LONG-TERM MODELING OF THE IMPACT OF DREDGING STRATEGIES ON MORPHO- AND HYDRODYNAMIC DEVELOPMENTS IN THE WESTERN SCHELDT

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Abstract: The natural morphological developments of the Western Scheldt and the impact of human activities on these developments are investigated using a process-based morphological model called FINEL2d. The historical period of 1965-2002 is simulated in a T0 scenario including all the human activities that have taken place in that period. Besides this T0 scenario two extreme scenarios are modeled for the same period. The T1 scenario is carried out without any human activities from 1965 onwards. In the T2 scenario regular dredging of the navigational channel takes place, but the dredged material is not distributed back into the Western Scheldt like in the T0 scenario. In this way insight is obtained into how human activities have influenced and will influence the tide in and the morphology of the Western Scheldt.
By modeling these different sediment strategies it is concluded that the applied strategy has had a large impact on the morphology of the estuary and tide during this period. The channels have deepened and the tidal flats have increased in the 1965-2002 in the model, because of which the hypsometry of the Western Scheldt has probably has become steeper over the last decades. The results also show significant effects on the propagation of the tide in the estuary. Due to the actual human activities over the past decades the tidal range in the estuary has increased by about 0.4m in Antwerp and accelerated the propagation of the tide with approximately 20 minutes. This corresponds to the observed phase shift in Antwerp over the past decades.
The extreme scenario in which all dredged material was removed from the estuary shows that the process of increasing tide levels in the estuary may continue in case that the human activities are intensified.

Keywords: Morphological modeling, dredging, Western Scheldt

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1 INTRODUCTION

The Western Scheldt is a highly morphological active estuary. The tide and the morphology are inter related, i.e. any change in tide causes a change in morphology and vice versa. Managing the estuary requires deepened knowledge and sophisticated decision making tools to be able to safeguard all the functions of the estuary with regard to nature, safety and access to the Port of Antwerp. The morphological timescales of large scale impacts, such as land reclamation, deepening of the navigational channel, sand mining and sea level rise are in the order of years to decades. For this reason investigating these impacts requires long-term morphological models. Until now long-term morphological predictions were mainly carried out by using (semi-)empirical models, like ESTMORF (e.g. Wang et al., 1999) and ASMITA (e.g. Kragtwijk et al., 2004). Process-based morphological models were not yet able to reproduce the morphological development very well over decades, partly because of the large amount of computational time involved, although its use on decadal scale begins to be more common practise (e.g. Van der Wegen et al, 2011, Van der Wegen and Jaffe, 2013). Focus of long-term research using process-based models was mainly on highly schematised estuaries like Hibma et al. (2003) and Van der Wegen and Roelvink (2012). In Dam (2007) a long-term morphological model of the Western Scheldt was presented that was successfully used in a hindcast of the period 1965-2002. In this paper a revision of the model of Dam (2007) is used to investigate the effect of human activities in this historical hindcast, focussing on the second half of the 20th century. The main research question in this paper is to establish the impact of human activities in the second half of the 20th century on the morphology and the tide in the Western Scheldt. Three scenarios are defined:

- T0: Real hindcast of the 1965-2002 period including dredging/disposal and sand mining;
- T1: Scenario 1965-2002 without any human interference;
- T2: Scenario 1965-2002 in which all dredged sediment of the navigational channel is taken out of the Western Scheldt.

The scenarios T1 and T2 are fictive, and show the range of effects from the case no human interference had taken place at all over the period 1965-2002 (T1) to an interference in which huge volumes of sediment are removed from the estuary (T2), with the factual T0 scenario in between.

The applied morphological model is a finite element based model called FINEL2d using an unstructured grid with triangular elements that covers the complete Western Scheldt estuary (Dam et al., 2007). Besides a hydrodynamic and morphodynamic module, a dredging module is used to model the three scenarios.

The content of this paper is as follows. In section 2 the Western Scheldt estuary is introduced and section 3 describes the applied FINEL2d model. Section 4 presents the morphological and hydrodynamic results and section 5 finally summarizes the conclusions.

2 WESTERN SCHELDT

The Scheldt estuary is one of the major estuaries of North-West Europe. The estuary is approximately 160 km long and is located both in Dutch and Belgian territory. The down-estuarine part (last 60 km) is called the Western Scheldt (Figure 1) and is characterised by a width of almost 5 km near the mouth and 1 km near the Dutch-Belgian border. The mean tidal range increases from 3.8m at the mouth to over 5.0m near Temse, almost 100 km from the mouth of the estuary (see Figure 2). The morphological changes in the Scheldt estuary are dominated by the tidal motion. The river discharge is of minor importance since the fresh water discharge, on average 120 m^3/s, is only 0.6% of the tidal prism at the mouth (Van der Spek, 1997). The estuary is well-mixed, meaning a horizontal rather than a vertical salinity gradient.

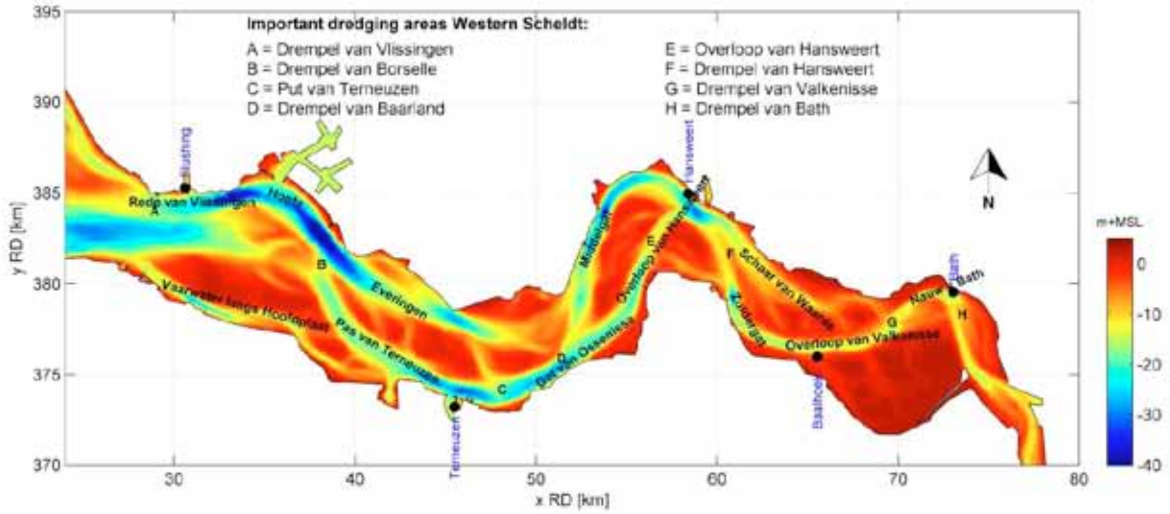

Figure 1. Layout of the Western Scheldt with most important channels, dredging areas and tidal stations.

