MSc. Thesis

Modelling the impact of large scale sediment dumping on the meso-scale hydro- and morphodynamics in the Western Scheldt

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Master thesis – Final report

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July 2015

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Summary
The current report aims to understand the hydro- and morphodynamic response of the Western Scheldt in a large sediment dumping operation. This study investigates the estuary's response to sediment dumping in the Everingen channel area, which is located in the middle of the Scheldt Estuary, The Netherlands. Furthermore, it studies whether these sediment nourishments could indirectly feed the nearby-located Baarland tidal flat. In this study, two morphodynamic models for the Scheldt Estuary were set up, using both the newly developed D-Flow Flexible Mesh software, for the numerical modelling, and the more established Delft3D software. The new software allows a local refinement of the grid in the area of interest for better hydraulic and morphological analysis and shorter computational times. Both models were calibrated and validated for the local hydrodynamics, and subsequently used to study several sediment dumping scenarios. As the sediment module within D-Flow FM was not available yet, the morphological impact of each dumping scenario is investigated using offline-predicted sediment transport patterns based on predicted velocities. These large dumping operations can cause intense changes in the local hydrodynamics and also significant morphodynamic changes not only locally but also in the wider macro-cell area. Indications of erosion and accretion in the Baarland flat were found without though having a clear view of the flat nourishment. Based on the study results, further investigation of dumping scenarios close to the area of interest is recommended.
Abstract

The current research describes a case study in the area of Scheldt Estuary which is located in the south-west Netherlands. The Scheldt Estuary is a common area of interest for research since it is a large estuary with dynamic morphology and many interests that sometimes conflict. The navigation channel to the port of Antwerp and to other ports along the Western Scheldt is regularly dredged. Next to the navigation, safety and ecology play an important role in the Western Scheldt. The sea level rise combined with a potential increase of storminess is a safety threat and the ecology is affected by the frequent dredging and dumping operations and the bank protection measures. These conflicts are seen not only in the Scheldt Estuary but often in most of the large estuaries. Numerical models are commonly used to predict hydraulic and morphologic changes due to natural changes and human interventions, to support estuarine management and policy.

In order to minimise the costs but also not to change the amount of sediment in the estuary, the dredged material is redistributed inside the estuary by dumping it in nearby channels. The trigger for this research were the results by Cleveringa et al, 2014 who focused on the morphological consequences after a dumping operation that was carried out in 1997-1998, in the Scheldt Estuary. The current report focuses on understanding the morphological response of the estuary to the dumping of a large amount of dredged material in the surrounding area of Everingen channel, one of the main channels of the estuary. For this study a specific area was selected inside the estuary in order to simulate different scenarios of dumping locations. The resulting sediment transport patterns provide insight into how the different scenarios affect the hydrodynamic and morphodynamic behaviour of the estuary. With these scenarios, the possibility to indirectly nourish an eroding intertidal area, by depositing the material at other locations, is investigated.

For the implementation of this research two different types of hydro-morphodynamic software packages were used; the recently developed D-Flow Flexible Mesh and Delft3D. The first one offers the advantage of unstructured grids with an easy local refinement, which saves computational time, while Delft3D is used mainly for comparisons to validate the new software. A new tidal propagation model was developed, to study the hydrodynamics and the morphodynamics in the area of interest. The sediment transport functionality was not available yet in D-Flow FM, therefore, sediment transport was computed offline, using the Engelund-Hansen formula, with predicted current velocities as input. The computed residual sand transport patterns were interpreted to understand the initial morphological response to sediment dumping.

The models were first compared using measured water levels, velocities and discharges. This comparison showed that both can accurately predict the hydrodynamics in the area of interest. Furthermore, the D-Flow FM and Delft3D model results were compared to each other and this showed a perfect match in most of the cases. The offline calculated sediment transport, using the Engelund-Hansen approach, was compared with Delft3D results using the standard formulation of Van Rijn 1993, online. The offline approach slightly overestimated the transport magnitudes but the directions were similar. The sediment transport computations and the accompanying morphological interpretation were validated using the measured morphologic response after the dumping operation of 1997-1998. Approximately 7 Mm³ were dumped in the Everingen channel. Both the model and the measurements show erosion of the entrance to the Zuid-Everingen channel. A non-erodible layer in the area, causes migration of the channel to the south. The model results indicate this morphological
response without giving a clear answer about the quantities of sediment but qualitatively it is an accurate method.

With the validated D-Flow FM model four dumping scenarios were simulated. Four different dumping sites were chosen: 1) Zuid-Everingen, 2) Drempel van Baarland, 3) Everingen Ebschaar and 4) Everingen in Middelplaat area. The sediment volume varied between ~6 and ~9 Mm$^3$. These locations aimed to cover a broad range of cases since they were not focused in one location but in the wider surroundings of the Baarland flat. The hydrodynamics in the area are affected by the operations but the impact is decreasing when moving away from the operation area. The residual sediment transports in the wider area are affected by the dumping operations, in most of the scenarios. This area exceeds even the boundaries of the macro-cell. The velocities and residual sediment transports in Baarland flat indicate erosion and accretion in the different scenarios without though a clear feeding of the flat. The closer the dumping location is to the Baarland flat, the higher the impact is on it. Further investigation is recommended, with different chosen locations which selection can be made based on the direction of the residual transports.
Acknowledgements

With the current report, the Master of Science in Hydraulic Engineering of Delft University of Technology is completed. The research was carried out at Deltares institute in Delft, The Netherlands.

Firstly, I would like to thank all the members of my graduation committee for their support and the sharing of ideas throughout the period of my thesis. Professor Marcel Stive for his suggestions and guidance as well as his interest in my project. Thanks to Lodewijk de Vet, for offering feedback and help that contributed in the implementation of my thesis. Jebbe van der Werf, for providing useful data and suggestions that improved the current study. Great thanks, to my daily supervisor Arnold van Rooijen, for his constant support, the help, the enthusiasm and the positive spirit as well as for his useful suggestions and the time invested in me.

With my current project I had the opportunity to work every day at Deltares. Many thanks to Deltares for providing me this great opportunity that will always remain as a great experience. I would like to thank fellow students and employees at Deltares for their help, their suggestions, the fruitful conversations, the coffee and lunch breaks. They made my staying extremely enjoyable.

Finally, I would like to thank my friends and family for their unconditional and constant support all these months and also for their tolerance and patience during the busy days of my project.

Nefeli Palaiogianni
Delft, July 2015
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1 Introduction

1.1 Background

The Netherlands is a geographically very low and flat country and a large part of the land was formed by the estuaries of three large European rivers: the Rhine, the Meuse and the Scheldt. The area of interest in this thesis is the Scheldt Estuary which is located in the South of the Netherlands, close to the border with Belgium.

![Figure 1.1: Location of Scheldt estuary on the Dutch map, indicated by the yellow box](image)

The estuarine system is a complicated and morphologically dynamic part of the coastal system. It is influenced by natural processes and human interventions inside the basin or in the coastal area. For safety and navigation reasons many estuaries have been treated by humans for land reclamation, sand excavation, embankments and dredging. This is also the case with the Scheldt estuary. All these human interventions cause significant changes in the bathymetric, hydraulic and sediment transport patterns of the estuary (Savenije, 2012).

Since the estuary is the transition between the water bodies of a river and a sea, it provides an aquatic environment different from the water bodies composing it. The combination of the nutrients, provided by sea and river, create an area that provides shelter to numerous animal species. With rich flora and fauna, the estuaries play a crucial role for the global environment and for the people they constitute a source of food and transport link between river and sea (Chenjuan et al, 2011). The Scheldt estuary is a representative example of the ecosystem described above.

The fact that estuaries are so important to humanity, in combination with the fact that they are easily affected by possible changes leads to a great need of extensive research for prediction
of their morphological, hydraulic and ecological reaction in any environmental change or human intervention. The past years, several hydro-morphodynamic models have been developed in order to simulate the future and possible changes of the Scheldt Estuary. The fact that it is imperative to protect the estuarine environment, gives the boost for the initiation of comprehensive research and investigation, with the use of last generation software and the combination of theoretical knowledge and practice. This research focuses mainly in the use of the state-of-the-art D-Flow Flexible Mesh software package for the extraction of the results and the conclusions.

1.2 Problem definition

The Scheldt Estuary is not only vital and important for the Netherlands but there are many interests served also for Belgium. The estuary, is for trading vessels, the only connection of Antwerp port with the North Sea and this is also a reason that it is not closed by a dam (DHV group, 2004), like it happened with most of the Dutch estuaries after the flood of 1953. On the one hand, the ecology in the whole estuary is essential to be preserved (ecology) but on the other hand the coastal area needs to be protected from flooding (safety) and at the same moment the port of Antwerp needs to be competitive by improving the navigation channels with dredging (navigation). As the different interests of the Scheldt Estuary could sometimes conflict, the area of Scheldt is an interesting topic for further research.

Figure 1.2: Schematic illustration of channels and tidal flats in the Western Scheldt (Cleveringa et al, 2014). Areas of interest indicated inside the box and the ellipses
The reason for selecting this area of interest arises by the fact that there is a frequent demand of maintenance dredging of the navigation channels for Antwerp port and the other ports along the estuary. The dredged material needs to be deposited in places close to the extraction area and in the case of a long and meandering estuary the solution is given by depositing the material inside the estuary, in the flat areas or in the flood channels. This report focuses on the investigation of large sediment dumping operations, in different areas inside the estuary. The surrounding area of Everingen channel is selected as a case study for this research. Figure 1.2 shows all the areas that are mentioned further on this report. One can see Everingen channel and Baarland tidal flat and also ‘Pas van Baarland’, ‘Everingen Ebschaar’ and ‘Drempel van Baarland’, all located southern of Baarland flat. In the scope of this work, only the local hydro- and morphodynamic impact is investigated, as well as the possibility of an indirect sediment nourishment of the tidal flat of Baarland.

1.3 Main research objective and sub-objectives

The main objective of this study is to:

Set up and validate a D-Flow Flexible Mesh model to assess the hydro- and morphodynamic impact of large sediment dumping operations in the Everingen channel and the surrounding area.

This main objective is reached by completing the following research sub-objectives:

- Set up a new hydrodynamic model for the Scheldt Estuary using the new D-Flow Flexible Mesh software
- Perform a hydrodynamic model calibration and validation using water level, velocity and discharge measurements
- Calculate sediment transport patterns using an offline application of the Engelund-Hansen formula
- Analyse sediment transport patterns for prediction of morphological changes and comparison with the actual measurements in the dumping operation occurred in '97-'98
- Apply the new model to determine the impact of different sediment dumping scenarios on the local hydro-morphodynamics
- Investigate whether the Baarland tidal flat can be indirectly fed by a sediment dumping in the surrounding areas

1.4 Methodology

The initial step of the procedure is an extensive literature research, pointed in the implementation of strategies in the Scheldt estuary. It is essential to be informed about the historical morphological and hydraulic changes in the estuary, with and without mankind interventions. All the information concerning the physical processes on the estuary is gathered. The techniques, processed and mechanisms mentioned on this report are explained and information about the used software packages is given. Finally, data on water levels, velocities, discharges and bathymetries are retrieved.

Next step is the model set-up which starts with the development of the grid that all the computations will be implemented. In this study, the impact of the dredged material disposal
in the Everingen area is investigated, so it is essential to refine the grid size in the area of interest. For this report, both Delft3D and D-Flow Flexible Mesh software packages are used. For Delft3D simulations the NeVla model grid is used while for D-Flow Flexible mesh a new grid with local refinement and coarsening is developed. The bathymetry can change depending on the year of the simulation thus it is necessary to apply the different bathymetries on the modelling grids. Other features that need to be implemented are the boundary conditions. Initial conditions about water levels are also selected. Salinity, waves and wind are not taken into account. For the computations, a 2D depth averaged formulation is used for both models. The offline approach of the residual sediment transport is elaborated. Finally, a calibration of the model is completed for different friction coefficients (Manning, Chezy).

The validation of the model is the next step of the methodology. The model can simulate conditions of the past with reference date and the extracted hydraulic data can be compared with the actual measurements taken by placed gauges in the estuary. The validation procedure includes simulations with both Delft3D and D-Flow Flexible Mesh software. Initially, a hydrodynamic validation is completed by comparing modelled water levels, velocities and discharges with measurements throughout the estuary. It continues with the sediment transport validation which compares the sediment transports computed by the offline approach with those computed online by Delft3D. Finally, in the morphological validation, the dumping operation of 1997-1998 is simulated and the residual sediment transports are translated into initial morphological changes which are compared with actual measurements.

After the model is validated the procedure of the different scenarios can start. For all the 4 scenarios, different areas of dumping are investigated with varying amounts of dredged material. A specific simulated period is selected for all the scenarios and a reference case without any dumping is simulated. The inputs of the model are kept constant with only the bathymetry changing, depending on the new depositing area. The outputs of the models are translated into residual transports that lead to an understanding of the initial morphological response of the estuary. In all scenarios, the reference case is subtracted from all results in order to investigate solely the impact of the dumping case.

The final part of the project is the elaboration of the conclusions which are based on the one hand, on the hydrodynamic behaviour and on the other hand, on the trend of the residual sediment transport. With an interpretation of the residual transports a qualitative indication of the future changes in the morphology of the area can be given. A comprehensive discussion over the whole research is completed, the final conclusions are drawn and recommendations of further investigation are proposed. A final summary of the proposed methodology steps can be seen in Table 1.1.

