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Idealized modelling of FCA-CRT in European estuaries: an example of the Scheldt estuary

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Abstract – **The concept of 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 in Belgium. 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 other European estuaries. This study investigated the different topo-bathymetry schematization methods and their impacts to the tidal propagation. Then an idealized model with the implementation of an FCA-CRT is used to explore the influences of its location on the estuarine hydrodynamics and tidal range reduction.**

Keywords: idealized modelling, FCA-CRT, estuary.

I. INTRODUCTION

The concept of 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 the Scheldt Estuary in Belgium. Through years of development, this nature-based solution has been proved to be an effective approach providing protection against flooding and improving resilience of the estuarine ecosystem under the threat of climate change [1].

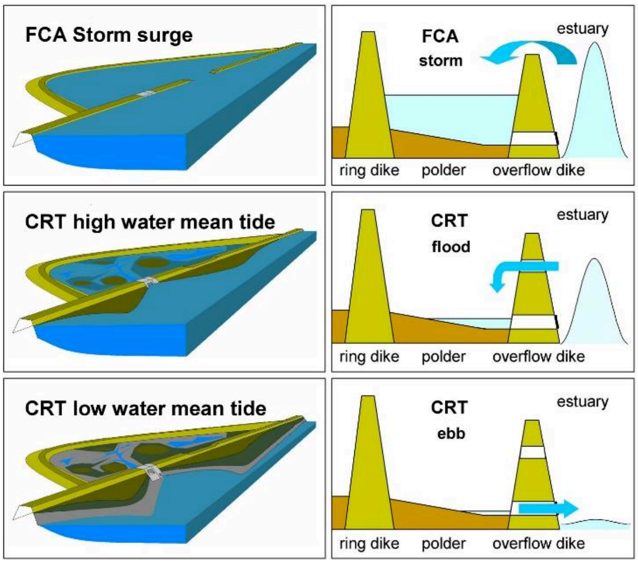

Figure 1. Functioning of a Flood Control Area (FCA) with Controlled Reduced Tide (CRT) at storm surge (upper panels), at high water mean tide (central panels) and at low water mean tide (lower panels) [1].

Figure 1 illustrates the concept of a functional FCA-CRT on the bank of an estuary.

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 six European estuaries across France, Germany, the Netherlands and the UK. This approach requires schematization of the geometry for each study area, in which the FCA-CRT is modelled as culverts, and only the important physical processes are considered [2].

To investigate the potential effects of FCA-CRT on tidal wave propagation 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 each of these simulations, a slightly different mesh with a specific design of the FCA-CRT must be used, which requires a considerable amount of effort in mesh creation, not to mention that the whole process has to be repeated for all six European estuaries. To make this process more efficient, an automated workflow has been developed based on a set of tools and algorithms that can perform topo-bathymetry schematization, mesh generation, simulation execution and post-processing, with given inputs. The process is based on Python scripts and other relevant packages to: (a) process the topo-bathymetric and water level data of each estuary; (b) prepare the necessary information for the Gmsh mesh generator [3]; (c) using the Gmsh API in Python to manipulate the mesh generation according to the desired FCA-CRT design; (d) translate the Gmsh generated mesh file (.msh) into the SELAFIN format mesh (.slf) to be recognized by TELEMAC-2D; (e) create a boundary condition file (.cli) that matches the new mesh; and (f) finally set-up of the schematized model for execution. Another important aim in this study is to use Python and TELAPY 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 higher performance computer for execution. The post-processing is also integrated in the automated workflow and the effects of FCA-CRT are analyzed.

This paper presents the integrated workflow with an example of the Scheldt estuary.

II. METHODOLOGY

The idealised modelling of an estuarine system usually consists of the following considerations:

- The schematization of the topo-bathymetry.
- The schematization of physical processes.
- The schematization of the measures.

These three aspects are discussed in detail in the following sections.

A. Topo-bathymetry schematization

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 [6], the Scheldt estuary (Figure 2) 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.

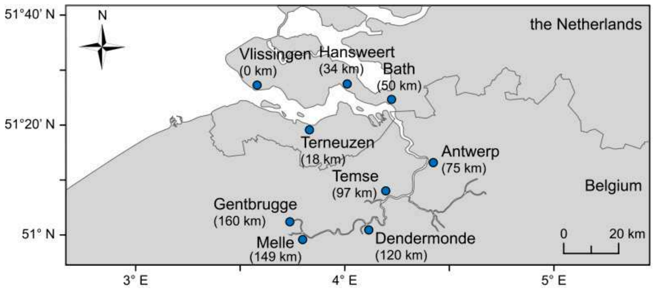

Figure 2. The tidal part of the Scheldt River from Vlissingen to Ghent [6].

