigation rectangle are the High Navigation Level (HNL) and the Low Navigation Level (LNL). The main management objective consists in keeping the water level in each NR is inside the navigation rectangle and close to the Normal Navigation Level (NNL). The waterways have to be supplied with natural rivers. Climate change impacts severely on the availability of water resources, more accurately during floods and drought. Flood periods are as problematic as droughts. For example, in extreme climate scenarios natural water reserves may reach their ecological limits in the absence of management of excess volumes of water. This case represents a deficit situation in water resources during drought. Thus, the resilience study of inland navigation networks is necessary. We can assume that the resilience study is an approach based on the fact to propose a set or rather a system of rules for maintaining “the proper” functioning or sometimes simply the functioning of an inland navigation network. The main objective would be to adapt to extreme conditions such as floods or drought. The needs of each of these situations are unlike those of the other that is why we need to establish a stable and adaptive resilience “system” (as we suppose that is a system of rules). Stable in the sense to resist change and adaptive in the sense of accompanying that change. When one fails to offer a solution, the system does not fail but reveals its limits (it can also be considered a form of adaptation). An understanding of the functioning and needs of each component of the network, in particular NR, is an important step in determining strategies that will be adapted on a microscopic level to each of them and on a macroscopic point of view to their interaction with the entire network and climate change. To address this issue, authors in Duviella et al. (2013) proposed an adaptive and predictive control architecture.

## 3. PROBLEM MODELING

### 3.1 Inland navigation reach model

The integrated model is proposed to model several configurations of inland navigation networks by considering two elementary configurations: a confluence and a diffidence (see Figure 1.a). Networks are composed with a finite number  $\eta$  of interconnected NR. NR are numbered and denoted  $NR_i$ , with  $i \in 1$  to  $\eta$ . The  $NR_i$  is modeled as a tank that contains a volume of water, denoted  $V_i(t)$ . According to the boundaries of the navigation rectangle, to the NNL and to the geometrical characteristics of each  $NR_i$ , it is possible to determine the volumes that corresponds to the NNL, the HNL and the LNL

such as  $V_i^{LNL} \leq V_i^{NNL} \leq V_i^{HNL}$ . The management objective is  $V_i(t) = V_i^{NNL}$  and at least  $V_i^{LNL} \leq V_i(t) \leq V_i^{HNL}$ . If this condition is broken, the navigation has to stop.

A  $NR_i$  is supplied and is emptied by controlled and uncontrolled water volumes (see Figure 1.b). Controlled water volumes gather the water that is coming from controlled gates and from the lock operations. Uncontrolled water volumes are all the withdrawals and supplies from water intakes located along the  $NR_i$ . It is also possible to consider the water exchanges with groundwater.

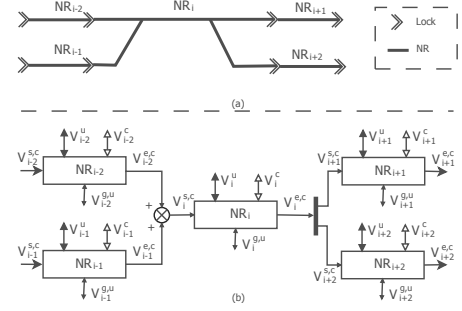


Fig. 1. (a) Inland navigation network, (b) its integrated model.

Thus, the set of controlled water volumes is composed of:

- controlled volumes from 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 the  $NR_i$ , 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.

The set of uncontrolled water volumes is composed of:

- uncontrolled volumes from natural rivers, rainfall-runoff, Human uses, denoted  $V_i^u$  ( $u$ : uncontrolled). These volumes are signed depending of their contribution to the volume  $V_i(t)$  in the  $NR_i$ .
- uncontrolled volumes from exchanges with groundwater, denoted  $V_i^{g,u}$  ( $g$ : groundwater). These volumes are also signed.

Based on the definition of the water volumes that contribute to the volume contained in the  $NR_i$ , it is possible to model its dynamics by:

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

The dynamics of the  $NR_i$  have to take into account the configuration of the network. For a confluence, the controlled volumes coming from all the NR that are located upstream the  $NR_i$  are added. For a diffidence, the controlled volumes that empty the  $NR_i$  correspond to the sum of the controlled volumes that supply the downstream NR (see relation (2)).

$$\begin{cases} V_i^{s,c}(t) = \sum_{j \in \Omega_i} V_j^{e,c}(t), \\ V_i^{e,c}(t) = \sum_{j \in \Theta_i} V_j^{s,c}(t), \end{cases} \quad (2)$$

where  $\Omega_i$  gathers all the index of the NR that supply the  $NR_i$ , and  $\Theta_i$  all the index of the NR that are supplied by the  $NR_i$ .

