Springer Water

Philippe Gourbesville
Jean Cunge
Guy Caignaert *Editors*

Advances in Hydroinformatics

SimHydro 2017—Choosing the Right Model in Applied Hydraulics

Springer

Springer Water

The book series Springer Water comprises a broad portfolio of multi- and interdisciplinary scientific books, aiming at researchers, students, and everyone interested in water-related science. The series includes peer-reviewed monographs, edited volumes, textbooks, and conference proceedings. Its volumes combine all kinds of water-related research areas, such as: the movement, distribution and quality of freshwater; water resources; the quality and pollution of water and its influence on health; the water industry including drinking water, wastewater, and desalination services and technologies; water history; as well as water management and the governmental, political, developmental, and ethical aspects of water.

More information about this series at http://www.springer.com/series/13419

Philippe Gourbesville · Jean Cunge
Guy Caignaert
Editors

Advances in Hydroinformatics

SimHydro 2017—Choosing the Right Model in Applied Hydraulics

Springer

Editors
Philippe Gourbesville
Polytech Lab / Polytech Nice Sophia
University Nice Sophia Antipolis
Sophia Antipolis
France

Guy Caignaert
Société Hydrotechnique de France
Paris
France

Jean Cunge
Société Hydrotechnique de France
Paris
France

ISSN 2364-6934 ISSN 2364-8198 (electronic)
Springer Water
ISBN 978-981-10-7217-8 ISBN 978-981-10-7218-5 (eBook)
https://doi.org/10.1007/978-981-10-7218-5

Library of Congress Control Number: 2017958585

© Springer Nature Singapore Pte Ltd. 2018
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Preface

Hydroinformatics, defined as management of information related to the water sector using ICT tools, is a large domain of engineering technology and sciences. Modelling and simulation are historically the points of departure for hydroinformatics and are one of the most important parts of it. Neither the SimHydro cycle of international conferences nor the present book has the purpose or ambition to cover thematically the whole extent of the subjects. The purpose is to concentrate on a limited number of specific areas and subjects that are not usually considered as such during most global international conferences.

Modelling in fluid mechanics, hydraulics and hydrology, whether using digital tools or scale models, has reached sufficient maturity to be in daily use by engineers for analysis, design and communication. Increasingly complex cases can be handled, thanks to ever-more sophisticated tools and increasingly abundant computing power. The emerging environment populated with new generation of sensors, using cloud-computing resources, producing big data, is challenging the current practices of modelling and requests innovation in methodology and concepts for a real integration into the decision-making processes. At the same time, the request to integrate vulnerability and resilience dimensions in the various engineering approaches is becoming more and more frequent.

With respect to these issues, however, a number of questions still remain open: coupling of models, data acquisition and management, uncertainties (both epistemic and random) of results supplied by models, use of 3D CFD models for complex phenomena and large-scale problems, etc. All these points are continuously explored and investigated by researchers, scientists and engineers. Like in all scientific domains, most recent and advanced developments have to be discussed and shared regularly in a growing community. The SimHydro 2017 conference, following the three previous editions, has contributed to this objective by providing a platform for exchanges and discussion for the different actors in the water domain.

SimHydro is a permanent cycle of conferences held every 2 years, hosted by Polytech Nice Sophia and organised by the Société Hydrotechnique de France and its partners. It aims, as the subject, at recent advances in modelling and hydroinformatics and at the participation and exchanges at European scale (it is open to all other researchers and participants but the purpose is to maintain a specific platform for the region that was a birthplace of both domains).

The latest SimHydro conference was held in Sophia Antipolis, France, from 14 to 16 June 2017. The conference was jointly organised by the Société Hydrotechnique de France (SHF), the Association Française de Mécanique (AFM), the University of Nice Sophia Antipolis/Polytech Nice Sophia and with the support of the International Association for Hydro-Environment Engineering and Research (IAHR), the Environmental and Water Resources Institute (EWRI) of the American Society of Civil Engineers (ASCE) and the Canadian Society for Civil Engineering (CSCE). Several sponsors also supported the conference: EDF, CNR, ARTELIA, SETEC-HYDRATEC, DHI, TENEVIA and GEOMOD. The conference attracted 152 delegates from 42 countries who participated in 20 sessions where 117 papers were presented. The programme was organised around nine main themes:

1. Hydro-environmental issues. Modelling in eco-hydraulics
2. Uncertainties and data assimilation
3. Scale models in hydraulics and their place and complementarities in simulation concepts
4. Flow instabilities in hydraulics: how to deal with?
5. Real-time modelling of Hydraulic structures and networks and events
6. Lessons learned from 2015 flash floods in the French Riviera (Côte d'Azur) area and other similar areas
7. Modelling tools for urban floods (pluvial, fluvial and marine submersions)
8. 3D two-phase flows (experiments and modelling)
9. Hydraulic machineries