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Literature review: Scheldt Estuary physics, dredging/dumping, older studies, software packages, erosion/sedimentation mechanism</td>
</tr>
<tr>
<td>2</td>
<td>Set up of the model: Construction of D-Flow Flexible Mesh grid, bathymetry, boundary conditions, offline approach, model calibration</td>
</tr>
<tr>
<td>3</td>
<td>Hydrodynamic validation of the models, offline sediment transport approach validation, morphodynamic validation</td>
</tr>
<tr>
<td>4</td>
<td>Set up of the dumping scenarios and analysis of the result</td>
</tr>
<tr>
<td>5</td>
<td>Discussion, conclusions, recommendations</td>
</tr>
</tbody>
</table>

Table 1.1: Summarising methodology in steps
1.5 Outline

An extensive literature review is conducted over the Scheldt Estuary and its physics (Chapter 2). In addition, a cumulative overview is given about the morphological changes that happened in the Scheldt throughout the last decades. The process of dredging and dumping is explained and further information is given about the software that is used for the simulations and the erosion/sedimentation mechanism.

The set-up of the models (Delft3D and D-Flow Flexible mesh) follows (Chapter 3). The model set-up includes the construction of the computational grid and set up of the boundary conditions as well as bathymetric data. The offline approach of sediment transport is also elaborated in this chapter. Finally, the model is calibrated by comparisons with measured water levels by using different friction coefficients.

The next step of this research is the validation of the models (Chapter 4). The validation includes hydrodynamic validation by comparing computed water levels, tidal components, discharges and velocities with measurements. The second part is the sediment transport validation, while it finishes with a morphodynamic validation by analysing residual sediment transports.

The next step is the implementation of the different dumping locations scenarios (Chapter 5). Each scenario is elaborated in a different chapter and for every case the final results are analysed.

Further, a general discussion is completed about the methods followed in this research (Chapter 6). Finally, the conclusions based on the study are given, followed by recommendations for further research (Chapter 7).
2 Literature review

2.1 Scheldt estuary topography

As it is mentioned in the introduction chapter, the Scheldt Estuary is located in the south of the Netherlands and it is one of the largest estuaries of the country. It starts from the North Sea and it riches up to Ghent. On the Dutch territory it consists of an ebb tidal delta facing the North Sea and the Western Scheldt (60 km) while on the Flemish territory it consists of the Zeeschelde (30 km) and the Bovenschelde (70 km) (Winterwerp et al., 2001), see Figure 2.1.

![Figure 2.1: Different divisions of the Scheldt estuary (Green: North Sea delta; Blue: Western Scheldt; Yellow: Zeeschelde; Red: Bovenschelde)](image)

2.2 Estuarine physics

Estuaries have physical characteristics that change in the different estuaries around the world. Usually, features like water depth, sediment transport, salinity and current speed are used in order to describe an estuary. The salinity is the measure of all the salts dissolved in the water and since the estuary is the transition from the river to the sea the water is a mix of fresh and ocean water. Estuaries are also affected by the tide intrusion. These water level variations can create intense tidal currents inside the estuary basin. The tides, the wind and the salinity differences can be the forces that produce the moving of the water, known as circulation (OMP, 2014). The density differences of the water create different layers inside the estuary since the denser salty water entering from the ocean stays in the bottom while the
fresh water coming from the rivers stays on the top layer as lighter; this procedure is called stratification. All these physical characteristics affect the way that the estuary responses on the different interventions. The most important data that are needed in order to get familiar with the processes in the Scheldt estuary are presented in the following sections. The stations shown in Figure 2.2 are located along the estuary and they will be mentioned in the following paragraphs.

Figure 2.2: Reference stations in the estuary and river Scheldt area

2.2.1 Tide

The tide generation originates indirectly from the gravitational pull of the moon and the sun on the water of the oceans. The sun and the earth revolve around a common centre of gravity and the attraction force is proportional to the masses and inversely proportional to their distance. In a similar way, also moon and earth rotate around a common centre of gravity. (Bosboom & Stive, 2013)

The gravitational pull of the sun is two orders larger than the gravitational pull of the moon but though the sun contributes only to the 30% of the tidal amplitudes of the ocean compared to the remaining 70% of the moon. This is because it is not directly the gravitational pull that generates the tides but the difference in the gravitational pull on oceanic waters that are located at different distances from the sun and the moon. This differential pull is responsible for the tide and it is consequently called tidal force. (Bosboom & Stive, 2013)

At the coasts, the tide is observed as daily water variations. These variations differ between different areas of the world as well as between different periods. Because of the tilt of the earth around the sun we get the seasonal variations. The daily variations depend on the earth's different latitudes. In the poles, the water level variations seem to have a period of
around a day while close to the equator the water levels follow these oscillations twice a day. (Bosboom & Stive, 2013)

The above situation explains the variety of different tidal components. The tidal constituents can be divided mainly in two categories regarding their frequency of occurrence as well as their generation force. The tide appearing twice per day is known as semi-diurnal tide while the one occurring ones per day is called diurnal tide. Regarding their generation force they are either lunar (generated by the differential pull caused by the moon) or solar (generated by the differential pull caused by the sun) (Bosboom & Stive, 2013). Table 2.1 below, presents most of the principal tidal constituents.

<table>
<thead>
<tr>
<th>Tidal component</th>
<th>Name</th>
<th>Period (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Semi-diurnal</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Principal lunar</td>
<td>M2</td>
<td>12.42</td>
</tr>
<tr>
<td>Principal solar</td>
<td>S2</td>
<td>12.00</td>
</tr>
<tr>
<td>Lunar elliptical</td>
<td>N2</td>
<td>12.66</td>
</tr>
<tr>
<td>Lunar-solar declinational</td>
<td>K2</td>
<td>11.97</td>
</tr>
<tr>
<td>Variational</td>
<td>MU2</td>
<td>12.87</td>
</tr>
<tr>
<td>Smaller lunar elliptic</td>
<td>L2</td>
<td>12.19</td>
</tr>
<tr>
<td><strong>Diurnal</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lunar-solar declinational</td>
<td>K1</td>
<td>23.93</td>
</tr>
<tr>
<td>Principal lunar</td>
<td>O1</td>
<td>25.82</td>
</tr>
<tr>
<td>Principal solar</td>
<td>P1</td>
<td>24.07</td>
</tr>
<tr>
<td>Lunar elliptical</td>
<td>Q1</td>
<td>26.87</td>
</tr>
<tr>
<td><strong>Quarter-diurnal</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shallow water overtide of principal lunar</td>
<td>M4</td>
<td>6.21</td>
</tr>
</tbody>
</table>

Table 2.1: Principal tidal constituents (Bosboom & Stive, 2013) and (Pawlowicz, et al, 2002)

For the Western Scheldt, the major tidal component is the semi-diurnal lunar component, M2. In Figure 2.3 one can clearly see the amplification of M2 amplitude while we move upstream to the estuary. The amplification is defined as the increase of the tidal wave height because of changes in the depth and width (decrease) of the estuarine system (van Rijn, 2010). This amplification is also compared in the period of 1973 to 2011. The station of Hansweert is the reference point where the amplitude mainly differentiates throughout the years (van der Werf & Briere, 2013) and this is probably a result of larger morphological changes (e.g. channel deepening).

![Figure 2.3: Change in $a_2$ amplitude throughout the period of 1973-2011 (van der Werf & Briere, 2013)](image-url)
The amplitude of M2 tide continues increasing until the upstream Temse station and it starts fading further upstream (Dam, 2013). For other components the amplification could stop earlier or later. For the case of the quarter-diurnal tidal component M4, whose interaction with M2 contributes to the sediment transport (Bosboom & Stive, 2013), the amplification increases even more upstream to the river area (Dam, 2013).

2.2.2 Wind

From the wind data of Figure 2.4 one can see that indeed the main direction of the wind is from the southwest especially in Terneuzen station which is more protected from the offshore winds. Depending on the station location inside the estuary, mainly the intensity but also the direction of the wind could vary. As a rule, the offshore wind speed is larger than the wind in the area inside the estuary. This is also shown in Figure 2.4 in which one can see that the wind intensity in Terneuzen station is lower than the values in the more offshore station Vlakte van de Raan.

![Wind in Vlakte van de Raan](image1)

![Wind in Terneuzen](image2)

*Figure 2.4: Average wind intensity and direction for year 1997 (Rijkswaterstaat database)*

2.2.3 Bathymetry

Intense changes in the depths of the channels, up to 20 m of deepening and shallowing, have been noticed in the period of 1964-2013 as it is presented in Figure 2.5 which demonstrates only the area of interest of this research.

In the period of 1955-2008 the water volume above the intertidal flats has decreased in sections Vlissingen-Hansweert (15 Mm³) while there was no change in section Hansweert-Bath. Increase of channel volume and decrease of water volume above the intertidal flats shows that tidal flow has become more dominant than tidal storage. (Kuijper, 2013)
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2.2.4 Sediment transport

The sediment median diameter varies inside the estuary; in the deep channels it can be around 0.2 mm while in the tidal flats it can be much finer. The suspended load is the dominant transport mode for the residual sand transport. The total net transport varies quite strongly along the Scheldt Estuary (van der Werf & Briere, 2013). The graph shows that in deeper waters there is a tendency to gain sediment while on the waters closer to the surface to lose sediment (Cleveringa & Dam, 2013). For the case of macro-cell 3, which is the area of interest for this report, Figure 2.6 presents, separately for the main and the secondary channels, the tendency of the sediment volume since 1950.

Figure 2.5: Bathymetry changes in period 1964-2013 in the Western Scheldt (Rijkswaterstaat database)

Figure 2.6: Sediment volume for macro-cell 3 since 1950 in the main and secondary channels (Cleveringa [2], 2013)
Macro-cell 3, after 1962, tends to lose large amounts of sediment with only the period of 1967-1976 showing some tendency to reverse this situation. The main trend shows increasing volumes of exported sediment every year.

2.3 Recent morphological studies

Many attempts have been made in the past in order to predict the estuary’s reaction in different types of interventions and many projects have been launched in order to preserve the estuary’s identity.

A representative example of these projects is “TIDE - Tidal river Development” which is a European Union partially financed project that tries to make integrated management and planning in the estuaries of Elbe, Scheldt, Humber and Weser rivers (Antwerp port Authority et al., 2013). A comprehensive study has been done about the influence of the morphology of the Scheldt Estuary mouth on the tidal propagation.

The TIDE project also focused on the dredging and disposal strategies by investigating the possibility of further dredging in the navigation channels and by quantifying the dredging volumes that need to be removed and deposited (MOW, 2013). The material type is also defined (sand vs silt) and statistics are given about the yearly dredging qualities and the destination of the material that needs to be deposited (see Figure 2.7).

Figure 2.7: Maritime fairway dredging and relocation sites (MOW, 2013)

Figure 2.8 shows the flood and ebb channels inside the estuary. In the wide areas of the Scheldt, the flood and ebb channels are separated while in the narrow river area of the Scheldt, they overlap. If a comparison is made between Figure 2.7 and Figure 2.8 it could be derived that the ebb channels are majorly used as maritime fairway for the Antwerp port but also for the smaller ports more downstream. This is an expected situation since from basic
tidal basins knowledge is known that ebb channels are deeper and narrower than the flood channels which tend to be shallow and wide. The first channel type serves better the need of the vessels that sail in the estuary.

Another important comprehensive research was launched by the LTV V&T project (Long-term vision of the Scheldt estuary, safety and accessibility), which is a consortium of Deltares, IMDC, Arcadis and Svašek Hydraulics, funded by the Dutch ministry of Public Works (Rijkswaterstaat) and the Flemish department of Mobility and Public Works. The project focuses on the maintenance of the navigation channels and the environmental permits for depositing the dredged material.

This project focuses more on the hydro-morphodynamic changes caused by dredging and dumping processes in the Scheldt Estuary. Since the estuary is the only connection with Antwerp port, the navigation channels were deepened and widened with two operations in the early 70’s and the late 90’s (DHV group, 2004) but also in 2011 a third deepening operation was completed (Santermans, 2013). The strategy chosen was to dredge and deposit the material to the shallow water channels inside the estuary. A comprehensive field measurements campaign was launched in 2004 and repeated with tests in 2006 in which the relocation of sediment material near the Walsroorden sandbar was examined (Vos et al, 2009).

During the dredging mission of 1997-1998 large deposits were carried out in the trench of Everingen flood channel and the Plate of Baarland and the response of the trench was monitored. The Everingen channel is located just downstream of Terneuzen river while the flat plate of Baarland is located a bit upstream of Terneuzen river (see Figure 1.2). The depth of the Everingen channel is quite large if one considers the fact that it is a flood channel and it is not used for navigation. After the dumping, the channel became shallower and wider while the area close to the dump side had the same effect with less intensity in the widening (Cleveringa [1], 2013). Figure 2.9 shows the result of the dredging operation in the bathymetry of the area. On the top part of the figure the dredging operation is clearly noticed by the intense changes on the bottom while the bottom part of the figure shows that the estuary
tends to return to the initial situation, by filling the dredged areas and by eroding the dumping sites. The LTV project analyses these missions completed in the past and it derives conclusions about the effect of these missions in the rest of the estuary.

Figure 2.9: Bathymetric changes in Western Scheldt after the dredging operation of 1997

All these studies attempt to better understand the behaviour of this complex system and to be able to model this behaviour for future interventions. They provide useful information and they construct part of the basis of the research.

2.4 Dredging and dumping

Dredging of the waterways in the Netherlands is vital for the economy of the country because it provides access to the ports of the country. Every year, millions of cubic meters are
dredged in order to maintain the maritime fairways (Bortone & Palumbo, 2007). The deposition of these dredged amounts is always a reason of research since the morphological changes in the area can have huge impact on the surrounding environment of the deposition site.