The Western Scheldt incorporates large areas of tidal flats and salt marshes. Nature is therefore an important function and stringent EU and national legislation is applicable to safeguard its natural values. Equally important are the functions of the estuary in the safety against flooding and the access to the Port of Antwerp.

The Western Scheldt is a multiple channel system. Ebb and flood channels show an evasive character separated by inter tidal shoals (Van Veen, 1950). The ebb channel has a meandering character, while the flood channel is straighter. The ebb flow reaches it maximum velocity near mean sea level (MSL), while the flood flow reaches its peak one hour before high water (Van den Berg et al., 1996). As a consequence the ebb flow is more concentrated in the channels, resulting in deeper ebb channels. The ebb channel is therefore generally designated as the navigational channel in the Western Scheldt. The Western Scheldt consists mainly of fine non-cohesive sediments; only at inter tidal areas mud can be found.

The tidal flats and surrounding ebb and flood channels form morphological macro cells (Winterwerp, 2001). At the locations where the cells coincide sills develop, which reduce the navigational depth of the fairway to the port of Antwerp and therefore require maintenance dredging (Meersschaut et al., 2004). The sills are indicated in Figure 1 by the capital letters. Several million m^3 are dredged annually to maintain the guaranteed depth of the navigational channel to the Port of Antwerp. This material is redistributed in the estuary. In addition on average 2 million m^3 of sand is mined annually from the Western Scheldt.

In the 1970's and 1990's a deepening and widening of the navigational channel has been carried out to allow vessels with greater draught to enter the port of Antwerp. Recently, in 2010, a third deepening has been completed. Most of the dredging had to be done at the sills. The annual dredging volumes (maintenance plus deepening) range from 5 million m^3 in 1968 to 14 million m^3 during the second deepening. After the second deepening the volumes seem to stabilise around 7 to 8 million m^3 per year. The dredged material is deposited back into the estuary in designated areas, usually in the secondary branches. During the last enlargement of the navigation channel a new disposal strategy was used (Plancke et al, 2010). Within this strategy dredged sediments are also being used to reshape the edges of certain intertidal flats and create ecological valuable habitats. This new strategy should be seen as a first step in a morphological management approach for estuaries, in which an holistic approach is adopted, taking into account the different ecosystem functions.

In the past centuries large land reclamations have narrowed the estuary, resulting in increasing tidal levels. The tidal amplitude and celerity also increased during the 1965-2002 period for which this research is carried out, but this is believed to be due to the dredging works (Taal et al., 2013). The tide is important for all functions related to the Scheldt estuary: safety, accessibility and nature.

- Safety against flooding is directly affected by a change in the tidal propagation.
- Accessibility is dependent on the bed level of the navigational channel in relation to the lowest astronomical tide (LAT). The tide further determines accessibility because of tidal windows and tidal (cross-current) flow.
- The time that an inter tidal area is dry is important for its ecological value; a change in the tide has thus an effect on the ecology. Furthermore an increase in tidal velocities generally reduces the ecological richness of the bed (e.g. Raffaelli and Hawkins, 1994).

The tide and morphology are inter related. In Wang et al. (2002) this is described by saying that (1) changes in morphology lead to (2) changes in tidal levels, which lead to (3) differences in ebb and flood velocities that (4) causes residual transport of sediment, with a feedback into (1).

3 FINEL2D MODEL

The process-based model that is applied in this study is called FINEL2d. The model is a 2DH process-based model based on the finite element method. The depth-integrated shallow water equations are the governing equations of the flow module. For details about FINEL2d reference is made to Dam et al. (2007). Other examples of the application of the FINEL2d model are Dam et al. (2005, 2009) and Dam and Bliek (2013).