The proposed integrated model requires the knowledge of all the possible water volume contributions. It is necessary to identify all the controlled volumes and to estimate all the uncontrolled volumes. This knowledge comes from the waterways managers.

In this paper, we propose to set some assumptions. Water exchanges with groundwater are nonexistent. The controlled water volumes  $V_i^c$  from water intakes are bounded with the known minimal and maximal daily volumes of water. The water volume that corresponds to each lock operation is known. Finally, the daily average number of ships that cross the inland navigation network is known.

### 3.2 Flow-based network modeling

We choose in the following to model inland navigation network as a graph. The answers related to questions about the specific requirements for operating a navigation system are made by considering a flow problem on this graph. The volume management in such a network is guaranteed by satisfying the constraints formulated for this problem.

Let consider a network,  $\mathcal{G} = (\mathcal{G}_x; \mathcal{G}_a)$ , defined as a connected Directed Acyclic Graph (DAG), where  $\mathcal{G}_x$  is the set of nodes and  $\mathcal{G}_a$  is the set of arcs. The set of nodes  $\mathcal{G}_x$  contains the nodes representing each reach in the navigation network  $NR_i$  and two additional nodes,  $O$  and  $N$ , respectively source and sink. We denote each directed arc  $a = (NR_i, NR_j)$  with nodes corresponding to navigation reaches, such as  $NR_i$  is the leaving node (the tail of arc  $a$ ) and  $NR_j$  is the entering node (the head of arc  $a$ ). To simplify notations, we will consider that nodes are labeled with the index of each NR, i.e.  $a = (NR_i, NR_j) = (i, j)$  or  $a = (O, NR_j) = (O, j)$ . As mentioned in (3.1), the link between two adjacent reaches NR represents a water volume amount. Thus, we consider an  $s$ - $t$  flow routing (source-to-sink flow) in the network described by the water volume path between different reaches. Figure 2 shows an example of a flow network model by considering the navigation network proposed in Figure 1. The arcs are directed according to the configuration of the navigation network. According to the proposed assumptions, the node  $O$  gathers all the volumes of water that supply the navigation network from natural rivers. The node  $N$  retrieves all the volumes of water from the navigation network. On every arc in  $\mathcal{G}_a$ , it is defined a flow variable  $\phi_a$ ,  $a \in \mathcal{G}_a$  that can be expressed by  $\phi_{ij}$ . This flow varies with respect to capacities constraints and demands relation on each node.

One step in the management of water volumes in the inland navigation network is, for example, if one refers to this network  $\mathcal{G}$ , to determine the flow that guaranties different navigation scenarios for a given period of time. That can be formulated as follows:

$$\text{Maximize } \phi \quad (3)$$

subject to

$$\begin{cases} l_a \leq \phi_a \leq u_a & \text{for } a \in \mathcal{G}_a \\ \Phi \geq 0 \end{cases} \quad (4)$$

by considering these additional constraints

$$\phi_{a^+} - \phi_a = d(i) \text{ for } i \in \mathcal{G}_x - \{O, N\}, \quad (5)$$

This constraints allows flow on a given node  $i$ , not to be conservative. In order to respect the navigation conditions on

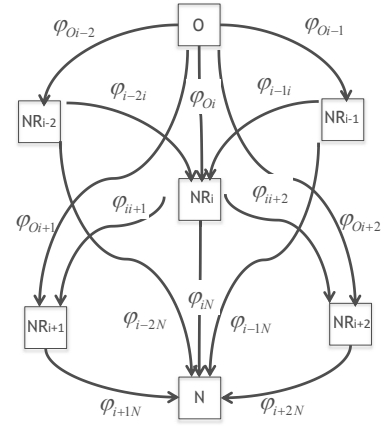


Fig. 2. Flow Network Model.

each reach  $NR_i$ , the demand of water volumes on each node representing a NR is defined as:

$$d(i) = V_i^{NNL} - V_i(t), \quad i \in \mathcal{G}_x - \{O, N\} \quad (6)$$

that must verify the following relation:

$$V_i^{NNL} - V_i^{HNL} \leq d(i) \leq V_i^{NNL} - V_i^{LNL} \quad i \in \mathcal{G}_x - \{O, N\} \quad (7)$$

where  $\Phi$  is a vector that contains all the flow  $\phi_a$ ,  $l_a$  and  $u_a$  the lower and upper bound capacities of the arc  $a$ ,  $a^+$  the arcs leaving the node  $i$  and  $a^-$ , the arcs entering the node  $i$ , and  $d(i)$  the demand of the node  $i$ . We also assume that  $\phi_{a^+}(O) = d(O)$  and  $\phi_a(N) = -d(O)$  as  $d(O)$  is the known supply on the source node.

