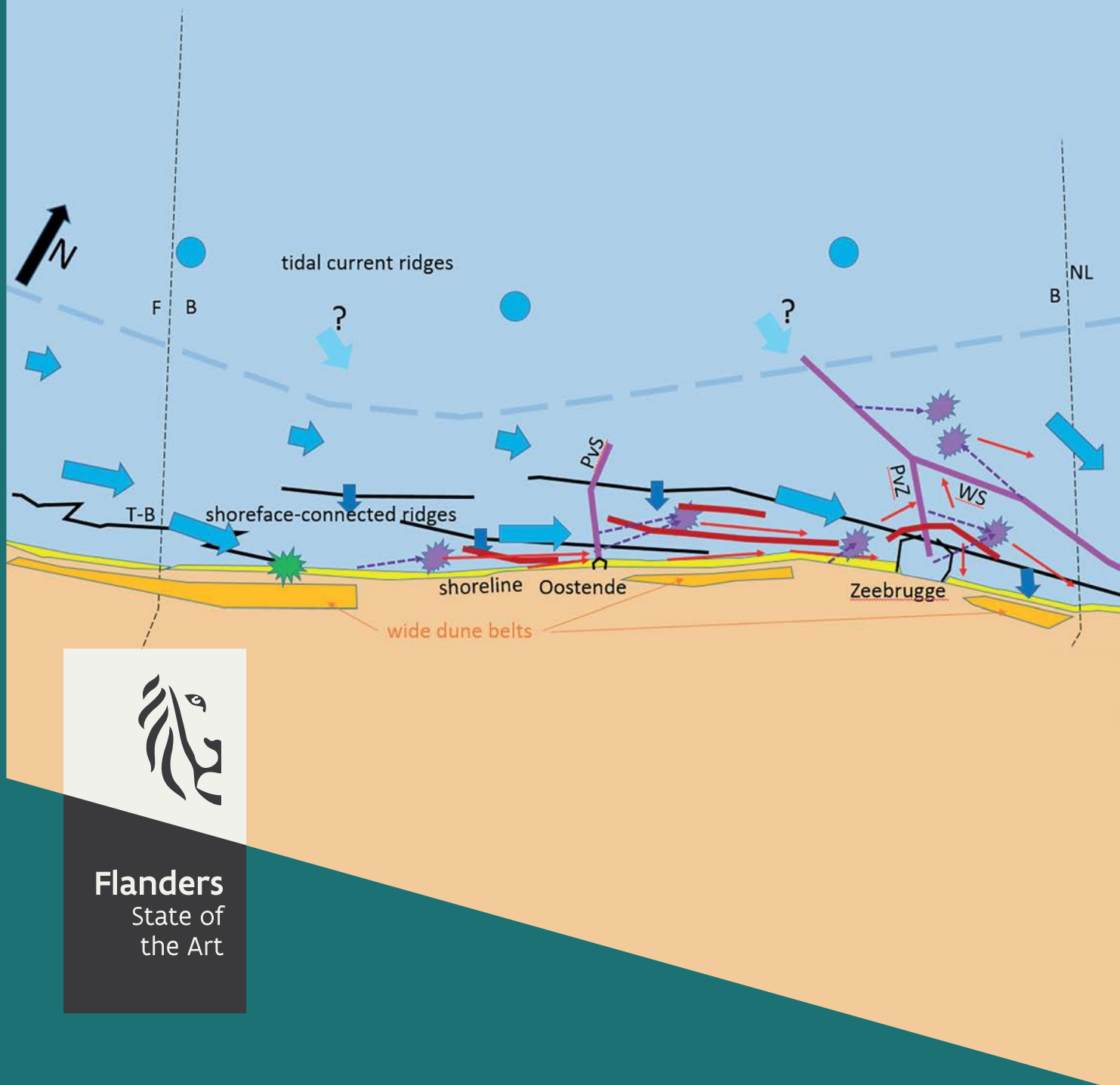




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MOZES – Research on the Morphological Interaction between the Sea bottom and the Belgian Coastline

Final report

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MOZES – Research on the Morphological Interaction between the Sea bottom and the Belgian Coastline

Final report

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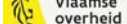
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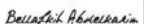
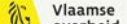
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Abstract

The MOZES-project (**MO**rfolgische interactie kustnabije **ZE**ebodem en **Str**and) investigated the morphodynamic interaction between the Belgian offshore seabed (shelf and nearshore) and adjacent shoreline aiming to improve regional morphodynamic understanding needed for effective coastal management. The project included data-driven research and numerical modelling.

An impressive bathymetric database spanning the last two centuries of the Belgian shelf in relation to coastal morphodynamics has been assembled. Natural morphodynamics include significant longshore sediment transport to the east, the movement of nearshore sand ridges to the east, and the encroachment of shoreface-connected ridge and tidal channels on the coast. This encroachment is interpreted as ultimately triggered by sea-level rise. Human interaction causes even more intense sediment movements and morphodynamics. Repeated beach nourishments contribute to coastal squeeze, while much of the nourished sand remains in the coastal system but settles in sheltered areas where it is less useful. Dredged fairways to the coastal harbours severed the natural transport paths over the shoreface-connected ridges to the beach and dune belt, depleting the attachment areas. Deep dredged fairways attract sediment from the environment. Dredging of all harbours and access channels means net removal of sediment from the coastal system. Dumping dredged material in nearshore current channels locally plugs them up, diverts the currents and triggers down current channel deepening. Harbour dams extending in the nearshore attract sediment in the alongshore sheltered nearshore areas, while new erosion troughs and channels are created at the offshore side (in addition to downdrift erosion).

Different types of numerical models were applied to better understand the effects of seabed changes on shoreline evolution, as well as the influence of the anthropogenic activities.

The nourishment needs for coastline preservation at the erosional hot-spot of Knokke-Zoute were investigated with 2DH models and a 1D coastline model. Results showed that these models can all reproduce the high erosion rates of beach nourishments at Knokke-Zoute as volumetric losses of the active profile (m^3/year) after calibration. Most importantly it was shown that the main driver of this erosion is the combination of wave related cross-shore transport and especially the large gradient of alongshore sand transport in the active zone which is caused by the harbour of Zeebrugge blocking alongshore transport from the southwest coastline. Appelzak channel and local protrusion of the coastline are secondary drivers of erosion of the beaches in Knokke-Zoute.

An idealized coupled shelf-nearshore model (2DH & Quasi2D) was developed to improve fundamental understanding of the impact of shelf ridges and adjacent channels on the decadal nearshore and shoreline morphodynamics. The observed large-scale bathymetric changes over the past 200 years were incorporated in a schematized form. Sea level rise, the hold-the-line strategy to maintain shoreline position and coastal squeeze were also accounted for in the model. Model results using sea-level rise rates from the IPCC scenarios for the next 50 years ($>3 \text{ mm/yr}$), combined with a hold-the-line strategy to maintain shoreline position and the associated coastal squeeze, indicate that future annual nourishment volumes in areas where coastline erosion is determined by the channel-ridge morphology may need to be about 2–5 times larger than those under the sea-level rise rates over the last 50 years ($\approx 1.5\text{--}3 \text{ mm/yr}$).

Lessons learned for coastal protection from MOZES project demonstrate the importance of considering decadal scale coastal morphological processes to establish sustainable solutions. The channels and ridges closest to the coastline as well as the coastal harbours and fairways are crucial influencing factors to be taken into account in the future nourishment strategies for coastal protection and development.

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1 Introduction

In 2020 Flanders Hydraulics and MDK-Coast Division discussed research needs to support coastal protection in Belgium. Morphological research to better understand the influence of the gully-bank sea bottom morphology on the coastline morphology was selected to be a top research priority. Therefor the MOZES research project was established as a partnership between Flanders Hydraulics and MDK-Coast Division, both co-financing this research project. MOZES is an acronym for “Morphological interaction between the sea bottom and the Belgian coastline”. Through a tender procedure specialised expertise from Antea Belgium with subcontracting from University Utrecht, Deltares and Rik Houthuys was appointed to carry out research on this topic together with Flanders Hydraulics researchers. The study area of MOZES is shown on Figure 1-1.

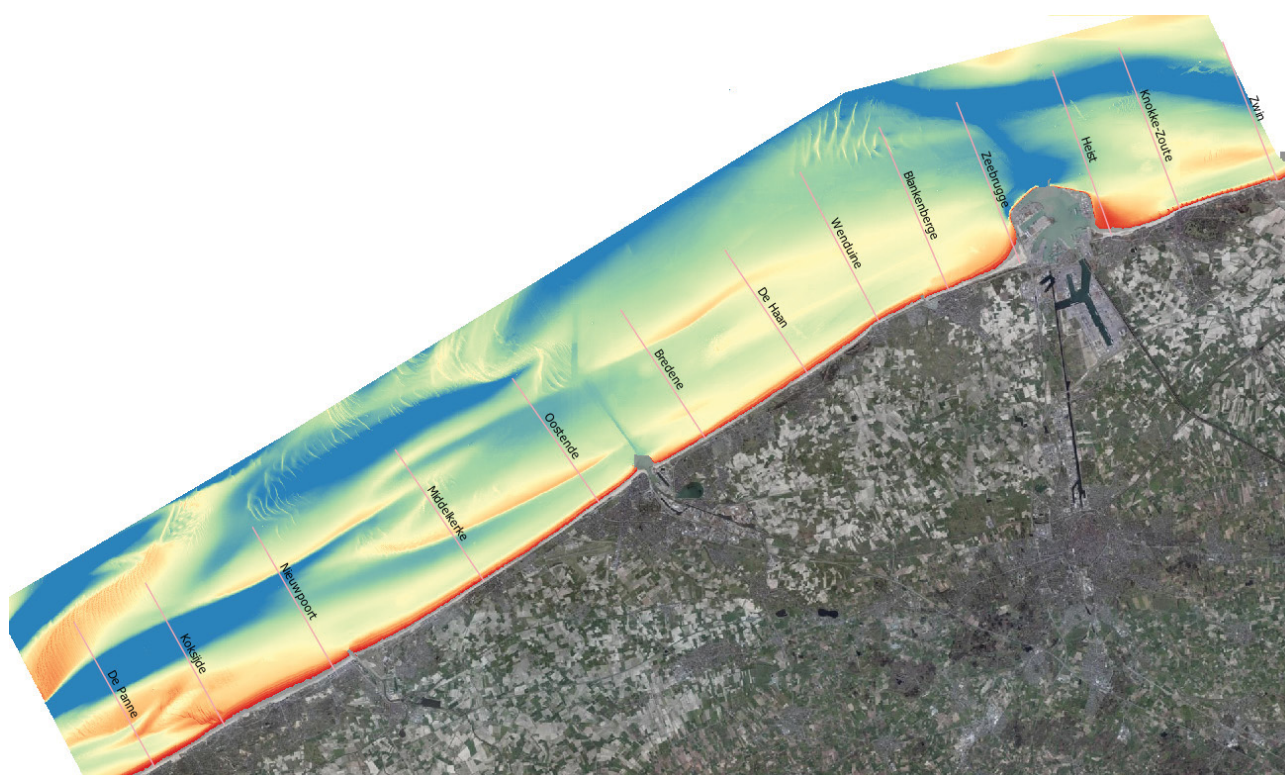


Figure 1-1 – Study area of MOZES project.

MOZES project includes data-driven research and numerical modelling on the morphological interaction between the sea bottom and the Belgian coastline. Results from the data-driven research are described in chapter 2; results from the numerical modelling in chapter 3.

The data-driven research consists of acquiring historical bathymetric and topographic data crucial for addressing the research questions within the MOZES project. These data are utilized to create Digital Elevation Models (DEMs) covering the entire area of interest at specific time points, spanning the last two centuries. The bathymetric datasets were examined for large-scale morphological change. These datasets are also available as input for numerical models, thereby contributing to research on the morphological evolution of nearshore channels and shoreface-connected sand ridges on decadal time scales.

The numerical modelling research consists of developing and applying a range of different model approaches. Idealised models are developed and applied to simulate the impact of the nearshore channel/ridge system on the coastline including the effect of accelerated sea level rise. In addition modelling the slow changes in the morphology of the channel/ridge system and its interaction with the coastline is addressed by a coupled modelling approach (2DH & Quasi2D) for an idealised geometry of the Belgian coastal zone. Two available complex process-based 2DH models (ScaldisCoast and FlemCo) are finetuned and used to investigate longshore transport along the Belgian coast, the natural feeding at the west coast and the effect of Appelzak channel on the erosional coastline of the east coast. For the east coast also a 1D coastline model is developed in ShorelineS.

This final report describes the final research results of the MOZES project 2020-2026. Interim research results were reported in Dujardin et al, 2023, Dujardin et al, 2024 and Dujardin et al, 2025.

The morphological GIS data and the numerical models obtained during MOZES project are managed by Flanders Hydraulics and available on request.

2 Data Analysis

2.1 Morphological analysis of the coastal system

Geomorphology is the study of the shape of the Earth's surface, and how it came about. This surface is the resultant shape of the action of numerous geographical processes. The same, or other, processes continue to remodel the surface. Especially at dynamic sites, such as coastal environments, geomorphology can contribute to unravel and document the current surface shaping processes.

The intertidal and supratidal parts of the coastal barrier system tend to respond quickly, even daily, and intensely, with vertical changes sometimes exceeding 1 m, to the forces that act in that environment: mostly waves, wind and tidal currents. Changes in the submerged nearshore bed morphology tend to respond more slowly to the local surface shaping processes, thereby presenting a more persistent character, in contrast to the beach part, where many changes back and forth take place. For the function of the coastal barrier system as a coastal defence, we are interested in the longer-term behaviour of the morphology, with a focus on states of minimal or maximal volume beneath the surface.

Information relevant for that topic is held in successive topographic and bathymetric maps of the coastal environment. Making digital elevation models (DEMs) of the elevation information of each survey, and comparing them with successive surveys, allows surface shape changes to be detected. Elevation gain in the coastal environment reflects natural sedimentation or the morphological effect of sand brought in by human interventions. Elevation loss either shows natural erosion or the morphological effect of the removal of sediment by human interventions.

Because we want to detect slow but persistent change, also old maps need to be incorporated in the morphological database. Therefore, this study both focuses on retrieving and digitising old maps and on using the many high-quality recent surveys of the Belgian coast.

While retrieving and vectorising old maps was labour intensive and time-consuming, the produced data layers added substantially to answer the research questions of the MOZES project.

The main research questions requiring the study of beach and nearshore morphology of this project were:

- the interaction between the slow change of the nearshore sand ridges and current channels, and the active zone of the beach;
- distinguishing between long-term natural change and shorter-term human-induced change;
- identifying trend changes and trying to find the cause.

It is realised that the full map series of the inner shelf became only available in the last months of the MOZES project. They are not yet explored in full depth. Yet, it is believed that some major morphological questions have now finally found an answer.

The Belgian coast is covered by a large high-quality database with yearly surveys of which all survey terrain points obtained since 2000 are also available in digital form. This data set has been analysed and interpreted in Houthuys et al. (2026). The report focuses on the most recent morphological trends of the active coast system and the first offshore kilometre and primarily analyses the effect of nourishment and maintenance dredging works. The results are used throughout the current chapter, and the results of this chapter complement some of its conclusions both back in time and in a wider, more offshore context.

2.2 The morphological method

The morphological analysis of the Belgian coastal and inner shelf area compares basically successive surface elevation maps, made of all available surveys. The following method is adopted for all research questions:

- Make rasters of all surveys, preferable of the same cell size and make sure the cells of successive surveys are aligned.
- Display all elevation maps using the same elevation colour classes (Figure 2-1 and Figure 2-2).
- Make elevation difference maps where the oldest maps is subtracted from the newest. Make a series of "step 1" difference maps (difference between successive surveys) and a series of "reference" difference maps (difference between each successive survey and a chosen reference survey. This can be the first of the last of a series through time).
- Display all elevation difference maps using the same elevation difference colour classes (Figure 2-3).
- The uniform map series can be switched on and off and queried in GIS.
- A very useful analysis strategy is to define in GIS a fixed geographical extent that shows the complete area of the morphological issue under study. The successive elevation and elevation difference maps can be exported in a Powerpoint slide show. Here, geographical change through time of erosion and sedimentation areas can be identified.
- Another useful strategy is calculating elevation contour lines and displaying some selected lines on all successive surveys. Also here, use a standardised legend (same colour or line type for same elevation). The superposed contour lines of successive surveys can be displayed in the same geographical extent and exported in the Powerpoint slide show. Here, movements of the selected contour lines through time are easy to identify.
- Define specific delimited areas based on the morphological issue that is under study. The default defined areas are the coastal sections and tracts (Houthuys et al., 2026).
- Calculate the volume beneath the bed surface for each available survey and contained inside the specific delimited areas. The volume is then often subtracted from the corresponding volume of a reference survey. The evolution through time of the volume differences per delimited area can be reported in tables or graphs.

Figure 2-1 and Figure 2-2 are the topographic and bathymetric elevation colour legends used throughout this chapter. Figure 2-1 uses half-metre classes and is best suited for the nearshore zone. The legend also renders the beach and dune elevations. Figure 2-2 uses metre classes and is optimal for the depths found on the Belgian shelf. Figure 2-3 shows the legend used for elevation difference maps used throughout Chapter 2.

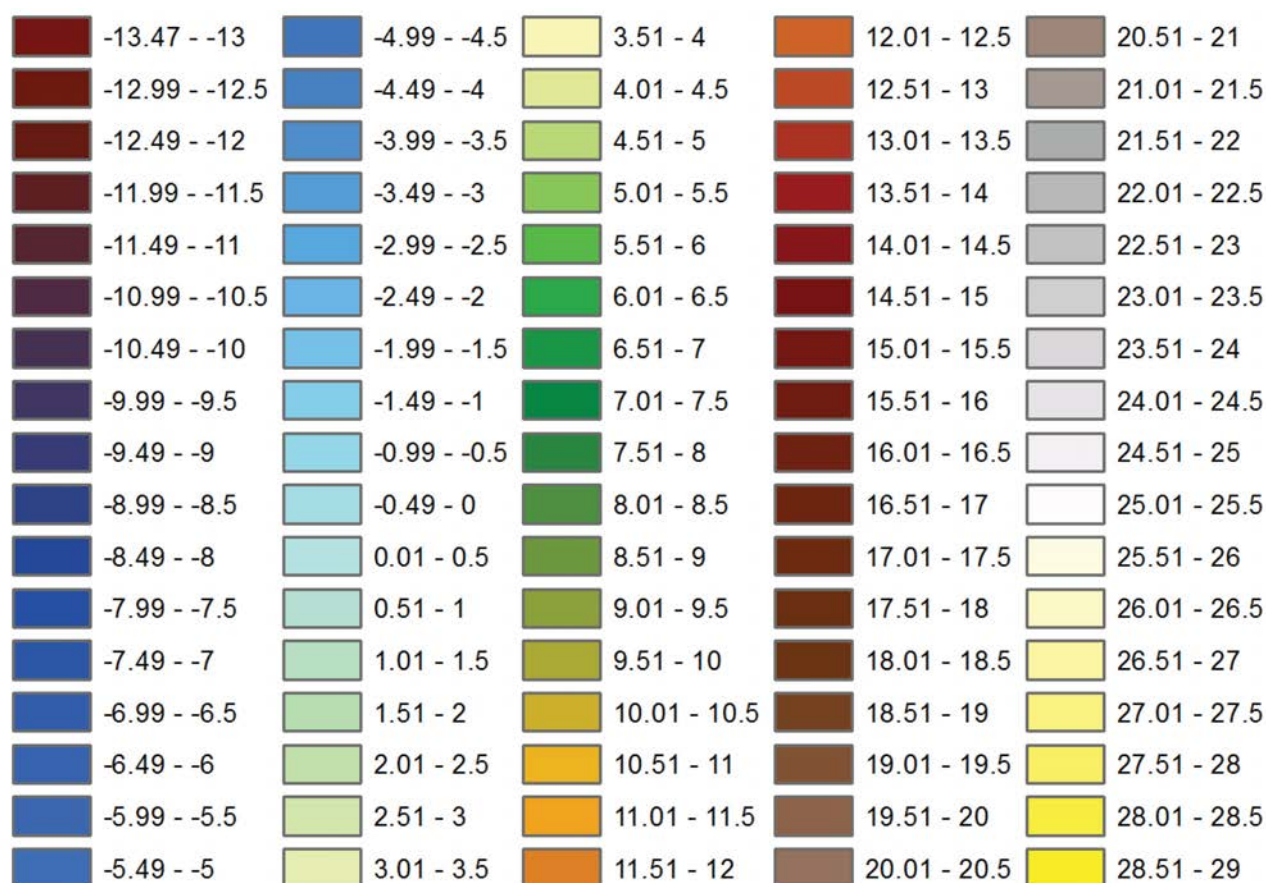


Figure 2-1 – Topographic-bathymetric legend 1 used throughout Chapter 2.
All elevations are in m TAW (negative depths); half-metre classes.

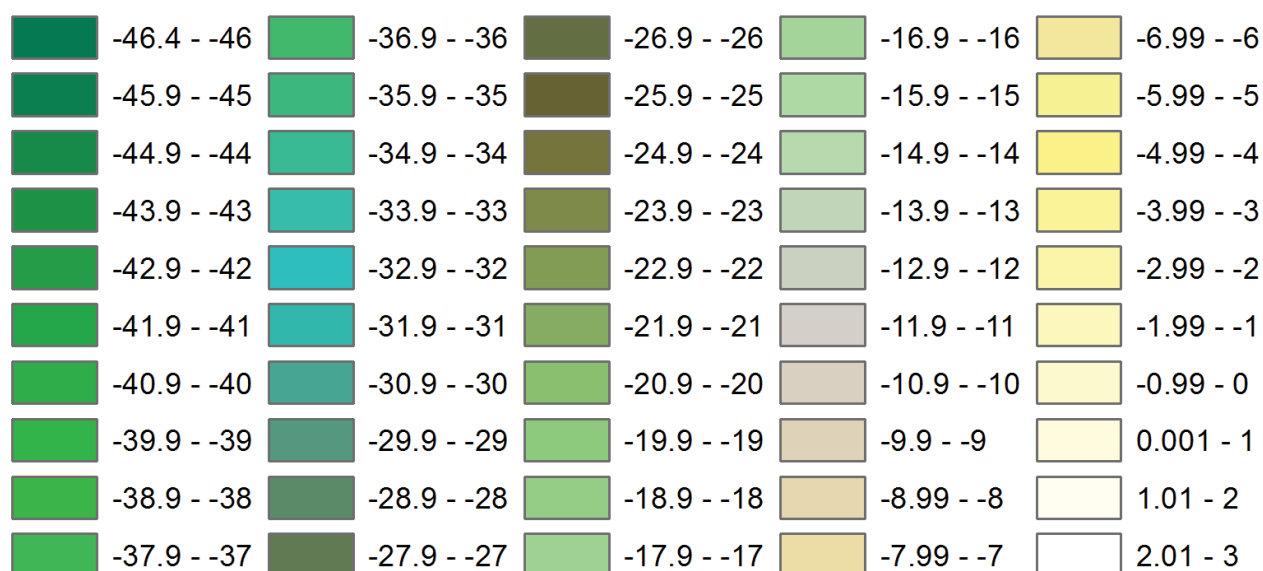


Figure 2-2 - Topographic-bathymetric legend 1 used throughout Chapter 2.
All elevations are in m TAW (negative depths); metre classes.

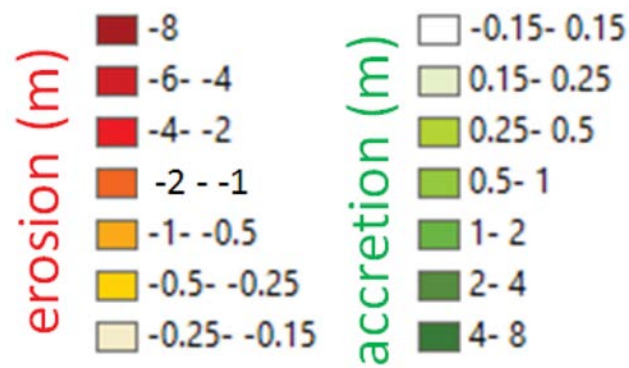


Figure 2-3 – General legend for elevation difference maps used throughout the morphological data analysis.

The Powerpoint presentation prepared for this study contains several series of maps, like used in the following Sections. This presentation also contains the underlying graphs and drafts of figures used. Other graphs have some Excel files containing the processed and displayed data. All this supporting material is available at FHR in the MOZES records.

2.3 Dealing with data uncertainty

The old map sources used in this study are presented in §2.4. Here, general remarks about location and depth uncertainty are grouped as they are of general application in the morphological study. The contribution of the different sources of error was explained in more detail in the report of the second working year (Dujardin et al., 2024, §2.2).

2.3.1 Location error

Location in the 19th and first half of the 20th century depended on on-board triangulation (Van Cauwenberghe, 1971). Lat-long triangulation based on the sun and the stars was well known. When the coast was visible, high fixed points such as bell towers could be used to do terrestrial triangulation. No in-depth studies of the error caused by this method are known. As an approximation, when the coast was in sight, the error is estimated at 50 m. When no fixed marks at the coast were available, the error is estimated at 100 m.

Electronic positioning systems have been used since World War II and continued to improve (Van Cauwenberghe, 1971).

Another error may arise from georeferencing plan scans of old paper maps. As all reference marks are used and an "Adjust" transformation has systematically been applied, it is thought that this does not add to the error.

Nevertheless, a visual check was performed on the fit of planimetric elements along the coast against the same elements on recent high-quality maps. Deviations ranging between 0 and 100 m were observed. As the planimetry was probably not always meant to be very detailed, it can be assumed that the error estimated from the match of planimetric elements is about 50 m.

