Model validation for the evolution of intertidal areas in the Western Scheldt

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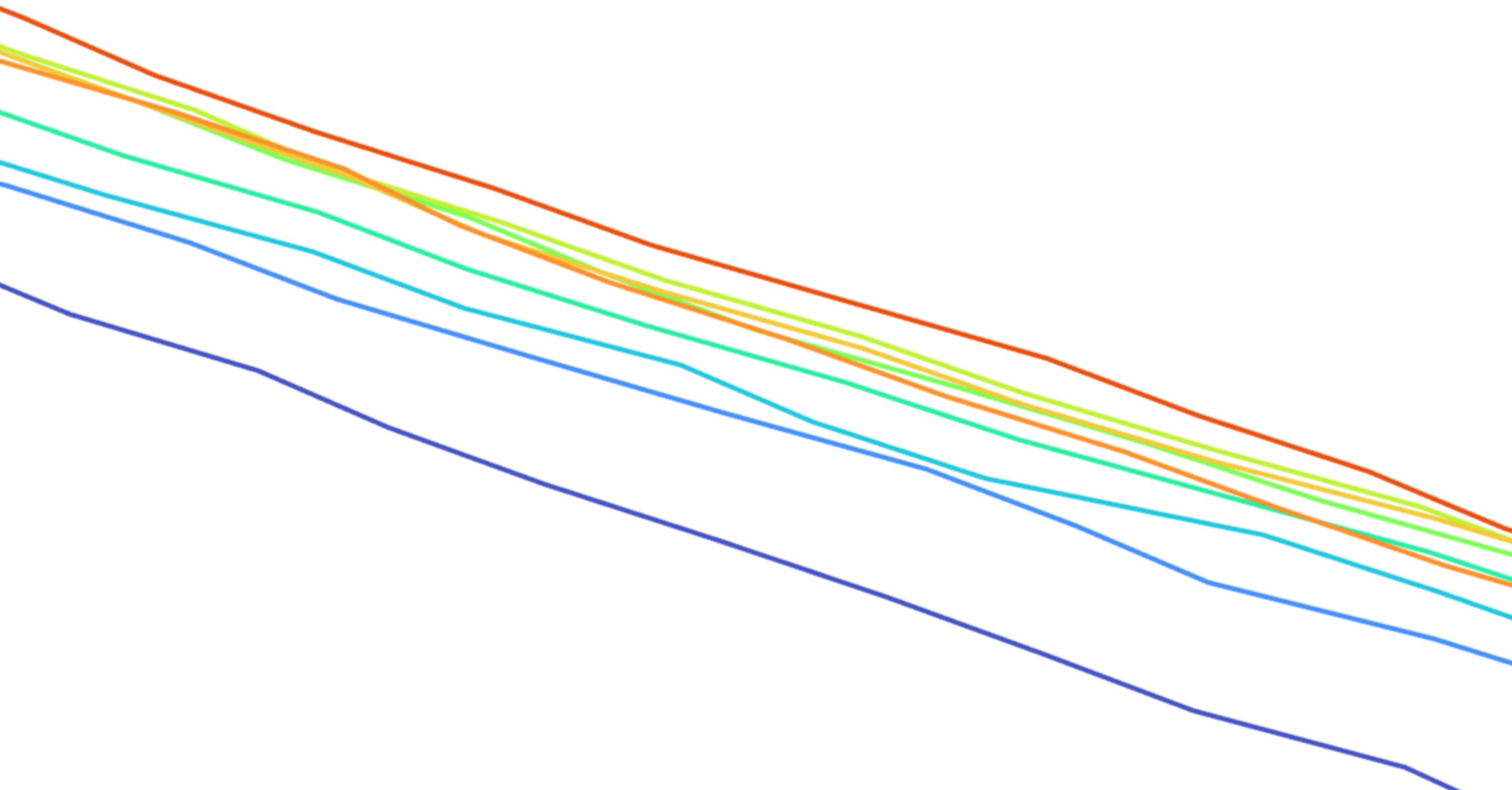
Delft, June 2024

University of Twente

Deltares



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Cover graphic: Detail of hypsometric curves of the intertidal area in the Western Scheldt

Preface

With this report, discussing the evolution of intertidal areas in the Western Scheldt, I am concluding my Bachelor's degree in Civil Engineering. In my thesis, I compare measurement data and modelling results, to get insight into a Delft3D model's skill to describe how intertidal regions have developed over the past decades. As sea level rise threatens these areas, I hope this study can contribute to maintaining ecologically healthy flats and marshes.

I have carried out this thesis at the Applied Morphodynamics Department of Deltares. Since the location of the office is in Delft, I lived in a new city for the short duration of my thesis. Having most of my social life in Enschede, this resulted in a lot of travelling at the weekends. However, I have enjoyed being in the office a lot, connecting with researchers from Deltares and discussing interesting topics with (quite a few) other like-minded interns and graduate students.

For the opportunity to work in a professional environment, I want to thank Mick van der Wegen, my external supervisor at Deltares who provided the assignment. Besides that, I would like to thank Mónica Aguilera Chaves, for the feedback and ideas, and the regular discussions. Furthermore, I want to thank Jebbe van der Werf, my internal supervisor from the University of Twente, who supported me a lot with the scientific side of my research.

I hope you enjoy reading this report. If there are any topics from my thesis you would like to discuss, feel free to approach me.

Lars Paternotte

Delft, 20 June 2024

Summary

The Western Scheldt is an estuary located in the southwest of the Netherlands. Ecologically valuable intertidal areas are found between the channels and fringing along the shore. These areas can be divided into flats (*Dutch: platen*) and marshes (*Dutch: schorren*). Sea level rise threatens the intertidal regions, as the size of this area might decrease with increasing water levels.

The research institute Deltares developed a Delft3D (process-based, numerical) model to forecast the morphological evolution of the Western Scheldt with global sea level rise of up to 2.63 m from 2020-2100. However, the model's skill to predict the development of the intertidal region was uncertain. To study this, hindcasts were done from 1964-2012 using the same model. In this study, the hindcast results are compared to bathymetric data from measurements by Rijkswaterstaat.

This report presents an analysis of the differences between the model results and measurement data. The development of the intertidal areas is compared on two spatial scales. First for the total area spanning from the mouth near Vlissingen to the east near Bath, and secondly for the same area split up into western, middle and eastern parts. Measured water level data in the estuary for 1965-2010 is considered to determine the intertidal range. Bed levels are studied from approximately mean low water during spring tide to mean high water during spring tide. Since the difference between low and high water, the tidal range, increases eastward and varies over time, the bed level boundaries of the intertidal zone vary in the analyses.

The results show that the model underestimates the total intertidal area both with and without including wave modelling. Besides that, the average height of the intertidal area is also underestimated, except for 2010. In both cases, the hindcast results with waves are generally closer to the bathymetric data than without waves. On average, the no-wave hindcast underestimates the total intertidal area with 8.6 million m^2, which is 12%. This hindcast underestimates the average bed level height with 15.1 cm on average. For the wave hindcast, this is 7.0 million m^2 (10%) for the total intertidal area, and 12.9 cm for the average bed level height. In contrast, the shapes of hypsometric curves of the intertidal area based on the hindcast without waves are more similar to the measurements than those based on the wave hindcast. On a smaller spatial scale, changes to the intertidal area over time are more pronounced in the model results than in the measured data.

Since the model results show comparable trends in the development of the Western Scheldt's intertidal region as the measured data for 1965-2010, the Delft3D model seems applicable for predicting the evolution of intertidal areas. However, model assumptions, particularly for dredging and dumping activities, limit the accuracy of the hindcasts.

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1 Introduction

1.1 Background

The Western Scheldt is an estuary in the southwest of the Netherlands, where the Scheldt River flows into the North Sea. Since it is an open connection to the sea, the Western Scheldt is subject to tidal variations in the water levels. As a result, intertidal areas are found in the estuary. These areas are submerged at high tide and exposed at low tide. In the Western Scheldt, intertidal areas are found along the shoreline and between channels. The intertidal areas form habitats for ecologically valuable flora and fauna, such as shellfish and migratory birds (De Vriend et al., 2011; Monbaliu et al., 2014). However, research suggests that sea level rise (SLR) poses a threat to intertidal areas (e.g. Elmilady et al., 2019; Van Der Wegen, 2013), as the size of these regions might decrease with increasing water levels. The degeneration of ecologically valuable intertidal areas is the reason to study the evolution of these regions. Moreover, if the effects of sand mining and different dredging and dumping strategies are known, measures can be taken to protect the intertidal areas.

It is uncertain what the effect of (extreme) SLR of up to 2.63 m worldwide would be on intertidal area development in the Western Scheldt. Research institute Deltares developed a process-based numerical model in Delft3D to investigate this. The model is called the Delft3D-Scheldt-SLR model and was also used in a study by Röbke et al. (2020) on the effect of different sediment management strategies on the morphological evolution of the Western Scheldt. To support the report by Röbke et al. (2020), this study aims to validate the model's ability to reproduce the evolution of the intertidal areas from 1965-2010. This is the period for which morphological hindcasts are available for the estuary. Evaluating the model's capability to predict the evolution of intertidal regions under future SLR, is out of the report's scope.

This study builds on a comparison of the evolution of the intertidal flats in the Eastern and Western Scheldt by De Vet et al. (2017), in which the changes of the hypsometry and slope of individual intertidal flats were studied. In contrast, this study is concerned with the hypsometry of the total intertidal area of the Western Scheldt and groups/regions of intertidal areas. Since individual intertidal flats migrate and merge over time, it is difficult to characterise them individually in both the measurements and the model results. Besides that, this report compares the hypsometries of the intertidal area for a larger timescale, i.e. between 1965-2010 compared to 2001-2013 in the study by De Vet et al. (2017).

1.2 Research aims and questions

This study aims to determine the differences between measured bathymetric data and two hindcasts by the Delft3D-Scheldt-SLR model in the intertidal area development of the Western Scheldt between 1965-2010. The conclusions of the report contribute to validating the model. Moreover, they help to understand the development of intertidal areas in the Delft3D-Scheldt-SLR model compared to measured bathymetric data from Rijkswaterstaat.

To achieve the research aim, this study has the following research questions:

- What are the main differences between measured bathymetries and computed bed levels for the intertidal areas of the Western Scheldt?
- What is the effect of including wave modelling on model outcomes on the evolution of intertidal areas?

1.3 Approach

To answer the questions, the report compares hypsometries based on measured bathymetries and water level data in the Western Scheldt with model results from two hindcasts for 1964-2012. The studied hypsometric curves describe the size and shape of the intertidal area for different years. For the comparison, the following steps were carried out:

- Define suitable areas for comparison of the measured bathymetric data with the model outcomes. It is necessary to define study areas which can be compared for the whole study period since the location of intertidal areas has changed over time.
- Study the definition of the (inter)tidal range. Since the tidal range varies spatially throughout the estuary and temporally throughout a spring-neap cycle and over decades, the intertidal bed levels also vary.
- Study the effect of the inclusion of waves in the model. The hindcast of the model is performed both with the inclusion of waves and without. These results are compared to determine if the inclusion of wave modelling leads to a more accurate trend in the model's results for the evolution of the intertidal areas.

Chapter 3 provides more detailed information on the methodology.

1.4 Reading guide

This study continues by describing characteristics of the study area and intertidal areas in Chapter 2. After that, the methodology used to compare the modelled data with the measurements is explained in Chapter 3. Consequently, Chapter 4 presents the comparison's results. The discussion of the results in Chapter 5, and the conclusions and recommendations in Chapter 6 are the final parts of the core of this report.

2 Study area

2.1 General description

The Western Scheldt has a length of about 95 kilometres and forms the lower estuary of the Scheldt River. The area spans from the Dutch-Belgian border in the east to the mouth of the Scheldt at Vlissingen in the west. The Western Scheldt is economically significant since it connects the port of Antwerp with the North Sea. Besides that, it provides ecologically valuable habitats for seabed animals, fish and birds (Van Dijk et al., 2021). Figure 1 shows an overview of the study area.

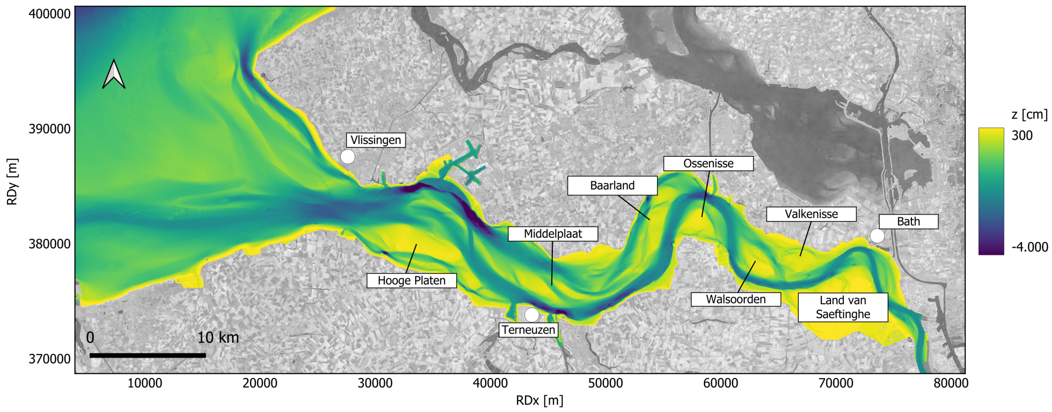


Figure 1: Overview of the study area. The bed levels are based on the bathymetry of 2020 (source: Rijkswaterstaat) and are with respect to NAP (Amsterdam Ordnance Datum, 0 m NAP is approximately the average water level of the North Sea).