Following a similar idea and utilizing the advantage of the TELEMAC-2D modelling framework, a new methodology that could maintain more topo-bathymetric features is proposed for the estuarine domain schematization in this study. To be more specific, the new method allows the presence of intertidal areas next to the main channel, and the shapes of the cross-sections along the estuary are computed by matching the observation-derived wet section areas at mean high water (MHW) and mean low water (MLW). The design of the mesh (distribution of the mesh nodes with spatial dependent size field) is also considered in this procedure.

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 [4][5]. 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 in [4] and [5] 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

1) Shape of the schematized estuary

The first step in the schematization of the topo-bathymetry is the mesh design since it determines the geometric contour or the shape of the schematized estuary. The shape is usually derived from the observed widths at multiple transects along the estuary. In the previous study [4], the estuary widths of the Scheldt were derived from the digital elevation model and the water level parameters.

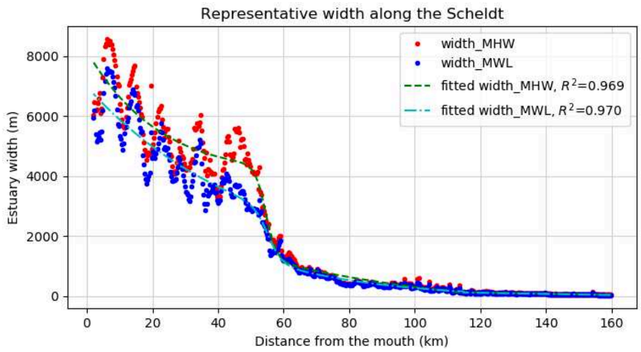

Figure 2

Figure 3. Measured width and fitted curved for the Scheldt Estuary.

Figure 3 shows the observed estuary widths W_{MHW} and W_{MWL} (width at mean water level, which is the average of W_{MHW} and W_{MLW}). Depending on the degree of preservation of topo-bathymetry features, the observed widths can then be fitted with specific functions for having non-smooth or smooth transitions from downstream to upstream. Later these functions are also used for generating the outline for the schematized domain.

2) Mesh generation

The second step involves the design of the mesh. To make the simulation efficient while maintaining enough features in topo-bathymetry, the mesh is designed as follows:

- A fixed number of nodes are evenly placed (with interval of *dx*) in the cross-sectional direction at every transect along the estuary.
- The distance between two transects or cross-sections (*dy*) is proportional to *dx* at the same location.
- The most outward nodes form the outline of the mesh, while the rest are considered as inside nodes

and control the generation of triangular elements within the domain.

The algorithm for generating the mesh outline and the embedded points is illustrated in Figure 4.

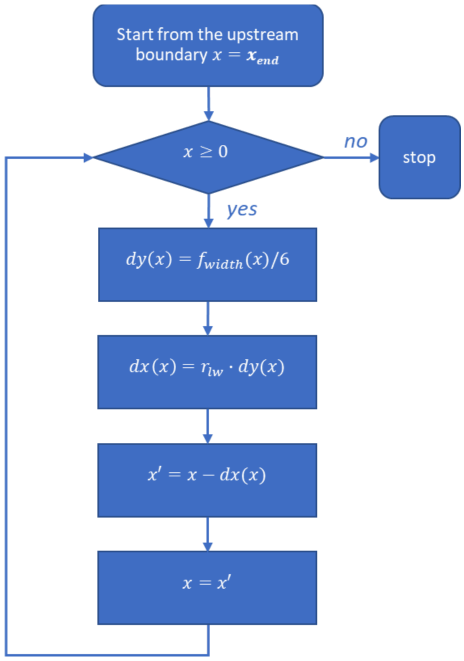

Figure 4. The algorithm for generating mesh nodes for a shcematized estuary ($f_{width}(x)$ is the fitted function for the estuary width).

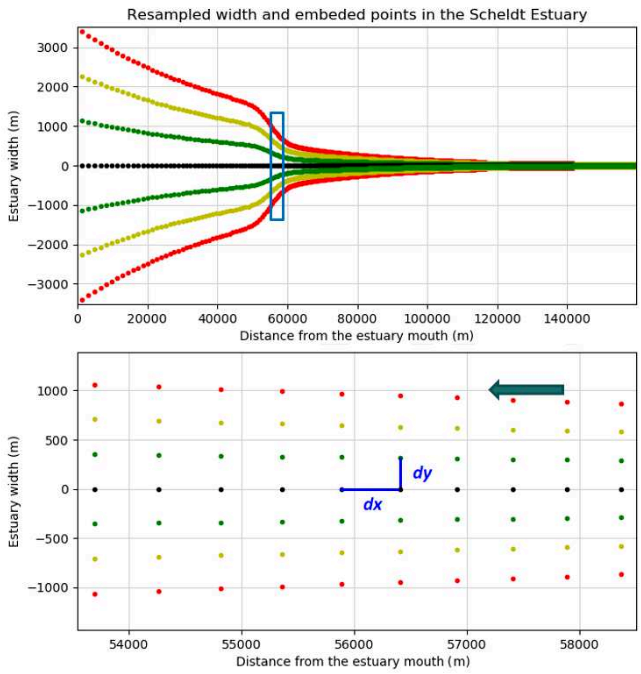

Figure 5. Algorithm generated points for the schematized Scheldt mesh (top: overview of the resampled points, bottom: zoom-in view of the nodes)

The generated outline nodes and inside nodes are shown in Figure 5.

