Chapter 11
Sensitivity Analysis of the Digital Twin of the Canal of Calais to the Outlet Gate Modelling

Roza Ranjbar, Lucien Etienne, Eric Duviella, and Jose Maria Maestre

Abstract Digital twins of hydrographical networks can be designed based on simulators. They aim not only at reproducing with accurate dynamics of the rivers and canals but also to analyze past events, to design, test, and compare new control algorithms. A delicate stage is an estimation of uncontrolled in/outputs along the canal during a specific event. Observers for the level variable reconstruction have been proposed in the literature. For real systems, the estimation of uncontrolled in/outputs is still challenging. Limiting uncertainties during this estimation requires accurate models of the controlled gate dynamics. Model of gates can be very complex particularly for sea outlet gates. Their dynamics are nonlinear with priming stages and flow drops by the end of low tides. The flow depends on the gate opening, its duration, the tide coefficient, and also the level in the canal. A highly operational approach consists of considering a delay at the opening of the gate, then an average flow, and finally a progressive limitation of the flow by the end of the low tide. Based on this operative model, the uncontrolled in/outputs along the canal are estimated. This method is applied on the canal of Calais located in the north of France. It is strongly supplied by runoff and several pumping stations during rainy events. The outlet gate which is characterized by very complex dynamics is modeled. Then the flow due to runoff and upstream pumping stations is estimated. The paper aims at proposing a sensitivity analysis of this estimation according to the proposed dynamical model of the outlet gates using real data.

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11.1 Introduction

Hydrographical networks are considered complex systems that are geographically distributed, managed in a way to appropriately answer the human's needs like drinking, irrigation, industry, etc. For the purpose of routing water resources, they are composed of hydraulic devices such as gates and pumps. In the case of designing elaborate management strategies, accurate models of hydrographical networks are required. Several hydraulic simulation software, mostly based on the Saint Venant equations, could be taken into account for measuring the above-mentioned strategies' performance [1, 2]. Although some of these software (SIC and SWMM) can join the standard control tools (PID), they are generally too complex for the goal of designing the management strategies [3]. Based on the introduced simulators and definitely thanks to the advances in Automation and Computing Science, it is now possible to design Digital Twins (DTs) of hydrographical networks. DTs are capable of reproducing the dynamics of real systems, easing the recognition of unknown inputs/outputs, and then play-back past scenarios for estimating the applied management strategies and finally assess and optimize the recent control strategies [4]. Among the issues specified above, the estimation of uncontrolled inputs/outputs along a hydrographical network is of severe importance particularly in the case of major events for the real systems. However, there are conventionally observers which are delicate for the other types of systems. They function based on reconstructing the state vector from the available outputs [5]. One method is building a model of the given system, operating it with the same inputs as the original one, and using the state vector of the model as an estimation to the unknown state vector. The drawback occurs if initial conditions were not set correctly or if there were some disturbances so that the model cannot provide an appropriate estimate for control. The second trend is to differentiate the available outputs many times and integrate the derivatives to obtain the state vector. The disadvantage of this method is that the estimate will be reduced by some additive noise. Thus, the best observer is the one that is in between these two procedures [6]. An observer for the level variable reconstruction has been proposed in [7] a robust fault detection and isolation (FDI) analysis based on zonotopic unknown input observers (UIOs) for discrete-time descriptor linear time-varying (LTV) systems are depicted in [8].

Nevertheless, the estimation of the discussed issue is still challenging when it comes to the real systems such as open-flow canals (included in the hydrographical networks) whose entire dynamics are based on nonlinear partial-differential hyperbolic equations dependent on time likewise the Saint–Venant's equations. Concerning the control point of view, the canals are required to be equipped with control gates and pumping stations. With respect to the dynamics behavior of canals, it is expected that designing and modeling the outlet gates would be complicated, especially for those gates which are located at sea [9].

Another argument with the inputs is the presence of uncertainties which should be limited as much as possible. In the case of water canals, while a model is able to predict the runoff due to the available data on rain events, the provided information reduces the uncertainties on inputs and for that of predictive control algorithms. For this purpose, an accurate measurement of the flow discharges and water levels is crucial. Inverse modeling approaches could be implemented in order to estimate the unknown input/output of past events. Next, the DT joins software like computer codes and programs that run the predictive and adaptive control strategies. The goal is to offer a suitable and novel management strategy that can be adjusted and assessed using the DT. This work is already done in [4]. To do so, by taking real data into account, levels and the controls already sent to the hydraulic devices (over a specific period of time), and by having known an initial condition, the water volume is computed. Hence, the missing flows could simply be achieved by determining the considered period of time. Once the unknown inputs/outputs are estimated, the past scenarios can be play-backed so that feedback on the applied management strategy would become available as it is presented in [3]. The performance of the applied strategies can provide vital information for the managers.

In this paper, a digital twin is presented to reproduce the dynamics of the Calais canal located in the north of France. For this purpose, advanced control on the hydraulic devices of the canal is implemented and the canal is simulated by the software of SIC^2. The data processing is made with classical tools available on Matlab. It should be mentioned that the data is related to the period of November 2019 in which there was a period of rain and a period of heavy rain. The previous management strategy of the canal followed the goals of navigation as well as the restriction of flood events. Ascertaining these objectives leads to a robust control over the unknown inputs and the outlet gate dynamics of the canal. Since the flow is extremely dependant on the extent of gate opening (between 0 to 25 dm in Calais canal) and the duration of that, the tide coefficient (spring or dead tide), and finally the water level in the canal, a new approach has been considered in this paper which is as follows:

First, the water level and the discharge at the outlet gates have been simulated. Then two different models are considered for the outlet gate to estimate the unknown discharges. When the model of the gate is considered with an ‘average flow’, some artificial oscillations are made to keep the simulated level close to the real one. On the other modeling, an approach of ’inserting delay and loss of flow’ has been applied to discover the same estimation. Basically, this study aims to investigate how sensitive is the digital twin of the Calais canal to these two approaches in outlet gate models and to conclude which one could be more effective.