The Western Scheldt is a multi-channel system consisting of ebb and flood channels. These are characterised by their shape and dominating flow; ebb channels have a residual flow in the seaward direction, often implying that sediment is transported seaward. These channels have a sill at the seaward end. Flood channels, on the other hand, have a residual flow in the upstream direction, and a sill at the upstream end (Van Veen, 1949; Vlaming, 2018). In the case of the study area, the meandering channel is the ebb channel and is dredged as the main navigation channel. Intertidal and subtidal flats separate this channel from parallel flood channels, which are straighter. The depth of the channels generally ranges between 10 and 50 meters (Elias et al., 2023).

2.2 Dredging and dumping

Until 1970, the morphology of the Western Scheldt was mostly influenced by natural forces, such as the tide and waves. Besides that, land reclamation projects altered the shoreline. After 1970, dredging and dumping (DAD) activities for the main channel's deepening and sand mining significantly influenced morphological development. Dredging activities increased the depth of the main channel to -14.5 m NAP between 1973-1976,

-16 m NAP between 1997-1998 and most recently in 2010, to a depth of -17.2 m NAP. To maintain the depth of the main channel and the harbours, annually 7-10 million m^3 is dredged. Besides that, between 1954 and 2014, 122 million m^3 of sand mining caused additional sediment losses (Elias et al., 2023).

The dumping locations of dredged sediment have changed over time. Before 1997, sediment was disposed of in secondary channels in the east of the estuary. On the other hand, between 1997 and 2010 most of the dumping occurred in the west of the estuary, as this was deemed more durable. After 2010, a flexible disposal strategy was used, which entailed dumping on the edges of intertidal flats to preserve the multi-channel system and ecologically valuable areas (Depreiter, 2012).

2.3 Forcing and sediment composition

The bed of the Western Scheldt is subject to forcing by the tide, waves and wind. The average tidal range in the estuary is circa 3.8 meters at the mouth near Vlissingen and increases to 5 meters at the Dutch/Belgian Border (De Vet et al., 2017; Röbke et al., 2020). The highest recorded water level in the estuary was during the storm surge disaster of 1953, 4.55 m above NAP at Vlissingen, and 5.60 m above NAP near the Dutch/Belgium border at Bath, compared to a mean high-water level of 2.07 and 2.75 meters respectively. The water displacement caused by the tide, the tidal prism, is much greater than the inflow from the discharge of the Scheldt River. Therefore, the river discharge seems of lesser interest when studying the morphodynamics in the estuary (Röbke et al., 2020).

The wave climate in the estuary is mild. The average significant wave height in the Western Scheldt is approximately 0.25 m. The Vlakte van de Raan contributes to the mild wave climate. This large and shallow shoal shelters the estuary from offshore waves from the North Sea (Elias et al., 2023; Nederhoff, 2016). Besides that, waves are locally generated by wind and to a lesser degree by shipping. The main wave direction is southwest, which is also the dominant wind direction. However, the largest waves occur during north-westerly storms, because of the longer wave trajectory on the North Sea. Wind speeds are on average 5.5 ms^{-1} (Röbke et al., 2020).

Most of the sediment in the estuary consists of sand with an average grain size of 200 μm, but mud, with a grain size smaller than 64 μm, can be found upstream, at intertidal shoals and in some degenerating channels (Röbke et al., 2020).

2.4 Intertidal areas

Areas which are exposed at low tide and flooded at high tide are by definition intertidal. However, large differences exist in the occurrence of species depending on the frequency and duration of inundation. The intertidal range can therefore be divided into a littoral and supralittoral zone. The littoral zone is bounded by mean low water during spring tide (MLWS) and mean high water during neap tide (MHWN) and is thus flooded almost each tidal cycle. The supralittoral zone consists of higher areas, which are flooded less often (Bouma et al., 2005). A rough estimation based on the water levels suggests that in the Western Scheldt, the boundary between the littoral and supralittoral zone, which is MHWN, is around 190 cm above NAP in the east of the estuary (Bath), and 130 cm above NAP near the mouth (Vlissingen).

A comparable definition is used by Schepers et al. (2018) for intertidal flats (*Dutch: platen*) and intertidal marshes (*Dutch: schorren*). Intertidal flats have little to no vegetation and are flooded every semi-diurnal high tide, whilst intertidal marshes are higher, less frequently flooded areas, covered by flood-tolerant plant species. These marshes are flooded and drained by tidal creeks. In the Western Scheldt, Land van Saeftinghe (for the location, see Figure 1) is the largest intertidal marsh area. Other marshes are small and isolated, and fringe along the shoreline (De Vriend et al., 2011). Some flora and fauna are bound to a certain type of intertidal area, whilst other species use different zones for different purposes. For example, some birds forage on intertidal flats, whilst they breed on higher-laying marshes in the supralittoral zone (Bouma et al., 2005).

3 Methodology

3.1 General methodology

Bathymetries from the *Vaklodingen* dataset of Rijkswaterstaat are used to compute the measured evolution of the intertidal area in the estuary. This dataset uses a combination of single beam, multi beam and LiDAR measurements to define a 20 by 20 meters raster (De Vet et al., 2017; Elias et al., 2023). Delft3D-Scheldt-SLR model hindcasts are compared to the measured data. This is done every five years from 1965 to 2010. The Vaklodingen dataset was available from 1955 to 2022 and the hindcasts for 1964-2012, so data from 1955-1964 and 2011-2022 have been excluded from the comparison.

A MATLAB script is used to analyse the intertidal area. For direct comparison of the measured and modelled data, the bathymetries from the Vaklodingen are interpolated on the grid used by the Delft3D-Scheldt-SLR model. Section 3.7 provides more information on this method. The effect of the interpolation on the results is analysed in Appendix D. A polygon drawn along the shoreline of the Western Scheldt defines the studied area. Section 3.3 describes the construction of this polygon.

After loading the bed level data and the polygon, the script determines which raster cells are within the polygon and have bed levels within the defined study intertidal range. Then, starting with the lowest bed level within the intertidal range, the summed area of the grid cells above this level is determined, which is the total intertidal area within the studied region. A hypsometric curve is then constructed by calculating the area above a series of step-wise increasing bed levels. This way, a curve is created which shows the relation between the size of the intertidal area and the bed level.

The analysis is done on two spatial scales, i.e. for the whole Western Scheldt and separately for the western, middle, and eastern parts of the estuary. This is done by defining seperate polygons for each region. By comparing the model with the data on two scales, the impact of local differences (e.g. large differences between the model results and the data in one part of the estuary) on the total outcomes can be studied. Besides studying the hypsometric curves, the size and average bed level of the intertidal area are also compared. Lastly, the computed bed levels are compared visually to the measured bathymetries.

3.2 Uncertainty and errors in the Vaklodingen data

The Vaklodingen dataset has stochastic (random) and systematic errors (bias) in determining the bed levels. Because the stochastic errors are in both negative and positive directions, they are negligible if a relatively large area is considered (Marijs and Parée, 2004). However, the systematic error of the Vaklodingen for intertidal areas has been determined as -0.20 m (Storm et al., 1993). This means that at least until 1990, the last year considered in the accuracy study by Storm et al. (1993), the bed levels of intertidal areas have been measured lower than was the case. De Vet et al. (2017) suggests that with the inclusion of LiDAR technology from 2001 onwards, the accuracy of the Vaklodingen has improved and errors are in the order of 10 cm.

3.3 Definition of the study areas

To analyse the evolution of the intertidal areas in the Western Scheldt from 1965 until 2010, the hypsometries are studied using a time interval of five years. However, the bathymetries of the Vaklodingen are not complete for all years. From 1960 to 1995, half of the estuary was measured yearly, alternating between the eastern and western parts. Data was also missing for smaller parts of the Western Scheldt for some years. Because of the incompleteness of some bathymetries, datasets of consecutive years were combined to cover the whole estuary. An overview of the adaptations to the bathymetries of the studied years can be seen in Table 1.

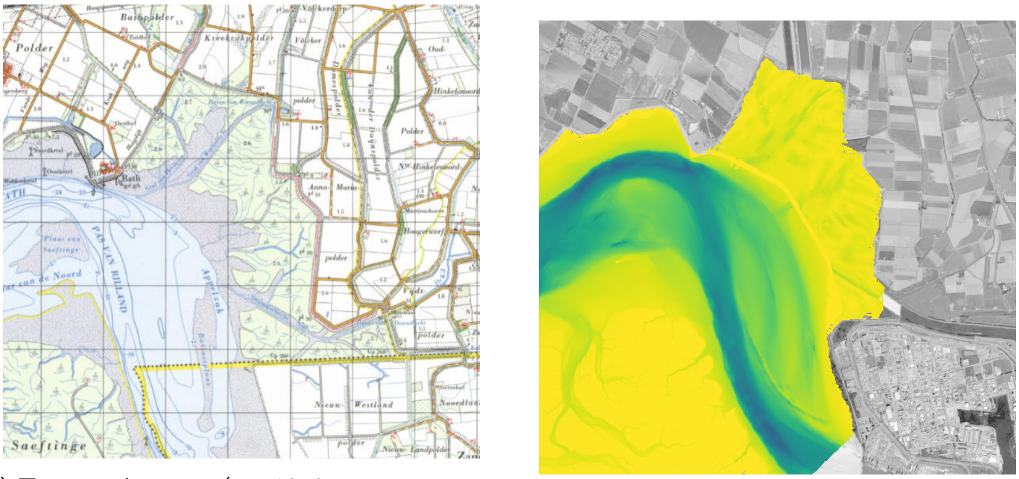
Table 1: Overview of adaptations to the bathymetries of studied years.

Year	
1965	Combined data of 1965 and 1966
1970	Combined data of 1970 and 1971
1975	Combined data of 1975 and 1976
1985	Not included, because of missing data between Vlissingen-Oost en Terneuzen between 1983 and 1987
1996	Used instead of 1995, because of the availability of a complete dataset

The Vaklodingen dataset was compared visually in QGIS to determine differences and define areas with consistent measurements for all considered years. Comparative figures which show the differences between the data of various years in the Vaklodingen are given in Appendix A. The comparison showed the following:

- From 1960 until 2010 the same area was measured, from Vlissingen to the Dutch-Belgian Border. In recent years the mouth area and part of the Western Scheldt east of Land van Saeftinghe have also been included in the data.
- Because of land reclamation and managed realignment (Dutch: ontpoldering), some areas were intertidal in the past but are now on the landward side of the embankments, and vice versa.
- After 2010, the shoreline has been included more accurately in the measurements. In the data until 2010, various areas which have been reclaimed were still included as parts of the Western Scheldt. The data was also missing some areas close to the shoreline.

An example of the last conclusion is the Bathse Schor, a former intertidal area in the east of the estuary reclaimed in the early 1970s. The Bathse Schor in 1970 can be seen in Figure 2. This area is still visible in the data of 2010, although the area has been reclaimed and the Scheldt-Rhine Channel was created (notice the yellow line of the dyke and the misalignment with the satellite image in Figure 2b).



(a) Topographic map (ca. 1970, source: topotijdreis.nl).

(b) Vaklodingen data 2010.

Figure 2: The Bathse schor in 1970 and 2010: The (former) intertidal area is still visible in 2010, although the dyke (solid yellow line) shows the real shoreline.

Because of the differences between different years and errors in the used dataset, the polygons are defined in such a way that data is present for all studied years. Besides that, the Land van Saeftinghe is excluded, since the measured data for this region contains errors (Elias et al., 2023). The polygon in Figure 3 defines the total study area of the Western Scheldt.

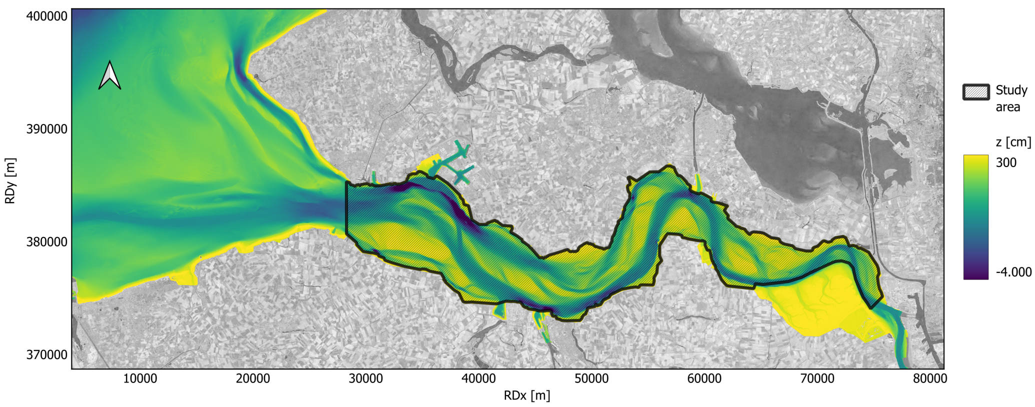


Figure 3: The studied polygon of the Western Scheldt. Some areas close to shore, as well as the Land van Saeftinghe, have been excluded from the study.

Studying the behaviour of intertidal areas on an individual scale is difficult because of their migratory nature. In the past sixty years, intertidal areas have merged and separated over time. Therefore, the study areas for the western, middle, and eastern parts of the estuary are defined using the main navigation channel. Since dredging activities prevent channel migration, it forms a border over which the intertidal areas have not migrated in the measured data from 1965-2010. The polygons can be seen in Figure 4.

