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# LIFE Sparc

## Sub report 5 – Idealized modelling of FCA and CRT in European estuaries

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Vanlede, J.; Lopez, S.; Bi, Q.; Smolders, S.

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# Abstract

This report describes a standardized method for setting up and automatically calibrating an idealized numerical model of an estuary that can be used to evaluate the functioning and effectiveness of Flood Control Areas with Controlled Reduced Tide (FCA-CRT). Such models were set up for five European estuaries (Scheldt, Elbe, Seine, Humber, Weser) in order to do a quickscan of the potential of a 100ha FCA-CRT at three different locations along the estuary. The functioning of the areas is evaluated for ecological development inside the areas, and for flood protection along the estuary. The presented method is generally applicable to other estuaries, and has only limited data requirements. The results show that inside the areas, a controlled reduced tide of approximately 15–25% of the estuarine tidal amplitude is achievable with a simple design rule for the culverts. One 100ha FCA also provides a reduction of high water levels during storms in the order of 1-5 cm. This effect extends tens of kilometers up- and downstream the location of the FCA, and is most pronounced when the FCA is located at an upstream location.

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# 1 Abbreviations

| Abbreviation | Meaning |
|---|---|
| **ANB** | Agentschap voor Natuur en Bos |
| **CRT** | Controlled Reduced Tide |
| **FCA** | Flood Control Area |
| **(M)LW** | (Mean) Low Water |
| **(M)HW** | (Mean) High Water |
| **RMSE** | Root Mean Square Error |
| **Sparc** | Space for Adaptating the River Scheldt to Climate Change |

# 2 Introduction

LIFE Sparc is a project under the LIFE programme (project number LIFE16 CCA/BE/000107). Sparc is the acronym for “Space for Adapting the River Scheldt to Climate Change”. The LIFE Sparc project proposes nature-based solutions to make the Scheldt estuary and its highly urbanised area more resilient to climate change. The aim is to provide much greater protection against flooding by creating open space for water and developing a robust estuary ecosystem.

The core concept of the nature-based solution combining Flood Control Areas (FCA) and Areas with a Controlled Reduced Tide (CRT) to give “Space to the River” is an original idea that has been developed, implemented and monitored in a pilot project in Flanders, Belgium. The experience gained at the pilot site Lippenbroek (a CRT studied during the LIFE project MARS) combined with the development of 8 additional realizations during this project (actions C1- C8), complemented with additional knowledge gained in this action will be used to assess the applicability of the core concept in other European Estuaries via an idealized modelling approach.

## 2.1 Flood control area with controlled reduced tide (FCA-CRT)

A Flood Control Area (FCA) is a designated zone along a river that can temporarily store excess water during peak flows or storm surges, thereby reducing flood risk for surrounding regions. Traditionally, these areas remain dry most of the time and only flood during extreme events, which often leads to ecological degradation because natural tidal dynamics are lost.

To overcome this limitation, the Controlled Reduced Tide (CRT) concept was introduced. CRT is an innovative hydraulic management system that reintroduces tidal influence into an FCA in a controlled manner. The system operates by allowing water to enter and exit the FCA twice a day, synchronized with the river’s tidal cycle. However, the amplitude of the tide inside the FCA is deliberately reduced. This is achieved by regulating inflow through inlet culverts, which permits only a limited volume of water entering during high tide. As a result, the tidal range within the FCA is smaller than the natural tide, preventing excessive flooding while maintaining essential tidal dynamics. During low tide, water drains back into the river through outlet culverts, mimicking the natural tidal cycle of a tidal river, as illustrated in Figure 1.

This controlled tidal regime creates conditions for the development of tidal marshes and mudflats, restoring habitats for rare species and improving biodiversity. Over time, the FCA-CRT becomes an integral part of the river’s estuarine ecosystem. The CRT principle was pioneered by professor Patrick Meire at the University of Antwerp and is now applied in the Scheldt estuary as part of integrated flood protection and nature restoration strategies.

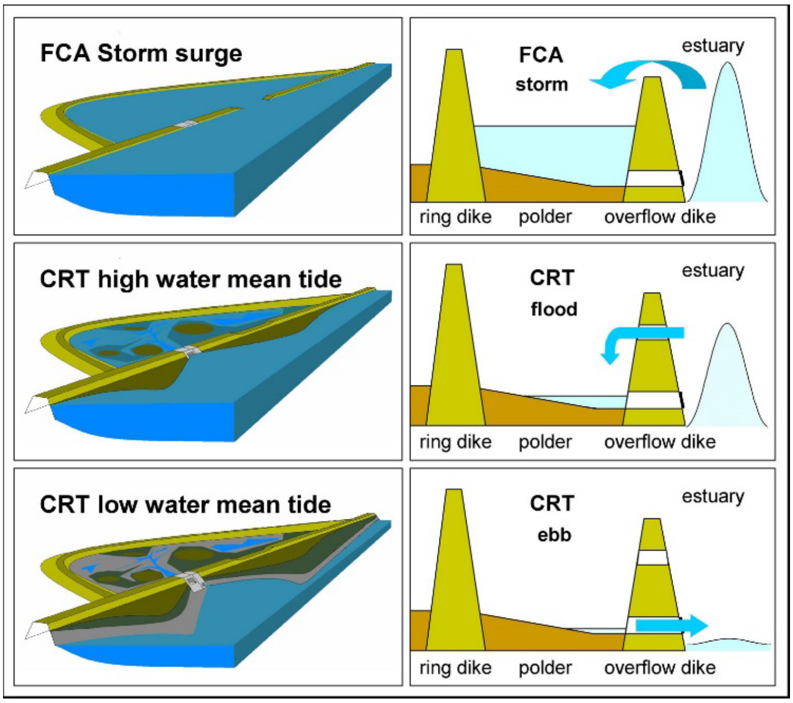



Figure 1 – Operational principle of a Flood Control Area with Controlled Reduced Tide (FCA-CRT)

## 2.2 Applicability in other European estuaries

The CRT technique is often unknown in the other EU member states but can also be used in other estuaries, especially under the following conditions:

- Available space is very limited, which means maximum storage capacity is required when the peak of the storm surge hits.
- The relative altitude of adjacent land is unfavourable in relation to the river, which prevents formation of proper mudflats - tidal marshes in case of depoldering.
- The embankment alongside the river needs to be retained and kept accessible.
- Large tidal fluctuations are undesirable in floodplains.
- Large depoldering operations are undesirable because the fairway is left without sufficient water at times

For the CRT system to function properly, a carefully dimensioned culvert construction with combined inlet and outlet has to be placed at a specific height within the tidal window. This is the only way to secure an appropriate neap-spring tidal variation, which is crucial for the development of mudflats and tidal marshes in the area.

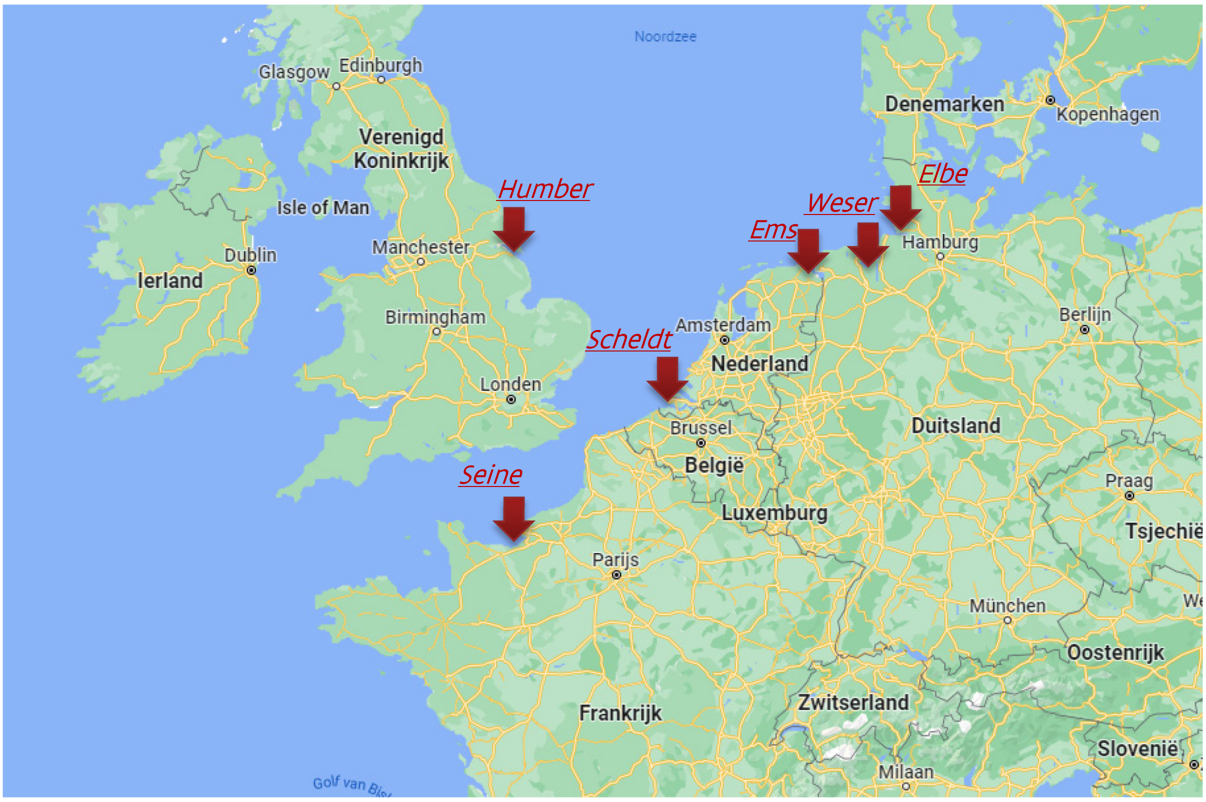



Figure 2 – Overview of the selected european estuaries considered for the "quickscan"

This study aims to perform a quickscan of the applicability of FCA and CRT in other European estuaries to obtain protection against flooding in combination with nature development. Experience in Flanders has shown that it is possible to combine the concept of a flood control area (FCA) with nature development and the functions of intertidal areas, by use of simple culvert constructions to introduce a controlled reduced tide (CRT). The quickscan will be performed in the following European estuaries (Figure 2):

- Scheldt estuary
- Elbe estuary
- Weser estuary
- Humber estuary
- Seine estuary

For each estuary, a numerical model will be created for investigating the effects of FCA-CRT in the domain.

The Ems estuary is omitted from this report, since we did not have access to a set of water level measurements in the Ems. The methods applied in this report are sufficiently general however for this work to be extended to the Ems (or any other estuary) should the data become available.

## 2.3 Idealized modelling instrument

In order to perform knowledge transfer of the FCA-CRT method to other European partners, an idealized modelling approach is proposed as a tool for assessing the applicability for five European estuaries across France, Germany, the Netherlands and the UK. This approach requires schematization of the geometry for each study area (topo-bathymetry schematization), in which the FCA-CRT is modelled (schematization of the measures), and only the important physical processes are considered (schematization of processes).

To investigate the potential effects of FCA-CRT on tidal wave propagation, its ecological functions, and optimizing its design for each estuary, a large number of simulations have to be carried out in order to exhaust all possible combinations. For this reason an effort has been made to automate the modelling process as much as possible.

# 3 Methodology for model set-up and calibration

## 3.1 Estuary schematization

### 3.1.1 Simplified estuarine geometry

In nature, the geometry of the estuary could change dramatically, starting much wider in the mouth region and then converging to a much narrower tidal river towards upstream. The bottom of the estuary usually varies in two directions, along the thalweg of the channel (deeper in the estuary mouth and shallower when it reaches further upstream), and across (deeper in the middle of the channel and shallower when it is close to the banks). When deriving the topo-bathymetry for building an idealised model, it is important to choose an appropriate method to perform schematization. In general, this complex natural geometry can be simplified while maintaining important properties like the characteristics of tidal propagation. In the previous study (Bi et al., 2021), the Scheldt estuary was schematized as a funnel-shaped single channel from the mouth at Vlissingen to the tidal weir and locks at Ghent. The bottom of the schematized domain was kept constant in the cross-section direction but variable in the horizontal direction following the trend of the measured bathymetry.

### 3.1.2 The TIDE dataset

In the framework of the TIDE project (http://www.tide-project.eu/), the topo-bathymetry and the main water level parameters (MHW and MLW) were collected from several European the estuaries including the Elbe, the Humber, the Scheldt, the Seine, and the Weser based on the previous surveys (Vandenbruwaene et al. 2013, Vandenbruwaene et al. 2018). The topo-bathymetric data of an estuary represents its widths and elevations of the subtidal, intertidal, and supratidal areas located within the dyke lines in the domain. The following data is reported and used in the schematization of the topo-bathymetry in this study:

- $Z_{MHW}$: mean high water level
- $Z_{MLW}$: mean low water level
- $A_{MWH}$: wet section area at mean high water level
- $A_{MLW}$: wet section area at mean low water level
- $W_{MHW}$: width at mean high water level
- $W_{MLW}$: width at mean low water level

### 3.1.3 Shape of the schematized estuary

The width at mean water level ($W_{MWL}$) is calculated as ($W_{MHW} + W_{MLW}$)/2) from the TIDE dataset. The derived estuary widths are curve fitted. The specific functions of the fitted widths at mean water level ($W_{MWL}$) for all the five estuaries were described in Bi et al. (2021).

### 3.1.4 Automated mesh generation

Mesh generation was conducted using the Python API for GMSH. The general algorithm for the generation of the mesh consists of the following steps:

1. From the thalweg of the estuary extract the width and bottom elevation of the channel.
2. Curve-fit the bottom elevation and channel's width along the channel's thalweg.
3. Provide the two fitting functions to the GMSH script.
4. At the downstream boundary, the mesh is generated with an edge length of 150m. Upstream, (approximately) the same amount of cells across the width is kept.
5. Generate the mesh.

The topological features of the Estuaries are fitted with N-degree polynomials, unless otherwise specified. The general description of such polynomials is as follows:

$$f(x) = a_0 + \sum_{n=1}^{N}(a_n x^n),$$

With x is the location along the thalweg (in km), N is the polynomial's degree, and the a's are the polynomial's coefficients. For the sake of simplicity, polynomials of order N are presented as follows:

$$f(x) = F(x, a_0, a_1, a_2, \dots, a_n).$$

In the following section a short description of the topological features of each estuary, plus the edge mesh refinement for each case, will be given. The functionals and corresponding coefficients used for the curve fitting of the topological characteristics of the Estuaries will be provided as well.

### 3.1.5 Model set-up

First the Gmsh generated mesh file (.msh) is converted into the SELAFIN format (.slf) of TELEMAC-2D. Then a a boundary condition file (.cli) is created that matches the new mesh. Finally the schematized model is set-up of for execution.

In this study the Python wrapper around the Telemac API (TELAPY) is used to create simulations from a model template and manipulate their inputs, i.e., meshes, steering files, boundary data, etc., to match each individual case to a specific design of FCA-CRT among a large number of combinations, and then submit them to a Linux-based high performance computer for execution. The post-processing is automated in Python.

## 3.2 Autocalibration

Usually the bottom friction is tuned for calibrating a model against measurements, such as water levels and/or velocities at multiple stations across the domain of interest. This is often a manual process and takes a lot of trial and error to find the optimal friction coefficient(s). Especially when the domain is split into multiple friction zones, it requires exhaustive attempts to look for the bottom friction in each zone since changing one friction will influence the others in the rest of the domain. Thus, an autocalibration functionality is preferred to make the entire workflow more efficient. A self-calibration approach is followed in this study, where a cost function is built on the model skill to reproduce the tidal range along the thalweg of each estuary. The measured and calculated tidal range values are used to calculate the Relative Mean Square Error (RMSE), or cost function, for each idealized Estuary. The general algorithm for the autocalibration process thus follows:

1. Run several simulations using TELEMAC (telapy) using different roughness coefficients.
2. Calculate the cost function versus roughness
3. Minimize the cost function.

The tidal range is selected as a metric to optimize, since a good resolution of the tidal range is a direct consequence of the accurate description of several physical processes that occur in the transient phase of a tidally-dominant estuary, such as:

1. Tide amplification due to topographical contractions, both at the bed and banks.
2. Tidal damping due to friction.
3. Reflection of the tidal wave
4. Influence of discharge on tidal propagation.

The tidal range is calculated as the difference between the Mean-High Waters (MHW) and the Low-Mean Waters (MLW) which, in turn, are the mean value of the local maxima and minima for a determined period of time, respectively. An example of the peak detection algorithm is shown in Figure 3.

5.

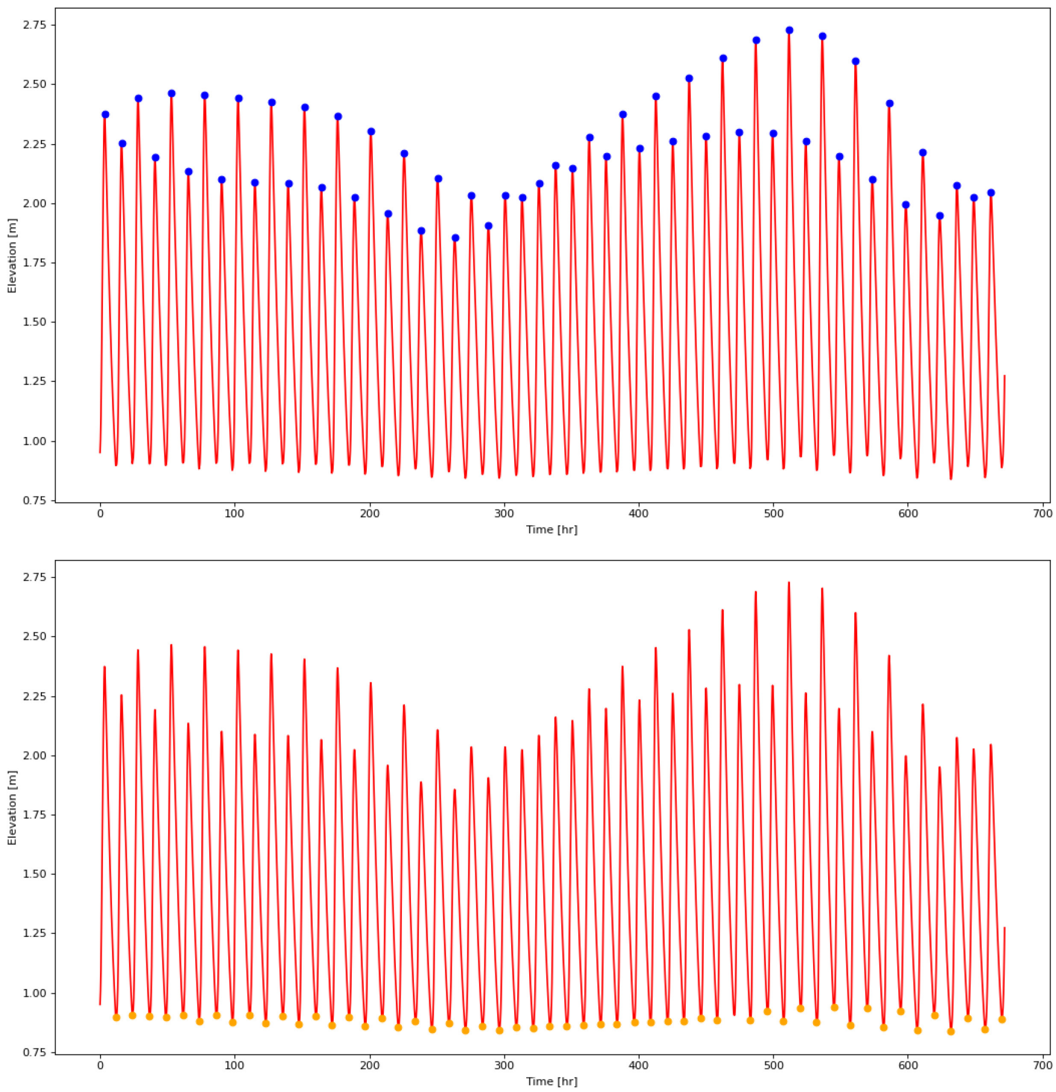



Figure 3 – Peak detection algorithm for local maxima (top panel) and local minima (bottom panel) applied on a water level timeserie from the Elbe estuary.

As cost function, we use the Root-Mean-Square Estimate (RMSE) of the tidal amplitude:

$$RMSE = \sqrt{\frac{1}{N}\sum_{N}(X_{obs} - X_{mod})^2}$$

where Xobs and Xmod are the observations and modelled results, respectively.

Clearly no calibration process over an idealized estuary will give “zero distance” between observations and models given the simplifications that are implied in the schematisation of each reach. The “suitability” of the simplified schematisation can also be verified via the present calibration: not finding a minimum over a range of reasonably adjusted roughness heights may be an indication of problems in the schematisation of the estuary.