The paper structure begins with some definitions and previous research works, the general description of the Calais canal and the main objectives of its management are introduced in Sect. 11.2. The simulation of the canal is explained in Sect. 11.3. The past scenarios determination and the new approach along with its results are illustrated in Sect. 11.4. Finally, conclusions are provided in Sect. 11.5.

11.2 Management of the Calais Canal

11.2.1 Description

The Calais canal belongs to the Wateringues territory located in the north of France, between the towns of Saint-Omer, Calais, and Dunkerque. This territory forms a triangle with an area of 100,000 ha (see Fig. 11.1a). It is principally supplied by the Aa river and the Hem river. Water from rain is collected thanks to the watergangs, i.e. a ditch or drainage structure to dry out these lowlands (see Fig. 11.1b). The watergangs constitute a huge meshed network with a total length of more than 1500 km. Because Wateringue section is a lowland in maritime plains below the high sea, the water in excess in the watergangs is pumped to the main navigation canals, and then routed to the sea to be discharged. One of these navigation canals is the Calais Canal located at the west of the territory.

The Calais canal keeps its role for navigation even if it is principally used to route water in excess to the sea. This canal is composed of the main reach from the lock of Hennuin to the sea in Calais. It has an average length $L = 26.72$ km, a width $W = 2$ m, and a depth of $D = 2.2$ m. It is supplied by three secondary canals: Audruicq canal, Ardres canal, and Guines canal (see Fig. 11.2). The water is discharged to the sea thanks to gates, two pumps in Calais and two pumps in Batellerie, with an own capacity of 4 m^3/s and 2 m^3/s, respectively.

From the Wateringue sections, there are 18 automated Pumping Stations (PS) along the canal. The PS are controlled by farmers when the water level in the watergangs is higher than the desired threshold. When a PS is switched on, it delivers a known average discharge, e.g. the Mower PS can deliver 0.35 m^3/s when it is operated. The flows from secondary canals are close to zero during normal periods, and the average flow of the Calais canal is 0.6 m^3/s. However, during times of rain, the flows from these canals can exceed 3 m^3/s, 1.4 m^3/s and 0.2 m^3/s, for Audruicq, Ardres and Guines canals, respectively. Based on these data, the maximal flow of the canal during strong rain events with all the PS switched on, is equal to 12.96 m^3/s.

The Calais canal is equipped with two-level sensors in Les Attaques and Calais, denoted Z_{attaq} and Z_{calais} respectively. A Supervisory Control and Data Acquisition (SCADA) system is used by the manager of the Calais canal for several years. Data from 5 PS (N^{lle} Eglise, 3 Cornets, Balinghem, Attaques and Potez), from the two sensors (Z_{attaq} and Z_{calais}), and the pumps and gates to the sea are collected every 2 min.

11.2.2 Management

The management objective of the Calais canal consists of keeping the water level close to the NNL (Normal Navigation Level) allowing the navigation. The level of the canal is controlled thanks to the gates in Calais, water being discharged by gravity.

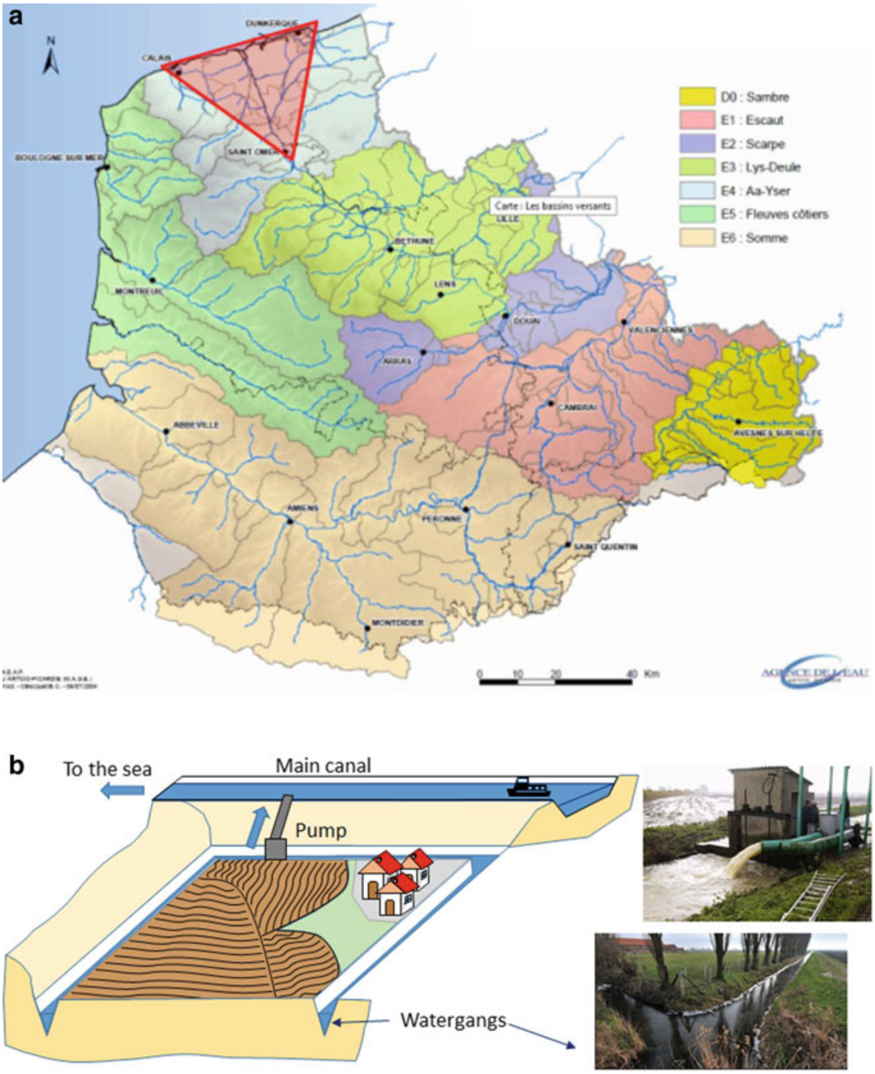

Fig. 11.1 **a** Map of the watersheds in the north of France and of the Wateringues Territory (red triangle). **b** Scheme of a Wateringue delimited with *watergangs*