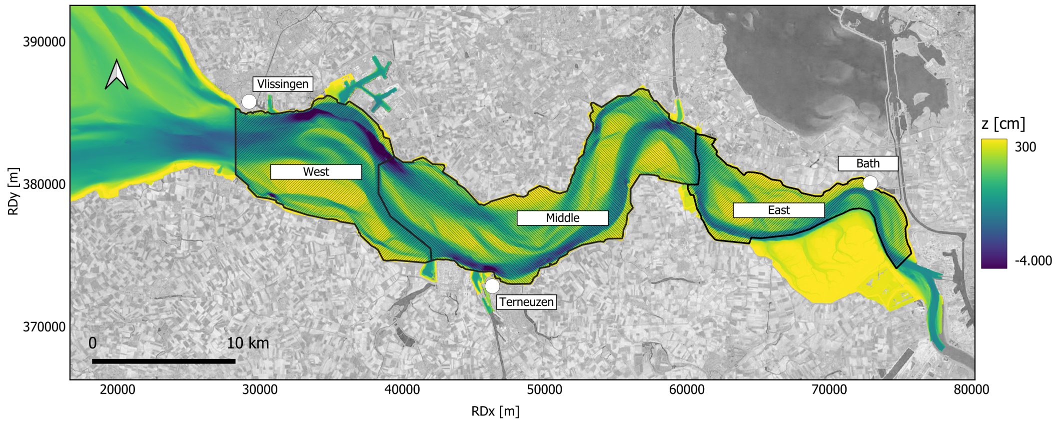


Figure 4: The three different study areas for the western, middle and eastern parts of the Western Scheldt.

3.4 Definition of intertidal range

Different definitions of the intertidal range can be used to determine the studied bed levels. The tidal range varies throughout the year, and, consequently, so do the bed levels submerged at high tide and exposed at low tide. The variations in the tidal range have both periodic causes, such as the spring-neap tidal cycle (about 28 days) and the nodal tidal cycle (18.6 years), and random causes such as storms. Besides that, because of the narrowing estuary, the tidal range in the Western Scheldt increases from the mouth area to the east of the estuary. As a result, an increasingly large range of bed levels can be considered intertidal towards the east of the Western Scheldt.

Logically, if the intertidal range is chosen larger, the intertidal area also increases. Therefore, the effect of three different definitions of the intertidal range has been studied. These were the intertidal ranges based on the mean high water and mean low water and for the 50% and 30% highest high water and lowest low water levels, for each considered year, at different measurement stations in the Western Scheldt (source: Rijkswaterstaat). The ecological definitions mentioned in Chapter 1 have not been analysed further.

A comparison of the definitions showed that the 50% and 30% margins excluded the high and low water levels during neap tides. Since the averages of the 30% highest high waters and lowest low waters are more influenced by extreme events such as storms, for this report the bed levels between the averages of the 50% highest high waters and lowest low waters are chosen as the intertidal range. The neap tides are excluded, so the used water levels are comparable to MHWS and MLWS and thus include both the littoral and supralittoral zone (see section 2.4). Further analysis of the water level data from Rijkswaterstaat and the effect of the intertidal range on the intertidal area and the hypsometries can be found in Appendix B.

To account for the increasing tidal range towards the east of the estuary, linear interpolation is used from the average 50% highest high and lowest low water levels in Vlissingen near the mouth to those of Bath in the east of the estuary (see e.g. Schepers et al., 2018, Fig. 17.4: The tidal range in the Western Scheldt increases almost linearly from Vlissingen to Antwerp). As a result, a different intertidal range is used for each x-coordinate of the study grid. This is done for each year, so the tidal range varies both spatially and temporally.

For the hypsometric curves, a step size of 20 cm is chosen for the considered bed levels. Therefore, the step size is similar to the systematic error in the dataset as described in Section 3.2. The sensitivity of the curves to smaller and larger step sizes has been studied. A comparison can be found in Appendix D.

3.5 Model description

The hypsometries, size and average height of the intertidal area based on the interpolated Vaklodingen data are compared with those based on two hindcast runs by the Delft3D-Scheldt-SLR model. This model is based on the validated and calibrated Delft3D-NeVla Model by Van Der Wegen et al. (2017). More detailed information on the setup of the model can be found in Appendix E.

In one of the hindcasts, waves have been included in the model, whilst in the other hindcast, the model is run without waves. In the wave model, a constant wave and wind field generate the waves. Table 2 gives an overview of the applied wave conditions. These conditions are based on offshore measurements at the Schouwenbank buoy station (Röbke et al., 2020). Because of the shallow Vlakte van de Raan in the mouth of the estuary, the waves enter the estuary at a lower height.

Table 2: Conditions applied in the wave hindcast (Röbke et al., 2020).

Parameter	**Average value**
Significant wave height H_{s}	1.41 m
Peak wave period T_{p}	6.5 s
Mean wave direction θ_{m}	292°
Wind speed V	5.5 ms^{-1}
Wind direction W	261°

Röbke et al. (2020) and Zheng et al. (2021) suggest that including waves in modelling has limited impact in describing general morphological developments in the Western

Scheldt. Nevertheless, Röbke et al. (2020) mention that it might contribute to accurately describing the evolution of intertidal areas.

In both model configurations, sand mining and dredging and dumping activities have been included. The effect of SLR on the water levels is assumed to be negligible from 1964 to 2012. Therefore the modelled morphodynamic changes do not take into account SLR.

3.6 Comparison of the measurements and the model

The water levels used to define the intertidal range are the same in the model as in the measurements. The analysed bed levels vary over time and space, based on the water level data from Vlissingen and Bath as elaborated upon in section 3.4. However, for the simulation, the model uses water levels based on one year of astronomical data. Therefore, the defined intertidal range does not correspond exactly with the intertidal range in the model simulations.

Bed levels are extracted from the hindcast with time steps of approximately one month. For years with complete data in the Vaklodingen, the modelled bed level data in the middle of the year is used in the comparison. If the bathymetry based on the Vaklodingen combines two consecutive years, the last modelled time step from the first year is used in the comparison (e.g. the modelled bed levels of December 1965 are used for comparison with the combination of the measured bathymetry of 1965 and 1966).

3.7 Interpolation on the Delft3D flow grid

The data from the Vaklodingen is interpolated on the flow grid used by the Delft3D-Scheldt-SLR model for direct comparison with the data from the model runs. This method reduces the runtime to determine the hypsometries and makes it possible to use the same linear interpolation of water levels in the estuary as in the analysis of the hindcasts. The model grid is based on the grid used by Van Der Wegen et al. (2017) for hindcasting the morphodynamics of the mouth of the Western Scheldt. The interpolation is done by importing the bathymetries in Delft3D version 4, using triangular interpolation in the QUICKIN tool. The interpolated depth files for each year are then used as input for the MATLAB script which calculates the hypsometric curves of the intertidal area.

The resolution of the flow grid increases from the North Sea boundary to the tributaries and is typically 200 m by 100 m in the estuary itself (Röbke et al., 2020). The resolution is therefore approximately a factor of ten smaller than the resolution of the Vaklodingen dataset. The lower resolution of the interpolated data results in about 3% less intertidal area than in the original data (see Appendix D).

4 Results

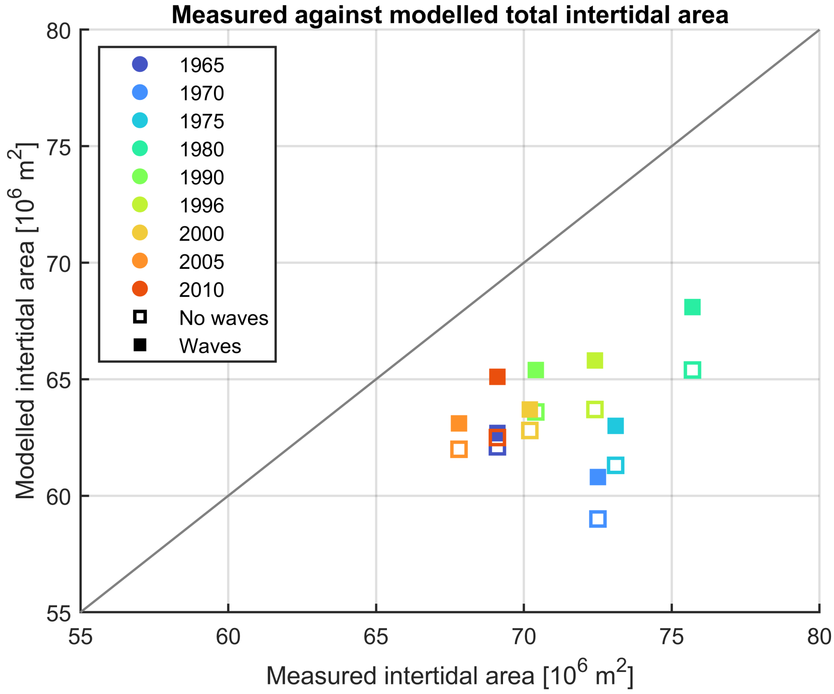
In this chapter, the general results are presented first. Afterwards, a comparison of the hypsometric curves in the measurements and both hindcasts is done for the total intertidal area in the Western Scheldt. Then the local results for the western, middle and eastern parts are shown. For the visual comparison, only the bathymetry in 2010 for the no-wave hindcast is considered. The wave hindcast shows similar trends, but in the no-wave hindcast, these trends are more pronounced and therefore more easily visualised. The resulting bed levels for 2010 in the wave hindcast are added in Appendix C, Figure 22a.

4.1 General trends

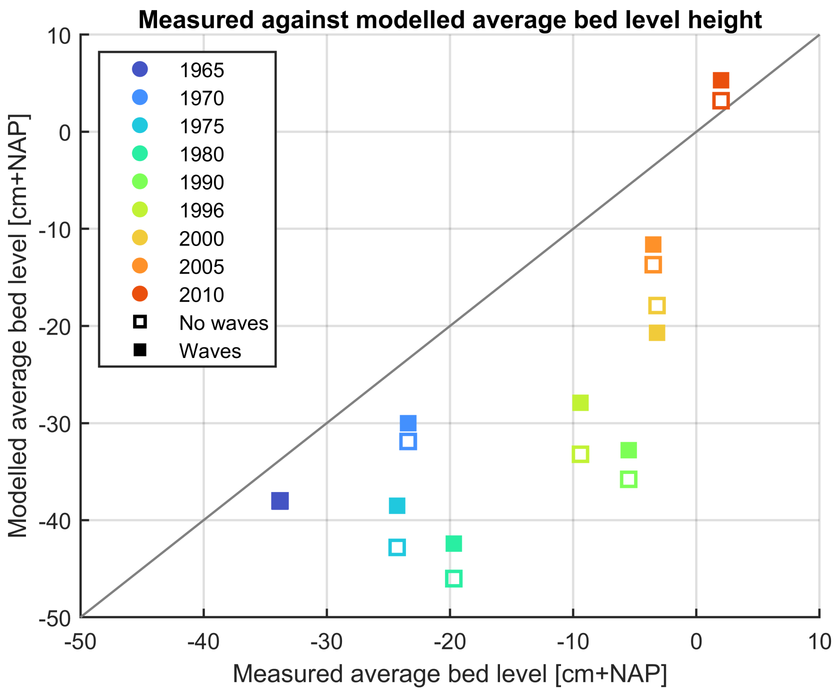
Figure 5a shows that the total area is closer to the measured data in the wave run than in the no-wave run. The same holds for the average bed level height in Figure 5b. The wave hindcast underestimates the total intertidal area with an average of 7.0 million m^2, which is 10%. In the no-wave hindcast, the average underestimation is 8.6 million m^2, equal to 12%. The average bed level of the intertidal area is underestimated by on average 15.1 cm in the no-wave hindcast, compared to 12.9 cm in the wave hindcast.

Figure 5b shows a gradual rise of the intertidal area in the measurements, as the average bed level increases from 1965 to 2010. This trend is reproduced in both hindcasts. Only in 2000, the average bed level height is higher in the no-wave model than in the wave model. Both models generally underestimate the total intertidal area and the average bed level height. However, for 2010 both the wave and the no-wave model overestimate the average bed level height.

Figure 5a also shows that the size of the intertidal area fluctuated over the years. From 1965 to 1980 the size increased, but from 1980 to 2010 it fluctuated, and in the end, decreased. However, the average bed level height gradually increased. This suggests that the profile of the intertidal areas has become steeper since 1980. The fluctuation of the total intertidal area was also noticed by De Vriend et al. (2011) and the steepening corresponds with findings from De Vet et al. (2017).



(a) Measured compared to modelled total intertidal area



(b) Measured compared to modelled average bed level height

Figure 5: Comparison of the measured and modelled total intertidal area and average bed level height for each year. The vertical distance from the square to the line shows the difference between the measurements and the hindcast results.

4.2 Vaklodingen dataset

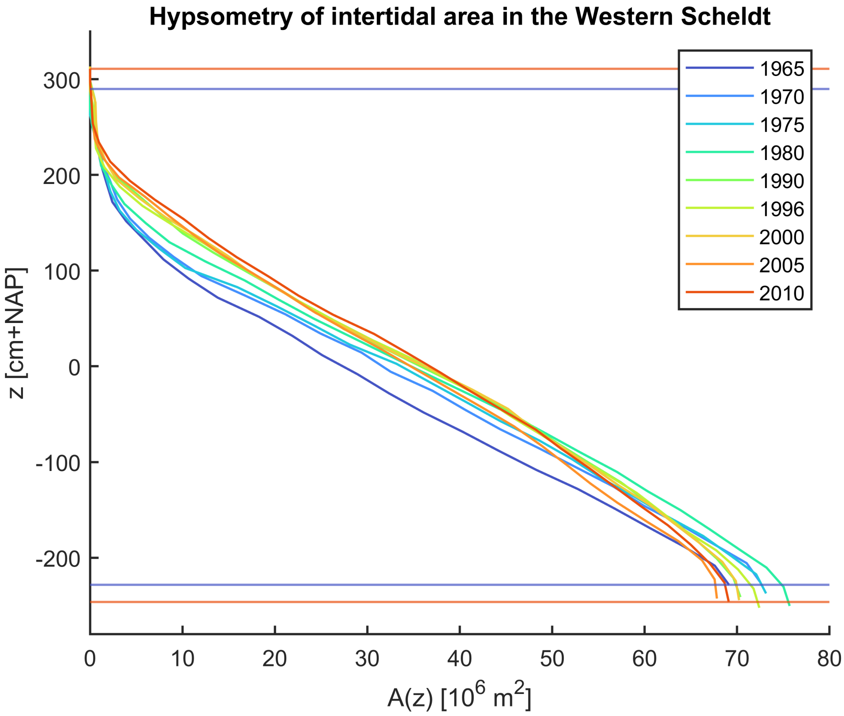
The analysis of hypsometries based on the Vaklodingen dataset in Figure 6a visualises the increase in the height of the intertidal areas over the past 60 years, which is most clear for the area above -100 cm NAP. The fluctuating size of the intertidal area can be seen at the end of the curves, as the total area increases from 1965 (dark blue) to 1980 (turquoise), but then decreases again (orange, red).