The cost-function is minimized using Bayesian Optimization techniques (scipy). This methodology accounts for C0- continuous datasets, such as those obtained by measurements (be it numerical or otherwise). This method is preferred to classical Least-Square minimizations for two reasons:

1. The cost function (RMSE) is not continuous and its “shape” unknown, a priori. One can make assumptions of continuity and shape (parabola), but this hinders the “automation” of the process.
2. Assumes zero error both in measurements and simulations. This is unrealistic even in this case where the absolute model error is unknown. Here, we will admit a 1% noise on the input data. This implies that the accuracy of the calibration’s output is also 1% of the obtained minimum.

The number of simulations run per estuary will be variable, depending on the minimization process.

# 4 Calibrated models of the 6 estuaries

Here, a short description of each estuary will be given, along with the results obtained from the calibration process.

## 4.1 Scheldt

### 4.1.1 System Description

The Scheldt estuary is defined as the part of the river basin under tidal influence. It is a well-mixed estuary opening to the southern North Sea and extends 160 km in length from the mouth at Vlissingen to Ghent, where sluices stop the tidal wave in the Upper Scheldt. The tidal wave also penetrates most of the upstream areas, entering the major tributaries Rupel and Durme, resulting in approximately 235 km of tidal river in the estuary. In the Scheldt estuary at Vlissingen, the tidal amplitude is about four meters. Further inland, the tidal range increases. The further upstream, the narrower the riverbed and the more the incoming floodwater is pushed up. Near Hamme, where the Durme flows into the Scheldt, the river reaches its highest water level. The locks around Ghent block the tide completely and ensure that the river further upstream is no longer influenced by the tide (Vlaams-Nederlandse Schelde Commissie, 2015).

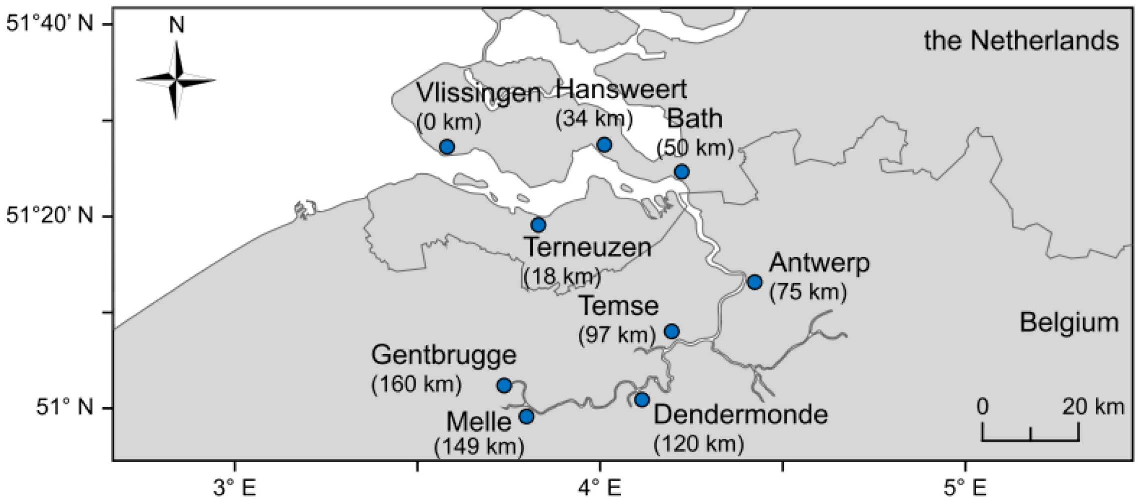



Figure 4 – Map of the tidal part of the Scheldt River from Vlissingen to Ghent (Dijkstra et al., 2019a)

The Scheldt estuary is one of the youngest and most natural estuaries in Western Europe. It consists of an approximately 60 km long fresh water tidal zone stretching from near the mouth of the Rupel tributary (~km 85) to Ghent, representing one of the largest freshwater tidal areas in Western Europe. It has a salinity mixing zone between Rupelmonde and Vlissingen/Breskens. The subtidal delta, seaward of Vlissingen forms the transition between the Western Scheldt and the North Sea. (Fettweis et al., 1998; Kuijper et al., 2004; Meire et al., 2005; van Kessel et al., 2011).

The Scheldt estuary can be divided into two major parts, the Sea Scheldt (Zeeschelde) (length 105 km), which is the Belgian part from Ghent to the Dutch/Belgian boarder, and the Western Scheldt (Westerschelde) (length 58 km), which is the Dutch part covering the middle and lower estuary. The Sea Scheldt consist of one single ebb/flood channel and has a total surface area of 44 km2. Mudflats and marshes in this area are relatively small and approximately account for 28% of the total surface. The Sea Scheldt hosts one of the largest harbours in Europe – the Port of Antwerp. Therefore, human activities are very important in this region and industrial developments are concentrated along the riverbanks. The intertidal zone is often missing or very narrow. The estuary is almost completely canalized upstream of Dendermonde (Hoffmann & Meire, 1997).

The Western Scheldt is a well-mixed region. Due to the influences of tidal waves and land changes, the Western Scheldt has a complex and dynamic morphology. The flood and ebb channels are interconnected, bordered by several large intertidal flats and salt marshes. The surface of the Western Scheldt amounts to 310 km$^2$, of which 35% is intertidal flats. The average channel depth is approximately 15–20 m (Meire et al., 2005).

### 4.1.2 Fitted topology of the river Scheldt

The characteristics of the idealized estuary and mesh refinement are shown in Figure 5.

$$f(x) = F(x, 15.0, -4.346\,E^{-4}, 1.134E^{-8}, -1.151E^{-13}, 3.727E^{-19}),$$

$$g(x) = F(x, 1.897, -2.742E^{-5}),$$

$$z(x) = F(x, 1.0, 9.213E^{-6}, 4.979E^{-11})$$

The function descriptor for the bottom elevation D(x) is the following:

$$-D(x) = \begin{cases} f(x), & x < 129.1\,km \\ f(129.1\,km) + f'(129.1)(x - 129.1), & x \geq 129.1\,km \end{cases}$$

For the width of the channel the following descriptor is applied:

$$W(x) = 1000e^{g(x)/z(x)}$$

Notice that the edge length of the mesh is directly proportional to W(x). A thorough description of the data fitting process is given in Bi et al. (2021). The final mesh is shown in Figure 6.

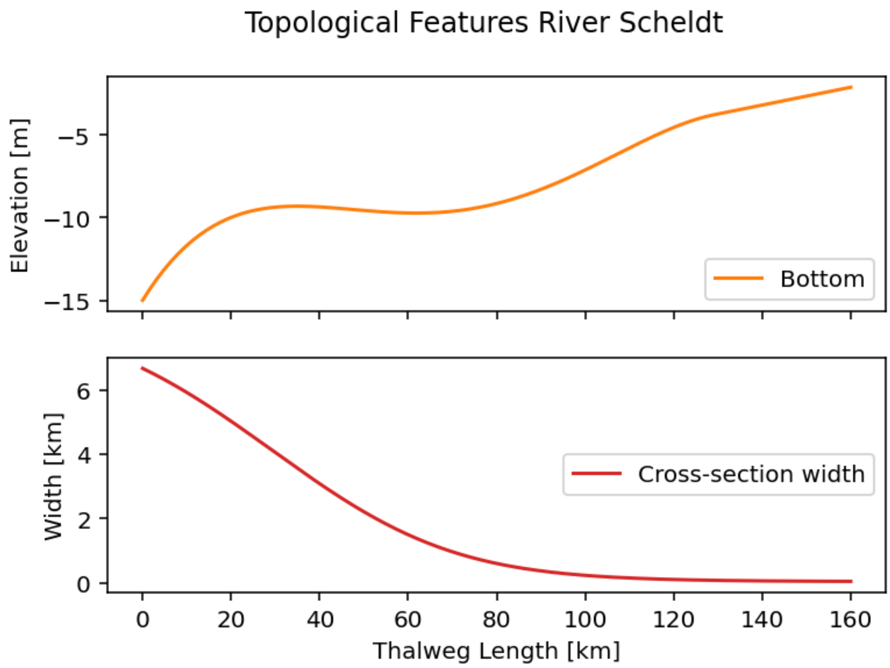



Figure 5 – Characteristics of the River Scheldt.

Table 1 – Geometric characteristics of the Scheldt

| Parameter [unit] | Symbol | Value |
|---|---|---|
| Width at the mouth [m] | W(0) | 6665 |
| Length [km] | L | 160.0 |

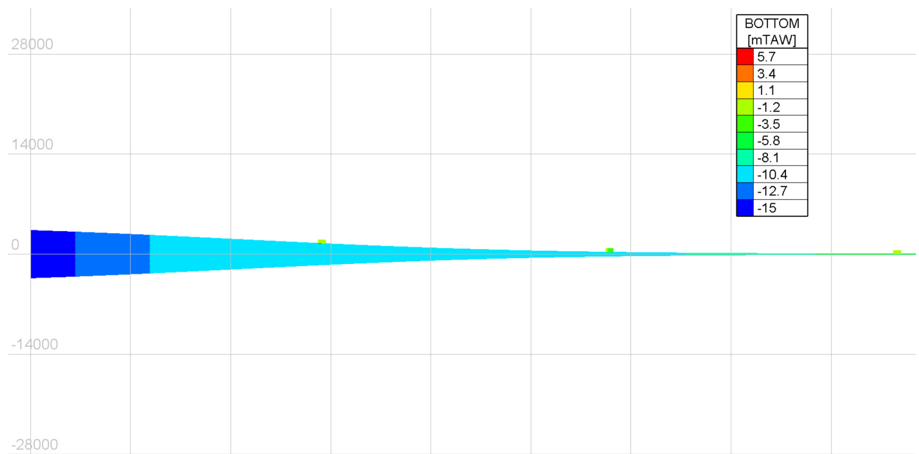



Figure 6 – Mesh of the Scheldt

### 4.1.3 Calibration of the roughness

Simulations on the idealized model are run for a period of 40 days simulation time, with a time step of 1 second. Further model characteristics are shown in Table 2.

Table 2 – Model characteristics of the Scheldt

| Parameter [unit] | Value |
|---|---|
| Downstream M2 tidal amplitude [m] | 1.79 |
| Upstream discharge [m³/s] | 60 |

The Nikuradse's equivalent roughness is used as an independent variable for the calibration process. The tidal range is extracted from the thalweg of the *idealized* estuary, that is, the axis of symmetry of the mesh. Results are shown in Figure 7.

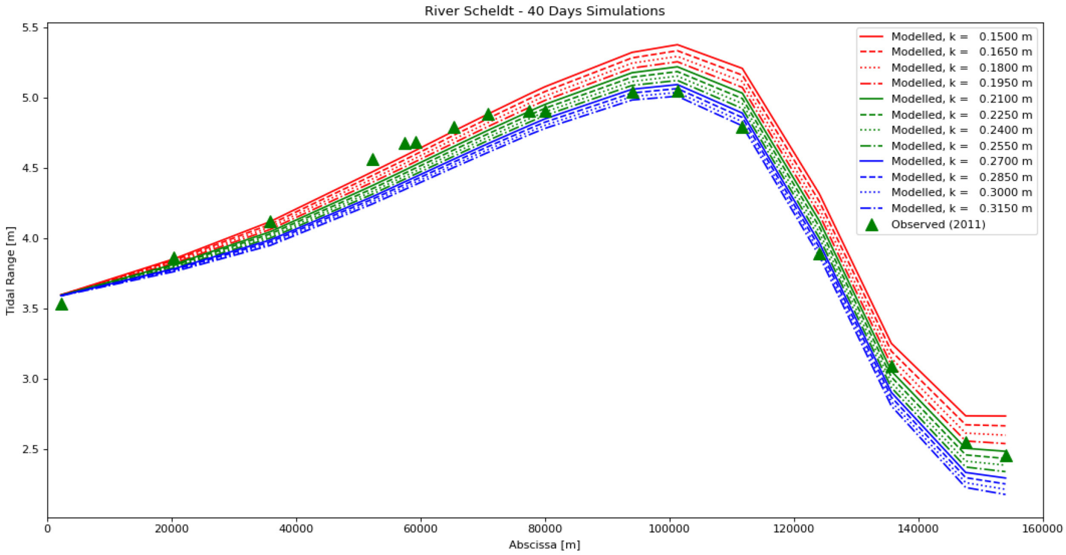



Figure 7 – Modelled and observed tidal range for the River Scheldt.

A classical Bayesian minimization process is used for the calibration of the roughness against experimental data. A visual result of the calibration process is shown in Figure 8. The optimal Nikuradse's roughness parameter for the Idealized model of the Scheld is k* = 0.2086 ± 0.0021 m with an RMSE of tidal amplitude of 11cm, which is about 3% of the tidal amplitude at the mouth.

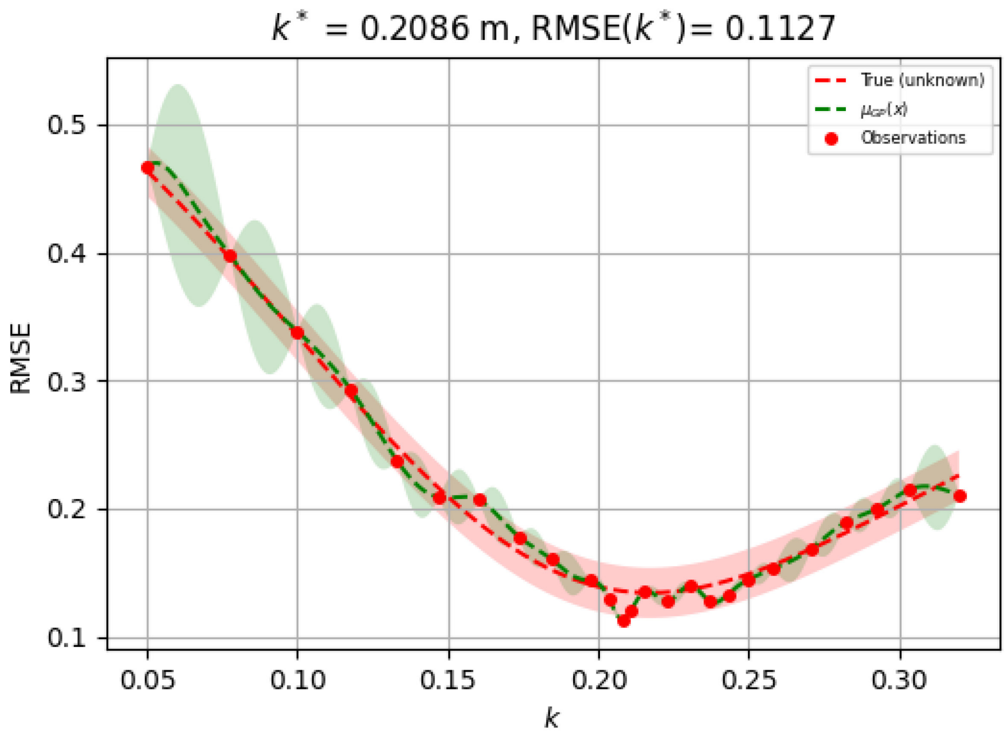



Figure 8 – Bayesian minimization process for the River Scheldt. “Observations” stand for model runs during the Calibration process

## 4.2 Elbe

### 4.2.1 System description

The Elbe Estuary is comprised of the lower reaches between the weir at Geesthacht and the transition to the North Sea. As long as no storm-tide conditions prevail, the tidal influence of the Elbe estuary is limited by the Geesthacht weir. From the Geesthacht weir to Bunthaus (near Hamburg), which is situated 20 km further downstream, the Elbe has a typical width of 300 – 500 m. This area is called the “Upper Tidal Elbe”. At Bunthaus, the River branches out into the Northern and Southern Elbe. The reunited Elbe continues as a river measuring around 500 m in total width. Seven kilometres further downstream, the river abruptly widens to 2.5 km at the Elbe bay called Mühlenberger Loch (Boehlich *et al.,* 2008). The “Lower Elbe” is a 108 km long section of the river Elbe, from western Hamburg downstream to its mouth into the North Sea near Cuxhaven. Starting at Mühlenberger Loch, it gradually widens from 2 km to 18 km. The economic importance of the Elbe Estuary is mainly due to its role as the most important shipping route for international maritime traffic.

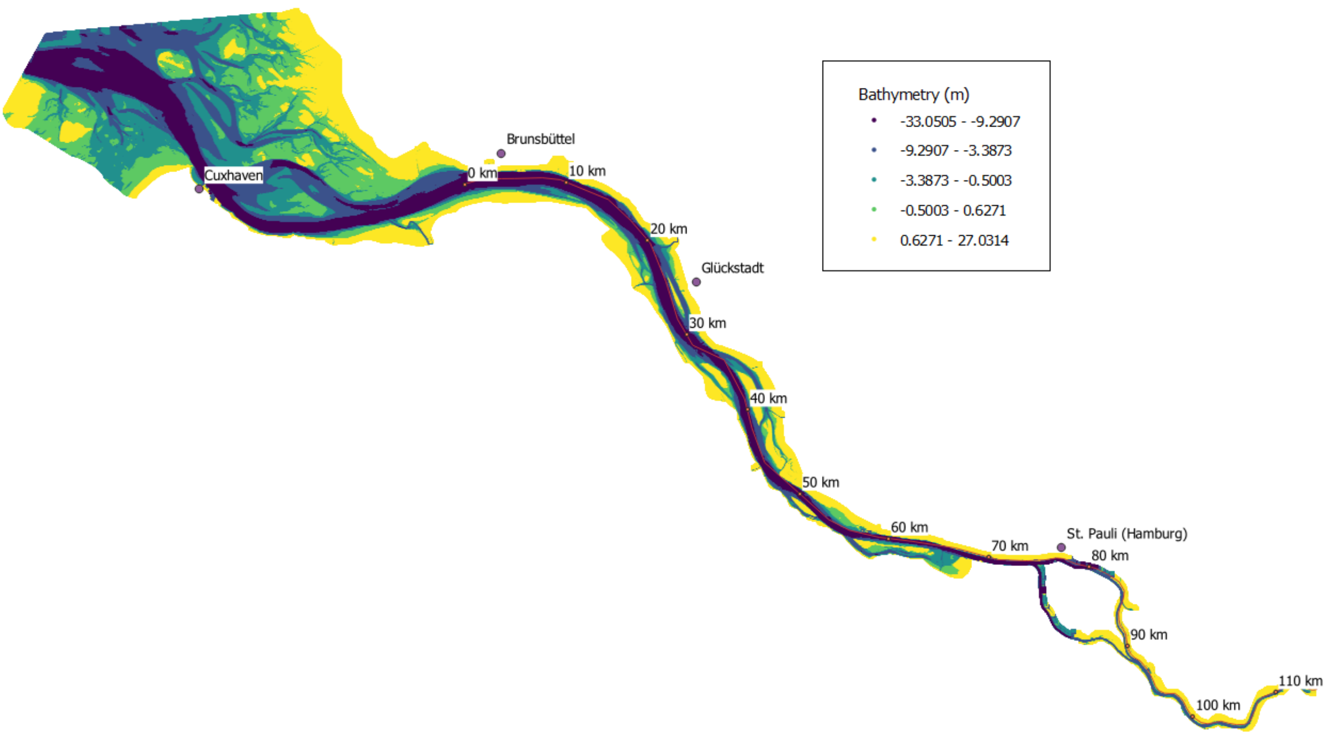



Figure 9 – Overview of the Elbe estuary

The mean freshwater discharge at Neu Darchau is 722 $m^3$/s, calculated over the time period 2001-2010. For a typical dry event (low discharge, P5) the discharge is 247 $m^3$/s, for a typical flushing event (P95) this is 1709 $m^3$/s. Low discharges are common during summer, whereas flushing events are more typical during winter. For the Elbe, the main channel discharge (i.e. discharge at Neu Darchau) is about 100 times larger than the tributary discharges, and hence tributary discharges are negligible. From the mouth to 74 km, the mean and maximum ebb and flood flow velocities respectively range between 0.2 and 0.9 m/s, and between 0.4 and 1.3 m/s. High discharge conditions result in higher ebb flow velocities and lower flood flow velocities compared to low discharge conditions (summer). At the most upstream part of the estuary, this effect is even more pronounced (74 – 114 km): close to the up-estuary boundary, the high freshwater discharge results in the absence of a flood flow velocity (value zero, only vertical tide), but clearly reaches higher values for the ebb flow velocity (up to 1.5-2 m/s).

The Elbe is a well-mixed estuary where it takes about 76 km for the mean salinity profile to decrease from 30 PSU to 1 PSU (i.e. a mean salinity gradient of 0.38 PSU/km). During periods with low (typical during summer) and high discharges (typical during winter), the salinity in the estuary is respectively higher and lower compared to the mean salinity profile. The maximum difference between the summer and winter salinity profiles is about 16 PSU, whereas the maximum variation between low water and high water is about 12 PSU for the winter, and 7 PSU for the summer (Vandenbruwaene *et al.* 2013).