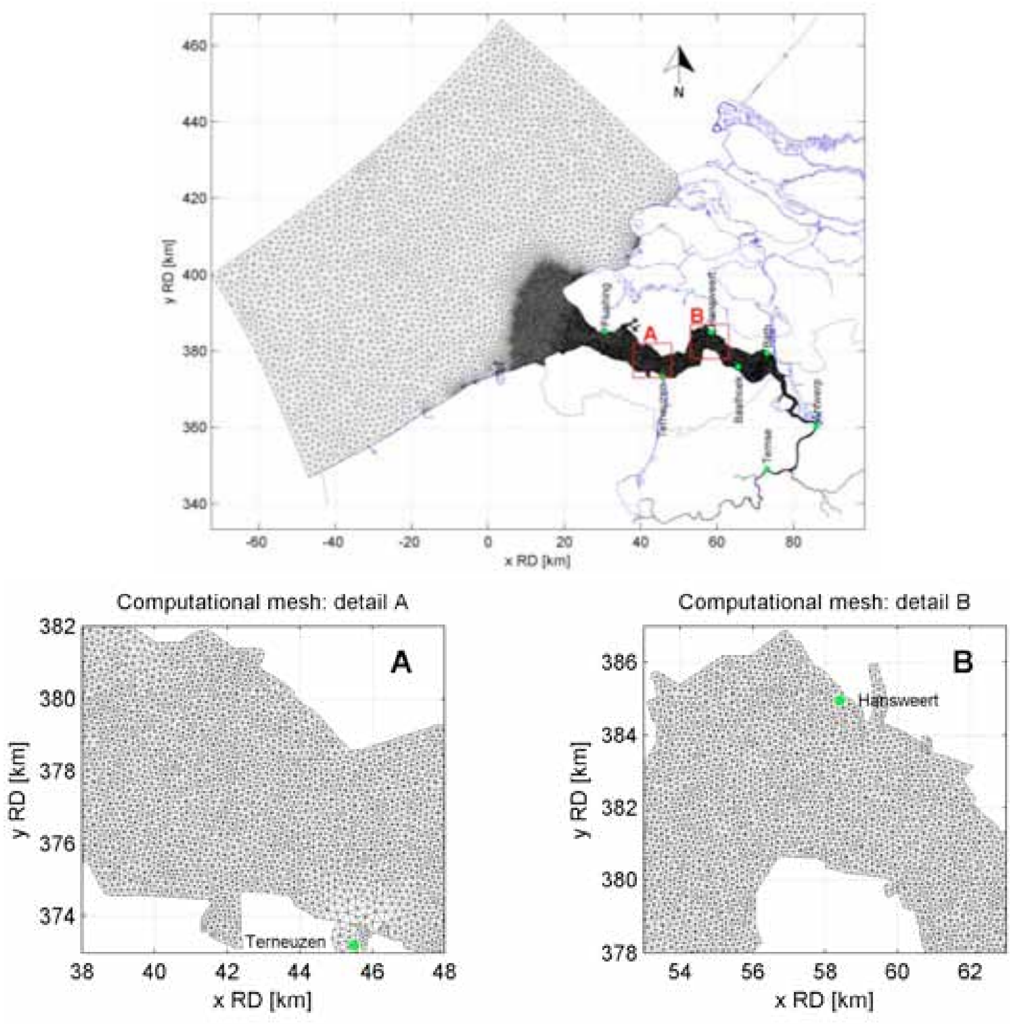

Figure 2. Computational mesh of the FINEL2d model; full grid (top) and details (bottom).

FINEL2d uses an unstructured triangular grid. The advantage of such a mesh in comparison to for example a finite difference grid is the flexible mesh generation. In FINEL2d no nesting techniques are required in regions of specific interest, where a higher degree of resolution is needed, while arbitrary coastlines and complex geometries can be resolved very well, see Figure 2.

The seaward boundaries of the computational mesh of the Western Scheldt are chosen approximately 40 km away from the coastline and coincide with the boundaries of existing models. The latter have been used to obtain the corresponding boundary conditions. The major part of the Scheldt estuary in Belgium is also included in the schematisation. In Figure 2 the whole mesh is shown. In the area of interest, the Western Scheldt, the average grid size is approximately 1.1 ha (see lower panels of Figure 2). Near the seaward boundaries the grid size is approximately 2.5 km^2. The total number of elements (triangles) of the mesh is 52,840.

On the seaward boundary of the model domain tidal boundary conditions are imposed, whereas on the river side constant (yearly averaged values) discharges are imposed. Since the estuary is tide dominated (Van der Spek, 1997) only the influence of the tidal action on the morphology is taken into account. It is assumed that the major morphological changes in the estuary are tidally driven. For simplicity reasons wave action is ignored, although inter tidal areas are influenced by waves. To speed up the morphological calculation the bed level changes at every time step are multiplied by a morphological acceleration factor (MF) , see Roelvink, (2006). In this case a MF of 24.75 is applied in accordance with Dam et al. (2007) meaning that one neap-spring cycle for the water motion represents a morphodynamic year.

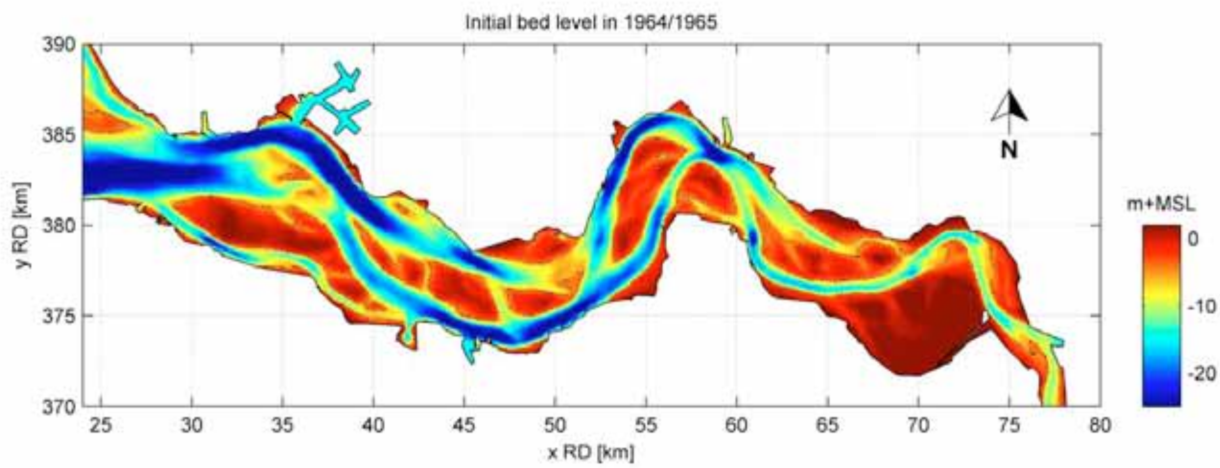

Figure 3. Initial bed level of the Western Scheldt (1964/1965). The MSL +5 m contour is indicated by the dashed black line. The depths are given in NAP (Dutch Ordnance Level), which is approximately MSL.

Since the major part of the Western Scheldt is dominated by the sand fraction, in the model only non-cohesive sediment is taken into account. Dredging can have an important impact on the morphodynamics in the Western Scheldt. Therefore this needs to be taken into account when performing a hindcast of the morphological developments of the last decades. In reality a navigational depth is guaranteed between the navigational buoys of the fairway. If the depth becomes too shallow a dredger deepens the area to the required depth. In FINEL2d a dredging module was developed based on the same principle. For each grid cell in the fairway a required depth is defined. If the depth in the grid cell is insufficient, sand is removed from the element and distributed according to a certain distribution key over depositing sites. The distribution key is established using historical data of the deposited material. For each historical year an input file is defined, since the buoys, the depositing areas and the maintained depth in the navigational channel may vary over the years. See Consortium Deltares, IMDC, Svašek, Arcadis (2013) for more information about this model input.

Sand mining is simulated in the model by removing the actually mined volume equally spread over the specified sand mining area. Since sand mining quantities and locations differ per year an input file for each year is specified. The morphodynamics of the estuary due to the combined effects of natural processes and dredge/depositing activities is continuously calculated, and the riverbed is updated accordingly.