Within these general themes, topics like coupling of models, data assimilation and uncertainties, urban flooding, data and uncertainties in hydraulic modelling, model efficiency and real situations, new methods for numerical models, hydraulic machinery, 3D flows in the near field of structure, models for complex phenomena have been covered. The conference, by attracting researchers, engineers and decision-makers, has promoted and facilitated the dialogue between communities with two symposia (Symposium 1: Uncertainty: a real test case on the Garonne river & Symposium 2: Physical models, their place and their complementarities with mathematical models in order to optimise hydraulic structure modelling) and one special session dedicated to the return of experience on the 2015 French Riviera floods where needs and expectations were widely discussed. Exchanges have been very fruitful on crucial questions related to sources of uncertainty in modelling, the crisis management during extreme flood events, the needs for operational forecasting systems, the state of the art in research and development in the domain of numerical fluid mechanics, the stakeholder's capacity to understand results, the means for dialogue directly or indirectly between the stakeholders and the model developers, and the information's exchange between stakeholders and developers.

In order to contribute to this dialogue and to provide useful references, following the successful experiences of 2012 and 2014, the organisers of SimHydro 2017 have decided to elaborate this book. This volume gathers a selection of the most significant contributions received and presented during the conference. The objective is to provide the reader with an overview of the ongoing developments and the state of the art taking place in four major themes that are as follows:

- Methods for modelling and uncertainty;
- Hydroinformatics systems and applications;
- Flood simulation and forecasting; and
- Advanced approaches to special and complex hydraulics applications.

Obviously, all dimensions of these themes cannot be covered in a single book. However, the editors are convinced that the contents may contribute to provide to the reader essential references for understanding the actual challenges and developments in these areas of the hydroinformatics field.

This volume represents the sum of the efforts invested by authors, members of the scientific committee and members of the organising committee. The editors are also grateful for the dedicated assistance of the reviewers who worked tirelessly behind the scene to ensure the quality of the papers. We hope this book will serve as a reference source on hydroinformatics for researchers, scientists, engineers and managers alike.

Sophia Antipolis
August 2017

Philippe Gourbesville
Jean Cunge
Guy Caignaert

Contents

Part I Methods for Modeling & Uncertainty

Part II Hydroinformatics Systems & Applications

Part III Flood Simulation & Forecasting

Part IV Advanced Approaches to Special and Complex Hydraulics Applications

Part I
Methods for Modeling & Uncertainty

This part of the book contains a selection of papers presented at SimHydro 2017 and belonging to two areas:

- Methods for modelling and uncertainty problems in modelling and
- Use of models.

In time, these two subjects were considered as one area. The question was how good were models, i.e. how certain was the quality of solution of the original equations given the algorithm and software applied. The situation changed and now the uncertainty concerns the much wider field of questions. Problems of methods for a number of years have been rather occulted by engineering community because of the everyday use of commercial software and an unfortunate idea that entered the minds of many, namely, that now everything can be modelled and that modelling solves all problems. New methods and algorithms were developed and known mainly by research community and were not massively employed because of commercial software easy to obtain and offer user-friendly interfaces. The situation seems to evolve and, precisely, SimHydro conferences allow each time the projection of new methods towards engineering community through a number of specific papers like those found in this part of the book.

Coming back to the uncertainty problems, some papers presented here enter conceptual levels that change the category of traditional approach. In engineering project and practice, when modelling is concerned, next to everything is uncertain:

- *First*: do you need a model? A model of what? Do you know the phenomena you wish to model? Hopefully, you do not expect that you will discover physical phenomena using models that are solutions of equations that describe these phenomena, what means that the latter are already known!
- *Then*: since known equations describe the physical laws that govern problems of your interest, what is the certainty of their numerical solutions provided by given algorithm?

- *Then*: are the data such as topography and similar sufficiently well known and introduced in the model to be at the level of required certainty of the results of the latter?
- *Then*: suppose you are interested in flooding problem and you use some industrial simulation software, are you sure that if through some tuning of resistance coefficients you could reproduce past observed flood, then the results for exceptional catastrophic ungauged flood will be as good? And if not, how good?
- *Other level of uncertainty*: how certain are information concerning the possibility of catastrophic dyke breaking along the river as compared to the uncertainty of results obtained from possibly best modelling of open channel flow system? What is the uncertainty of the conclusion of studies face to the question of a decision-making manager: 'when, at which discharge observed upstream, should I evacuate cities and industries situated in lateral valley protected by dykes that can break?'. Here, we are not any longer at the level of uncertainty of the results of modelling but at the level of uncertainty of consequences of decisions that, nevertheless, are based or conditioned by the results of the models. In other terms, the uncertainty in water resources management and engineering becomes the subject of overall approach, and traditional sensitivity studies (Monte Carlo and similar) of the given model results are standard peripheral activity. Not surprisingly, this general approach appearing in some papers of this part of SimHydro 2017 comes from nuclear safety domain, and they no doubt promise future developments and applications.