### 4.2.2 Fitted topology of the river Elbe

The characteristics of the idealized estuary and mesh refinement are shown in Figure 10. The following polynomials are used for curve fitting:

$$f_1(x) = F(x, 1.88E^{-04}, -5.35E^{-03}, 4.07E^{-02}, -1.68E^{-02}, -1.09825134E^{01})$$

$$f_2(x) = F(x, -2.69E^{-08}, 5.10E^{-06}, -3.11E^{-04}, 3.41E^{-03}, 3.37E^{-01}, -1.24e^{+01}, 1.15e^{+02})$$

$$f_3(x) = F(x, 6.20E^{-04}, -1.87E^{-01}, 2.12E^{+01}, -1.07E^{+03}, 2.02E^{+04})$$

$$f_4(x) = F(x, -1.97E^{-03}, 5.02E^{-01}, -3.34E^{+01})$$

$$f_5(x) = F(x, 4.63E^{1}, -3.48E^{3})$$

$$f_6(x) = F(x, -6.61E^{-1}, 7.31E^{1}, -1.31E^{3})$$

The function descriptor for the bottom elevation D(x) is the following:

$$D(x) = \begin{cases} f_1(x) & x < 20.0 \\ f_2(x) & 20.0 \leq x < 66.0 \\ f_3(x) & 66.0 \leq x < 82.0 \\ f_4(x) & x \geq 82.0 \end{cases}$$

For the width of the channel the following descriptor is applied:

$$W(x) = f_5(x) \tanh\left(\frac{x - 82.0}{12.0}\right) + f_6(x)$$

Notice that the edge length of the mesh is directly proportional to W(x). A thorough description of the data fitting process is given in Bi et al. (2021). The final mesh is shown in Figure 10.

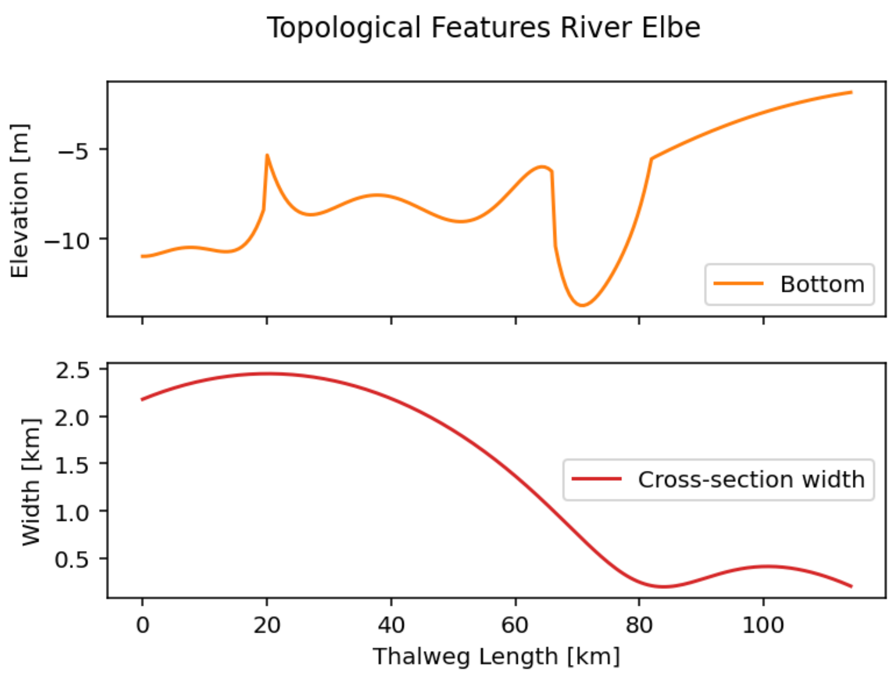



Figure 10 – Characteristics of the River Elbe

Table 3 – Geometric characteristics of the Elbe

| Parameter [unit] | Symbol | Value |
|---|---|---|
| Width at the mouth [m] | W(0) | 2175.0 |
| Length [km] | L | 114.0 |

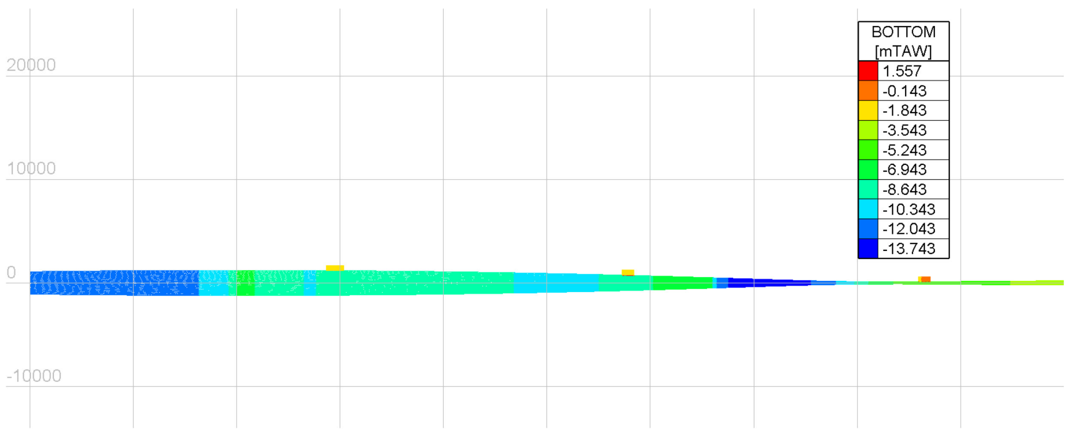



Figure 11 – Mesh of the Elbe.

### 4.2.3 Calibration of the roughness

Simulations on the Idealized model are run for a period of 40 days simulation time, with a time step of 1 second. Further model characteristics are shown in Table 4.

Table 4 – Model characteristics of the Elbe

| Parameter [unit] | Value |
|---|---|
| Downstream M2 tidal amplitude [m] | 1.44 |
| Upstream discharge [m³/s] | 722 |

The Nikuradse's equivalent roughness is used as an independent variable for the calibration process thus each simulation is run with an increasing synthetic roughness for a period of 40 calendar days. The tidal range is extracted from the thalweg of the *idealized* estuary, that is, the axis of symmetry of the mesh. Results are shown in Figure 12.

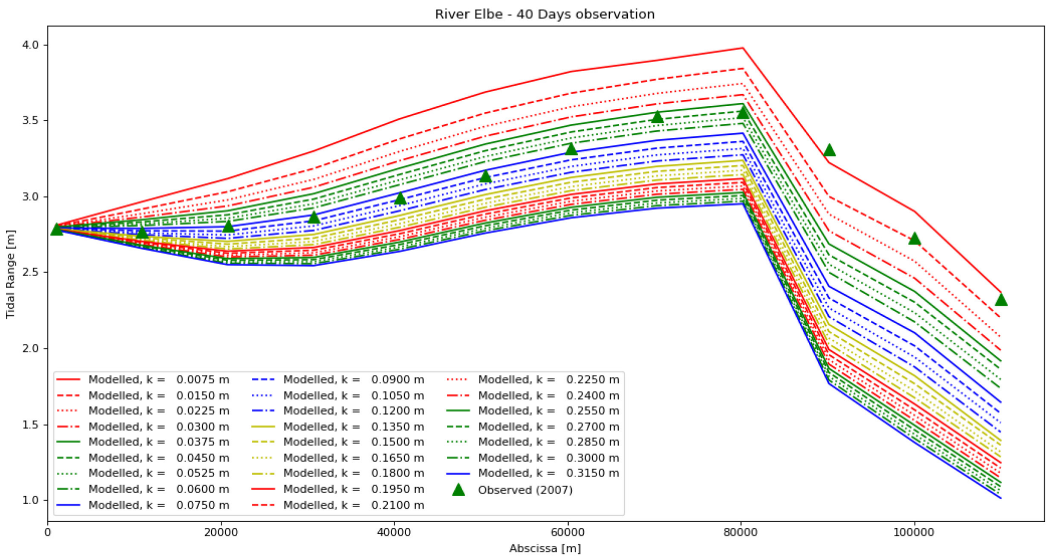



Figure 12 – Modelled and observed tidal range for the River Elbe

A classical Bayesian minimization process is used for the calibration of the roughness against experimental data. A visual result of the calibration process is shown in Figure 8. The optimal Nikuradse's roughness parameter for the Idealized model of the Elbe is k* = 0.0293 ± 0.0003 m with an RMSE of tidal amplitude of 22cm, which is about 8% of the tidal amplitude at the mouth.

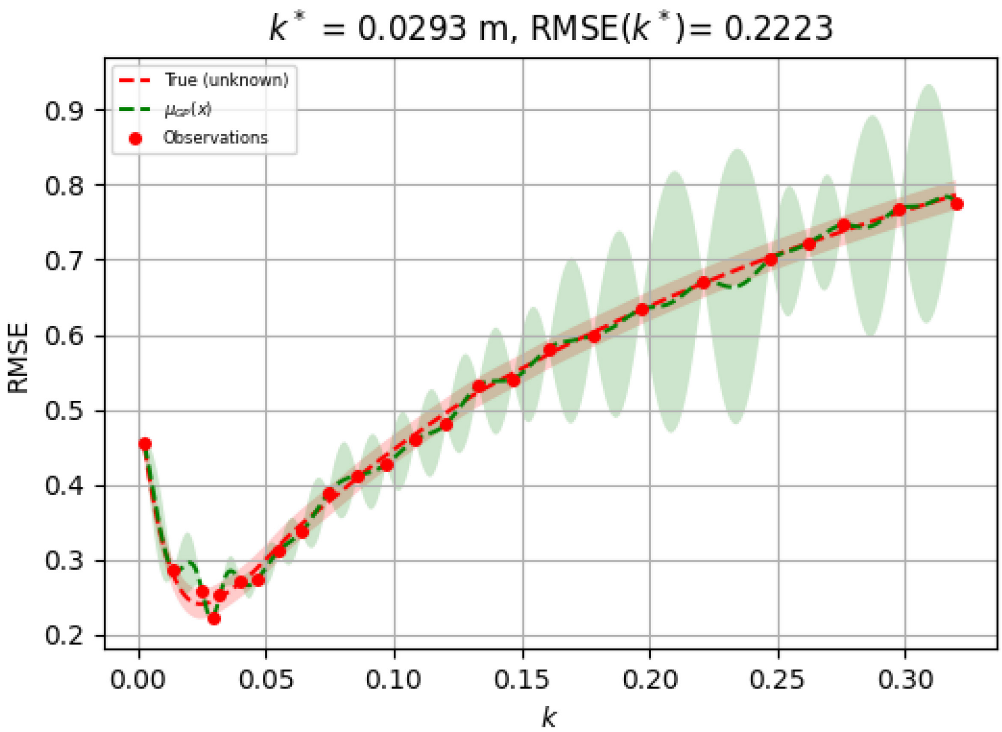



Figure 13 – Bayesian minimization process for the River Elbe. “Observations” stand for model runs during the Calibration process

## 4.3 Seine

### 4.3.1 System description

The Seine estuary is open to the English Channel, on the north-west coast of France and is about 160 km long. At the mouth, the tidal range reaches 7 m during spring tides. The river has a mean discharge of 480 $m^3/s$, draining a basin of 74,000 km2 where 40% of the French population and industry is concentrated (Brenon *et al.,* 1999).

The present-day tide-dominated Seine estuary displays a typical funnel shape. The morphology of the estuary is mostly artificial, resulting from its adaptation to man-made modifications. The Seine has been channelized and dredged 120 km upstream from the mouth to allow navigation from the sea to the inland port of Rouen. At the mouth, intensive dredging is necessary to maintain water depth at 5-6 m below the zero sea level; the width of this channel decreases from 1,000 m at the mouth to only 200 m, 30 km upstream (Lesourd *et al.,* 2001).

The Seine estuary is a converging estuary with a strong decrease in width along the mouth area, and a gentle decrease in width along the section Honfleur towards the up-estuary boundary. In the mouth area the width ranges between 15 km and about 1 km, while upstream Honfleur the range is between 800 m and 100 m. From 125 km up to 160 km the difference in width between MHW and MLW is the largest, demonstrating that this section has the largest area in tidal flats. The cross-section averaged depth at MHW is for the largest part of the Seine estuary around 10 m. Only upstream Rouen there is a strong decrease in cross-section averaged depth with values around 5 m. This difference in depth can be explained by the deepening and maintenance of the fairway downstream Rouen, in order to make the harbour of Rouen accessible for vessels. The change in thalweg depth1 along the Seine estuary is comparable with the change in cross-section averaged depth (Vandenbruwaene et al., 2013).

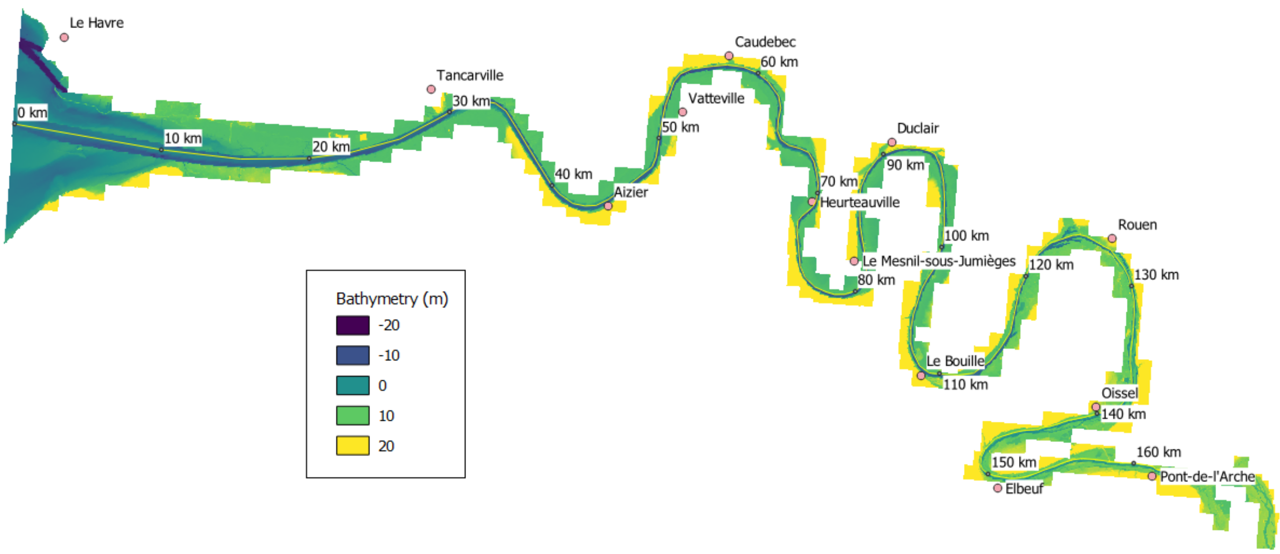



Figure 14 – Overview of the Seine estuary

The Seine is a macrotidal estuary; at the mouth (Le Havre), tidal amplitude varies from 3 m at neap tides to 7.5 m at spring tides. This estuary is hypersynchronous; the maximum tidal amplitude is up to 8 m within the estuary. The dynamic tidal upstream limit is represented by Poses Dam, 160 km inland. Tidal currents are strong in the estuary; flood currents whose velocity can reach 2.5 m/s during spring tides predominate. The estuary is relatively well sheltered from swells originating in the western English Channel (Lesourd *et al.,* 2001). Local winds induce dominant waves from west to north-west. Seaward of the estuary, the wave period is 4 to 5 s, with a decennial maximum significant height of about 5 m (Laboratoire Central d'Hydraulique de France, 1973). Wave action affects the lower water depths (a few meters), below which tidal currents predominate (Larsonneur *et al.,* 1982).

### 4.3.2 Fitted topology of the river Seine

The characteristics of the idealized estuary and mesh refinement are shown in Figure 15. The following polynomials are used for curve fitting:

$$f_1(x) = F(x, -1.70E^{+00}, -5.81E^{-01}, 4.43E^{-02}, -1.54E^{-03}, 2.57E^{-05}, -1.99E^{-07}, 5.80E^{-10})$$

$$f_2(x) = F(x, -1.39E^{+03}, 3.06E^{+01}, -2.24E^{-01}, 5.49E^{-04})$$

$$f_3(x) = F(x, 1.07E^{+02}, -2.48E^{+01})$$

$$f_4(x) = F(x, -1.97E^{-03}, 5.02E^{-01}, -3.34E^{+01})$$

The function descriptor for the bottom elevation D(x) is the following:

$$D(x) = \begin{cases} f_1(x) & x < 114.5 \\ f_2(x) & x \geq 114.5 \end{cases}.$$

For the width of the channel the following descriptor is applied:

$$W(x) = 1000e^{f_3(x)/f_4(x)}$$

Notice that the edge length of the mesh is directly proportional to W(x). A thorough description of the data fitting process is given in Bi et al. (2021). The final mesh is shown in Figure 16.

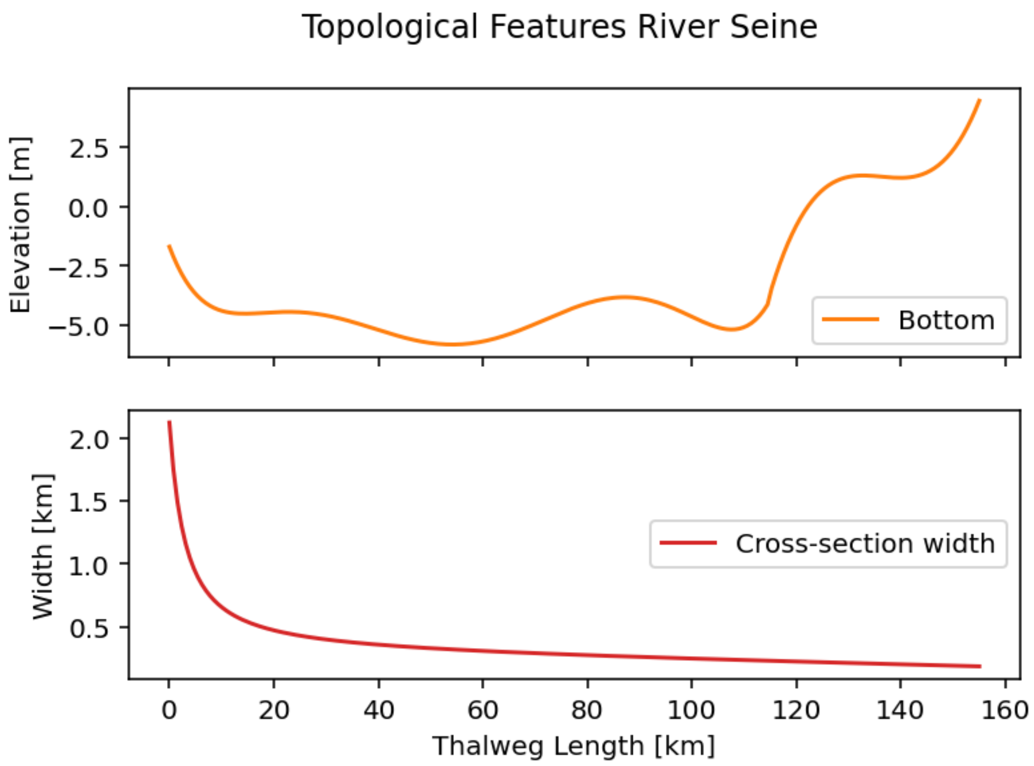



Figure 15 – Characteristics of the River Seine

Table 5 – Geometric characteristics of the Seine

| Parameter [unit] | Symbol | Value |
|---|---|---|
| Width at the mouth [m] | W(0) | 2120 |
| Length [km] | L | 150.0 |

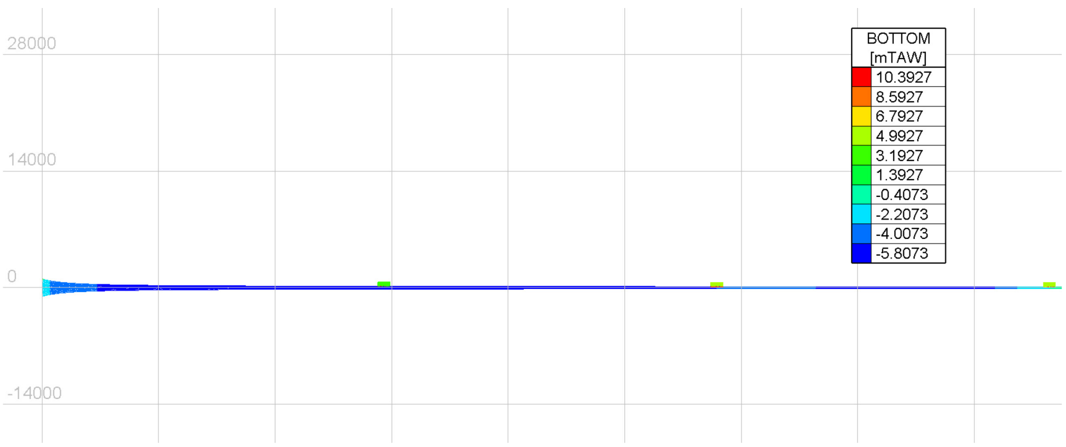



Figure 16 – Mesh of the Seine

### 4.3.3 Calibration of the roughness

Simulations on the Idealized model are run for a period of 40 days simulation time, with a time step of 1 second. Further model characteristics are shown in Table 6.