The calibration of the model on the water motion and the sandy morphology for the entire Scheldt estuary is carried out in Dam et al. (2007) with an update in 2013 (Consortium Deltares-IMDC-Svašek-Arcadis, 2013). The hydrodynamic model is calibrated on water levels at the main tidal stations, as indicated in Figure 2. This resulted in a global nikuradse roughness k of 0.01 m. The model is validated on tidal currents in both the channels and inter tidal areas. The hydrodynamic model shows good agreement between observations and model results (Consortium Deltares-IMDC-Svašek-Arcadis, 2013). The morphodynamic model is calibrated on the period 1998-2002 (Consortium Deltares-IMDC-Svašek-Arcadis, 2013). The optimal settings for the morphodynamic model found in the calibration are given in Table 1. These settings are used in the model computations discussed in this paper.

Tabel 1. Model settings

Parameter	**Value**
Sediment transport formula	Engelund Hansen (Engelund-Hansen, 1967)
Grain size (d_{50})	Variable (150 μm up to 300 μm)
Fall velocity of sand	0.015 m/s
Morfological acceleration factor (MF)	24.75
Morphological start-up period	1 year
Non erodible layers	From government data
Hydraulic roughness	1 cm

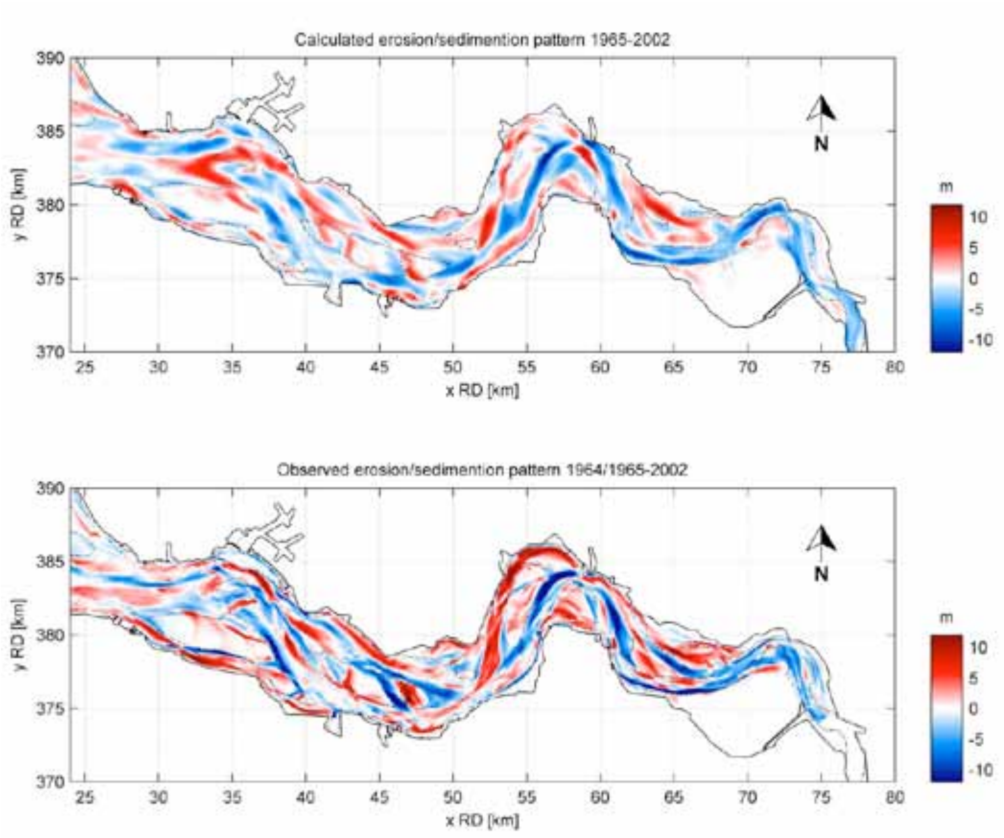

Figure 4. Simulated erosion/sedimentation pattern between 1964/1965 and 2002 (top panel) and observed erosion/sedimentation pattern (lower panel). Red indicates sedimentation; blue indicates erosion. The MSL +5 m contour of the bed level in 2002 is indicated with a dashed black line.

A validation of the years 1965 to 2002 is described in Dam et al. (2007), which was updated recently (Consortium Deltares-IMDC-Svasek-Arcadis, 2013). This validation period is equal to scenario T0, which includes all the human activities as they have occurred. Starting point is the bathymetry of 1964, see Figure 3, and a start-up period of 1 year. This means that the model requires a start-up time to enable for the initialisation of the sand transport and the adaption of the initial bottom, which was interpolated from GIS data. It was found that a spin-up time of 1 year is sufficient to account for these factors.

Scenario T0 represents the real hindcast period of 1965-2002. The simulated erosion/sedimentation pattern of these years is displayed in Figure 4, together with the observed erosion/sedimentation pattern. For some areas good agreement is found for the large scale variations (Middelgat-Overloop van Hansweert, Zuid-Everingen), but in other areas and for the smaller scales important differences can be seen (e.g. Schaar van Waarde, Schaar van Spijkerplaat). The morphological changes are in the order of metres to 10 metres over 38 years.

Since the model is equipped with a dredging module the calculated dredging locations of the model can be compared to the actual dredging locations. In Figure 5 this is shown for the eastern part of the Western Scheldt, where the model results are plotted (in colour) together with the actual dredging areas of the sills. The model is capable of reproducing the locations of the large dredging sites; from west to east: Overloop van Hansweert, Drempel van Hansweert, Drempel van Valkenisse, and Drempel van Bath (see Figure 1 for their locations). Figure 6 shows the calculated and actual total dredging volume over the 1965-2002 period. The calculated dredging volumes are generally comparable to the actual dredging volumes. Please note the increase of dredging volumes in the 1970's and 1990's, which represent the two deepenings of the navigational channels.

A Brier-Skill Score (BSS) is a measure how good the model performs (Sutherland et al., 2004). A BSS value of 0.14 is obtained from the 1965-2002 period. This means that the model has performing skill. From the BSS value of 0.14, a reasonable erosion/sedimentation pattern, the correct dredging volumes and spatial distribution of dredging amount, it is concluded that the model is sufficiently accurate to be used to evaluate different scenarios.