At this point, it is essential to introduce the term of “morphological dredging” which is actually dredging in a morphologically dynamic system. It is generally accepted that all dredging processes affect the morphology but not all the dredging is morphological. The latter one requires an understanding of the behaviour of the estuary in order to predict the changes after the interventions (Peters, no date). The term of “morphological dredging” was first used in order to present the dredging strategies developed for the maintenance and the capital dredging of the navigation channel of the Congo inner delta. What actually happened was redistribution of the sediment inside the delta by dredging the channels and depositing the material in other surrounding areas in order to change the plan form of the river (Plancke et al, 2007). This technique was also used in the Walsoorden sandbar, inside the Scheldt Estuary, that eroded since several decades. This was also the case in the deposition of the material in the Everingen channel in 1997-1998.

It has been proved by previous studies of the last century that sediment deposition and extraction from inside of a basin could lead to serious changes on the identity of the basin. The tidal prism, which is the total volume of water entering or leaving the estuary per half tidal cycle (Bosboom & Stive, 2013) will change, the estuary can change from flood dominant to ebb dominant and all these hydraulic changes can cause also morphological changes that could cause erosion or deposition of sediment inside the basin.

The technique of redistribution of the sediment has gained so much attention because it is a possible solution for the sediment equilibrium inside the estuaries. By just replacing the sediment in different locations the estuary will just tent to redistribute the sediment in other locations but it is likely that there will be no demand for finding sediment sources from outside of the estuary or the side flats in order to replace the losses. All these assumptions need to be examined and then to be validated in order to be able to reach to scientifically correct conclusions.

2.5 Erosion and sedimentation mechanism

According to Bosboom and Stive 2013 “sediment transport can be defined as the movement of sediment particles through a well-defined plane over a certain period of time”. The transport rates, S, expressed in m³/s/m are defined as the volumes of sand per second per meter width. The changes in transport rates along an area cause deposition or erosion. This change in transport rates and its morphologic effect is seen in Figure 2.10.

From upstream to downstream direction the transport rates decrease from S₁ to S₃ with S₁>S₃ so the volumes of sand per second per meter width will decrease, so the sediment moving in the downstream direction is deposited along the way. The area below S₁ erodes because we assume that no sediment is coming from upstream to cover the sediment loss, while the area downstream of S₁ starts accreting with the sediment coming from the area below S₁. The initial changes in morphology are seen in panel b of Figure 2.10.
Modelling the impact of large scale sediment dumping on the meso-scale hydro- and morphodynamics in the Western Scheldt

With this sedimentation/erosion mechanism, a qualitative estimation of initial morphological changes can be completed. Increasing sediment transport rates indicate eroding area while decreasing transport rates indicate accreting area downstream.

2.6 Hydro-morphodynamic software

For the hydrodynamic simulations there is a need to use a last generation software in order to reproduce these complicated processes taking place inside the estuarine basin. In the scope of this research, two different software packages are used; Delft3D and D-Flow Flexible Mesh, which are elaborated in the following paragraphs.

At this report, for brevity and space saving Delft3D will be also referred with the abbreviation “D3D” while D-Flow Flexible Mesh with the abbreviations “D-Flow FM” or even “DFM”.

2.6.1 Delft3D

Delft3D is a 2D-3D modelling suite for simulating hydrodynamics, sediment transport, morphology and water quality. It has several available modules with the most relevant to this study being Delft3D flow (FLOW), morphology (MOR) and waves (WAVE). The FLOW module, which is used in this study, is a hydrodynamic and transport simulation programme which calculates non-steady flow and transport phenomena that are a result of tidal and meteorological forces (Deltares, 2015).

Delft3D uses the basic curvilinear grid without having the capability of implementing irregular connections for local changing of the grid resolution. On the one hand, its pure curvilinear grid allows a smooth flow but on the other hand, it causes high resolution in the inner bends and coarse resolution in the out bends. Local refinement is not possible since the grid lines should continue until the boundaries of the grid.
2.6.2 D-Flow Flexible Mesh

D-Flow Flexible Mesh is a 1D-2D-3D hydrodynamic simulation package that gives the possibility of flexible meshes. The traditional type of grid, used also by Delft3D, is curvilinear but D-Flow FM offers meshes created by triangles, pentagons etc (see Figure 2.11) and also 1D modelling of the channels; and all these grids can be bonded and combined (Deltres, 2014). At the moment of writing, the software is still in development so many functions such as waves, sediment transport and morphology are not used in this research.

![Figure 2.11: Combination of curvilinear and triangular grid in D-Flow FM](image)

D-Flow FM software is a promising future machine with faster computations than Delft3D and more accuracy when it is required. Since with the help of triangles, curvilinear grids can be connected, different refinement can be implemented in the different areas. In the case that the simulation area is large but the area of interest is small, the flexible mesh is the best choice; it combines a coarse grid in the wider area and a fine grid in the examined areas. An example of this connection of grids with different resolution is seen in Figure 2.12.
The next generation of hydro-morphodynamic software is essential for the improvement of the simulations. Models are evolving, becoming more user friendly and easy to handle, they give more flexibility in the construction of the grid and their formulations are improved in order to better reproduce the real life values. The participation in one of these validation procedures can be considered, also on its own, as an important scientific research topic since it gives feedback for further development.
3 Model setup

This chapter describes the set-up of the models that are used for the current study. In this report two software packages are used; Delft3D and D-Flow Flexible Mesh. The only difference between the models build for those software packages, is the grid. The rest of the model set-up is identical for both models. The following chapters elaborate the development of the models.

3.1 Grid construction

During the model set-up, different grids are used for Delft3D and D-Flow FM. Both grids cover the same area which includes a large part of the North Sea, the ebb-tidal delta, the mouth and the Western Scheldt as well as all the Flemish rivers (Sea Scheldt, Durme, Rupel, Beneden, Nete, Grote Nete, Kleine Nete, Dijle and Zenne) (van der Werf & Briere, 2013). The differences between the grids are explained in the following paragraphs.

3.1.1 Delft3D grid

The grid used for Delft3D simulations in this research, is the one already developed for the NeVla (Nederlands Vlaams) model. More information about Delft3D NeVla model, its calibration and validation can be found in the conference paper of van der Werf et.al 2015. The grid is used without any changes on the resolution or the extend of the area. The grid’s resolution varies around ~400 m on the Sea area, to between ~50 and ~100 m in the Western Scheldt, up to ~10 m on the rivers upstream (van der Werf & Briere, 2013). The grid is shown in Figure 3.1.

![Figure 3.1: Delft3D - NeVla model grid in Delft3D environment with the surrounding land boundaries](image-url)
3.1.2 D-Flow Flexible Mesh grid

For D-Flow FM simulations a new grid is developed that differs from Delft3D grid because it is coarser in the Sea area, around ~1000 m, while it is finer in the area of interest, inside the Western Scheldt part, with ~20 m resolution. The D-Flow FM grid is developed specifically for the current research and an extended explanation for its construction is given in Appendix B. The NeVla grid is used as a basis to conceive the general idea of the resolutions but several coarsening and refinement operations are opposed to the newly constructed D-Flow FM grid.

The use of D-Flow Flexible Mesh has many advantages in the construction of the simulation grid. When the area of the simulation is really extended compared to the area of interest then the local refinement is a useful tool. As it has already been mentioned before, the area of interest is just restricted in macro-cell 3 of the Western Scheldt estuary and it is presented inside the black box in Figure 3.2. This area is the most refined one since it is the one studied. This refinement is considered adequate enough to show the sediment transport results but also not too fine to create serious problems in the time step of the simulation.

![Figure 3.2: Final grid with a triangular connection detail](image)

All the connections are easily made with the use of triangles as it is shown in Figure 3.2 with the zoomed image. The refinement or the coarseness need to be made gradually. The use of successive lines of triangles in order to make a fast transition from a coarse to fine grid is not possible because it does not allow a good orthogonality of the grid (see Appendix B). Further, a smooth transition of the grid does not cause any numerical delays on the simulations.

3.2 Bathymetry

In the introduction, it was mentioned that the estuary is a morphologically dynamic environment. Because Western Scheldt is the entrance of Antwerp port every year dredging and dumping operations take place in the estuary. This situation makes the morphodynamics of the estuary even stronger. These reasons created a need to keep track of the changes on
the bed morphology so data since 1926 can be found over the bathymetry along the Dutch coast.

Rijkswaterstaat which is a part of the Dutch ministry of Infrastructure and environment is responsible mainly for the design, construction, management and maintenance of the main infrastructure facilities in the country. One of its duties is also to select and gather all the available bathymetry data, as well as to execute new measurements every year so it can keep track of the morphological changes. Part of the covered area is shown in Figure 3.3.

All the data are available in NetCDF (Network Common Data Form) which is a set of software libraries and data formats that support the creation, access and sharing of scientific data. The needed data are extracted and processed with coordinates transformation from the World Geodetic System 1984 (WGS 84) into Amersfoort RD New coordinates which are used by the model. The data from the different areas are gathered together and the bathymetry profiles are created for all the years of interest.

3.3 Boundary conditions

In the scope of this report, astronomical boundaries are selected so the model is flexible to simulate any period in time without the restrictions of the time series boundaries. For the creation of the boundary conditions Delft Dashboard is used and its interface is presented in Figure 3.4.

Delft Dashboard is a Matlab based graphical user interface aimed at setting up new and existing models. The coupling with Delft3D FLOW is fully implemented and the coupling with
other modules is in development. A large number of coupled toolboxes allow Delft Dashboard to complete fast and easy model input generation. (Publicwiki Deltares, 2015)

![Delft Dashboard interface](image)

**Figure 3.4: Delft Dashboard interface**

The data used by Delft Dashboard mainly resulted by the venture of Topex/Poseidon. This venture was launched in 1992 by CNES (Centre National D’Etudes Spatiales) and NASA (National Aeronautics and Space Administration). One of the things they measured was ocean surface topography to an accuracy of 4.2 cm, and while the initial mission was planned for 3 years TOPEX Poseidon delivered data from orbit for 13 years. The mission ended in January 2006 but it provided with many data that improved the understanding of ocean circulation and its effect of global climate. (NASA, 2015)

The final result of the boundary points is presented in Figure 3.5. All the different points are characterised by different values in the tidal components. In all the boundaries (NW, NE, SW) the tidal components represent water level variations. The discharge from the rivers is not taken into account because its contribution is insignificant compared to the tidal wave. The annual discharge of Schelde river is estimated in 10 million m$^3$ of water flowing to the sea which is an average flow of 115 m$^3$/s (ISC CIE, 2015) while the water entering and leaving the river area close to Schelle station could exceed 5000 m$^3$/s in a period of spring tide.
Delft Dashboard is an easy engine to create astronomical boundary conditions. Although it does not include all the tidal components, it does take into account the most important ones. The tidal components produced by Delft Dashboard are given in Table 3.1:

![Figure 3.5: All the 73 boundary points of the D-Flow FM model](image)

<table>
<thead>
<tr>
<th>Tidal component</th>
<th>Nature</th>
<th>Name</th>
<th>Period (solar hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Principal lunar</td>
<td>Semi-diurnal</td>
<td>M2</td>
<td>12.42</td>
</tr>
<tr>
<td>Principal solar</td>
<td>semi-diurnal</td>
<td>S2</td>
<td>12.00</td>
</tr>
<tr>
<td>Lunar elliptical</td>
<td>semi-diurnal</td>
<td>N2</td>
<td>12.66</td>
</tr>
<tr>
<td>Lunar-solar declinational</td>
<td>semi-diurnal</td>
<td>K2</td>
<td>11.97</td>
</tr>
<tr>
<td>Lunar-solar declinational</td>
<td>diurnal</td>
<td>K1</td>
<td>23.93</td>
</tr>
<tr>
<td>Principal lunar</td>
<td>diurnal</td>
<td>O1</td>
<td>25.82</td>
</tr>
<tr>
<td>Principal solar</td>
<td>diurnal</td>
<td>P1</td>
<td>24.07</td>
</tr>
<tr>
<td>Lunar elliptical</td>
<td>diurnal</td>
<td>O1</td>
<td>26.87</td>
</tr>
<tr>
<td>Lunar fortnightly</td>
<td>long-term</td>
<td>MF</td>
<td>327.90</td>
</tr>
<tr>
<td>Lunar monthly</td>
<td>long-term</td>
<td>MM</td>
<td>661.30</td>
</tr>
<tr>
<td>Principal lunar shallow water overtide</td>
<td>quarter-diurnal</td>
<td>M4</td>
<td>6.21</td>
</tr>
<tr>
<td>Shallow water overtide (M2+S2)</td>
<td>quarter-diurnal</td>
<td>MS4</td>
<td>6.10</td>
</tr>
<tr>
<td>Shallow water overtide (M2+N2)</td>
<td>quarter-diurnal</td>
<td>MN4</td>
<td>6.27</td>
</tr>
</tbody>
</table>

*Table 3.1: Tidal components created by Delft Dashboard as an input to the model (ORNL, 2015)*
A comparison with the principal tidal components of Table 2.1 shows that Delft Dashboard takes into account all the important constituents.

3.4 Offline approach

It is already mentioned that D-Flow FM is a software package under development and processes such as sediment transport and morphology are not yet available to use. For this reason, an offline approach for the calculation of sediment transport is used which is translated further into initial morphological tendency. This offline approach uses the hydrodynamic output of the models and translates it into sediment transport. The period of interest is simulated without any morphological changes and the hydrodynamic output data are gathered. These data are used further for the computation of the sediment transport. With this offline approach the impact of the morphological changes into the velocities (and indirectly computed transports) is not taken into account. In this way the initial reaction of the sediment transports is calculated.