Next, Gmsh is utilized for generating non-uniform triangular elements. The outline and the embedded nodes are arranged in a specific format and the info is passed to the mesh generator via its python API.

Gmsh uses its own file format (.msh, version 4) to store information of a generated mesh following a convention described in the Gmsh reference manual [6]. A python tool was then developed for converting the Gmsh file format into the selafin format (.slf) used by the TELEMAC system. The following mesh data is considered essential and required during the translation between two formats:

- Node number of each mesh node and its coordinates (x, y),
- Definition of each element (connection table with nodes arranged counterclockwise for ensuring positive determinant),
- Node number of the boundary nodes at both open and close boundaries.

The same python tool can also generate the boundary conditions file (.cli) automatically based on the info passed to Gmsh.

3) Resolving the transect profiles

The methodology in [6] assumes the bottom of a schematized estuary is flat in the cross-sectional direction but varies smoothly in the horizontal direction. This is usually not true for real estuaries due to the presence of intertidal areas, which not only affect the tide propagation but also lead to more complex morphological evolutions. Thus, including intertidal area and its potential influence should be considered in the domain schematization.

In the design of the mesh, nodes (including outline and inside nodes) are evenly distributed along each transect. Including intertidal areas will lead to changing elevations at these nodes transect by transect. Hence, a new method is proposed in this study based on the following assumptions:

- Evenly distributed nodes (seven in total) are placed along each transect and the lengths of the transects resemble the observed widths at mean high water W_{MHW}.
- The transect profile is assumed to have platforms next to the main channel representing the intertidal areas.
- The wet cross section areas at Z_{MHW} and Z_{MLW} (A_{MHW} and A_{MLW}, respectively) should correspond to the measured data mentioned in [4].

Figure 6 shows the predefined transect profile with the relevant parameters required for solving the two unknowns, the platform elevation Z_P and the main channel bottom elevation Z_B.

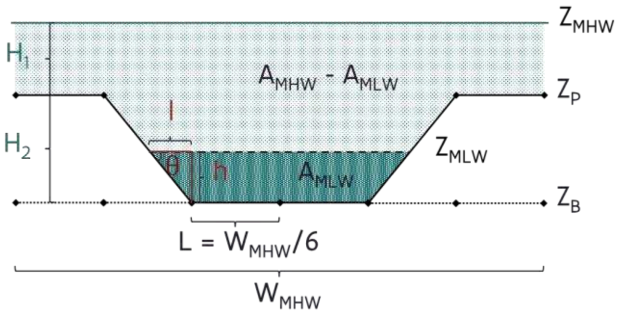

Figure 6. The targeted transect profile for matching the measured wet cross section areas at MHW and MLW

According to the definition of the cross section in Figure 6, the following equations must be satisfied:

$$A_{MHW} = 6L \cdot H_1 + 3L \cdot H_2 \quad (1)$$

$$A_{MLW} = 2L \cdot h + l \cdot h \quad (2)$$

Because

$$Z_{MHW} - Z_B = H_1 + H_2 \quad (3)$$

$$tan\theta = \frac{h}{l} = \frac{H_2}{L} \quad (4)$$

and

$$Z_{MLW} - Z_B = h \quad (5)$$

$$H_1 = Z_{MHW} - Z_P \quad (6)$$

$$H_2 = Z_P - Z_B \quad (7)$$

The eq. (1) and eq. (2) could be rewritten as

$$A_{MHW} = 6L \cdot (Z_{MHW} - Z_P) + 3L \cdot (Z_P - Z_B) \quad (8)$$

$$A_{MLW} = 2L \cdot (Z_{MLW} - Z_B) + \frac{L}{(Z_P - Z_B)} \cdot (Z_{MLW} - Z_B)^2 \quad (9)$$

where, the interval between the evenly spaced nodes along the cross-section L = W_{MHW}/6.