The slope of the curves steepens above 200 cm NAP and below -200 cm NAP. This is partly caused by the spatially varying intertidal range used in the analysis. Near Bath, the intertidal range is larger than near Vlissingen. Bed levels above approximately 250 cm NAP and below -200 cm NAP are thus only considered intertidal in the east of the estuary near Bath. As a result, the difference between the size of the intertidal area above e.g. -220 and -200 cm NAP is small, leading to a steeper slope in the hypsometric curves. Besides that, there is little area above 250 cm NAP in the Western Scheldt besides Land van Saeftinghe, which is not included in this analysis.

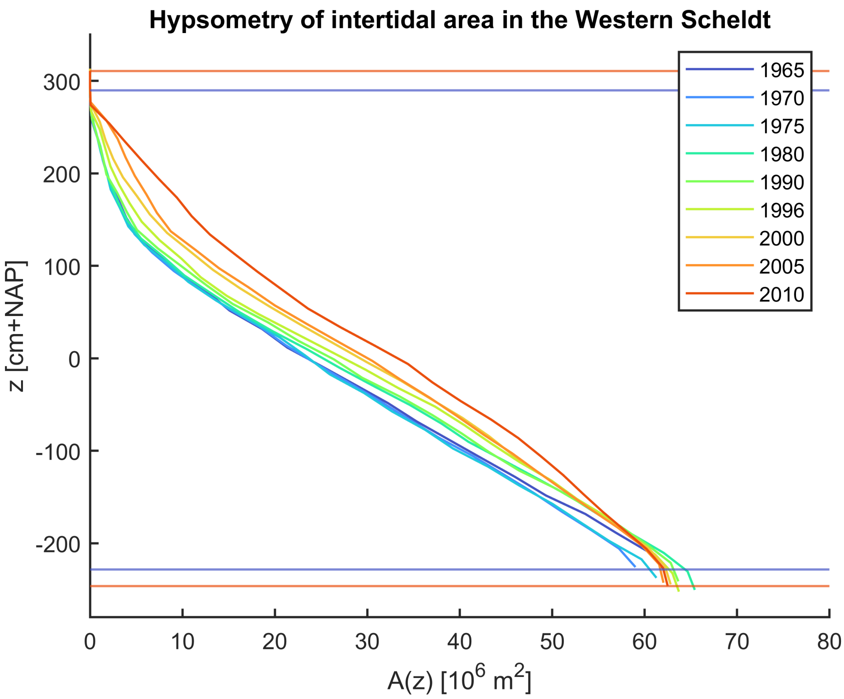
4.3 Model results (no waves)

In the model results for the no-waves hindcast run, as visualised in Figure 6b, the total intertidal area is underestimated. However, the increase in height of the intertidal areas is visible in the hindcast. For 2010, the model seems to overestimate this increase, since the difference between 2005 and 2010 is larger in the model results than in the measurements.

Generally, the hypsometric curves have a similar shape as in the measured data. The most noticeable difference in the shape of the hypsometric curves is the increasing slope at the areas above 100 cm NAP. The hypsometric curves from Vaklodingen dataset show an increasingly gradual trend over time (compare the slope above 100 cm NAP from 1965 and 2010 in Figure 6a with those of Figure 6b). However, in the hindcast, this trend is less visible.



(a) Vaklodingen dataset



(b) No-wave model results

Figure 6: Comparison between the hypsometric curves based on the Vaklodingen dataset and the no-wave model results for 1965-2010. The horizontal lines show the intertidal zone near Bath for 1965 (blue) and 2010 (red).

4.4 Model results (waves)

Figure 7b shows the hypsometries of the intertidal area based on the model's hindcast with the inclusion of wave modelling. The total intertidal area is consistently slightly larger than the model run without waves, but still smaller than based on the Vaklodingen dataset (compare with Figure 7a). The increase in the slope of the curves near 100 cm NAP moves over the years towards lower bed levels and is more pronounced than in the no-waves hindcast.

4.5 Local results

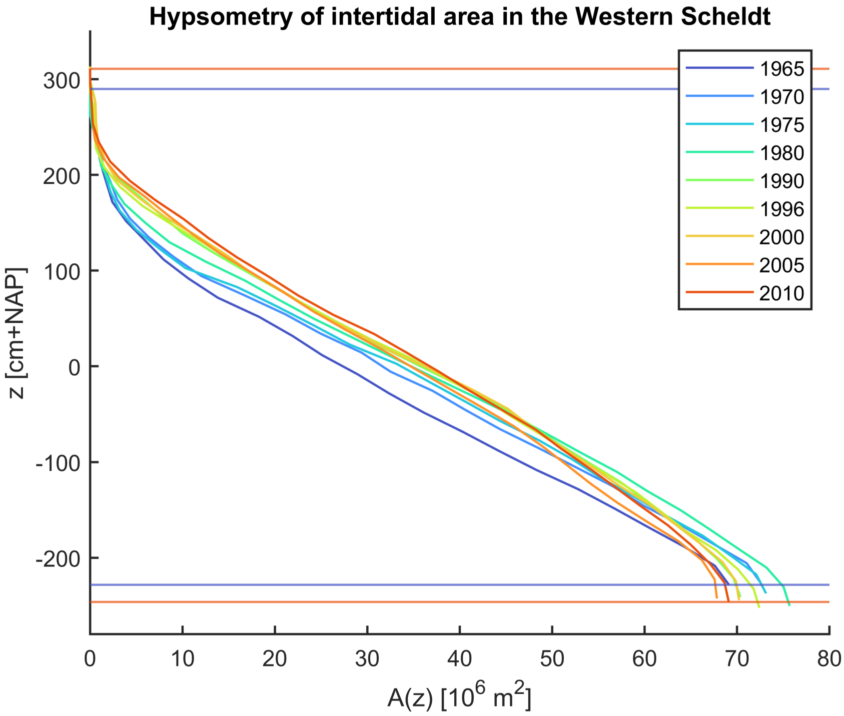
Figure 8 provides an overview of the hypsometric curves of the intertidal areas in the western, middle, and eastern parts of the estuary. The local hypsometries based on the Vaklodingen, as visible in Figure 8a, show that the intertidal area in the middle part of the Western Scheldt has decreased over the last 60 years, whilst the area in the eastern part increased in both size and height. In the west, the total intertidal area has remained relatively constant but increased in height.

Although the data suggests few changes in the hypsometry of the intertidal area in the western part, the waves model results in Figure 8c show a decrease from 1965 to 1980, followed by a large increase from 1980 to 2010. The size of the western intertidal areas also increases in the no-waves hindcast. This increase is visible in Figure 8b. Besides that, the concave of the curve in the areas above approximately 0 cm NAP is downwards in both hindcasts, while in the measured data it is upwards. Moreover, in the wave hindcast, the slope of the curve decreases between 0 cm and 100 cm NAP, after which it increases again. The curve based on the Vaklodingen is more gradual.

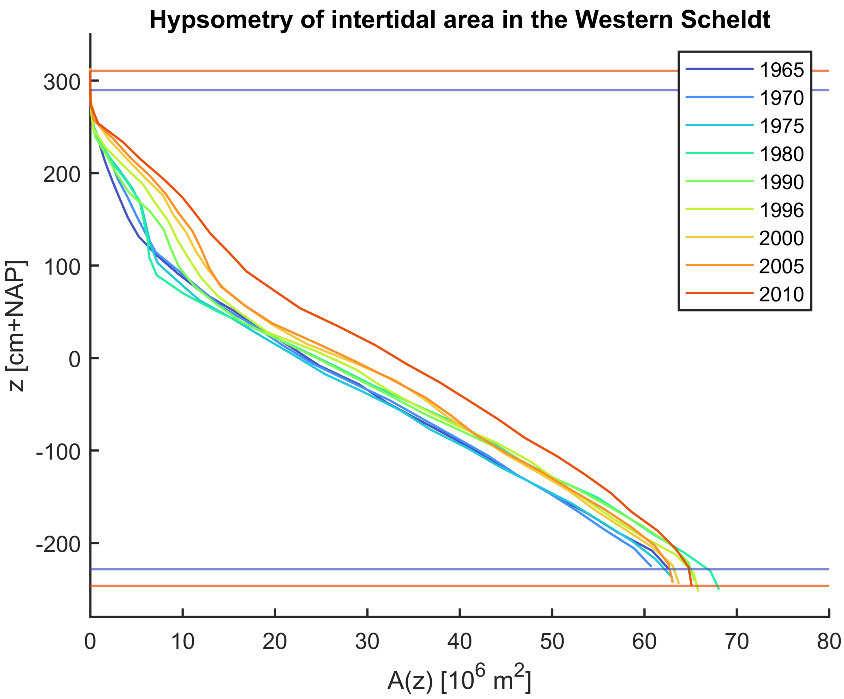
The main difference in the visual comparison of 2010 data shown in Figure 9 is the shape of the northeastern part of the Hooge Platen, as the model results show a supralittoral region. This region is not seen in the measurements.

The trend in the total area in the middle part of the estuary is similar to the original data in both model runs, as all suggest that the area decreased over time. However, the steepness of the hypsometric curves gradually increases in the hindcasts, which indicates an increase in the steepness of intertidal areas. This is more pronounced in the wave model than in the no-wave model. In the measurements, the increasing steepness is also visible, but to a lesser degree.

Compared to the measurements, the shoal of Baarland has migrated more towards the south in the hindcast, as visible in Figure 10. Besides that, close to the channel, the height of the intertidal area along the shore southwest of Baarland is over-predicted in the model.



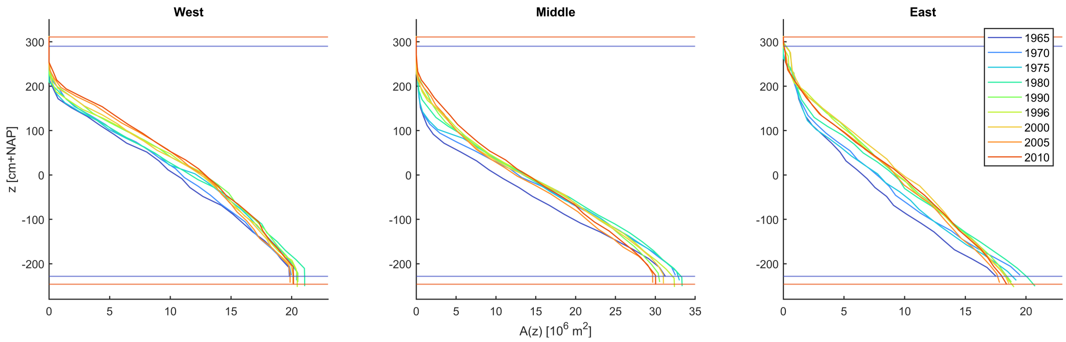
(a) Vaklodingen dataset



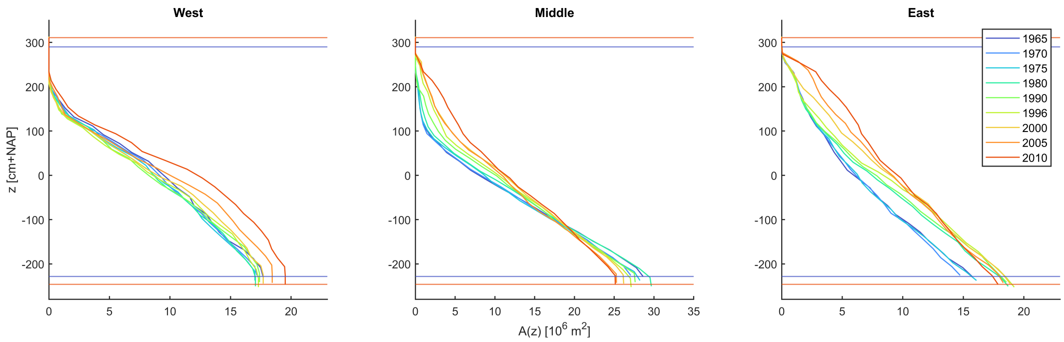
(b) Wave model results

Figure 7: Comparison between the hypsometric curves based on the Vaklodingen dataset and the wave model results for 1965-2010. The horizontal lines show the intertidal zone for 1965 (blue) and 2010 (red).