Philippe Gourbesville
Jean Cunge
Guy Caignaert

Large Markov Decision Processes Based Management Strategy of Inland Waterways in Uncertain Context

Guillaume Desquesnes, Guillaume Lozenguez, Arnaud Doniec and Éric Duviella

1 Introduction

It is now well recognized that human activities have a big impact on climate change. It is mainly due to the emission of greenhouse gas (GHG). The last report of IPCC [1] indicate that anthropogenic GHG emissions "came by 11% from transport" from 2000 to 2010. They recommend technical and behavioral mitigation measures in the transport sector. One solution should be a shift of the truck traffic to the inland waterway network that would provide both economic and environment benefits [2, 3]. These mitigation measures are also advocated by the last historical agreement of the COP21 in Paris. This one aims at limiting the temperature increase to 1.5 °C from 2100. By focalizing on inland navigation, it is thus expected an increase of traffic [4], with an estimated growth of 35% [5], and an increase of the frequency and intensity of flood and drought periods in close future. Management of inland waterways must deal with this new challenge.

An inland waterway network (IWN) is a large scale system build by humans, to responds to their needs, which can be divided in reaches connected by locks. To allow navigation, the level of a reach has to be in a certain range called the navigation rectangle. The role of IWN managers consists in minimizing the time where reaches are outside of their navigation rectangle, by optimizing the water

---

G. Desquesnes (✉) · G. Lozenguez · A. Doniec · É. Duviella
IMT Lille Douai, URIA, 59000 Lille, France
e-mail: guillaume.desquesnes@mines-douai.fr

G. Lozenguez
e-mail: guillaume.lozenguez@mines-douai.fr

A. Doniec
e-mail: arnaud.doniec@mines-douai.fr

É. Duviella
e-mail: eric.duviella@mines-douai.fr

P. Gourbesville et al. (eds.), *Advances in Hydroinformatics*, Springer Water,
https://doi.org/10.1007/978-981-10-7218-5_1

resource allocation amongst reaches using locks, gates or pumps. It allows to avoid important economic and ecological costs.

To overcome this issue, efficient adaptive water resource management strategies have been designed in [6] dealing with the expected constraints. These management strategies allow determining the resilience of IWN and optimizing water resource allocation. However, the used approaches are based on deterministic model of IWN and are limited when uncertainties have to be considered. For instance, the exact number of boats crossing the locks every day is not always known, uncontrolled withdrawals and water intakes are located along the reaches, exchanges with groundwater can occur and obviously weather phenomena will influence the water levels. Hence, it is necessary to introduce a stochastic modeling of the inland water networks. The IWN are modeled as large Markov Decision Processes (MDP), as introduced in [7], taking into account uncertainties to obtain a resilient planning for the network. This model is tested with real data from the IWN of the north of France.

This article is organized as follows: first we introduce more formally the inland waterway networks and its operation. Then in a second part, we will quickly introduce Markov Decision Processes and the modeling of IWN using such formalism. Finally, the results and resilience from the modeling of real data will be presented.

2 Inland Waterway Network Management

An inland waterway network (see Fig. 1) is a large scale system, mostly used for navigation. It can provide safe and efficient transports of goods [8]. It is mostly composed of interconnected canalized rivers and artificial channels that are divided by locks. Any part of a river or channel separated by at least two locks is a navigational reach. For simplicity sake, *navigational reach* will be called *reach* for the rest of this article.

The goal of an inland waterway manager is to maintain a correct level of water in all reaches to make navigation possible. This level has to respect conditions defined by the navigation rectangle of the reach (see Fig. 2) and be as close as possible from the Normal Navigation Level (NNL). The lower and upper boundaries of the navigation rectangle are respectively the Lowest Navigation Level (LNL) and the Highest Navigation Level (HNL). The non-respect of the navigation rectangle could results in damage of both the network and the boat and so forbid navigation.