The thickness of the lines on the maps is 15 to 20 m while some bold lines are even 50 m wide. Obviously this is related to the relatively small scale of these maps. The location of the depth points is not always clear. On the 1938 chart, figures are often 250 m wide and 125 m. Locating the point in the centre of the figure causes an uncertainty of the order of 50 m.

For modern surveys, since the 1970s, the planimetric error is often below 1 m.

For completeness, uncertainty on topographic position is usually much better. In recent Lidar surveys, it is maximally 0.1 m (RSME).

2.3.2 Depth error

Depth measurements were done manually using a lead line. This method was mechanized in the 19th century. The reading had to be reduced to a reference water level. Inshore, the error on this measurement was probably less than 0.5 m, offshore it probably exceeded this value.

On the 1866 chart, depths below -10 m are generally rounded to whole metres. This introduces an additional error of 0.5 m.

Héquette & Aernouts (2010) mention an error range, which includes the error range of the instrument (sounding line in 1911 and single channel echosounder in 1977) as well as errors due to inaccuracy in ship positioning and to tidal correction, estimated at ± 1.0 m in 1911 and ± 0.6 m in 1977, for bathymetric data on hydrographic field sheets of the French Hydrographic Survey in the Calais area.

The reference level is the (lower) low water surface. This was probably well known in the nearshore but no knowledge was available on this surface in the offshore domain. In addition to this, the reference surface must have risen through time along with general sea-level rise. The DEMs of the shelf have been corrected for sea-level rise (see §2.4.7).

It can be assumed that all small-scale navigation charts show a selection of local shallowest points. This is common practice to ensure safe navigation. For morphology studies, this selection introduces a depth bias: certainly on ridges and in shallow areas, the shallowest points determine the charted depth points and therefore the DEM bed values. Often, submerged dunes are present in these areas. The magnitude of the bias depends on the height of these dunes and may vary from a few decimetres to even a few metres on some parts of the Flemish Banks. An a-posteriori correction for this bias cannot be performed, as dune fields are often very mobile.

Bathymetric surveys in the recent decades are much more reliable. Not only do modern positioning and sounding systems perform better, also the cover in depth points is much higher than earlier on.

In the study of the sediment fill of the access channel to Oostende (see §2.8), several surveys were available that had been done on the same day, one using SB (single-beam echosounding), the other MB (multibeam echosounding). One overlapping survey was selected (datasets 140402_PVS_SB_210 and 140402_RO_MB_300) to get a feel on depth uncertainty on modern bathymetric surveying. It appears that depth differences between both simultaneous surveys of 5 to 15 cm occurred. The differences were more or less equally spread over the overlapping area, with the SB dataset being on average 0.087 m deeper than the MB data.

In the practice of the present morphological study, an uncertainty on depth was adopted as follows:

- +/- 0.5 m for averages over wide areas, to +/- 1 m on individual points, for the old bathymetric charts of 1804-1938,
- +/- 0.25 m for the inner shelf bathymetric surveys of the 1960s to early 1990s,
- +/- 0.15 m for the recent bathymetric surveys.

For completeness, uncertainty on altimetry is usually much better. In recent Lidar surveys, it is maximally 0.05 m (RSME). Deliveries are independently controlled. Control checks often report an uncertainty between 0.02 and 0.04 m.

2.3.3 Error on depth difference

For the propagation of uncertainty on depth when two depths are subtracted, the usual rule is followed that the adopted uncertainty is multiplied by the square root of two.

To assess the uncertainty of the volume differences: they are obtained by multiplying the volume difference area by the uncertainty on elevation difference (0.21 m for modern nearshore bathymetry and 0.05 m for modern Lidar survey altimetry).

2.3.4 Error on depth series

The study of morphological change makes use of series of subsequent surveys of the same area. As a consequence, all elevation or volume time series allow to assess consistency in time of observed trends. In the volumes reported in the coastal trend study (Houthuys et al., 2026), statistical indications of error are reported systematically with the calculated trends per section or tract.

The present study mainly examined the submerged domain. Especially here, it has generally been observed that morphological change is slow and consistent. So, as a general rule, if random change is observed, this is already a reliable indication of a large contribution of depth errors in the consecutive bathymetric surveys. Complementary, when morphological features, depths and volumes change in a consistent way through time, this change has a higher confidence compared with locations where morphology, depths and volumes are scattered through time. The higher the number of available surveys, the better the confidence.

2.3.5 Error on depth trend

Similar observations apply to the error on depth trend through time. In each location, the successive depths can be plotted in a time graph. If the points are scattered around the zero line, there is no systematic trend of the depth in that location. If the points display a systematic change in time, this change can be expressed by the trend (slope of the linear line fit through the points). The standard error of the slope is a good measure of the error of the trend: the smaller the standard error, the more reliable the trend.

2.3.6 Conclusion

The (standard) error on the pre-1950 bathymetric charts can be evaluated at about 100 m on location and between 0.5 and 1 m on depth. The error increased from inshore to more offshore areas. In morphological assessments, sea-level rise and depth point selection bias must be allowed for. For bathymetric surveys in the following decades, the error is evaluated at +/- 0.25 m. From the 1990s on, it is about +/- 0.15 m. If the change of morphological features and depth at a certain location shows a consistent trend through time, this trend has a higher confidence compared with locations where depth values are scattered through time. The higher the number of available surveys, the better the confidence of the observed trend.

2.4 Inventory and digitisation of morphological and sedimentological data

2.4.1 Data gathered and used in this study

The quantity and quality of bathymetric and topographic data of the Belgian coast and shelf assembled in this project are the backbone of the subsequent analyses and interpretations. A large amount of work has been invested to obtain these data.

All useful dune and beach elevation maps and nearshore and shelf bathymetry charts have been gathered and, if not yet available in digital form, digitised and vectorised. The surveys belong to these categories:

- Belgian shelf and neighbouring parts of the Dutch and French shelf:
 - Historic bathymetric surveys of large parts of the Belgian shelf (1804, 1866, 1908, 1938): vectorised in this project. It can be assumed that the surveys underlying these published charts spanned one or more years preceding the publication date.
- Recent bathymetric survey mosaics of the Belgian shelf (2004, 2014 and 2022 sets): extracted from bathymetric database Triton, complemented with surveys of the Dutch part (see §2.4.5). Belgian inner shelf: 1960s, 1970s, 1980s, 1990s bathymetric surveys: vectorised in this project (outsourced).
- Belgian nearshore and beach:
 - 1980s-1990s nearshore bathymetry: vectorised in this project (outsourced).
 - 1980s-1990s beach and dune front elevation: vectorised in this project (outsourced).
 - Recent nearshore bathymetry: digitally available since 1998.
 - Recent beach and dune front elevation: digitally available since 2000.

The last two datasets consists of yearly, often twice-yearly Lidar DEMs of the beach and dune front; yearly nearshore SB echosounding DEMs; and occasional MB echosounding DEMs of particular nearshore areas. This dataset is described and analysed in Houthuys et al. (2026). That study also assembled and analysed nourishment volumes and dredged volumes near the beaches. The results of Houthuys et al. (2026) are used and integrated in this study.

Some additional sources, used more sporadically, are:

- The 1828 dune map of the Belgian coast.
- The 1874-1885 Public Works dune map

Data on dredged material disposal in the inner shelf zone are from Van Lancker et al. (2004) and Fettweis (2024). Finally, also recent data on the bed surface sediment type have been gathered.

2.4.2 Outsourced vectorisation of beach elevation, nearshore and inner shelf bathymetry

A lot of 1960s to 1990s surveys are preserved at Coastal Division in Oostende. All relevant charts and maps have been scanned and are available as good-quality images. The information held in these scanned maps is mostly not available in digital vector format. In the MOZES project, a selection of representative surveys was vectorised so that DEMs could be made. In view of the amount of work, this part of the project was outsourced.

2.4.2.1 Selection and preparation of the scanned images

Table 2-1 gives an overview of the selected surveys and involved plans to be vectorised.

Table 2-1 – Overview of the outsourced vectorisation work.

Map type	Survey	Source of elevation	Scale	Number of sheets
Situatieplan (beach and dune front)	Spring 1983	Photogrammetry	1/1000	41
Situatieplan (beach and dune front)	Spring 1985	Photogrammetry	1/1000	7
Situatieplan (beach and dune front)	Spring 1989	Photogrammetry	1/1000	16
Situatieplan (beach and dune front)	Autumn 1989	Photogrammetry	1/1000	25
Situatieplan (beach and dune front)	Storm 1990	Photogrammetry	1/1000	41

Situatieplan (beach and dune front)	Spring 1992	Photogrammetry	1/1000	41
Plan van vooroeverloding (nearshore)	Spring 1986	SB echosounding	1/5000	1
Plan van vooroeverloding (nearshore)	Autumn 1987	SB echosounding	1/5000	1
Plan van vooroeverloding (nearshore)	Autumn 1989	SB echosounding	1/5000	3
Plan van vooroeverloding (nearshore)	Storm 1990	SB echosounding	1/5000	3
Plan van vooroeverloding (nearshore)	Spring 1992	SB echosounding	1/5000	8
Minuutblad van loding (inner shelf)	1962-1969	SB echosounding	1/20,000	3
Minuutblad van loding (inner shelf)	1974-1978	SB echosounding	1/20,000	3
Minuutblad van loding (inner shelf)	1984-1987	SB echosounding	1/20,000	3
Minuutblad van loding (inner shelf)	1991-1993	SB echosounding	1/20,000	3

Most of the scanned beach maps had at the time of scanning been georeferenced using a 1st order polynomial affine transformation based on four control points. This is ok for a quick visual inspection of the contents, but not sufficient for the accuracy that can be obtained and is required in this project, as the original paper maps were rolled or folded and are thus distorted. The nearshore maps and inner shelf maps have not even this simple georeferencing. Therefore, the maps of each vectorisation work package were georeferenced before sending the images out for the outsourced vectorisation work.

All maps show gridlines or crosses marking either geographical coordinates, the projected system UTM31 based on ED50 or the Belgian Lambert 1972 system. The program cConvert provided by the National Geographic Institute was used to convert coordinates to the target system, Belgian Lambert 1972.

Georeferencing was done in GIS using all available reference marks inside the information part of each map to define transformation links to the target coordinates, that can be read off the maps. For a best fit, a spline transformation was used. After the links have been placed, the transformation information is stored in an auxiliary file .AUX.XML using the Update Georeferencing command. The original raster dataset is not changed.

2.4.2.2 Specifications of the outsourcing

The main criteria were:

- Vectorise all elevation or altitude information, and the outline of groynes and seawalls on the plan.
- Deliver elevation or bathymetric contour lines as a polyline shapefile; deliver elevation or bathymetric depth points as a point shapefile. The elevation or depth value is stored in an attribute taking the value such as on the map.
- Quality of the work is evaluated based on these criteria:
 - o completeness
 - o location correctness: 1 m deviation allowed for maps on 1/1000, 5 m for 1/5000 and 10 m for 1/20,000
 - o value correctness
 - o topological correctness (e.g. no crossing contour lines)

An invitation to submit a quotation was sent to 4 providers. Based on the selection criteria (price 30%, delivery time 30%, quality 40%) the work was outsourced to Sparks bvba, 1601 Sint-Pieters-Leeuw.

2.4.2.3 Inspection of deliveries

Overall, the outsourcing went very well. Deliveries were on time and of high quality. Of each partial delivery, an inspection was done using the quality specifications and an inspection report was made.

The detailed specifications, list of successive assignments and deliveries is documented.

2.4.3 In-project vectorised data of the Belgian shelf

The hydrographic maps of the Belgian continental shelf allow us to study large-scale morphological change on the time scale of two centuries. They were digitized in this project, and a 10m-DEM was made of each available map.

2.4.3.1 Description

The 1866-1908-1938 maps were selected, scanned and used in the project Quest4D (Janssen *et al.*, 2012). The 1804 maps are an additional source allowing us to push back the start of the observation period, at least for the inner shelf and the mouth of the Westerschelde. The maps were made under French rule to build an important harbour in Antwerp. They were measured using geometer principles and can therefore be considered as the first reliable map of the area (Baudez, 1989). Here are some metadata:

1804 (2 maps)

Name on the map: (1) Reconnaissance hydrographique de la côte Nord de France. Covers the inner shelf including the Flemish Banks from Gravelines to Oostende. (2) Carte réduite des côtes des Pays-Bas (depuis Ostende jusqu'à Hellevoetsluis).

Author: C.F. Beauteemps-Beaupré

Coordinate system on the map: (1) for longitude: nautical miles east of Calais. Latitude not specified, probably orthonormal. Distances are in nautical miles (60 miles per degree: 1 mile = 1.852 km). (2) Lat-long. Longitude east with respect to the meridian of the Paris Royal Observatory (2°20'14,025" east of Greenwich)

Datum: local lower low water at spring tide. Depths are in feet (pied de France or pied du roi, set equal to 4500/13853 m = 0.3248 m in 1799) (fr.Wikipédia.org, Anciennes unités de mesure françaises) (conversion table to m available on map (2))

Survey period: (1) 1802 – 1803 (Baudez, 1989). Map mentions publishing date Vendémiaire An XI (September-October 1802); however, Baudez (1989) states it was published in 1804 (2) 1801 – 1811; the Westerschelde part in 1804 (Baudez, 1989). Map was published in 1817.

Map scale: 1/100,000



Figure 2-4 – Extract of the 1804 chart near Oostende.

1866

Name on the map: Carte Générale des Bancs de Flandres compris entre Gravelines et l'embouchure de l'Escaut

Author: A. Stessels

Coordinate system on the map: geographical coordinates, zero meridian of Paris (2°20'14,025" east of Greenwich)

Datum: local low water at spring tide (metres)

Survey period: not mentioned. Map was published in 1866.

Map scale: (1) 43 nautical miles in 0.9 m $\cong$ 1/88,500 (marks on map), probably same scale as next; (2) 1/88,888 (Baudex, 1989)

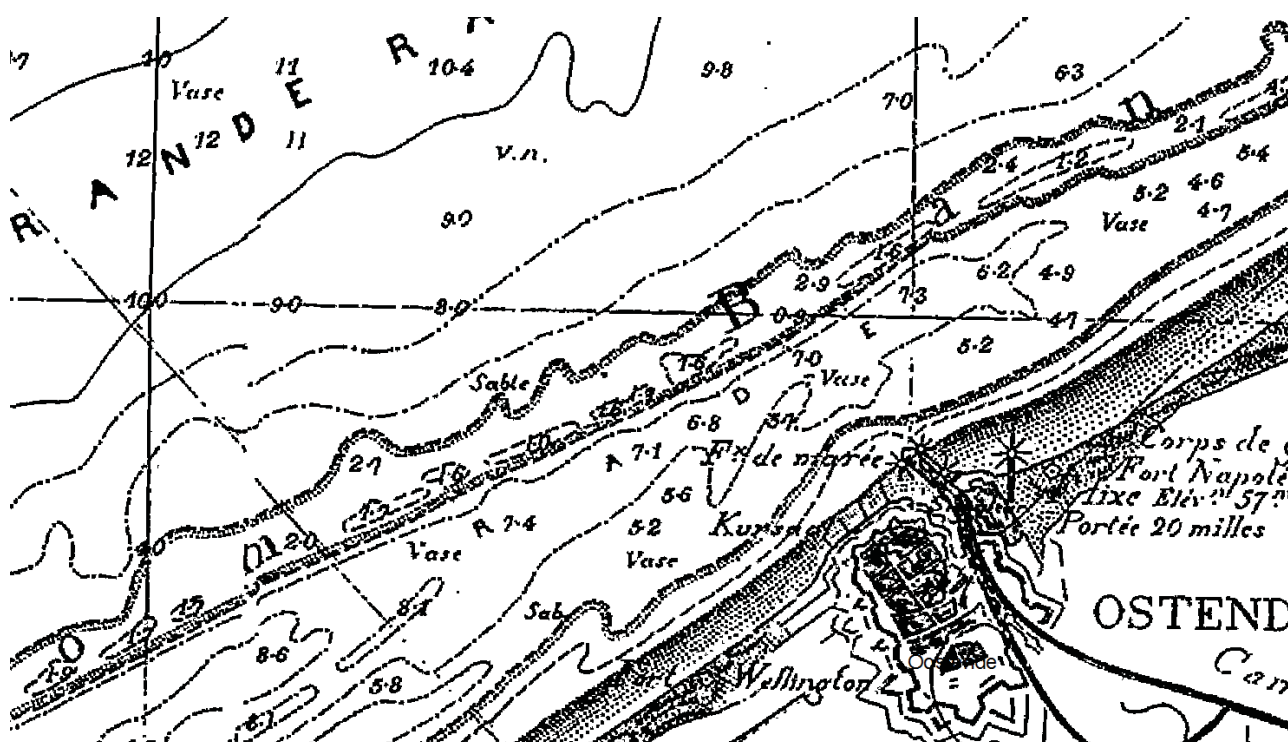


Figure 2-5 – Extract of the 1866 chart near Oostende.

1908

Name on the map: Mer du Nord – Dunkerque-Flessingue

Author: Ponts et Chaussées, Service special de la côte, Hydrographie

Coordinate system on the map: geographical coordinates, zero meridian of Greenwich

Datum: local low water at spring tide (decimetres)

Survey period: 1901-1908 + updated until 1st May 1911.

Map scale: 1/80,000

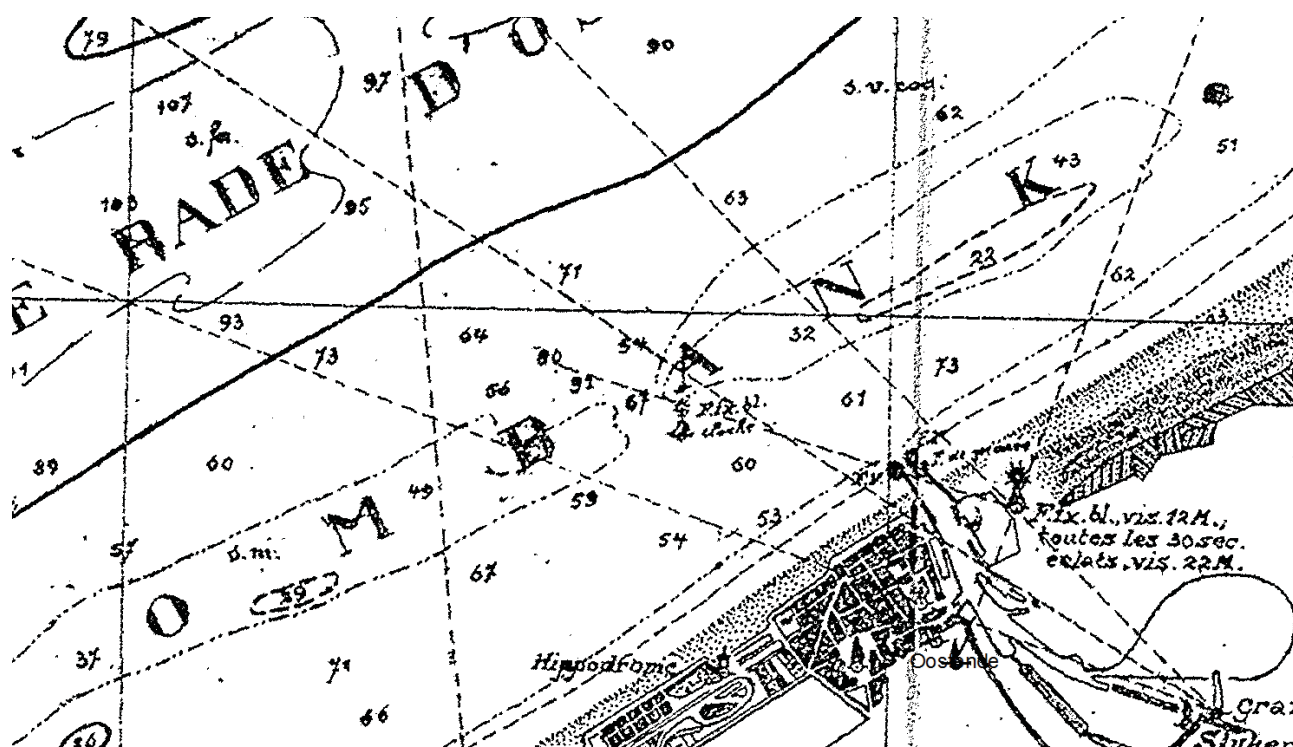


Figure 2-6 – Extract of the 1908 chart near Oostende.

1938

Name on the map: Noordzee, Vlaamsche Banken 1938

Author: M.J. Lauwers, assisted by P. Wessels and L. Vercruysse, Ministerie van Verkeerswezen, Beheer van het Zeewezen, Hydrographie

Coordinate system on the map: geographical coordinates, zero meridian of Greenwich

Datum: local low water at spring tide (decimetres)

Survey period: 1938 (probably also the preceding years).

Map scale: 1/100,000

The map was complemented by Dutch and French data in the periphery. The map contains insets of the ports of Dunkerque, Oostende, Zeebrugge, showing more detail for the local bathymetry.

The error remained the same. Afterwards, a spline transformation was used, that reduces the error to zero at the reference marks.

All depth points and depth contour lines on both 1804 maps were digitized in the current project. It is clear from the two maps that the depicted depth contour lines were constructed from the depth points that are also shown in the maps. As the number of depth points is limited compared with recent surveys, the depth contour lines are often poorly constrained, resulting in wobbly lines. Where the modern maps show that the large-scale morphology has straight, streamlined features, the wobbly 1804 contour lines were somewhat generalized to better match the modern morphology. In the overlap area between both maps, most contour lines match. Where they deviated, a gradual transition was made through the overlap area from the western to the eastern map. The depth points in the overlap area that do not clearly match were digitised from both maps.

Depth labels on the 1804 charts are in feet. The usual French feet at that time is 0.3248 m (see description of chart above). The depths were converted in metre using this value.

The 1866, 1908 and 1938 maps were georeferenced by Janssens et al. (2012). They made use of all available coordinate reference marks and used the transformation "Adjust". This uses a calculation aimed at obtaining both local and global precision.

The -8 m depth contour and the depth points had already been digitized by Janssens *et al.* (2012). Clearly, some automated method was used that also caused a few local errors. As an example, sometimes number labels were interpreted as depth contours. This has been corrected. Some depth points are located on wrecks and are shown between brackets. They have been removed, as they are no representation of the bed. The remaining depth contours of the 1866 map were digitised in the MOZES project.

The same procedure was followed for the remaining maps. In a few localized cases where large submerged dunes are now known to occur, the intricate course of the contour lines has somewhat been generalized.

A special processing step was applied: the construction of interpreted additional contours. This was thought to be necessary as the number of depth points was relatively small compared with the complex sandbank morphology, so that these large bed features were not optimally described. In addition, in deeper water, no depth contour lines are present on the charts. For instance, the 1938 chart does not contain contours below -10 m. This step proved crucial to produce a realistic seabed morphology model.

Using only data pictured in the charts produced often angular digital terrain surfaces (in GIS, for this a TIN or Triangular Irregular Network surface is used) with false interpolations. To overcome this problem, additional contour lines were interpreted for all four charts. In shallow areas, often additional contour lines were interpreted at half depth intervals between the existing contour lines. In deeper water, often no contour lines were present on the charts and sufficient contour lines to describe the large-scale bed morphology were added. The position of the interpreted contour lines was confined by the existing contour lines and by the depth points. By adjusting the distance between the existing contour lines, an interpreted morphology can be added. For instance, a convex ridge top surface can be created by shifting the intermediate interpreted contour line somewhat towards the deeper of the existing contour lines. Also crest and trough terminations can be better expressed using intermediate depth contours. The style and shape of the interpreted contour lines was inspired by the modern bathymetry, which is available at high resolution and accuracy. The fact that the position of the interpreted contour lines is confined by the contour lines and depth points present on the chart avoids the introduction of a bias imposed by the present-day morphology. Only the shape of the morphology was adopted, where possible, so as to considerably improve the morphology that was often poorly interpreted on the old charts.

In addition, a few additional depth points were added, with an interpreted depth value. This was done where a structure line would otherwise intersect surrounding depth contours.

For the construction of the 10 m-DEM of the 1974-1978 inner shelf survey, due to the lower density of survey points, additional depth contour lines were digitized from the original maps in some selected areas where large dunes are found.

After completing the interpreted additional contour lines and depth points, structure lines were added in a separate 2D polyline shapefile. The structure lines represent trough and crest lines and also slope lines where the slope is not evident from the surrounding contour lines. The structure lines are introduced to impose triangle edges during setting up the TIN surface. The structure lines are inserted in the TIN as "hard lines" so that no triangle intersects a structure line. The structure lines are first created as 2D polylines. The polylines are drawn so that vertices are only placed on depth points or at intersections (often vertices) of the depth contour lines. This is necessary to avoid false depth assignments along the line segments of the structure lines.

The structure lines were made 3D features as follows. A temporary TIN was made using the depth points and depth contour lines as input. The latter were inserted as hard structure lines. The 2D polylines of the structure line file were then assigned Z coordinates by using the ArcGIS tool "Interpolate Shape" where the temporary TIN was the Input Surface, and the 2D polylines were the Input Feature Class. Checking "Interpolate Vertices Only" ensured that Z values were only derived at the polyline vertices that lie on data points and lines from the chart. The result of this operation is a 3D polyline file: this contains Z values all along the line segments and they are interpolated linearly between the vertices.

2.4.4 Processing of digitised data into DEMs

A similar procedure was used to process into DEMs on the one hand the outsourced vectorised depth and elevation data and on the other hand the in-project produced depth data of the 1804, 1866, 1908 and 1938 charts.