Table 6 – Model characteristics of the Seine

| Parameter [unit] | Value |
|---|---|
| Downstream M2 tidal amplitude [m] | 2.65 |
| Upstream discharge [m³/s] | 480 |

The Nikuradse's equivalent roughness is used as an independent variable for the calibration process thus each simulation is run with an increasing synthetic roughness for a period of 40 calendar days. The tidal range is extracted from the thalweg of the *idealized* estuary, that is, the axis of symmetry of the mesh. Results are shown in Figure 17.

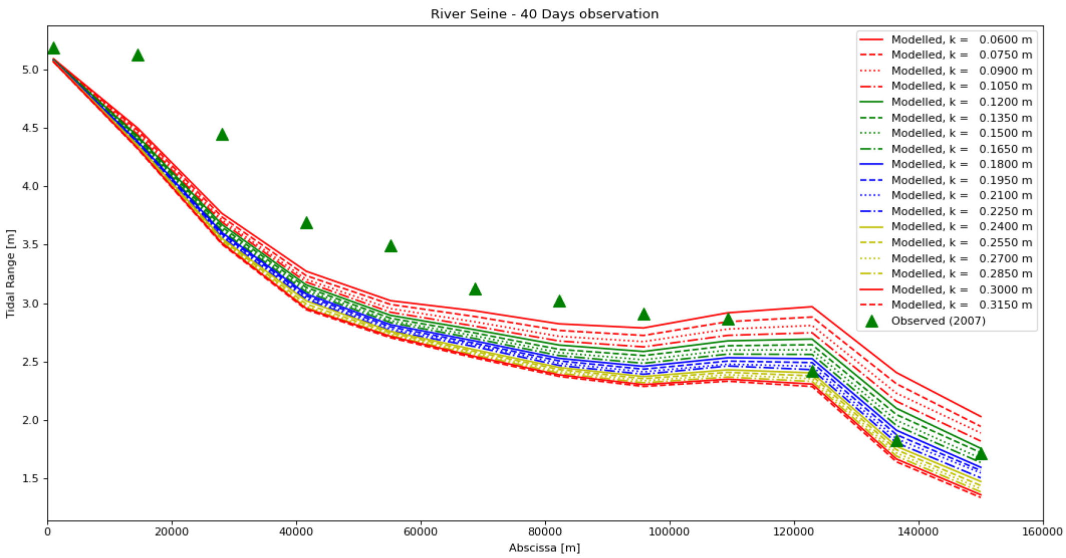



Figure 17 – Modelled and observed tidal range for the River Seine

A classical Bayesian minimization process is used for the calibration of the roughness against experimental data. A visual result of the calibration process is shown in Figure 18. The optimal Nikuradse's roughness parameter for the Idealized model of the Seine is k* = 0.0917 ± 0.001 m with an RMSE of tidal amplitude of 40cm, which is about 8% of the tidal amplitude at the mouth.

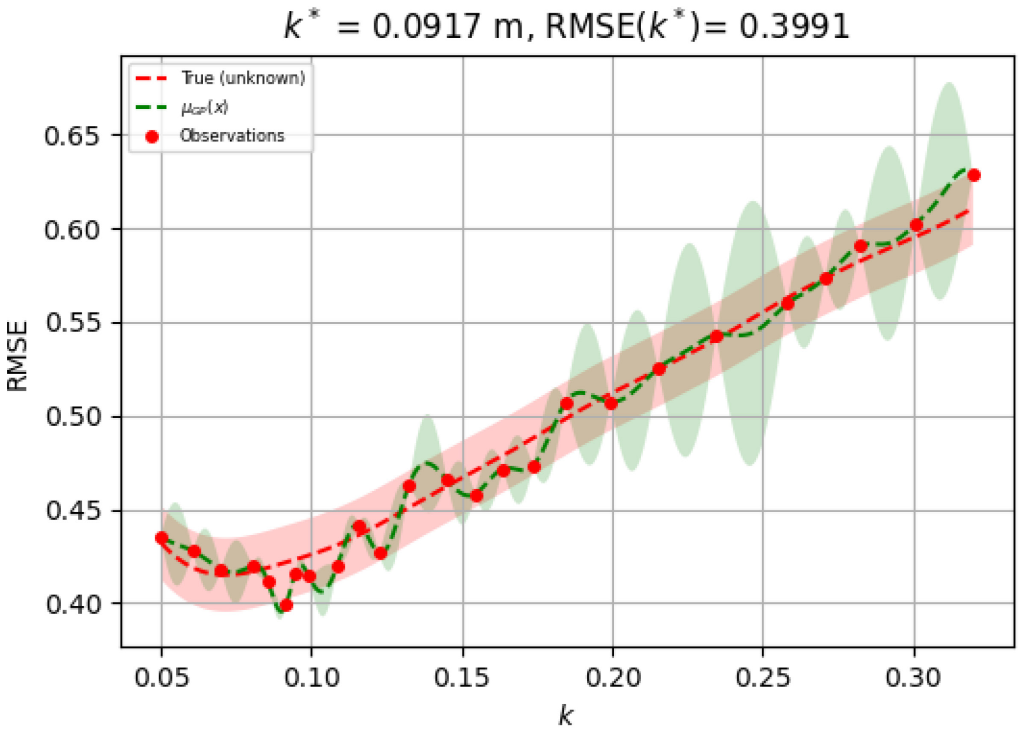



Figure 18 – Bayesian minimization process for the River Seine. “Observations” stand for model runs during the Calibration process

## 4.4 Humber

### 4.4.1 System description

The Humber is a large tidal estuary on the east coast of Northern England. It is formed at Trent Falls, Faxfleet, by the confluence of the tidal rivers Ouse and Trent. From there to the North Sea, it forms part of the boundary between the East Riding of Yorkshire on the north bank and North Lincolnshire on the south bank. The tidal Trent is a canalised estuary approximately 80 km in length, stretching from Cromwell Weir in the south to the Humber confluence at Trent Falls in the north. The tidal Ouse is approximately 60 km long, stretching from Naburn Weir, near York, to Trent Falls at the downstream end, and has several tributaries: the Wharfe, which joins the main channel at Cawood, Derwent at Drax, Aire at Asselby and Don at Goole (Mitchell *et al.,* 1999).

The Humber estuary is a typical converging estuary, mainly from 2 km to 32 km. The thalweg depth clearly decreases from the mouth up to 24 km, whereas the decrease from 24 km up to the up-estuary boundary is more gentle. The Humber-Ouse estuary can be considered as a multi-channel system from 19 km up to the junction with the Trent. The Ouse, Trent, and the most downstream part of the Humber (downstream 19 km) can be considered as single channel systems (i.e. only one subtidal channel). The decrease from mouth to up-estuary boundary in estuary width and/or estuary depth results in a decrease of the wet section. The mean freshwater discharge at Skelton (Ouse up-estuary boundary) and North Muskam (Trent upestuary boundary) is respectively 44 and 72 $m^3/s$ for the year 2010. Including the Trent, the Ouse and all tributaries of the Ouse (Wharfe, Derwent, Aire and Don), this results in a mean discharge into the Humber of 209 $m^3/s$. During flushing events (P95, typical during winter) and dry events (P5, typical during summer) the discharge at Skelton is respectively 143 and 9 $m^3/s$, and at North Muskam respectively 177 and 29 $m^3/s$ (Vandenbruwaene et al., 2013).

The Humber is a well-mixed estuary where it takes about 60 km for the mean salinity profile to decrease from 30 PSU to 1 PSU (i.e. a mean salinity gradient of 0.48 PSU/km). During periods with low (typical during summer) and high discharges (typical during winter), the salinity in the estuary is respectively higher and lower compared to the mean salinity profile. The maximum difference between the summer and winter salinity profile is nearly 16 PSU, whereas the maximum variation between low water and high water is about 6 PSU for winter and summer (Vandenbruwaene et al., 2013).

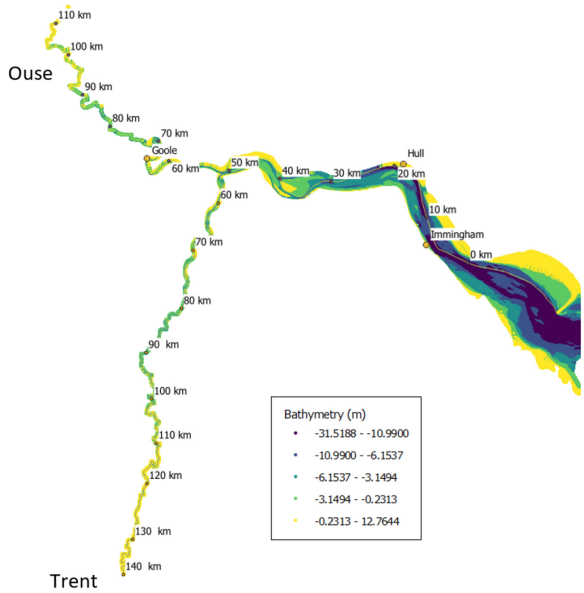



Figure 19 – Overview of the Humber Estuary

### 4.4.2 Fitted topology of the river Humber

The characteristics of the idealized estuary and mesh refinement are shown in Figure 20. The following polynomials are used for curve fitting:

$$f_1(x) = F(x, -0.6, -2.55E^{-5})$$

$$f_2(x) = F(x, 8.95E^{+02}, -7.02E^{+01}, 5.95E^{+00}, -2.44E^{-01}, 4.18E^{-03}, -2.50E^{-05})$$

The function descriptor for the bottom elevation D(x) is the following:

$$-D(x) = f_1(x)\tanh\left(\frac{x - 13000.0}{5000.0} + 1.0\right) + 10.0$$

For the width of the channel the following descriptor is applied:

$$W(x) = f_2(x)$$

Notice that the edge length of the mesh is directly proportional to W(x). A thorough description of the data fitting process is given in Bi et al. (2021). The final mesh is shown in Figure 21.

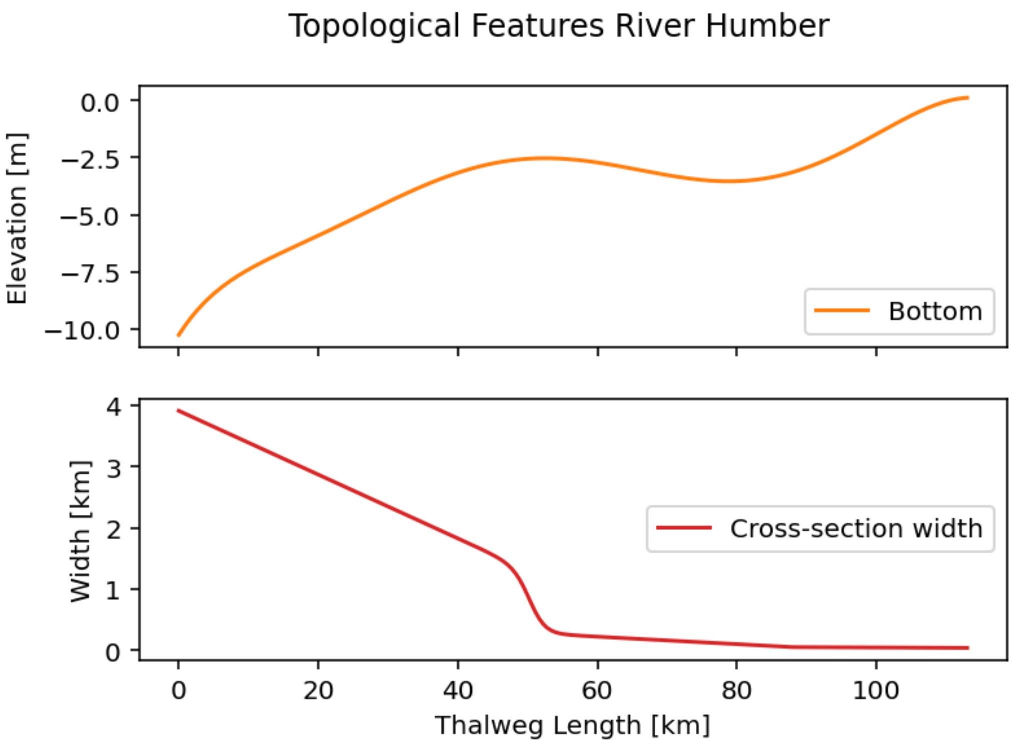



Figure 20 – Characteristics of the River Humber.

Table 7 – Geometric characteristics of the Humber

| Parameter [unit] | Symbol | Value |
|---|---|---|
| Width at the mouth [m] | W(0) | 3913 |
| Length [km] | L | 113.0 |

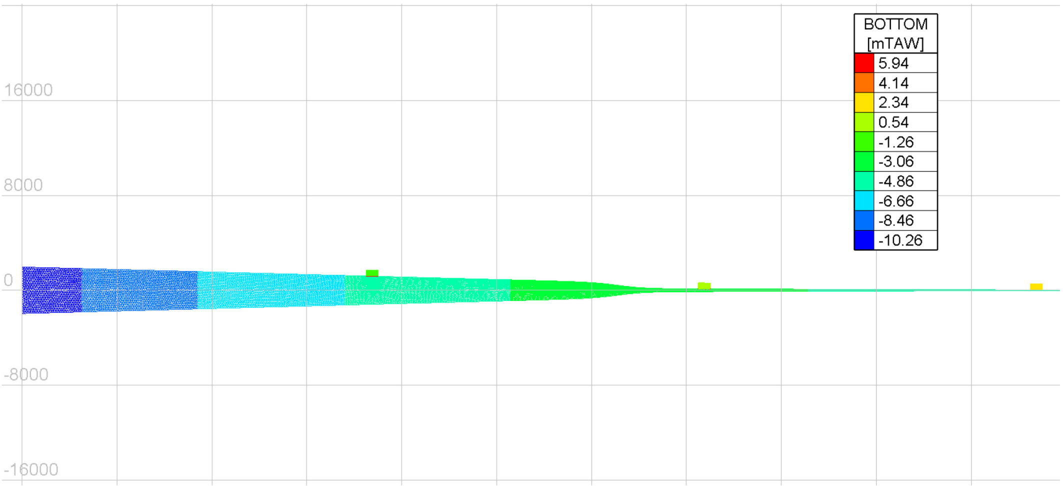



Figure 21 – Mesh of the Humber.

### 4.4.3 Calibration of the roughness

Simulations on the Idealized model are run for a period of 40 days simulation time, with a time step of 1 second. Further model characteristics are shown in Table 8.

Table 8 – Model characteristics of the Humber

| Parameter [unit] | Value |
|---|---|
| Downstream M2 tidal amplitude [m] | 2.25 |
| Upstream discharge [m³/s] | 209 |

The Nikuradse's equivalent roughness is used as an independent variable for the calibration process thus each simulation is run with an increasing synthetic roughness for a period of 40 calendar days. The tidal range is extracted from the thalweg of the *idealized* estuary, that is, the axis of symmetry of the mesh. Results are shown in Figure 22.

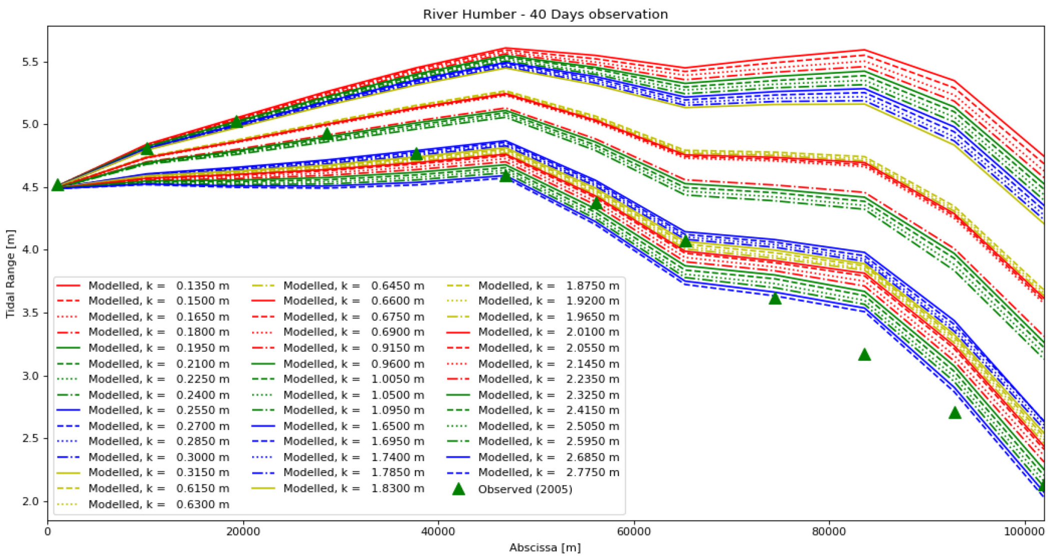



Figure 22 – Modelled and observed tidal range for the River Humber

A classical Bayesian minimization process is used for the calibration of the roughness against experimental data. A visual result of the calibration process is shown in Figure 23. The optimal Nikuradse's roughness parameter for the Idealized model of the Humber is k* = 2.309 ± 0.023 m with an RMSE of tidal amplitude of 25cm, which is about 5% of the tidal amplitude at the mouth.

Note the very high value of uniform roughness that results from the automatic calibration. We believe this is related to the strongly tapering shape, with a sudden narrowing of the estuary around km 50 (see Figure 20), combined with the fact that we only schematise the Ouse tributary, thereby neglecting the Trent. If the simplified geometry of the Humber does not capture important elements, in our method this can only get compensated with the roughness value, leading to unrealistically high (or low) values. The observations in Figure 22 point to tidal amplification in the first 20km, with tidal damping dominant further upstream. All models with uniform roughness and the simplified geometry however, show tidal amplification until ~km45. This points to something missing in the physical description in the model that merits further research.

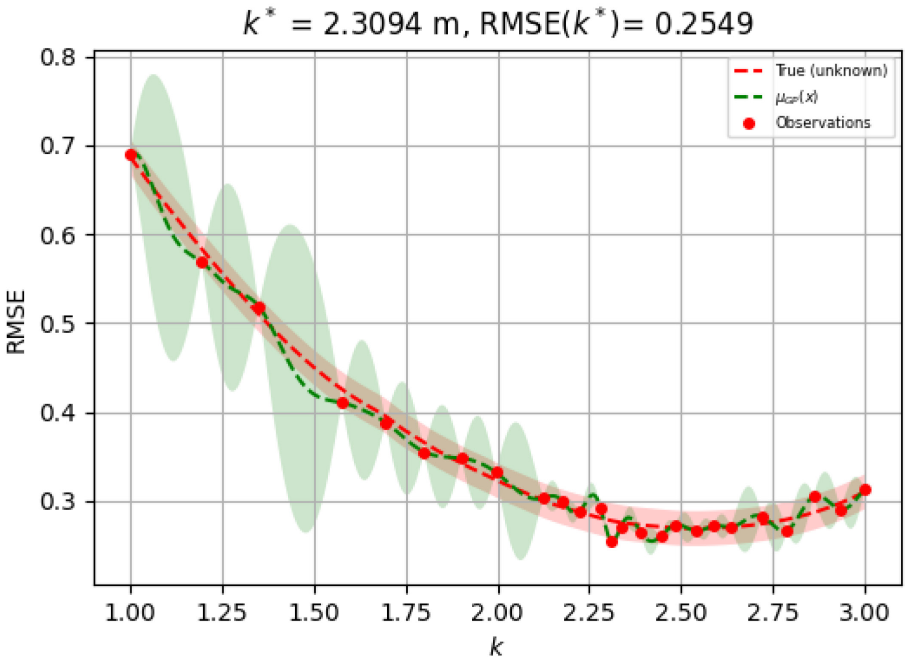



Figure 23 – Bayesian minimization process for the River Humber. “Observations” stand for model runs during the Calibration process

## 4.5 Weser

### 4.5.1 System description

The Weser estuary discharges into the southern North Sea. The upper mesotidal to lower macrotidal Weser estuary is located along the southern North Sea coast of Germany. It is a heavily engineered estuary, having been repeatedly deepened and straightened for use as a major navigation channel for large ships up to the city of Bremen (Franzius, 1991; Wienberg, 2003). As a consequence, the range of the semidiurnal tide at Bremen has increased from about 0.13 m in 1882 to over 4 m in 1990 (Bundesanstalt für Gewässerkunde, 1992).