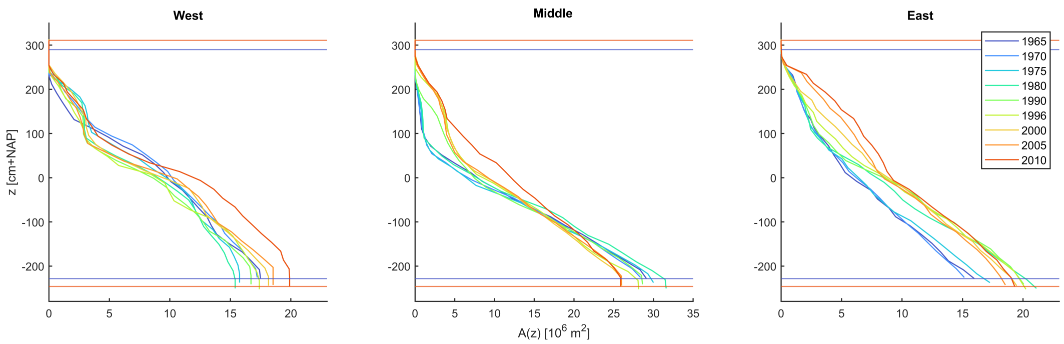
In the eastern part of the Western Scheldt, the total intertidal area in 2010 is comparable to the measured data in both hindcasts. However, the model suggests an increase between 1996 and 2005 in the waves model (Fig. 8c), which does not correspond to the data. Besides that, the slope of the hypsometric curve decreases until 1990, before it strongly increases again, especially in the areas above 0 cm NAP. This trend is not seen in the Vaklodingen dataset in Figure 8a, as it suggests a relatively constant slope over all years over the intertidal area.



(a) Vaklodingen dataset



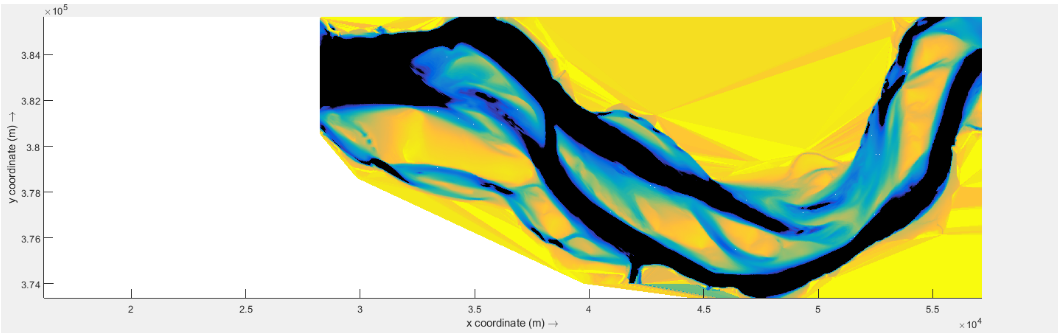
(b) No-wave model results



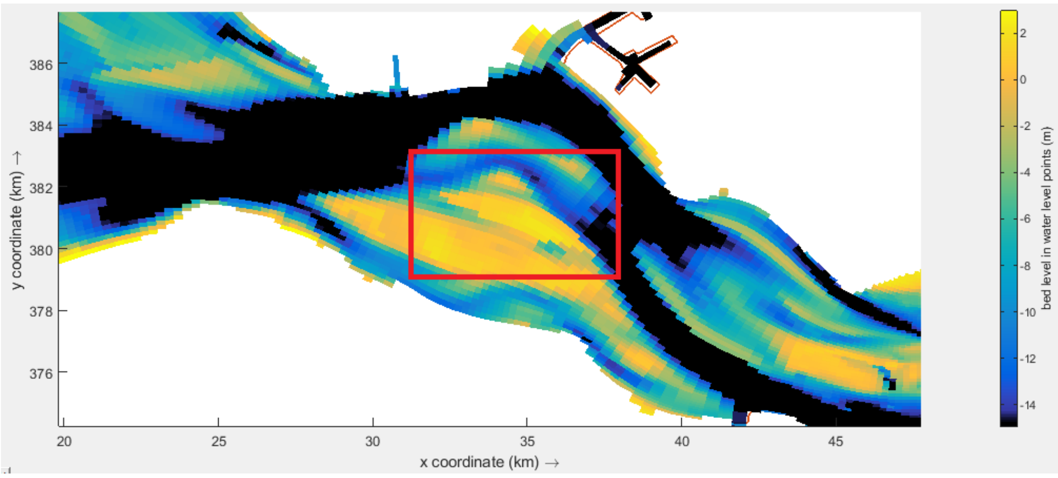
(c) Wave model results

Figure 8: Comparison of the hypsometric curves for the western, middle and eastern parts of the Western Scheldt for the Vaklodingen dataset and the model results with and without waves.

The visual comparison of the hindcasts and the measurements shows significant differences. In both hindcasts, the intertidal flats of Walsoorden and Valkenisse (see Fig. 1) have strongly migrated relative to the measurements. The channel between the two intertidal shoals is not visible in the hindcast results. Figure 11 compares the eastern part of the Western Scheldt in 2010 for the no-wave model and the measurements. The results for the wave-model are similar.

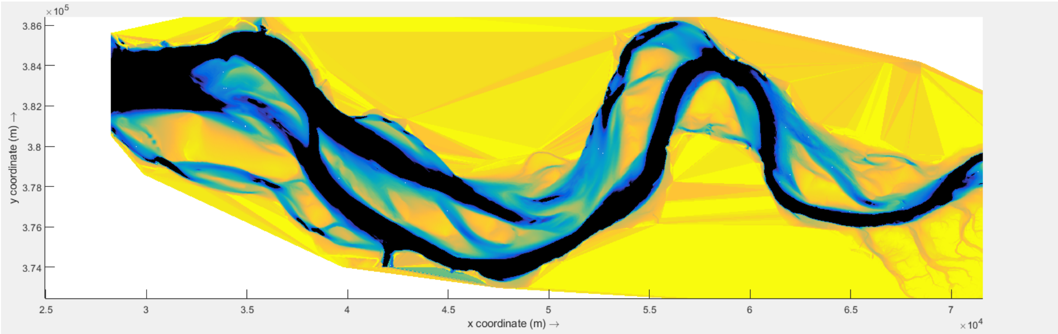


(a) Bathymetry according to the Vaklodingen dataset

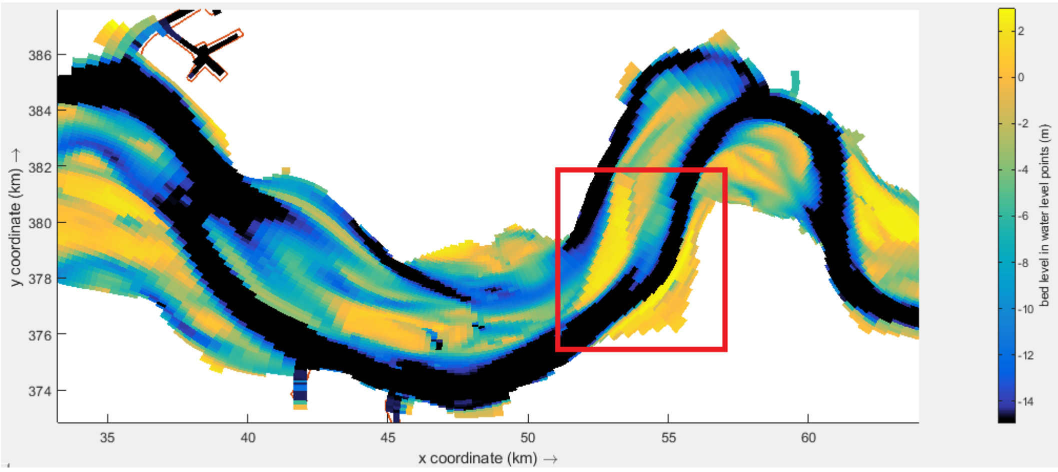


(b) Bathymetry according to the no-wave model

Figure 9: Comparison of the measured and modelled (no-wave) bathymetry of the western part of the Western Scheldt in 2010.

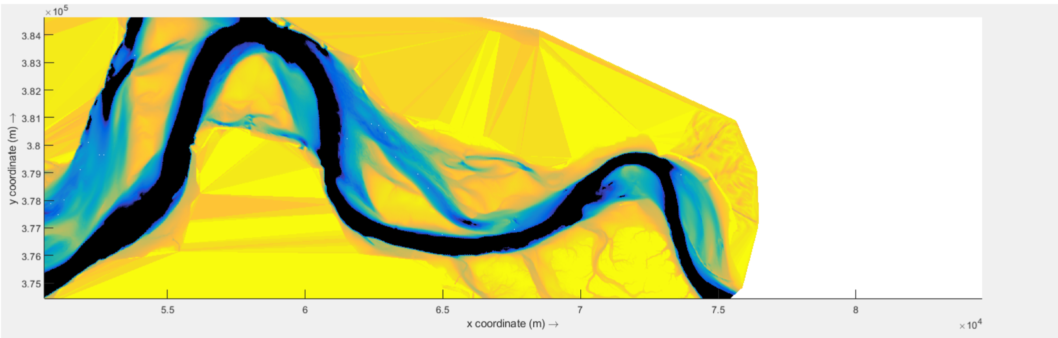


(a) Bathymetry according to the Vaklodingen dataset

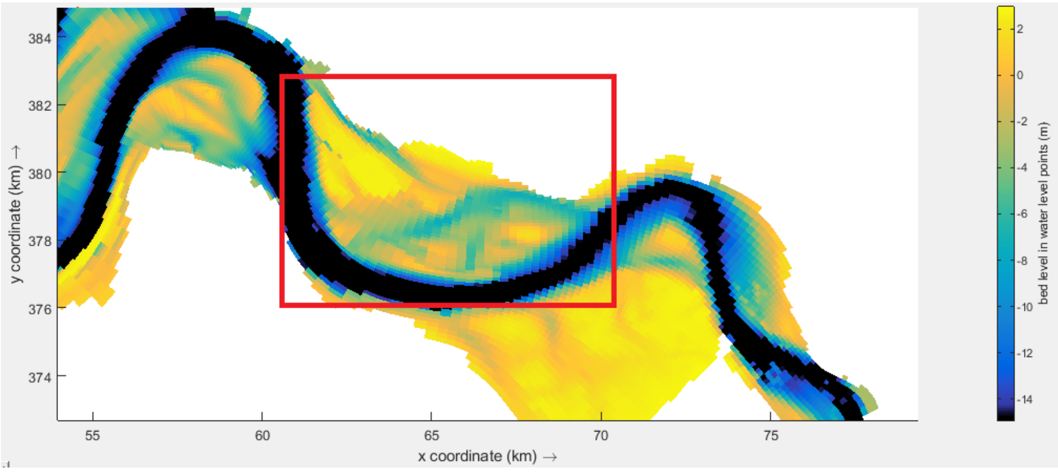


(b) Bathymetry according to the no-wave model

Figure 10: Comparison of the measured and modelled (no-wave) bathymetry of the middle part of the Western Scheldt in 2010.



(a) Bathymetry according to the Vaklodingen dataset



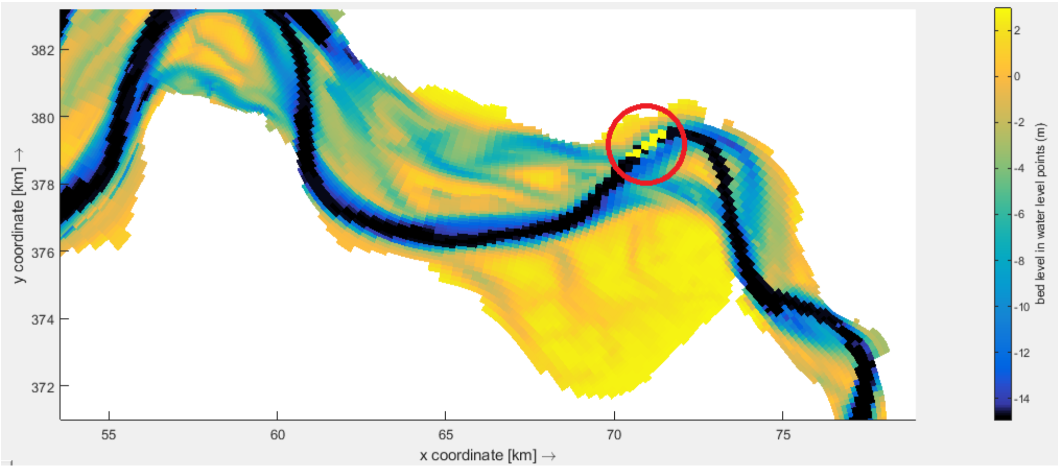
(b) Bathymetry according to the no-wave model

Figure 11: Comparison of the measured and modelled (no-wave) bathymetry of the eastern part of the Western Scheldt in 2010. In the model, the shape and location of the intertidal flats are significantly different than in the measurements.

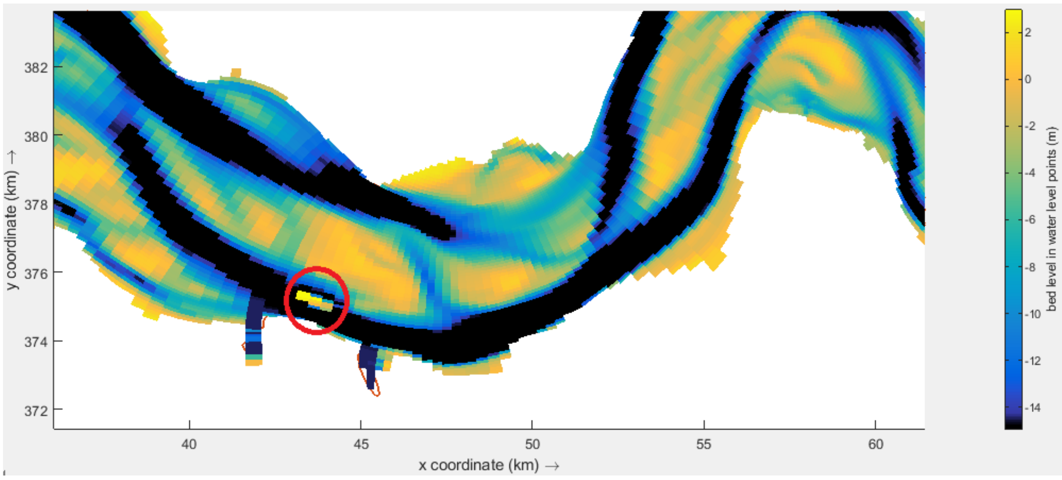
5 Discussion

5.1 Dredging and dumping definitions in the hindcasts

Visual analysis of the hindcast results revealed differences between the hindcast results and the Vaklodingen in 2010. The definition of dumping in the hindcasts likely contributed to these differences. In the model, sediment is dredged and dumped in one time step, although it is a gradual process in practice. When large quantities of sediment are dumped in one location, this most likely leads to differences between the model and the observations. Examples are seen in the east of the estuary in 1975 and the middle in 1965. In the hindcasts, 'hills' of sediment above 3 m NAP suddenly arise. These sediment hills take several years to erode in the model. Figure 12 shows these examples.