For normal situations, boats crossing locks is the main perturbation of the water level, since using a lock drains water from a reach towards another reach. Multiple other factors affect the water level, such as ground exchanges, natural rivers joining in a reach, the weather and other unknown exchanges, like illegal discharges. Locks are not dedicated to control water level as they are only tools to help compensate the difference of elevations in the network. However, specialized structures are presents all over the network to control the level of water. Structures, such as gates or dams

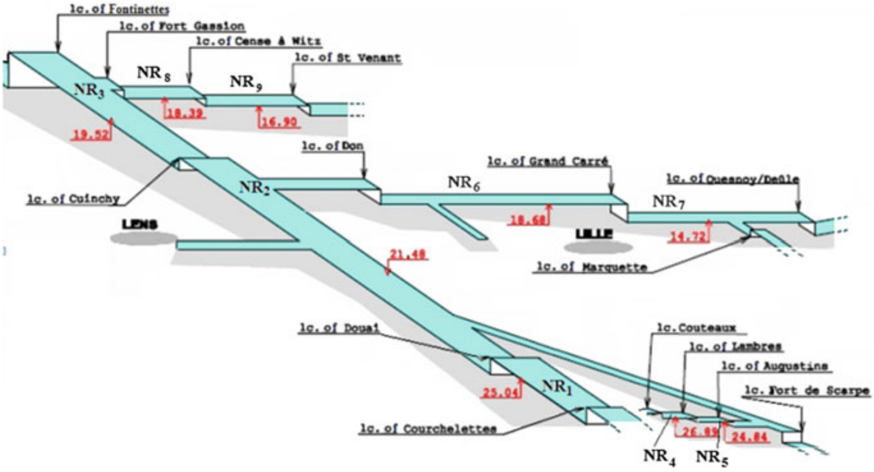

Fig. 1 Small part of the north of France IWN

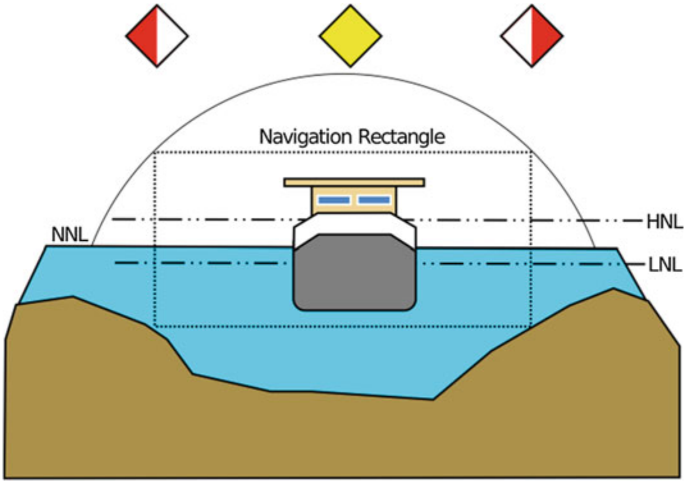

Fig. 2 NNL and navigation rectangle

are used to send water downstream and when available, pumps can be used to send some upstream. Those are the mains structures used to displace the water resource between the reaches of the network.

At the moment, navigation is only allowed during daytime periods, with few exceptions, notably on Sunday. Reaches management is based on human expertise gathered over time. However, new policies leading to traffic increase and climate change will impose new constraints that will heavily impact the current management strategies. An adaptive and resilient approach based on Markov Decision

Processes has been proposed to anticipate the impact of those constraints and ensure the navigation requirements at each point of the network. It determines a global planning for the water distribution on the whole network by taking into account the uncertainties of climate events and of the navigation demand. The allocation of water is planned over a certain horizon to allow better anticipation of possible future events. Information on the current state of the inland waterway network is collectable in real time through a network of level sensors equipping the reaches.

3 Markov Decision Process

3.1 Definition

Markov Decision Process (MDP) is a generic framework modeling control possibility of stochastic of stochastic dynamic system as a probabilistic automaton. The framework is well adapted to the inland waterway network supervision since the state of the network is fully observable (in state of water volumes) and the control is uncertain due to uncontrolled water transit.

A MDP is defined as a tuple $\langle S, A, T, R\rangle$ with S and A respectively the finite state and action sets that define the system and its control possibilities. T is the transition function defined as T: $S \times A \times S \rightarrow [0, 1]$. $T(s, a, s')$ is the probability to reach the state s' after doing the action a in state s. The reward function R is defined as R: $S \times A \times S \rightarrow \mathbb{R}$, $R(s, a, s')$ gives the reward obtained by attaining state s' after executing a from s.

A policy function π: $S \rightarrow A$ is an assignation of action to each system state. Optimally solving a MDP consists in finding an optimal policy π^* that maximizes the expected reward. π^* maximizes the value function of Bellman equation [9]:

$$V^{\pi}(s) = \sum_{s' \in S} T(s, \pi(s), s') \times (R(s, \pi(s), s') + V^{\pi}(s')) \tag{1}$$

Multiple algorithms exists to solve optimally a MDP, a notable version is *Value Iteration* [10].