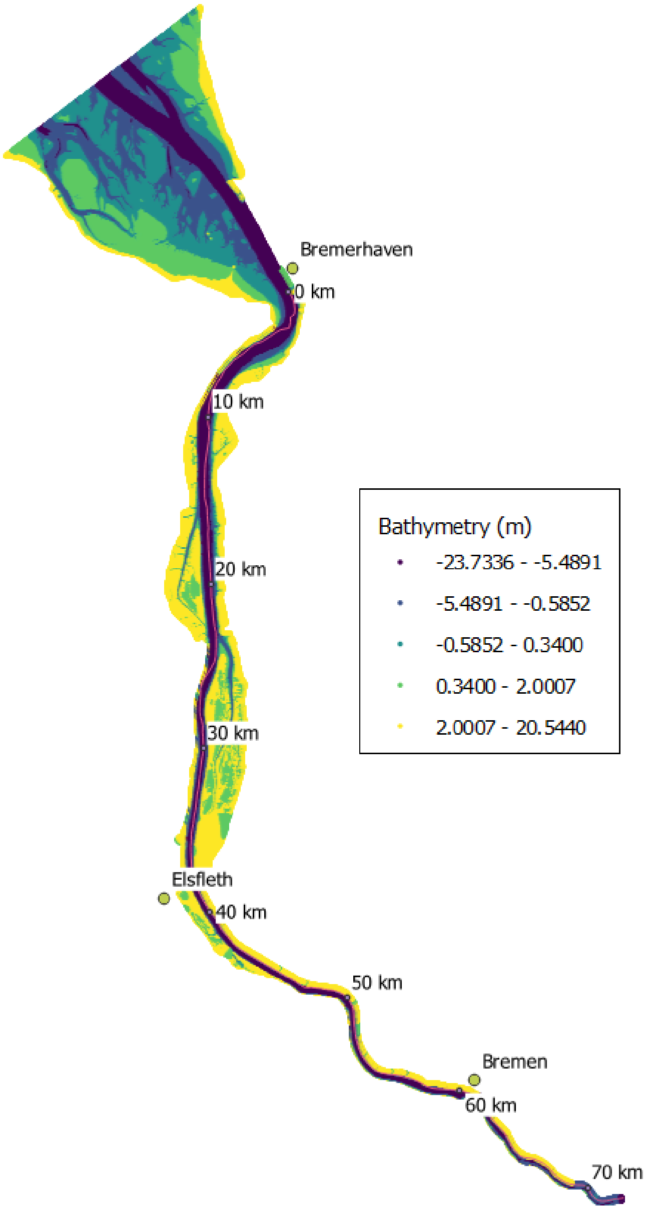



Figure 24 – Overview of the Weser Estuary

The tidally influenced stretch of the Weser is about 120 km long, extending from the weir at Bremen to the open North Sea. The seaward limit has been defined as the location where salinity levels are almost constant over individual tidal cycles, irrespective of seasonal fluctuations (Grabemann and Krause, 2001). The Weser estuary is the shipping channel to the harbours of Bremen and Bremer-haven. The estuary can be subdivided into an upper, channel-like section between Bremen and Bremerhaven, with a sustained navigation depth of 9 m at low-water springs, and a lower, funnel-shaped section with a double channel system between Bremerhaven and the open North Sea, bounded by tidal flats and with a navigation depth of 14 m (Schrottke *et al.,* 2006).

As for the Elbe, the Weser estuary is featured by 3 more or less prismatic channels, one from 5 - 35 km, one from 35 - 45 km, and one at the most upstream part of the estuary. The thalweg depth gradually decreases from mouth to up-estuary boundary, with at 53 km a sudden shallowing of the thalweg depth. The Weser estuary is a multi-channel system from the mouth up to 43 km, and a single channel in the most upstream part (43 - 73 km). The wet section of the Weser has a typical decrease from mouth to up-estuary boundary (Vandenbruwaene et al., 2013).

The mean freshwater discharge at Intschede is 331 $m^3/s$, calculated over a time period from 2001 to 2010. For a typical dry event (low discharge, P5) the discharge is 122 $m^3/s$, and for a typical flushing event (P95) this is 798 $m^3/s$. Low discharges are common during summer, whereas flushing events are more typical during winter. For the Weser, the main channel discharge (i.e. discharge at Intschede) is significantly higher than the tributary discharges, and hence tributary discharges are negligible. From the mouth to 63 km, the mean and maximum ebb and flood flow velocities respectively range between 0.1 and 0.6 m/s, and between 0.2 and 1.3 m/s. High discharge conditions (winter) result in higher ebb flow velocities and lower flood flow velocities, compared to low discharge conditions (summer). At the most upstream part of the estuary, this effect is even more pronounced (63 - 73 km): close to the up-estuary boundary, the high freshwater discharge results in the absence of a flood flow velocity (value zero, only vertical tide), but clearly reaches higher values for the ebb flow velocity (up to 1.5-2 m/s). The Weser is a well-mixed estuary where it takes about 68 km for the mean salinity profile to decrease from 30 PSU to 1 PSU (i.e. a mean salinity gradient of 0.43 PSU/km). During periods with low (typical during summer) and high discharges (typical during winter), the salinity in the estuary is respectively higher and lower compared to the mean salinity profile (see Figure 26, respectively P(95%) and P(5%) profiles). The maximum difference between the summer and winter salinity profile is about 16 PSU, whereas the maximum variation between low water and high water is about 11 PSU for winter and summer (Vandenbruwaene et al., 2013).

### 4.5.2 Fitted topology of the river Weser

The characteristics of the idealized estuary and mesh refinement are shown in Figure 25. The following polynomials are used for curve fitting:

$$f_1(x) = F(x, -3.19E^{-04}, 2.03E^{-02}, -2.01E^{-01}, -8.73)$$

$$f_2(x) = F(x, 1.05E^{-05}, -1.78E^{-03}, 1.19E^{-01}, -3.87, 4.43E^{+01})$$

$$f_3(x) = F(x, -2.63E^{-02}, 2.24E^{+00}, -4.79E^{+01}, 1.28E^{+03})$$

$$f_4(x) = F(x, 2.53E^{-03}, -5.94E^{-01}, 5.13E^{+01}, -1.93E^{+03}, 2.74E^{+04})$$

The function descriptor for the bottom elevation D(x) is the following:

$$D(x) = \begin{cases} f_1(x), & x < 32.0\ km \\ f_2(x)\ , & x \geq 32.0\ km \end{cases}$$

For the width of the channel the following descriptor is applied:

$$D(x) = \begin{cases} f_3(x), & x < 32.0\ km \\ f_4(x)\ , & x \geq 32.0\ km \end{cases}$$

Notice that the edge length of the mesh is directly proportional to W(x). A thorough description of the data fitting process is given in Bi et al. (2021). The final mesh is shown in Figure 26.

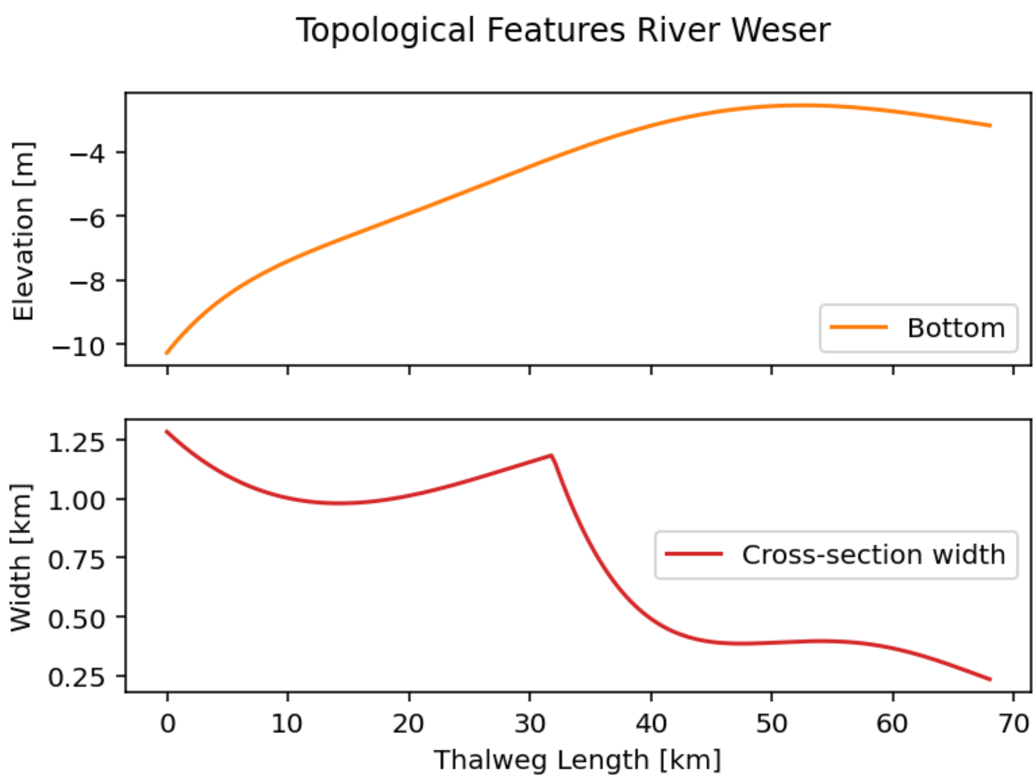



Figure 25 – Characteristics of the River Weser.

Table 9 – Geometric characteristics of the Weser

| Parameter [unit] | Symbol | Value |
|---|---|---|
| Width at the mouth [m] | W(0) | 1285 |
| Length [km] | L | 68.0 |

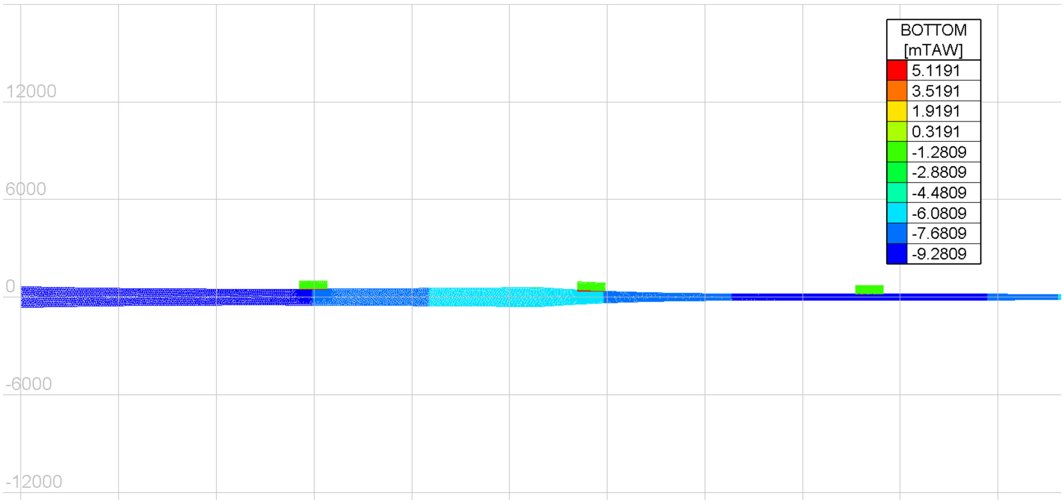



Figure 26 – Mesh of the Weser

### 4.5.3 Calibration of the roughness

Simulations on the Idealized model are run for a period of 40 days simulation time, with a time step of 1 second. Further model characteristics are shown in Table 10.

Table 10 – Model characteristics of the Weser

| Parameter [unit] | Value |
|---|---|
| Downstream M2 tidal amplitude [m] | 1.73 |
| Upstream discharge [m³/s] | 331 |

The Nikuradse's equivalent roughness is used as an independent variable for the calibration process thus each simulation is run with an increasing synthetic roughness for a period of 40 calendar days. The tidal range is extracted from the thalweg of the *idealized* estuary, that is, the axis of symmetry of the mesh. Results are shown in Figure 27.

Note that none of the models represent the decrease in tidal amplitude in the upstream reaches (x>40km). This might mean that the geometry is too simplified for the model to capture the tidal damping upstream, and needs to be investigated further.

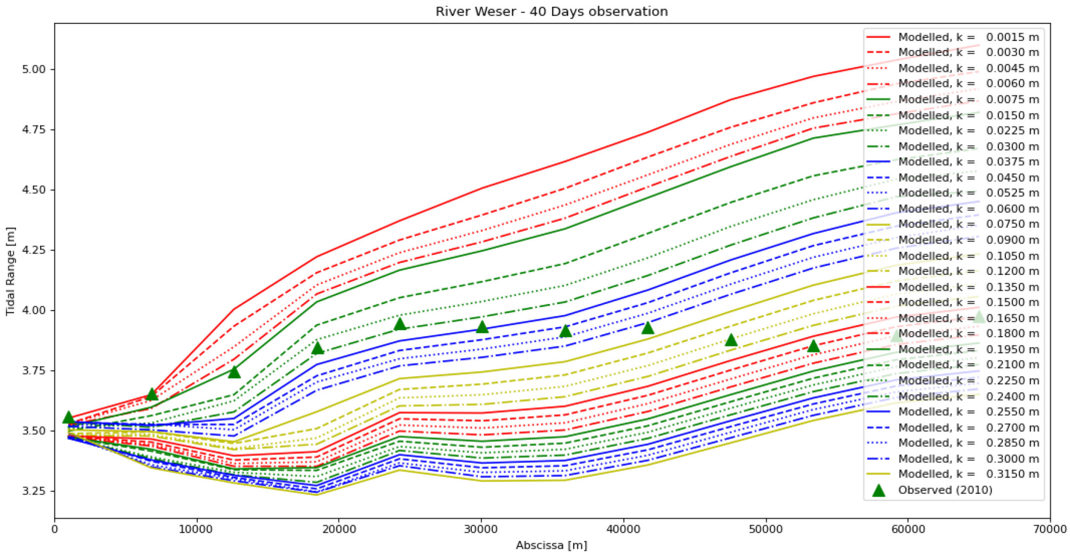



Figure 27 – Modelled and observed tidal range for the River Weser

A classical Bayesian minimization process is used for the calibration of the roughness against experimental data. A visual result of the calibration process is shown in Figure 8. The optimal Nikuradse's roughness parameter for the Idealized model of the Weser is k* = 0.0663 ± 0.007 m with an RMSE of tidal amplitude of 20cm, which is about 6% of the tidal amplitude at the mouth.

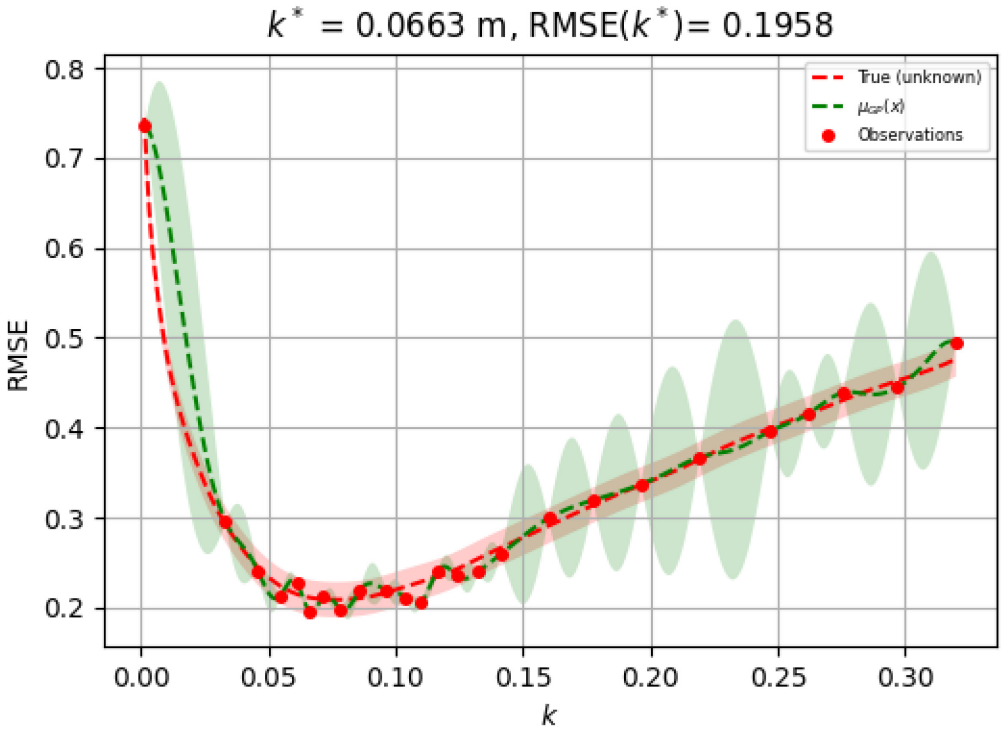



Figure 28 – Bayesian minimization process for the River Weser. "Observations" stand for model runs during the Calibration process

# 5 Effect of Flood Control Areas with Controlled Reduced Tide on estuaries

## 5.1 Research Question

What is the effect of attaching a flood control area with a controlled reduced tide (FCA-CRT, see §2.1) on the tidal propagation in an estuary?

- The proper functioning of the CRT part of the area is evaluated by the tidal characteristics inside the area.
- The proper functioning of the FCA part of the area is evaluated by the reduction in the high water level during storm conditions in the estuary.

Since there are many degrees of freedom in this question, we narrow it down in the design of experiment below. Our intention is not to do a detailed analysis, but to give a first order estimate of the functioning of a FCA-CRT area in other European estuaries, so more a “Proof of Concept” of a “typical” implementation.

## 5.2 Design of Experiment

### 5.2.1 Downstream boundary condition

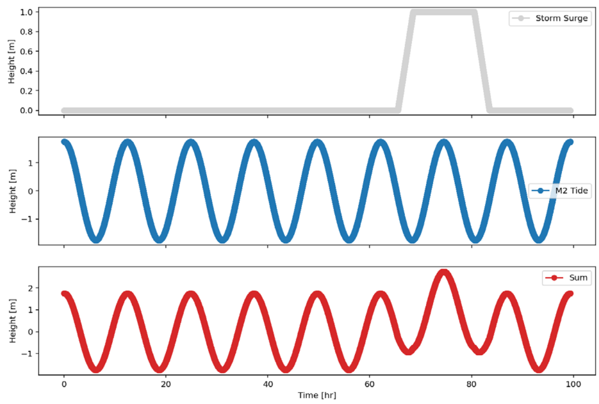
In order to address the research question on the CRT functioning, we use a simple semi-diurnal tide, which can be achieved by applying only the M2 component of the downstream station. This M2 amplitude is known from the harmonic boundary condition of the calibrated models (see chapter 4).

In order to evaluate the effect of the area during a storm, a surge of 1m is added during a period of 6 hours around HW with a ramp-up of 3h and ramp-down of 3h. The peak of the storm surge is set to coincide with a high water.

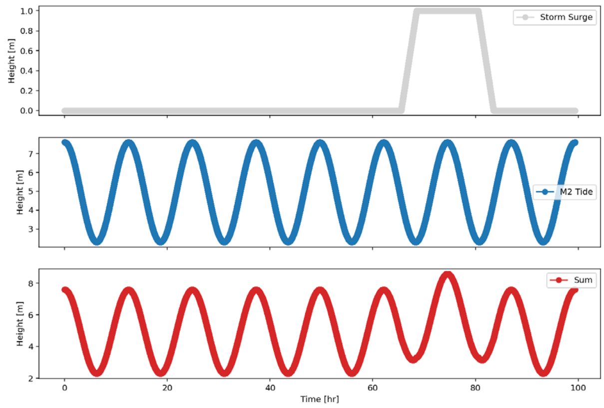
The duration of each run can be limited to ~85h:

- 2d of spinup time with pure M2
- 1 tidal cycle of pure M2 to evaluatie CRT
- 1 tidal cycle with storm surge of 1m (6h duration centered around HW)
- 1 normal tidal cycle at the end to allow for the FCA-CRT area to drain after the “storm”

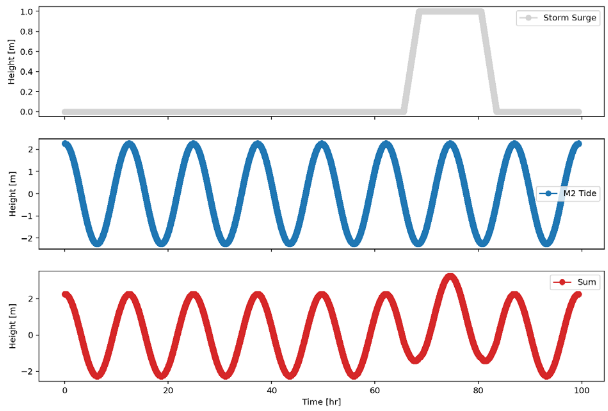
The water depth signals for the different estuaries are shown in Figure 29. The blue line shows the pure harmonic (M2) signal. The storm surge of 1m is shown in grey. The total water level that is used as downstream BC in the model is shown in red.