3.4.1 Sediment transport

Engelund-Hansen formulation is a total load formulation (suspended load + bed load) and it can be applied in most of the cases. It is only based on the hydrodynamic results of the software. There is one limitation though of the formula related to the grain size. For grain diameters smaller than 0.15 mm the actual sediment discharge can be larger than predicted. This is probably caused due to large suspension which tends to change the velocity distribution (Engelund-Hansen, 1967). The grain size used in all the simulations of this report is 0.2 mm so it does not enter the forbidden area of the formula.

For the calculation of sediment transport both models follow exactly the same set-up conditions; boundary conditions, bathymetry, friction coefficient, sediment transport formulas. The main idea for the sediment transport calculation is to use the velocities computed by D-Flow FM and Delft3D and with the following Engelund-Hansen formula to calculate the sediment transport per unit width.

\[ S_s = \frac{0.05}{\sqrt{g \cdot C^3 \cdot \Delta^2 \cdot D_{50}}} u^5 \]

In which \( S_s \) is the transport of sand per unit width \( [m^3/s/m] \), \( u \) is the depth averaged velocity \( [m/s] \), \( g \) is the gravity acceleration \( [m/s^2] \), \( C \) is the Chezy coefficient \( [m^{1/2}/s] \), \( \Delta \) is the relative sediment density \( [-] \) and \( D_{50} \) is the grain diameter \( [m] \).

The transformation of Manning coefficient into a Chezy coefficient can be implemented with the formula below:

\[ C = \sqrt[3]{\frac{h}{n}} \]

In which \( n \) is the manning coefficient \( [s/m^{1/3}] \) and \( h \) is the total water depth \( [m] \).
This offline approach needs to be validated. To do so, the standard online approach of Delft3D is used with the established Van Rijn 1993 sediment transport formulations. The comparisons made for the validation are carried out for three results:

- Offline calculation of sediment transport with the formula above by using D-Flow FM velocities
- Offline calculation of the sediment transport by now using Delft3D output velocities
- Online output of Delft3D for the sediment transport by imposing Van Rijn 1993 formulation

Even though velocities can look similar, transport patterns may differ between the two modelling systems. For this reason comparison between computed transports are essential. In addition, the results calculated with the offline approach are tested with the actual sediment transport of a validated model.

3.4.2 Morphological translation

According to Jeuken and Wang (2000), sediment transport varies in time and space. In this chapter we focus on the different time scales of transport in order to estimate the morphological evolution. Sediment transport can be distinguished in

- **Instantaneous transport** $s$, which is the transport in each moment of the life of the river/estuary/sea (positive in flood direction)
- **Ebb transport** $se$, which is the integral of instantaneous transport over ebb period
  \[ se = \int_{T_{ebb}}^{a} |s| \ dt \]
- **Flood transport** $sf$, which is the integral of instantaneous transport over flood period
  \[ sf = \int_{T_{flood}}^{a} |s| \ dt \]
- **Residual transport** $sr$, which is the integral of instantaneous transport over the whole tidal period (positive in flood direction)
  \[ sr = \int_{0}^{T} s \ dt = sf - se \]

In other words, the residual transport shows the transport direction and size that remains in the end of a period after adding the sediment transport of each cell in x- and y-direction over the period of the simulation. In this report all the residual transport results are for a spring-neap tidal cycle and they are presented in sediment transport units $[m^3/s/m]$ since they are divided by the number of the time steps.

3.5 Model calibration

The Scheldt Estuary is a large estuary with narrow and wide areas, different vegetation and depths. It is expected that friction varies in the different areas mentioned. Intense vegetation as well as shallow areas implies high friction. The friction imposed to the model is one
important parameter for the quality of the results since in the shallow area it has a big effect on the dumping of the tidal wave. By imposing a low friction, the tidal wave is allowed to reach higher values while with a high friction the tidal wave is decreased. For the selection of the most representative friction coefficient in the area, a short sensitivity analysis is carried out, which compares the model results with the measured data in the stations.

The measurements of the water level time series in the different stations of the estuary are also collected by the database of Rijkswaterstaat. There are available data every 10 minutes for all the selected representative stations along the estuary. The data are given in a time standard of UTC+1. On the contrary, the tidal components created by Delft Dashboard are given in Greenwich Mean Time (GMT) which matches the Coordinated Universal Time (UTC). Because of the above time difference all the data used are converted into Greenwich Mean Time by subtracting one hour from the actual time values. All the resulted graphs are also presented in Greenwich Mean Time.

The different friction conditions that are compared use either Manning or Chezy coefficients but also different values for these two types of coefficients. At this point, it should be mentioned that Manning coefficient is a roughness coefficient so higher values mean rougher bed while Chezy coefficient is a smoothness coefficient so higher values mean smoother bed.

The sensitivity analysis could be divided in two parts before the final conclusions are drawn about the friction coefficient that will be used in the model. For this calibration, D-Flow FM model is used in all the simulations with the different coefficients. For all the simulations D-Flow FM model is used.

The first part is the comparison of the water levels calculated by the model, with those of the measurements. Figure 3.6, Figure 3.7 and Figure 3.8 present those first comparisons of the different results. The three stations selected are following the upstream direction. This means that Westkapelle is closer to the sea boundaries while Bath is further inside the estuary, closer to the river area.

![Figure 3.6: Sensitivity analysis for friction coefficient in Westkapelle station](image-url)
From a first look at Figure 3.6 one can see that the results of the different models tend to be the same without significant variations. There is a constant overestimation of high and low water by the models. There is also a phase lead of the model in the case of the high water pick. This figure does not allow to draw any conclusions about the best friction coefficient.

In Figure 3.7 and Figure 3.8 the differences between the simulations are becoming more intense. Clearly, Chezy coefficient of $C=50 \text{ m}^{1/2}/\text{s}$ starts to show that it deviates more from the rest of the model results. Depending though if it is a high water or low water period and if it is spring or neap tide the results of the simulations differ.

**Figure 3.7: Sensitivity analysis for friction coefficient in Terneuzen station**

**Figure 3.8: Sensitivity analysis for friction coefficient in Bath station**

It is important to mention that the model used for this project does not take into account processes like wind, waves, salinity and several tidal components. These processes are selected to be ignored because they are not considered to have a significant effect in the
water levels in the areas of interest. This ignoring though means that the comparisons of the water levels simulated by the model, with those measured is not an absolutely correct way to teach to conclusions about the accuracy of the model.

Tide is expected to play the major role and to be the dominant sediment transport driver so the modelling of tidal propagation should be completed correctly. A comprehensive way to do that is the tidal components. The tidal components are extracted by the time series of the measurements as well as of the modelled results. For a correct comparison the resulted tidal components are compared. The results for tidal components M2, S2 and M4 are presented in the figures below. The evolution of the amplitudes and phases along the estuary stations is shown.

Figure 3.9: Computed amplitude (upper panel) and phase (lower panel) of M2 component

Figure 3.9 presents how the amplitude and the phase of the major tidal component, M2, changes along the estuary. All friction coefficients seem to match well with the phase computed by the data while the amplitudes seem to have larger deviations. From the graph, it follows that by increasing the roughness of the bed, the tidal amplitude decreases which is an expected behaviour.
In Figure 3.10 the same values are observed but for the second largest component, S2. There is a constant underestimation of the amplitude computed by the models, in the order of 15 cm as the largest deviation. Chezy coefficients seem to have an intense deviation compared to Manning coefficient. The phase matches well in all the cases until Vlissingen station but more upstream it starts to deviate, especially for Chezy coefficients.

The behaviour of the tide changes while it moves upstream in the estuary. The modelling of the tidal wave is more difficult in shallow waters. The tidal amplitude amplifies; the wave length decreases and resonance phenomena increase the complexity of the tidal pattern. The interaction of $M_2$ with itself will generate higher harmonics like $M_4$, $M_6$, $M_8$ and $M_{12}$. These are shallow water constituents with smaller amplitudes and smaller periods and they are known as overtones. (Andersen, 2003)

According to Bosboom and Stive (2013) the interaction of $M_2$ and $M_4$ tidal components is important for the sediment transport of the estuary. Different phase lags between the two components lead to different behaviours as it is shown in Figure 3.11.
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For \(-\pi/2<\varphi<\pi/2\) there is flood dominance while for \(\pi/2<\varphi<3\pi/2\) there is ebb dominance in the estuary. For the cases on the left part of Figure 3.11 the interaction term is at its maximum since \(\cos\varphi_{M4-M2}=\pm 1\) so the flood and ebb velocities differ most in magnitude. For \(\varphi=0\) the velocity signal is flood dominant and no sawtooth asymmetry is observed and this behaviour leads to a net import of coarse sediment. For \(\varphi=\pi\) the velocity signal is ebb dominant without again any sawtooth asymmetry and it leads to a sediment export. For the right panels, the velocity signal demonstrates saw-tooth asymmetry but has equal flood and ebb current magnitudes and durations so there is no net sediment transport. (Bosboom & Stive, 2013)

In Figure 3.12 the amplitudes and phases are compared for the tidal component M4. From the upper panel of Figure 3.12 it is clear that the model follows the trend of the data amplitudes with initially a small overestimation of the amplitudes and upstream of Vlissingen station a small underestimation of the situation. All modelled situations give a continuing tendency of the amplitude to decrease after Westkapelle. The panel of the phases shows again that the models follow the same tendency with the data but with a small overestimation of the results extracted by the models.

In the amplitude panel the data give a sudden increase of the amplitude in Bath station. This behaviour is not normal but it could be caused because of possible changes on the bathymetry. Probably this behaviour could also be caused because the magnitude of M4 is really small compared to the rest of the components so any possible irritation of the water could be taken into account and it could distort the signal of the component.
Figure 3.12: Computed amplitude (upper panel) and phase (lower panel) of M4 component

The selected coefficient, after this calibration, is Manning coefficient with a value of $n=0.026$ s/m$^{1/3}$ and the results of it are presented in the validation chapter.
4 Model validation

The use of numerical models has made predictions and forecasting of the changes in dynamic environments, an easier task. Though, the trick in numerical modelling is to know the level of accuracy in which it can predict the future changes. In order to be able to use a model for predictions, the model needs to be proved accurate enough. In other words, it needs to be validated before it is used to derive several conclusions about the hydro-morphodynamic behaviour of the modelled area. The validation, in this chapter, is divided in three sections; the hydrodynamic validation which includes comparisons of water levels, velocities and discharges, the sediment transport validation and the morphodynamic validation. It is important to mention again that for all the simulations a constant Manning friction coefficient of $n=0.026 \, \text{s/m}^{1/3}$ is selected from the model calibration of Chapter 3.

4.1 Hydrodynamic validation

In this chapter, the results of the hydrodynamic validation are presented. For the completion of the validation, the water levels, discharges and velocities modelled by D-Flow FM are compared with the measured data but also with Delft3D results.

4.1.1 Water levels

In chapter 3.5, it was mentioned that the comparison of modelled and measured water levels is not a correct comparison since the current model does not take into account processes such as waves, storm surge and wind set-up. The mentioned processes play a role on the final water levels but they are not considered important for sediment transport (waves are important in the tidal flats). The comparison of water levels is though a good way to check any possible time lags and the overall tidal behaviour. Figure 4.1 shows the stations selected for the comparisons.

Figure 4.1: Map of stations used for the water levels validation
The results are presented in the following figures from downstream to upstream direction. A period of one week is presented, which simulates the transition from spring to neap tide. The model used for the comparisons is the one developed with D-Flow FM.

Figure 4.2 shows the results of the stations in the mouth of the estuary, closer to the boundaries. There is a good match between modelled and measured water levels. The results are in phase with the data and the amplitudes have small deviations. One could observe that the model overestimates the water level in the period of spring tide while it underestimates it in the period of neap tide.

Figure 4.3 shows water levels for the stations in the main area of the Western Scheldt. There is still an underestimation of the modelled water levels during neap tide and a slight overestimation of the low water during spring tide. The amplification of the tidal amplitude can be observed.

Figure 4.4 shows the results on the stations in the river area. The tidal amplification is now clearer. The tendency of the modelled results continues as before but with high water, during spring tide, to be predicted more accurately than in the previous stations. The general conclusion about the results is that they are accurate besides the fact that several processes are not taken into account.
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Figure 4.3: Comparison of water levels in the stations inside Western Scheldt

Figure 4.4: Comparison of water levels in the stations in the river part of the Scheldt
The resulted amplitudes and phases of the most important tidal components are presented in the following figures and they are also compared with the results extracted by Delft3D which is set-up with the same values. In both model cases the resulted, after the model calibration, Manning friction coefficient of $n=0.026 \text{ s/m}^{1/3}$ is used.

In Figure 4.5 one can see that the Delft3D and D-Flow FM results overlap. In the case of the amplitude, the two models give exactly the same results with only in Bath station to have a small deviation. The model results, compared with the data, overestimate the amplitude of M2 for about 2.5%, which is an acceptable deviation. The phases overlap for every station for both models and data. M2 is the largest component and since the relation with the data is good then the accuracy of the model is sufficient.