3.2 Application to the Inland Waterway Management

A quick simplified reminder of the modeling of IWN using Markov Decision Process, introduced in [7] is proposed here. The aim is to plan the best course of actions for the entire network over τ time steps, under possibly evolving conditions. For example, the fluvial traffic could have an unexpected increase on some reaches, leading to an increased locks usage; a sudden downpour would increase the volumes of affected reaches.

A time step represents a period of twelve hours in the network. At the moment, they model the active navigation periods during daytime and the inactive periods during the night. Large time steps are used to smooth the uncertainties on the traffic and other temporal variations, as well as considering the water level to be uniform on each reach.

3.2.1 Definition of States and Actions

A state of the system, will represent the complete value of the network at a given time, and thus be an assignation of volumes for each reach of the network at a given time step. Similarly, an action will represent the amount of water moved by each transfer point (lock, pump, gate or dam) corresponding to the decision of a manager.

However, the MDP formalism requires discrete states and actions set. Since the volumes observed (obtained from level measures) and transferred between each reach are continuous, they had to be discretized in intervals. All possible volumes of the reach are divided in regulars intervals (see Fig. 3), with the exception of the first and last intervals. They represent values outside of the navigation rectangle, so respectively all values under the LNL and over the HNL. To simplify the model, they are considered to be of infinite size. Transfer points follow a similar discretization, however as they are considered fully controllable they do not have intervals of infinite size.

Formally, the set of states S is defined as the combination of all possible intervals of each reach at all time steps. In a network of N reaches the set can be written as:

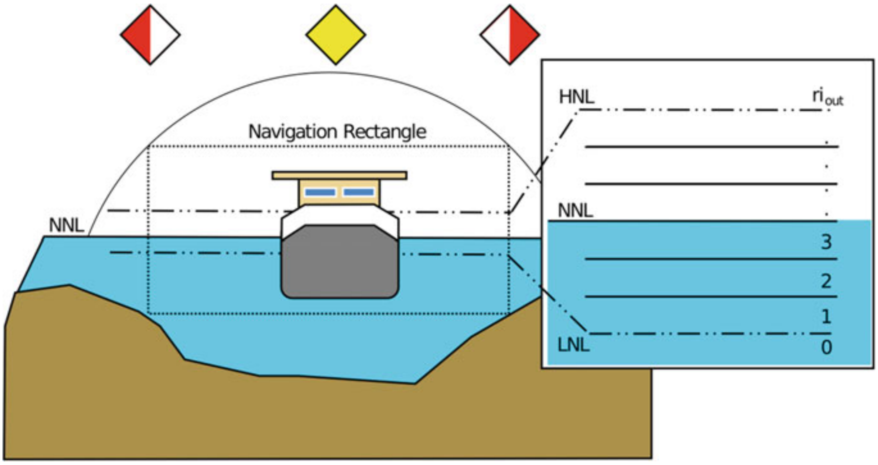

Fig. 3 Discretization of a reach water volume in intervals

$$S = \{0, \ldots, \tau\} \times \prod_{i=1}^{N} [0, ri_{\mathrm{out}}] \tag{2}$$

Having the time step modeled in the state add the possibility to express temporal probabilities on uncontrolled or unknown inputs and outputs of the network.

Similarly the set of actions A is defined as the combination of the intervals of volumes transferred by each transfer point. Unlike the states, actions are time independent as, the assumption is made that the control capacities don't change over time. A is defined as:

$$A = \prod_{i,j \in [0,N]^2} A_{i,j} \tag{3}$$

where $A_{i,j}$ is the set of possible volumes intervals for points of transfer linking reach i to reach j. The reach with identifier 0 represents external elements, such as external rivers, that connects and is able to bring or take from any managed reach. The status of those external elements is not modeled in the state, they might correspond to reaches of a foreign country managed by another organism. It is important to note that the number of transfer points is limited as the inland waterway network is sparsely connected. In all transfer points $A_{i,j}$, between two unconnected reaches i and j, no transfer is possible $(A_{i,j} = \{0\})$.

Details on the transition function construction will not be presented in this article. It simply corresponds to the probability of uncertain water displacement that take into account the discretization. More information and details are available in [7].