In some cases, managers allow an oscillation of the level as long as it remains within the navigation rectangle. The navigation rectangle is delimited by two boundaries around the NNL; with the LNL = NNL − 0.1 m (Low Navigation Level) and the HNL = NNL + 0.15 m (High Navigation level). These oscillations are due to the non-availability of the gates in Calais during high tide. Hence, the level in the canal increases during high tide and decreases during low tide when the gates in Calais

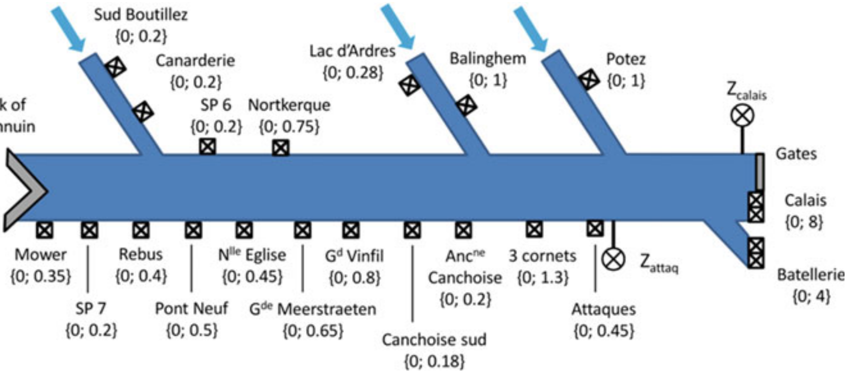

Fig. 11.2 Schematic view of the Calais canal

can be opened. The control of the canal level around the NNL would require the use of pumps during high tides, resulting in a very high electrical cost.

During rainy periods, the Calais canal is usually closed to navigation, and all boats are evacuated. When no boat is present in the canal, the level can oscillate more, dealing with the sea tides, to limit the usage of the pumps. However, canal overflow has to be avoided by keeping the level below NNL + 0.3 m. When heavy rainfalls, it is usually necessary to switch on the pumps during high tide and to open the gates as much as possible during low tide. During low tide, the pumps can also be used if the quantity of water discharged to the sea with the gates is not sufficient.

11.3 Simulation Architecture of the Calais Canal

11.3.1 Digital Twin

The management of the Calais canal can be still improved with new tools from Artificial Intelligence and Automatic Control. One possibility consists in reproducing the dynamics of the canal with a simulator. A digital twin has been proposed in [4] (see Fig. 11.3). Based on this DT, it is possible to reproduce past events with the objective to analyse the management strategies, evaluate new control strategies and optimization tools, and provide a real-time decision tool for the managers. By focusing on the first objective, it is necessary to follow some steps: (a) selecting a representative episode, (b) collecting and processing data, (c) modelling the hydraulic devices, (d) estimating the unknown inputs based on the simulator.

The selection of representative episodes is made with the assistance of the manager, based on their expertise. They provide the associated data with a sample time of 2 min. The data processing is made with classical tools available on Matlab. The modeling of hydraulic devices is particularly challenging.

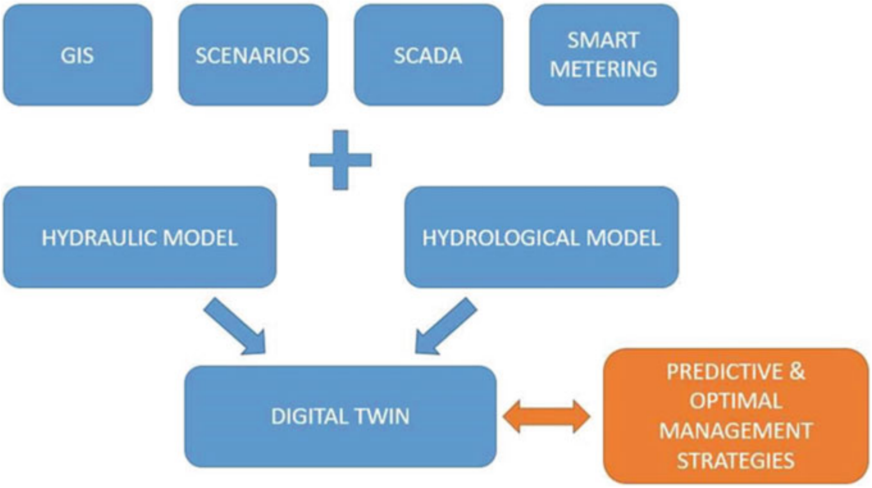

Fig. 11.3 Framework for the DT of hydrographical networks

11.3.2 Gate Dynamics

The modeling of the gates consists of determining the flow according to the gate opening. Average values of the flow according to the gate opening have been provided by the managers. These values depend on the three types of the tide (see Fig. 11.4). Some mathematical functions have been identified according to these data [4]. However, the functions are dependant on average values which are constant for the duration of the gate opening. They do not take into account the evolution of the canal and sea levels that have a significant impact on the flow values.