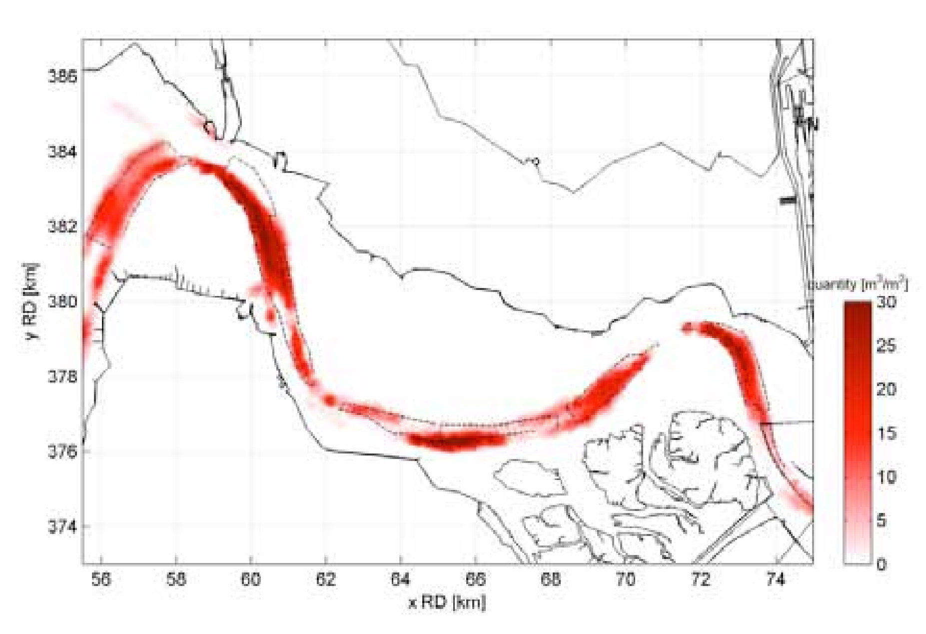

Figure 5. Calculated total dredging amount per grid cel for the period 1965-2002 (in color) and the actual dredging areas (dashed black line).

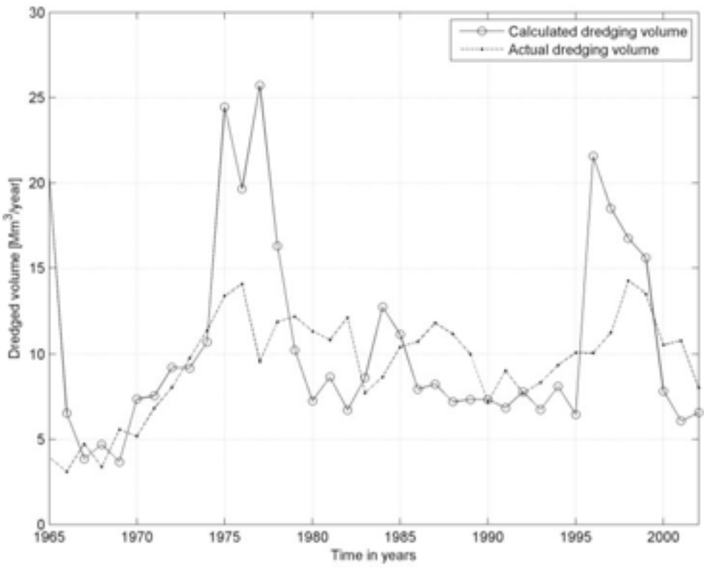

Figure 6. Calculated and actual total dredging amount per year for the entire Western Scheldt for 1965-2002

4 MORPHOLOGICAL SCENARIOS 1965-2002

For the 2 fictitious “extreme” scenarios T1 and T2 the same settings given in Table 1 are used. The bathymetry of 1964 is used as a starting point, similar to the T0 scenario (see Figure 3). In scenario T1, a simulation is performed without any human interference. This means that in the model computation dredging, distribution of the dredged material and sand mining are not taken into account. In scenario T2 both dredging and sand mining are included, however the dredged material is taken out of the Western Scheldt and not distributed back into the system. In Table 2 the three scenarios are summarized. Autonomous behavior (e.g. morphological adaptation due to the historical land reclamations) is included in all three scenarios and so the relative changes between these simulations show the relative effect of these sediment strategies. The question that has to be answered after analyzing the results of the three scenarios is how human activities have influenced the morphology and the tide of the Western Scheldt in the past and what can happen if human activities are intensified in the future.

Tabel 2. Scenario definition

Scenario	**Dredging**	**Distribution of dredged material**	**Sand mining**
T0: real hindcast scenario	Yes	Yes	Yes
T1: no human activities	No	No	No
T2: no distribution of dredged material	Yes	No	Yes

The bed level of the year 2002, which is at the end of the 38 year model simulation, is for each of the three scenarios shown in Figure 7. Especially in the eastern part of the Western Scheldt, distinct differences between the bed levels can be seen. Most prominent is the bed level of the T1 scenario. In this case the sills become shallow (less than 10 m), because they are not maintained by dredging. The secondary channels in the eastern part are more morphodynamic active when no human activities take place. The Eastern part shows distinct evasive ebb and flood characteristics in Scenario T1, as described by Van Veen (1950), while the T0 and T2 scenario are more dominated by the navigational channel, which is kept at its place. In the T0 scenario the secondary branch “Schaar van Waarde” shows severe sedimentation (see Figure 1 for the location of this branch). This is due the distribution of the dredged material from the navigational channel. However it should be mentioned that the formation of a new channel in the Schaar van Waarde that took place in reality, is not reproduced in the hindcast. Therefore it seems that the model does not accurately reproduce the morphological behaviour of the disposed sediments in this secondary channel. Since Scenario T1 and T2 do not have this distribution of dredged material the “Schaar van Waarde” is much more pronounced.