Solving the set of eq. (8) and eq. (9) provides the results of the two unknowns Z_P and Z_B that define the profile of the cross section. The python package SymPy for symbolic mathematics is used to solve the set of equations. Note that eq. (6) can be seen as a quadratic equation of Z_B because of the term $(Z_{MLW}-Z_B)^2$, thus solving the equations consequently result in two sets of solutions of H_1, H_2 and Z_B, in one of which it is possible to have $Z_{MLW} < Z_B$. The criterion for selecting the valid solution is that the platform elevation Z_P should fall in between Z_{MHW} and Z_{MLW} at most of the locations, so only one solution remains valid and is used later in the model.

Again, depending on the degree of preservation of topo-bathymetry features, the resolved platform and bottom elevations can be fitted with polynomial functions to smooth out the unwanted local variations. An example is shown in Figure 7.

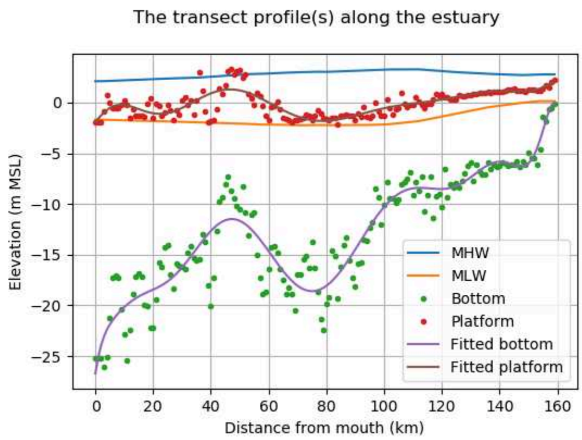

Figure 7. The resolved platform and main channel bottom elevations in the Scheldt estuary with coresponding fiteed polynomial curves.

B. *Schematization of the enginerring mitigation (FCA-CRT)*

The engineering mitigation considered in this study, i.e., the FCA-CRT, consists of sophisticated hydraulic structures separating the main estuary channel from an adjacent area of land adjacent that can experience flooding during periods of high water. Both the structure and the area of the land must be schematized in an idealised domain. As such, the water volume exchange between the main estuary channel and the FCA-CRT are modelled by culverts in TELEMAC-2D. The following schematization of the FCA-CRT is used in the model (Table I).

Table I Configuration of the culverts linking the main channel and the FCA-CRT

Dimensions of the area	Rectangle, 2500 m by 1200 m	
Mesh size	200 m	
Culverts	12 inlets	Each culvert: length 20m, width 2.6m, height 2.2m
	8 outlets	
Location of the area	Moving along the estuary in each simulation	

To demonstrate the effects on the estuarine hydrodynamics, the FCA-CRT is placed at different locations in different simulations. A python tool is made for generating batches of the models with specified configurations of the FCA-CRT in each one of them. In this case, it is used to shift the location of the FCA-CRT in each simulation, each time 15 km towards upstream starting at 15 km from the mouth area in the first simulation.

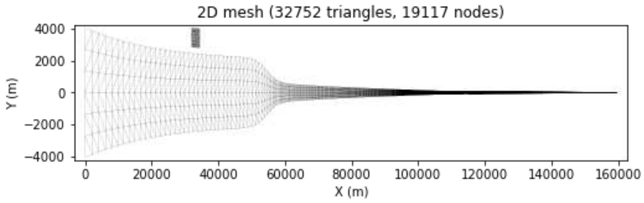

Figure 8. The mesh of the schematized Scheldt estuary with a FCA-CRT

The dimensions of the FCA-CRT and its location relative to the estuary are passed to Gmsh via its API in order to generate a smaller scale separate mesh, and then attached to the main estuary mesh. The boundary conditions file (.cli) is updated as well in order to include the boundary definitions for new area in the original mesh. An example of the estuary mesh (with curve-fitted widths) that has an FCA-CRT can be seen in the example in Figure 8. It is worth mentioning that the storm scenario is not considered in this study, in this case the FCA-CRT allows inflow and outflow via culverts, and there is no overflow from the main channel to the FCA-CRT above the overflow dike. Hence, the FCA-CRT area can be detached from the main mesh, the advantage is that its grid size will not be subjected to the mesh size in the estuary and the dimensions of the FCA-CRT can be defined freely.

C. *Esturine process schematization*

There are many physical processes happening in an estuarine system, e.g. (tidal) wave propagation, transport of suspended matter, salinity mixing, and other relevant ecological processes. In the idealised modelling, depending on the research focus, only the important processes are necessary to be included in the model.