By considering the level Z_{calais} close to the gate in Calais and the opening of the gate, a more detailed view of the dynamics of the gate can be observed. For illustration, the data from 6th November 2019 are depicted in Fig. 11.5. This episode corresponds to a heavy rainy episode during the dead tide period. When the gate is opening (sample 60), it can be observed that a delay of several samples (3 samples, i.e. 6 min) appears before any change in the level. Then, the level of the canal is increasing to more than 10 cm while the gate is opened. This phenomenon seems to be related to the loading of the hydraulic device. The level of the canal starts to decrease after 7 samples (14 min) following a constant slope during 90 samples (3 h). From sample 160, the slope of the level starts to decrease until sample 260, corresponding to a loss of flow. 200 samples (6 h and 40 min) after the opening of the gate, the level starts to increase again showing that the flow discharge in the canal is higher than the flow to the sea. The gate is finally closed and the level continues to rise.

Other episodes for different conditions, e.g. spring tide without rain and smaller gate opening, show similar dynamics of the gate to the sea. That implies to taking into account a delay after the opening of the gate and a loss of discharge after a while

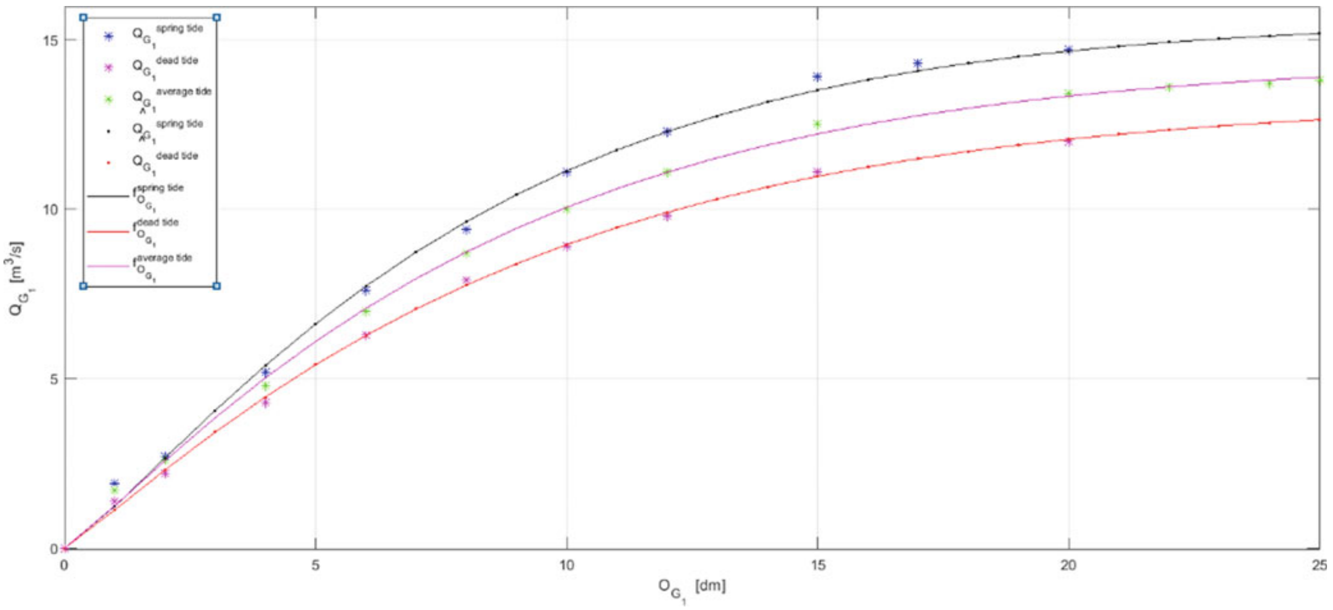

Fig. 11.4 Estimated discharge Q_G [m^3/s] function of gate opening O_G [dm] according to the type of tide, with the points given by managers (star), and the estimated points (dot)

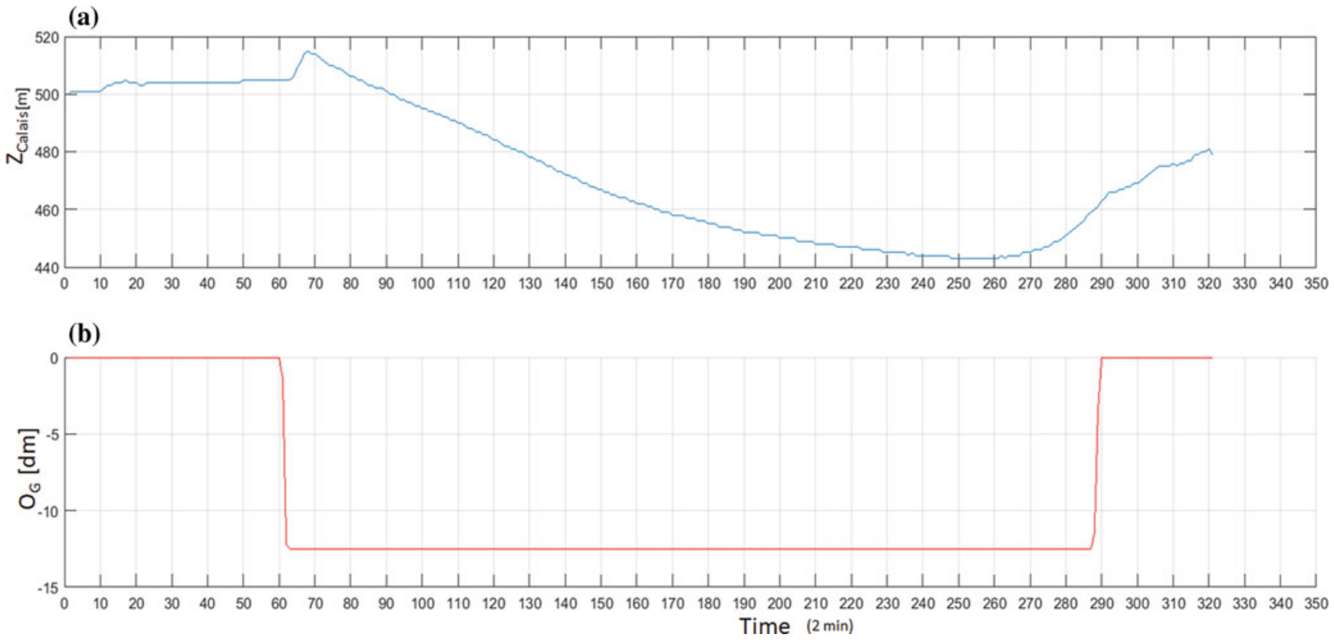

Fig. 11.5 **a** Level in Calais Zcalais, **b** gate opening O_G for November 6th, 2019, time in sample of 2 min