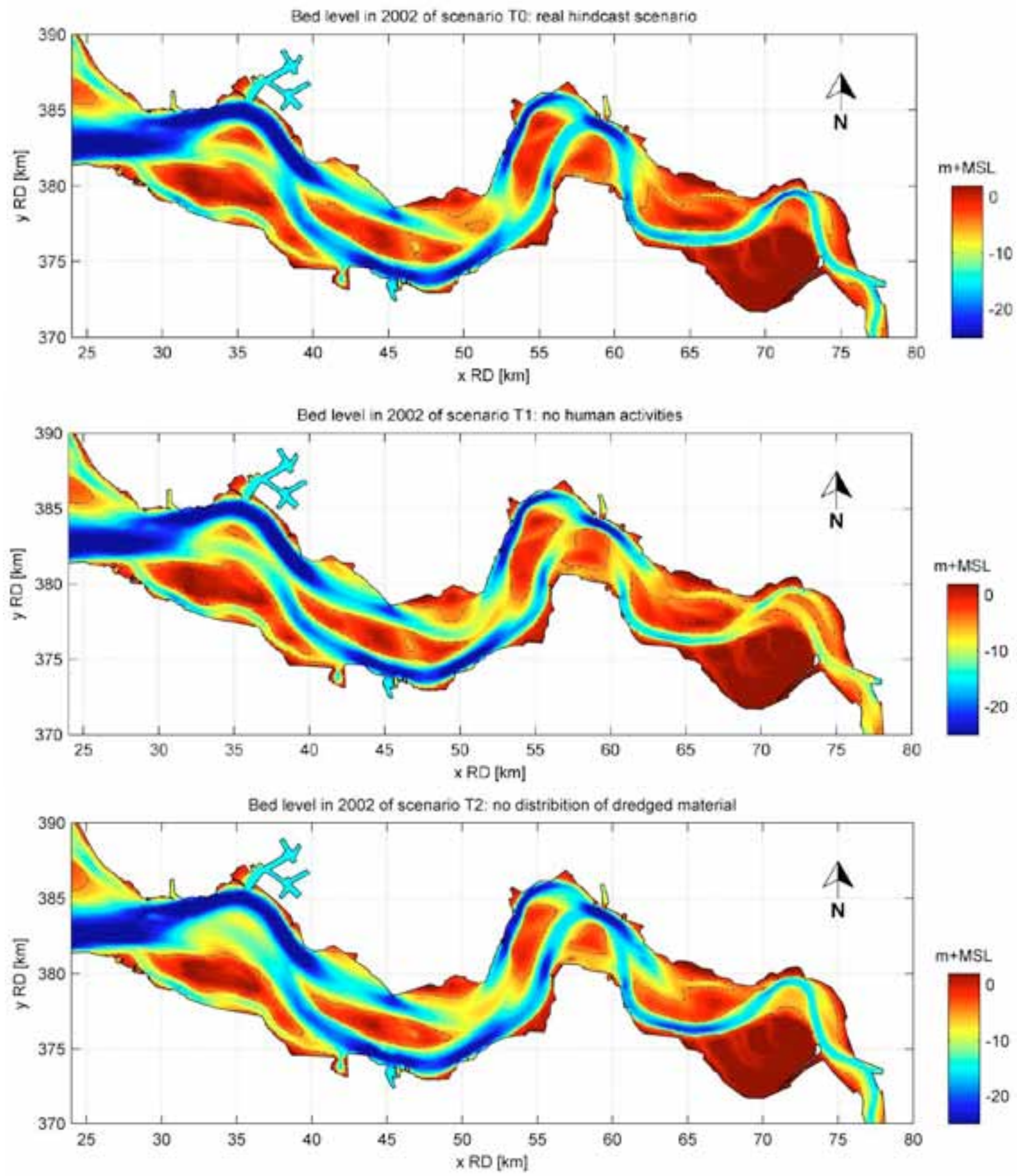

Figure 7. The bed level of the Western Scheldt at the end of the FINEL2D model simulations (2002) for scenario T0 (top panel), scenario T1 (middle panel) and scenario T2 (lower panel). The MSL +5 m contour of the bed level in 2002 is for each scenario indicated with a dashed black line.

The difference in bed level of the three scenarios is given in Figure 8. The top panel of Figure 8 represents the difference between the bed level of scenario T0 and T1 in 2002 after a morphological time of 38 years. From this figure the large (relative) sedimentation of the navigational channel in scenario T1 can be seen in the eastern part. Also the relative erosion of the secondary channels and intertidal areas is shown. The eastern part of the Western Scheldt is clearly influenced by human activities. The dredged material of the navigational channel in the eastern part is mainly distributed in secondary channels. As a consequence these channels become shallower in comparison to scenario T1 where no human activities take place. The lower panel presents the difference between the bed level of scenario T0 and T2 in 2002. Since dredged material is extracted from the system, mainly relative erosion is visible, both at intertidal areas and in the channels.