Table II Model configurations

Boundary forcing	Upstream	Constant discharge 60 m^3/s
	Downstream	Tidal constituents (A_{M2} =1.89m, Φ_{M2}=0.0, f_{M2} =1.405e-4, A_{M4}=0.15m, Φ_{M4}=-2.269e-2, f_{M4} =2f_{M2})*
Model parameters	Turbulence model	The Smagorinsky model
	Bottom roughness	Dynamic friction law [8] with ks=0.3m
	Tidal flats	Yes, option 3 with consideration of porosity
	Timestep	10 s
	Duration	20 days

*M2 and M4 are the two major tidal constituents in the Scheldt estuary, and their amplitudes, phases and frequencies are denoted by A, Φ and f respectively. The values are based on [6] with adjustment for matching the tidal amplitude at downstream boundary with the observation.

In this study, the estuarine hydrodynamics is the main focus. The model has two open boundaries, at the downstream boundary (sea boundary), water elevations with two major tidal constituents (M2 and M4 tides) are prescribed, while at the upstream boundary a constant freshwater discharge is imposed. The turbulence (eddy viscosity) is resolved by the Smagorinski model. The overview of the model set-up can be seen in the Table II.

The above model configurations have been applied to all the simulations in this study. The differences in each individual model run are discussed in the next section. Note that considering the Scheldt estuary is well-mixed, the salinity is not included in the models.

III. RESULTS

Two groups of simulations were carried out in this study. The first group aimed to understand the influences of the topo-bathymetry features on the hydrodynamics in a schematized model, while the second group was dedicated to highlighting the effects of the FCA-CRT on the tidal propagation in along the estuary.

A. *Effects of the topo-bathymetry schematization*

The schematization of topo-bathymetry is one of the most important aspects in idealized modelling since the shapes of the estuary will have impacts to the tidal propagation. Different ways of schematization in this sense may result in different hydrodynamics in the domain, which could impact the validity of an idealized model.

In order to gain more insights, three meshes derived from different topo-bathymetry schematization methods are tested in three separate TELEMAC-2D simulations (Table III).

Table III Topo-bathymetry schematization methods used in this study

Method	Transect profile
iFlow method [6] (flat bottom)	Rectangle, curve-fitted width W_{MWL} (see Figure 3), bottom elevation of each transect: $Z_B = \frac{(Z_{MHW} + Z_{MLW})}{2} - \frac{1}{2}\frac{(A_{MHW} + A_{MLW})}{W_{MWL}}$
Proposed method (with tidal flats)	See Figure 6, Z_P and Z_B are solved from eqs. (8) and (9). No curve-fitting to W_{MHW}, Z_P and Z_B.
Proposed method (with tidal flats, smoothed)	See Figure 6, Z_P and Z_B are solved from eqs. (8) and (9). Curve-fitted W_{MHW}, Z_P and Z_B.

The schematized estuarine widths and platform/bottom elevations are shown in Figure 9, and the actual meshes used in the simulations can be seen in Figure 10. The only difference among these model runs is the mesh and the topo-bathymetric info associated with it, the rest of the model configurations are kept the same as in Table II.

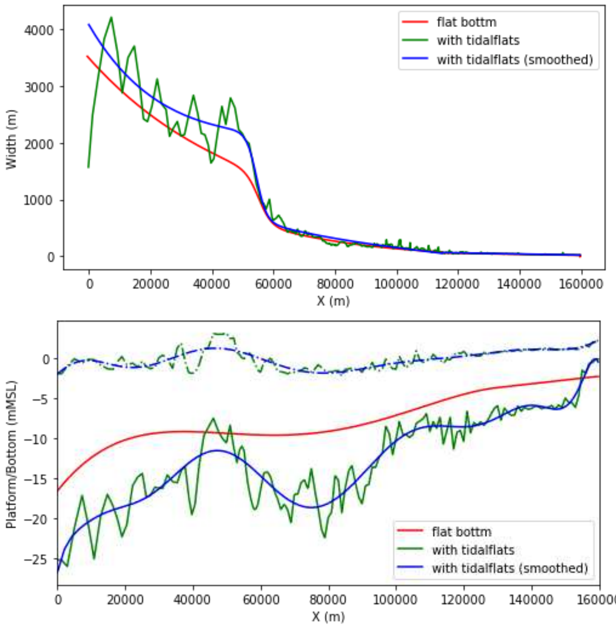

Figure 9. The half of the widths and the platform/bottom elevations of the three meshes (dotted lines: platform elevation, solid lines: bottom elevations)