Table 11.1 Parameters for the approximation of the gate dynamics

Type of tide	Tide coefficient	Δ—Delay (sample)	Φ—Loss of flow (%)
Spring	>75	160	98
Intermediate	60< and <75	165	99
Dead	<60	170	99.8

whatever is the state of the Calais canal and the sea. However, the starting time of the loss of flow and the value of the loss depending on the type of tide. Based on several episodes, the delay and percentage of loss of flow have been identified and are given in Table 11.1. The type of tide depends on the tide coefficient.

The principle is to keep the average values of the flow according to the gate opening from Fig. 11.4, by introducing a delay of 10 samples (20 min) before applying the value of the discharge. Then, according to the varying delays in Table 11.1, a percentage of loss of flow is applied at each sample time until the gate is closed:

$$Q_G(k) = Q_G(k-1) \cdot \varphi_{tide}, \quad \text{for k} > \text{k}_\text{s} + \Delta \tag{11.1}$$

with k_s the time of the last gate opening, Δ the delay, and φ_{tide} the loss of flow coefficient depending of the type of tide, where Q_G is the flow of the gate.

Based on this approach, the loading of the hydraulic device phenomenon is not reproduced.

11.4 Past Scenarios Determination

11.4.1 Implementation of New Gate Dynamics

The digital twin of the Calais canal is implemented by considering an episode from 1st to the 6th of November 2019. This episode is characterized by a rain event from the 2nd of November, and a heavy rain event that starts from the 4th of November. The first approach consists of considering the average values of the flow according to the gate opening from Fig. 11.4. The real level is depicted in Fig. 11.6 in blue and the simulated one in dashed magenta. The first red threshold corresponds to HNL, the second one (dashed red line) the overflow limit. Based on Fig. 11.6, it is possible to see that the simulation allows following the real measurement, but there are some peaks at 00:00 and 12:00 on November 3rd, and to others on November 4th at 00:00 and on November 5th at 00:00. These peaks are due to the application of a constant flow during all the gate openings. The loss of flow phenomenon is not reproduced.

In Fig. 11.7, the same episode is considered, with real measurement in blue. In this case, there is no peak and the simulated level is closer to the real one. The simulated level is obtained by considering the new model of the gate implementing delay and loss of flow as it is depicted in Fig. 11.8b. In this Figure, depending on the sea level

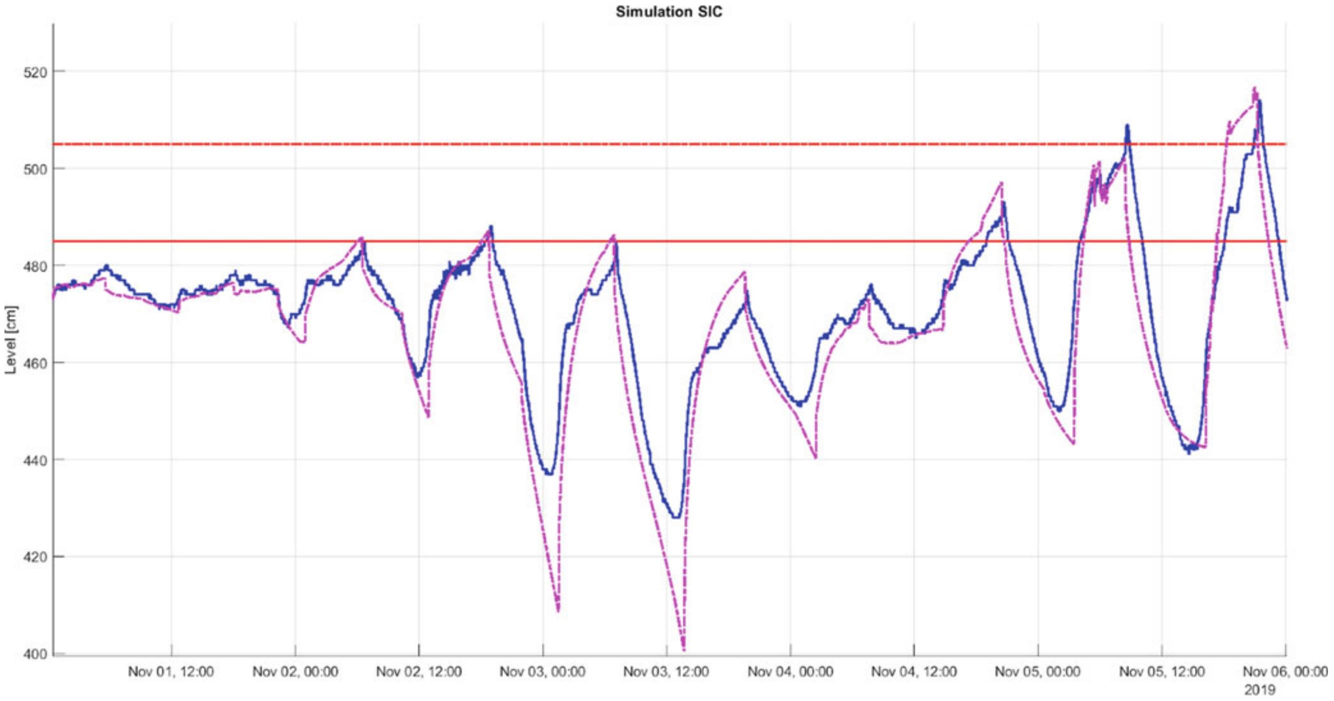

Fig. 11.6 Level of the Calais canal from November 1st to November 6th, 2019, in blue (real measurement), in magenta (simulated one), by considering an average flow for the gates