The design of the integrated model (see Figure 1.b) helps to build the flow network and to determine the capacities that are expressed in volume. The lower and upper bound capacities of the arc  $a$ , i.e.  $l_a$  and  $u_a$ , depend on the configuration and equipment of the inland navigation networks. Hence, we define  $\Psi$  the set of the index of the upstream NR that are not supplied by another NR, and  $\Xi$  the set of the index of the downstream NR that not supply another NR. By considering example in Figures 1 and 2, these sets are  $\Psi = \{i-2, i-1\}$ , and  $\Xi = \{i+1, i+2\}$ . Thus:

- upper bound capacities for arcs between two NR, i.e.  $\{(i-2, i), (i-1, i), (i, i+1), (i, i+2)\}$  in Figure 2, are computed as the sum of the maximum available controlled water volumes ( $V_i^{s,c}$ ),
- lower bound capacities for arcs between two NR, are only the required water volumes for the navigation ( $V_i^{s,c}$ ), depending on the  $b \in \mathbb{N}$  the number of ships that cross each NR,
- upper bound capacities for arcs between  $O$  and  $NR_j$ ,  $j \in \Psi$ , i.e.  $\{(O, i-2), (O, i-1)\}$ , are computed as the sum of the maximum available controlled water volumes ( $V_i^{s,c}$ ), the maximum available water volumes from water intakes (maximum positive  $V_i^c$ ) and the positive uncontrolled water volumes ( $V_i^u$ ),
- lower bound capacities for arcs between  $O$  and  $NR_j$ ,  $j \in \Psi$ , are the sum of the required water volumes for the navigation ( $V_i^{s,c}$ ) and the positive uncontrolled water volumes ( $V_i^u$ ),
- upper bound capacities 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 (maximum positive  $V_i^c$ ) and the positive uncontrolled water volumes ( $V_i^u$ ),

- lower bound capacities for arcs between  $O$  and  $NR_j$ ,  $j \notin \Psi$ , are only the positive uncontrolled water volumes ( $V_i^u$ ),
- upper bound capacities for arcs between  $NR_j$ ,  $j \notin \Xi$ , and  $N$ , i.e.  $\{(i-2, N), (i-1, N), (i, N)\}$ , correspond to the sum of the maximum water volumes that can empty the  $NR$  (minimum negative  $V_i^c$ ) and the negative uncontrolled water volumes ( $V_i^u$ ),
- lower bound capacities for arcs between  $NR_j$ ,  $j \notin \Xi$ , and  $N$ , are only the negative uncontrolled water volumes ( $V_i^u$ ),
- upper bound capacities for arcs between  $N$  and the  $NR_l$ ,  $l \in \Xi$ , i.e.  $\{(i+1, N), (i+2, N)\}$ , are the sum of the maximum available controlled water volumes ( $V_i^{e,c}$ ), the maximum water volumes that can empty the  $NR$  (minimum negative  $V_i^c$ ) and the negative uncontrolled water volumes ( $V_i^u$ ),
- lower bound capacities for arcs between  $N$  and the  $NR_l$ ,  $l \in \Xi$ , are the sum of the required water volumes for the navigation ( $V_i^{e,c}$ ) and the negative uncontrolled water volumes ( $V_i^u$ ).

### 3.3 CSP & Relaxation

In the following, we propose a CSP approach to determine the resilience of our system in the flow network  $\mathcal{G}$ . Indeed, by definition CSP allows to evaluate in a finite domain a number of possible solutions. Unlike classical methods of solving a flow problem where the solution consists of finding a *s-t* flow augmenting path, CSP solving is based on search algorithms that aim on domain exploration for values of consistent variables. For example one may want to “augment” the water volume between two reaches but in that case we can not maximize flow between these two reaches so the arc connecting them is excluded from the optimal path. While in a CSP perspective, we will try to “best” satisfy this constraint of water volume required between the two reaches and if it is not satisfied it will be considered as an event to address in our resilience study. Hence, the approach we consider, for volume management in the navigation network, is to first solve a constraint satisfaction problem that can check as a priority that the level of water in the reaches is as close as possible to the NNL, and releases and river inputs are near zero. Such a problem is over-constrained and given the conflictual aspect of the problem: in order to maintain the water level around the NNL between two reaches while one may be a reach water lack while the other is in surplus of water; we then need to consider more flexible constraints such tolerating releases and river inputs. Which generally comes back to consider a Max-CSP problem Dechter (2003) when it comes to satisfy a maximum number of constraints. Starting from an over-constrained problem we relax to ensure the satisfaction of new and more permissive constraints. In this formulation as variables, we have:

- $\phi_a$ , flow variable on each arc  $a \in \mathcal{G}_a$ , the domain  $D(\phi_a)$  of  $\phi_a$  expressed as a discrete interval whose bounds are calculated according to the number of ships  $b$ .
- $d(i)$  demand variable for every reach  $i$  in the network. The domain  $D(d(i))$  is set according to navigation conditions (see 3.2).

In addition to flow conservation constraint on each node, we consider that the two following constraints are possible:

$$|\phi_a - \min(D(\phi_a))| = 0, \quad (8)$$

when  $a \in \{(i-2, N), (i-1, N), (i, N)\}$  and

$a \in \{(O, i), (O, i+1), (O, i+2)\}$ . With  $\min(D)$  and  $\max(D)$  respectively the minimal and maximal values of variables domain. This constraint helps reduce the relative contributions to releases or external resources compared to the ensembles of contributions.

$$|d(i) - V_i^{NNL}| = 0, \quad i \in \mathcal{G}_x - \{O, N\} \quad (9)$$

This constraint helps to keep water volume on each reach around NNL. We consider a relaxation of the problem in order to enlarge the set of solutions. For this, during the resolution, the constraints above (8) and (9) will be relaxed one after the other which comes in some way to progressively identify the responsible arcs of problem infeasibility.

$$\left| \sum_a \phi_a - \sum_a \max(D(\phi_a)) \right| = 0, \quad (10)$$

$a \in \{(i-2, N), (i-1, N), (i, N)\}$  and

$a \in \{(O, i), (O, i+1), (O, i+2)\}$

$$\left| \sum_i d(i) - z \right| = 0, \quad i \in \mathcal{G}_x - \{O, N\} \quad (11)$$

such as,

$$\sum_i \min(D(d(i))) \leq z \leq \sum_i \max(D(d(i))), \quad (12)$$

The following algorithm show how constraint programming is integrated to calculate the maximum flow.

```

input :  $b$ , Integrated Model,  $\mathcal{G}$ 
output:  $\Phi, d$ 
local : CSP

for  $\phi_a, a \in \mathcal{G}_a$  do
  | compute  $l_a$  and  $u_a$ ;
end

for  $\phi_a, a \in \mathcal{G}_a$  do
  | add  $\phi_a$  as variable of the CSP, with  $[l_a; u_a]$  as domain;
  | add  $d(i)$  as variable of the CSP, with  $[V_i^{LNL}; V_i^{HNL}]$  as domain;
  | add  $d(i) = \phi_{a+} - \phi_a$ ,  $i \in \mathcal{G}_x - \{O, N\}$  as constraint of the CSP;
  | add constraints (8) and (9);
end

solve the CSP to obtain the value of the  $\phi_a, a \in \mathcal{G}_a$ ;

if No solution then
  | remove (8) from problem constraints set;
  | add (10) as constraint of the CSP;
  | solve the new CSP;
  if No solution then
    | remove (9) and (10) from problem constraints set;
    | add  $z$  as variable such as (12);
    | add (11) as constraint of the CSP;
    | solve the new CSP;
end

return  $\Phi, d$ 

```

## 4. SIMULATION RESULTS

We apply our method on a network model composed of five reaches respecting the configuration described in Figure 3.a. This configuration is characterized by the presence of a junction reach. Each reach is supplied with a daily volume  $V_i^{s,c}$ . For example,  $NR_1$  is supplied by operations of the lock  $L_1$  with a