(a) Bathymetry of the eastern part of the Western Scheldt in 1975 according to the no-wave hindcast



(b) Bathymetry of the middle part of the Western Scheldt in 1965 according to the no-wave hindcast

Figure 12: No-wave hindcasts results for 1965 and 1975, showing dumping locations in the red circles, where hills of sediment arise.

The dredging and dumping definitions probably cause some of the differences between the hindcasts and the model described in Section 4.5. Plotting the polygons used to define the dredging and dumping locations on the modelled bathymetry of 2010 shows various intertidal areas in the exact location of the polygons. Figure 13 highlights three areas where this effect is most pronounced. Within these regions, the intertidal area in 2010 is significantly larger and higher in both hindcasts than in the measurements.

Because of the effect of dredging and dumping on the modelled bed levels, the current model does not seem applicable for studying the evolution of individual flats or marshes. However, DAD does not seem to influence the general trends in the hypsometric curves for the whole estuary (fluctuating size, increasing height). The model might therefore be applicable if the trends for intertidal area development are studied for 2020-2100.

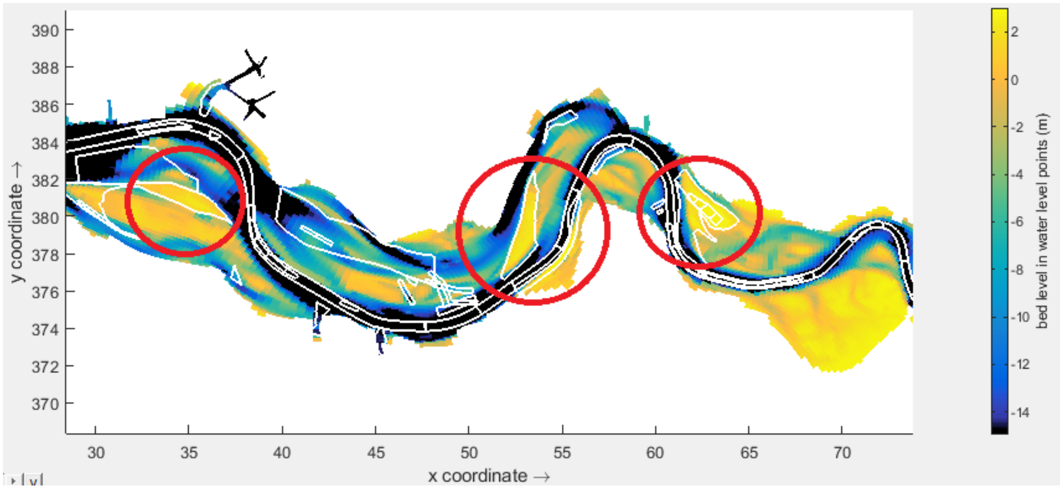


Figure 13: Bathymetry of the Western Scheldt in 2010 according to the no-wave hindcast, including the polygons defined for dredging and dumping (white). The three highlighted areas show intertidal areas at the location of polygons.

5.2 The effect of assumptions for the tidal range

The definition of the intertidal range plays an important factor in the calculated size of the intertidal area. However, different choices can be made for the highest and lowest studied bed levels. For example, De Vet et al. (2017) used mean low water (MLW) and mean high water (MHW) as boundaries, while according to the ecological definitions used by Bouma et al. (2005), the bed levels between MLWS and MHWN are the most relevant for the studied area in the Western Scheldt, since it consists mostly of intertidal flats.

In this study, the choice has been made to analyse the bed levels between the measured 50% highest high waters and lowest low waters for each year. This leads to a considerably larger intertidal range than the two above-mentioned definitions. If a smaller intertidal range is defined, the calculated intertidal area would shrink. However, this would be the case for both the measurements and the hindcasts. Using different boundaries for the bed levels in the analysis would not change the modelled bed levels. Therefore it would probably not lead to different conclusions on the differences between the measurements and the hindcasts. The model could still underestimate the total intertidal area and the average bed level height compared to the measured bathymetries.

In Figure 21 in Appendix B, the effect of the tidal nodal cycle on the calculated intertidal area is analysed. Since the tidal range is larger in some years than in others, changes in the hypsometric curves could be relatively large compared to changes in the bathymetry of the Western Scheldt. The analysis showed that 1965 and 2005 had relatively small tidal ranges compared to other years. On the other hand, 1980 was at the top of a tidal nodal cycle. This likely influenced the results, since 1980 shows the largest intertidal region in the measurements and the hindcasts, whilst 1965 and 2005 are the smallest years in the measurements. In the hindcast results, 1965 and 2005 are within the four smallest years.

The tidal nodal cycle was not included in the model's configuration for this study. In the hindcasts, the water levels were based on one year of astronomical tidal data. Excluding the tidal nodal cycle might affect the modelled bed levels, assuming that a larger tidal range leads to more sediment displacement. If the average yearly tidal range in the model is relatively large, i.e. at the peak of the tidal nodal cycle, bed level changes could be relatively large compared to the observations. On the other hand, Figure 21 shows that the tidal range at Terneuzen is between 470 cm and 490 cm, so the largest tidal range is (only) 4% larger than the smallest tidal range. Therefore, excluding the tidal nodal cycle from the model might have contributed to the differences between the measurements and the hindcasts, but the effect is probably limited.

5.3 Inclusion of wave modelling

The effects of including wave modelling in the hindcast seem contradictory. On the one hand, including waves leads to better estimations of the total intertidal area and the average bed level compared to the measurements. On the other hand, changes to the hypsometric curves are more pronounced in the wave hindcast compared to the no-wave hindcast. Therefore, the shape of the hypsometric curves is more similar to the measurements in the no-wave hindcast.

Including waves in the model could lead to more erosion. More erosion could result in more pronounced changes to the hypsometries. However, more erosion does not explain the larger and higher intertidal area in the wave hindcast compared to the no-wave hindcast. A possible explanation could be that waves lift sediment from the bed. The sediment might then be disposed of at tidal flats since the flow velocity across these regions is low. If waves thus lead to more erosion from channel beds and sedimentation at shoals, the intertidal area might grow and rise if waves are included in the model.

5.4 Interpolation of the original data

Interpolation of the Vaklodingen data on a grid with a factor of ten lower resolution leads to data losses. This leads to a decrease of 3% in the intertidal area for the total Western Scheldt. The trend in the hypsometries is the same when the original data is considered as when it is interpolated, as visualised in D. Therefore, the courser grid resolution does not play a large role in the differences between the model outcomes and the measurements

5.5 Setup of the model

The model configuration does not include SLR for the hindcast from 1964-2012. However, the water level data from the measurement stations in Vlissingen and Bath suggest SLR of approximately 1 cm every 6 years, as described in appendix B. Research suggests that with SLR intertidal areas are likely to increase in height, although the increase in height is less than the SLR (e.g. Elmilady et al., 2019; Röbke et al., 2020). Since measured water levels, which include SLR, are used to determine the intertidal range, excluding the rise of the intertidal area caused by SLR could contribute to the hindcasts underestimating the intertidal area's size.

Besides that, only sand is included as sediment in the model. However, Röbke et al. (2020) suggests that including mud might protect the sand from being eroded. Therefore, not including mud in the hindcasts could contribute to more pronounced changes to the bed level in the model compared to the measurement data.

Another factor which could play a role in the differences between the observed bathymetries and the modelling outcomes is the number of dimensions in the model. Both hindcasts are 2D. However, 3D modelling could include currents caused by salinity and temperature differences in the water. Possibly, this would lead to different sediment movements. However, the effect this would have on the hypsometries, the height, or the location of intertidal areas in the model is uncertain.

6 Conclusions and recommendations

6.1 Conclusions

6.1.1 Differences between the hindcast results and the measurements

This study is an initial analysis of the ability of the Delft3D-Scheldt-SLR model to create hindcasts of the evolution of intertidal areas in the Western Scheldt. On a large spatial and temporal scale, the results suggest that the hindcasts produce similar trends in the hypsometric curves as the measurements. However, the total intertidal area and the average bed level height are underestimated in both hindcasts. If wave modelling is included, the hindcast underestimates the size of the intertidal area by 7.0 million m^2 on average, and the average bed level by 12.9 cm. In the no-wave hindcast, the average underestimations are 8.6 million m^2 and 15.1 cm respectively.

If the hypsometric curves are considered on a smaller spatial scale, i.e. for the western, middle and eastern parts of the estuary, differences between the hindcasts and the measurements are more pronounced. Besides that, the visual comparison reveals that in the hindcasts intertidal areas develop and rise at different locations than the measurements suggest. In both hindcasts, intertidal areas show a pronounced increase in height at locations defined for dumping dredged sediment.

6.1.2 Effect of wave modelling

Including wave modelling in the hindcast leads to an increase in total intertidal area and bed level height. Therefore, they are generally closer to the measured data than a hindcast without waves. On the other hand, the shapes of the hypsometric curves based on the no-wave hindcast are more similar to those based on the measurements.

The hypsometric curves suggest that morphological changes are more pronounced in the wave hindcast than in the no-wave hindcast. These changes are even less pronounced in the measurements, as the location and height of individual intertidal areas are visually more constant in the measurements than in the model.

6.2 Recommendations

A more in-depth comparison of the measurements and the hindcasts could include separately investigating the model performance for the littoral and supralittoral zones. The boundary, mean high water during neap tides, could be extracted from the measured water level data. This would give more insight into the model's ability to predict the ecological impact of SLR on intertidal areas.

Moreover, the definitions of dredging and dumping seem to influence the development of intertidal areas in the hindcasts significantly. To improve the hindcasts, the definitions of DAD could be reconsidered. Currently, sediment is instantly dredged and dumped directly at the sea bed in one time step. Further research could consider the possibility of modelling dredging and dumping activities over time, and studying how this would affect the modelled intertidal area development in the Western Scheldt. The accuracy of the documentation of past DAD activities in practice could also be studied.

Another improvement to the model could be including mud as sediment in the model, or applying 3D modelling instead of 2D. Further research could study the effects of these changes on the differences between the measurements and the model's hindcast.

Besides that, the effect of including slight SLR (circa 1 cm every 6 years) in the hindcasts for 1964-2012 could be studied. By including SLR in the model, the intertidal areas possibly rise. This could provide additional insights into the effect of SLR on the development of intertidal areas in the forecast for 2020-2100.

The model could be validated further by studying the impact of different dumping locations and quantities on the development of intertidal areas. If the model is fully validated, further research could go into the evolution of intertidal areas in the model's forecast for 2020-2100. Based on those outcomes, a strategy could be developed to maintain the ecological value of the intertidal regions in the Western Scheldt estuary under SLR.

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Appendices

A Vaklodingen dataset

As mentioned in Section 3.3, the study area's measurement data has flaws. At least ten areas are not complete or correct in all datasets. These areas are either still in the data after reclamation or have always been intertidal but have not always been measured. Some areas have been depoldered in the last decades and were only part of the data after 2015. An overview of excluded areas can be seen in Figure 14 and are clarified in table 3.

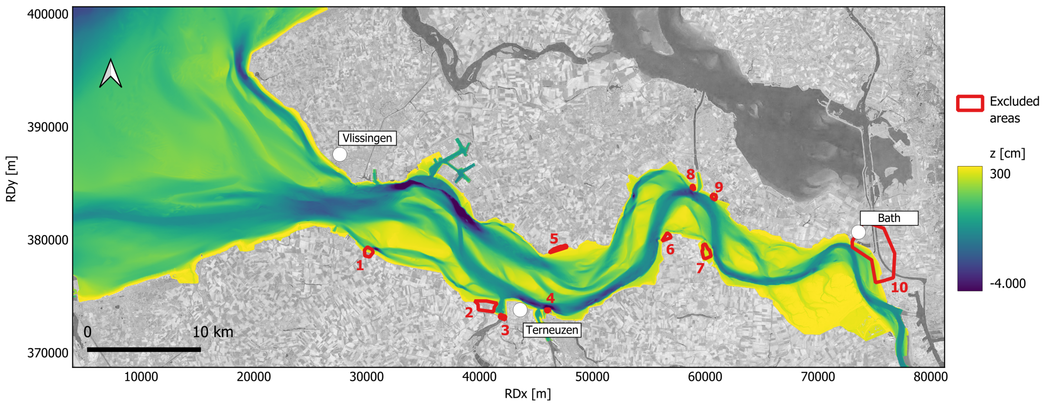
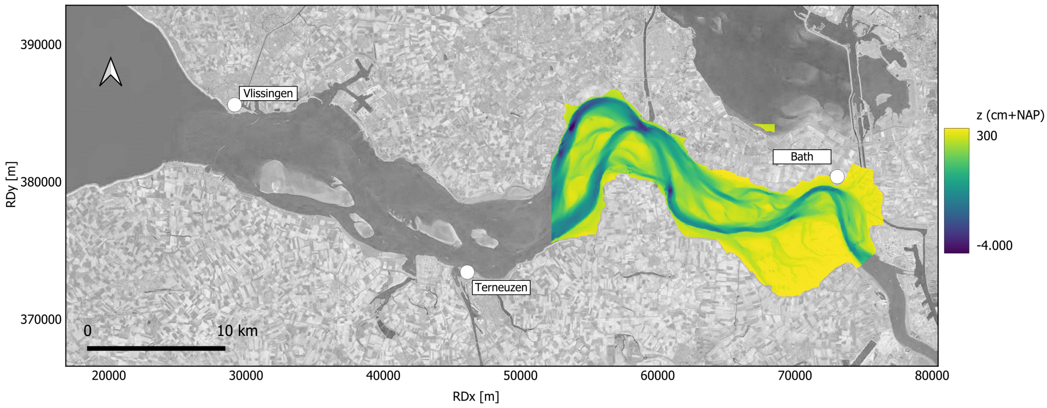


Figure 14: Overview of the excluded areas in the Western Scheldt (bathymetry 2020).