Although M2 components shows a good match with the data it is important to check some more components like S2 which is the second largest one. D-Flow FM and Delft3D show similar results for the amplitudes while both of them seem to underestimate the component compared to the data results (see Figure 4.6). The deviation could reach 15% which is quite high but this deviation is expected not to influence the sediment transport results. This deviation is probably caused by a process that misses from the settings that both models use but there is also a possibility of calibration in the boundary conditions since the deviation already exists there. On the contrary to the amplitudes, the phases of the models seem to overlap with those extracted from the measurements.
The last tidal component for comparison is M4 and it is presented in Figure 4.7. As mentioned already in Chapter 3.5, the interaction of M2 and M4 components is important for the sediment transport. M4’s amplitude is significantly smaller than the previous two components but the results between the models are also good. Initially there is an overestimation of the amplitude downstream of Westkapelle station but upstream of the station the models underestimate the amplitude. In the area of interest the difference between models and data is around 2 cm.

The results between the models, in all the cases, are almost overlapping so this shows that the new software does not lack in ability to calculate water level changes, compared to the established Delft3D software. The newly developed D-Flow FM software produces results as good as the standard Delft3D. Both models are not able to produce perfectly the water levels because of the simplification made to ignore several processes, but for the scope of this study, which is the sediment transport, this lack is not an issue.
Figure 4.7: Amplitude and phase of M4 component for data and model of uniform manning friction $n=0.026$ s/m$^{1/3}$
4.1.2 Velocities

The second part of the hydrodynamic validation is the comparison of velocities in different cross sections of the estuary. Figure 4.8 shows the selected cross sections on the map.

![Cross sections used for velocity validation](image)

Figure 4.8: Cross sections used for velocity validation

The measurements are available in Rijkswaterstaat's database (2015). Table 4.1 gives information about the cross sections; the names of the channels that the measurements are carried out and the measurement day. The measurements are completed in a period of 12 hours from 5:00 am to 5:00 pm. The simulation period is also covering the same period with the available data.

<table>
<thead>
<tr>
<th>Cross section number</th>
<th>Cross section name</th>
<th>Simulation/Measurements day</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gat van Ossenisse</td>
<td>13 October 2004</td>
</tr>
<tr>
<td>2</td>
<td>Middelgat</td>
<td>13 October 2004</td>
</tr>
<tr>
<td>3</td>
<td>Nauw van Bath</td>
<td>28 October 2004</td>
</tr>
</tbody>
</table>

Table 4.1: Information about the cross sections used for velocity validation

The velocities are measured in the Cartesian coordinate system with x- and y-axis. Velocity $u$ represents the velocities in $x$-direction with a positive sign to the east, while velocity $v$ represents $y$-direction with positive values to the north. The subscript “avg” indicates that velocities are depth averaged but also averaged along the cross section. In the following figures, the results of the velocity comparisons are illustrated.
Figure 4.9: Velocities in cross section 1 (Gat van Ossenisse)

Figure 4.9 shows the velocities measured and modelled in cross section 1 which is the Ossenisse ebb channel. The results of both models overlap for both x- and y-directed velocities. For both directions, though, models overestimate the velocities for both ebb and flood period. A possible explanation is the selection of a uniform friction coefficient. The velocity wave also leads in phase compared with measurements so combining with the higher modelled values the friction is probably higher in the area than set in the model.

Better conclusions can be also drawn by Figure 4.10 which shows the velocities in the Middelgat channel. The low U velocities are reproduced well by both models which overlap in this case too. There is a slight overestimation of the ebb velocities during ebb period in y-direction. The uniform friction is also the most possible reason for that. In both figures of cross section 1 and 2 the deviation is larger during ebb period where the friction effect is more intense because of lower water levels.
The last area where the velocities are checked is cross section 3 in Nauw van Bath, seen in Figure 4.11. By looking at the water levels, during the simulation, it is recognised that the simulation is during spring tide period. It is the first figure that gives a difference between the two models. In x-direction Delft3D overestimates the ebb velocities while it underestimates the flood velocities, always compared to D-Flow FM model. Compared to the measured velocities, both models over predict the velocity magnitudes. In y-direction, the models show a good much with the measurements during ebb period while they both over predict the flood period. For these deviations three main explanations can be given; the lack of friction in the model in this specific area, as well as the complexity of the area which is located next to the enormous Saeftinge flat and the intense bending of the channel.
According to (Bosboom & Stive, 2013 p-430) the interaction between M2 and M6 tidal components lead to saw-tooth asymmetry in the velocity signal. For a phase difference of \( \varphi = \frac{\pi}{2} \) the shape of velocity looks like the red line of the bottom panel of Figure 4.12. Since the models do not include M6 component it is expected that the shape of the modelled velocities will not reproduce this saw-tooth asymmetry. The same asymmetry is observed in all the data from the cross section velocities.
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Figure 4.12: Phase difference between tidal components M2 and M6 (reproduced from Van de Kreeke and Robaczewska, 1993)

The final conclusions over the validation of the velocities show that there are several deviations between measurements and modelled results. The main reason for this difference could be the simplification in the model to use a uniform friction coefficient. Another reason could also be the limited number of tidal components that were applied as boundary conditions and they have an impact on the water levels. These deviations probably can be recommended for further research but they are not taken into account in this report. The models of Delft3D and D-Flow FM showed identical results in the first two cases and small deviations in the last one. The main conclusion is that velocities are represented well enough by both models.

4.1.3 Discharges

The third and last part of the hydrodynamic validation includes the comparison of discharges in different cross sections of the estuary. The cross sections are selected in a way that they are close to the area of interest but also representative for the larger area. All cross sections include a flood and an ebb channel which are examined separately. Figure 4.13 shows the selected cross sections in the Scheldt map.
The data used for the discharges come from the Hydro Meteo Centra of Zeeland (HMC Zeeland) of Rijkswaterstaat. Below, in Table 4.2, the channel names and their type are given; if they are flood or ebb channels as well as the period that the measurements are carried out. Each measurement lasted for about 12 hours from around 5:00 am to 5:00 pm.

<table>
<thead>
<tr>
<th>Cross section name</th>
<th>Channel name</th>
<th>Channel type</th>
<th>Simulation/Measurements day</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Wielingen</td>
<td>Flood</td>
<td>5 June 2000</td>
</tr>
<tr>
<td></td>
<td>Sardijngeul</td>
<td>Ebb</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Everingen</td>
<td>Flood</td>
<td>4 July 2000</td>
</tr>
<tr>
<td></td>
<td>Pas van Terneuzen</td>
<td>Ebb</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Gat van Ossenisse</td>
<td>Flood</td>
<td>13 October 2004</td>
</tr>
<tr>
<td></td>
<td>Middelgat</td>
<td>Ebb</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Schaar van Waarde</td>
<td>Flood</td>
<td>13 October 2000</td>
</tr>
<tr>
<td></td>
<td>Zuidergat</td>
<td>Ebb</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2: Information about the cross sections used for discharge validation

At this point, it is important to mention that positive discharge means discharge to the upstream direction, during flood, while negative discharge means water movement to the downstream direction, during ebb. In the following graphs the above mentioned can be explained in flood and ebb terms. Comparing the water levels with the discharges it is obvious that flooding period coincides with positive discharge and by flooding period it is meant the transition of low water into high water.
Figure 4.14: Discharges in cross section 11

Figure 4.14 presents the results of the model compared with the data, for cross section 11 which is located in the mouth of the estuary. The first impression about the flood channel Wielingen is that DFM and D3D give an identical estimation of the discharge. Compared to the data, the impression is that the models are quite accurate. There is a small overestimation of the negative discharges and a small underestimation of the positive discharges. The situation in Sardijnegeul looks different for the two models. This big deviation is probably a result of the different grid. Sardijnegeul is a really narrow channel while the grid of DFM is quite coarsened in the mouth area. This, results probably in deviations of the bathymetry between the models so different cross sectional areas. The match of D3D with the measurements is good. The sawtooth asymmetry is not produced by the model but this is already an issue because of the velocities.

The water levels between the two models are identical so any deviations between them are because of differences in bathymetry or velocities. The estuary is a morphologically dynamic system and the bottom measurements are conducted throughout the year, so several small deviations between real life and used bathymetry for modelling are possible. The differences between models and measurements are caused by differences in the estimation of the velocities or by bathymetrical changes which lead to different cross sectional areas but also because of the uniform friction coefficient which is not realistic for the whole area.
The results in Figure 4.15 present the discharges and water levels in cross section 7 which is the closest to the area of interest. For the flood channel Everingen, both models give the same discharge. Flood discharge is well reproduced while ebb discharge is overestimated. This means that probably the ebb velocities are estimated higher than data because of lack of friction or that the channel’s geometry is poorly calculated. For the ebb channel Pas van Terneuzen models and data match better during ebb discharge while there is a small underestimation of the flood pick.
Figure 4.16: Discharges in cross section 6

Figure 4.16 presents the results of cross section 6 that includes tidal channel Middelgat and ebb channel Ossenisse. In both channels, modelled results are similar with DFM, slightly overestimating the discharges. There is still an overestimation of the modelled discharges during ebb period while for Middelgat there is an underestimation of the flood discharge.
Figure 4.17 shows the last cross section which is located in the tidal channel Schaar van Waarde and the ebb channel Zuidergat. The saw-tooth asymmetry of the measured data is even more intense in this area. Although the models cannot reproduce exactly the shape of the graph, they follow the same trend. It is also observed more pointed ebb period for Schaar van Waarde and more curved ebb period for Zuidergat; exactly like the red line of the data.

The validation of discharges is completed with success since data and measurements show a good fit. Since the discharge is a function of the velocity and the cross sectional area which is related to the water levels and bathymetry, the results cannot be perfect because many deviations are included. Besides these differences, the models are considered to reproduce well enough the real life situation.

4.2 Sediment transport validation

For the sediment transport validation the offline approach, explained in Chapter 3.4, is used. The velocities between D-Flow FM and Delft3D are compared in the hydrodynamic validation and the conclusion was that both magnitudes and directions are in a good match. The comparison of sediment transport between the models is though necessary because it can
reveal the differences between the velocity magnitudes since the transport is a function of $-u^5$.

The general idea of the sediment transport validation is to compare the results produced by the offline approach with those produced by an online simulation. As a result, 3 different cases are compared. The first case uses the velocity output of DFM as an input for the offline calculation of the sediment transport. The second case is the same approach with the use of velocities produced by Delft3D. The third and last case is the sediment transport calculated by Deltt3D model with the use of the custom Van Rijn 1993 formulation. These three cases are compared in the following figures for four different time phases of the tidal cycle (high water, ebb, low water and flood). For all the simulations the same period and model set-up is selected. For the comparisons, the dumping operation of 1997, in Everingen channel, is simulated. Figure 4.18 shows the examined area and the dumping location.

![Figure 4.18: Examined area for sediment transport and morphology validation](image)

In Figure 4.19 one can see the sediment transport during the peak of high water. The velocities during this period are low so the sediment transport is expected to be small too. Indeed, sediment transport is zero in most of the areas, with some exceptions especially around the dumping location. The velocities are ebb directed which means that velocity leads the water levels, a situation that is expected. The results of the offline approach for the two models look the same; magnitudes and directions. Although DFM gives quite larger magnitudes north of the dumping operation while D3D gives larger values south of it. The arrows follow a reasonable direction along the flow. The online approach of van Rijn gives the same directions but the magnitudes are reduced in a factor of approximately 2. Since this research does not aim in giving quantitative results then this overestimation of the magnitudes is not a big problem for providing qualitative tendency of the initial morphological changes.

Figure 4.20 shows the sediment transport during a time step of the ebb period. This time step is close to the low water peak and since the velocities lead the water levels, in this time step, they are really reduced. They are again directed downstream and the offline approaches to give similar results. The Van Rijn formulas result in smaller sediment transports.
Figure 4.21 represents sediment transport during low water peak. Velocities lead water levels so they have already started increasing but now in the flood direction. The opposite situation from Figure 4.19 is observed. DFM gives larger values for south of the dumping site while D3D gives larger values for the northern area. Van Rijn online approach matches with the offline approach in direction but magnitudes are again smaller.

Finally, Figure 4.22 gives the sediment transport in the flood period. The velocities are in their maximum value and so does the transport. The magnitudes are significantly increased and they are spread in the whole dumping area and not around it. The online approach gives again lower values but same directions. The offline results look similar.

The van Rijn formulations are based in a different approach which takes into account bed slopes, bed composition and sediment availability so the sediment transport is not just a function of the velocities. The different approaches give similar results but Engelund-Hansen overestimates the transport compared to the Van Rijn approach. This is the case in all the moments of the tidal cycle.
Figure 4.19: Sediment transport during high water, for DFM and D3D offline approaches with Engelund-Hansen 1967 formulation as well as D3D online transport with Van Rijn 1993 formulation.
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Figure 4.20: Sediment transport during ebb, for DFM and D3D offline approaches with Engelund-Hansen 1967 formulation as well as D3D online transport with Van Rijn 1993 formulation
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Figure 4.21: Sediment transport during low water, for DFM and D3D offline approaches with Engelund-Hansen 1967 formulation as well as D3D online transport with Van Rijn 1993 formulation
Figure 4.22: Sediment transport during flood, for DFM and D3D offline approaches with Engelund-Hansen 1967 formulation as well as D3D online transport with Van Rijn 1993 formulation.
The results of the sediment transport show that the offline approach is an accurate way to calculate transport patterns on a complicated model. The figures presented above, show that Delft3D Van Rijn 1993 transport results are smaller than the ones calculated offline. This information is taken into account but since the quantity of sediment is not the purpose of this research, this deviation does not cause any issues. In addition, this overestimation is during all the tidal moments so the residual transport results are expected to be more similar between online and offline approaches.

4.3 Morphodynamic validation

In 1997-1998 a large dumping operation was executed in the Everingen channel. For the morphological validation the changes of this operation are modelled and they are compared with measurements of the bed level changes. Morphology is not directly calculated but instead, the residual transport is calculated and it is interpreted in a way to explain the morphological changes.