2.4.4.1 General procedure

The produced elevation and depth vectors (lines and points) of each survey are input for a TIN surface. The elevation attribute is used as elevation input in the TIN. The elevation or depth has to be converted to a datum that can be converted to TAW (this is specific per data source and is explained in the following sections). The raw TIN is next delimited to the data area, i.e. the area covered by contour lines and depth or elevation points, so that no extrapolations are made. Afterwards, a raster was interpolated on the TIN. For bathymetric surveys, 10 m-cell rasters were produced. For topographic surveys digitised from 1/1000 scale plans, 2 m-cell rasters were produced. If the raster is not yet in TAW, a final conversion from LAT or M(L)LWS to TAW is done.

2.4.4.2 Specific steps for the outsourced vectorised data

These are the specific steps according to the source data type:

- beach and dune foot maps
 - The surveys have elevation points or contour lines with reference to Z MOW. In the vectorisation delivery shapefiles, a field was added in the attribute table with the elevation in TAW (this was obtained using Field Calculator by subtracting 0.11 from the elevation value).
 - Most of the areas inside groins, the seawall slope and the boulevard contain no elevation data on the vectorised maps, except for a few altitude points. In order to produce a realistic terrain surface, these areas are filled with more recent available data (i.e. from the Autumn 2000 survey). This strategy supposes no change has occurred since the processed survey on the structures, which is certainly the case for the large majority of the structures. Even in the case of a change, this remains the best strategy to avoid interpolations through the groins as a flat area.
 - Add some breaklines (e.g. in troughs and along bar crests, between elevation points on the seawall) to avoid spurious interpolations.

- nearshore maps:
 - The surveys have elevation points with reference to Z MOW. In the vectorisation delivery shapefiles, a field is added in the attribute table with the elevation in TAW (this was obtained using Field Calculator by subtracting 0.11 from the elevation value).
- inner shelf maps:
 - The inner shelf maps are in dm below MLLWS (= "H"). In the point shapefiles, a field is added to contain the elevation in m MLLWS; this is calculated from the field "Hoogte" using Field Calculator. This elevation is input to a TIN and then a 10 m-raster in MLLWS. The latter is then converted to TAW using Raster Calculator with the following expression: "[current raster] - "gllws_to_taw_vlaamsebanken_l72.tif"
 - We also make a mosaic raster in TAW of the entire project area using three neighbouring surveys of successive years. If a gap is present between the rasters, an auxiliary raster is first made from a TIN interpolating the survey points around the gap. The mosaic preserves the cell values of the most recent survey in overlapping areas.

2.4.4.3 Specific steps for the in-project vectorised 1804, 1866, 1908 and 1938 data

A definitive TIN was made, using the in-project vectorised depth points and contour lines and the 3D structure lines, both as hard lines. On this definitive TIN a 10 m-raster was interpolated.

A final step consisted in converting the raster to TAW. All map values were first converted to metres below chart datum (M(L)LWS) (depths are negative values after conversion). It was assumed that the measurements in the chart can be converted using a conversion grid from LAT to NAP (instead of M(L)LWS to NAP) and then adding 2.333 m to convert from NAP to TAW. The use of the LAT to NAP conversion grid assumed that the error introduced by assuming depth values in LAT instead of M(L)LWS is smaller (maximum 0.15 m at Nieuwpoort) than the possible errors introduced by interpolating several reduction grids. The additional possible error is also much smaller than the estimated error on depth (§2.3).

The 1804 map clearly mentions that depths were reduced to MLLWS. The 1866, 1908 and 1938 mention depths are in MLWS. However, when series of DEMs are played through time, it was clear that only in the 1938 chart the bed was overall deeper than in all other maps. The same appeared from graphs displaying average depths inside defined boxes. Overall, systematically deeper values appeared by 0.3 to 0.5 m with respect to the time trends using the other surveys. A difference ranging from 0.37 and 0.43 m between the MLWS surface and the MLLWS surface was reported from tidal observations at the Belgian coast over the period 1941-1970 (Van Cauwenberghe, 1977). It was concluded that in spite of the specific map legends, the 1866 and 1908 were actually in MLLWS, while the 1938 chart used MLWS. To compensate for this inferred different datum per chart, a correction was applied to the 1938 DEM: the DEM values were reduced by 0.4 m, so as to simulate a DEM in MLLWS.

2.4.4.4 Produced data sets

These data sets have been produced for the charts of year (YYYY) 1804, 1866, 1908 and 1938:

- depth points: point shapefile YYYY_pt.shp, with attribute "z" containing depth in metres (depths are negative values) and attribute "Source" containing "map" for points digitized from the map and "int" for interpreted depth points
- depth contour lines: 2D polyline shapefile YYYY_pl.shp, with attribute "z" containing depth in metres (depths are negative values) and attribute "Source" containing "map" for contour lines digitized from the map and "int" for interpreted contour lines
- structure lines (crests and troughs): 3D polyline shapefile YYYY_RidgeTroughLines3D.shp. The z coordinate of the vertices of the structure lines are derived from the previous two files
- depth raster (resolution 10 m): G_YYYY_TAW_10

These data sets are located here:

P:\20_079-MorfoInteract\3_Uitvoering\Deeltaak1_DataAcquisition\Shelf\YYYY.

This location also holds the georeferenced image that was processed.

2.4.5 Collection of recent shelf DEMs

Recent shelf DEMs are digitally available in the Flemish Hydrographic Database TRITON. For the large-scale analysis of the inner shelf area that is of relevance to the coastal morphology, it was decided to extract three time steps. The exported data were converted to Lambert 1972. It was also attempted to extend the surveyed area with the neighbouring part of the French and Dutch coastal shelves. These resulting data sets are located here: P:\20_079-MorfoInteract\3_Uitvoering\Deeltaak1_DataAcquisition\Shelf\YYYY.

2.4.5.1 2004 (1999-2005 surveys)

The dataset `kub_bth_gllws_mt_19992004_20m_L72.tif` was exported in Lambert 1972. It is a mosaic of surveys conducted between 1999 and 2004 at 20 m resolution. It was converted from MLLWS to TAW using the conversion raster `"g_latnap_L72r"`. This operation assumes the error of neglecting the vertical difference between MLLWS and LAT is of the same order as the error present in the individual mosaicked surveys. The cover was extended using Dutch `"vaklodingen"` conducted in 2005 (20 m cell size), and exported in Lambert 1972 and TAW. This extension was mosaicked to the Belgian cover, where in the overlap the Belgian survey was given priority. For the sake of subsequent grid operations, the 20 m cell raster was resampled to 10 m resolution.

The final assembled raster is `G1999_2005TAW`. In the large-scale morphological analysis, this raster is short referred to as `"2004"` and in calculations also the date of 2004 is used.

2.4.5.2 2014 (2004-2014 surveys)

A mosaic was made of two TRITON exports: `kub_bth_taw_mt_20042014_50m_L72.tif` (a mosaic of Belgian shelf surveys conducted between 2004 and 2014) and `kub_bth_lat_mt_2014_10m_L72.tif` (Dutch surveys of the Westerschelde outer estuary including the Zeebrugge area), after both rasters had been converted to negative depths and the second one from LAT to TAW. The mosaic is named `G2004_2014TAW` and has (for the Belgian part) been resampled to 10 m cell size. Unfortunately, the resample created linear interference patterns with a preferential west-east orientation. This pattern does not affect the processing and interpretation results on the scale of the shelf. In the large-scale morphological analysis, this raster is short referred to as `"2014"` and in calculations also the date of 2014 is used.

2.4.5.3 2022

2.4.5.3.1 Flemish Hydrography

A 10 m resolution raster was downloaded from <https://bathy.agentschapmdk.be/spatialfusionviewer/mapViewer/map.action> on 9 September 2022. It contains the date of 2 March 2022. This raster is in ETRS89 UTM31N with depths in LAT. Depths were converted to TAW by subtracting the raster `"lattotaw_vb2"` using Raster Calculator. In order to allow overlay operations, a projected version in Lambert 72 was produced using ArgGIS tool `"Project Raster"` and the transformation `"Belge_l1972_To_ETRS_1989_2"`. The result is the 10 m-raster `g202203tawl72`. The cover was extended for the wide Westerschelde mouth environment using Dutch `"vaklodingen"` conducted in 2022 (20 m cell size), and exported in Lambert 1972 and TAW. This extension was mosaicked to the Belgian cover, where in the overlap the Belgian survey was given priority. For the sake of subsequent grid operations, the 20 m cell raster was resampled to 10 m resolution.

The final assembled raster is G_2022_TAW. In the large-scale morphological analysis, this raster is short referred to as "2022" and in calculations also the date of 2022 is used.

2.4.5.3.2 EMODnet

In order to obtain a cover of the neighbouring French areas, with a resolution sufficient on the scale of ridges and channels, the EMODnet (European Marine Observation and Data Network; <https://emodnet.ec.europa.eu/geoviewer/>) most recent bathymetric dataset was downloaded on 24 May 2024. The downloaded datasets of tile E4 contain the area of interest of the MOZES project. These datasets were updated until 2022. They have a low resolution. The mean depth is based on a source resolution of 1/16 arc minute (~125 meter). The exported dataset is in WGS_1984 with depth in LAT. Transformed to the Lambert projection, the raster cells are rectangular and about 73 m wide by 115 m high.

The EMODnet 2022 dataset poses some challenges. First, the date of survey depends on the area of concern and varies widely. Second, it covers a very large area and has a relatively low resolution. Finally, it is in geographical coordinates and not projected. A projected dataset in Lambert 72 is however needed for overlay analysis.

Although the dataset carries the time stamp 2022, this is only the date of download. The data are a patchwork of older soundings (Figure 2-8). The part covering the Belgian Continental Platform contains surveys conducted between 2004 and 2021. It is probably largely the same data that underlie the 2022 Flemish Hydrography cover. The French part is older, using surveys conducted between 1970 and 1990.

Tile E4 contains a wide area down to the Spanish waters. It contains the mouths of the Westerschelde but not the Westerschelde itself. A clip was made of a sufficiently large area containing the MOZES area of interest using ArcGIS tool "Raster Clip".

Projecting the dataset in Lambert 72 not only produced rectangular grid cells, but also some empty cells inside the data area. The cells were populated with an average of the surrounding cell values using the tool Elevation Void Fill. This operation expands the raster with one row of cells. After creating a data contour polygon using the Raster Domain tool and trimming the filled raster on this contour using the Extract by Mask tool, a workable version of the EMODnet bathymetry in Lambert 72 was obtained. It was noted that interference patterns are present in this version. They appear only after zooming in. On the scale of the study area, the result is acceptable.

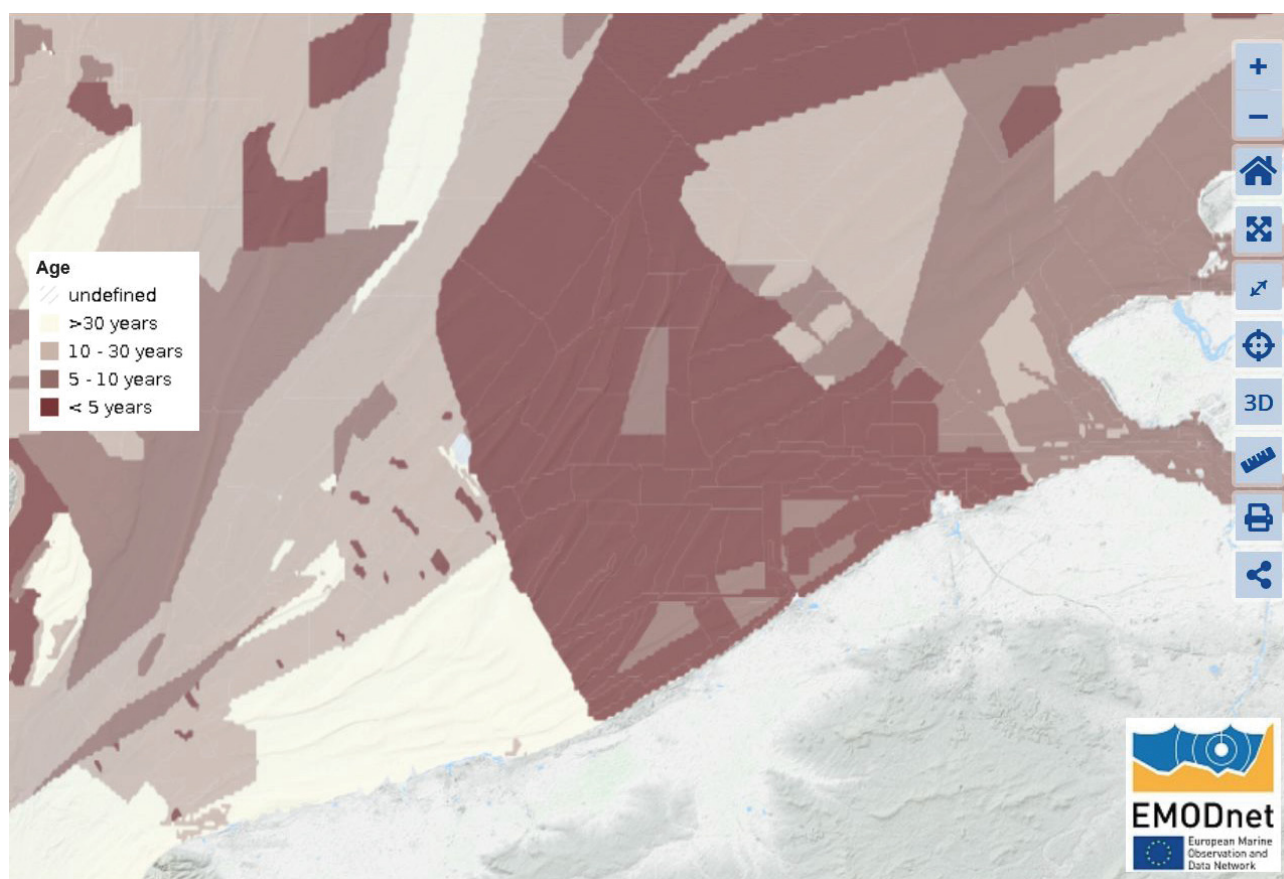


Figure 2-8 – Age map of the 2022 EMODNET bathymetric dataset.

2.4.5.3.3 Dunkerque windfarm

Inquiry with our French colleagues revealed that regular bathymetric surveys are no longer carried out on the French shelf off Dunkerque. This is unfortunate as the inner shelf near Dunkerque is highly dynamic. One small area adjacent to the Belgian inner shelf is affected by the development of an offshore windfarm. Here, a good-quality MB bathymetric survey was conducted in 2016 and 2017. The data underlying the preparatory studies of this project were kindly put at the disposal of the MOZES project by the French Direction Générale de l'Energie et du Climat.

The dataset contains a fine-resolution (cell size 0.5 m) RGB colour image of the bathymetry rendered in colour classes. The surface morphology is excellently imaged. Unfortunately, the pixel values are RGB colour values and not the depths. The bathymetric survey delivery report mentions the delivery of .asc files containing the depth values. They were not found in the delivered dataset. As the data received us in the final stages of the MOZES project, we no further insisted on receiving depth values. The colour image was used to verify the movements of the large-scale bed features. The area covered is the small ridge south of Oost Dijk, Binnen Ratel and part of Breed Bank (Figure 2-9).

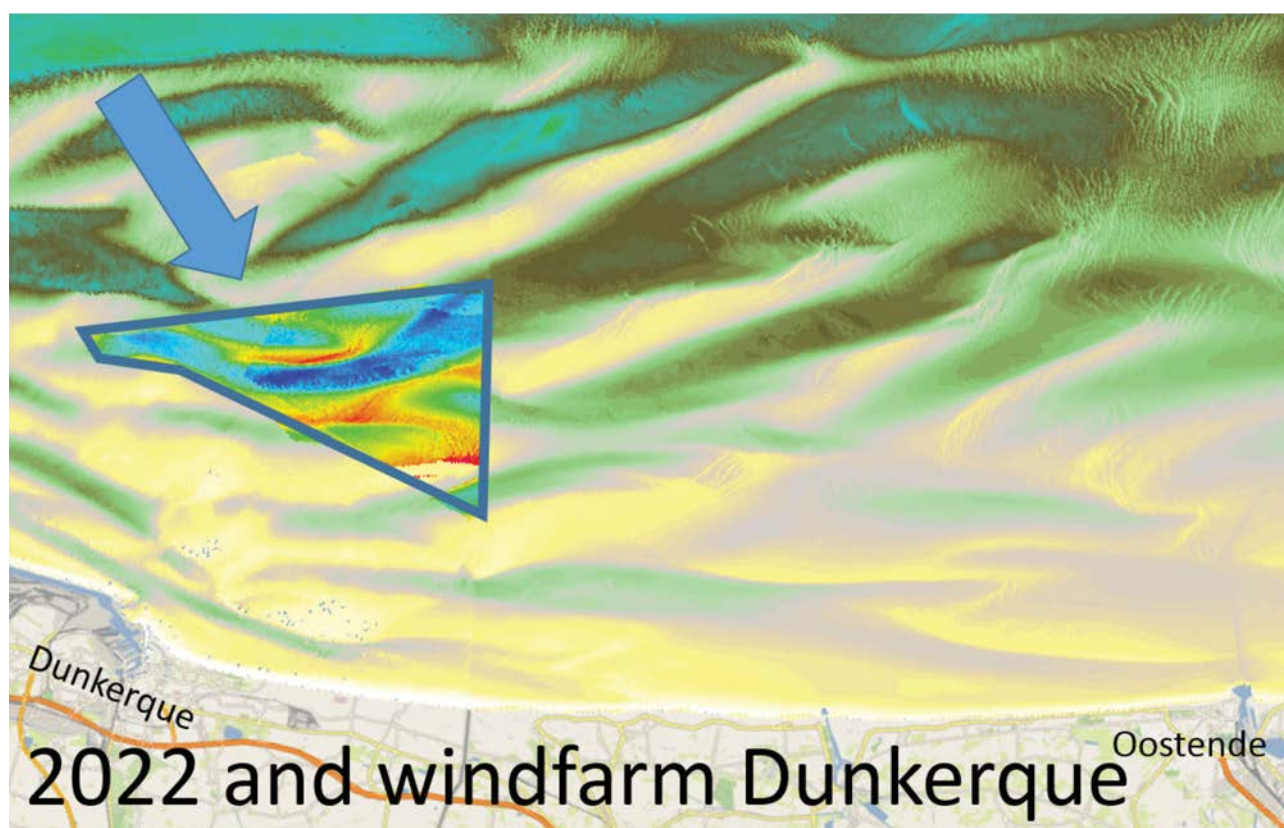


Figure 2-9 – Area covered by the 2016-2017 windfarm MB bathymetric survey (colourful triangle off Dunkerque).

2.4.6 Additional sources

2.4.6.1 1828 coast and dune belt map

Colleagues of the TESTEREP project informed us of the Belgian coast dune belt map, made under Dutch administration in 1828 and held in the Nationaal Archief at Den Haag (Quant, 1828). The Belgian coast is depicted at scale 1/15,000 in two long map sheets. Scans are available at Flanders Hydraulics. It is a pictorial map that accurately depicts the location, outline and shape of the coastal dunes at the time. It also shows the high- and low-water marks and coastal infrastructure such as groynes. The map was used in this project only to make some transects through the dune belt between Westende and Oostende.

2.4.6.2 1874-1885 Public Works dune map

The VLIZ archive contains 36 dune maps of the Belgian coast, made in 1874-1885. These maps are available as scans at VLIZ (their reference: **Ponts et Chaussées. Flandre Occidentale (1874-1885). Carte de la côte de Belgique 1:5.000 dressée entre 1874 et 1885. Administration des Ponts et Chaussées: Bruxelles**). They were requested and obtained from VLIZ and used in this project only to complete the transects through the dune belt between Westende and Oostende. These maps are an invaluable source of information on the state, location and altimetry of the Belgian dunes back then. The low- and high-water marks, elevation contour lines and infrastructure such as groynes are clearly depicted (Figure 2-10). Moreover, elevation and bathymetric profiles spaced about every 0.5 km are present on the map. The profiles also cross the complete dune belt. The dune shapes are shown using easily understandable symbols.



Figure 2-10 – Extract of the 1874-1885 Public Works dune map taken at Oostende.

Georeferencing of the maps needed for the long transects was relatively easy with errors of the order of 10 m, indicating a good geometric quality of the maps.

These maps are the first known source of the elevation of the beaches and the dunes at the Belgian coast. They were partly vectorised in this project, and they certainly deserve to be elaborated into DEMs in a follow-up project.

2.4.6.3 Sediments

Information on the seabed sediment characteristics were gathered as much as possible in order to have a better system understanding of the morphodynamics in the study area. However, sediment data density is very low compared to bathymetric data density.

2.4.6.3.1 Survey for the Living Lab Raversijde project

Nine Van Veen grab samples were taken by MUMM in the framework of the SUSANA campaign with RV Simon Stevin for the Living Lab Raversijde project in March 2023. The location of the samples as well as the D50 grain size is shown in Figure 2-11. The sorting was calculated as half the difference between D10 and D90, both expressed in Krumbein phi. It appears that both the seaward slope and the crest area of the Stroombank contain fine to medium sand. Note that the grain size at the crest of Stroombank is slightly coarser than at its seaward flank. The sand at the crest is much better sorted than at the seaward flank: the average sorting of the three crest samples is 0.56 and of the three seaward slope samples 1.74. These results can be interpreted as a sorting effect indirectly indicating net sand transport from the seaward slope to the crest area. The good sorting at the crest, combined with the overall smooth morphology there, also indicate wave reworking.

The three samples from the Kleine Rede flow channel contain muddy sediment. The poor sorting averaging at 4.01 for the three samples indicates a sedimentary area receiving mostly sediment from suspension (mud) but also from current transport (D90 in all three samples is same sand size as D50 of Stroombank).

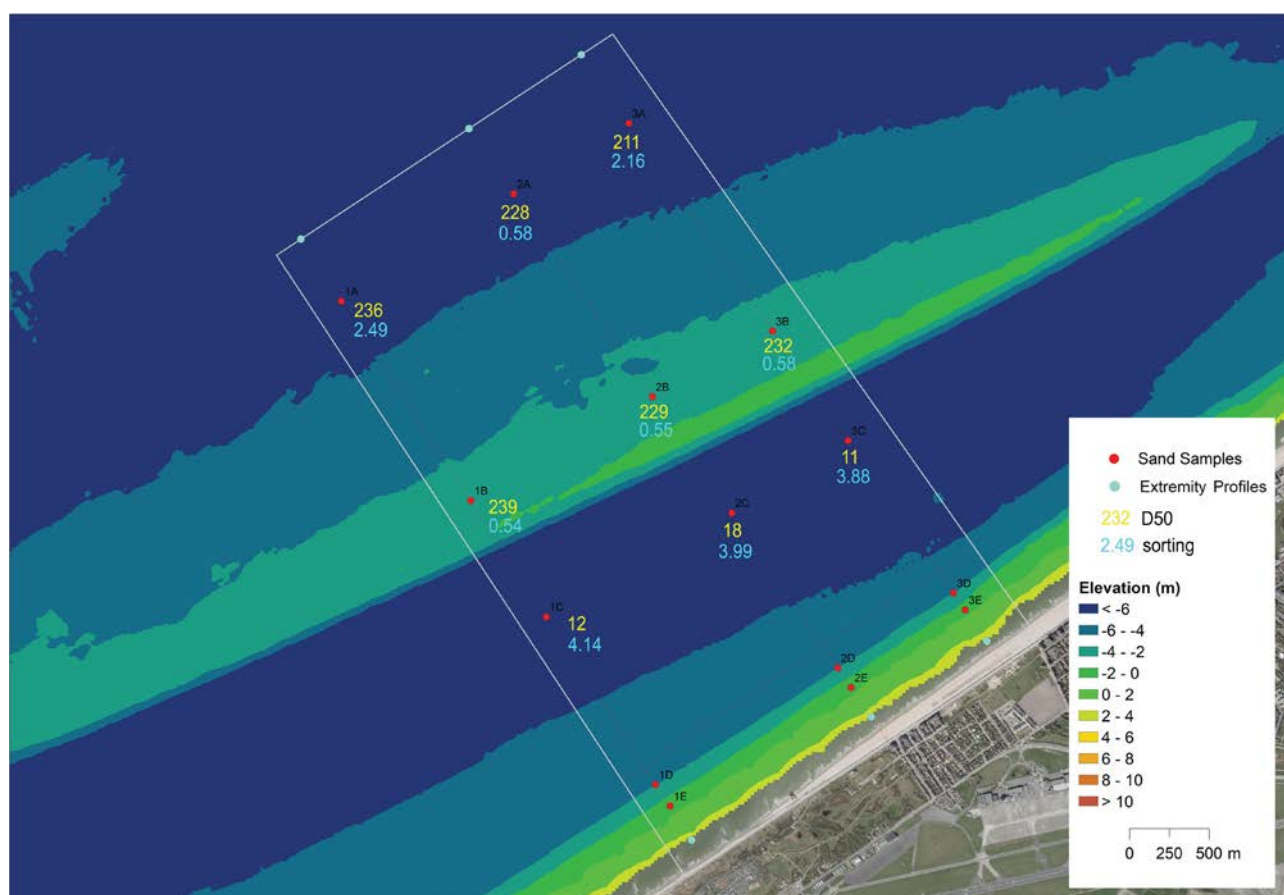


Figure 2-11– Location of grab samples (rod dots) and median grains size D50 (yellow figures) in µm. Background is simplified bathymetry; Stroombank traverses the image while the coast near Raversijde is in the lower right corner.

2.4.6.3.2 Bed sediment taken in relation to dredging operations near Oostende

Maritime Access provided results of a sampling campaign in 2018 of bed samples near Pas van Stroombank, the navigation access channel of Oostende harbour. From the analysis results, the Total Organic Matter content, grain size D50 and grain size sorting were plotted in Figure 2-12.