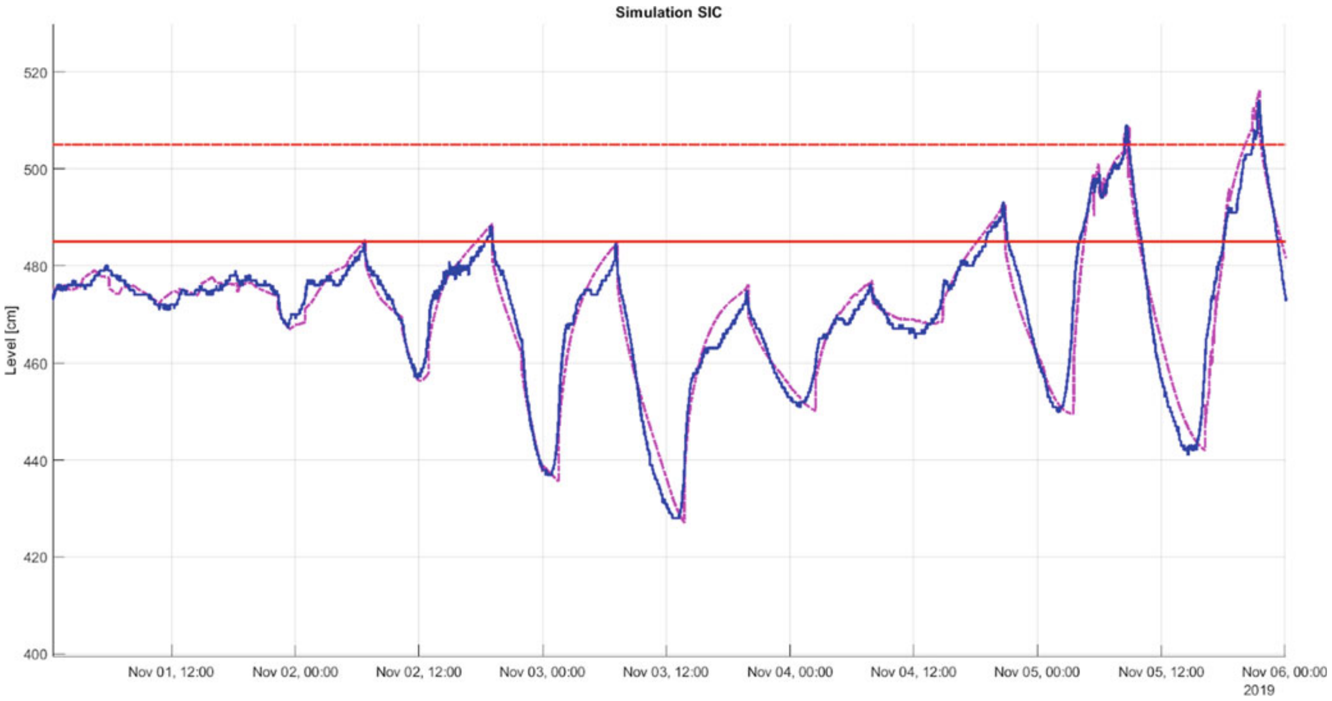

Fig. 11.7 Level of the Calais canal from November 1st to November 6th 2019, in blue (real measurement), in magenta (simulated one), by considering a loss of flow and delay for the gates