The first part of this process is to find the information about the quantities of the sediment and the deposition areas. The available data are quite precise about the quantities but the level of accuracy about the deposition site is low. A combination of two different sources gives a clearer perspective over the deposition sites. The first source is report A-31 “Baggeren en storten” from the LTV project, explained in Chapter 2.3, which gives the dredged and dumped quantities in the different channels and plains inside the estuary. In the years 1997 and 1998 the areas that were dredged were located in the vicinity of Borssele, Terneuzen and Hansweert only and the amounts were above 2 m$^3$ and almost 4 m$^3$ respectively (Santermans, 2013). The deepening of the already deep channels does not affect the tidal prism of the estuary so the dredged quantities are not taken into account on the modelling.

Everingen channel and Gat van Ossenisse are two of the commonest locations for the deposited material. In 1997 Ellewoutsdijk was used for the first time and since then it is used every year. In the years 1997 and 1998 the total amounts deposited in the Western Scheldt exceed the 8 m$^3$ and 12 m$^3$ respectively. In those years, the Everingen and Ellewoutsdijk which both belong to macro-cell 3 are used again for the deposition of large amounts of sand (Santermans, 2013).

What is important to mention is that in all these dredging and dumping operations several amounts of mud were also dredged and dumped but because of the small quantities and for simplicity reasons these amounts are not taken into account. Table 4.3 summarizes the dumped qualities for years 1997, 1998, 1999 and for the areas of interest.

<table>
<thead>
<tr>
<th></th>
<th>Ellewoutsdijk</th>
<th>Everingen</th>
<th>Total macro-cell 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>2,395,208</td>
<td>1,729,661</td>
<td>4,124,869</td>
</tr>
<tr>
<td>1998</td>
<td>4,327,977</td>
<td>2,087,328</td>
<td>6,415,305</td>
</tr>
<tr>
<td>1999</td>
<td>79,269</td>
<td>3,314,154</td>
<td>3,393,423</td>
</tr>
</tbody>
</table>

Table 4.3: Sand qualities [m$^3$] dumped in the two main dumping sites of macro-cell 3 (source: Santermans, 2013)

The above source gives a clear insight of the dumped quantities but the area of the deposition is not clear. For this reason, the above data are combined with the data of Rijkswaterstaat found in the MEMO report of Cleveringa et al, 2014. In this second case, the data are given in macro-cell sub-divisions as seen in Figure 4.23.
The areas of interest are marked with the codes of 519 and 416 that belong to boxes 5 and 4 respectively. For these areas, also the amounts of deposited material are given in Table 4.4 below.

<table>
<thead>
<tr>
<th>Date</th>
<th>Section 416</th>
<th>Section 519</th>
<th>Total macro-cell 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>31-12-1997</td>
<td>3,132,184</td>
<td>1,249,413</td>
<td>4,381,597</td>
</tr>
<tr>
<td>31-12-1998</td>
<td>5,301,099</td>
<td>1,704,474</td>
<td>7,005,573</td>
</tr>
<tr>
<td>31-12-1999</td>
<td>465,209</td>
<td>3,135,923</td>
<td>3,601,132</td>
</tr>
</tbody>
</table>

Table 4.4: Sand qualities [m$^3$] damped in macro-cell 3 for period 1997-1999 (source: Sandbalance Rijkswaterstaat from Cleveringa et al, 2014)

By comparing Table 4.3 and Table 4.4 it is obvious that the total amounts deposited in macro-cell 3 are almost the same. Another conclusion driven, is that part of the Everingen channel used as dumping site, belongs to sub-division 416 while the whole Ellewoutsdijk is located in sub-division 416. With the combination of this information the deposition operation is reproduced. The model has now a new bathymetry that is expected to change the hydro-morphodynamics of the area.
Figure 4.24 gives information over the dumping location, the bathymetry change after the operation and the effect on the discharges. The upper left panel shows the exact location of the dumping and the cross section selected in order to present the cross sectional bathymetry changes. The upper right panel shows the depth changes in cross section U. There is clearly a reduction of the depth up to 8 m. The third panel presents the modelled discharges both with DFM and D3D, before and after the dumping operation. About the discharge it is known that:

\[ Q = A \cdot u \]

Where \( Q \) is the discharge [m\(^3\)/s], \( A \) is the cross sectional area [m\(^2\)] and \( u \) is the velocity perpendicular to the cross section [m/s]. The comparison of DFM and D3D for the initial case, without dumped material, gives almost identical results and the same is also the case when the models are compared after the dumping operation. The comparison, though, between the two cases of dumping and no dumping shows some differences. The discharge is reduced after the dumping operation and this is an effect of the cross sectional area reduction. The reduction of the discharge though is not as strong as expected so the effect of dumping is checked also in the velocities.
Figure 4.25: Velocities in the area of the dumping operation

Figure 4.25 gives an overview of the velocities in the dumping area before and after the operation. Three locations are selected downstream, on top and upstream of the cross section. The pointed curves are the ebb velocities and the rounded ones the flood velocities. The results between the models are again similar. The main observation in the figure is that velocities are up to 30% increased after the dumping of the sediment. This big increase of the velocities explains why the discharge remained almost the same. The dumping operation does not only have an impact on the velocity magnitudes but also on the duration of flood and ebb. Flood period is decreased while ebb period is increased. This indicates a movement of sediment transport in the ebb direction.

The case of the dumping operation is simulated by both D-Flow FM and Delft3D and the residual sediment transport is calculated with the offline approach, for modelling systems. The offline approach is compared with an online calculation as well as it was done in chapter 4.2 for the sediment transport validation. Figure 4.26 presents the residual transport calculated with Engelund-Hansen offline approach for D-Flow FM and Delft3D as well as the residual transport calculated online with the Van Rijn formulation, by Delft3D.
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Figure 4.26: Residual transport for offline approach with Engelund-Hansen for DFM and D3D and online approach with Van Rijn 1993 for D3D
The three cases of Figure 4.26 give similar residual sediment transport pattern. Initially the similarities in all the three plots will be explained and later the differences.

For all the cases, quite high amounts of transport are coming from the Zuid-Everingen secondary channel. A small part of the transport continues in the downstream direction while the largest part of it turns and moves upstream. This is caused because the residual transport in the south part of Everingen channel is flood directed for all the cases. On top of the dumping location the residual transport heads downstream with the highest values in the downstream end of the deposition. The magnitudes between the tree models are similar.

The main difference between the three plots is in the Van Rijn approach that shows an upstream directed transport upstream of the dumping location. Furthermore, residual transport arriving from Zuid-Everingen is smaller in magnitude with the Van Rijn online approach.

The comparison of these different models and approaches concludes that D-Flow FM offline results are almost identical with the offline Delft3D results and they look a lot alike the online Van Rijn approach. There is a clear improvement of the results of the sediment transport validation which gave an overestimated transport calculated offline. This overestimation is time uniform and since the residual transport is the remaining transport after a spring-neap tidal cycle the offline and online results have similar magnitudes. For this reason, DFM results, only, can be used from this point of the research without further comparisons with Delft3D offline or online approaches.

Although the residual sediment transport results are validated by comparisons between the software packages they still need to be compared with a measured situation. To do so, the residual transports are calculated, by D-Flow FM model, for the initial situation without dumping and for the situation after the dumping operation. The two results are also subtracted in order to check the contribution caused only by the dumping operation. These three cases are presented in Figure 4.27.

In the upper panel of Figure 4.27 the residual transports of the area are seen without the dumping operation. The initial thing noticed is that transports are quite high which could be explained by two basic reasons. The estuary is morphologically really dynamic or the constant dredging and dumping operations have disturbed the sediment equilibrium or a combination of both. In the north part of Everingen channel, the main direction of residual transport is downstream while in the south part of the channel the direction is upstream. Large residual transport is observed inside the secondary channel Zuid-Everingen which is directed downstream until it intersects with the main Everingen channel and it shifts to the right following the upstream residual transport flow. In the middle panel, the residual transports after the dumping operation are presented. It is obvious that the residual transport follows the same directions with the initial case, but in many areas the magnitudes are significantly increased. This contribution of the dumping operation is seen clearly in the bottom panel in which the initial case is subtracted. The operation increases the residual transport not only in the deep part of the Everingen channel but also in the shallow area of the channel, on the south part, on top of Middelplaat. It creates also an intense flood directed residual transport in the intersection of Zuid-Everingen with Everingen main channel.
Figure 4.27: Residual transport before and after dumping operation and their difference all calculated by DFM offline E-H approach.
The connection of the residual sediment transport with the morphological changes is made with Figure 4.28. The upper panel shows the measured changes in cross section U. The migrating entrance of Zuid-Everingen coincides with the intense residual transports in the flood direction seen already in Figure 4.27. Normally, intense transports mean deepening and not migration but the existence of a non-erodible layer in this area, as seen in the bottom panel of Figure 4.28, causes the channel’s migration to the south where more sediment is available. The residual transport is also increased on top of the deposition area so one could
expect erosion but because of the occasional sediment dumping the opposite situation is observed and accretion is measured, as seen in the upper panel.

4.4 Conclusions

This chapter included a validation of the new D-Flow FM model by comparing it with measurements as well as with the results produced by Delft3D.

The hydrodynamic validation showed that the two models, developed by Delft3D and D-Flow FM, produce almost identical results. The comparisons of the modelled results with the measurements show some deviations that can be explained. The fact that a uniform friction coefficient is used in the whole model is a major reason for the water level deviations. The different areas have different friction, because of vegetation for instance, and this situation is simplified in the model. The water levels produced by the model do not include the effect of waves, storm surge and wind but the measurements do, so this difference of real life and model leads to deviations. By comparing the tidal components produced by measurements and model the situation is better because the components do not include the above processes in any of the two cases. The velocities and discharges modelled, show good match with the measurements. The deviations noticed are probably caused mainly by the selection of a uniform coefficient and by bathymetry differences during modelling and measurements.

The sediment transport validation shows that the offline approach is a method that can simulate the sediment transport patterns in the same way as an established online approach. The offline results of Delft3D and D-Flow FM look almost identical. Compared with the online Van Rijn formulation, the offline results overestimate the magnitudes but the directions are accurately represented.

The morphodynamic validation was carried out to hind-cast the morphological changes after the dumping operation of 1997-1998, in the Everingen channel. For the interpretation of morphological changes, residual transports are calculated by D-Flow FM model. The difference between the residual transport of the initial situation and the situation after dumping shows that indeed the operation enhances the residual transports in the area. The plot of the erodible layer thickness shows that in the area there is a non-erodible layer and this is the reason that the channel migrates to the south instead of deepening. The hind-casting of the operation works as a morphological validation of the method used in this report.
5 Dumping scenarios

In Chapter 4, the model is validated for hydrodynamics, sediment transport and morphology. In order to investigate the effect of the dumping operations in the flood and secondary channels of macro-cell 3 of the Western Scheldt, several scenarios are simulated and with the offline sediment transport approach, conclusions about the initial morphological response are drawn.

The simulations are completed for the bathymetry of the year 2013 which is the reference case without any dumped material and this is the comparison scenario for all the scenarios. Four different scenarios are set-up, each with a different dumping location but quite equal sediment quantities. For every scenario, the discharges and velocities in the dumping area are compared with the reference case in order to analyse the change in hydrodynamics. Furthermore, the residual transport is calculated for every scenario and also the difference of the residual transports between scenarios and reference case is presented. The later one shows individually only the effect of the scenario without the effect of the natural residual transport of the estuary. Finally, velocities are also compared in several locations around Baarland, between reference case and scenarios. In this way, the impact of the scenario is seen on the tidal flat. It should be mentioned that the impact of waves, which are ignored in this study, is important for the sediment transport in the tidal flats. For this reason, any conclusions about the Baarland tidal flat are partial and only based on the tidal force mechanism.

For all the scenarios that are examined in this chapter it is tried to keep realistic amounts of dumped material. The results are extracted by using the hydrodynamic data of D-Flow FM software. The model set-up is the same as implemented in the whole research; astronomical boundary conditions of water levels, no discharges, salinity or wind and a uniform Manning friction coefficient of n=0.026 s/m^{1/3},after the model calibration.

5.1 Reference situation

This is the reference case that is used for the comparisons with the scenarios results. The simulation is free of any dumping operation so the natural evolution of the estuary is monitored. The hydrodynamic results of this case (velocities and discharges) as well as the residual transports are compared with the results of the scenarios. In this way the effect of the dumping operations is clearly seen in the initial hydrodynamic and morphodynamic response of the estuary. Table 5.1 shows the settings for the reference situation.

<table>
<thead>
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<th>Setting</th>
<th>Value</th>
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<tbody>
<tr>
<td>Code name</td>
<td>Reference situation</td>
</tr>
<tr>
<td>Case name</td>
<td>-</td>
</tr>
<tr>
<td>Bathymetry</td>
<td>2013</td>
</tr>
<tr>
<td>Area of interest</td>
<td></td>
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</table>
Figure 5.1 presents the residual transport for the reference case as well as a presentation of the main areas that are used for the interpretation of the figures. The main direction of the residual transport is in the ebb-downstream direction. More specifically, Gat van Ossenisse and Pas van Terneuzen main ebb channels present ebb directed residual transports. This is the case with Everingen Ebschaar but also the Everingen main channel. The ebb directed residual transports are maximised in the area of Pas van Baarland. In Straatje van Willem the residual transports of the north-west part are directed also downstream but on the south-east part they are directed upstream. North of Pas van Baarland the residual transports are also flood directed but with smaller magnitudes. In Zuid-Everingen the residual transport follows the ebb direction but in the intersection with the Everingen main channel the sediment is drifted to the right, following the flood direction.