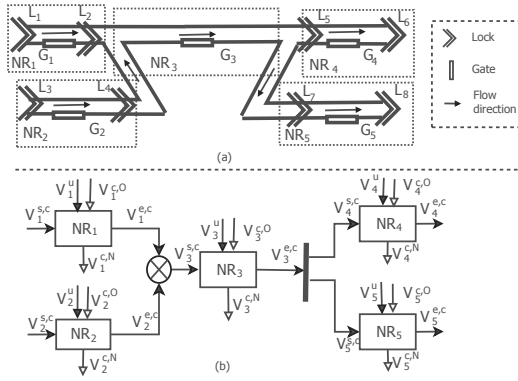


Fig. 3. (a) Inland navigation network composed of 5 NRs, (b) its integrated model.

daily volume  $V_1^{s,c,L}$ , and by the gate  $G_1$  with a daily volume  $V_1^{s,c,G}$ . The characteristics of the NR are summarized in Table 1, with volumes from gate  $V_i^{s,c,G}$  and from lock  $V_i^{s,c,L}$ . Where

Table 1. Characteristics of the NR, with volumes in thousand of  $m^3$ , volumes as  $V_i^{s,c,G}$  computed according to available discharges that are expressed in  $m^3/h$ ,  $b_j$  the operation number of lock  $L_j$

NR	NR <sub>1</sub>	NR <sub>2</sub>	NR <sub>3</sub>	NR <sub>4</sub>	NR <sub>5</sub>
$V_i^{NNL}$	11.250	2150	4500	6450	8.946
$V_i^{LNL}$	10.750	2050	4300	6150	8526
$V_i^{HNL}$	12000	2300	4800	6900	9.576
$V_i^{s,c,L}$	$5b_1$	$3b_2$	$3.7b_1 + 3.5b_2$	$6b_4$	$3b_5$
$V_i^{s,c,G}$	0	$[0, 0.5T]$	$[0, 3T]$	$[0, 2T]$	$[0, 1T]$
$V_i^{e,c,G}$	$[0, 2T]$	$[0, 1T]$	$[0, 2.5T]$	$[-0.5T, 0]$	$[0, 3T]$
$V_i^{e,c,L}$	$3.7b_1$	$3.5b_2$	$6b_4 + 3b_5$	$25b_4$	$2b_5$
$V_i^{c,O}$	$[0, 1T]$	$[0, 0.5T]$	$[0, 1T]$	$[0, 3T]$	0
$V_i^{c,N}$	$[-1T, 0]$	0	$[-2T, 0]$	$[-5T, 0]$	$[-2T, 0]$
$V_i^u$	$1T$	$0.5T$	$0.75T$	$0.5T$	$-0.25T$

$T$  is period of management strategy,  $T$  in hours. These volumes were estimated based on average discharges. Negative volume values are used to distinguish an emptying situation. These data represent a normal navigation period given a management horizon  $T$  expressed in hours. We considered two management scenarios during drought and flood. The parameters of the problem described in 3, were calculated in Table 1 on a 24-hour management horizon. The algorithm 1 was implemented in Java using the *Choco Open Source Java library* Jussien et al. (2008) for computing the solution of the CSP proposed. The results presented in Figures 4 and 5, refer respectively to scenarios of drought and flood. We assumed that the number of ships navigating in the network is known *a priori*, denoted  $b$ , with  $b = b_j, j = 1, \dots, 5$ . In each of these situations, we represent the network state when the maximum number of ships is reached and when the volume of water in reaches is solicited. In Figure 4, we studied three scenarios with drought case considering that volumes of input water resources compared to the normal period (see Table 1) were decreased by 25% (see Figure 4.a), 50% (see Figure 4.b) and finally 75% (see Figure 4.c). The impact of drought manifests itself in the network, so that, from a number of ships; downstream reaches ( $NR_3$  and  $NR_4$ ) are undersupply because the demand for water consumption becomes important (values in red (see Figure 4)) in this case study one of the upstream reaches ( $NR_2$ ) is in surplus. Resources and water requirements in the network are not being distributed in a uniform basis, so that each part of the

network respond to this lack of water differently. In addition to this navigation limitations are to expect in this network in a drought case, *i.e.*, navigation can not be tolerated for a number of ships greater than 36/day when a decrease of 25% of water resources is indicated and not to a number greater than 28/day when there is a decrease of 75%. Downstream reaches emptied as soon as we have 9 ships that circulate in the network when the percentage of drought is 75% and 21 ships when there is a percentage of 25%. In the Figure 5, two flood scenarios are