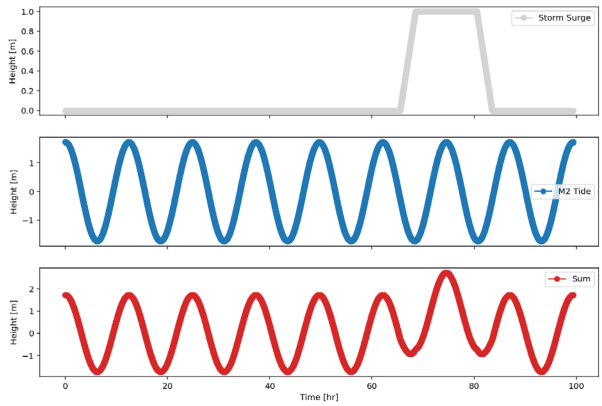

Scheldt



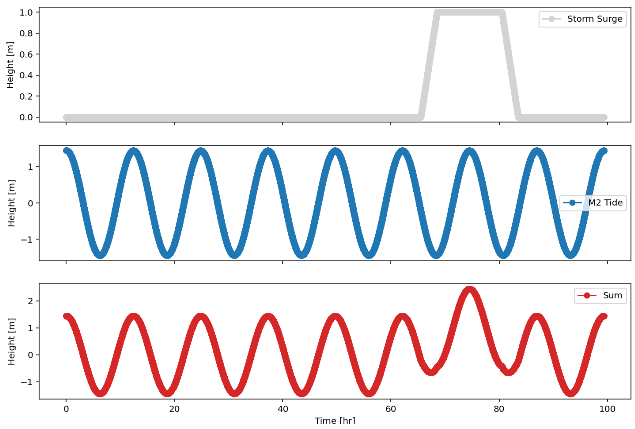

Seine




Humber




Weser




Elbe

Figure 29 – Downstream boundary conditions for the different esturaria, including the storm surge signal.

### 5.2.2 Upstream boundary condition

The models for the scenario analysis are forced with the same upstream boundary condition as the calibrated model: an average fresh water discharge at the upstream end.

### 5.2.3 A "Typical" FCA-CRT

In this report, we propose to evaluate the effect of a "typical" FCA-CRT area. For this, we base ourselves on the characteristics of the FCA-CRT areas that are developed within LIFE Sparc:

| Name | Type | Area [ha] | Number of INLET culverts | Number of OUTLET culverts |
|---|---|---|---|---|
| **Vlassenbroek** | Flood Control Area with Controlled Reduced Tide (FCA-CRT) | 91 | 6 | 8 |
| **Wal Zwijn** | FCA-CRT | 148 | 7 | 12 |
| **De Bunt** | FCA-CRT | 67 | 5 | 8 |

Within this study, we will focus on the effect of a FCA-CRT with a fixed surface area: 100 ha. That corresponds to a square with sides of 1km.

In reality, the mean height inside a FCA-CRT depends on the actual topography, and on how long the area has been separated from the estuary due to impoldering (cutting of the natural sediment supply). In order to have sufficient depth in each area to provide volume buffer during storms, and in order to have functional outlet culverts, we propose to set the bathymetry in each FCA to MLW +1m.

### 5.2.4 Culverts

The function of the culvert structures in a FCA-CRT is twofold:

- Introducing a reduced tide every tidal cycle in the FCA-CRT area
- When overflowing occurs during a storm (FCA), the area should be emptied as soon as possible, in order to potentially capture overflow during a subsequent high water.

Typically, the design of a FCA-CRT area is an iterative process that is done using realistic models of the estuary. To the author's knowledge, there is no description in literature of a method to do this in an idealized model context.

As can be expected from the intended functioning of these areas, there is a relation between the surface area of each area, and the number of in- and outlet culverts (see Figure 30)

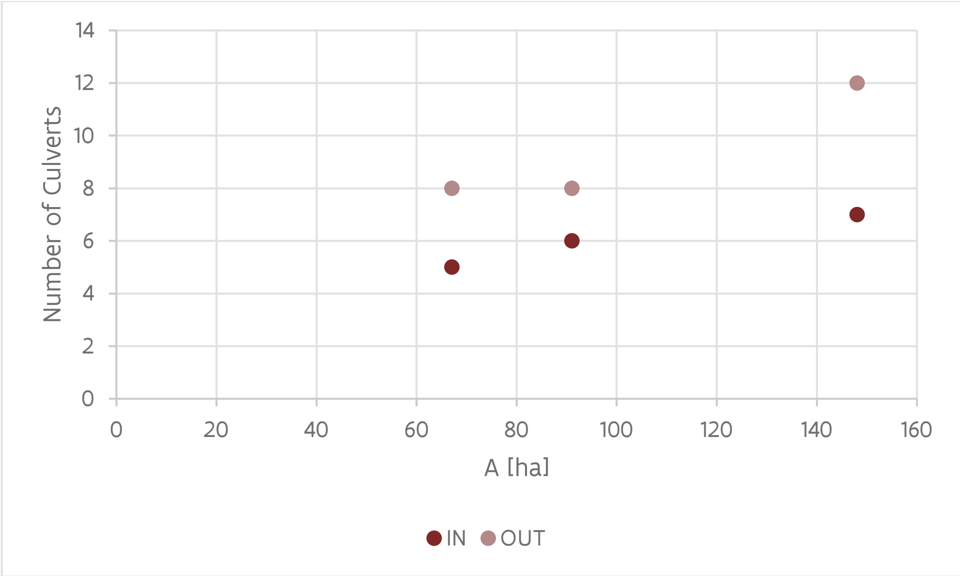



Figure 30 – Number of in- and outlet culverts in function of surface area

For a target surface area of 100ha, we will choose 6 inlet and 8 outlet culverts.

For each of the FCA-CRT areas that are developed within Life Sparc, the width of each culvert was 3m, and the height 2,2m. We'll take these values over in this study.

The (floor) height of the in- and outlet culvert is typically an iterative exercise since it determines the tidal characteristics inside the area. Since in- and outflow are gravimetric, the height of the in- and outlet culvert should be interpreted within the tidal frame. We propose the following implementation:

- The inlet culvert is placed relatively high in the tidal frame at MHW – 1.5m. That way inflow occurs each tidal cycle around HW
- The outlet culvert is placed at MLW +1.5m. Outlet culverts are equipped with a non-return valve, so outflow can only happen when the water level in the estuary is below the water level of the FCA
- For the Seine case, the tidal amplitude sometimes drops below 3m (middle and upstream location, see §6.3.1). For those locations, we take MHW -1.25m and MLW +1.25m for the culvert heights, respectively. This is necessary to make sure that the inlet culvert is always higher than the outlet culvert.

Note that with the bathymetry in the FCA set to MLW +1m, and the outlet culvert floor height set at MLW +1.5m (or MLW +1.25m in the Seine case), there can never be a complete emptying of the FCA. For the development of tidal vegetation, also drying would be needed. In reality, the FCA bathymetry would of course not be flat, and would for example contain a creek onset to achieve proper drainage of the area at each tide. This is a known limitation of the simplifying assumption of a flat bathymetry in the FCA. This will have no impact however on the target metric (reduction of tidal amplitude) we use for the tidal regime in the area.

### 5.2.5 Height of the overflow dike

In reality, the height of the overflow dike in the Scheldt is chosen for optimal effect for a set of design storms (e.g with a return period of 1000 years). In this study we will not perform an analysis of the effect of the height of the overflow dike.

Since we know the height of the surge that we'll be applying (1m at HW), the height of the overflow dike is taken as the local HW + 90cm, in order to assure FCA functioning of the area in the idealized model during the synthetic storm.

### 5.2.6 Width and location of overflow dike

The top of the dike is aligned with the imaginary line corresponding to the lateral bank of the main channel at the location of the FCA. The overall width of the dike is 50.0 m, meaning that approximately 25 m will be at either side the aforementioned line. That is, an area between 2.5 to 5.0 ha will be occupied by the dike at the FCA side and at the main channel side.

### 5.2.7 Location of the FCA-CRT area

We know from literature (e.g. Li et al., 2016; Stark et al., 2017) that the location of a retention basin or depoldering in the estuary matters for the effect of the area on the tidal propagation in the estuary.

Therefore we propose to test three different locations for a FCA-CRT area:

- Near the mouth: L/4
- In the middle of the estuary: at L/2
- Near the upstream end at 3L/4

With L the length scale of the tidally influenced length of the estuary.

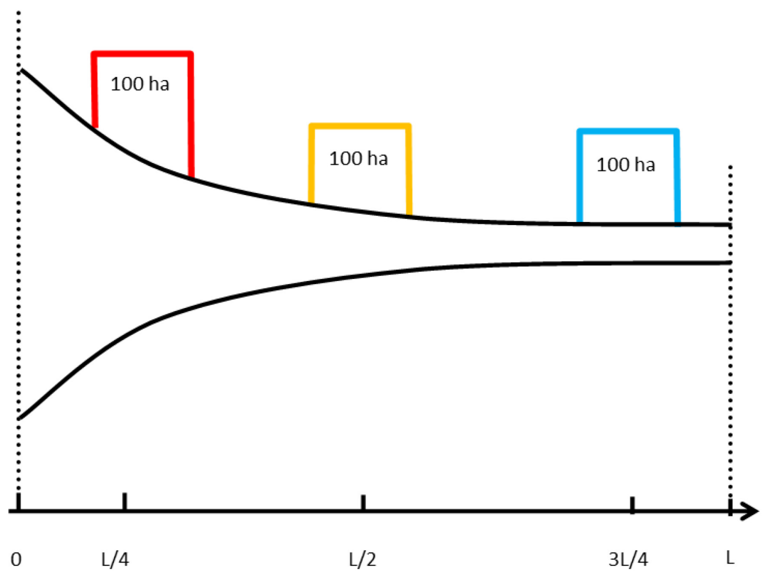



Figure 31 – Design of Experiment - Location of FCA/CRT areas in the simplified case. Upstream (blue), middle (yellow) and downstream (red)

### 5.2.8 Model runs

For each estuary, 4 runs are performed with the same boundary conditions (M2 + storm surge)

- No FCA-CRT (reference, equivalent to calibrated model)
- FCA-CRT near the mouth
- FCA-CRT in the middle
- FCA-CRT upstream

### 5.2.9 Model output

In order to address the research questions stated in §5.1, the model needs to have minimally the following output:

- Time series of water levels in the flood control areas, in order to
  - Check the reduced tide conditions during an average tide
  - Check the filing and emptying during the storm condition
- High water line in the estuary
  - To check the reduction in HW during storm tide due to FCA functioning

### 5.2.10 Water level in the FCA and main channel

The water level in the FCA is not a single value, but a field across the FCA. Here, a weighted averaged calculation of the water level is performed over the 100 ha using the FE mesh-dual element's area as weight for the water level WL in the node. The weighted-average water level WL in the FCA is expressed in the following way:

$$WL_{FCA} = \frac{1}{A_{FCA}} \sum_{i=1}^{nelems} WL_i A_i.$$

On the other hand, the water level in the main channel just corresponds to the value encountered at a determined abscissa along the axis (or thalweg) of the channel.

# 6 Results and Discussion

## 6.1 Scheldt

### 6.1.1 FCA-CRT characteristics

Table 11 shows the characteristics of the FCA-CRT in the different scenarios. They follow from the MHW and MLW at the respective locations, as explained in §5.2.

Table 11 – FCA-CRT characteristics for the different scenarios in the Scheldt case.

| Parameter [unit] | FCA-CRT near the mouth | FCA-CRT in the middle | FCA-CRT upstream |
|---|---|---|---|
| Surface Area [ha] | 100 | 100 | 100 |
| Location from the mouth [km] | 40 | 80 | 120 |
| MHW at location of FCA [m] | 2.13 | 2.60 | 2.79 |
| Height of the overflow dike [m] | 3.03 | 3.51 | 3.68 |
| MLW at location of FCA [m] | -1.92 | -2.19 | -1.52 |
| Bathymetry in FCA [m] | -0.93 | -1.20 | -0.42 |
| Floor height of inlet culvert [m] | 0.63 | 1.10 | 1.29 |
| Floor height of outlet culvert [m] | -0.43 | -0.70 | -0.01 |

### 6.1.2 Model results

Figure 33 shows the water level (after spinup) in the estuary and in the FCA-CRT. Three different variants are calculated: either with the FCA-CRT near the mouth, in the middle of the estuary or near the upstream end (see also §5.2.7).

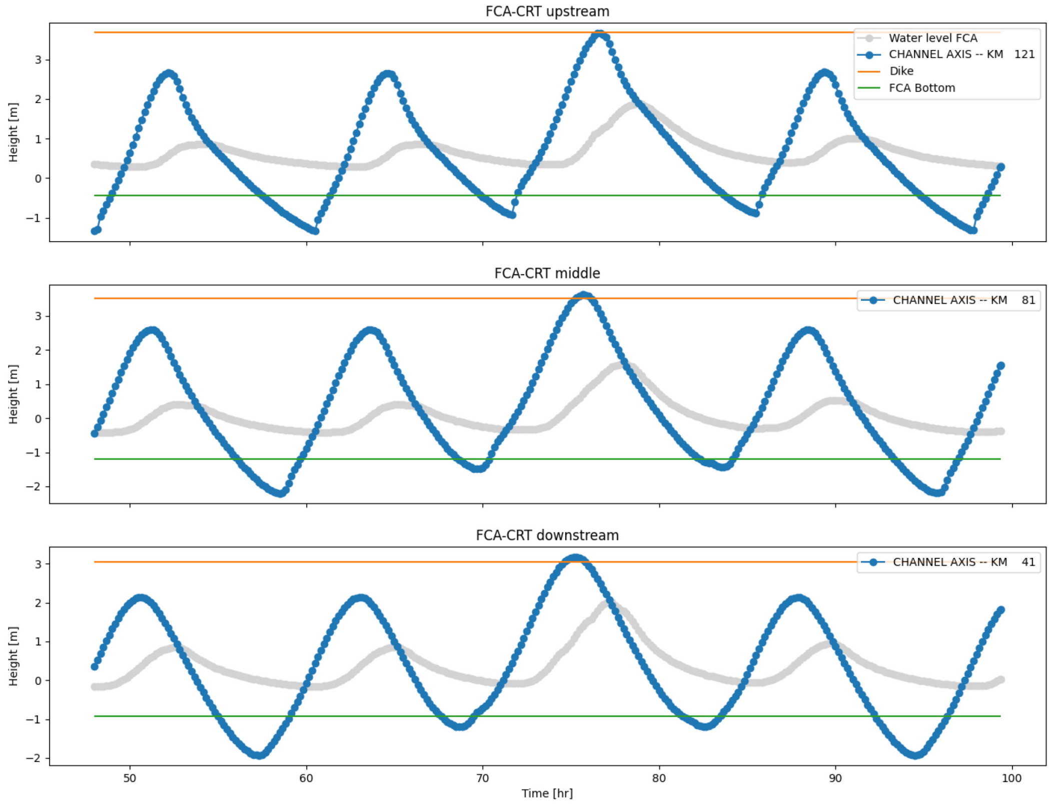



Figure 32 – Water level in the Scheldt estuary and in the FCA-CRT in locations upstream (top), middle (middle) and downstream (bottom)

### 6.1.3 Evaluation of CRT function

Table 12 evaluates the proper functioning of the CRT by quantifying the tidal amplitude in the FCA-CRT during calm/average conditions and the minimum and maximum water depth. For all three locations a reduced tide is achieved in the FCA-CRT areas with the following characteristics:

Table 12 – Tidal characteristics in the FCA-CRT in the Scheldt case

| | **FCA-CRT near the mouth** | **FCA-CRT in the middle** | **FCA-CRT upstream** |
|---|---|---|---|
| Tidal amplitude in estuary at location of FCA [m] | 4.05 | 4.79 | 4.31 |
| Tidal amplitude in CRT during calm conditions [m] | 1.01 | 0.81 | 0.56 |
| Tidal amplitude in CRT as a fraction to tidal amplitude in the estuary [%] | 25% | 17% | 13% |
| Max water depth in CRT during calm conditions [m] | 1.79 | 1.60 | 1.27 |
| Min water depth in CRT during calm conditions [m] | 0.78 | 0.78 | 0.71 |

### 6.1.4 Evaluation of FCA function

The Flood Control Area will fill in during the synthetic storm surge. This will lead to a reduction in the HW in the estuary, which improves the safety against flooding in the estuary. This effect is calculated by comparing the model runs with a reference model without a FCA and without dikes.

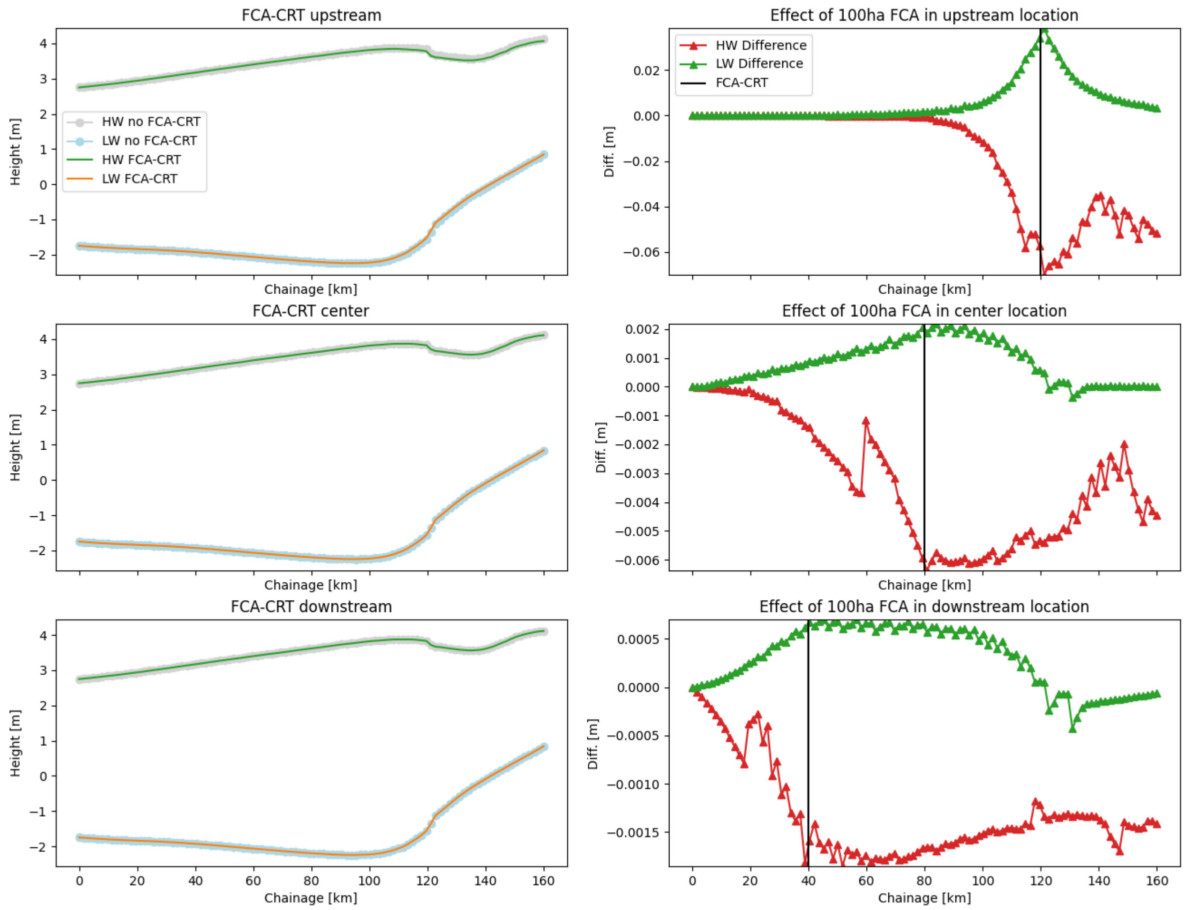



Figure 33 – Effect of 100ha FCA CRT in the Scheldt locations upstream (top), middle (middle) and downstream (bottom) on HW and LW during a synthetic storm

The impact of the FCA's at different CRT locations is shown in Figure 33. Clearly, the biggest impact on the high water is seen when the FCA is placed upstream. This corresponds well with results obtained with more detailed models (Stark et al., 2017).

Note that Figure 32 indicates that the FCA does not fill completely during the synthetic storm. In our simplified case, we could model a higher storm surge, or a combination of storm surges, or lower the height of the overflow dike. In reality, the design of the area would be optimised for maximum effect (lowering of HW in the estuary) for a given set of design storms.