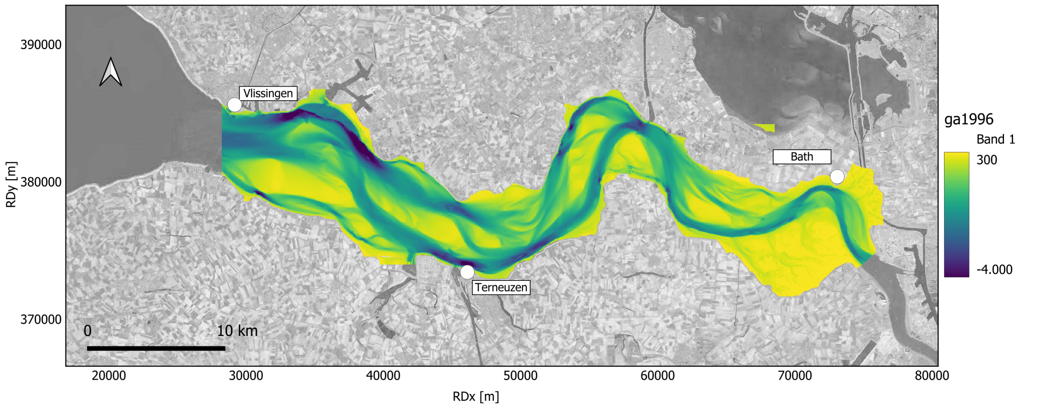
Table 3: Overview of excluded areas in the Western Scheldt estuary.

#	Location	Reason
1	Near Nummer Eén	Reclaimed, but included in the data until 2010
2	Former Savoyaardplaat, now Valuepark	Reclaimed, but included in the data until 2010
3	Braakmanhaven	Only included in the data after 2010
4	Terneuzen	Intertidal area only included in the data after 2010
5	Zuidgors	Reclaimed, but included in the data until 2010
6	Hoek van Ossenisse	Reclaimed, but included in the data until 2010
7	Former Noorddijk polder	Depoldered, only included in the data after 2010
8	Westnol near Hansweert	Intertidal area only included in the data after 2010
9	Veerhaven	Intertidal area only included in the data after 2010
10	Schor van Bath	Reclaimed, but included in the data until 2010

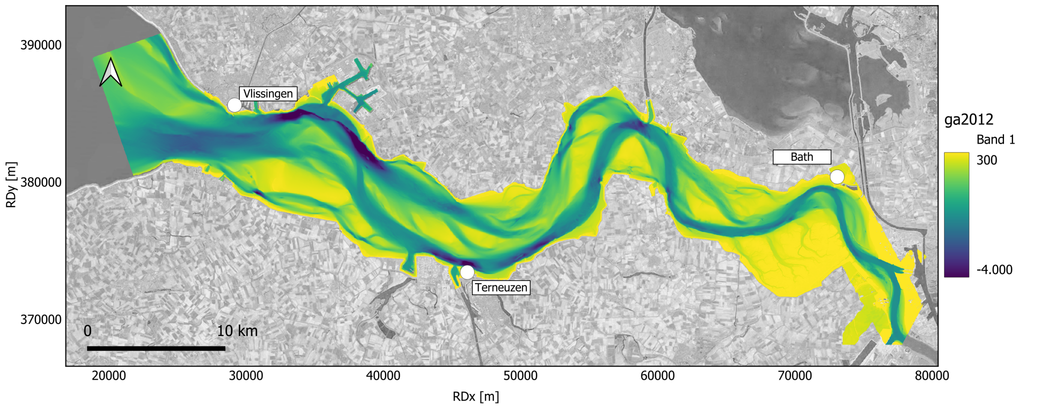
Some maps were merged, and the data limited the size of the study area. In Figure 15, illustrative examples of different years for the bathymetries are given.



(a) Vaklodingen data 1965: Half of the estuary.



(b) Vaklodingen data 1996: Whole estuary, excluding mouth and upstream area.



(c) Vaklodingen data 2012: Whole estuary, including mouth and upstream area.

Figure 15: Illustrative examples of the Vaklodingen dataset.

B Water levels and intertidal range

The range of intertidal bed levels has been one of the main points of interest in this study. Throughout the study, the assumptions for the considered bed levels have become more elaborate. This process will shortly be elaborated on in this appendix, to provide background information on the development of the results, which use spatially and temporally varying water levels throughout the estuary. Besides that, the influence of these assumptions is studied.

Initially, constant water levels were assumed for the intertidal range, based on literature and the average intertidal range between Vlissingen and Bath of approximately 4.5 m (e.g. Elias et al., 2023; Röbke et al., 2020). This led to hypsometric curves as seen in Figure 16. Compared to the final results, the shape of the hypsometric curves is similar, except for the steep edges. However, the total area is smaller, since the constant intertidal range is smaller than the measured intertidal range near Bath.

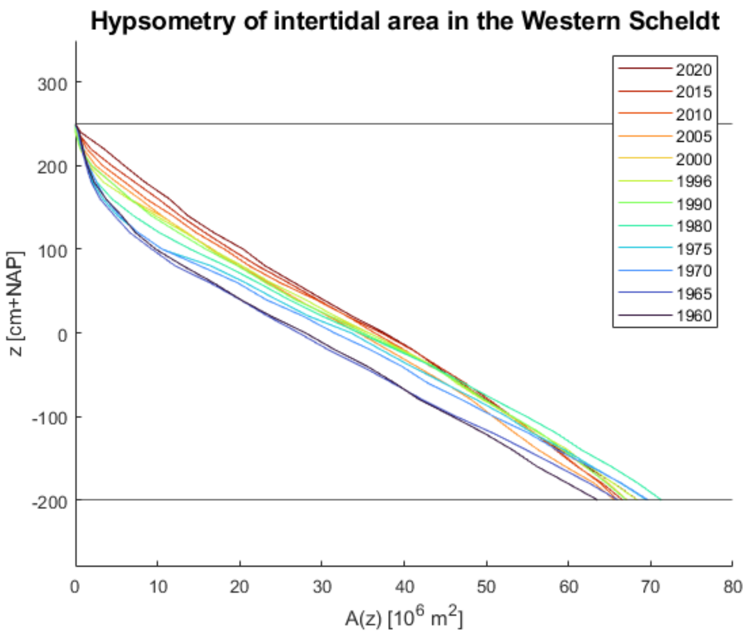
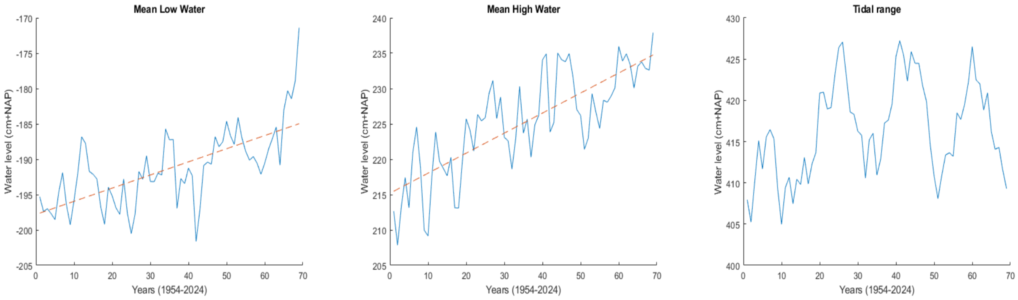


Figure 16: Hypsometric curves based on the original data with a constant intertidal range of -200 cm NAP and 250 cm NAP.

Later, water level data for various measurement stations in the Western Scheldt was available. Analysing these results showed increasing water levels for mean low and high water, see Figure 17. This suggests sea level rise for the studied period. Water level data from the measurement station near Terneuzen is used as an example since it is located towards the middle of the Western Scheldt. For other locations, similar trends are observed. In Figure 17c, the tidal nodal cycle is clearly visible.



(a) Mean low water level (b) Mean high water level (c) Tidal range

Figure 17: MLW, MHW and tidal range for 1954-2023 near Terneuzen.

Based on this data, mean low and high water for each year were used as the new definition of the intertidal range. However, MLW and MHW include the neaps. As a result, the considered water levels were not the boundaries of regularly flooded areas (i.e. more than circa 30% of the time). To account for this, the effect of considering the 50% and 30% highest high waters and lowest low waters was studied. In Figure 18, the tidal range near Terneuzen is visualised for three definitions. The differences between the tidal range and TR (50%) and TR (30%) are on average 62 and 87 cm respectively. These values are similar for Vlissingen and Bath.

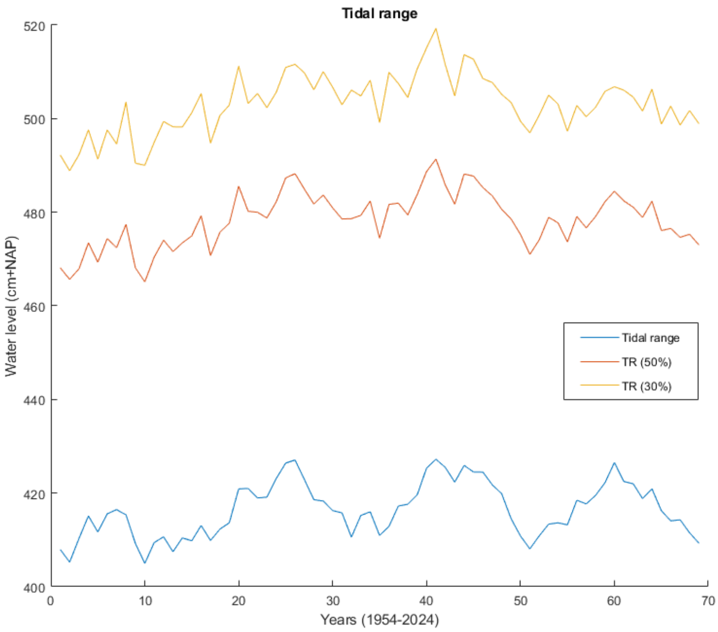
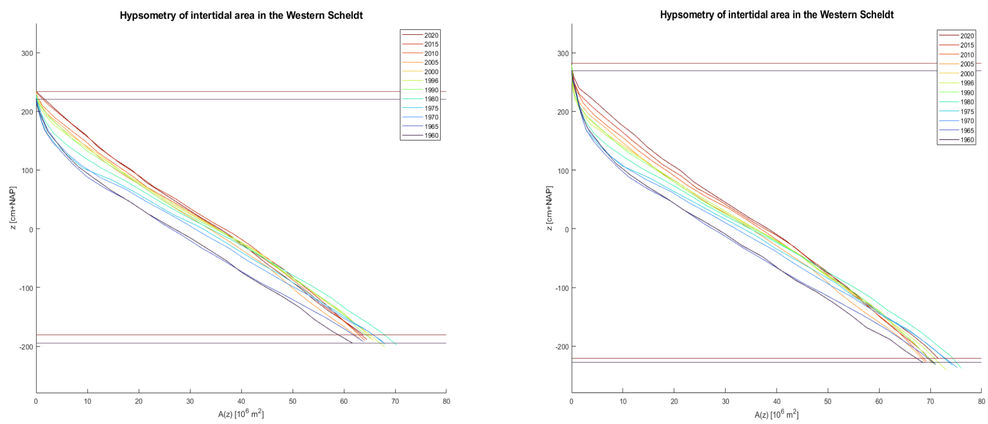


Figure 18: Tidal range in Terneuzen for MLW-MHW and the 50 and 30% highest high waters and lowest low waters.

Figure 19 shows the hypsometric curves of the Western Scheldt based on MLW and

MHW and the 30% highest high and lowest low waters at Terneuzen. The total intertidal area increases significantly if more bed levels are considered intertidal, but the general trend in the hypsometric curves does not change. For the validation of the model, it therefore seems of lesser importance what the considered water levels are. However, for describing the evolution of the littoral and supralittoral zone, the considered bed levels are important.



(a) MLW-MHW (b) 30% highest HW and lowest LW

Figure 19: Comparison between the hypsometric curves with two definitions of the intertidal range.

Finally, the choice was made to use the 50% highest HW's and lowest LW's and interpolate these linearly from Vlissingen to Bath. This choice was made based on a visual analysis of tidal plots, which showed all high and low waters for a certain period. The tide plot of the 50% highest HW's and lowest LW's at Terneuzen for 1980-1999 is shown in Figure 20. The data has been linearly interpolated from Vlissingen to Bath in the final results.