The bed sediment inside the harbour dams is definitely muddy. The sample in Kleine Rede is fine sand. The very poor sorting reflects the important admixture of fine particles. The two samples on Stroombank are fine to medium sand, and well sorted, thus containing no mud. Going more seawards, the sand becomes finer and probably again muddier.

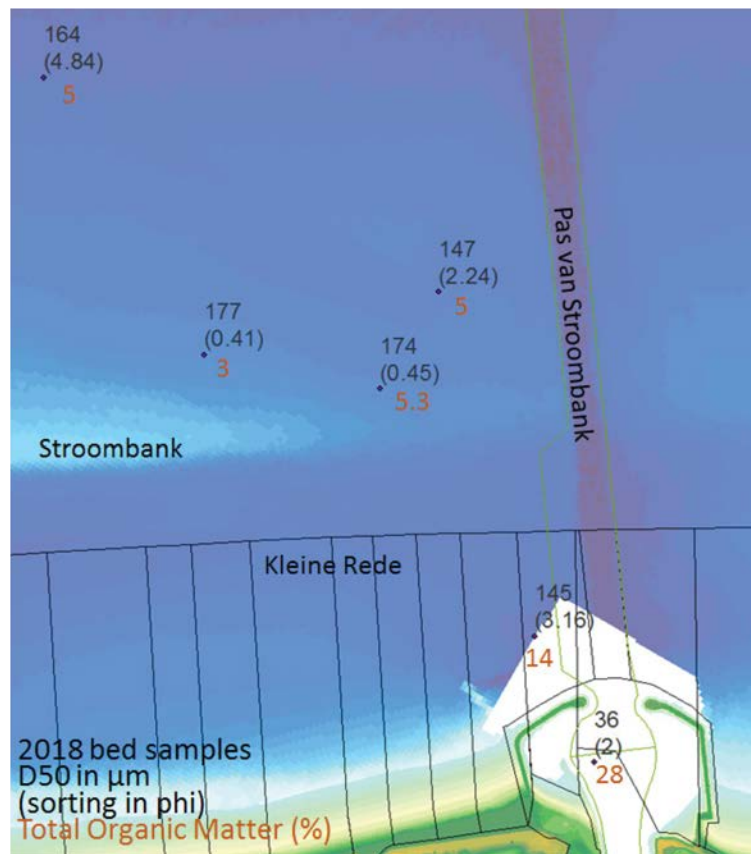


Figure 2-12 – Results of bed samples taken in 2018 near Pas van Stroombank.

2.4.6.3.3 Seabed sediment maps of the inner shelf

The latest seabed substrate map of the Belgian Part of the North Sea was published by MUMM in August 2023, on a 125 m pixel resolution (available at <https://metadata.naturalsciences.be/bmdc.be/dataset:2762>). A proxy of the surficial sediment type was mapped using automated seafloor classification using derivatives of very-high resolution multibeam bathymetry from Flemish Hydrography (a mosaic at 1 m resolution composed of MB surveys performed from 2015 to 2022), informed by sediment dynamics and geological processes. The mapping was steered towards a Folk classification (Folk, 1954) representing a maximum of fifteen major textural groups defined on ratios of silt-clay ($< 63 \mu\text{m}$), sand ($63 \mu\text{m}$ to 2 mm) and gravel ($> 2 \text{ mm}$) percentages. The original classification (15 classes) was merged into 6 classes and 4 classes, the latter to align with the requirements of Europe's Marine Strategy Framework Directive. The map classifies bedforms and bed roughness into habitat bed sediment classes. The classification was trained in areas where gravel substrate is of large ecological importance, and where this substrate is frequently covered by migrating large and small sandy dunes. An additional classification method used bed roughness. Training was further supported by sediment analyses from samples. An extract of the map showing the inner shelf is given in Figure 2-13.

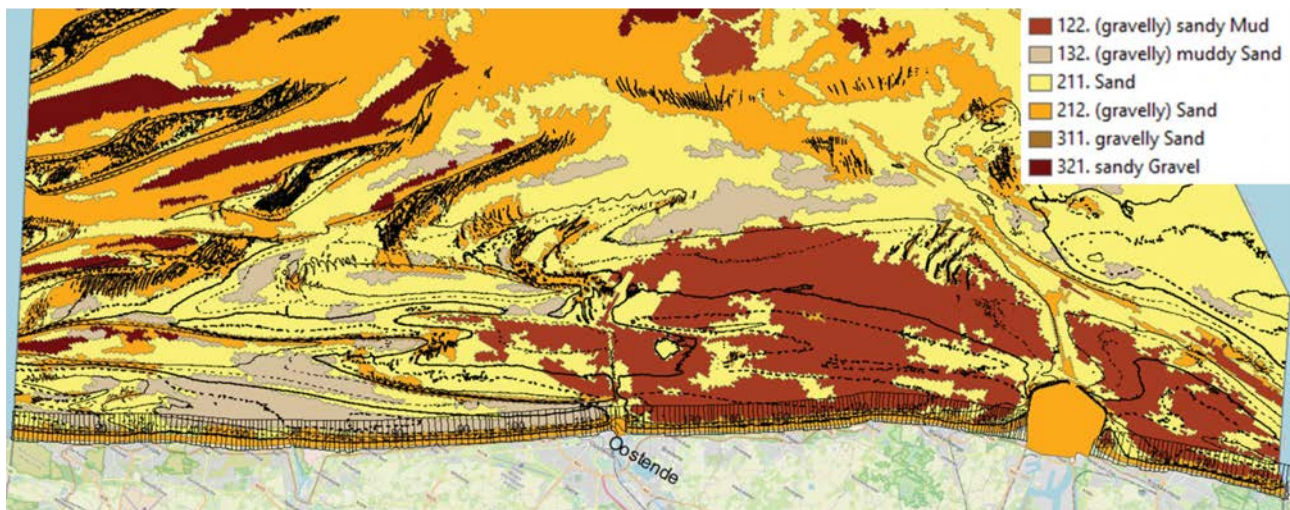
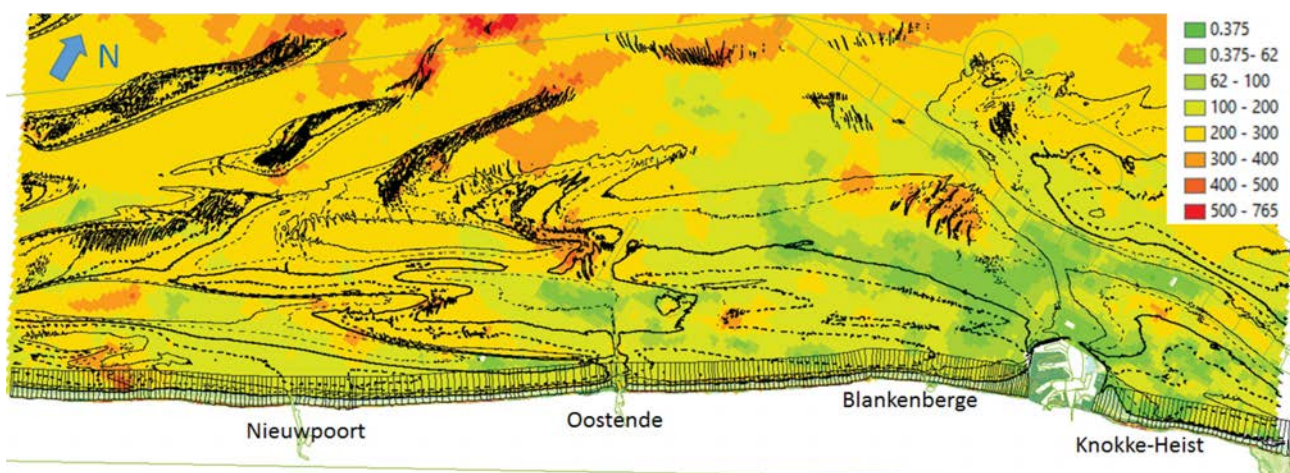


Figure 2-13 – Seabed substrate map of the inner shelf.

This map must be used taking the classification procedure into account.

Especially in the shallow depths of the inner shelf and the nearshore, MB mosaics consist of narrow strips, often surveyed on separate days. And often here, the bed is rather flat. This results in artificial roughness often more related to survey and mosaic issues rather than real bed variations. Other artefacts may arise from dredging. The navigation channels often show dredging furrows, producing a roughness similar to sandy substrates with dunes. In the inner shelf zone, flat areas with low roughness were trained as muddy sand. Finally, the nearshore and shoreface was not detailed as they were not needed in the habitat map. They have been lumped in one sand class. Around coastal defence structures and in and near harbours the sediment type may differ; in the latter it is mostly mud.

The map provides a rational spatially covering image of the seabed sediment, but it has its shortcomings due to the procedure used to realize it. It is therefore supplemented by a classical grain size map based on samples.

Figure 2-14 – D50 of seabed. Source: Verfaillie et al. (2006). Colour classes are D50 in μm (see legend).

The maps of Figure 2-14 and Figure 2-15 are derived from samples taken over a long time. Some samples may have been taken over a century ago, while the inner shelf is subject to large change due to harbour construction, dredging of navigation channels, etc. The map interpolates the area between the data points.

The interpolation was bathymetrically steered. It is remarked however that bathymetry in the inner shelf is often flat and therefore gave poor guidance to the interpolation.

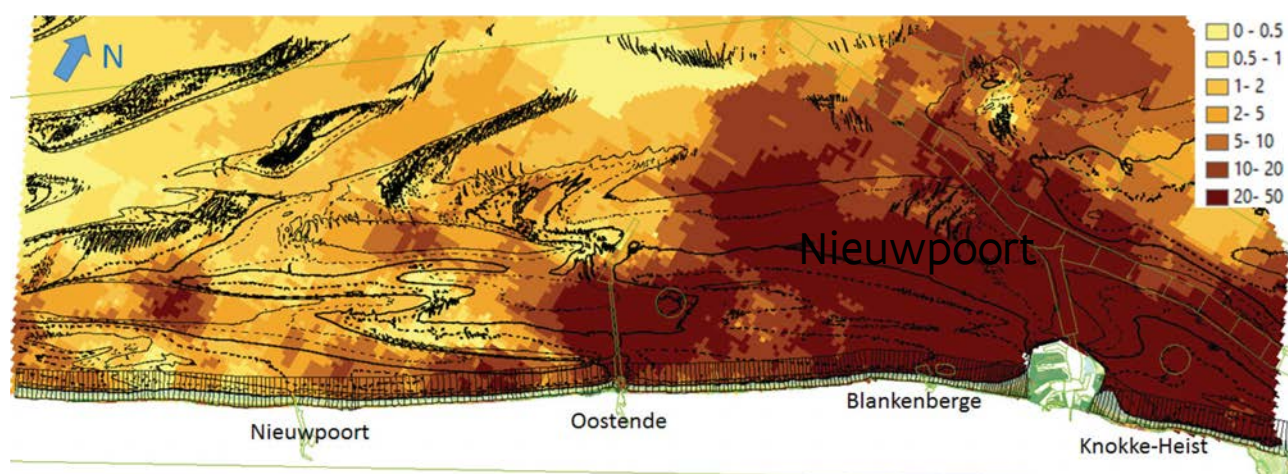


Figure 2-15 – Silt/clay content of seabed. Source: Verfaillie et al. (2006). Colour classes are mud content in % (see legend).

The maps demonstrate the sandy nature of the inner shelf bed. The ridges are often coarser grained than the channels between them. Overall, the grain size fines towards the area of Zeebrugge and the Westerschelde Mouth. The mud content increases in the same direction. Mud content is also higher in the channels between the ridges. Some ridges are shown to have a high mud content on their top where this probably is not the case in reality (e.g. Wenduine Bank, Paardenmarkt). This may be an interpolation effect. MUMM currently prepares an update of the seabed grain-size map.

2.4.7 Taking sea-level rise into account

All historic maps contain depths in (lower) low water spring. It can reasonably be assumed that observations of tidal levels in the coastal harbours in the period of surveying led to establish the level of that surface. It follows that the depths mentioned on historic bathymetric maps refer to the (lower) low water spring level at that time. This also applies to the modern maps. They are referenced in LAT. Also the conversion of soundings to LAT uses contemporary conversion rasters or maps.

Appendix B establishes a relation of the relative sea-level rise at the Belgian coast for the past ~200 years. From this, the offsets with respect to present-day lower low water spring are derived (Table 2-2).

Table 2-2 – Offsets in bathymetric map reference caused by sea-level rise.

Year	Offset to 2004.5 [m]	Offset to 2022 [m]
1804	-0.22534	-0.27
1866	-0.18656	-0.232
1908	-0.14817	-0.193
1938	-0.11305	-0.158
1965	-0.074349	-0.119
1976	-0.056121	-0.101
1985	-0.039934	-0.085
1992	-0.026465	-0.072
2004	-0.0011401	-0.046
2014	0.023121	-0.022
2022	0.045062	0
2025	0.053897	0.009

In the 19th and probably early 20th centuries, it can further be assumed that the knowledge of offshore tide levels was limited and that the nearest coastal port was used to reduce soundings to the reference level. This may create a bias towards deeper seabed elevations, as since the middle of the 20th century, it is known that tidal amplitude isolines are strongly oblique to the coast and offshore tidal amplitudes are lower than at the nearest coast. The bias can be estimated to be lower than the general vertical uncertainty assumed for the older surveys.

The bathymetric DEMs used in the large-scale morphological analyses over the period 1804-2022 have been corrected for this offset, using 2022 as a reference. This allows us to consider the sea-level rise-corrected maps as having all the same reference level and the volume and average depth changes derived from them as representing real sediment volume changes. The sea-level rise-corrected DEMs are located here:

P:\20_079-MorfoInteract\3_Uitvoering\Deeltaak1_DataAcquisition\Shelf\SLRcorrectedShelfrasters.

2.5 Preparation of data needed in WP 2 to 4

2.5.1 Bed elevation rasters of Appelzak and Knokke-Zoute 1999-2003

The morphological evolution after the 1999 beach nourishment at Knokke-Zoute was taken as a calibration case for the detailed numerical models in the MOZES project.

Care was taken to align the cells, as calculating elevation and volume differences between non-aligned rasters induces the GIS to recalculate the raster cells thereby often interpolating the cell elevations in accordance with the bed surface. Such operations produce incorrect elevation and volume difference results. Especially on the most inclined parts of the bed, artificial and incorrect additional elevation differences may be generated that even exceed the uncertainty on depth measurement of +/-0.15 m.

All bed elevation rasters between Spring 1998 and Spring 2003 of beach and nearshore were provided, in Lambert 72 and TAW.

An incorrect bed interpolation was observed in the Spring 2003 nearshore survey in section 233 (westernmost section of Knokke-Zoute). This was due to a substantial gap in sounding points near some high bed points located on the shoreface part of a groyne. The correction was conducted by interpreting depth contour lines in the area of incorrect interpolation, based on the previous and following survey and based on the available sounding points around the incorrect interpolation area. The depth contour lines were added in the TIN of the Spring 2003 nearshore survey, and from that a corrected 10 m-raster was interpolated.

2.5.2 Bed rasters Appelzak and Knokke 2019-2025

The morphological evolution after the 2019 beach nourishment at Knokke-Zoute was taken as a validation case for the detailed numerical models in the MOZES project. The models were also used to examine the morphological change after the 2023 beach nourishment and the 2020-2021 and 2023-2024 nearshore nourishments.

All bed elevation rasters between Spring 2019 and Spring 2025 of beach and nearshore were provided, in Lambert 72 and TAW.

2.5.3 Characteristic contour lines on beach east of Zeebrugge for ShorelineS

A set of historic coastlines was extracted from the morphological database spanning the last decades and covering the coastline east of Zeebrugge to the Zwin inlet. The +1.39 (= low-water mark) and +2.33 m (= 0 m NAP) TAW contour lines were interpolated from the beach DEMs of

- 1983 (18 May)

- 1986 (26 May)
- 1989 (9 April)
- 1999 (6 June)
- 2004 (2 September)
- 2019 (20 April)
- 2023 (17 June)

2.5.4 Alternative slice volumes per coastal tract east of Zeebrugge for ShorelineS

The volume differences per elevation slice per coastal tract from Houthuys et al. (2026) of the 8 tracts east of Zeebrugge were made available for validating the ShorelineS simulations. Overall, these volumes have been calculated over the entire section width. This implies that nearshore volume also contains contributions from seabed parts that are shallower than -4.11 m TAW but are no part of the active coastal system (e.g. the crest of Paardenmarkt sand ridge where this is present inside the fixed section boundaries). For the ShorelineS model validation, it would be better to confine the volumes to the active coast profile.

Therefore, for this occasion an alternative delimitation of the sections was created at the seaward side at the slope break at the base of the shoreface (Figure 2-16). If this slope break was farther offshore at the oldest used survey, the new boundary was placed there. If it was farther at the newest survey, the boundary was placed at that location. In tracts 45, 46 and 47, there can be some doubt where the lower slope break of the active profile is located, as the presence of "Plaat van Heist" makes the nearshore there very wide. For these tracts, two limitations were created, at the upper slope break of the beach profile (landward of the shoal), and another at the seaward slope break, at the offshore side of the shoal.

The volumes were calculated in the same way as in Houthuys et al. (2026). They were calculated in the new, confined sections for the Spring surveys of 1983 (beach) and 1986 (shoreface), and subsequently 1992, 2000, 2007, 2015 and 2023. The series was stopped in 2023 right before the large offshore nourishment at Knokke-Zoute.

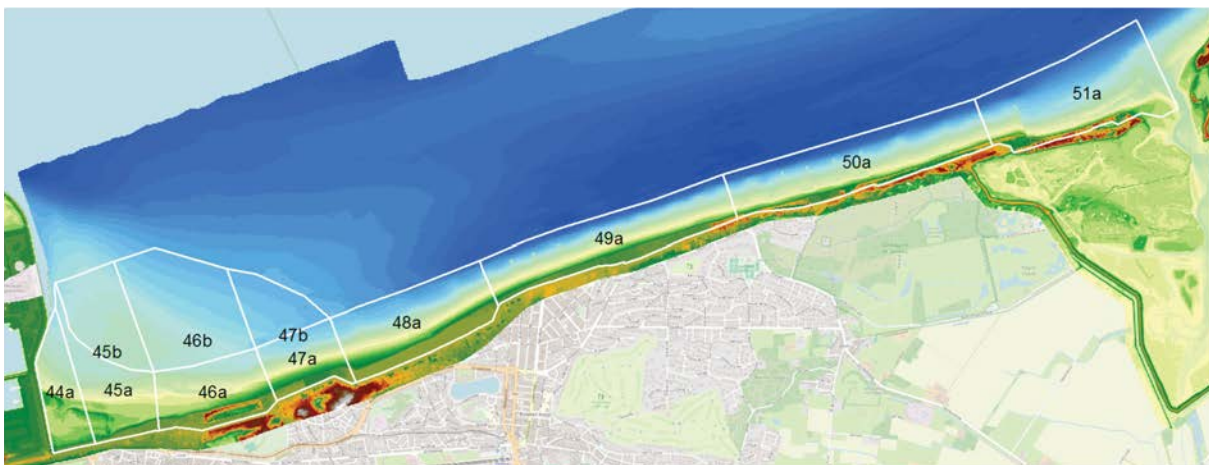


Figure 2-16 – Alternative coastal tract boundaries with seaward extent limited to the lower slope break of the active beach profile.

As reference survey, 2023 was taken, because the first survey used had a different survey year for the emerged (1983) and submerged (1986) part. This means that the volume of all elevation slices was set to 0 for 2023, and that the absolute volume calculated for 2023 was subtracted of all the other volumes.

The volume of the emerged elevation slices of tract 49 are strongly influenced by the repeated nourishments carried out there. Because of the wide time spacing of the alternative volumes, the influence of individual nourishments is not well captured. For the influence of the sand nourishments at Knokke-Zoute, reference is made to the original yearly volumes in Houthuys et al. (2026), where also the nourished volumes per nourishment are reported.

2.5.5 Historical dune profiles near Stroombank for idealised models

A set of historical, long profiles across the coastal barrier and Stroombank were needed to create an original representative profile for simulations in the idealised models used in the MOZES project. The profiles ideally also describe the elevation in the coastal lowland and across the dune belt, and are preferably taken also from historic surveys.

Along six transects, the elevation was derived from the following old maps:

- Beach and dune topography 1828 (source: old dune belt map, Quant, 1828): only low and high water marks (taken to be at 0 and +6 m TAW, respectively). There is no elevation information in the dunes and a crude approximation of the dune profile was taken from the 1870 profile.
- Beach and dune topography 1870 (source: old IGN map): only low and high water marks (taken to be at 0 and +6 m TAW, respectively) and some elevation points present in the dune belt.
- Nearshore, beach and dune topography 1874-1882 (source: old Public Works map of the coast): linear interpolation of elevations from profiles present on the map onto the defined transects. The map date is 1874 for transects 5 and 6, and 1879-1882 for transects 1 to 4.
- Beach topography 1939 (source: old IGN map): only low and high water marks (taken to be at 0 and +6 m TAW, respectively); and a rough, generalised profile through the dune belt partly based on the 1870 topographic map, and where possible based on the 1950s topographic map.
- Beach topography 1983 combined with 1983 or 1984 dune topography in transects 3, 4 and 5. The seawall elevations in transects 1, 2 and 6 are from 2000.

The 1828, 1870 and 1939 topographic maps had to be georeferenced using some scarce control points. The planimetric uncertainty is estimated at about 20 metres. The 1874-1882 had better and more control points, yielding a lower uncertainty estimated at 5 to 10 m.

All transects save n° 4 cross urbanised dune belt. It can be assumed that during the urban development, the dune tops were flattened. The 1870 elevation is probably the original natural elevation of the dune tops.

For more recent years, good and complete profiles were extracted from the following DEMs (spring survey):

- Lidar (beach) 2000
- Lidar (beach) 2007
- Lidar (beach) 2010
- Lidar (beach) 2015
- Lidar (beach) 2020
- Lidar (beach) 2025

These profiles have a point about every 20 m.

2.6 Morphodynamics of the nearshore and inner shelf over the past 200 years

The analysis in this section focuses on morphological change over the period 1804-2022 of large-scale morphological features on the Belgian shelf and neighbouring areas of the French and Dutch shelf. The “shelf” covers the area from the shoreface base to 20-30 km offshore, depending on the cover of the available surveys. With “inner shelf”, the first 10-15 km are meant. The time intervals of the maps from 1804-1938 are large and map precision is low (see introductory paragraphs of this chapter). As a result, only features on the scale of sand ridges and channels can be evaluated. The precision and survey interval improves from the 1960s onward. The period 1960s-early 1990s however covers only the inner shelf, i.e. approximately the first 10 km from the shoreline.

2.6.1 Depth contour line shift

Depth contours were calculated on all inner shelf rasters (1804, 1866, 1908, 1938, 1967 (= averaged date for the 1962 to 1969 inner shelf bathymetry mosaic), 1976 (= averaged date for the 1974 to 1978 inner shelf bathymetry mosaic), 1986 (= averaged date for the 1984 to 1987 inner shelf bathymetry mosaic), 1992 (= averaged date for the 1991 to 1993 inner shelf bathymetry mosaic), 2004 (= averaged date for the 1999 to 2005 shelf bathymetry mosaic, 2014 (= averaged date for the 2004 to 2014 shelf bathymetry mosaic) and 2022 (mosaic of Flemish Hydrography cover of Belgian shelf, 2022 Dutch cover of Westerschelde mouth area and 2022 EMODnet for French part). For the current large-scale morphological analysis, a selection of the 0, -2, -5, -8 and -12 m contours were displayed, using a different line type for each selected depth. The lines were displayed using a different colour per bathymetric dataset (Figure 2-17). The depths are in TAW and have not been corrected for sea-level rise. It was evaluated that the uncertainty on position exceeds possible shifts in depth contour location due to a sea-level rise correction. In the more quantitative analyses of the next sections, sea-level rise correction was applied.

The successive bathymetric rasters were displayed using a set of fixed extents and then shown as a time series in the Map Series supporting material. Systematic change or no change was observed and marked using the change marks of Figure 2-17. Changes back and forth are interpreted to represent no systematic movement. The systematic movements of the large-scale morphological features have been quantified over the entire observation period 1804-2022. Displacements are expressed in km; important and systematic vertical change in m. The values in the analysis result maps are a rounded mean of the change representative of the neighbourhood of the change marker. When a shift in depth contours corresponds to a net displacement of a large-scale morphological feature, the shift arrow is shown in blue. When a contour line shift is accompanied by overall growth of the large-scale morphological feature, the shift arrow is shown in green. When a contour line shift is accompanied by overall decline (volume loss) of the large-scale morphological feature, the shift arrow is shown in red (Figure 2-17).

It is noted that 1866 is often an outlier where the position of some major banks and channels shifts back and forth compared to 1804 and 1908. Hence, it is concluded that either the geometry of the 1866 chart is of less quality, or the georeferencing introduced a bias, or both.

Depth contours (m TAW)	Change Analysis	
	Depth contour shift	Depth change
— 0		
— -2	net shift (km)	no change
— -5		
— -8	accretional shift (km)	total vertical accretion (m)
--- -12		
■ 1804	erosional shift (km)	total vertical erosion(m)
■ 1866		
■ 1908		
■ 1938		
■ 1962/69		
■ 1974/78		
■ 1984/87		
■ 1991/93		
■ 1999/2005		
■ 2004/2014		
■ 2022		

Figure 2-17 – Legend for the depth contour line change analysis.

Change figures quantify change over the entire observation period (displacement in km, vertical change in m).