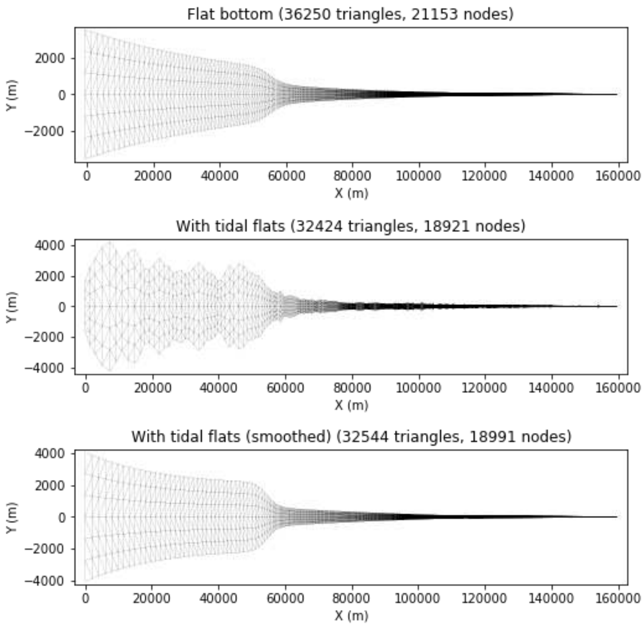

Figure 10. Overview of the meshes used in the simulations

The modelled results are then processed and compared with the observed data provided by [4]. To be more specific, the MHW, the MLW and the tidal range is computed in all the cases and compared with the values derived from the 10-year water level measurements in the Scheldt estuary.

Figure 11 shows that the mesh with tidal flats matches best the observed MLW and tidal range along the estuary, but it underestimates the MHW in the region 0-140 km and overestimates it from 140 km to 160 km. One of the reasons for the relatively poor agreement with the observed MHW especially near the upstream boundary could be due to the imposed constant discharge. In reality, flow can reverse its direction from downstream to upstream during flood around this location. The constant discharge in the model disturbs the flood/ebb transitions in the area, hence causes deviations from the measurements.

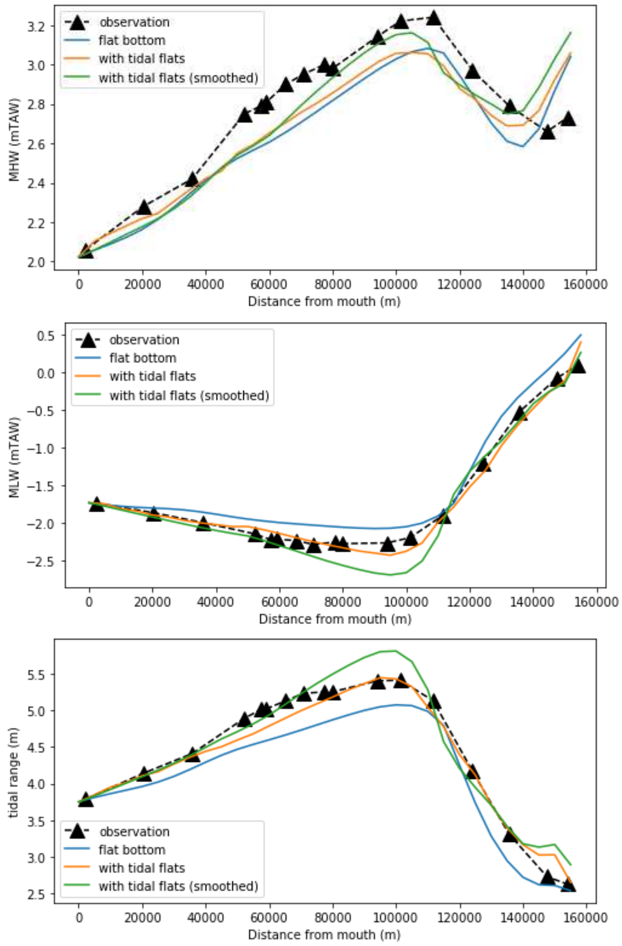

Figure 11. Comparison of MHW, MLW and tidal range

Compared to its non-smoothed version, the smoothed mesh with tidal flats produces similar horizontal patterns but the larger deviations from the observations. In general, it overestimates the tidal range in the region between 60 km and 110 km, which is mainly due to the underestimation of the MLW in the same region. This indicates that the detailed topo-bathymetric features affect the tidal propagation in the estuary and cannot be neglected. It also seems that the local variations in widths and elevations have larger influence in certain region that the other. But it is expected to have less tidal wave attenuation with the smoothed mesh.

The mesh with flat bottom predicts different horizontal patterns in MHW, MLW and tidal range. The peaks in these curves are always further upstream with 10 km shift compared to the observations. This means lack of topo-bathymetric features could lead to different tidal characteristics in the estuary.