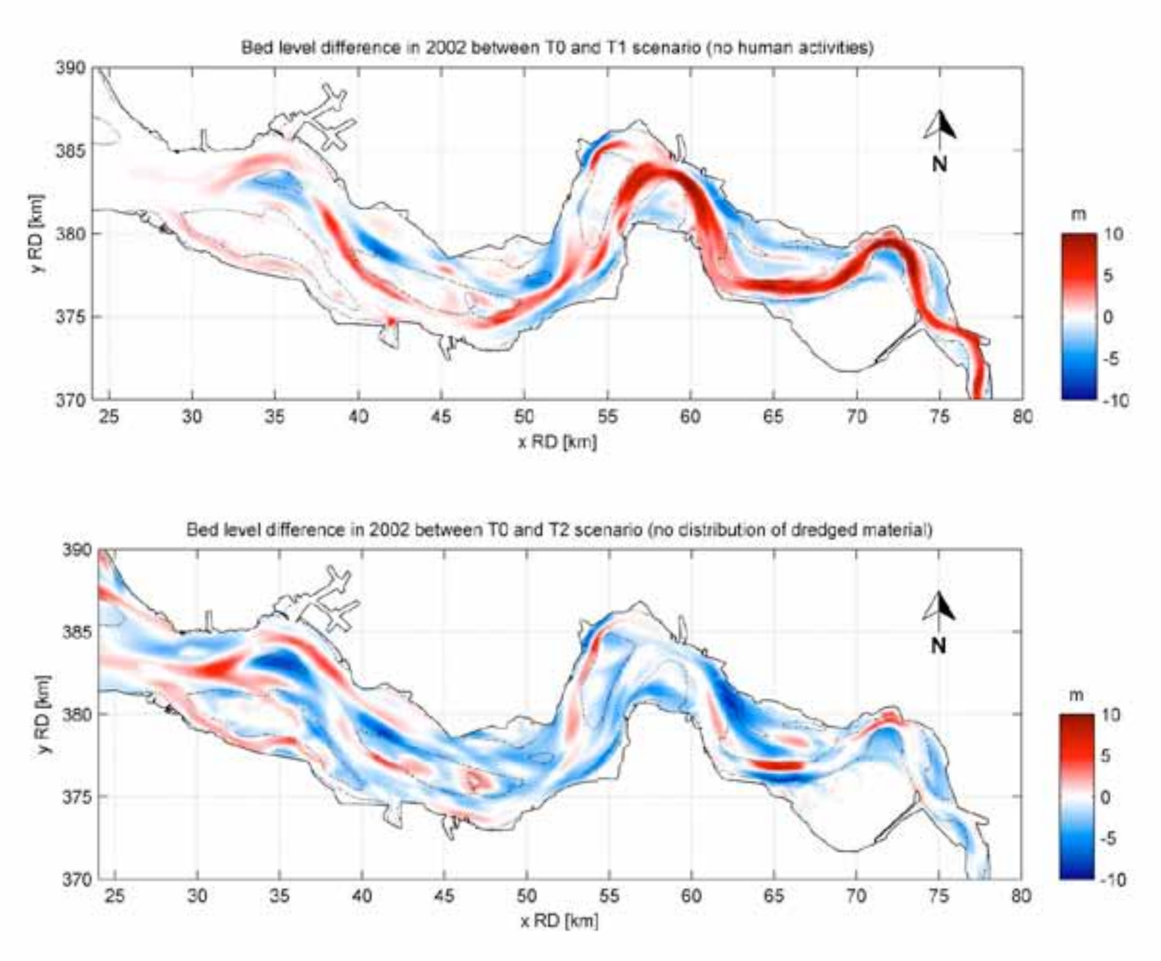

Figure 8. Bed level difference in 2002 between scenario T0 and scenario T1 (top panel) and scenario T0 and scenario T2 (lower panel). Red indicates more sedimentation in scenario T1/T2 than in scenario T0; blue indicates more erosion in scenario T1/T2 than in scenario T0. The MSL +5 m contour of the bed level of scenario T0 in 2002 is indicated with a dashed black line.

The difference in the morphology of the Western Scheldt for the three scenarios is noticeable in the tidal range as well. It should be mentioned that the hydrodynamic boundaries are kept constant at the sea- and landward boundary. This means that effects of sea level rise are not taken into account in the simulations. The sea level rise of the past century was around 10 cm in Flushing. In the considered period of 38 years sea level rise would only concern a few centimetres, which is considered negligible. The tidal range for several water level stations along the Western Scheldt is given in Figure 9, in which the stations are plotted from west to east. The calculated tidal range of the model in 1965 is shown as well as the observed tidal range of 1965 and 2002. The observed tidal range shows a large increase of the tidal range in the eastern part from 1965 to 2002 (green lines). This is reproduced by the model where in the western part till Hansweert the effect on the tidal range is minimal and in Bath and Antwerp there is a large increase in tidal range (compare the 1965 (model) and T0 (2002) lines). The scenario with the smallest effect on the tidal range is logically scenario T1, which does not include human impacts. Note that this scenario does show a small increase in tidal range in comparison to the 1965 tidal ranges. The actual situation, presented in scenario T0, leads to a higher tidal range than scenario T1. In Antwerp the increase in tidal range from 1965 is calculated at around 40 cm. Scenario T2, in which the dredged material is extracted from the system, results in an even higher tidal range. The increase in tidal range has consequences for ecology, safety against flooding and navigational access, as pointed out in section 2. Note that in reality the maximum tidal range is located 20km upstream from Antwerp, whereas the model shows a maximum somewhere between Bath and Antwerp. This is believed to be a model artefact because the bed upstream from Antwerp is kept constant in the model at the level in the 1960's, while in reality it has deepened. The results should therefore be interpreted carefully.

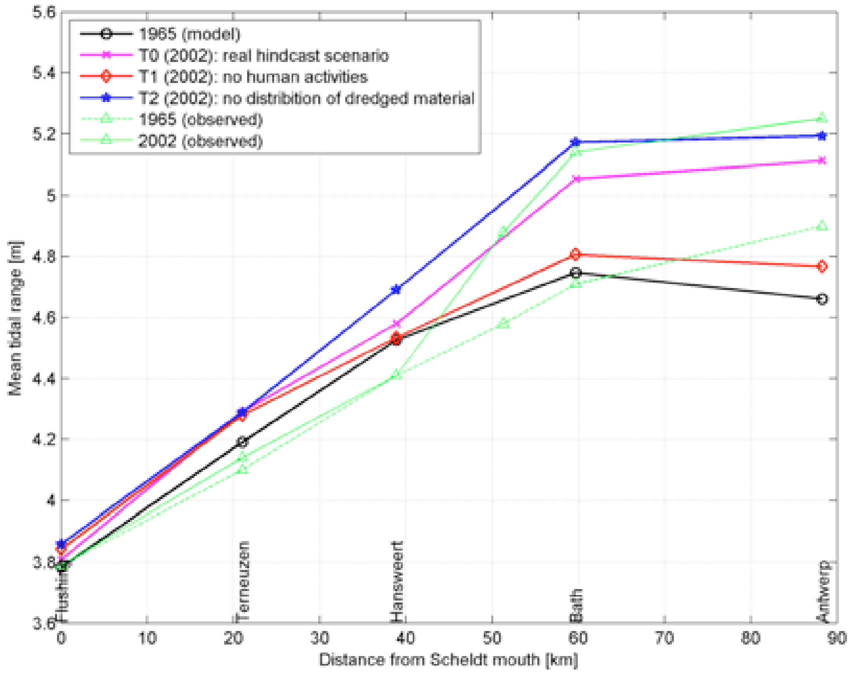

Figure 9. Mean tidal range for the three scenarios and observed tidal range in both 1965 and 2002.