## 6.2 Elbe

### 6.2.1 FCA-CRT characteristics

Table 15 shows the characteristics of the FCA-CRT in the different scenarios. They follow from the MHW and MLW at the respective locations, as explained in §5.2.

Table 13 – FCA-CRT characteristics for the different scenarios in the Elbe case.

| Parameter [unit] | FCA-CRT near the mouth | FCA-CRT in the middle | FCA-CRT upstream |
|---|---|---|---|
| Surface Area [ha] | 100 | 100 | 100 |
| Location from the mouth [km] | 28.5 | 57 | 85.5 |
| MHW at location of FCA [m] | 1.65 | 1.84 | 2.04 |
| Height of the overflow dike [m] | 2.55 | 2.80 | 3.09 |
| MLW at location of FCA [m] | -1.30 | -1.30 | -1.42 |
| Bathymetry in FCA [m] | -0.30 | -0.30 | -0.42 |
| Floor height of inlet culvert [m] | 0.15 | 0.34 | 0.54 |
| Floor height of outlet culvert [m] | 0.19 | 0.20 | 0.08 |

### 6.2.2 Model results

Figure 34 shows the water level (after spin up) in the estuary and in the FCA-CRT. Three different variants are calculated: either with the FCA-CRT near the mouth, in the middle of the estuary or near the upstream end (see also §5.2.7).

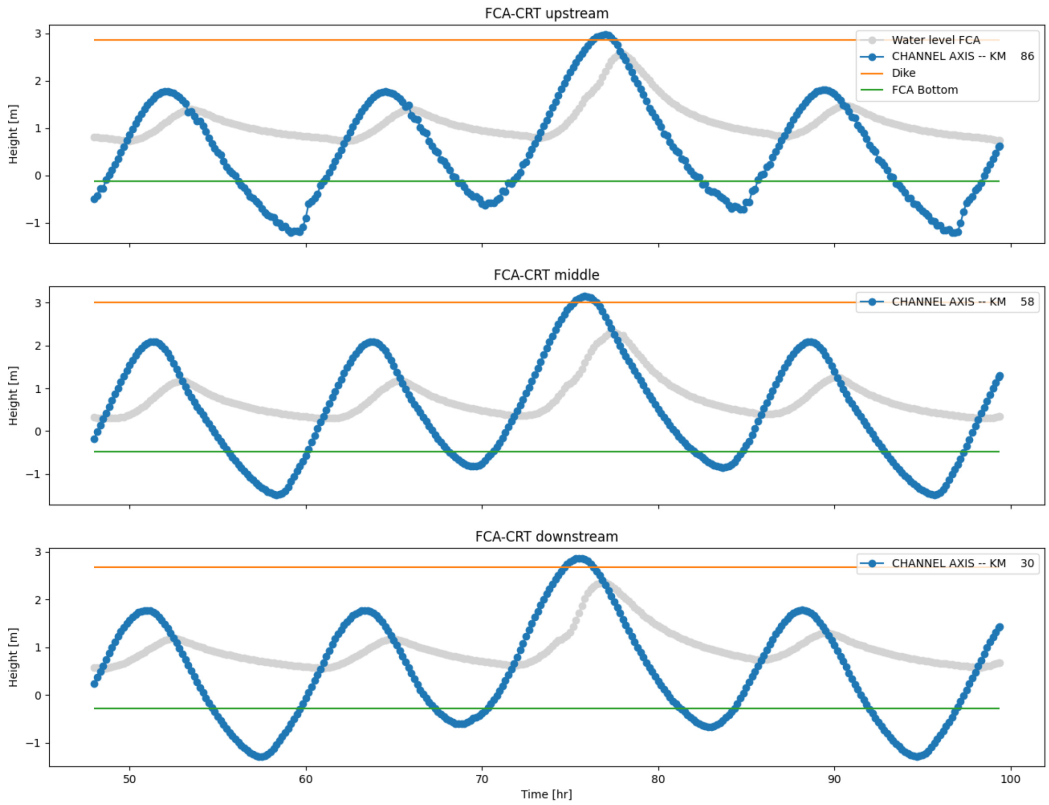



Figure 34 – Water level in the Elbe estuary and in the FCA-CRT in locations upstream (top), middle (middle) and downstream (bottom)

### 6.2.3 Evaluation of CRT function

Table 14 evaluates the proper functioning of the CRT by quantifying the tidal amplitude in the FCA-CRT during calm/average conditions and the minimum and maximum water depth. For all three locations a reduced tide is achieved in the FCA-CRT areas with the following characteristics:

Table 14 – Tidal characteristics in the FCA-CRT in the Elbe case

| | FCA-CRT near the mouth | FCA-CRT in the middle | FCA-CRT upstream |
|---|---|---|---|
| Tidal amplitude in estuary at location of FCA [m] | 2.95 | 3.14 | 3.46 |
| Tidal amplitude in CRT during calm conditions [m] | 0.67 | 0.89 | 0.62 |
| Tidal amplitude in CRT during calm conditions [m] | 23% | 28% | 18% |
| Max waterdepth in CRT during calm conditions [m] | 1.70 | 1.48 | 1.61 |
| Min waterdepth in CRT during calm conditions [m] | 1.03 | 0.60 | 0.98 |

### 6.2.4 Evaluation of FCA function

The Flood Control Area will fill in during the synthetic storm surge. This will lead to a reduction in the HW in the estuary, which improves the safety against flooding in the estuary. This effect is calculated by comparing the model runs with a reference model without a FCA and without dikes.

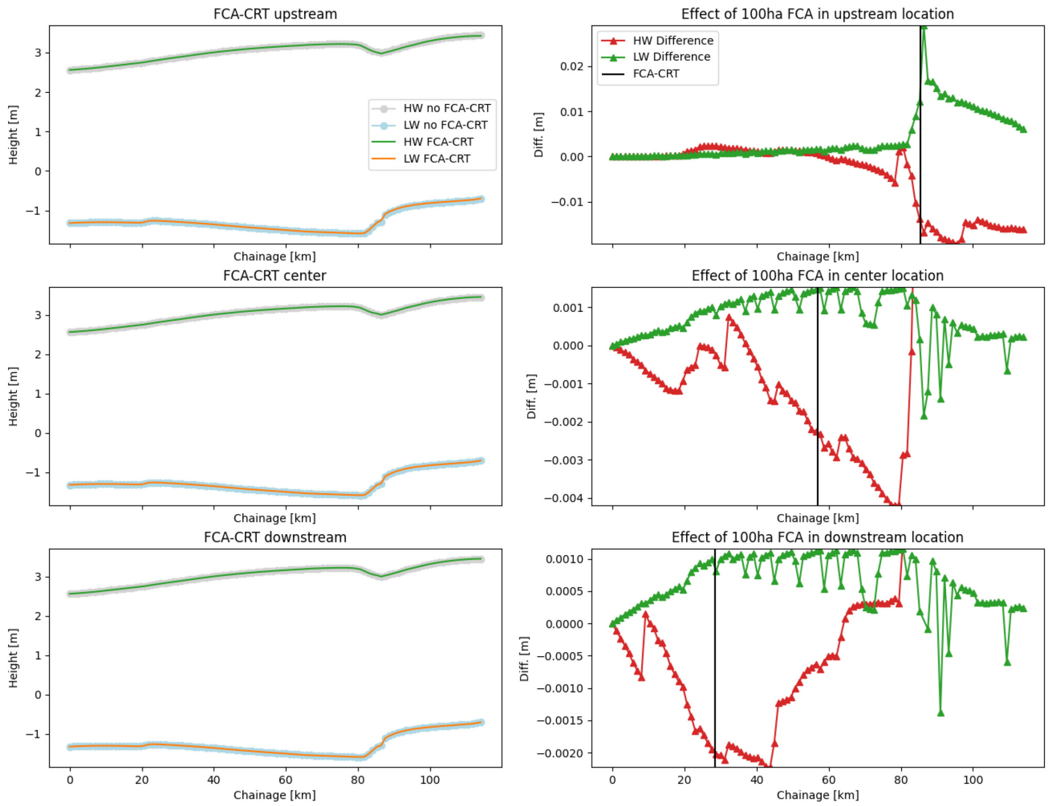



Figure 35 – Effect of 100ha FCA CRT in the Elbe in locations upstream (top), middle (middle) and downstream (bottom) on HW and LW during a synthetic storm

The impact of the FCA's at different CRT locations is shown in Figure 35. Clearly, the biggest impact on the tidal range is seen when the FCA is placed upstream.

The wiggles in the center and downstream cases (right panel in Figure 35) might be caused by slight (< 1mm) numerical instabilities in the solution. This should be further investigated, but do not change the main conclusions.

Note that Figure 34 indicates that the FCA does not fill completely during the synthetic storm. In our simplified case, we could model a higher storm surge, or a combination of storm surges, or lower the height of the overflow dike. In reality, the design of the area would be optimised for maximum effect (lowering of HW in the estuary) for a given set of design storms.

## 6.3 Seine

### 6.3.1 FCA-CRT characteristics

Table 15 shows the characteristics of the FCA-CRT in the different scenarios. They follow from the MHW and MLW at the respective locations, as explained in §5.2.45.2.

The culvert heights indicated with an asterisk for the middle and upstream locations deviate from this design rule and are taken MHW -1.25m and MLW +1.25m for the culvert heights, respectively (see also §5.2.4).

Table 15 – FCA-CRT characteristics for the different scenarios in the Seine case.

| Parameter [unit] | FCA-CRT near the mouth | FCA-CRT in the middle | FCA-CRT upstream |
|---|---|---|---|
| Surface Area [ha] | 100 | 100 | 100 |
| Location from the mouth [km] | 37.5 | 75.0 | 112.5 |
| MHW at location of FCA [m] | 7.16 | 6.89 | 6.92 |
| Height of the overflow dike [m] | 8.06 | 7.80 | 7.82 |
| MLW at location of FCA [m] | 3.60 | 3.99 | 4.02 |
| Bathymetry in FCA [m] | 4.65 | 5.01 | 5.04 |
| Floor height of inlet culvert [m] | 5.66 | 5.64* | 5.67* |
| Floor height of outlet culvert [m] | 5.10 | 5.24* | 5.27* |

### 6.3.2 Model results

Figure 36 shows the water level (after spin up) in the estuary and in the FCA-CRT. Three different variants are calculated: either with the FCA-CRT near the mouth, in the middle of the estuary or near the upstream end (see also §5.2.7).

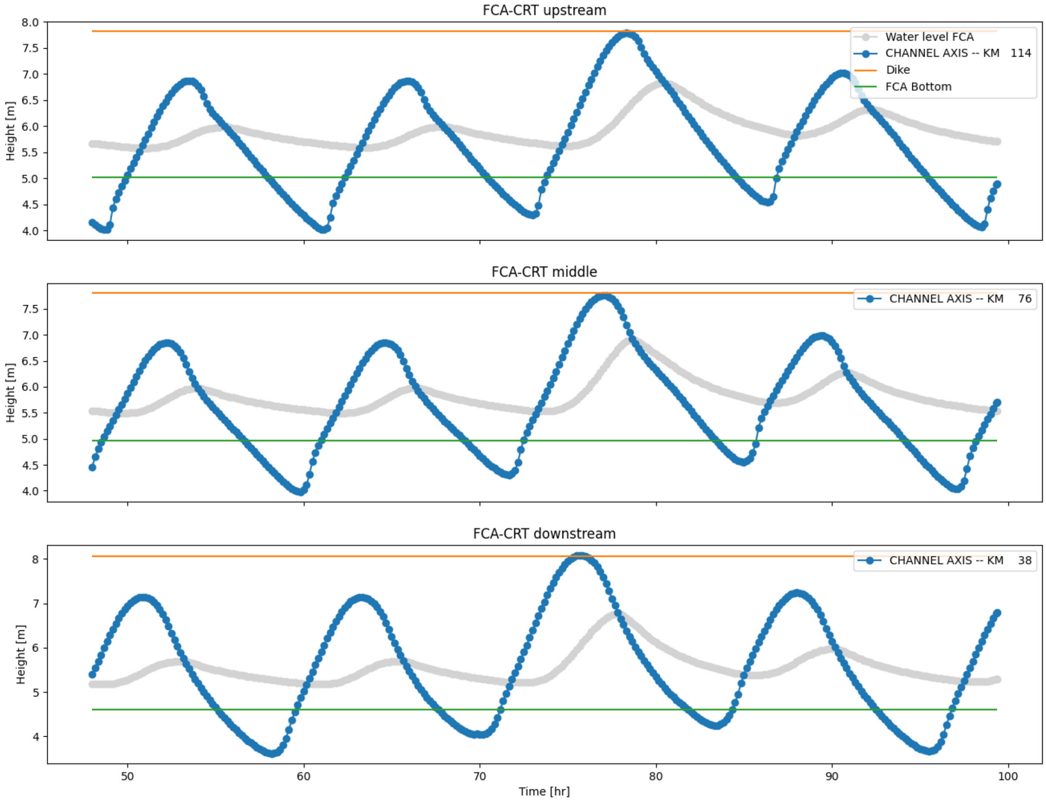



Figure 36 – Water level in the Seine estuary and in the FCA-CRT in locations upstream (top), middle (middle) and downstream (bottom)

### 6.3.3 Evaluation of CRT function

Table 16 evaluates the proper functioning of the CRT by quantifying the tidal amplitude in the FCA-CRT during calm/average conditions and the minimum and maximum water depth. For all three locations a reduced tide is achieved in the FCA-CRT areas with the following characteristics:

Table 16 – Tidal characteristics in the FCA-CRT in the Seine case

| | FCA-CRT near the mouth | FCA-CRT in the middle | FCA-CRT upstream |
|---|---|---|---|
| Tidal amplitude in estuary at location of FCA [m] | 3.56 | 2.91 | 2.90 |
| Tidal amplitude in CRT during calm conditions [m] | 0.51 | 0.49 | 0.41 |
| Tidal amplitude in CRT during calm conditions [m] | 14% | 17% | 14% |
| Max waterdepth in CRT during calm conditions [m] | 5.69 | 5.98 | 5.99 |
| Min waterdepth in CRT during calm conditions [m] | 5.18 | 5.49 | 5.58 |

### 6.3.4 Evaluation of FCA function

The Flood Control Area will fill in during the synthetic storm surge. This will lead to a reduction in the HW in the estuary, which improves the safety against flooding in the estuary. This effect is calculated by comparing the model runs with a reference model without a FCA and without dikes.

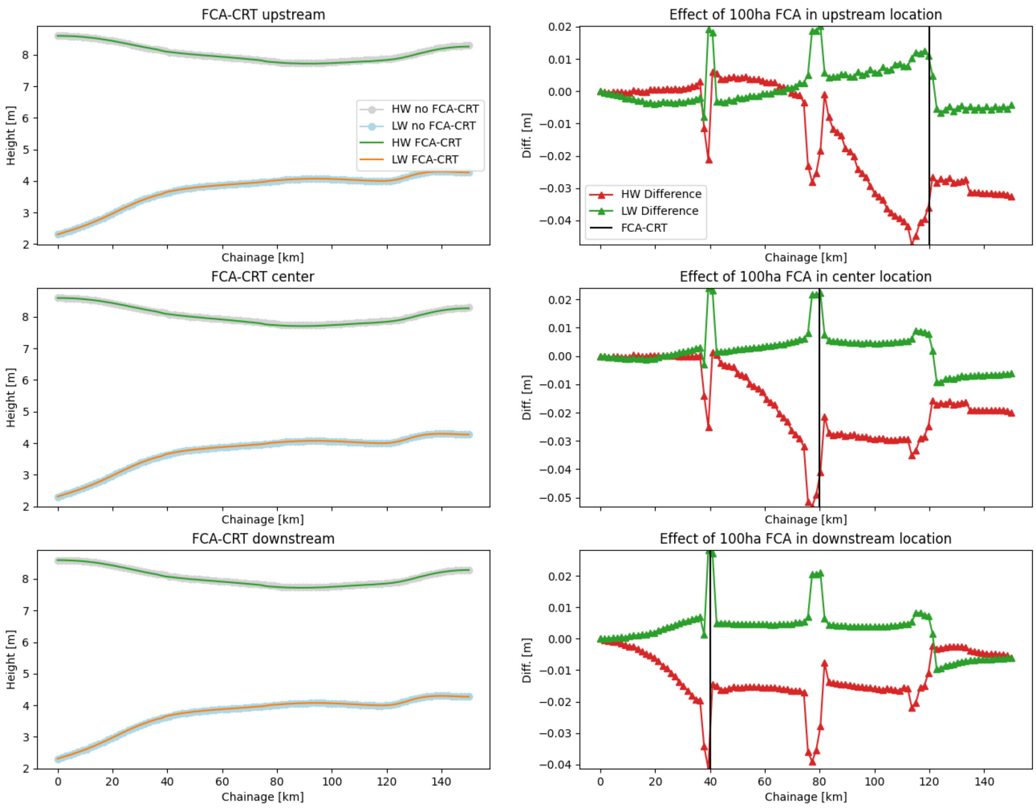



Figure 37 – Effect of 100ha FCA CRT in the Seine in locations upstream (top), middle (middle) and downstream (bottom) on HW and LW during a synthetic storm

The impact of the FCA's at different CRT locations is shown in Figure 37. Notice that the idealized shape of the Seine varies in such a way that produces little wave amplification due to contractions in the zones of influence of the FCA-CRT. More specifically, the width of the channel varies only on the first 20 km, after which it remains relatively stable and narrow (< 500 m). Additionally, the tidal range is relatively low thus making the water storage in the FCA's lower.

Note that Figure 36 indicates that the FCA does not fill completely during the synthetic storm. In our simplified case, we could model a higher storm surge, or a combination of storm surges, or lower the height of the overflow dike. In reality, the design of the area would be optimised for maximum effect (lowering of HW in the estuary) for a given set of design storms.

## 6.4 Humber

### 6.4.1 FCA-CRT characteristics

Table 17 shows the characteristics of the FCA-CRT in the different scenarios. They follow from the MHW and MLW at the respective locations, as explained in §5.2.

Table 17 – FCA-CRT characteristics for the different scenarios in the Humber case.

| **Parameter [unit]** | **FCA-CRT near the mouth** | **FCA-CRT in the middle** | **FCA-CRT upstream** |
|---|---|---|---|
| Surface Area [ha] | 100 | 100 | 100 |
| Location from the mouth [km] | 28.25 | 56.50 | 84.75 |
| MHW at location of FCA [m] | 6.63 | 6.81 | 7.17 |
| Height of the overflow dike [m] | 7.53 | 7.71 | 8.07 |
| MLW at location of FCA [m] | 2.09 | 2.46 | 3.46 |
| Bathymetry in FCA [m] | -0.59 | 0.17 | 0.75 |
| Floor height of inlet culvert [m] | 5.13 | 5.31 | 5.67 |
| Floor height of outlet culvert [m] | 3.59 | 3.96 | 4.96 |

### 6.4.2 Model results

Figure 33 shows the water level (after spin up) in the estuary and in the FCA-CRT. Three different variants are calculated: either with the FCA-CRT near the mouth, in the middle of the estuary or near the upstream end (see also §5.2.7).