3.2.2 Reward Function

The objective of the planning is to maintain all reaches within their navigation rectangle and to try to minimize their distance to their NNL. This corresponds to the following function, to maximize, defined in cooperation with expert of the management of inland waterways.

$$R(s, a, s') = f(a) - \sum_{i=1}^{N} \begin{cases} (\mathrm{NNL}_i - ri'_s)^2 & \text{if } ri'_s \in \mathrm{Rec}_i \\ g^2 & \text{if } ri'_s \cap \mathrm{Rec_i} = \emptyset \\ (0.5 \times g)^2 & \text{if } ri'_s \cap \mathrm{Rec}_i \neq \emptyset \quad \text{and } ri'_s \notin \mathrm{Rec}_i \end{cases} \tag{4}$$

where the function *f(a)* represent costs relative to the usage of the different transfer points. For example, using an electric pump costs more than opening a gate. This function will be highly specific to each reach and network. NNL_i is the volume corresponding to the NNL of reach i. ri'_s is the volumes of reach i in state s'. g is a penalty cost for halting the navigation when the water level is fully outside of the navigation rectangle. Half the cost is applied when the interval is only partially outside the rectangle of navigation.

This reward function penalized drastically the distance to the NNL, with a prohibitive cost when outside of the navigation rectangle. A smaller cost is used optimize the choice of transfer points used.

4 Application on Real Data

The Douai-Fontinettes-Grand Carré subnetwork in the north of France inland waterway network has been modeled using the proposed modeling and plan over. This network is composed of three reaches with different navigations conditions (see Table 1). The three reaches, represented by circles, are connected by gates and locks, as arrows (see Fig. 4). Those reaches are connected to unmodeled part of the network by transfer points (arrows: 0, 1, 2, 7, 8, 9, 10, 11) that consists in locks, gates and external rivers. Their water levels are divided in 12 intervals, 10 of them with a fixed size, the first and last are considered of infinite size. In this scenario, only three transfer points are controllable by the manager of the subnetwork (arrows: 4, 6, 11), with respectively 124, 375 and 352 actions each.

Multiple operating scenarios corresponding to real case applications have been proposed to test the proposed planning approach. All those scenarios are over eight 12 h time steps corresponding to 4 days. The traffic values for each lock correspond to the average traffic of the subnetwork for a single period (see Table 2). The minimum and maximum transfer capacity of controllable transfer points are fixed and supposed to be the same for each scenario (see Table 3). The values transferred by each other transfer points will be dependent of the scenarios and so will be introduced during their presentation. The planning of all scenarios has not been subject to variations, however those will be present during the simulations to test the resilience. Due to the size of the model, a distributed version of the algorithm had to be used for the resolution. This lead to solutions that are local optimum. The decomposition of the subnetwork for the distribution is shown by the different colors of transfer points (see Fig. 4).

As actions of the modeled network corresponds to intervals of volumes by each controllable transfer point, the simulations use random values drawn from each interval of the chosen action instead of choosing the best or average values.

Table 1 Network properties

Reach	Name	LNL (m^3)	NNL (m^3)	HNL (m^3)	Interval size (m^3)
0	Douai-Don-Cuinchy	8,660,177	8,778,810	9,016,076	26,363
1	Cuinchy-Fontinettes	9,348,300	9,458,280	9,568,260	24,440
2	Don-Grand-Carré	3,766,098	3,824,038	3,881,978	12,876

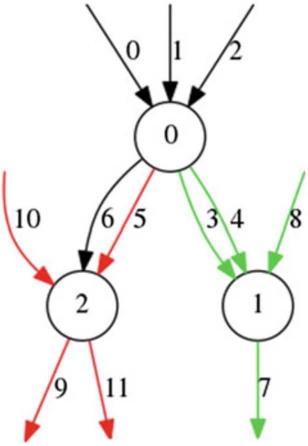

Fig. 4 Decomposition of the subnetwork

Table 2 Average traffic and volumes transferred per lock per 12 h

Lock	0	3	5	7	9
Traffic (boat)	21	13	14	10	16
Volumes (m^3)	140,889	45,838	82,656	230,000	117,424

Table 3 Controllable transfer points capacities per 12 h

Transfer points	4	6	11
Volumes (m^3)	0–432,000	0–1,296,000	0–2,592,000

The goal is to have a better perception of quality of the interval selected by the policy. Because the volumes transferred are chosen randomly, fives simulations were made for each scenario. This help visualizing the consequences of the random selection of transferred volumes of the used policy. A single policy is produced for each scenario but is simulated on different conditions, both expected and unexpected. Five different conditions are tested per scenario. The first three tests correspond to expected conditions of traffic and water availability. In the first test, all reaches start at their NNL, in the second they start close to their HNL and in the third one they begin close to their LNL. In the last two tests, the traffic is respectively 10% higher and lower than the expected at all time.