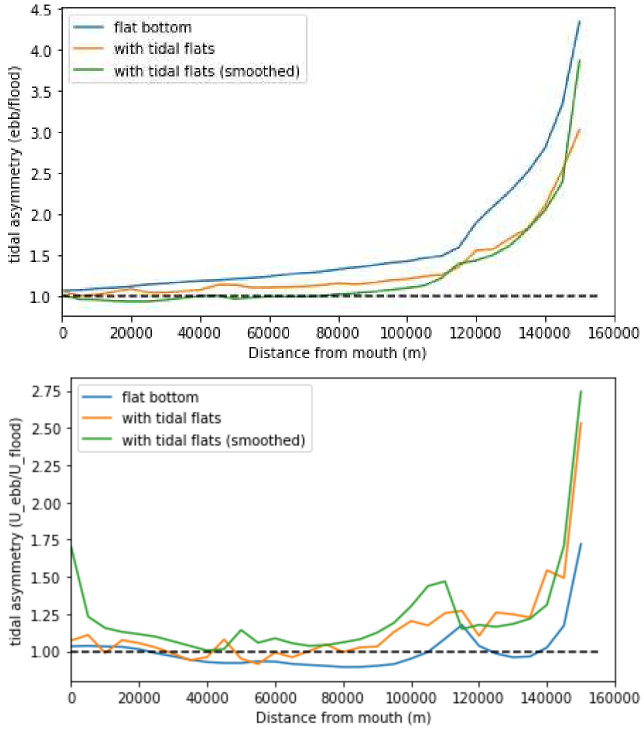

Figure 12. Comparison of tidal asymmetry in the main channel (top: ebb duration/flood duration; bottom: mean ebb velocity/mean flood velocity)

The effects of the topo-bathymetry can be further demonstrated in Figure 12. Two tidal asymmetry indicators were computed, namely the duration asymmetry and velocity asymmetry. The duration asymmetry shows that both meshes with tidal flats result in a less ebb dominant system, meaning that the ebb phase becomes shorter and flood phase longer. Especially with the smoothed version, due to less resistance, the downstream region from 0 km to 60km becomes slightly flood dominant.

The similar trend can also be observed in the velocity asymmetry. The results show that both ebb and flood velocities are increased when using the two meshes with tidal flats and the overall trend is that the system in these two cases become less flood dominant and, in some areas, more ebb dominant. Because the ebb velocity increases even more in the case with smoothed mesh with tidal flats, the system becomes entirely ebb dominant.

B. Effects of the FCA-CRT

The effect of the FCA-CRT on the reduction of tidal range has been assessed with a batch of simulations, in which the location of the FCA-CRT is changed in each run, but the size and the configurations of the culverts are kept the same. All the simulations were done with the smoothed mesh with tidal flats.

Figure 13 shows the tidal range is reduced by the presence of the FCA-CRT near the location where it is implemented. Downstream of it we can also observe a slight increase (compared to the reduction) of the tidal range due to the release of the stored water during ebb. The effect of the reduction is larger in the upstream and becomes smaller towards downstream where the tidal prism greatly increases.

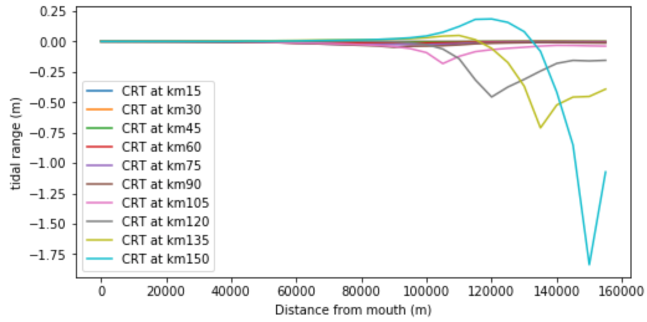

Figure 13. Tidal range differences along the estuary in the scenarios (with FCA-CRT implemetned) compared to the reference (FCA-CRT inactive)

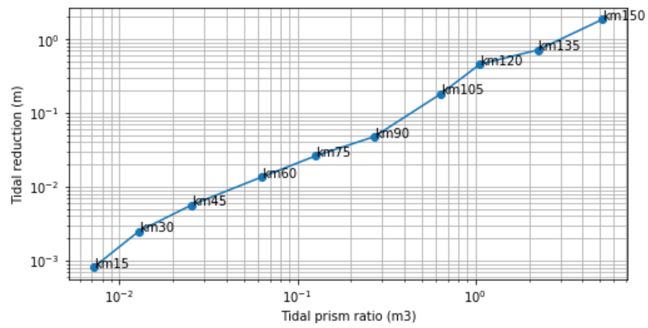

Figure 14. The ratio of the volume passing the transect where the FCA-CRT is implemented in the period between MHW and MLW to the volume entering FCA-CRT in the same period