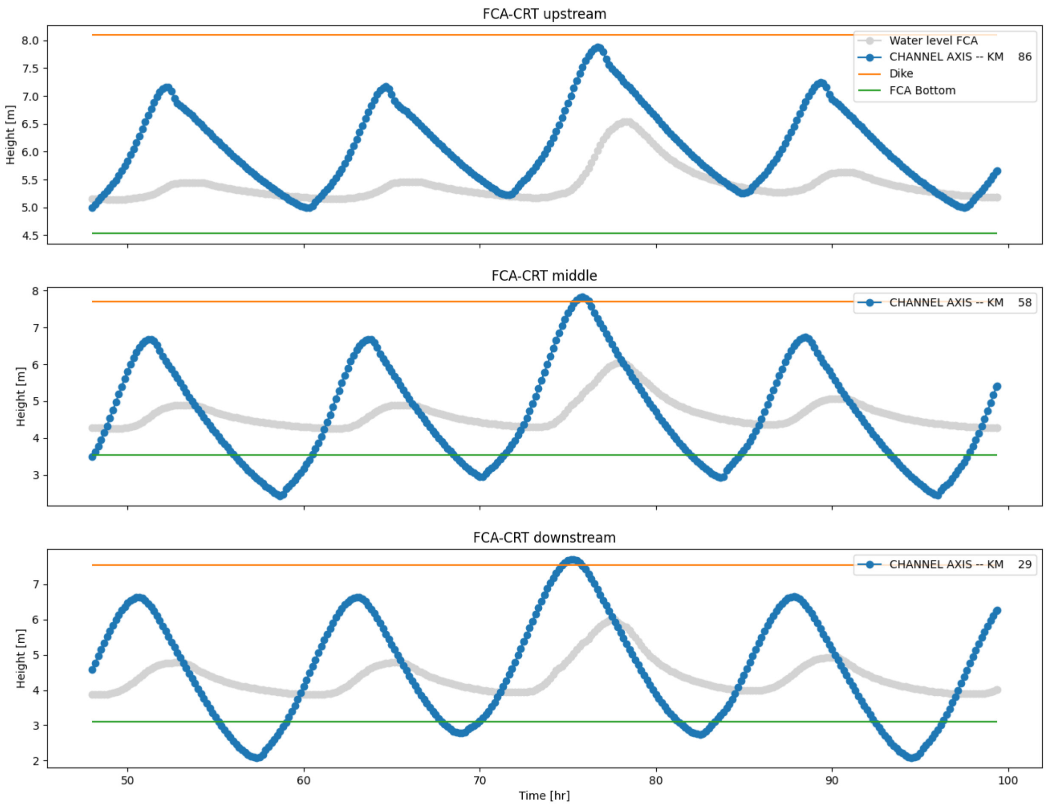



Figure 38 – Water level in the Humber estuary and in the FCA-CRT in locations upstream (top), middle (middle) and downstream (bottom)

### 6.4.3 Evaluation of CRT function

Table 18 evaluates the proper functioning of the CRT by quantifying the tidal amplitude in the FCA-CRT during calm/average conditions and the minimum and maximum water depth. For all three locations a reduced tide is achieved in the FCA-CRT areas with the following characteristics:

Table 18 – Tidal characteristics in the FCA-CRT in the Humber case

| | **FCA-CRT near the mouth** | **FCA-CRT in the middle** | **FCA-CRT upstream** |
|---|---|---|---|
| Tidal amplitude in estuary at location of FCA [m] | 4.55 | 4.35 | 3.70 |
| Tidal amplitude in CRT during calm conditions [m] | 0.90 | 0.64 | 0.32 |
| Tidal amplitude in CRT during calm conditions [m] | 20% | 15% | 9% |
| Max waterdepth in CRT during calm conditions [m] | 4.78 | 4.90 | 5.46 |
| Min waterdepth in CRT during calm conditions [m] | 3.88 | 4.26 | 5.14 |

### 6.4.4 Evaluation of FCA function

The Flood Control Area will fill in during the synthetic storm surge. This will lead to a reduction in the HW in the estuary, which improves the safety against flooding in the estuary. This effect is calculated by comparing the model runs with a reference model without a FCA and without dikes.

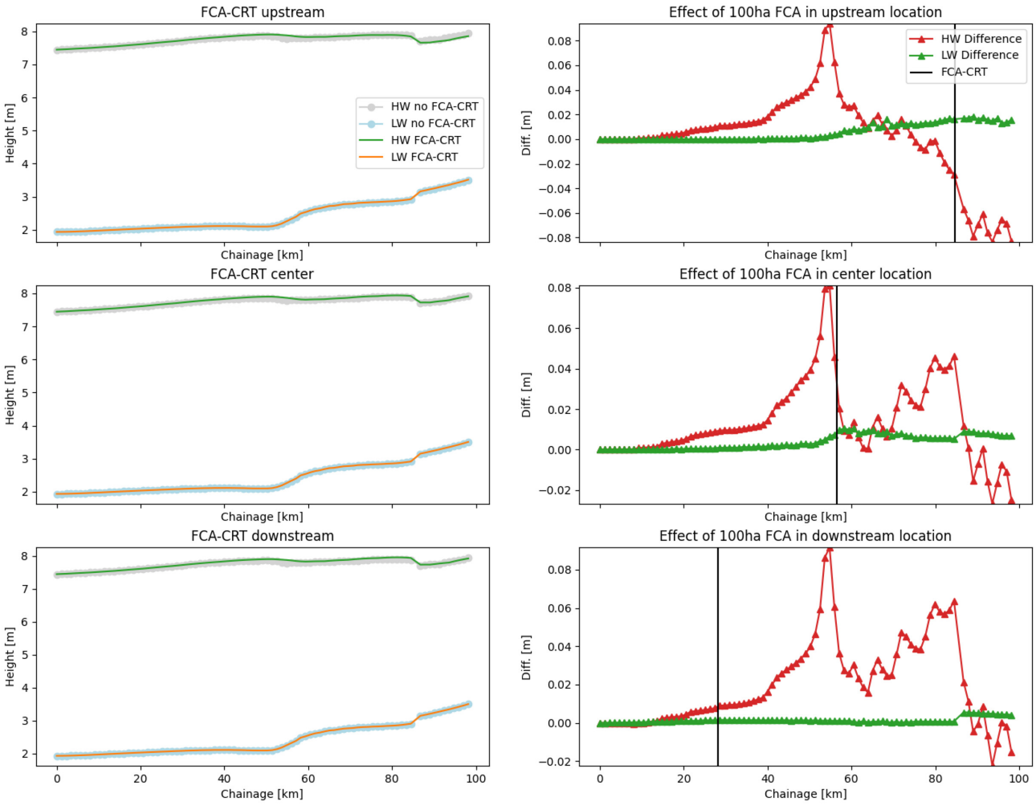



Figure 39 – Effect of 100ha FCA CRT in the Humber locations upstream (top), middle (middle) and downstream (bottom) on HW and LW during a synthetic storm

The impact of the FCA’s at different locations is shown in Figure 39. This result is unexpected, as the effect on HW is dominated by an *increase* of HW in all three scenarios. After careful examination of model input, we didn’t find any errors in model schematisation. This result might be related to the fact that the model has very hight values of roughness after it’s automatic calibration, which might have impacted the numerical stability of the model. More research is needed here to get to the bottom of this.

Note that Figure 38 indicates that the FCA does not fill completely during the synthetic storm. In our simplified case, we could model a higher storm surge, or a combination of storm surges, or lower the height of the overflow dike. In reality, the design of the area would be optimised for maximum effect (lowering of HW in the estuary) for a given set of design storms.

## 6.5 Weser

### 6.5.1 FCA-CRT characteristics

Table 19 shows the characteristics of the FCA-CRT in the different scenarios. They follow from the MHW and MLW at the respective locations, as explained in §5.2.

Table 19 – FCA-CRT characteristics for the different scenarios in the Weser case.

| Parameter [unit] | FCA-CRT near the mouth | FCA-CRT in the middle | FCA-CRT upstream |
|---|---|---|---|
| Surface Area [ha] | 100 | 100 | 100 |
| Location from the mouth [km] | 17 | 34 | 51 |
| MHW at location of FCA [m] | 1.73 | 1.90 | 2.19 |
| Height of the overflow dike [m] | 2.63 | 2.80 | 3.09 |
| MLW at location of FCA [m] | -1.55 | -1.38 | -1.42 |
| Bathymetry in FCA [m] | -0.55 | -0.38 | -0.42 |
| Floor height of inlet culvert [m] | 0.23 | 0.40 | 0.69 |
| Floor height of outlet culvert [m] | -0.05 | 0.11 | 0.07 |

### 6.5.2 Model results

Figure 33 shows the water level (after spin up) in the estuary and in the FCA-CRT. Three different variants are calculated: either with the FCA-CRT near the mouth, in the middle of the estuary or near the upstream end (see also §5.2.7).

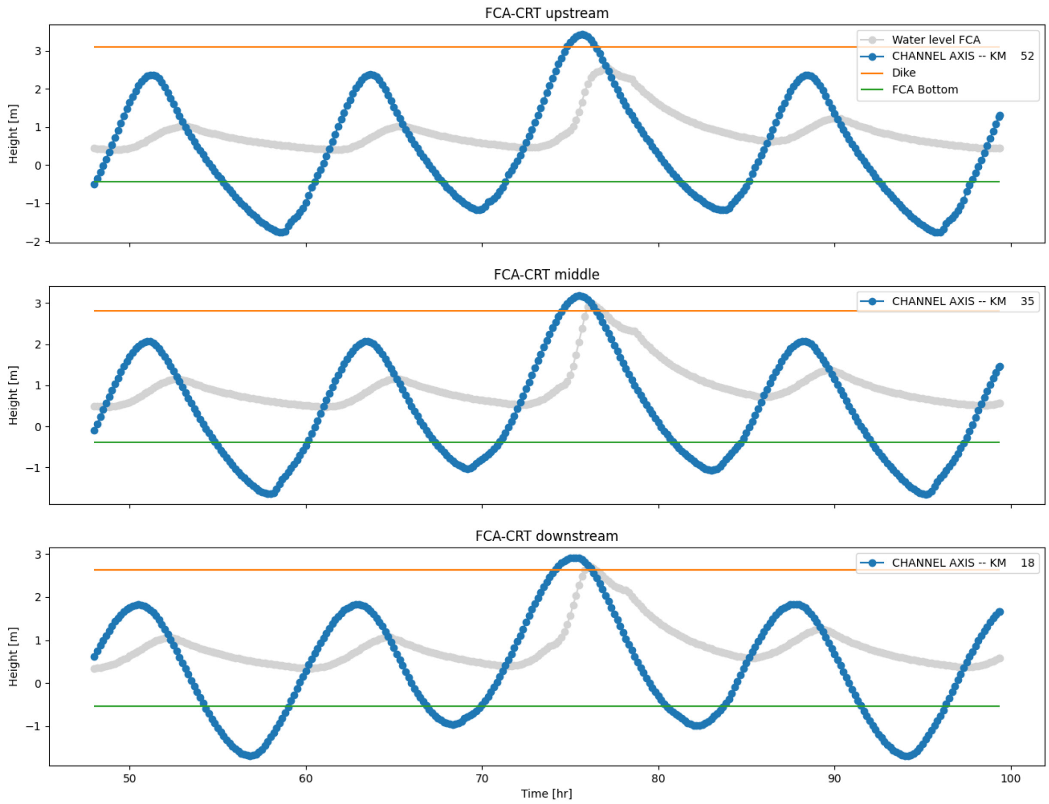



Figure 40 – Water level in the Weser estuary and in the FCA-CRT in locations upstream (top), middle (middle) and downstream (bottom)

### 6.5.3 Evaluation of CRT function

Table 20 evaluates the proper functioning of the CRT by quantifying the tidal amplitude in the FCA-CRT during calm/average conditions and the minimum and maximum water depth. For all three locations a reduced tide is achieved in the FCA-CRT areas with the following characteristics:

Table 20 – Tidal characteristics in the FCA-CRT in the Weser case

| | **FCA-CRT near the mouth** | **FCA-CRT in the middle** | **FCA-CRT upstream** |
|---|---|---|---|
| Tidal amplitude in estuary at location of FCA [m] | 3.28 | 3.28 | 3.61 |
| Tidal amplitude in CRT during calm conditions [m] | 0.62 | 0.69 | 0.73 |
| Tidal amplitude in CRT during calm conditions [m] | 19% | 21% | 20% |
| Max waterdepth in CRT during calm conditions [m] | 1.57 | 1.54 | 1.49 |
| Min waterdepth in CRT during calm conditions [m] | 0.95 | 0.85 | 0.76 |

### 6.5.4 Evaluation of FCA function

The Flood Control Area will fill in during the synthetic storm surge. This will lead to a reduction in the HW in the estuary, which improves the safety against flooding in the estuary. This effect is calculated by comparing the model runs with a reference model without a FCA and without dikes.

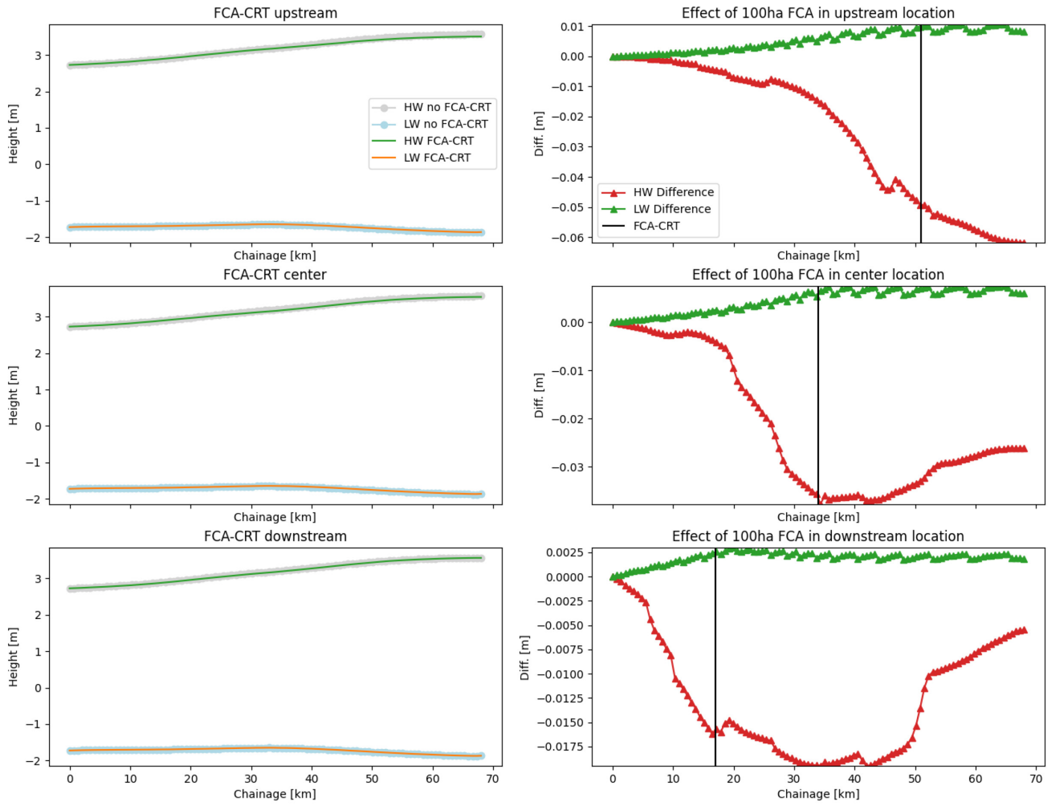



Figure 41 – Effect of 100ha FCA CRT in the Weser in locations upstream (top), middle (middle) and downstream (bottom) on HW and LW during a synthetic storm

The impact of the FCA's at different locations is shown in Figure 41. The effect is clearly largest for the FCA in an upstream location.

Note that Figure 41 indicates that the FCA does not fill completely during the synthetic storm. In our simplified case, we could model a higher storm surge, or a combination of storm surges, or lower the height of the overflow dike. In reality, the design of the area would be optimised for maximum effect (lowering of HW in the estuary) for a given set of design storms.

# 7 Conclusions

The CRT technique is often unknown in other EU member states but can also be used in other estuaries, especially under the following conditions:

- Available space is very limited, which means maximum storage capacity is required when the peak of the storm surge hits.
- The relative altitude of adjacent land is unfavourable in relation to the river, which prevents formation of proper mudflats - tidal marshes in case of depoldering.
- The embankment alongside the river needs to be retained and kept accessible.
- Large tidal fluctuations are undesirable in floodplains.
- Large depoldering operations are undesirable because the fairway is left without sufficient water at times

For the CRT system to function properly, a carefully dimensioned culvert construction with combined inlet and outlet has to be placed at a specific height within the tidal window. This is the only way to secure an appropriate neap-spring tidal variation, which is crucial for the development of mudflats and tidal marshes in the area.

The report presents a standardized method for modeling tidal propagation in estuaries in an idealized way. The idealized models are calibrated based on tidal measurements and provide a testing bed for assessing the impact of FCA-CRT on flood protection and their potential for ecological development. The results emphasize the importance of site selection and design parameters for the performance of FCA-CRT areas in various estuarine contexts.

The methodology that we propose is generally applicable to any estuary and only needs a limited amount of data:

- Width of the estuary along the thalweg. This can be estimated from satellite images or maps, or derived from bathymetric data
- Cross-sectionally averaged depth along the thalweg. This can be derived from bathymetric survey data, or derived from nautical maps
- Water level data along the thalweg for calibration and for the downstream boundary condition. For this report, we limited us to average HW/LW levels that could be derived from existing reports
- Long term average upstream discharge. This value is generally available from literature.

The modelled tidal amplitude of the Humber after automatic calibration suggests that the current method might be an oversimplification for the Humber. This estuary merits further research to establish what characteristics (e.g. a more realistic cross section) should be added for the model to achieve a good fit with the observed tidal amplitudes. For this reason, the results for the Humber are omitted from the further discussion.

## 7.1 Set up of scenarios in idealized models

Using the idealized models, this report proposes a quickscan method to quickly assess the potential effect of a flood control area on the reduction of HW, and on the reduced tide that can be achieved in a CRT area. The quickscan is applied for an area of 100ha in size, using default geometric characteristics for overflow dike height and culvert design, but these parameters can be easily changed in follow-up research.

In order to assess the impact of the location of the flood control areas in the estuary, three scenarios are assessed for each estuary: the flood control area is implemented either downstream (at L/4), in the middle (at L/2) or upstream (at 3L/4), with L the length scale of the estuary.

## 7.2 Quickscan for CRT potential

The CRT potential for the three possible locations of a 100ha CRT with default design parameters is assessed by quantifying the tidal amplitude in the FCA-CRT during calm/average conditions. Table 21 shows the tidal amplitude as a fraction of the tidal amplitude in the estuary at the location of the CRT.

This result shows that the "default" CRT design (see §5.2.3) achieves a reduced tidal amplitude that is approximately between 15% and 25% of the estuarine tidal amplitude. This attests to the general applicability of the CRT idea to unlock the potential of ecological development in areas that can also have a safety function (see next paragraph).

Of course the actual design of a CRT would be done with more detailed models to capture the estuarine tides more accurately. Also the target tide in a CRT depends on the kind of nature development that is wanted in each area. But it is still striking that the CRT design rules that we follow in this study achieve such similar tidal reductions in such separate estuarine systems.

Table 21 – Quickscan for potential CRT functioning: ratio of tidal amplitude in the CRT to tidal amplitude in the estuary

| Tidal amplitude ratio in the CRT | Downstream | Middle | Upstream |
|---|---|---|---|
| **Scheldt** | 25% | 17% | 13% |
| **Elbe** | 23% | 28% | 18% |
| **Seine** | 14% | 17% | 14% |
| **Humber** | - | - | - |
| **Weser** | 19% | 21% | 20% |

## 7.3 Quickscan for potential safety benefits

Table 22 shows the result of the quickscan in terms of the expected safety benefit of a 100ha FCA in the three potential locations in each estuary. These results are expressed in cm reduction of HW, at the location of the FCA. Typically this effect is strongest at the location of the FCA, but extends also tens of kilometers up- and downstream of the FCA location.

Table 22 – Quickscan for potential safety benefit: reduction in HW [cm]

| Reduction in HW [cm] | Downstream | Middle | Upstream |
|---|---|---|---|
| **Scheldt** | <1 | <1 | 6 |
| **Elbe** | <1 | <1 | 2 |
| **Seine** | 4 | 5 | 4 |
| **Humber** | - | - | - |
| **Weser** | 1 | 3 | 6 |

In general, the safety effect is stronger if placed upstream in an estuary than downstream. This can be attributed to the fact that the tidal volumes are typically lower upstream (smaller cross sections, smaller tidal amplitude), so the relative effect of filling a 100ha FCA around HW of a storm tide is larger when the FCA is located upstream

# References

Bi, Q.; Vanlede, J.; Mostaert, F. (2021). LIFE Sparc – action C10: Transfer to other estuaries (Replicability & Transferability): Sub report 1 – Inventory and comparative study. Version 2.0. FHR Reports, 16_072_1. Flanders Hydraulics Research: Antwerp.

Li, C., Schuttelaars, H. M., Roos, P. C., Damveld, J. H., Gong, W., & Hulscher, S. J. M. H. (2016). Influence of retention basins on tidal dynamics in estuaries: Application to the Ems estuary. Ocean & Coastal Management, 134, 216–225. https://doi.org/10.1016/j.ocecoaman.2016.10.010

Stark, J.; Smolders, S.; Meire, P.; Temmerman, S. (2017). Impact of intertidal area characteristics on estuarine tidal hydrodynamics: A modelling study for the Scheldt Estuary. Estuar. Coast. Shelf Sci. 198: 138–155. doi:10.1016/j.ecss.2017.09.004

Vandenbruwaene, W.; Plancke, Y.; Verwaest,T.; Mostaert, F. (2013). Interestuarlne comparison: Plydro-geomorphology: Plydro- and geomorphodynamlcs of the TIDE estuaries Scheldt, Elbe, Weser and Plumber. Version 4. WL Rapporten, 770_62b. Flanders Hydraulics Research: Antwerp, Belgium.

Vandenbruwaene, W.; Plancke, Y.; Mostaert, F. (2018). ANPHYECO-Seine – Hydro-geomorphology of the Seine estuary: Interestuarine comparison and historical evolution. Version 4.0. FHR Reports, 14_120_2. Flanders Hydraulics Research: Antwerp.

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