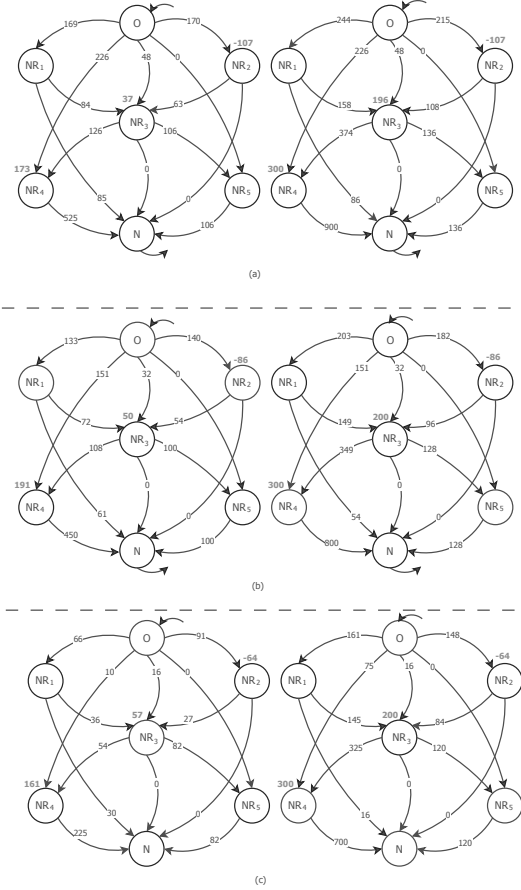


Fig. 4. (a) Drought 25% left  $b = 21$  and right  $b = 36$ , (b) Drought 50% left  $b = 18$  and right  $b = 32$ , (c) Drought 75% left  $b = 9$  and right  $b = 28$

studied in the network. Figure 5(a) describes the distribution of water volumes in the network when a flood estimated at an increase of 100% of water resources is indicated. The second scenario (see Figure 5(b)) represents an increase of about 200% of water resources. In this case, we notice that, at the contrary of the drought case, upstream reaches ( $NR_1$  and  $NR_2$ ) are both in surplus.  $NR_3$  as a junction reach, it is rather on surplus or undersupply which is the case of the downstream reach  $NR_4$ . Water volume changes in reaches are apparent even for one ship navigating in the network in the case of flood percentage of 200% (See Figure 5(b) left). The difference is substantial compared to a 100% increase when the reaches were filled of water or emptied as from a number of ships equal to 28 in the network (See Figure 5(a) left). On the other hand, the maximum number of ships allowed to navigate in the case 100% percentage of flood is 43 whereas it is 45 in the case of 200%. This means that the way in which the volume of water is distributed in the network, depending on the interactions

between the reaches, is important in determining the maximum capacity of the network in terms of navigation.

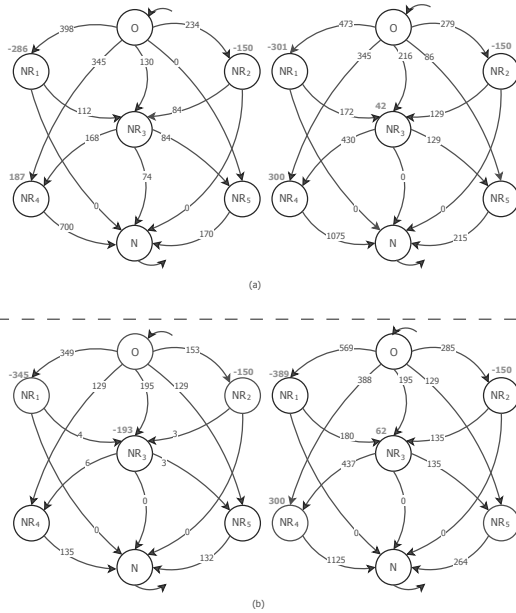


Fig. 5. (a) Flood 100% left  $b = 28$  and right  $b = 43$ , (b) Flood 200% left  $b = 1$  and right  $b = 45$

## 5. CONCLUSION

In this paper, a constraint satisfaction problem based on flow transport graph is proposed to determine the resilience of inland navigation networks against increase of the navigation demand and extreme events as drought and flood periods. The proposed tools are based on an integrated model of inland navigation networks. The constraint satisfaction problem allows determining the optimal management of water volumes during extreme events. The main objective is to keep the navigation conditions on each section of the navigation networks. If the navigation conditions are guaranteed, navigation transport could take part of the multimodal transport as a competitive transport mode. The proposed tools are tested using a network composed of five interconnected navigation reaches. The results show the efficiency of the method to evaluate the ability of the network to satisfy navigation conditions in the case of extreme climatic events. In future works, uncertainty on navigation demand and on available water resource will be considered.

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