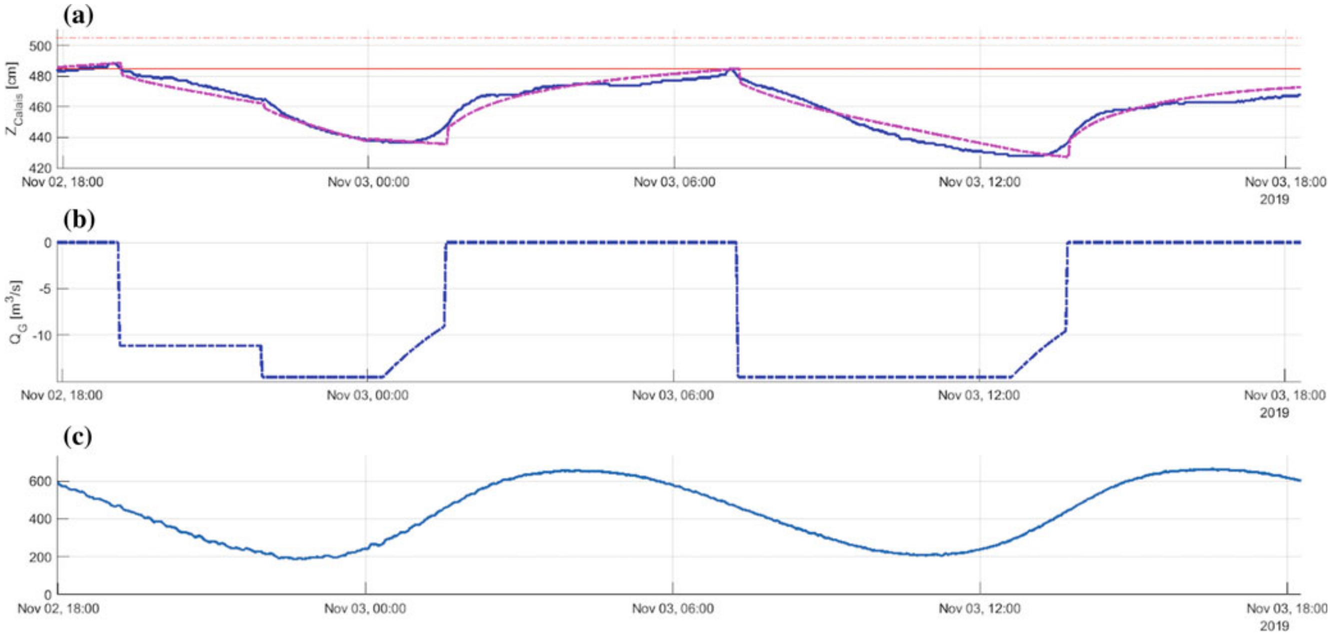

Fig. 11.8 **a** Level of the Calais canal from November 2nd to November 3rd 2019, in blue (real measurement), in magenta (simulated one), **b** the flow of the gate QG with a loss of flow and delay, **c** the sea level

(see Fig. 11.8c), the delay at the opening of the gate and the progressive loss of flow, e.g. at 00:00 and 12:00 on November 3rd can be observed.

11.4.2 Estimation of Unknown Inputs

According to the dynamics of the gate, it is necessary to estimate the unknown inputs based on the simulator. This step is required to replay past scenarios because it is necessary to estimate as best as possible the entire water inputs to the Calais canal from PS and secondary canals. Considering the model of the gate with the average flow and the model of the gate with loss of flow, the unknown flows from secondary canals have been estimated in Tables 11.2 and 11.3, respectively, by considering periods of 6 h. These unknown flows are depicted in Figs. 11.9 and 11.10, respectively. The step to estimate them consists in an inverse model. The adjustment variables to keep the simulated level close to the real one are the three flows of the secondary canals, according to the knowledge of activation of the PS, the pumps, and the opening of the gates. The dynamics of the canal and particularly the transfer delays are reproduced thanks to the digital twin of the Calais canal.

When the model of the gate is considered with an average flow, the estimated unknown flows of the secondary canals oscillate between the highest values to zero during the rain event on November 2nd (see Fig. 11.9a). These oscillations are made artificially to keep the simulated level close to the real one. However, there is no physical interpretation of these oscillations, because rain can not be such a variable, specially in this catchment area. This effect does not appear when the loss of flow and delay are considered for the dynamic of the gate on November 2nd (see Fig. 11.10a). It is the contrary for the heavy rain event, where more oscillations appear from November 5th for the second model of the gate. This is probably due to an underestimation of the average flows when the level of the Calais Canal exceeds the HNL. In this case, the flow should be much bigger.

According to the values in Tables 11.2 and 11.3, the mean and standard deviation of the estimated unknown discharges are computed for each canals according to the two approaches (see Table 11.4). That shows the first approach leads to biggest estimated values with more oscillations than the second approach.

This study shows how sensitive is the digital twin of the Calais canal to the outlet gate models. The modeling approach integrating the loss of flow and the delay seems more suitable than the average flow approach. However, a more detailed and systematic modeling approach is still required.

11.5 Conclusions

This paper is investigating the sensitivity analysis of the digital twin of the Calais canal to the modeling approach to the outlet gate. First, a model of the gate based

Table 11.2 Estimated unknown flows of secondary canals based on the model with average flow

Flow	Nov 1st				Nov 2nd				Nov 3rd				Nov 4th				Nov 5th			
	0–6	−122	−18	−0	−6	−12	−18	−0	−6	−12	−18	−0	−6	−12	−18	−0	−6	−12	−18	−0
Ardruicq	0	0	0	0.2	0.8	1.7	0.6	0.3	0.1	0	0	0	0	0	0.1	1	4.5	6	4.5	2.5
Ardres	0	0	0	0.1	0.7	1	0.4	0.2	0.1	0	0	0	0	0	0.1	0.5	2.5	3.6	3.6	0.8
Guines	0	0	0	0	0.1	0.2	0.1	0.1	0.1	0	0	0	0	0	0.1	0.2	0.8	1.1	0.8	0.6

Table 11.3 Estimated unknown flows of secondary canals based on the model with loss of flow and delay

Flow	Nov 1st				Nov 2nd				Nov 3rd				Nov 4th				Nov 5th			
	0–6	−12	−18	−0	−6	−12	– 18	– 0	– 6	−12	– 18	– 0	– 6	– 12	– 18	– 0	– 6	– 12	– 18	– 0
Ardruicq	0	0	0	0.2	1.4	1.8	0.4	2.5	0.2	2.5	0.1	0.1	0.1	0.1	0.1	0.7	6.6	5.9	7	2.5
Ardres	0	0	0	0.1	0.7	1.4	0.2	0.8	0.1	0.8	0.1	0.1	0.1	0.1	0.1	0.4	2.6	2.8	4	0.8
Guines	0	0	0	0	0.1	0.2	0.1	0.4	0	0.4	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.4	0.1	0.6