2.6.1.1 Flemish Banks, Hinder Banks, Westerschelde outer delta

As the uncertainty on farther offshore morphology is larger than for the inner shelf, a separate analysis on a small scale was done for this area (Figure 2-18). This area is not covered by the inner shelf maps (1967, 1976, 1986, 1992) and the French part is only covered by the EMODnet 2022 dataset, which represents there a 30 year-old situation.

The Hinder Banks are not covered by the 1804 survey. Three large ridges show a displacement to the east: Westhinder by about 2 km, Oosthinder (just east of Westhinder) and Bligh Bank (just east of Oosthinder) by about 1 km. It is observed that the shift would have occurred between 1908 and 1938. No shift was observed between 1938 and 2022, apart from an about 300 m eastward shift of the northern branch of Westhinder. Noordhinder (just west of Westhinder) is not well captured on the older charts. The southern branch of Fairy Bank is shown on all charts from 1866 on. The crest of this bank shows probably a small shift to the southeast since 1938. The 1866 and 1908 position is between 1938 and 2022.

The results for the Hinder Banks are not well supported by the data. It appears that the 1908 chart just copied the 1866 contours. As this area is relatively far offshore, the 1866 contours are not certain. It results that, lacking another independent survey, no conclusions can be drawn on change or no change of the Hinder Banks.

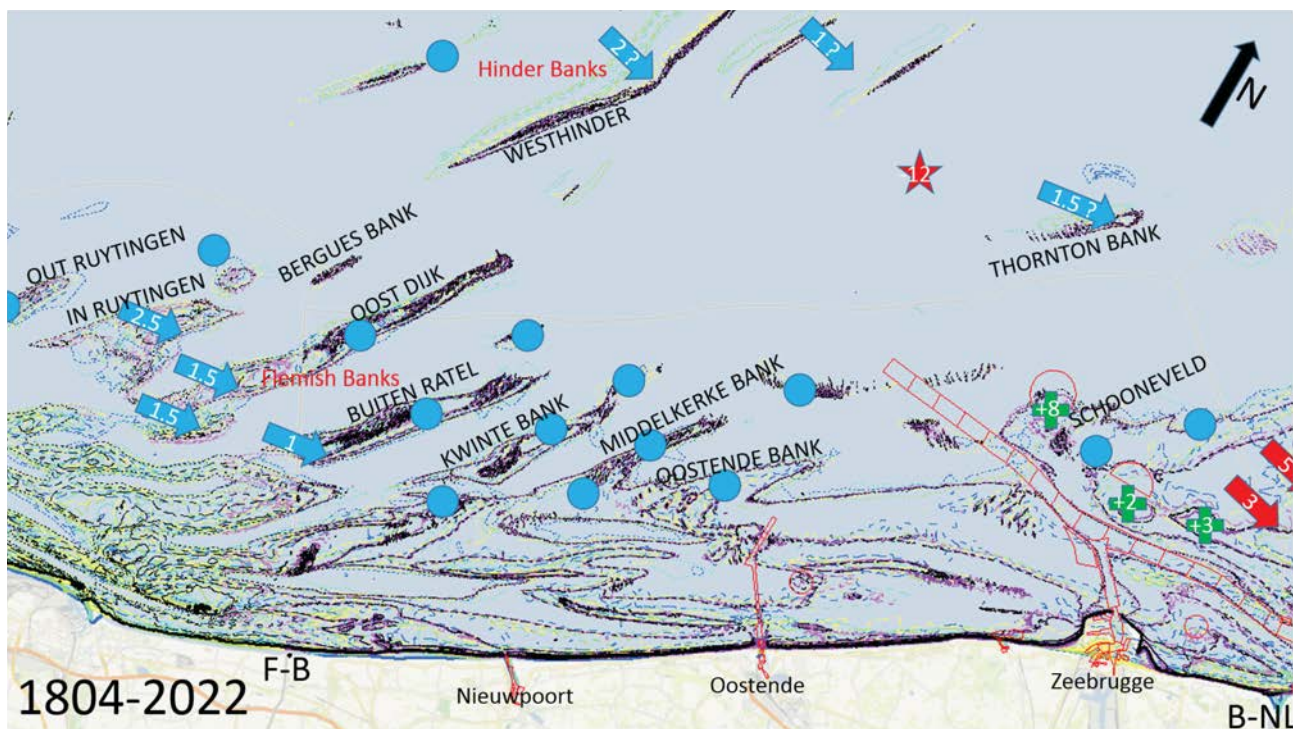


Figure 2-18 – 1804-2022 contour line and depth change analysis, offshore part of the inner shelf.
From Dunkerque to the Westerschelde mouth.

Thornton Bank is represented on the 1804 chart, as a small data outlier. Its position is highly uncertain. The crest area oscillates between 1866 and 2022. Most likely, the ridge was stable over the observation period. A small area west of Thornton Bank shows a deepening by 12 m since 1866/1938. This is interpreted to be due to a poor rendering of the local bathymetry in this area on both the 1866 and 1938 (copied data?) charts.

The Flemish Banks are present in all shelf charts from 1804. They appear to have remained in the same place. One subarea however does show systematic displacements. This observation concerns the entire In Ruytingen ridge, the most landward part of Oost Dijk and Buiten Ratel, and the small ridge landwards of Oost Dijk.

The shift in contour lines is considerable and seems to decrease from west to east inside this subarea: from 2.5 km eastwards for In Ruytingen to 1 km eastwards for Buiten Ratel. It should be realized that the French part of this subarea has no recent survey in the 2022 EMODnet bathymetry, so the total displacement since 1804 is probably even larger than indicated in Figure 2-18.

The outer part of the Westerschelde ebb tidal delta shows no shift in the deeper contour lines since 1804, whereas the shallower contour lines show an important shift eastwards. Some areas display a considerable vertical accretion. This change occurred mostly between 1938 and 2022 and is the result of dredge slurry disposal.

2.6.1.2 French part west of the Belgian inner shelf

This area is of importance for Belgium as it may serve as a sediment source area under longitudinal net eastwards sediment transport. This area has a large reserve of sand as the ridges are often wide and are developed high (their crests often emerge at low tide). It is also a morphologically very dynamic area (Figure 2-19). This area is not covered by the Belgian inner shelf maps (1967, 1976, 1986, 1992). For Binnen Ratel and parts of Breed Bank, also the 2016 dedicated Dunkerque windfarm park MB survey was used to obtain more certainty about the local large-scale feature movements.

Natural dynamics prevail, but land reclaims for the Grand Port Maritime and the construction of Avant-Port Ouest de Dunkerque in 1980 largely influenced the littoral zone. They blocked the littoral drift and the nearshore area here suffers structural erosion (Cartier et al., 2020). Dunkerque Channel requires dredging works by yearly amounts in the order of 0.5 Mm³. New constructions require one-off dredging efforts of several Mm³.

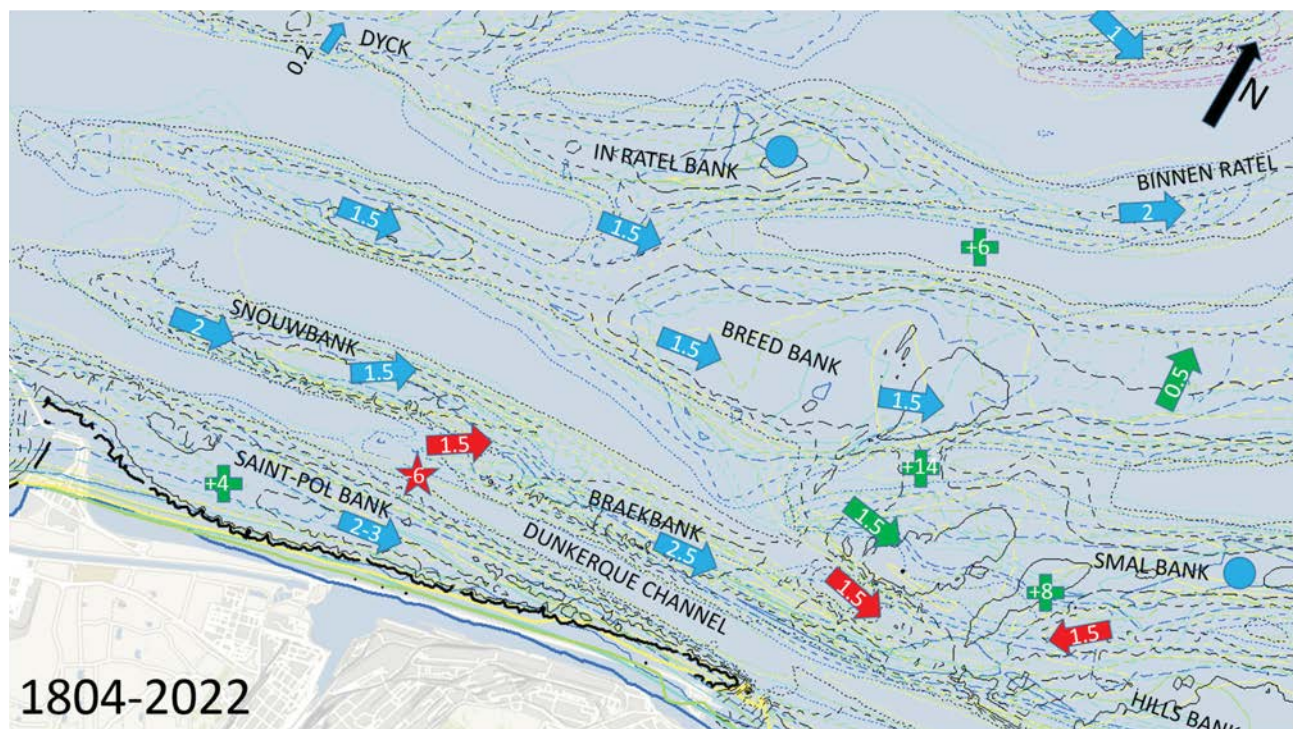


Figure 2-19 – 1804-2022 contour line and depth change analysis, inner shelf Northern France.
From Avant-Port Ouest de Dunkeque to Bray-Dunes.

Proceeding from offshore, Dyck is almost stable and In Ratel Bank's crest was largely stable over the observation period. In contrast, Binnen Ratel and all the length of Breed Bank, Snouwbank and Braekbank considerably shifted eastwards (parallel to the coastline). There is a weak trend of larger displacement when going from offshore to inshore. It should be realized that the total movement over 1804-2022 is probably even larger than indicated in Figure 2-19 as this area has no recent survey in the 2022 EMODnet bathymetry, which would rather represent the 1970-1990 situation, with the exception of Binnen Ratel and parts of Breed Bank (2016 MB survey available).

Also the flow channels and especially the passes between the channels are highly dynamic. The channel between Binnen Ratel and Breed Bank sanded up by a considerable 6 m. The channel between Breed Bank and Smal Bank practically disappeared: where on the early charts a flow channel was present, the latter banks were connected by a shallow "ridge bridge" in the 2022 EMODnet bathymetry.

Possibly, tidal flow was taken over by a new connection between Braekbank and Smal Bank and its extension between Smal Bank and Hills Bank. This recent flow channel is situated more inshore than the abandoned channels. Likewise, the connection between Snouwbank and Braekbank has in the recent decades been cut and a new channel now clearly separates Snouwbank from Braekbank. Near this site, the Dunkerque Channel or Chenal Intermédiaire is now at least 6 m deeper than in the earlier charts. The latter change is probably related to dredging works, as the deepening occurred mainly between 1938 and 2022 (or rather 1970-1990).

Finally, the shoreface west of Saint-Pol Bank accreted, while Saint-Pol Bank itself shifted considerably to the east. The morphological change here mostly occurred after and triggered by the construction of Dunkerque Avant-Port Ouest (Cartier *et al.*, 2020).

2.6.1.3 Belgian West Coast

Figure 2-20 shows the result of the depth contour line shift analysis of the Belgian West Coast from the French border to Middelkerke. It is the area with the strongest imprint of natural morphodynamics. Natural, as no large-scale dredging or nourishment occurs on the inner shelf.

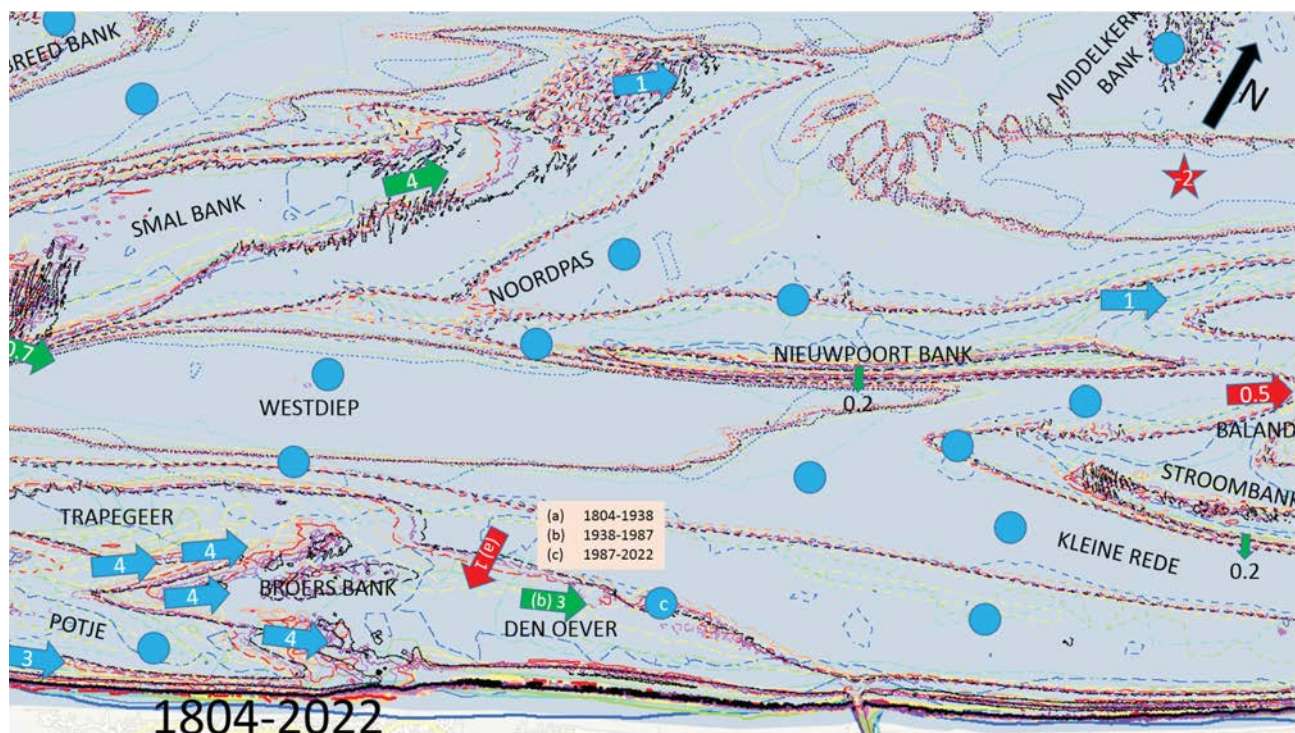


Figure 2-20 – 1804-2022 contour line and depth change analysis, Belgian West Coast, from De Panne to Middelkerke.

Proceeding from offshore, most of Smal bank, Noordpas, Nieuwpoort Bank, Middelkerke Bank and the flow channels between these banks show no systematic change over the observation period. A notable exception is a shallow part of Smal Bank, off the resort of Koksijde, where water depths decrease to about -2 m TAW. Here, an important eastward shift of the shallow area is observed. The landward flank of Smal Bank off De Panne and the landward flank of Nieuwpoort Bank show a less intense but systematic landward shift. Finally, the shallow ridge branching seaward near the NE tip of Nieuwpoort Bank also moves to the east. The channel north of Nieuwpoort Bank deepened.

In the nearshore ridges zone, most channels show no systematic change.

The shallow ridge system Trapegeer – Broers Bank, with its shallowest parts emerging at low tide, is very dynamic. All shallow nearshore parts show a fast movement eastwards in the alongshore direction. Note however that over the observation period the point of attachment of the ridge system to the coast did not move. Possibly, the point of attachment was already at the same place at the time of the foundation of the fishermen's village of Koksijde in the 13th century ("ijde" means a place where ships can be dragged on the beach) (Termote, 1992). Note that also the location and depth of the flow channel Potje have not changed since 1804. A protrusion of the -5 m depth contour presently situated west of De Panne moved 3 km alongshore eastwards.

Den Oever shows a complex morphological evolution. A small ridge confusingly also named "Broers Bank" was situated 3 km from the low-water mark off Oostduinkerke in 1804. In 1866 this ridge had moved westward by about 750 m towards Koksijde-De Panne. In 1908 it had merged with the shallow ridge off Koksijde, and its name was transferred to the shoal with which it had merged. The seaward protrusion formed by the merged ridge had disappeared by 1938. The morphological evolution of Den Oever, the wide shoreface of Oostduinkerke, over 1908-1938-1967 implies the interpretation that most of the sand of the former small ridge contributed to making Den Oever shallower and giving it a milder slope. By about 1992, the gain due to this supply mechanism started to be lost again, but at a very slow rate. The morphological changes described here are shown in Figure 2-20 by three symbols labelled a-b-c in the label box near Den Oever.

Together, the morphological evolution of the several small ridges in the area shows the following points:

- The name "Broers Bank" is attached to the location off Koksijde ("broers" refers to the monks of the ancient monastery of "Ten Duinen"). The name was given to whatever ridge was closest to Koksijde.
- Both small ridges, separated from Hills Bank/Trapegeer in the west, and at least one ridge migrating westward off Oostduinkerke, have been given this name.
- The movement of the different ridges demonstrates a convergence of sand towards Koksijde.
- As the attachment point, at least in historical times, did not move, it must have served as an entry point of offshore delivered sand to the beaches and dunes near Koksijde.
- This can even explain the presence of the wide dune belt at the Belgian west coast (Houthuys et al., 2021; Verwaest et al., 2022).

East of this area, off Middelkerke, the flow channel between Nieuwpoort Bank and Baland Bank shifted 0.5 km to the east. The western part of Stroombank does not show an alongshore movement, but a small landward shift of the landward flank is observed.

2.6.1.4 Belgian Middle Coast

Figure 2-21 shows the result of the depth contour line shift analysis of the Belgian Middle Coast from Middelkerke to Wenduine. The largest human interference on the inner shelf of this area is the maritime access to and the 2009 expansion of Oostende harbour.

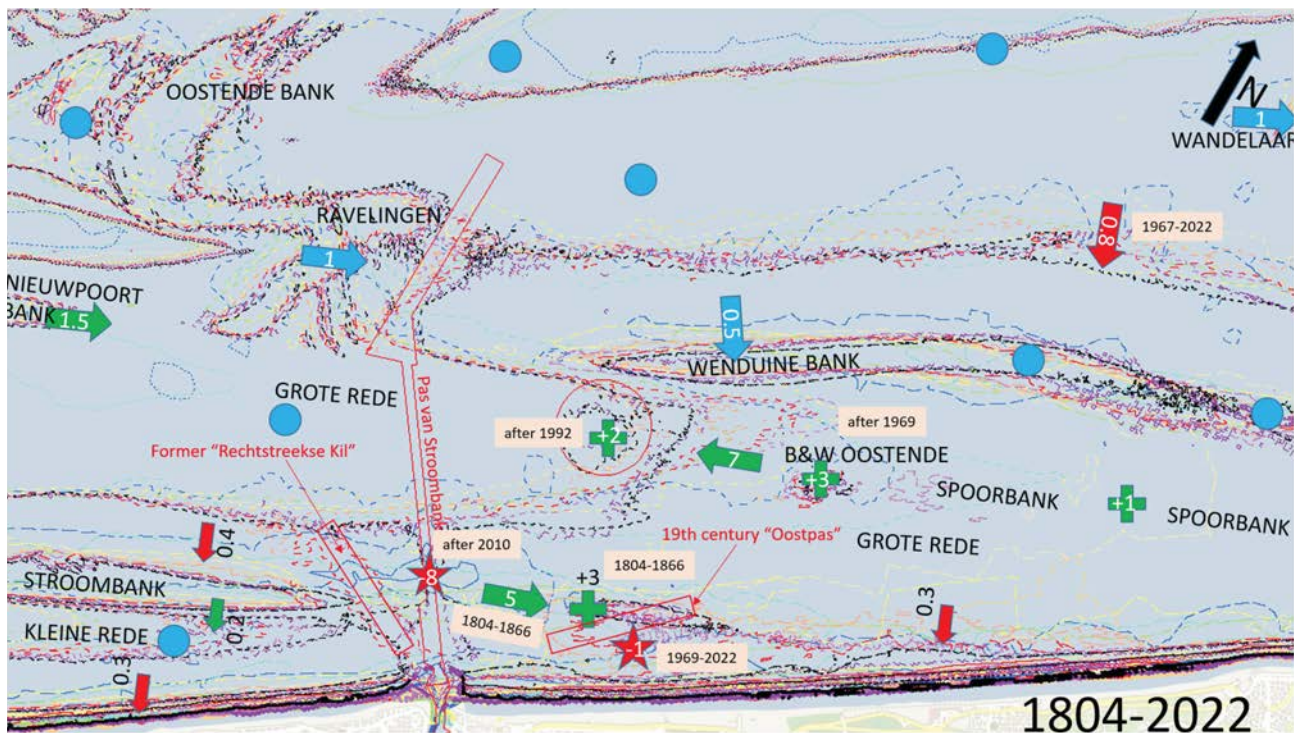


Figure 2-21 – 1804-2022 contour line and depth change analysis, Belgian Middle Coast, from Middelkerke to Wenduine.

The transition area between the shoreface-connected ridges and the tidal sand ridges (upper part of Figure 2-21) shows no systematic depth contour line shifts. The eastern end of Nieuwpoort Bank and the dune field of Ravelingen shifted eastwards. Wenduine Bank has a pivot point, indicated by a blue dot in Figure 2-21. The branch west of this pivot point moved landwards. The branch east of the pivot point did not move in a systematic way. The very mildly sloping seaward flank of Wenduine Bank became slightly steeper. More specifically, the base of the bank moved landward. This movement began after 1978 and is likely a morphological response to the construction of Zeebrugge Outer Harbour in the 1980s.

While the western part of the flow channel Grote Rede did not change, the part east of Oostende showed important shallowing. The change is related to dredge slurry dumps operated at dump site Bruggen & Wegen Oostende (BWO) around or after 1938. The recent accretion (after 1992) by 2 m reflects the changed location of the dump site BWO. The long coast-parallel ridge that developed east of the first dump site (marked in Figure 2-21 by "+3 m") is not visible due to the selected depth contour lines. This new bank, that formed after 1992, is named in this report "Spoorbank" (trace bank, because the bank is literally a trace of sediment east of the dump site). The developments triggered by dump activities at BWO are analysed in more detail in §2.9.

Where they touch the shoreface, the landward flanks of both Grote Rede and Kleine Rede show a long-term landward shift. The centre of Kleine Rede shows no change. The section of Stroombank visible on Figure 2-21 also shifted landwards, like the part shown in Figure 2-20.

The eastern end of Stroombank in the nearshore of Oostende displays important changes that are morphological responses to dredging activities. It is possible that already around 1800 the connection between Stroombank and the shoreface at Bredene was severed due to human interference: the 1804 chart shows a deeper channel near Bredene. The 1866 map shows that the shallow crest area of Stroombank had grown (recovered?) by 5 km towards the attachment point with the coast east of Bredene. This evolution could be interpreted as the repair under natural transport after man created the channel off Bredene around 1800. It was reasoned earlier that Stroombank must have connected to the shore in the centuries before 1800 (Houthuys *et al.*, 2021). A man-made channel severing Stroombank from the coast and dug around 1800 is however hypothetical.

A first navigation channel crosscutting the ridge near Oostende was already present in 1908. It has been maintained by dredging ever since. This channel dates from shortly after 1880 (Devos *et al.*, 2014). As it was made to provide a direct access to the harbour, it was named "Rechtstreekse Kil". Around the same time, the connection between Stroombank and the shoreline east of Bredene was (a second time?) severed from the coast attachment by dredging, to promote flow currents to clear the navigation channel Kleine Rede near Oostende. This artificial channel was named "Oostpas". While the maintenance of Oostpas appears to have been abandoned by 1938, Rechtstreekse Kil was well kept and later widened and deepened. In 2009, a new navigation channel with a deeper bottom was dredged to Oostende harbour (see section 2.8). This explains the -8 m change at that location.

Due to the successive interventions, the evolution of the eastern part of Stroombank (east of Oostende) is complex. Between 1804 and 1866, the bank crest gained 3 m vertically while it extended itself by 5 km so that the connection to Bredene shoreface was repaired. Between 1866 and 1908, it had lowered by 3 m at the location of Oostpas, an artificially created channel.

2.6.1.5 Belgian East Coast

The Belgian East Coast from Blankenberge to Cadzand is strongly affected by the expansion of Zeebrugge Harbour in 1979-1986. Therefore, the geographic change analysis is reported in two maps, the first until 1967, before Zeebrugge Harbour expansion (Figure 2-22), and the second from 1967, after the expansion (Figure 2-23). The resulting evolution over the entire period is shown in Figure 2-24.

While the Westerschelde ebb tidal delta top (Vlakte van de Raan) shows no change at the Belgian-Dutch border (this is just west of the North arrow in Figure 2-22 to Figure 2-24), two areas north of the navigation channel Wielingen-Scheur did shallow by about 2 m. The eastern one accreted earlier than the area at S2. S2 is a dredged slurry dump site presently in use; the other site is a former dump site.