4.1 Normal Conditions

The first scenario corresponds to the normal conditions of navigation, with navigation allowed only during daytime periods. No perturbation are anticipated on the network and the expected traffic corresponds to the average value. The volumes transferred by the uncontrollable transfer points in this scenario are defined in Table 4.

On Fig. 5, it is possible to see the evolution of the relative distance of the three reaches to their NNL over time under normal condition and expected traffic, with a value of 100 corresponding to a volume at the HNL and a value at −100 to the LNL. One can see the volumes of the three reaches oscillating around their respective NNL. The oscillations are due to the discretization of both the state and action in interval. An interval of volume corresponds to a single state, which means a single action from the policy, however the optimal actions for two opposite points in the interval might be different. For example, if an interval englobes the NNL, the optimal choice for the upper part of the interval would be to decrease the volumes while for the lower part it would be preferable to increase it. The impact of the oscillation is dependent on the size of the intervals, and smaller discretization would lead to better results but with an increased size of the model.

If the reaches start from a suboptimal position (see Figs. 6 and 7), they are able to recover to a solution close to their NNL by following the planning produced. It is

Table 4 Uncontrollable volumes per 12 h

Transfer point	1	2	8	10
Volumes (m^3)	283,392	−43,200	27,216	51,840

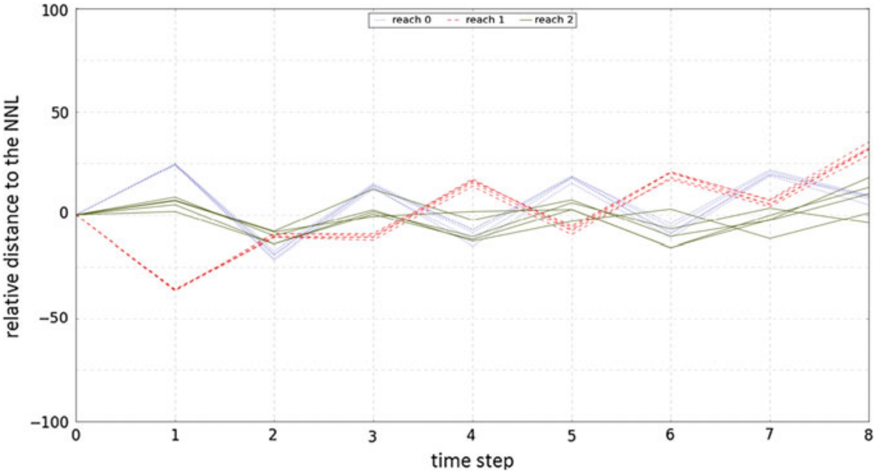

Fig. 5 Normal conditions, starting from the NNL

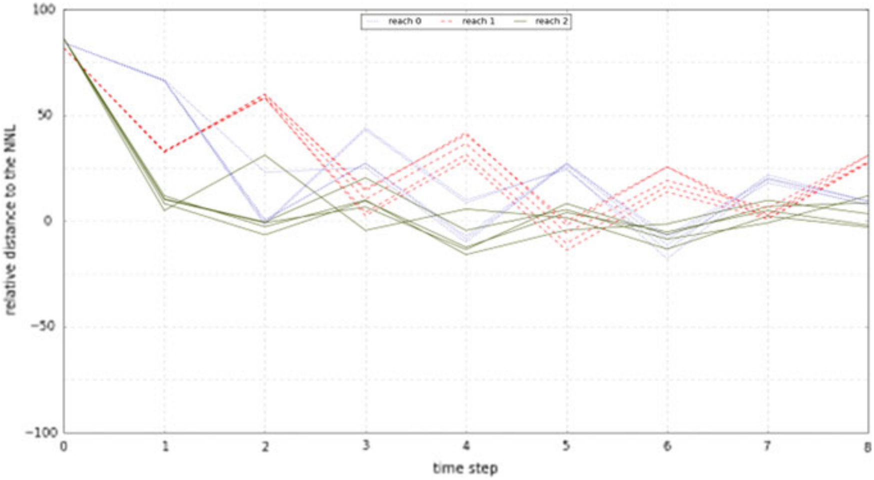

Fig. 6 Starting close to the HNL

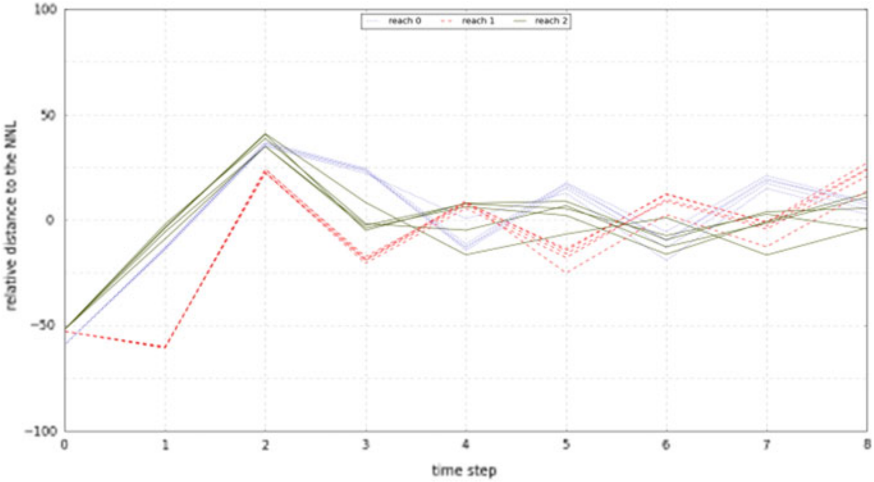

Fig. 7 Starting close to the LNL

possible to see that coming back from the LNL is easier than from the HNL. This due to the fact that, in this network, storing water is easier than removing it.

The last two experimentations consist in having respectively an increase (see Fig. 8) or decrease (see Fig. 9) of the traffic compared to the expected value. In both cases the reaches manage to stay relatively close to their NNL, even if the limits, of the plan resilience, seem to be showing in the case of a smaller traffic than expected as, reach 0 has trouble to reduce its water level.

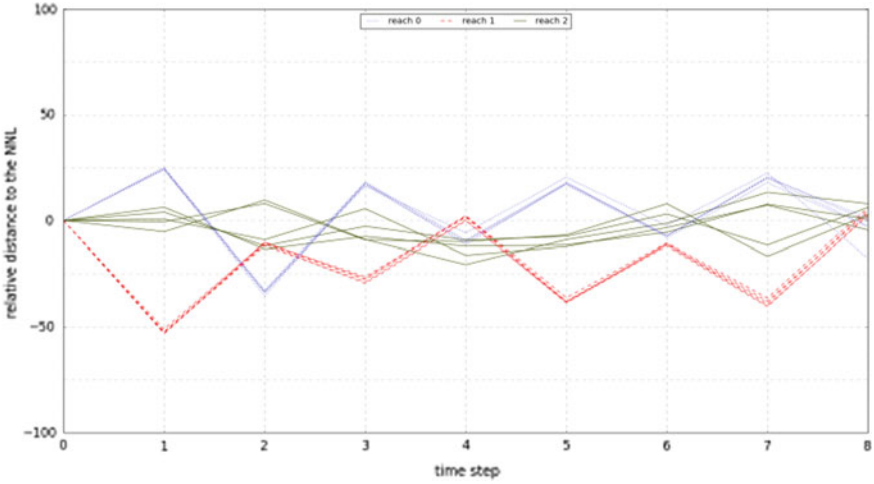

Fig. 8 Traffic 10% greater than expected

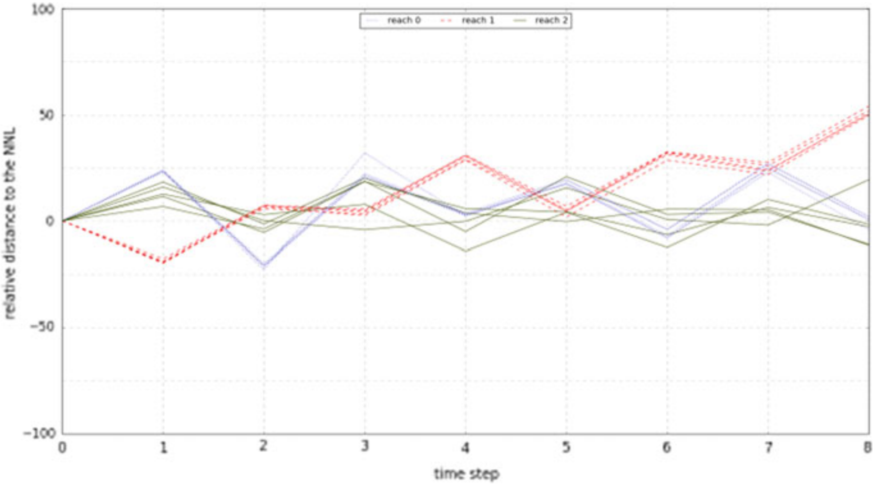

Fig. 9 Traffic 10% lower than expected

For this scenario, the produced plan was able to maintain ideal navigation conditions in expected cases, to recover from bad events that leaves the network at suboptimal water levels and was able to adapt to unexpected traffic conditions.