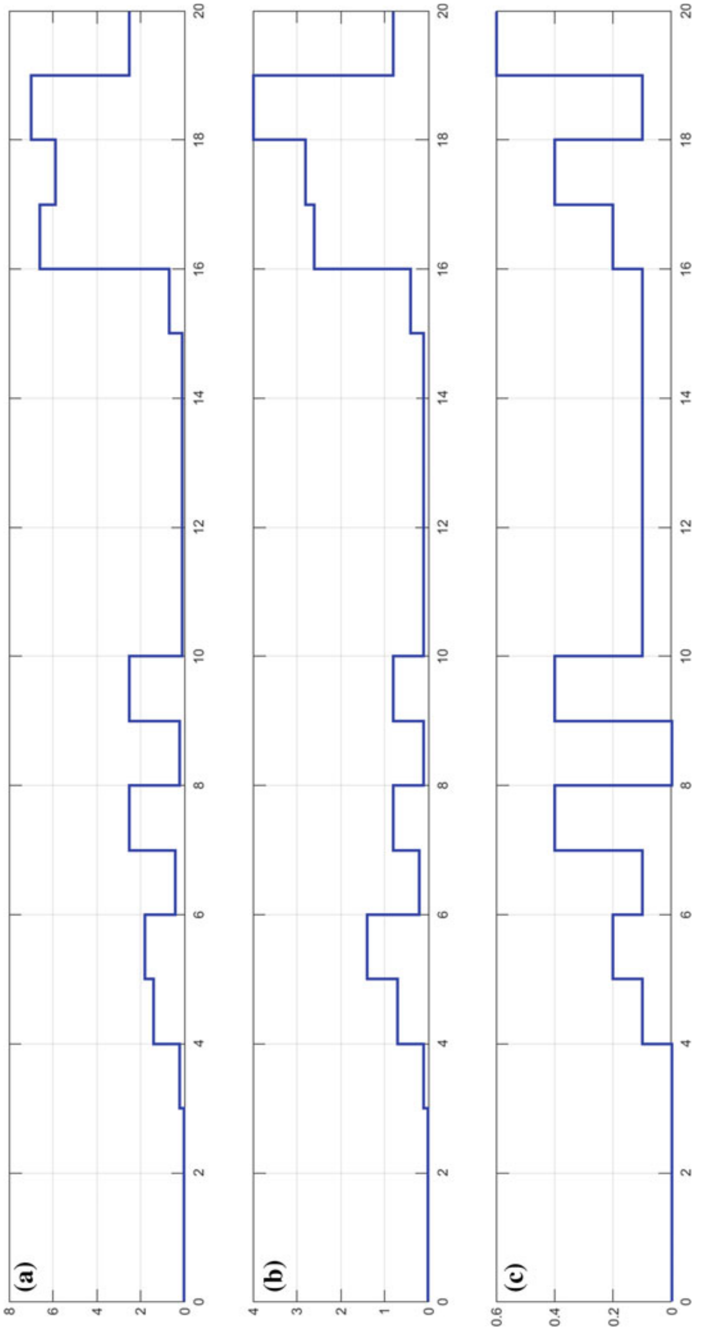

Fig. 11.9 Estimated flows based on the model with average flow, from **a** Ardruicq canal, **b** Ardres canal, **c** Guines canal

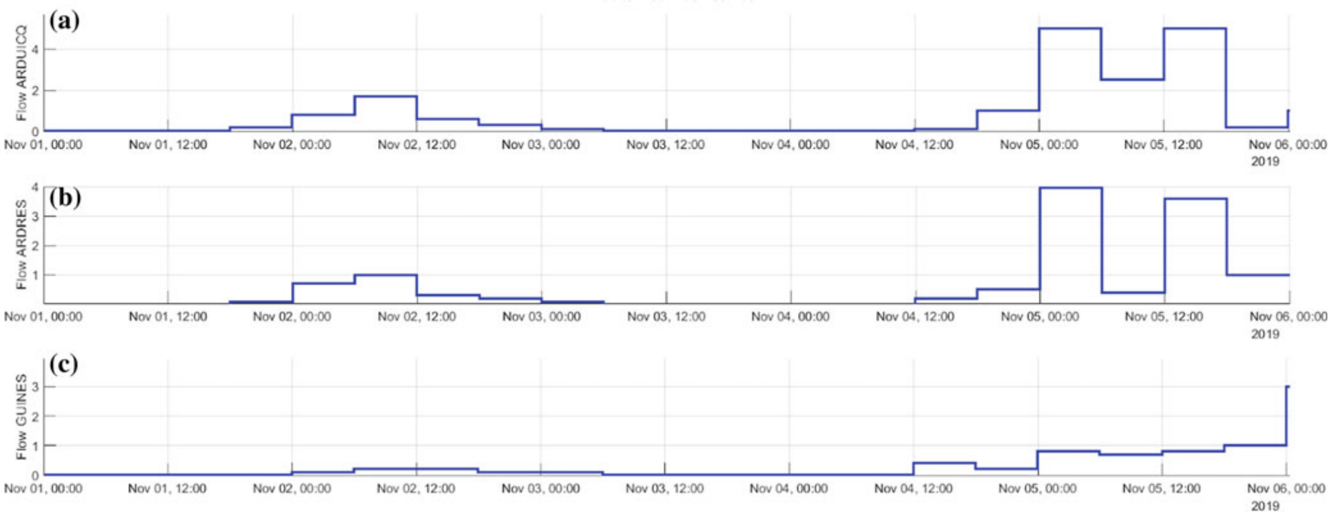

Fig. 11.10 Estimated flows based on the model with loss of flow and delay, from **a** Ardruicq canal, **b** Ardres canal, **c** Guines canal

Table 11.4 Mean and standard deviation of the estimated unknown flows of secondary canals

Canals	1st approach (average flow)		2nd approach (loss of flow and delay)	
	Mean	Std	Mean	Std
Ardruicq	1.65	2.25	1.51	2.26
Ardres	0.76	1.1	0.72	1.1
Guines	0.17	0.19	0.15	0.16

on average values of the flow according to the type of tide is proposed. Second, a model of the gate taking into account a delay and loss of flow is proposed. The second approach leads to a better estimation of unknown flow from secondary canals for levels of the canal inside the navigation rectangle. However, the efficiency of this model is losing when the level of the canal is high. It should be necessary to consider a new model for this interval of level. More specifically, a more detailed and systematic modeling approach is required. Techniques from Machine Learning will be investigating to model the dynamics of the gate, integrating delays, non-linearities, and hybrid dynamics, based on real data. This new model will be integrated with already designed control architectures of the Calais canal, and more specifically Hierarchical Model Predictive Control strategy.

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