Almost every erosional change (red markers in Figure 2-24 in the area offshore of Zeebrugge) occurred after 1967 (Figure 2-23) and is related to dredging works to create and maintain the navigation channels to Westerschelde and to Zeebrugge, and the morphological response of the environment. Indeed, dredging is only effected in the navigation channels Scheur and Pas van 't Zand. Nevertheless, these works apparently indirectly deplete the surrounding flat seabed areas near Wandelaar, north of Wenduine Bank and near Bol van Heist. The areas at the offshore side of Zeebrugge Harbour dams are subject to stronger currents since the construction of the dams. The morphological response to the stronger currents is local scour of the seabed.

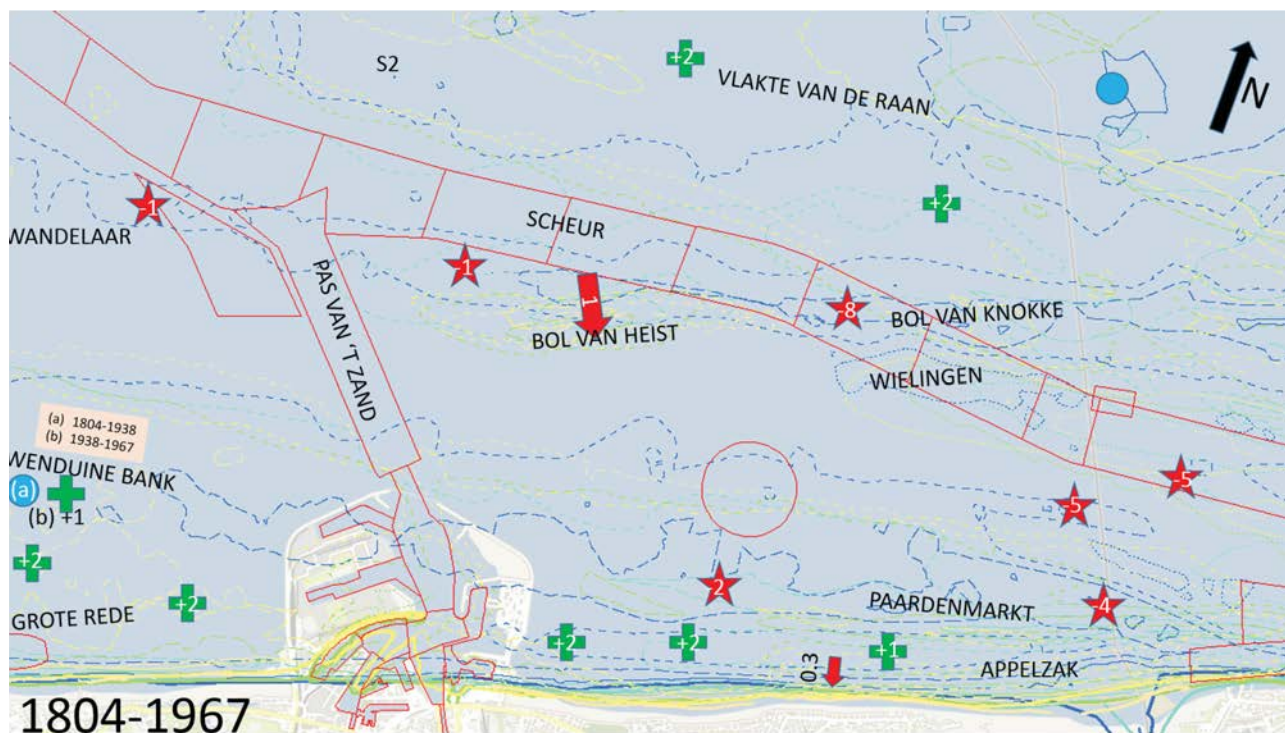


Figure 2-22. – 1804-1967 contour line and depth change analysis, Belgian East Coast, from Blankenberge to Cadzand.

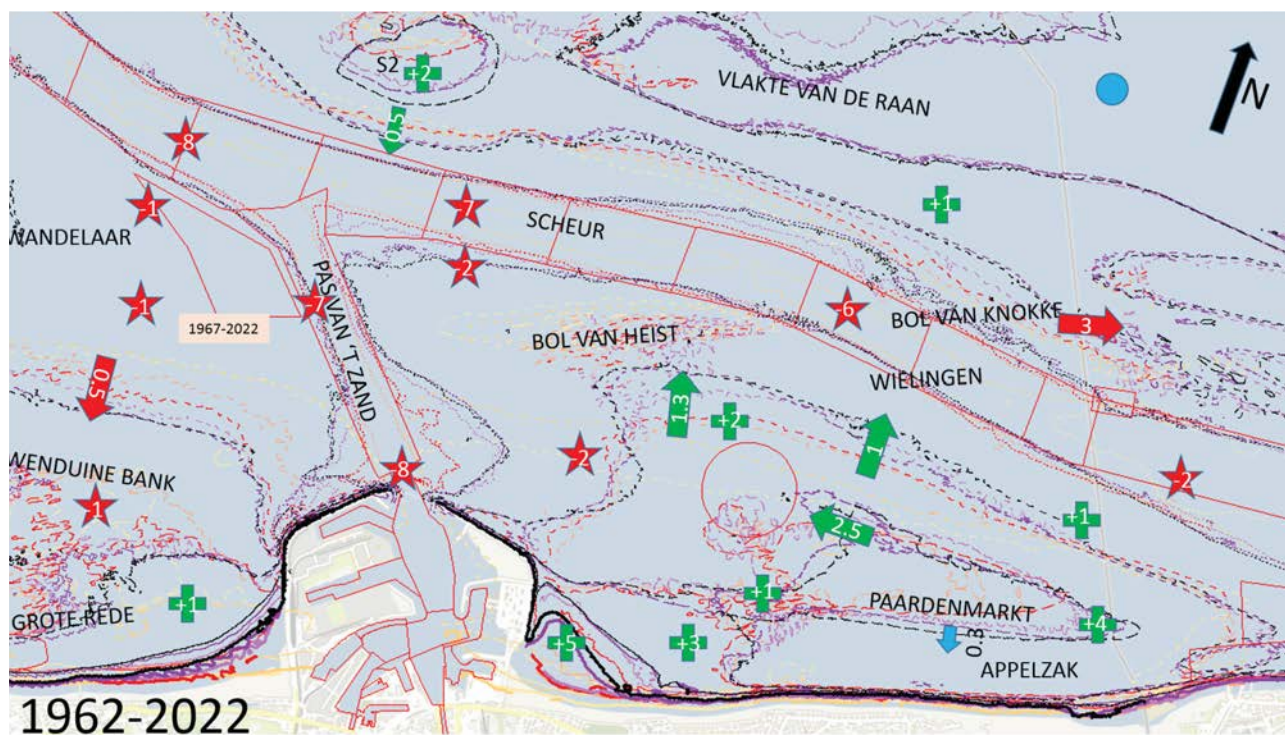


Figure 2-23. – 1967-2022 contour line and depth change analysis, Belgian East Coast, from Blankenberge to Cadzand.

At the east side of Zeebrugge, the Paardenmarkt crest area deepened by 2 m between 1804 and 1967 after which it recovered by 1 m. More to the east, the Paardenmarkt crest between Knokke and Zwin was highly dynamic, but the resulting 2022 situation there now resembles again the 1804 situation. The only systematic change is a landward approach by 0.3 km. In addition, Appelzak channel shows large morphodynamics, and in spite of the deepening trend of the last decades, its floor is in 2022 still 1 m shallower than in 1804. It can be inferred that after the construction of the Leopold II dam, flow currents were lower in this channel, which as a result shallowed up between the construction of the first dam at Zeebrugge until that port was largely expanded in the 1980s. The evolution since the 1960s is examined in detail in §2.7.

The beach between Wenduine and Heist must have suffered erosion in the first decades of the 19th century. Groynes are present along this part of the coast on the Dutch 1828 dune map (Quant, 1828), while there are no groynes on the 1804 map. The construction of the Leopold II dam just before 1900 may have been the trigger of more beach erosion, now also in Knokke-Zoute. Groynes are present between Heist and Knokke-Zoute for the first time on the 1939 map. Beach erosion there was studied in 1938-1940 by the newly founded Flanders Hydraulics Institute in its "Model 41" report that proposed a progressive subsidence ("un abaissement progressif") of the ground surface as the ultimate cause of coastal erosion between Zeebrugge and the Dutch border. However, using the present knowledge, it can be put forward that the beach and shoreface drift was blocked by the Leopold II dam, resulting in sand depletion at Knokke. Erosion has ever since been observed there, and also after the large beach 1977-1979 nourishment. Blocking of alongshore sand transport continued after the seaward expansion of Zeebrugge in 1979-1986 (Houthuys et al., 2022). Over the past two centuries, the landward flank of Appelzak channel, which is also the shoreface, shifted about 0.3 km landwards.

Opposed to the beach evolution, the wide shoreface area of Heist and Duinbergen shallowed by 5 to 7 m since 1804. Most of the sedimentation here occurred after the construction of Zeebrugge Outer Harbour. Sedimentation still continues here today. See for more detail in §2.7.

2.6.1.6 Summary

Generally, the offshore part of the inner shelf (Flemish Banks) shows no systematic morphological movement over the last two centuries. In the more nearshore zone of the shoreface-connected ridges, significant movements of the ridges to the east, in the alongshore direction, are observed. The movements are largest in the area of the French-Belgian border and there, the magnitude of the alongshore movement increases in the onshore direction. Furthermore, most shoreface-connected ridges also show an onshore movement component, but at rates that are only 1/5th or less than the alongshore movement rates. Some passes between the nearshore ridges in the North-French part of the study area disappeared (they were filled up by sediment) while other new passes were created. The new passes are more landward than the abandoned ones. The attachment points of the shoreface-connected ridges to the coast did not shift, probably since the late Middle Ages. The shoreface base tends to move landwards at rates comparable to the landward shift rate of the shoreface-connected ridges. The depth of many channels separating the sand ridges does not change. The shallowest parts of Westerschelde ebb tidal delta shifted landwards, towards the Westerschelde estuary.

It is thought that the ongoing sea-level rise is the ultimate driving force of the described cross-shore movements. The residual west-to-east sediment transport is the ultimate driving force of the described alongshore movements. Both the encroachment of shoreface-connected ridges and the nearshore channels on the coast and the alongshore movements of certain nearshore sand ridges and passes are interpreted to reflect the natural morphological response to the ongoing sea-level rise.

Human interference triggered even more important morphological changes. The creation of navigation channels cross-cutting the nearshore sand ridges depleted the downdrift (eastern) part of the affected ridges. In the neighbourhood of important dredged fairways, also the surrounding seabed lost sediment. Due to flow constriction, scour channels developed at the seaward side of the new harbour dams that protrude in the nearshore area. At the same time, sedimentation occurs updrift and downdrift of the new harbour dams.

Most nearshore shallowing is observed at the downdrift (east) side of the outer harbours. Finally, dumping of dredge spoils created long-lasting positive bed changes. At Bruggen & Wegen Oostende, even a new, 10 km long low ridge developed downdrift of the dump site.

2.6.2 Evolution of ridge height and channel depth

As theoretical models [Nnafie et al., 2014-1] describing the development of shoreface-connected ridges under natural hydrodynamic conditions show growth of ridge crests, oriented oblique to the shoreline, at the expense of the surrounding seafloor that is deepened into channels, it was decided to examine the evolution of the height of the nearshore-connected ridges in the Belgian inner shelf.

A set of 22 locations was selected (Figure 2-25) to represent the three major zones near the Belgian coast: 1-8 are on the shoreface-connected ridges (SFCR) (7 is on the newly formed "Spoorbank" net-transport downwards of Oostende dredge dump); 9-16 are in the transition zone and 17-22 are in the zone of the tidal sand ridges (TSR).

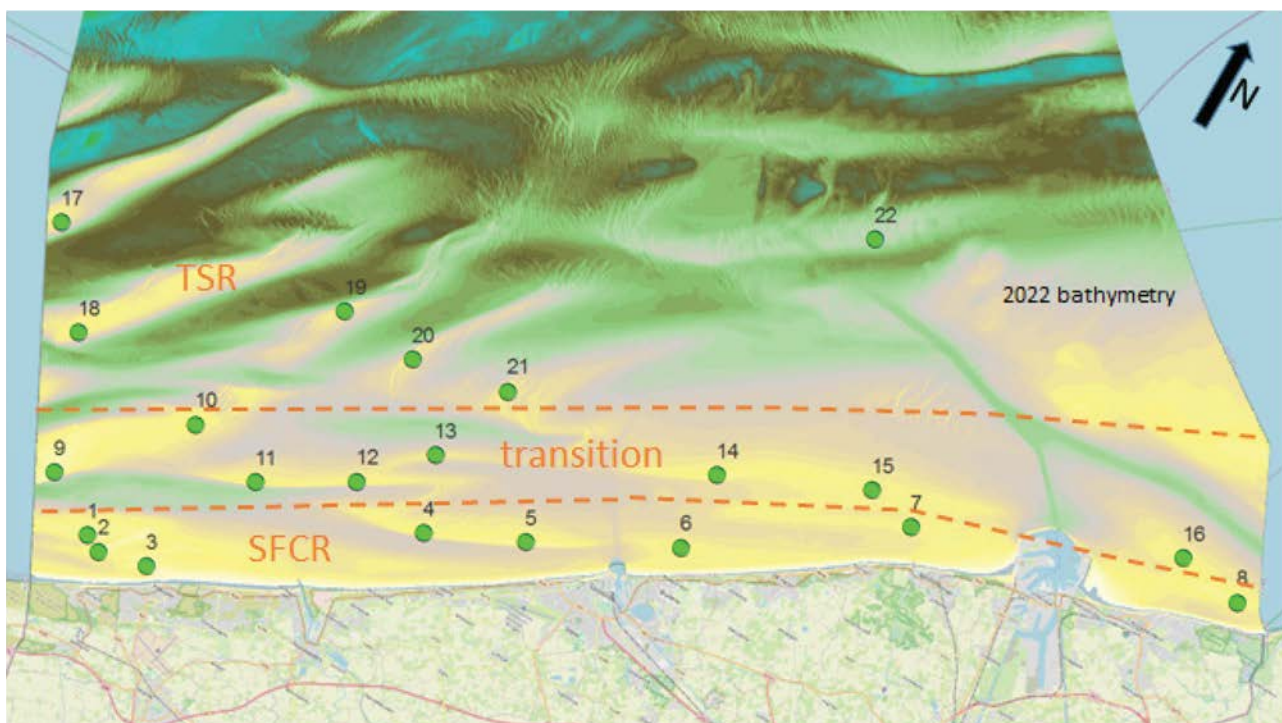


Figure 2-25 – Belgian inner shelf, 2022 bathymetry. Selected points for the 1804-2022 evolution of ridge height.

Using the point files containing the vectorised depth points of the scanned maps spanning 1804-2022, the shallowest and deepest point was recorded in about a 1 km radius around each research location. In the case where significant systematic movements of the large-scale bedforms are observed (see previous section), the search area for the shallowest and deepest point was extended so that the actual movement of the large-scale bedform is compensated for. The deepest point was systematically recorded from the channel landward of the ridge crest. The 1804 depths were converted into metres. The depths were converted to 2022 bed levels by applying the correction like explained in section 2.4.7.

The results are plotted in Figure 2-26 to Figure 2-28. The figures contain grouped points per zone. The vertical scale expresses sea-level rise-corrected depth in m. The evolution of the bank crest and trough elevation at each individual point is shown by two line graphs in the same colour, with a different colour per research point. Therefore, the upper curve in each colour connects the ridge crest points and the lower curve the corresponding trough points. In order to evaluate the evolution of the ridge height at a given location, one should focus on the top and bottom curve of the same colour in the figures.

There is a general tendency for ridge crests in the SFCR zone to rise through time, and so do the corresponding deep points in the channels (Figure 2-26). The strongest tendency to rise is seen in Broers Bank and Paardenmarkt. Point 6 at the eastern end of Stroombank is influenced by dredging works for the navigation to Oostende. In 1965, the upper and lower curves meet (Figure 2-26) expressing the fact that the ridge disappeared. Point 7 ("Spoorbank", the trace downdrift of the dredge dump site) only developed after the late 1990s. This ridge is a rare case where the neighbouring channel deepened. The morphology in the wide area of Spoorbank is examined in more detail in §2.9.

The height of the ridges (distance between the upper and lower same colour curves) does not increase, it rather tends to diminish.

The crest heights and corresponding channel depths in the transition zone (Figure 2-27) also rise, but at lower rates than in the SFCR zone. Again, the ridge height (difference between crest and channel point depth) does not change over the observation period.

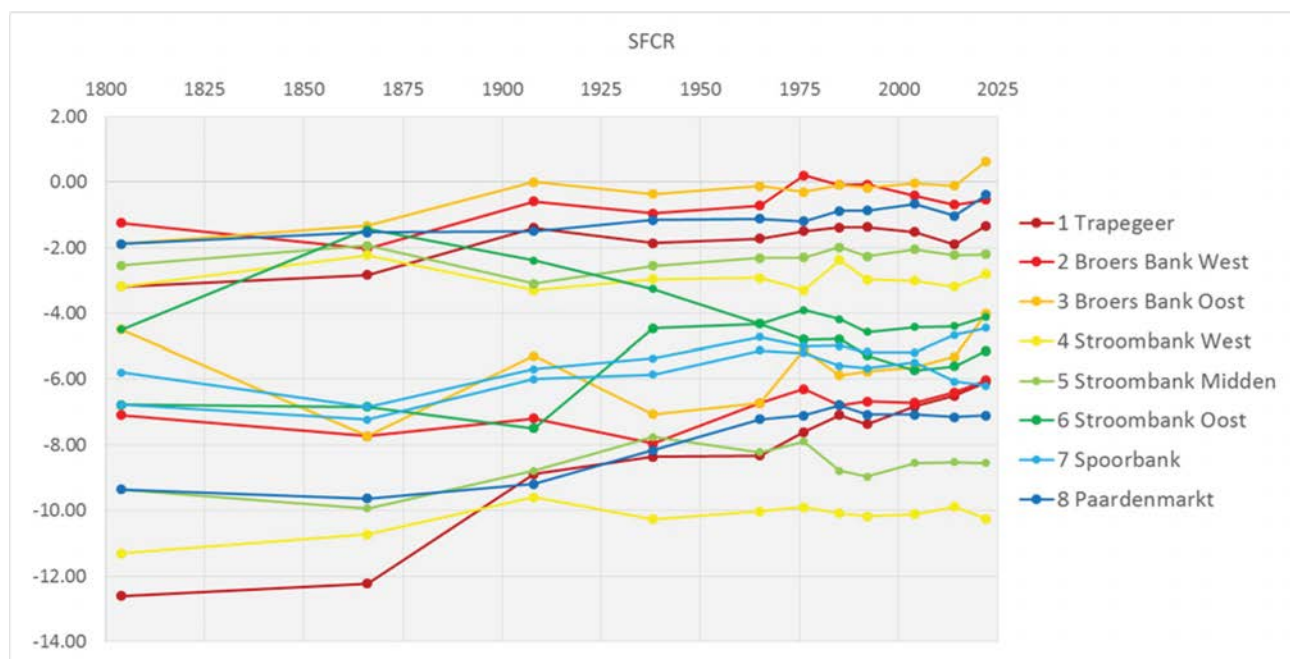


Figure 2-26 – Evolution of crest level and corresponding channel level of some selected ridge locations in the SFCR zone.

Colours represent the different locations. Per location, the upper line represents the level evolution of the ridge crest, while the lower line represents the level evolution of the nearby trough. The evolution of the ridge height can be appreciated by the distance between the two corresponding lines.

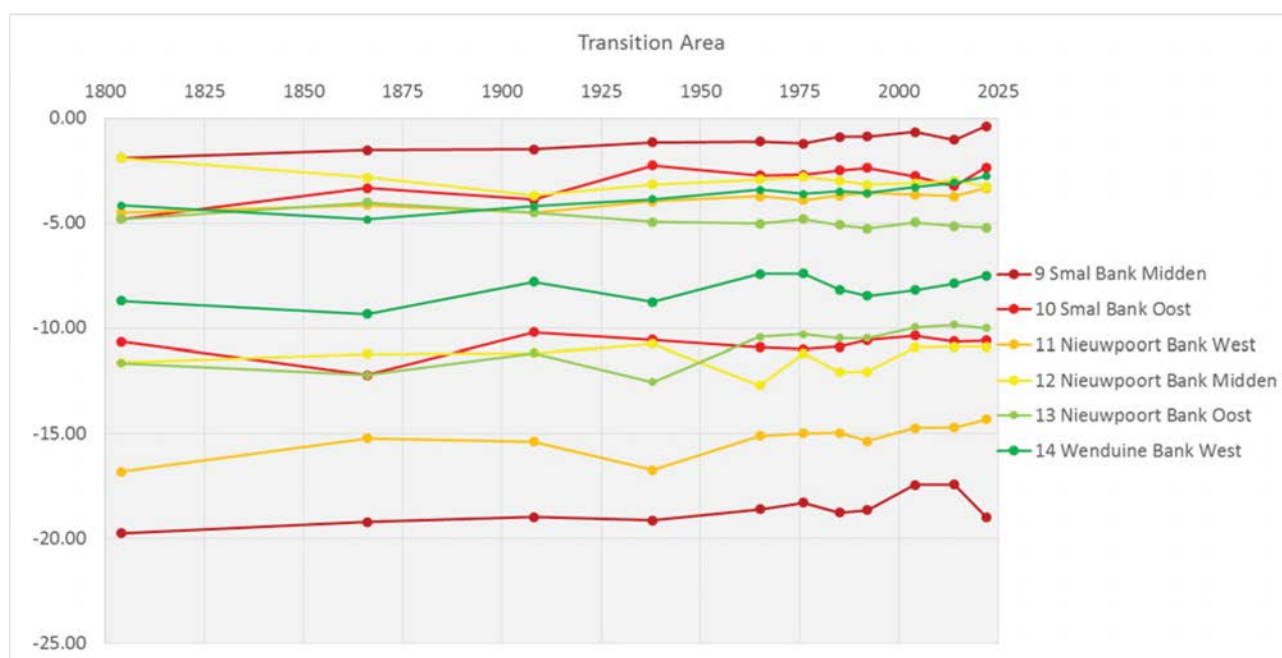


Figure 2-27 – Evolution of crest level and corresponding channel level of some selected ridge locations in the transition zone.

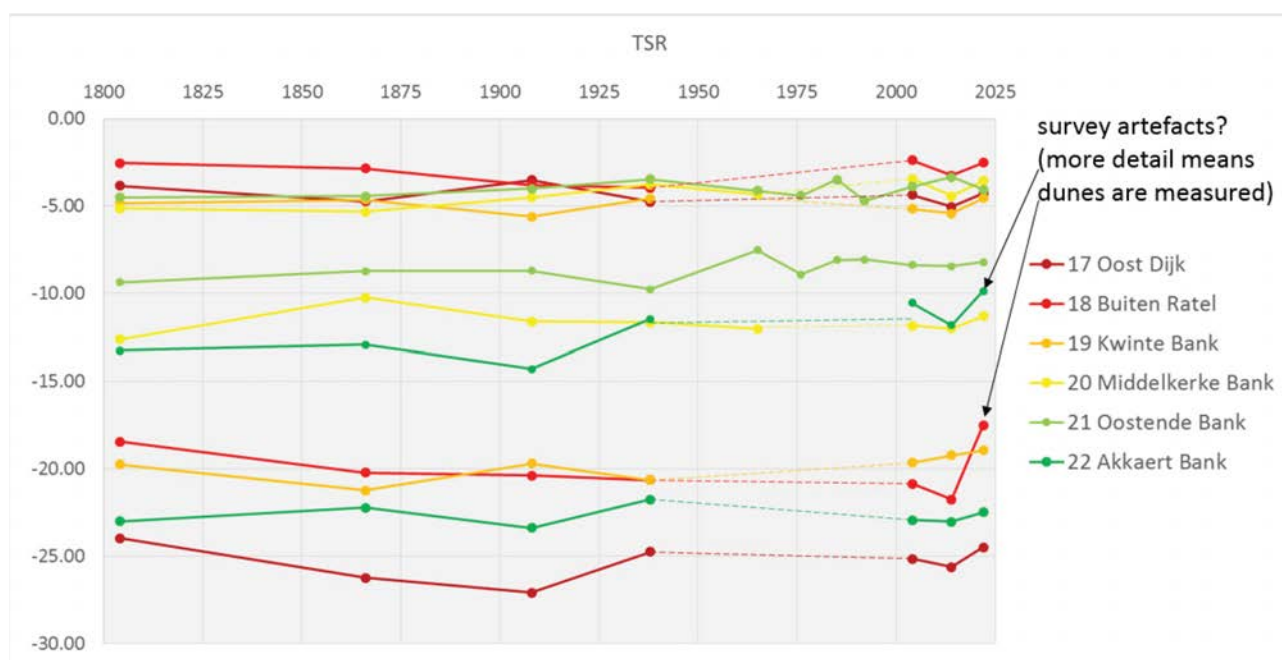


Figure 2-28 – Evolution of crest level and corresponding channel level of some selected ridge locations in the TSR zone.

The dashed line segments connect points in the graph where no 1960s-1990s survey is available.

The change in crest and channel depth is small to absent in the TSR zone (Figure 2-28). Point 22 (Akkaert Bank) seems the exception. However, the crest area contains large dunes and was probably less well captured in the older charts. Most likely, here also, there is no change. The increase of channel depth near point 18 (Buiten Ratel) in 2022 is also an outlier.

When allowing for depth selection bias, like explained in §2.4, the "no change" trend of the tidal sand ridges and the "general shallowing" trend of the shoreface-connected ridges is even more confirmed.