The main conclusion about the residual transports of the reference case is that the patterns are already complicated and morphological changes occur even without dumping. The system is not in equilibrium as morphology is concerned. It is important to mention, for the better understanding of the results, that in the residual transport plots the size of the arrows does not indicate erosion or sedimentation but the difference between the successive arrows does. For instance, the arrows in the ebb channel Pas van Terneuzen are large so this would mean loss of sediment in the specific area, but the arrows in the upstream direction are the same size so the loss is filled by the gain of sediment from upstream. Another example is given in the middle of Straatje van Willem where the residual transports are divergent, so there would be an indication of erosion. Large amounts of sediment are coming though from Everingen Ebschaar to cover these losses.

These types of behaviours will be explained also in the cases of the scenarios and they will be compared with this reference case in order to examine separately the effect of each dumping operation.
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Figure 5.1: Residual transport for reference case and indication of the channels and tidal flats in the area of interest
5.2 Scenario 1 – Closure of Zuid-Everingen

The first scenario is the deposition of the material in the Zuid-Everingen channel. It aims on understanding the impact and importance of the secondary channels in the macro-cell hydro-morphodynamics.

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<thead>
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<td>Scenario 1</td>
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<tr>
<td>Case name</td>
<td>Closure of Zuid-Everingen</td>
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<td>Bathymetry</td>
<td>2013-sc1</td>
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<tr>
<td>Deposition area</td>
<td><img src="image" alt="Deposition area" /></td>
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<tr>
<td>Volume deposited</td>
<td>~9 Mm³</td>
</tr>
</tbody>
</table>

Table 5.2: Scenario 1 information

In Table 5.2 one can see the area that the dumping is implemented as well as the three cross sections downstream, on top and upstream of the dumping area, used for the monitoring of the discharges and velocities. The total volume dumped is approximately ~9 Mm³ and the final bed level, after the deposition, reaches the mean water level, so during low water the channel is considered shut off.

After the dumping, the discharges in the cross sections are examined and compared with the reference case. As a first response to the dumping a decrease of the discharges is expected. Figure 5.2 presents the discharge before and after the dumping for the three cross sections. The impact of the dumping is huge. It is mentioned that the dumped material reaches the mean water level so for lower water levels there is a complete blocking. For this reason, discharges are zero for a large period of the tidal cycle. The impact is quite the same for all the three cross sections.
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Figure 5.2: Discharge changes for scenario 1

Figure 5.3: Velocity changes for scenario 1
In order to better understand the behaviour of the hydrodynamics, the velocities in the cross sections are also examined. In the case of the dumping operation in 1997-1998 the velocities were significantly increased. Figure 5.3 shows clearly that this scenario 1 dumping operation gives a different picture. Velocities are significantly reduced and they are also zeroed during the closure of the channel. The big difference between the cases is that 1997 operation just decreased, in a small percentage, the cross sectional area while here the channel is shut off for half of the tidal cycle. This decrease in velocities will probably cause gradual sedimentation which could cause a bonding of the west and east Middelplaat tidal flats. The velocities during flood will increase in Everingen channel because there will be no secondary channel to accept part of the heavy loads.

Figure 5.4 presents, in the upper panel, the residual transport calculated for dumping operation of scenario 1. The main directions of the residual transports resemble those of the reference case in Figure 5.1. The intensity of the arrows is different but the morphological tendency remains the same. By looking at the bottom panel, the difference between residual transport of scenario 1 and reference case is calculated, in order to examine the separate impact caused only by the dumping scenario. The direction of residual transports is diverging in the deepest point of Pas van Terneuzen, a situation that indicates further deepening. Intense residual transport is observed arriving from Everingen Ebschaar and Straatje van Willem with a downstream direction. This sediment is heading towards Everingen channel but with smaller magnitudes so there is an indication of deposition south of Pas van Baarland.

By looking separately at the area of Baarland tidal flat, there is no significant indication of sedimentation or erosion. The upper panel of Figure 5.4 shows a constant transport of the same intensity while the lower panel shows insignificant transport. The velocities in the area of Baarland flat are also examined separately in Figure 5.5. There are four different observation points located around the flat. The differences between scenario and reference case are not big especially in point 1 and 2 the differences are not noticeable. In observation points 2 and 3 there is a slight increase of the velocities in both directions. This increase indicates higher transports so possibility of erosion.
Figure 5.4: Residual transport for scenario 1 and difference with reference case
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Figure 5.5: Velocity changes in Baarland tidal flat for scenario 1
5.3 Scenario 2 - Closure of Drempel van Baarland

Drempel van Baarland is a shallow area north of the Gat van Ossenisse ebb channel. The concept of this scenario is to close off the communication between the main tidal and ebb channel of the macro-cell so sediment from Baarland cannot be lost on the deep bottom of the ebb channel. For this operation, ~7 Mm³ are used as seen in Table 5.3 also with the location of the deposition and the monitoring cross sections. The final bottom level in this area, after the dumping, is at the mean water level.

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<table>
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<tr>
<th>Deposition area</th>
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<td><img src="image" alt="Deposition area map" /></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Volume deposited</th>
<th>~7 Mm³</th>
</tr>
</thead>
</table>

Table 5.3: Scenario 2 information

From Figure 5.6, it is obvious that the impact of the dumping on the upstream and downstream discharges is small while on top of the dumped material the discharge is decreased. The velocities in Figure 5.7 show even less changes. The hydrodynamics of the area are not significantly affected by the operation. Discharges and velocities downstream and on top of the operation are slightly decreased while upstream they are slightly increased. The conclusion is that the area of Drempel van Baarland is not used by the tide as a passage between the main channels so the closure of it does not affect much the hydrodynamics of the surrounding area.
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Figure 5.6: Discharge changes for scenario 2

Figure 5.7: Velocity changes for scenario 2
Figure 5.8 presents the residual transports calculated for scenario 2 as well as the difference from the reference case. The upper panel of the residual transport shows again an ebb directed transport in Pas van Terneuzen and Gat van Ossenisse. Intense residual transport patterns coming from Everingen Ebbschaar with maximum magnitudes before they reach the Straatje van Willem. The general pattern follows the pattern of the reference case.
By looking at the bottom panel, only the effect of the scenario is presented, since the residual transport of the reference case is subtracted. Scenario 2 dumping causes a flood directed transport in Gat van Ossenisse which is not strong enough to change the final direction of the residual transport of the upper panel and the reference case. The scenario on its own also magnifies the ebb directed transports in the intersection of Everingen Ebschaar with Straatje van Willem.

Separately looking at Baarland flat, the residual transport passing from the south and south-east side is uniform so there is no clear indication of morphological changes. By looking at velocities of Figure 5.9 one sees that the differences with the reference case are not intense. Velocities of observation point 1 are slightly increased so more sediment transport is indicated. For points 2, 3 and 4 the x-directed velocities are not significantly affected but in the y-direction the south directed ones (negative sign in the graph) are reduced while the north directed increased again. This behaviour indicates increased sediment transport towards the tidal flat which could mean sedimentation.
Figure 5.9: Velocity changes in Baarland tidal flat for scenario 2
5.4 Scenario 3 – Shallowing of Everingen Ebschaar

Next case studied is the deposition of the material in the area known as “Ebschaar naar de Everingen” or simply mentioned here as “Everingen Ebschaar”. It is located south of the tidal flat of Baarland. It is a quite deep area so it cannot be closed off with normal quantities of dumped sediment. The operation aims on making this area shallower in order to see the effect on the neighbouring tidal flat. Information about the location of the area, the deposited volume and the monitoring cross sections and observation points can be seen in Table 5.4.

<table>
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<td>Deposition area</td>
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<tr>
<td>Volume deposited</td>
<td>~6 Mm$^3$</td>
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Table 5.4: Scenario 3 information

Figure 5.10 presents the cross sectional discharges downstream, on top and upstream of the dumping location. The only location that shows some slight change is the one upstream of the dumping site. The explanation about this behaviour of the discharges is that Everingen Ebschaar is a wide area so any changes on the bathymetry could be compensated by larger flow in the areas around the dumping location. The cross sections selected cover this whole larger area so the changes are not significant.

The same behaviour is also observed in the velocities, presented in Figure 5.11. Only upstream of the dumping area the velocities are slightly decreased and this could be caused by the fact that flow of water is now spread in a larger area and is not located in the previously deeper Everingen ebschaar so their intensities are decreased.
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Figure 5.10: Discharge changes for scenario 3

Figure 5.11: Velocity changes for scenario 3
Figure 5.12 shows the residual transport for scenario 3 and the difference with the residual transport of the reference case. The reference case also dominates in the residual transport patterns although the large arrows arriving from Everingen Ebschaar stop abruptly just before the intersection with Straatje van Willem. This is explained from the bottom panel of figure 5.12 which shows only the difference caused by the dumping operation of scenario 3. There is a converging residual sediment transport in the beginning of Everingen Ebschaar which will cause a large sedimentation in the area.
In the south-east side of Baarland tidal flat, close to observation point 1, the dumping operation causes diverging residual transport which indicate erosion. The velocities for Baarland flat are seen in Figure 5.13. Compared to all the previous cases, the velocities present the largest deviations compared to the reference case. This is quite expected since the dumping operation is completed next to the tidal flat so the effect is more intense. The velocities in all the observation points are increased in all directions and especially in y-direction to the south. This increase of the velocities indicates larger sediment transports directed away from the flat, so erosion of them will follow.
Figure 5.13: Velocity changes in Baarland tidal flat for scenario 3
5.5 Scenario 4 – Shallowing of Everingen in Middelplaat area

The last case, studies the dumping of sediment in the shallow area of the Everingen channel located in the north part of Middelplaat. This operation aims in understanding the importance of dumping in the shallow part of a channel instead of the deep part of the channel as happened in the operation of 1997-1998. Table 5.5 shows the dumping location, the monitoring cross sections and observation points and the dumped material quantity.

<table>
<thead>
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<tr>
<td>Case name</td>
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<td>Bathymetry</td>
<td>2013-sc4</td>
</tr>
<tr>
<td>Deposition area</td>
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</table>

Table 5.5: Scenario 4 Information

Figure 5.14 and Figure 5.15 show in the locations downstream, on top and upstream of the dumping site the modelled discharges and velocities respectively. A comparison of them is given with the reference case. Both figures show almost no difference in discharges and velocities before and after the operation. There is an insignificant decrease of the discharge and an insignificant increase of the velocity mainly downstream and on top of the dumping site. The dumping location does not have an impact on the hydrodynamics of the wider area of the Everingen channel.
Figure 5.14: Discharge changes for scenario 4

Figure 5.15: Velocity changes for scenario 4
Figure 5.16 gives the residual transport calculated for scenario 4 and the difference between the residual transports of scenario 4 and the reference case. By looking at the upper panel, the residual transport patterns are similar to the reference case of Figure 5.1. There is still though a main difference; the residual transport in the Everingen channel, downstream of Zuid-Everingen is significantly increased, ebb directed. Indeed, by looking at the bottom panel the impact of the scenario is mainly focused only in that area. It causes quite large residual
transports heading downstream. At the same time, on the south side of the Everingen channel the residual transport is still in flood direction but with smaller magnitudes.

From the bottom panel of the residual transport differences it is clear that the impact of scenario 4 is restricted in the Everingen channel so not many changes are expected in the velocities near Baarland. By looking at Figure 5.17 it is obvious that reference case and scenario 4 results coincide. There is no impact of this dumping operation in the area of the tidal flat.
Figure 5.17: Velocity changes in Baarland tidal flat for scenario 4
5.6 Conclusions

In this chapter the hydro-morphodynamic impact of each case study-scenario was presented.

In the case of scenario 1, the partial shutting of the Zuid-Everingen channel results in decrease of the velocities and discharges downstream, in the vicinity and upstream of the dumping location. The separate morphological effect of the scenario shows movement of the sediment mainly in the ebb direction with high intensity south of Pas van Baarland. A clear effect on the Baarland flat is not found but slightly increased velocities indicate possible erosion.

One of the conclusions about scenario 2 is that the dumping operation does not affect the hydrodynamics strongly in the area. In addition the dumping operation tends to turn the residual transport of Pas van Ossenisse in the flood direction and to deposit sediment in the intersection of Straatje van Willem and Everingen Ebschaar. The velocities in the flat of Baarland could indicate a possibility of sedimentation in the southern part.

For the dumping operation of scenario 3 it is concluded that it does not affect the wider hydrodynamics of the area. On the contrary, it has a local effect in Baarland tidal flat in which it increases the velocities that are responsible for possible loss of sediment from the flat. This shallowing of the Ebschaar has the opposite effect than the one wanted in the flat. The residual transport does not deviate from the pattern of the reference case but the scenario individually causes a deposition of sediment in the intersection of Everingen Ebschaar with Straatje van Willem.

For the dumping operation in scenario 4 it is concluded that the hydrodynamic impact is negligible while the morphodynamic impact is restricted to the area of dumping only. Velocities and discharges in the area are not affected. The residual transport patterns show an agreement with the reference case with the difference of a strong residual transport in Everingen channel directed downstream. The Baarland tidal flat is not affected by the operation.

Based on the results from these dumping scenarios it can overall be concluded that each case causes different morphological response of the estuary but at the same time it enhances the main trend of residual transports. The effect in the area of Baarland is stronger when the operation is closer to the tidal flat. A clear feeding of the flat was not achieved but indications of erosion and accretion were seen in most of the cases.
6 Discussion

For the completion of this report several choices and simplifications had to be made, that affect the final results. This chapter discusses the possibilities and the choices that were made. It gives the explanation and the reasoning for several of the decisions.