The average phase difference of the tide compared to Flushing is given in Figure 10 for both the model results as the observed phase differences. Figure 10 shows that the calculated phase difference in Antwerp in Scenario T0 increases with approximately 20 minutes compared to the 1965 scenario. This corresponds with the observed tidal celerity increase in Antwerp of 15- 20 minutes of both the high and low waters (Plancke et al., 2012). This is not shown in Figure 10 as this absolute phase difference compared to Flushing was not available. In the western part the effect on the phase difference is minimal from 1965 to 2002 in both the model as the observed phase difference. In Bath the effect on the phase difference between 1965 and 2002 begins to be clear in both the model as the observations and is further increased towards Antwerp.

In the western and middle part of the Western Scheldt, the phase difference in scenario T1 slightly decreases with respect to scenario T0. This corresponds with the observed phase differences over this period. The largest impact can be seen in the eastern part of the Scheldt, from Bath to Antwerp. Scenario T1 shows a small increase in tidal celerity. The largest effect however has Scenario T2; compared to the actual scenario T0, a further 15 minutes increase in tidal celerity can be seen.

This leads to the conclusion that human activities in the Western Scheldt have influenced the tidal range and celerity in the estuary. The extreme scenarios indicate a band width in Figure 9 and Figure 10 and show what could have happened if other sediment management strategies would have been applied.

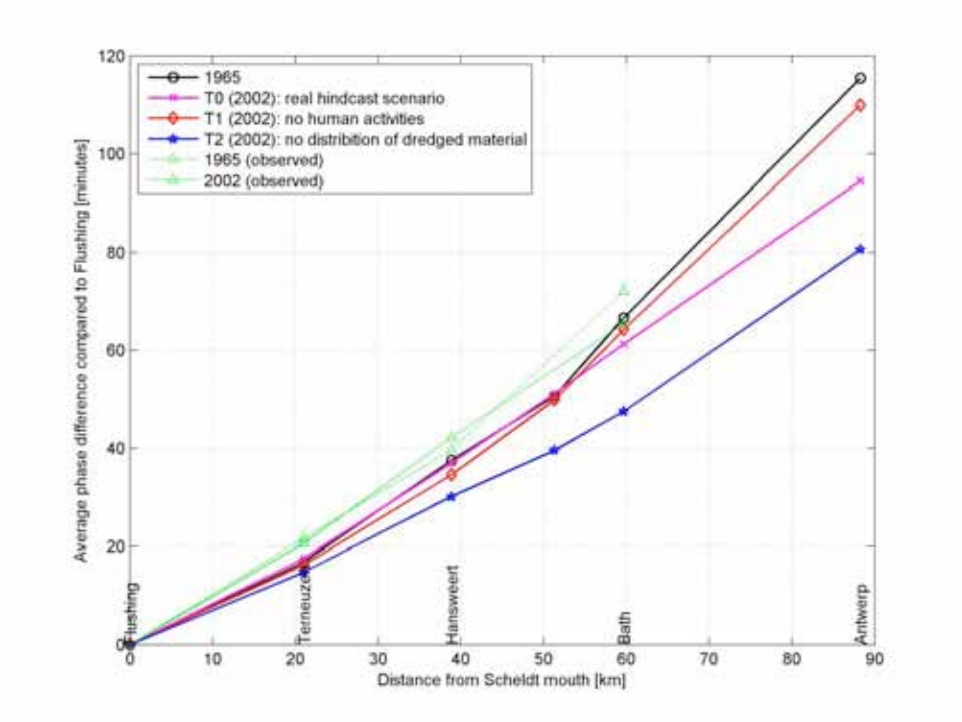

Figure 10. Phase difference for the three scenario's in 2002

Table 3: Inter tidal area in 2002 for the 3 scenarios

	Intertidal area (higher than -2m MSL)	Difference with T0
T0: real hindcast scenario	7560 ha	
T1: no human activities	7410 ha	-2%
T2: no distribution of dredged material	6840 ha	-10%

In Table 3 the inter tidal area in 2002 is given for the three scenarios (although it is known that the low water varies in the estuary, inter tidal area is for simplicity reasons defined as the area above -2m NAP, which is approximately MSL). The T0 scenario shows the highest amount of inter tidal area. Interestingly the T1 scenario (without human activities) shows a decrease of 2% of inter tidal area. The T2 scenario shows a larger decrease of 10% inter tidal area in comparison to the T0 scenario. This leads to the conclusion that the distribution of dredged material, which is only present in scenario T0, results in more inter tidal area in the model. As a result the hypsometry of the Western Scheldt steepens as a result of a deepened navigational channel and more inter tidal area. Waves, which have been neglected in the model, do have a morphological influence on the inter tidal area, so this conclusion should therefore be interpreted carefully.

5 CONCLUSIONS

The presented FINEL2d morphodynamic model of the Western Scheldt estuary shows that a realistic hindcast of the sea bed development in the estuary can be made over a period of decades (1965-2002). Good agreement is found in overall patterns, although many differences can be seen in detail. By investigating two 'extreme' scenario's (no human activities on the one hand, and removal of all dredged material from the estuary on the other) it is demonstrated that human interference has had a significant influence on the morphology and tide of the estuary during this period.

The model shows that due to the historical human interference of dredging, distribution and sand mining, the channels have deepened and the tidal flats have increased, by which the Western Scheldt probably has become steeper over the 1965-2002 period. The results also show significant effects on the propagation of the tide in the estuary. Due to the actual human activities over the past decades the tidal range in the estuary has increased by about 0.4m in Antwerp and advanced the propagation of the tide with approximately 20 minutes. This corresponds to the advancing of the tide which has been noticed in Antwerp over the past decades. The extreme scenario where all dredged material was taken out of the estuary shows that the process of increasing tide levels in the estuary may continue in case that the human activities are intensified.

The FINEL2d morphodynamic model of the Western Scheldt estuary has proven to be able to calculate the erosion/sedimentation pattern fairly accurate over several decades, while computation time is limited. Computational time for this model is 1.5 hour per morphological year on a 16 core 2.64 GHz machine. This makes the model a useful tool for decision making processes, especially when it is used to compare different scenario's to each other. In this way the calculated sea bed developments and changes in tide are considered relative to the autonomous development, which makes the results more outspoken and more reliable.

6 ACKNOWLEDGEMENTS

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