In conclusion, the ridges and channels in the shoreface-connected ridge zone have risen, those in the transition zone too, but at a lower rate, and in the tidal sand ridge zone, there is no change. Overall, the relative height of all ridges, expressed by the bed level difference between the ridge crest and the corresponding channel, did not change in the observation period.

2.6.3 Volumetric analysis

In spite of the relatively large uncertainty on location and depth of the historic chart data, it is thought that a large-scale volume balance of the seabed can be attempted. This is approached by computing volume differences in a few large rectangular areas or boxes.

As the results above indicate a different large-scale morphological behaviour in the inshore and offshore area, boxes were defined in three coast-parallel rows: the most inshore one contains the nearshore ridges, the middle one is the transition area and the most offshore one contains the tidal current ridges. It is pointed out here that the most offshore row is not completely covered by bathymetric data in each survey. When a defined box was almost completely covered by bathymetric data, an estimated average depth of the not-covered part (based on earlier or later surveys) multiplied by the not-covered area was added to the volume inside the box.

In the alongshore direction, 5 columns of boxes were created. The three middle ones coincide with the Belgian part of the North Sea, where good-quality recent bathymetry is available from Flemish Hydrography. The westernmost boxes are in French territorial waters and the easternmost in Dutch waters (Figure 2-29). As the bathymetric rasters do not cover the intertidal beach, the inner boxes were bounded at about the low-tide mark. There is no change of the position of the low-water mark at this small scale, except around the harbours, that have been left out of the boxes.

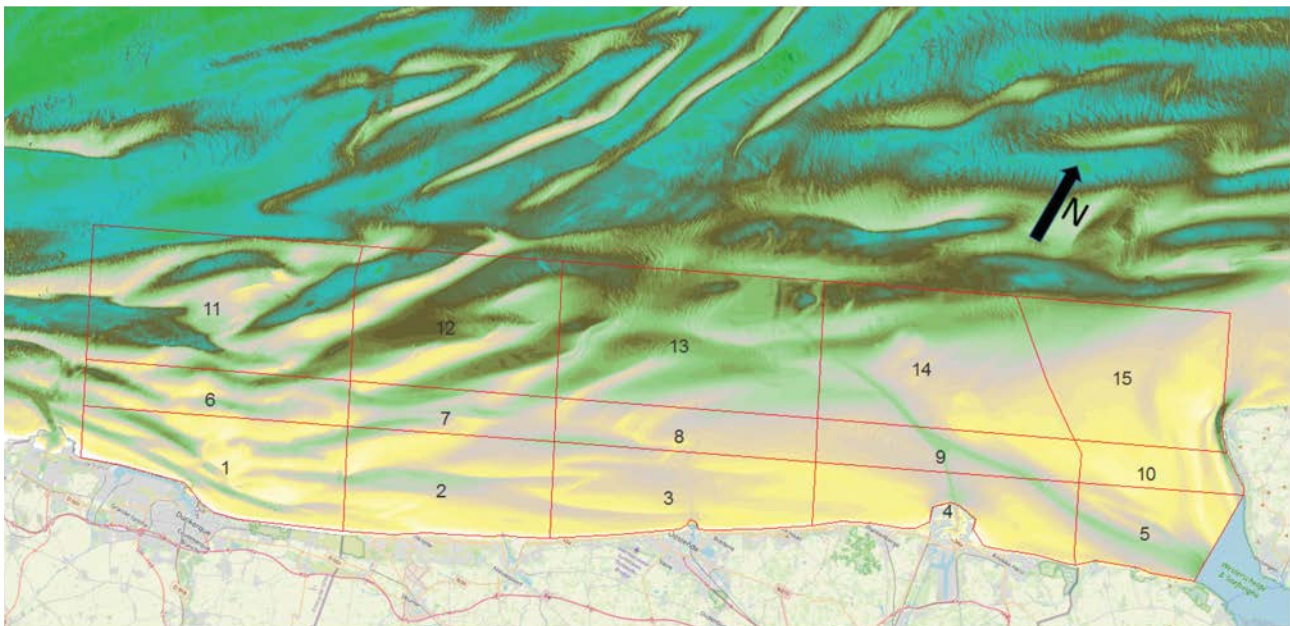


Figure 2-29 – Definition of large boxes (fine red lines) for the analysis of the large-scale long-term sediment budget. Background is 2022 bathymetry.

As the 2022 survey has the best quality, volume differences were calculated for each historic chart to the 2022 survey. For the boxes on Belgian territory, the 2022 Flemish Hydrography survey (projected to Lambert 72) served as a reference. For the Dutch part, the Dutch 2022 was used as a reference. For the French part, the EMODnet 2022 survey (projected to Lambert 72) was taken as a reference.

In practice, it does not matter whether sea bed difference maps are made using rasters in MLLWS/LAT or TAW as the same operation ([raster in MLLWS/LAT] – [conversion raster LAT to NAP] + 2.333 [constant difference between NAP and TAW]) has been applied to convert the MLLWS/LAT rasters to TAW. In this analysis, use was made of the sea-level rise correct rasters in TAW. All volumes were then subtracted from the corresponding volume for the 2022 reference raster, so that volume differences were obtained.

Dividing the computed volume difference per box by the box area yields the mean bed level difference per box, corrected for sea-level rise.

The results of the volume calculations are presented in Figure 2-30. It is reminded here that the volume difference are shown as points in time. Most surveys are the publication of soundings conducted over several years preceding the data of publication. A vertical bar was added to convey a sense of uncertainty on the average depth differences displayed. For the surveys until and including 1938, the uncertainty is estimated at $0.5\text{ m} (\sqrt{(0.5\text{ m})^2 + (0.15\text{ m})^2} = 0.52\text{ m} \cong 0.5\text{ m})$, for the other 20th century surveys 0.25 m was used and for the 21st century surveys 0.15 m.

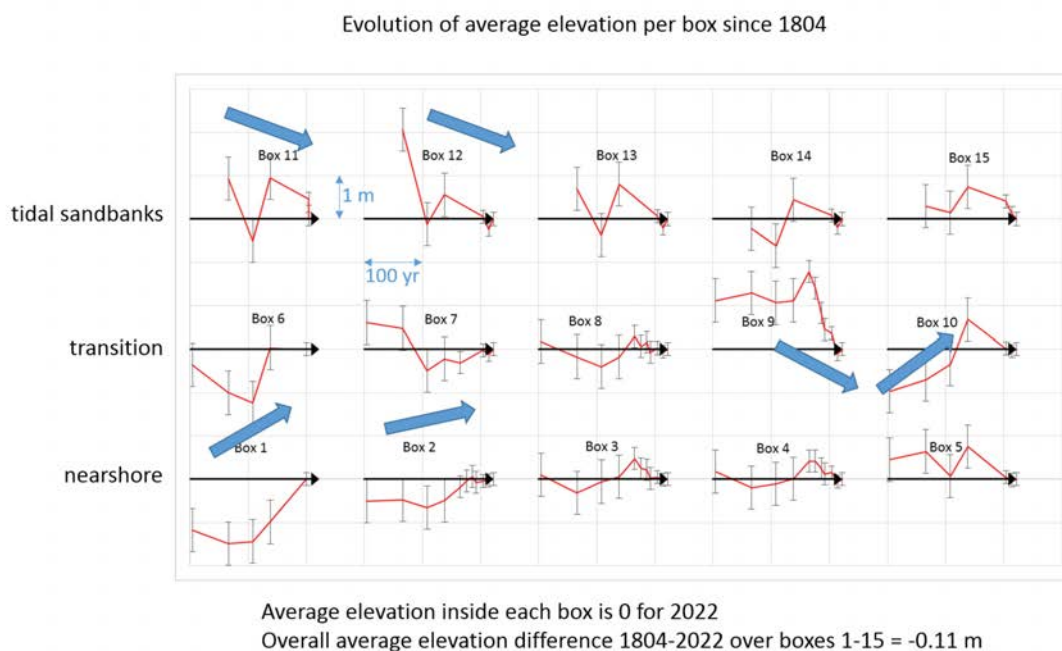


Figure 2-30 – Time plots of bed level difference in all boxes, relative to the 2022 bathymetry.

Average depth differences are corrected for sea level rise. The vertical bars indicate uncertainty on depth difference. In this figure, the graph of each box is plotted at the same relative position as the real position of the boxes (Figure 2-29). All graphs start in 1804 and end in 2022. The distance between the vertical grid lines is 100 years. The horizontal (time) axis in all graphs is at average bed level difference 0. The distance between the horizontal grid lines is 1 m (depth difference). All graphs show average bottom height difference with respect to the reference survey, 2022. The value at 2022 is always 0.

Here are the main findings:

- In the nearshore Boxes 1 and 2, in Northern France and at the Belgian West Coast, the bed shallowed up by over a 1 metre (1) and over 0.5 m (2). Also the transition Boxes 6 and 7 tended to shallow while the offshore Boxes 11 and 12 have a small negative trend.
- The nearshore Boxes 3-5 at the Belgian Middle and East Coast and the Zeeland-Flemish coast show no significant trend in depth change.
- The depth increase by over 1 m on average in Box 9 (Transition area, Belgian East Coast) since the 1960s is mainly caused by deepening of the navigation channels.

- The offshore Boxes 13 (Belgian Middle Coast) to 15 (outer Westerschelde ebb tidal delta) have no significant average depth change.
- The transition Box 10 (top of Westerschelde ebb tidal delta) accreted by about a metre. This change is likely related to the natural shift of the crest part of the ebb tidal delta towards the Westerschelde estuary. The average depth evolution inside boxes 9, 10 and 14 is also influenced by disposal of dredged slurry. This activity tends to create shallower beds (Fettweis et al., 2024).

Generalising for the entire analysis area, the main findings are presented below:

- The total change across two centuries is slightly negative: -0.11 m. This is a change within the uncertainty boundaries.
- In all boxes, there is a weak hint of a systematic trend when going onshore. The most offshore boxes lost sediment, the transition boxes show no change while the nearshore boxes mostly show growth. This trend is most clear in the "natural" western most boxes.

The latter finding can be interpreted as an expression of the seabed adaptation under rising sea level: sediment is pushed onshore. However, in reality this is not a purely cross-shore shift. The analysis of the contour line movements shows a large longshore component in the movement of large-scale bed features, that probably exceeds the cross-shore component.

2.6.4 Discussion

The detailed morphological evolution of the Belgian coast since the 1980s (emerged part, beach and dune front) /1990s (submerged part, shoreface and nearshore) is reported by Houthuys et al. (2026).

The analysis presented now expands both the analysis area and the observation period, as inner shelf maps since 1804 have been used. It is pointed out that only movements of large-scale morphological features are relevant, given the uncertainty, both in time and location, of the older surveys. Some local evolution trends raised questions that necessitated more detailed studies, essentially based on the better-quality surveys of the recent decades. They follow in sections 2.7 (wider nearshore area east of Zeebrugge), 2.8 (sedimentation in the navigation channel to Oostende) and 2.9 (wide environment of dump site Oostende and Grote Rede).

It was found that in an offshore zone, containing the tidal sand ridges, no systematic movement of the large bedforms has been observed, while in general, this zone may have lost sediment. The loss is of the same order or in some areas just exceeds the uncertainty on the data. On the other hand, in an about 7 km wide nearshore zone, containing the shoreface-connected ridges, large and systematic movements of the large-scale bedforms to the east, smaller and systematic onshore movements, and general shallowing, albeit in the order of the data uncertainty, occur. Between the nearshore and the offshore zone, there is an about 4 km wide transition zone where the offshore trends gradually transition into the nearshore trends. In this zone, also the orientation of the shoreface-connected ridges (their long axis approaches to the shoreline going east) changes to tidal current ridges with a different orientation (their long axis moves away from the shoreline when going east along the ridge). The transition zone shows no systematic change in sand volume.

The alongshore movements of entire sand ridges in the nearshore zone reach up to 5 km over two centuries in the area straddling the French-Belgian border and even 5 km in 60 years when only a local segment of the sand ridge is involved (Stroombank near Oostende between 1804 and 1866). Furthermore, most shoreface-connected ridges also show an onshore movement component, but at rates that are only 1/5th or less than the alongshore movement rates.

The net eastward movement of sand ridges applies to relatively small sand ridges such as Trapegeer, in northern France and the west part of the Belgian nearshore, for the ridges that are not attached to the shoreline. On the shoreface-connected ridge Broers Bank at Koksijde, strong sand fluxes are evidenced by the morphology of large dunes on the ridge (Montreuil et al., 2024; Houthuys et al., 2026). But rather than causing this ridge to migrate eastwards, the sand flux merges with the beach and causes the beaches east of Broers Bank to accrete.

For Stroombank, an important alongshore sand transport is shown by the strong change between 1804 and 1866, and also by the fast fill in the navigation channels that crosscut the ridge (see §2.8). The rate of shoreward movement is lower than the rate of alongshore movement. Both movement directions are also inferred from the large-scale internal structure of the eastern part of the sand ridge (Cartelle et al., 2026): this has both eastward and landward dipping large-scale clinoforms inside the upper, main part of the ridge. The sand ridge originated near Nieuwpoort and initially accreted also in western direction. The younger, eastern part has an only 9 centuries old body overlying a base dated at between 1000 and 3000 years ago.

The attachment points of Broers Bank, and also of the shoreface-connected ridges Stroombank and Paardenmarkt, to the coast did not shift, probably so since the historic times. Houthuys et al. (2021) put forward the hypothesis that the attachment point of the shoreface-connected ridges may be the point of entry of offshore sand supply to the coast-dune system. A long strip of young coastal dunes, such as at Bray-Dunes – De Panne – Koksijde – Oostduinkerke could thus testify to an alongshore migration of the attachment point of Broers Bank. However, probably since the late Middle Ages, the location of the attachment point seems to have been where it is also now.

There is a weak indication that the rate of alongshore and cross-shore movements of sand ridges and the channels and passes that separate them in the transition and nearshore shore increase in the onshore direction, while at the same time the attachment points to the shore show no alongshore migration at the time scale of the data. The latter observation is interpreted as a morphological indication of entry points of offshore-sourced sand to the beach and dune system...

Over the two-century observation period, the height of all sand ridges, expressed by the bed level difference between the ridge crest and the corresponding channel, did not change. Theoretically, starting from a flat bottom, shoreface-connected ridges grow in height at the expense of the surrounding channel beds (Nnafie et al., 2014). Such a growth is however not observed for the Belgian shelf case since 1804. The large-scale bedforms may represent a morphological equilibrium state.

When taking sea-level rise into account, and the fact that the charts' reference surface has risen along with it, and also accounting for the large area concerned and the uncertainty on the historic bathymetric data, the established global sediment budget for the Belgian inner shelf results in no net change. Overall, the nearshore part shows a weak to (near the French-Belgian border) significant trend of accretion while the most offshore part has a correspondingly erosional trend. Overall, the amounts of sand loss in the offshore zone are nearly equal to the amounts of sand gain in the nearshore zone.

It is thought that the described 1804-2022 large-scale morphological changes represent natural change, driven by natural hydrodynamic processes combined with the ongoing sea-level rise. A generalised response to sea-level rise seems to be the piling up of sand towards the coast. Such large-scale transfer is widely observed worldwide, also during earlier sea-level cycles documented in geological sediments (Catuneanu, 2006). In the case of the Belgian inner shelf, this is clearly not a purely cross-shore transfer, as the alongshore large-scale bedform movements are even larger than the cross-shore movements.

The receiving area, i.e. the nearshore zone, would under completely natural conditions have migrated inland, i.e. transgression would take place (Catuneanu, 2006). Since the 16th century, the coastline has remained more or less at its present position (Houthuys *et al.*, 2021). This is the result of seawalls and groynes stabilising the beach, and embankments protecting the inland lowlands so that they did no longer inundate and sediment was no longer transferred to the inland part of the coastal plain. The efforts to fixate the coastline culminated in the last decades in extensive and repeated beach nourishments, so that overall they even prograded the shoreline by tens of metres, locally up to 100 m.. As a result, accommodation space is lost in the nearshore area. Combined with the shoreward long-term movement of ridges, this may lead to locally stronger currents and channel deepening. The hypothesis of nearshore channel constriction (the same tidal volume is flowing through ever narrowing flow sections) as the driver of nearshore channel bed deepening was put forward by Houthuys *et al.* (2022) and was confirmed in an update of the coastal morphological monitoring (Houthuys *et al.*, 2026). It emerged as a morphological system only over the last decades.

Channel deepening may be a temporary stage. If sediment supply from offshore continues, combined with continued nourishments of beaches and shoreface, a stage may be reached where current erosion is outpaced by sediment supply. Then a general sanding up of the nearshore may set in. The volume and time scale of this flipping point is unknown. The particular morphological evolution of Appelzak near Knokke-Zoute may be an illustration of such a morphological trend change. The indications and sediment budgets related to that particular area are addressed in section 2.7.

The large-scale landward shift of the shallow crest area of Westerschelde's ebb tidal delta, towards the estuary, may also be a response to sea-level rise. The trend reported here for the last two centuries is probably partly captured in Elias *et al.*'s (2016) subarea k, Vlakte van de Raan, of the Westerschelde. They report erosion in the order of 1 m at the seaward side and sedimentation in the (smaller) landward part, locally exceeding 2 m, between 1964 and 2011. In SW-Netherlands, it was observed that closure of the sea inlets changed the hydrodynamic regime from mixed to wave dominated. The outer delta moved both landwards (i.e. towards the Westerschelde Estuary) and alongshore, northwards. The total volume present in the wide area did not change significantly during the last 50 years. The change in hydrodynamic regime can however not have played at the Westerschelde mouth. Therefore, the large-scale shift reported here is thought to reflect a response to gradual and ongoing sea-level rise.

The human activities near the harbours have a huge impact on the seabed in the wide environment of the activities.

Man has ever tried to improve nautical access. Already around 1804, Stroombank was disconnected from the shoreface at Bredene, probably by dredging. The impact on the beach back then is not known. The recovery of Stroombank by 1866 was spectacular. The shallow crest area was extended over a distance of 5 km towards the coast near Bredene, testifying to the large longshore transport. Since the dredging of a new navigation channel, Rechtstreekse Kil, this time crosscutting Stroombank, the shoreface connection area of the sand ridge was again and definitively depleted. This may be an important cause of beach erosion in the 20th century in Bredene and De Haan (De Moor, 1991; Houthuys *et al.*, 2022).

The impact of harbour construction and dredging at Zeebrugge is even more far-reaching. Its influence on the nearshore affect primarily the wide area of Appelzak and Paardenmarkt (§2.7). The navigation channel Pas van 't Zand was created across Hard Zand, the local name of the sandbank linking Wenduine Bank to Paardenmarkt, before 1908. Its floor was at least 3 m below the crest of the ridge. As a result, the crest of Paardenmarkt suffered depletion and was lowered by 2 m between 1908 and 1967.

Even larger-scale change was observed after 1967. It is caused by Zeebrugge Outer Harbour, constructed in 1979-1986, and the deepening of Pas van 't Zand and Wielingen-Scheur by dredging. These works apparently ultimately depleted the surrounding flat seabed areas near Wandelaar, north of Wenduine Bank and near Bol van Heist, where a wide surrounding area deepened by 1 to 2 m, locally near the channels even up to 5 m. The areas at the offshore side of Zeebrugge Harbour dams are subject to stronger currents since the construction of the dams. The morphological adaptation is scour of the seabed. At the same time, seaward accretion was observed at the wide, gently sloping north flank of Paardenmarkt, especially off Heist and Knokke. This has to do with the disposal of dredged material on dump site Zeebrugge Oost (§2.7).

2.6.5 Conclusions

The large-scale inner shelf bed morphological evolution of the Belgian inner shelf and the surrounding parts of the French and Dutch territorial waters was studied using the bathymetry of the area charted from 1804 on.

In the offshore part of the inner shelf, containing the tidal current ridges, no systematic movement of the large bedforms has been observed, while in general, this zone may have lost sediment. The loss is of the same order of, or just exceeds, the uncertainty on the data. On the other hand, in an about 7 km wide nearshore zone, containing the shoreface-connected ridges, but excluding the beach, large and systematic movements of the large-scale bedforms to the east, smaller and systematic onshore movements, and general shallowing, albeit in the order of the data uncertainty, occur. Between the nearshore and the offshore zone, there is an about 4 km wide transition zone where the offshore trends grade into the nearshore trends

The attachment points of the shoreface-connected ridges however did not move, probably so since the historic times. The shoreface base tends to move landwards at rates comparable to the landward shift rate of the shoreface-connected ridges. The height of the nearshore sand ridges did not change, though often both crest and channel appear to have risen over the past two centuries. The shallowest part of Westerschelde ebb tidal delta shifted landwards, towards the Westerschelde.

It is thought that the described 1804-2022 large-scale morphological changes represent natural change, driven by natural hydrodynamic processes combined with the ongoing sea-level rise. This would imply that the observed piling up of sand towards the coast would represent a generalised response to sea-level rise.

The receiving area, i.e. the nearshore zone, is not allowed to migrate inland. The shoreline is kept fixed at its current position and extensive nourishments even pushed the shoreline a few tens of metres seaward. As a result, accommodation is lost in the nearshore area. Combined with the shoreward long-term movement of the nearshore sand ridges, this may lead to higher flow currents in the channels and bed deepening. If sediment piling up near the coast would continue, a tipping point might be reached where general sanding up of the nearshore may set in. The volume and time scale of this flipping point is unknown.

Human interference also triggered important morphological changes. They overshadow the natural morphological changes in intensity. The creation of navigation channels cross-cutting the nearshore sand ridges depleted the downdrift (eastward) part of the affected ridges, thus probably also depriving the downdrift beach of sand supply. In the neighbourhood of Wielingen-Scheur and Pas van 't Zand, a wide surrounding area deepened after the 1960s survey by 1 to 2 m, demonstrating that large-scale dredging below the generalised seabed depth also affects the environment. Due to flow constriction, scour channels developed at the seaward side of the new harbour dams that protrude in the nearshore area. At the same time, sedimentation occurs updrift and downdrift of the new harbour dams. Combined nearshore and beach accretion is observed at the updrift (west) side of the outer harbours, while accretion at the downdrift (east) side is also important but only affects the nearshore.

2.7 Sediment balance of the nearshore area east of Zeebrugge: nourishments versus harbour-induced change

2.7.1 Introduction

The beach Knokke-Zoute is a hotspot of erosion. Already before the extension of the harbour of Zeebrugge in the 1980's, erosion was studied and the presence of the Leopold II-dam in Zeebrugge, built in 1896-1907, that blocked coastal drift, was understood to be a cause of the erosion (Flanders Hydraulics archive, dossier MOD 265, 1970-1981¹). In 1977-1979, a large beach nourishment was carried out from Heist to Zwin, over a coastal length of about 9 km. This work was then the largest in its kind on the Belgian coast. It was done to prepare the beaches east of Zeebrugge for sand depletion, expected to occur after the construction of Zeebrugge's new outer harbour (1979-1986). The nourishment implied placing about 8.5 Mm³, or on average almost 950 m³/m coastal length. After the large 1980 nourishment, while along most of the coast east of Zeebrugge beach erosion was limited or absent, several maintenance nourishments were needed, on average every 3 to 5 years, in the most erosional part: Knokke-Zoute. In the last two decades, the frequency of maintenance nourishments was even further increased, following the recommendations of the Coastal Safety Assessment studies. The sand applied by the successive nourishments was relatively coarse sand borrowed offshore.

At the same time, the nearshore area (defined here as the about 1 km wide area offshore from the shoreface foot) has parts that attract sand (Plaat van Heist, Paardenmarkt sand ridge) while other parts, at least in some periods, show strong erosion (Appelzak).

The sand budget of the area of the regular coastal monitoring surveys in the coastal zone from Zeebrugge to the Dutch border is reported by Houthuys et al. (2026):

- In the beach part (elevation slice above +1.39 m TAW), the sand volume was in 2025 over 2 Mm³ larger than in 1979 (note: after the large, 8.5 Mm³ nourishment). This is entirely due to nourishment. About 4.4 Mm³ sand has been nourished over the period, with increasing amounts in the recent decades. Most of the nourishments were carried out at Knokke-Zoute.
- The shoreface part (elevation slice between +1.39 m and -4.11 m TAW) had in 2025 almost 6 Mm³ more volume than in 1992. About 1.5 Mm³ if this can be directly attributed to shoreface nourishments.
- The seabed part (below -4.11 m TAW) had in 2025 just under 1 Mm³ less volume than in 1992.

The somewhat surprising conclusion – given our appreciation of this area as highly erosional – is that there is more sediment in the area than before 1979/1992: +7 Mm³, of which 5.9 Mm³ is accounted for by nourishments. There is apparently also a net import from offshore.

After each beach nourishment at Knokke-Zoute, coastal processes remove most of the replenished sand from the nourishment area. It's not clear where it settles ultimately, and which proportion of the eroded sand ends up where. In spite of this beach erosion, the nearshore receives other sand than only nourishment-sourced sand. What is its source?

The research question is tackled in four steps:

- how does a typical nourishment at Knokke-Zoute evolve morphologically and can this tell us something of the destination of the eroded sand?

¹ Citation from a letter in this archive: <<De verdediging van de stranden van de Oostkust wordt door de uitbouw van de haven van Zeebrugge nog scherper gesteld dan nu. Het natuurlijk zandtransport zal na de uitvoering van de werken te klein zijn om een snelle natuurlijke opvulling van de stranden te verwachten, zodat de stranden kunstmatig zullen moeten gevoed en opgehoogd worden.>>

- what is the morphological sediment balance in the nearshore area?
- what is the morphological sediment balance in the wider offshore area?
- what is the role of nourishments and dredged material disposal in the area?