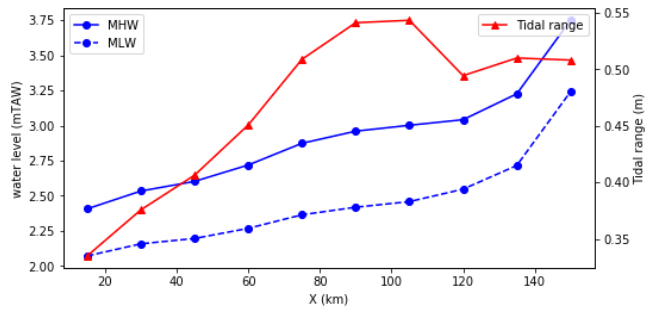

Figure 15. The MHW, MLW and tidal range in the FCA-CRT against the lcoation of the FCA-CRT

Further analysis shows that the reduction of tidal range can be linked to the ratio of tidal prism, which is the ratio of the volume passing the transect where the FCA-CRT is implemented in the period between MHW and MLW to the volume entering FCA-CRT in the same period (Figure 14). The reduction of tidal range increases exponentially, and more volume entering the FCA-CRT after 120 km and further upstream.

Besides the influence in the main channel, the tidal characteristics inside the FCA-CRT was investigated. Figure 15 shows the MHW, the MLW and the tidal range in each scenario case. In general, the water levels increase as the location of the FCA-CRT moves upstream. The highest tidal range is achieved when placing the FCA-CRT at 105 km and it reduces the tidal range in the main channel by 18.2 cm. In case of requiring less disturbance to the system while maintaining the tidal dynamics in the area, then placing at 90 km will be an optimal option since it only reduces the tidal range by 4.8 cm.

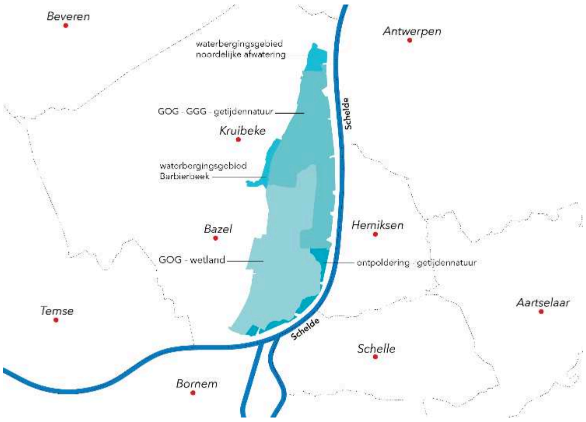

Figure 16. Location of the Bazels FCA-CRT [9].

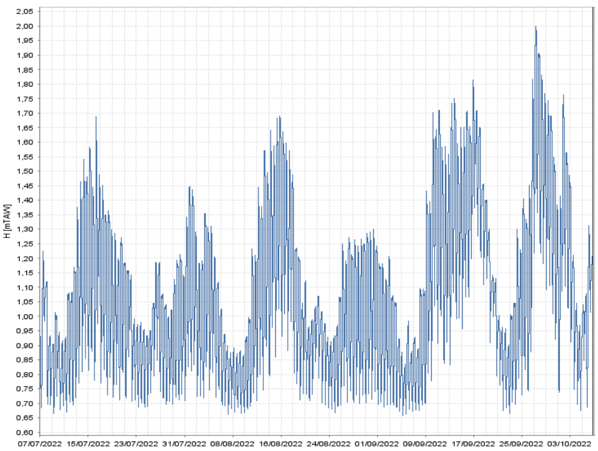

Figure 17. The timeseries of water level in Kruibeke-Bazels FCA-CRT (source: waterinfo.be).

The results are found comparable the pilot projects in the Scheldt estuary. One of the examples is the Kruibeke-Bazels FCA-CRT [9]. The area is situated at 85 km, with 450 ha mud flats and salt marshes now be used as a nature reserve, in which the tidal nature is created via the FCA-CRT concept. The tidal range in the area ranges from 0.5 m to 0.7 m according to the measurements in the past 3 months (6 July – 6 October 2022) (Figure 17).

IV. CONCLUSIONS

An idealized modelling approach is proposed in this study for studying the influence of the FCA-CRT on the estuarine hydrodynamics. As one of the important aspects in the idealized modelling, the schematization of the topo-bathymetry of the estuary was further investigated. The comparison of three difference schematization methods shows that the topo-bathymetry features could impact the tide propagation. More features it can preserve in a schematized domain, higher accuracy it may achieve in an idealised model. The detailed topo-bathymetric variations in the mesh does not only affect the tidal range, but also the tidal asymmetry, and it may lead to different tidal characteristics that deviate from real system.

The second part of this study investigated the influence of a FCA-CRT on the reduction of tidal range by placing it at different locations. The results show that, for a given configurations of the culverts, depending on the ecological and hydrodynamic targets, there always exists an optimal location, where the tidal characteristics in the FCA-CRT is more favourable and it has desired impact to the system. It is worth mentioning that this is only a preliminary study, although it has demonstrated how the methodology can be used to optimize the FCA-CRT design.

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