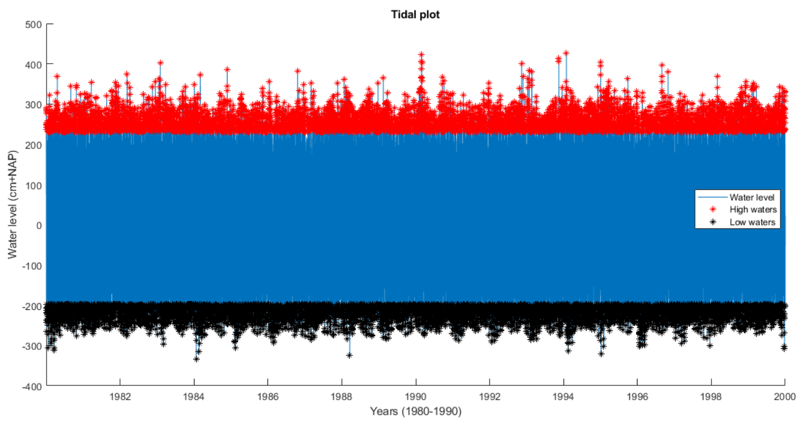


Figure 20: Plot of the 50% highest high and lowest low water levels from 1980-1999 at the measurement station of Terneuzen.

In Figure 21 the studied years are plotted on the tidal range, to study the effect of the tidal nodal cycle on the results. It shows that for 1965 and 2005, i.e. the first and eighth considered years, the tidal range is smaller than in the other years. In contrast, 1980 is at the top of the tidal nodal cycle. In the results, 1980 is the year with the largest measured and modelled intertidal range, whilst 1965 and 2005 are (amongst) the smallest. (Studied years are 1965, 1970, 1975, 1980, 1990, 1996, 2000, 2005 and 2010.)

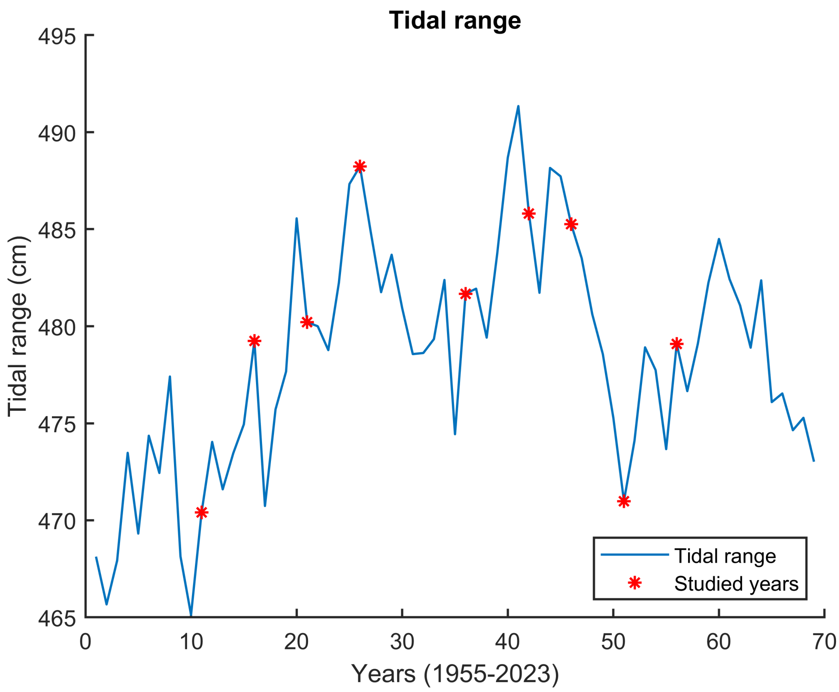
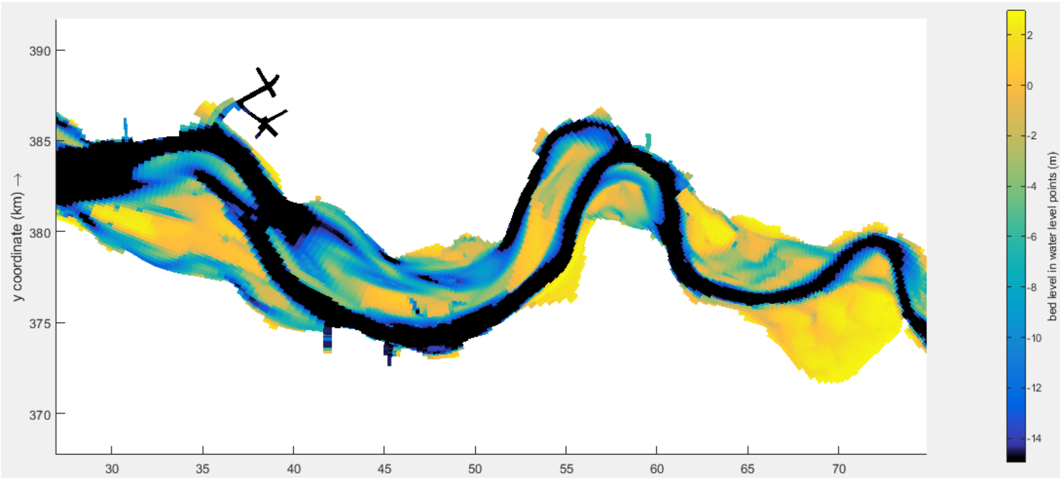


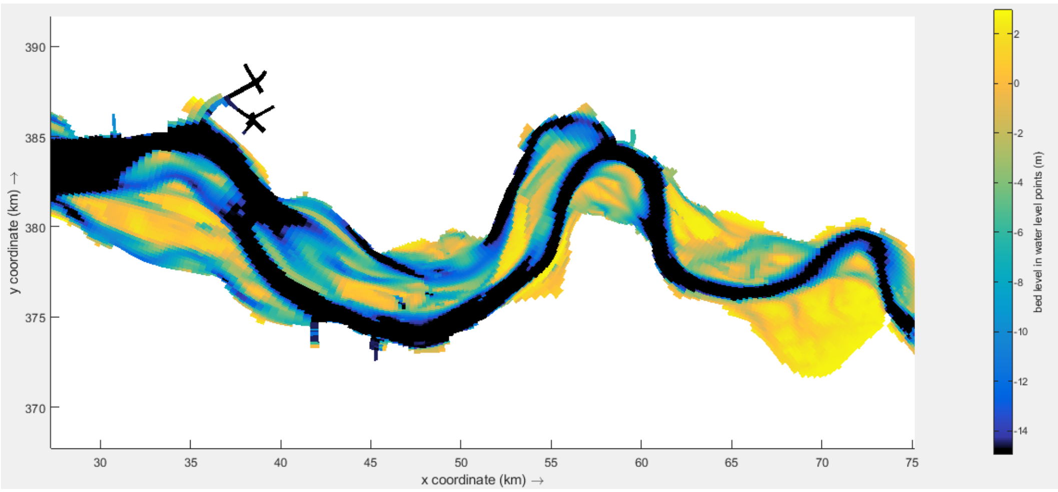
Figure 21: Plot of the tidal range based on the 50% highest high and lowest low water levels from 1955-2023 at the measurement station of Terneuzen, with red stars for each studied year.

C Wave hindcast results

Figure 22a shows the bed levels in 2010 according to the wave hindcast results. Elements mentioned for the no-wave hindcast in Chapter 4 are also visible in this figure. Examples are the rise of intertidal areas at the location of dumping areas, such as the Hooge Platen, southwest of the shoal of Baarland, and near Walsoorden/Valkenisse in the east of the estuary. For comparison, Figure 22b shows the bed levels according to the no-wave hindcast.



(a) Bed levels in 2010 according to the hindcast with wave modelling.

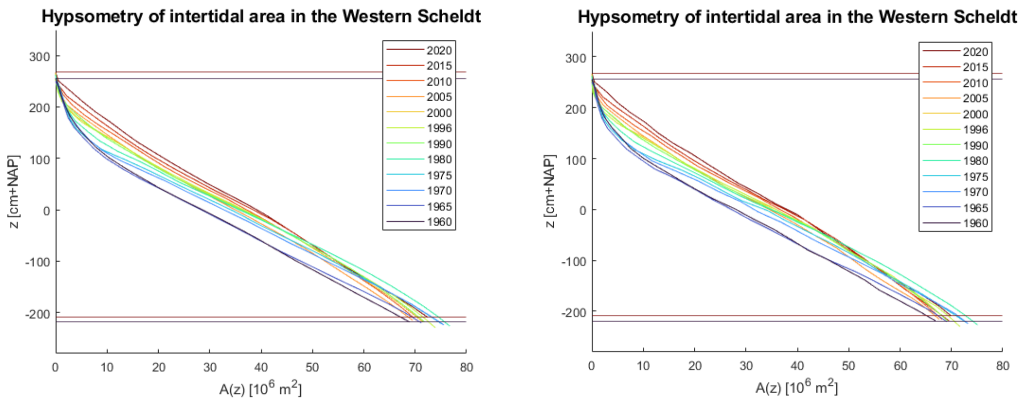


(b) Bed levels in 2010 according to the hindcast without wave modelling.

Figure 22: Modelling results for the bed levels in 2010 for the wave and the no-wave hindcast.

D Effect of interpolation and step size

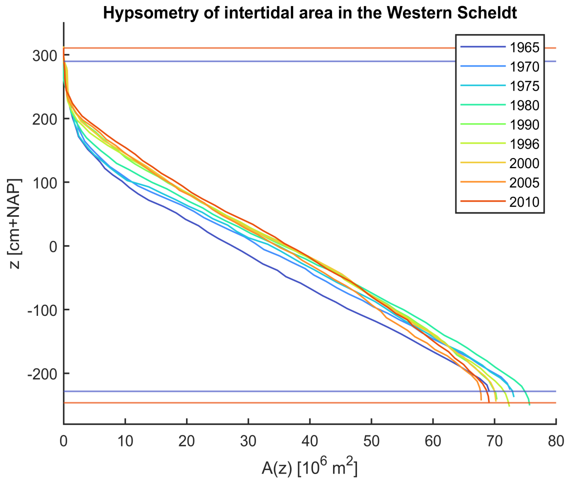
The original data was compared to the interpolation on the Delft3D flow grid, to see if large differences occurred. This was not the case, as visible in Figure 23. The main difference between the original data and the interpolation is the consistently smaller intertidal area based on the interpolation (ca. 3%). Besides that, the larger cell size leads to less smooth curves than in the original data.



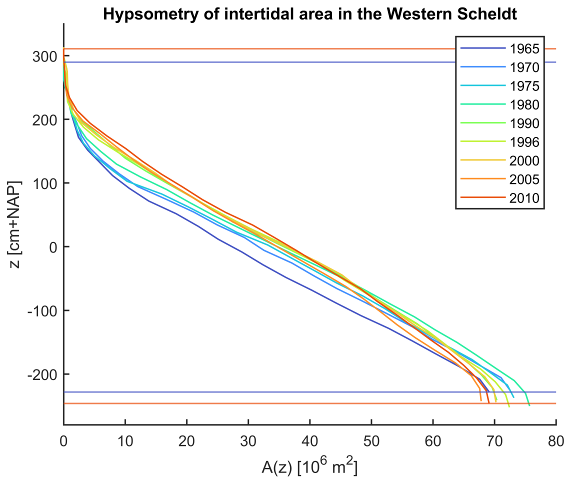
(a) Original data (b) Interpolated data

Figure 23: Comparison between the hypsometric curves based on the original data and the interpolation of the original data on the D3D-Scheldt-SLR flow grid.

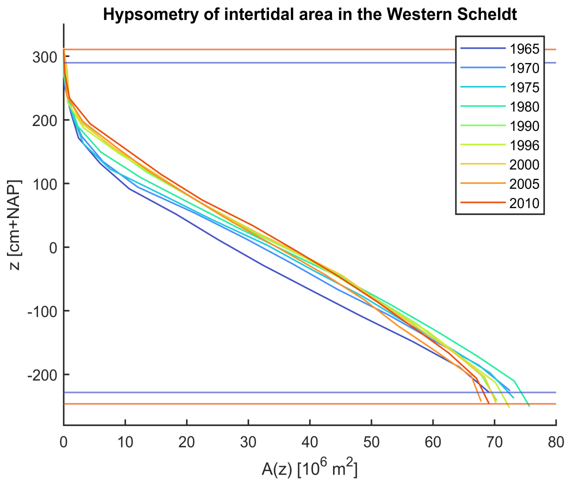
The hypsometric curves have been developed for a step size of 10, 20 and 40 cm. These can be seen in Figure 24. A smaller step size leads to more details but does not change the general trends in the curves.



(a) Step size of 10 cm.



(b) Step size of 20 cm.



(c) Step size of 40 cm.

Figure 24: Comparison of the hypsometric curves based on the Vaklodingen dataset for different step sizes for the considered bed levels.

E Model setup

The model setup is the same as in the study by Röbke et al. (2020). In that study, the effect of different values for some parameters was studied, but no thorough calibration was performed (Röbke et al., 2020).

Table 4: Overview of model parameter settings in the Delft3D-Scheldt-SLR Model (adapted from: Röbke et al. (2020)).

Parameter	**Value/setting**
Hydrodynamic simulation time	355 days
Time step	12 s
Wave communication interval	60 min
Wave computational mode	Stationary
Morphological scale factor	82.54/51.59 [-]
Morphological simulation time	48 years
Horizontal eddy viscosity	1 m^2s^{-1} (uniform)
Horizontal eddy diffusivity	1/10 m^2s^{-1} (uniform)
Bottom friction (Manning's n	0.023 $sm^{-1/3}$
Total river discharge	120 m^3s^{-1}
Median sand diameter (D50)	200 μm
Sediment transport formulation for sand	Van Rijn (1993)
Sediment transport formulation for mud	Partheniades (1965)
Current-related suspended and bed-load transport factor (Sus, Bed)	0.5 [-]
Wave-related suspended and bedload transport factors (SusW, BedW)	0.3 [-]
Settling velocities for mud	0.0005 ms^{-1}/0.002 ms^{-1}
Erosion parameter for mud M	$1*10^{-4}$ $kgm^{-2}s^{-1}$
Critical bed shear stress for erosion of Mud ($TcrEro$)	0.25 Nm^2
Lateral bed slope factor (α_{bn})	100 [-]
Salinity	Not included