6.1 Using unstructured grid methods

The first topic that can be discussed is the selection of D-Flow Flexible Mesh software. The main advantage of the new software is the possibility of a flexible grid which allows easy coarsening and refinement locally. In the case of the current report, the area of interest is a small part of the whole grid used for the simulations. In cases like that, the solution is given by nesting the area of interest in order to reduce the computational time. The available data used for the validation were not only spread in the wider Western Scheldt area but also in different years. The nesting procedure needed then to be completed for a larger area and several times, for all the years of simulation. These space and time variations of the measurements are not a problem for the new software because the computational time can be easily reduced by coarsening the areas that are not interesting for the simulation, so nesting is not necessary. In the current grid, the sea side is four times coarser than the original NeVla model and most of the parts of the Western Scheldt are two times coarser. The area of interest is two times refined in each direction, for better analysis. This coarsening of D-Flow FM grid reduced its cells and the computational time in half, compared to Delft3D.

6.2 Choice for boundary conditions

The boundary conditions are selected with the aim to be flexible in the simulation period because of the random measurements. Astronomical water levels cannot be as precise as time series variations but some extra deviations on the water levels are not considered to have a large impact on the modelling of sediment transport, which is the main research topic. The discharges from the rivers are ignored because of their small magnitudes which lead to insignificant contribution to the modelled results. Wind is also ignored because of its insignificant contribution to the sediment transport in the area of interest, located within the estuary. The goal of this report could be achieved without using a 3D model or salinity variations, which have no contribution to sediment transport, so a 2D depth averaged model that ignores salinity differences is selected. Finally, the contribution of waves is not taken into account. A first reason for this choice is that D-Flow FM was not able to successfully simulate this process during the period of this research but also the fetch of the estuary is not large enough to allow development of high waves. The waves do not have a big impact on the deep channels but they are quite important for the sediment transport in the tidal flats in cases of severe storms. In general though, the tide dominates in the development of the flats. This study looks at sediment transport at the Baarland flat and all the conclusions are driven without involving the contribution of waves.

6.3 Offline sediment transport approach

The selection of the Engelund-Hansen approach is a way to calculate sediment transport using a relatively simple method. The hydrodynamic part is available and validated and this approach relates velocities with sediment transport. Bed slope effects, upwind bed composition and sediment availability are not taken into account, but a quite accurate
estimation is possible. For the validation of this approach a comparison with a standard method was selected. The Van Rijn 1993 formulation, with the Delft3D software, is a commonly used approach for sediment transport calculation, so similarity of this online approach with the offline approach indicates a valid method. With the use of the Engelund-Hansen approach the sediment transports are now available only by using the hydrodynamic part of the simulations. A further step needs to be made, though, in order to interpret the transports into initial morphological response. The idea was that the adding of all the sediment transport results in x- and y-direction, in a period of a spring-neap tidal cycle would result in a remaining transport for every cell point, a residual transport. For the morphological interpretation, the residual transport gradients are used. This means that the difference of the residual transport in the neighbouring and successive cells gives a picture of erosion or deposition. Increasing of the residual transport indicates erosion while decreasing of the residual transport indicates accretion. In the same way, diverging residual transports mean erosion while converging residual transports indicate accretion. The problem with this method is that the accuracy is restricted as far as the amounts of sediment eroded/accreted and the exact locations are concerned. It gives a good initial estimation of the general tendency but for a precise calculation a different method should be used.
7 Conclusions and recommendations

7.1 Conclusions

Maintenance dredging is required yearly in the Scheldt estuary to safeguard navigation through the channels, to the Antwerp port, as well as other ports along the Western Scheldt. The dredged material is deposited in areas that are close to the dredged channels in order to reduce the costs. At the same time, these areas should not allow the dumped sediment to return back to the navigation channels. Over the past years a technique called “morphological dredging” is examined, in which the morphological behaviour of the estuary is taken into account when depositing sediment. The main objective of this study is to understand this behaviour and to use this understanding to analyse the effects of several sediment dumping scenarios. In addition, this thesis aims to validate the new hydro-morphodynamic software, D-Flow Flexible Mesh for the Scheldt Estuary.

One of the research objectives was to set-up a new Scheldt Estuary model with the new D-Flow Flexible Mesh software. Astronomical water levels were used for the boundary conditions of the model. The computational grid used for the simulations is based on the so-called Delft3D NeVla-schematisation, and was refined locally in the area of interest and coarsened in the rest of the grid. Because of the advantage of the unstructured grid, the coarsening and refining was relatively easily implemented. By reducing the amount of unnecessarily fine cells, D-Flow FM simulation times were half compared to the original Delft3D model.

Based on the hydrodynamic validation of D3D and DFM models, it is concluded that both are able to accurately reproduce water levels, velocities and discharges. Tidal components amplitudes are accurately simulated, with the results showing about 3% deviation of the main tidal component (M2) amplitude between the models and the measurements. Apart from the comparison of the two models with the measurements, there was also a comparison with each other. This comparison showed almost identical results in most of the cases and since the only difference between the models was the computational grid it is concluded that the coarsened grid is not lacking in accuracy.

Based on the comparison of sediment transport results, between the online Van Rijn ’93 approach and the offline Engelund-Hansen approach, it is concluded that the later one can accurately predict the direction and with a relatively small overestimation, also the magnitudes of sediment transport. The overestimation does not affect the final conclusions.

The residual transports calculated by the offline approach explained the morphological response of the dumping operation of 1997-1998. The hind-casting of this operation showed the ability of the residual transport approach to predict initial morphological response.

One of the research objectives was to develop several sediment dumping scenarios that investigate different dumping locations and quantities. The hydrodynamic analysis showed that in most of the scenarios, the area of the operation is affected, since velocities and discharges change. The effect of the operation is also found in the residual sediment transport patterns which are significantly influenced by the operation. The residual transport results showed that a relatively large area of the estuary can be affected, beyond the scale of
the macro-cell. Furthermore, there is a large connection of the dumping location and material quantity with the residual transport pattern changes.

The final research objective was to check if an indirect nourishment of Baarland tidal flat is possible. The four scenarios that are developed and simulated in this report did not show a clear response that could favour the nourishment of the tidal flat but only indications. The residual transports in Baarland flat looked steady, although in several of the scenarios the velocities in the flat were affected. The closer to the flat the dumping location was, the larger the hydrodynamic impact on the flat. Several indications of erosion and sedimentation were given. The scenarios could not produce a clear flat nourishment but the showed that other dumping scenarios may be more promising.

7.2 Recommendations

Every study aims at contributing in the gaining of knowledge over a broad or more specific topic of interest. It is impossible though to cover all the possibilities and questions that arise during the research period. For this reason, during the current study, several recommendations for future research can be proposed.

The first part of these proposals is related to the software used for the current report, D-Flow Flexible Mesh, but also with the model set up. This software offers a promising amount of possibilities by the implementation of its flexible grid but during this research many of the processes were not yet developed. Waves during storms, is a case that could be interesting to investigate in the same scenarios. Especially the effect of waves is larger in the tidal flats. The hydrodynamic simulations would be more realistic with the existence of waves and the sediment transports would possibly give different values on the flats. The boundary conditions can also be improved by using time series for a certain year instead of tidal components which on the one hand have the advantage of being applied in all years and periods but on the other hand they might lack in accuracy. The time series have the advantage of taking into account all the possible processes such as waves, wind set-up and storm surge so the resulting boundary conditions are expected to be closer to real life conditions.

Another point that needs to be investigated further is the resulted sediment transports. In the current study the results were not compared with measurements but with the results extracted by the established software Delft3D with the use of the standard formulation of Van Rijn 1993. For a better validation, comparison of the model results with measurements would be recommended.

Another recommendation is the investigation of more scenarios. In this study four scenarios are investigated with different locations and deposited amounts. Shallow areas, secondary channels, tidal flats; all the combinations that are produced by combining dumping locations and dumped quantities are vast and these four scenarios cannot be representative for all the possible cases. All the scenarios showed an ebb directed residual transport in Everingen Ebschaar so a dumping operation upstream of the channel could be suggested. In the same way, the residual transport north of Pas van Baarland is directed upstream so a dumping on the area could feed the Baarland flat. Further examination of more cases could show completely different sediment transport patterns and the nourishment of Baarland could be indirectly achieved.
A final recommendation would be the actual investigation of these scenarios with morphological changes calculated by a numerical model like Delft3D or D-Flow FM, when the last one will be fully developed. The combination of morphological changes and residual sediment transports can give a better insight on how these two processes are related. The residual transport is a fast way to predict the possible initial morphological changes and it is just based on the hydraulic information. The disadvantage of it is that the predictions are rough and qualitative while the morphology is the means to achieve a prediction with actual sedimentation and erosion quantities.
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A Description of D-Flow Flexible Mesh

D-Flow FM is a 1D-2D-3D hydrodynamic simulation package that runs on flexible meshes. The word ‘Flexible’ means a combination of the familiar curvilinear grid, that is used by Delft3D, with triangles, pentagons, etc. as well as 1D channel networks (Deltares, 2014). D-Flow FM is based upon the numerical concept of Delft3D and SOBEK1D2D (Kernkamp et al, 2011). On the following paragraphs, several parts of the numerical approach of the software are summarised.

A.1 Grid

The unstructured meshes use fundamentally different data structures for flow simulations than the curvilinear meshes. Below, in Figure A.1 one can see the conceptual hierarchy of mesh and flow data. (Deltares [1], 2014)

Two important features of the unstructured grid are the concepts of orthogonality and smoothness. The concept of orthogonality requires firstly the circumcenter of each cell to lie within the cell and secondly it implies the flow link connecting the circumcenters of two neighbouring cells to intersect orthogonally with the interface between them (Kernkamp et al, 2011). The concept of smoothness requires neighbouring cells to be of the same surface area. In other words and in a quantitative way, orthogonality is the sine of the angle between flow link and net link while smoothness is the ratio of the area of two neighbouring cells. In an ideal case both parameters equal 1, which means angle of 90° and equal cell size respectively. (Delatres, 2014)
A.2 Hydrodynamic equations

D-Flow Flexible Mesh uses the depth-averaged, homogeneous shallow water equations for the calculation of the hydrodynamics. The equations are given below:

\[
\begin{align*}
\frac{\partial H}{\partial t} + \nabla \cdot (H \vec{u}) &= q \\
\frac{\partial \vec{u}}{\partial t} + adv(\vec{u}) + g\nabla \zeta + c_f \vec{u} |\vec{u}| + 2\Omega \times \vec{u} &= d
\end{align*}
\]

In which \(H\) is the total water depth, \(V \equiv [\partial_x, \partial_y]^T\) is the horizontal gradient operator, \(\vec{u}\) is the depth-averaged horizontal velocity vector, \(\zeta\) is the water level relative to a reference plane, \(\Omega\) is the earth rotation vector and \(adv(\vec{u})\) is the advection term. The constants \(g\) and \(c_f\) declare the gravity constant and the bottom friction coefficient respectively. The right hand side \(q\) contains source terms while \(d\) contains external forcing. The first equation represents the continuity equation while the second one the momentum equation. (Kernkamp et al, 2011)
B  Grid design

The basis of the grid used for the current report is the one from the NeVla (Netherlands and Vlaams) model which is a 2DH model based on Schalwest-2000 and ZeeSchele models. It includes a specious sea and all the Flemish tidal rivers (Grasmeijer, 2013). In the framework of the project LTV O&M (Long Term Vision, Research & Monitoring) Scheldt estuary, a Consortium of Deltares-IMDC-Svasek-Arcadis developed a Delft3D model using the same grid (van der Werf & Briere, 2013). The last Delft3D grid was transformed by Deltares into D-Flow FM grid by implementing triangular connections in order to avoid unwanted high resolution on the rivers. The last D-Flow FM grid is the actual basis used for the construction of the final grid of this report.

In the current grid the rivers are kept on their original resolution but several resolution changes are implemented on the Western Scheldt area. The sea area is even 4 times coarser compared to the original model while the area of interest is 2 times finer than the original grid. All the changes on the grid are presented below schematically.

Figure B.1: Different resolution domains for the Scheldt model

Figure B.1 gives an overview of the different domains of the grid. Area 1 is selected to be much coarser than the rest of the grid because it saves a lot of computational time and it is not an area of interest in this report. Area 4 is the most refined area of the domain because it is the actual area of interest surrounding Everingen channel and Baarland plain. The transition from a coarse area to a refined one is done gradually so the resulted grid consists of 8 domains.

In Figure B.2 the variations on the grid size can be clearly seen. In addition, a representative cell size is given for all the domains without thought that size to be constant. Depending on the domain’s extend and curvature the cell size changes locally. For instance, on the inner
part of a bend the cell size is smaller than on the outer part and also when the domain becomes narrower the cell’s width also decreases.

![Figure B.2: Close look of the grid domains with an average cell size parallel x perpendicular to the flow](image)

The last step before the completion of the grid is the fulfilment of the orthogonality and smoothness criteria. The orthogonality of the grid is kept everywhere less that 5% which is a low value if one takes into account the complexity of the grid especially in the rivers area. On the main grid, the most difficult areas with poor orthogonality are found in the triangular connections or in the staggered boundaries of the grid. Figure B.3 visualises these two cases of bad orthogonality.
Figure B.3: Orthogonality problem: (left) on the triangular connections between the grids, (right) on the edges of the grid.
C Channels and tidal flats in the Western Scheldt

Figure C.1: Channels and tidal flats in the Western Scheldt

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