2.7.2 Method and data used

Use is made of the results of the updated coastal trend report (Houthuys et al., 2026) and the bathymetric data layers of the inner shelf produced in the current project. For the morphological analysis of nourishments at Knokke-Zoute and the subsequent evolution, also the regular coastal monitoring elevation and bathymetry maps were used, as they are frequent surveys, conducted at least every year and often twice a year. Map series of bathymetry through time illustrate the main morphological changes. Volume computations inside project-specific defined areas allow us to quantify the evolution through time of sediment volumes and average elevations. Depth contour line shifts further clarify morphological change.

The volume evolution is area-wise compared with the amounts of sand imported or exported by human activities. The nourished sand volumes are taken from Houthuys et al. (2026). The location and amount of dredge disposals are from Fettweis et al. (2024).

2.7.3 Morphological analysis of a typical beach nourishment at Knokke-Zoute

2.7.3.1 The 1999 nourishment

The 1999 Knokke-Zoute nourishment was selected for calibrating the detailed numerical models because it was a substantial nourishment followed by several years of no new intervention. Unfortunately, no nearshore surveys were conducted between 2000 and 2003. Beach surveys are available even twice a year, but there is no beach survey available for 2003.

The nourishment was placed in sections 233 to 243, in March to May 1999. The supplied volume on board was 486,418 m³. Of this, an estimated 85% was supplied above the low-water mark (+1.39 m TAW) and 15% below it (mostly just below it).

While the backshore (supratidal part of the beach) platform was not affected, the nourishment prograded the backshore slope by about 30 m. The vertical gain on the foreshore was about 1 m. The vertical gain on the supratidal and intertidal beach was about 1 m.

The morphological evolution after the 1999 Knokke-Zoute nourishment showed that the backshore slope receded during 3 years after the nourishment. It showed a temporary and partial reset 1 year after the nourishment; it is unknown whether this was due to bulldozing or a new nourishment only in this area. There was no effect on the shoreface slope and neighbouring channel bed. There was a temporary effect (accretion) in the first sections east of the nourishment area. In December 2002, most but not all of the sand nourished in 1999 was gone. There was no substantial sedimentation area in the vicinity of the nourishment area, so most of the sand was carried away outside the nourishment area.

Apart from the temporary reset of the backshore slope, this is a representative evolution for Knokke.

Figure 2-31 shows the combined beach and nearshore bed elevation difference map between the morphology at Spring 1999, just after the beach nourishment, and the elevation at Autumn 2002 (beach) and Spring 2003 (nearshore part). This maps thus shows the overall bed level change over (almost) four years evolution after the nourishment.

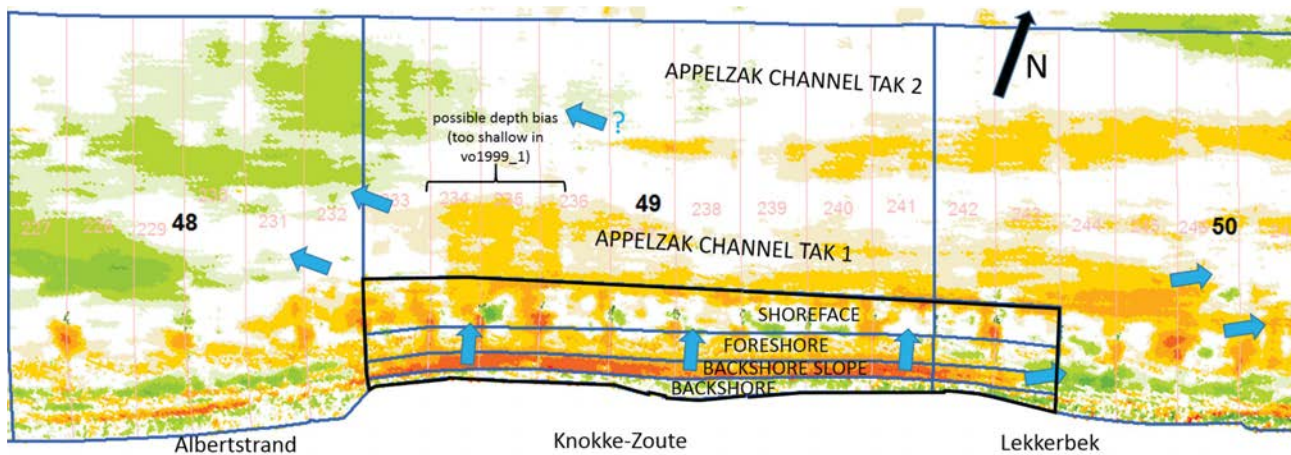


Figure 2-31 – Knokke-Zoute, area affected by the 1999 nourishment (thick black outline).

Background map: elevation difference map Autumn 2002 (beach) and Spring 2003 (nearshore) minus Spring 1999. Fine pink lines and numbers are coastal sections. Thick black line is the area of the 1999 nourishment, including the shoreface (that was not nourished). Approximate elevation boundaries (m TAW) between the partial areas: +7 (backshore/backshore slope), +3 (backshore slope/foreshore), 0 (foreshore/shoreface), -6 (shoreface foot). Blue arrows are net sand transport directions, derived from morphological change.

Most erosion was observed on the backshore slope (Figure 2-31). Somewhat milder erosion occurred on the foreshore. The upper shoreface showed some erosional and some accretional areas. The lower shoreface (most seaward part) showed net erosion, in line with the adjacent part of the Appelzak channel bed, that is also erosional off Knokke-Zoute and Lekkerbek.

Figure 2-32 presents the evolution of volumes over time and differentiated in the four coast-parallel strips of Figure 2-31 that together make up the black outlined box (ALL). The first time step is the increase due to the nourishment. The Spring 1999 survey is taken as reference volume, or 0 in the time plot. Whereas a volume of 486,400 m³ sand had been applied, the measured increase between Autumn 1998 and Spring 1999 was 451,600 m³.

The evolution after Spring 1999 shows that the upper foreshore (= backshore slope in Figure 2-31) is the first area to suffer erosion. Also, the backshore, lower foreshore (= intertidal beach) and shoreface suffered erosion during the first half year after the nourishment. This also means that the eroded sand was completely removed outside the nourishment zone including the shoreface. Afterward, the backshore and lower foreshore did not erode further, while upper foreshore kept losing sand and shoreface only underwent slight erosion. Around late 2002 – early 2003, all the nourished sand was removed. A new nourishment was indeed carried out in 2004.

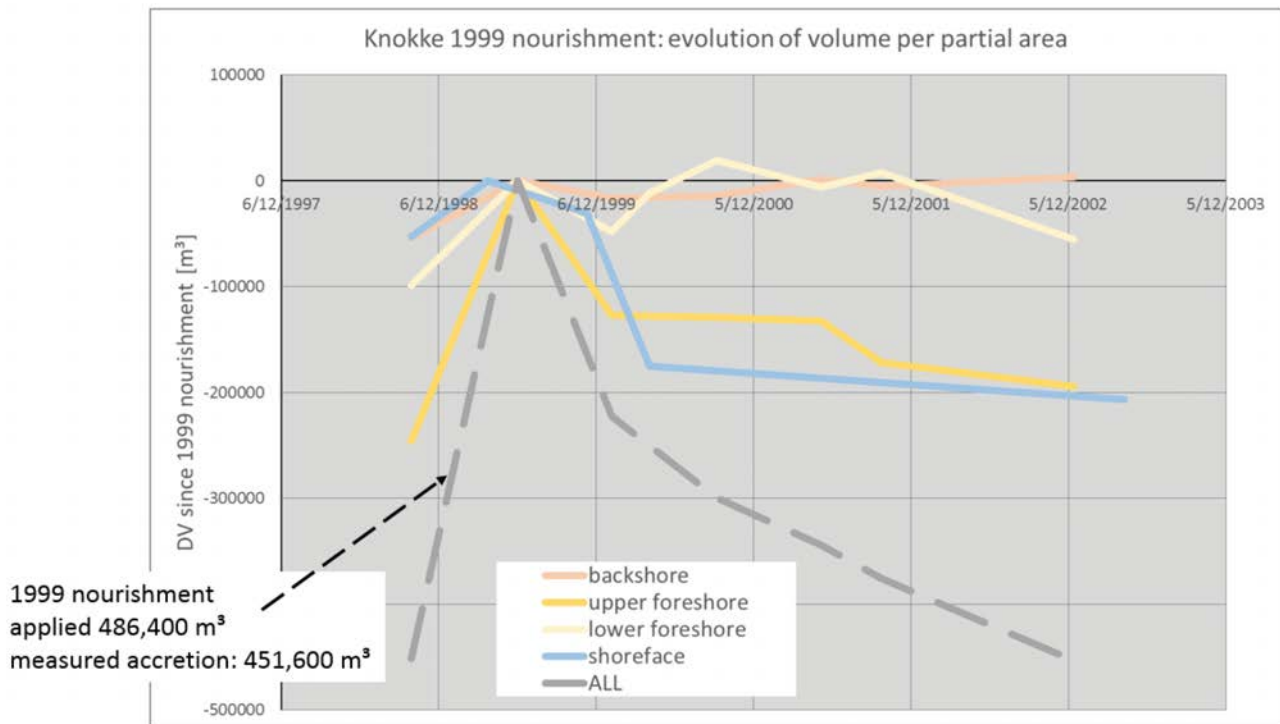


Figure 2-32 – Volume evolution in the four boxes shown in Figure 2-31 (upper foreshore = backshore slope).

Based on a set of cross profiles in sections 235 and 239, containing a profile for all the available surveys, the generalised profile evolution sketch of Figure 2-33 was made. It demonstrates the profile change due to the nourishment ('step 1'), and the evolution in the following years ('step 2', 'step 3'). It shows an initial gain of the upper shoreface. The involved volume is smaller than the corresponding eroded volume at the backshore slope and foreshore.

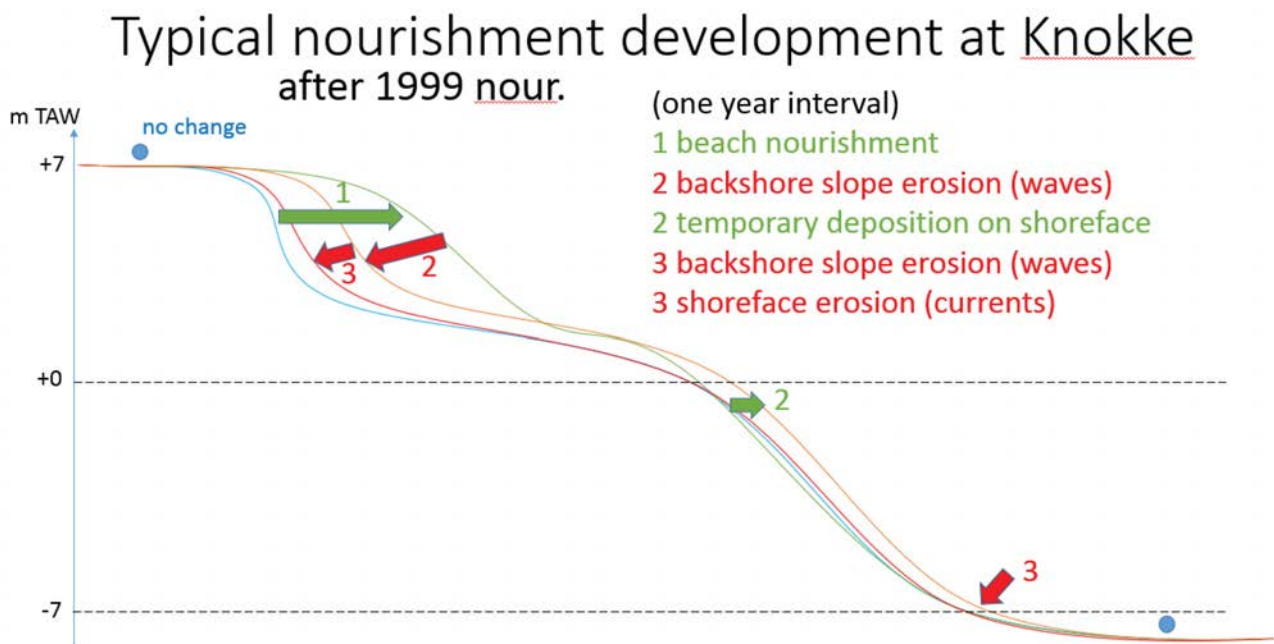


Figure 2-33 – Generalized evolution of the beach and shoreface profile after the 1999 beach nourishment at Knokke-Zoute.

The profile development is typical for nourishment at Knokke-Zoute. From the morphological position of the most erosive part of the profile, it can be inferred that it is mostly waves that attack the nourished backshore berm. The temporary storage of a part of the eroded sand on the upper shoreface is in agreement with this process. The removal of this sand and the erosion of the shoreface in general, including the shoreface foot, is likely the action of currents. Note that there is no deposition on the Appelzak channel bed. All eroded sand was exported from the nourishment zone and its shoreface.

Where is the eroded sand finally transported to? The elevation difference map series (available in the Map Series supporting material) gives some clues. These morphological clues are also summarised by the blue arrows in Figure 2-31. Initially, there is a net sand transfer from the upper foreshore and backshore slope toward the shoreface and the nearshore channel "Appelzak". During this first half year of relatively intense erosion, there is no morphological indication for lateral export by beach drift, neither to west nor east. All successive survey intervals confirm that the offshore export of eroded beach sand continues, but now there are morphological indications that the sand is moved both seaward and eastward. This is indicated by the slightly angled orientation of the blue arrows on the foreshore in Figure 2-58. Note also the accretion of the foreshore in the first sections east of the nourishment area. Most of the eroded sand is thought to have been exported towards the Appelzak channel, where it found no final destination. Especially the part of the channel closest to the shore ("Tak 1", see Figure 2-31) suffered widespread deepening over the first years. Here, the accretion areas on Appelzak's bed west of Knokke-Zoute seem to be the receiving areas. There are also some morphological indications of sand transport over Appelzak's bed to the east.

Based on this analysis, a qualitative sand budget can be put forward for the 3 to 4 years following the 1999 beach nourishment at Knokke-Zoute:

- The nourishment area including the shoreface (that was not directly nourished) loses all nourished sand (all = 10 parts).
- The foreshore east of Knokke-Zoute receives 1 part.
- The Appelzak Tak 1 bed east of Knokke-Zoute receives 1 part.
- The Appelzak Tak 1 & Tak 2 bed west of Knokke-Zoute receives 8 parts.

The main process driving erosion and sand transport on the beach is wave action. The main process driving erosion and sand transport on the shoreface and channel bed are tidal currents.

2.7.3.2 The 2019 beach nourishment

The 2019 beach nourishment at Knokke-Zoute was used as a second case for calibration and validation of the detailed numerical models in the MOZES project. The case has many similarities to the 1999 case, although there is more interference with sand nourishment works in the neighbourhood of Knokke-Zoute. The multitude of nourishments over the last decade is described in Montreuil et al. (2026) and Houthuys et al. (2026). The morphological evolution may thus not be as "pure" as the 1999 case.

The beach nourishment involving 293,000 m³ took place in February-March 2019 in sections 234-243 (Figure 2-34). A morphological increase of only about 200,000 m³ was measured between the Spring 2018 and Spring 2019 surveys. This is due to erosion that has probably occurred before, during and after the nourishment (the Spring 2019 beach survey was on 20th April). As no sedimentation around the nourishment area can be found, relatively important losses are inferred to have occurred during and soon after the nourishment activities.

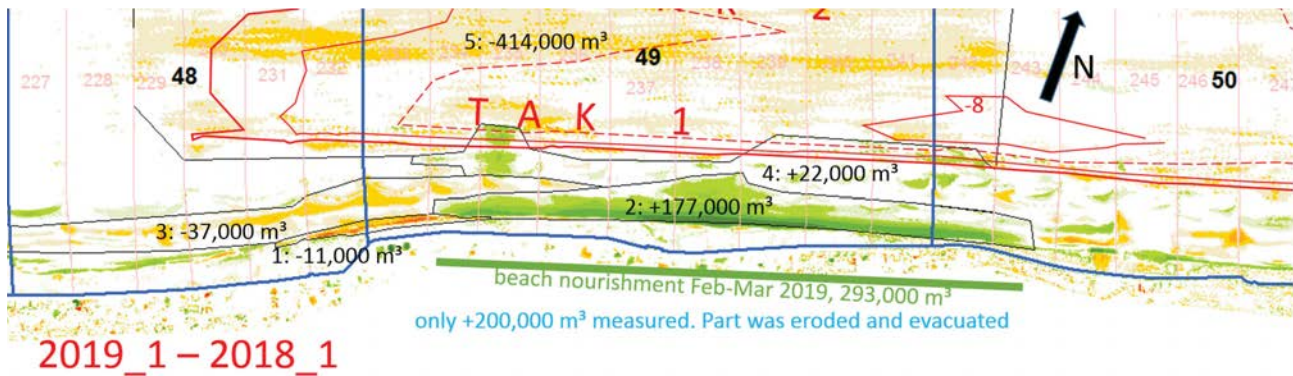


Figure 2-34 – Location of the 2019 beach nourishment at Knokke-Zoute (green area 2 and green horizontal bar).

Background map is elevation difference between Spring 2019 and Spring 2018. The measured volume increase on the beach, due to the nourishment, is calculated in specific delimited areas (fine black outline) 2 and 4. Red lines are schematised selected depth contour lines of -8, -7 (dashed), -6 (full) and -5 (thick full line) m TAW at Spring 2019,

A small nearshore nourishment involved the supply of 15,000 m³ in May-Jun 2020 on the Appelzak channel bed in sections 235-240.

This is the morphological evolution between Spring 2019 and Spring 2020 (note: all successive difference maps and volume computation areas can be found near slide 178 of the supporting material):

- Erosion of the beach nourishment, especially at the backshore slope ($-107,000 \text{ m}^3$). This is about half of the nourished sand.
- Temporary storage ($+54,000 \text{ m}^3$) of eroded sand on the shoreface, and in some sections east of the nourishment area also at the backshore slope foot.
- Accretion in Tak 1 ($+176,000 \text{ m}^3$) and Tak 2 ($+211,000 \text{ m}^3$) of Appelzak channel was widespread and larger than the nearshore nourishment by $15,000 \text{ m}^3$. Also a zone further offshore inside Appelzak accreted by $+199,000 \text{ m}^3$. There is no obvious explanation for this large channel bed accretion that totals $+586,000 \text{ m}^3$. Also, there can be no link with the beach erosion as at least half of the eroded sand was stored on the upper shoreface. Unfortunately, there are indications that the Spring 2019 nearshore survey was possibly biased towards the deeper values by about 0.10 m . This may explain an error of $243,000 \text{ m}^3$. The accretion not being spread evenly over the nearshore, but in some longshore bands, shows that at least the remaining part of the accretion (at least $+343,000 \text{ m}^3$) is a real morphological change. The morphological monitoring provides no explanation for this growth.

A large beach nourishment took place in Feb-Mar 2021 in sections 223-230 (at and near Duinbergen, west of Knokke-Zoute) applying 982,000 m³; a small beach nourishment was carried out in Mar-May 2021 in sections 241-246 applying 33,500 m³; a nearshore nourishment in Nov-Dec 2020 applied 131,000 in sections 235-240 and another one in May-Jun 2021 supplied 162,000 m³ in sections 235-240 (note: the Spring 2021 nearshore survey was done on 31/05/2021, so midway through this last nourishment).

This is the morphological evolution between Spring 2020 and Spring 2021:

- Continuation of erosion of the 2019 beach nourishment, now over a wide area covering the foreshore (-136,000 m³).
- Temporary storage (+270,000 m³) of eroded sand on the shoreface, and at the shoreface foot. The accretion area extends a few sections eastward of the nourishment area. This amount is about the sum of the erosion of the nourishment area in two years.
- A small and narrow accretion area in sections 241 to 246 (+11,000 m³) can be linked to the small local sand nourishment there.
- Accretion in Tak 1 (+594,000 m³) is the result of the two nourishments there. However, the accretion exceeds the nourished amounts.

- In Tak 2, a slightly erosive area ($-55,000 \text{ m}^3$) is found off Knokke-Zoute, while eastwards of this a slightly accretional area ($+133,000 \text{ m}^3$) is found.
- Overall, the accretion in Appelzak channel was widespread and larger than the sum of the nourished volumes and the eroded volumes at Knokke-Zoute. The nourishment at Duinbergen is thought to not be an additional source of sediment as it was observed that erosion after the nourishment there was very limited. There is no obvious explanation for the widespread accretion in Tak 1 in excess of the nourishment sources.

Another small beach nourishment took place in Feb-Mar 2022, involving the supply of $30,000 \text{ m}^3$ in sections 230-231. A nearshore nourishment in May-Jun 2021 supplied $162,000 \text{ m}^3$ in sections 235-240 on Appelzak's channel bed (note: this nourishment was also mentioned at the previous time step. The Spring 2021 nearshore survey was done on 31/05/2021, so part of that nourishment may still affect the 2022 to 2021 bathymetry difference map).

This is the morphological evolution between Spring 2021 and Spring 2022:

- Both the Duinbergen 2021 beach nourishment and the Knokke-Zoute 2019 beach nourishment suffered erosion, primarily at the backshore slope.
- The erosion of both nourishments is most probably the source of the foreshore accretion at Knokke Zoute and Lekkerbek.
- The low-water mark area at Knokke-Zoute suffered mild erosion.
- The shoreface and channel floor of Tak 1 showed a widespread mild accretion ($+151,000 \text{ m}^3$). The Duinbergen and Knokke-Zoute beach nourishment areas are a likely source of the accretion, together with the remaining part of the May-June 2021 nearshore nourishment.
- A significant accretion ($+129,000 \text{ m}^3$) was observed off Albertstrand on the shallow ridge separating Tak 1 and Tak 2. It is interpreted here as a morphological adaptation of the area surrounding the nearshore nourishments in Tak 1 in the previous year. The location would imply a predominant spreading from the nourishment area by the ebb current.

This description together with the annotated maps and two cross profiles available in the supporting material maps series, confirm that the morphological evolution after the 2019 beach nourishment mirrors the one observed for the 1999 beach nourishment. In one aspect, it deviates: there is more and longer temporary storage of sand eroded from the beach on the shoreface. This may have to do with the important channel bed nourishments of 2020 and 2021. As the overall depth in Tak 1 of Appelzak decreased by over 0.5 m, this morphological change must have had an effect on the tidal current structure in the channel. It can be inferred that the overall currents near the shoreface were somewhat diminished due to the offshore nourishments.

When making abstraction for this deviating aspect, the scheme of Figure 2-33 is also valid for the 2019 nourishment. A corresponding qualitative sand budget is more difficult to establish given the influence of the additional nourishments in the neighbourhood.

2.7.3.3 The 2023 beach nourishment

The 2023 beach nourishment at Knokke-Zoute was used as a third case for calibration and validation of the detailed numerical models in the MOZES project. The case has many similarities to the 1999 and 2019 cases, as far as only the beach was affected.

The nourishment involved the supply of $511,000 \text{ m}^3$. In area 1 of Figure 2-35, a volume increase of $483,000 \text{ m}^3$ was measured between Spring 2022 and Spring 2023. It can be concluded that most of the nourished sand remained in situ during the nourishment works.

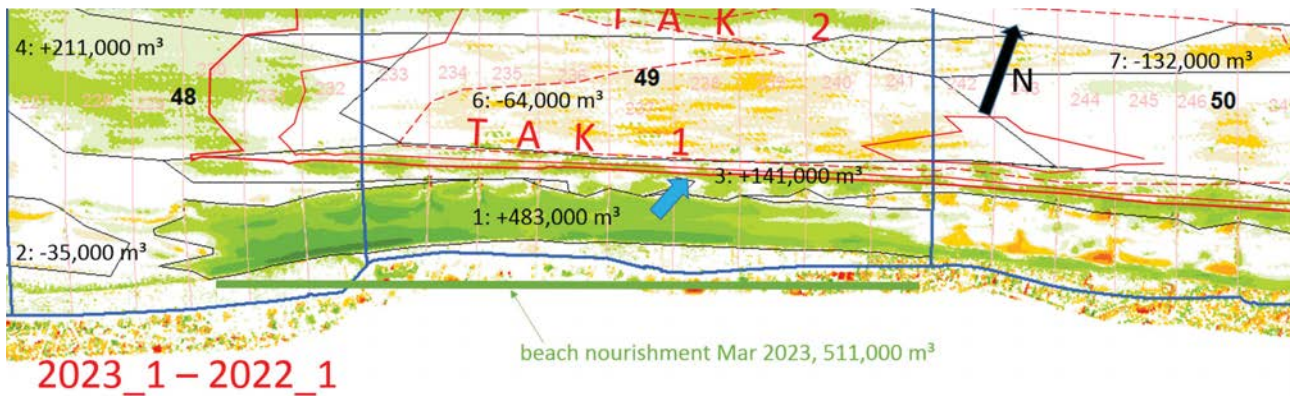


Figure 2-35 – Location of the 2023 beach nourishment at Knokke-Zoute (green area 1 and green horizontal bar).

Background map is elevation difference between Spring 2023 and Spring 2022. The measured volume increase on the beach, due to the nourishment, is calculated in specific delimited area 1.

2.7.3.4 The 2020-2024 nearshore nourishment

During the construction of the new sea lock in Terneuzen, large amounts of fine sand became available. It was decided to use this sand for a campaign of nearshore nourishments at Knokke-Zoute (Montreuil et al., 2026). The first nourishments had already started in 2020 and 2021 (see description of 2019 beach nourishment).

The bulk of the operation involved the supply between October 2023 and February 2024 of 1.2 Mm³ in a nourishment area off Knokke-Zoute. This area is shown in violet in Figure 2-36. The area has two parts: a channel bed part in Tak 1 of Appelzak channel, where the bed is at about -7 m TAW (before the nourishment), and a shoreface part, where groynes extend from the beach to the channel bed.

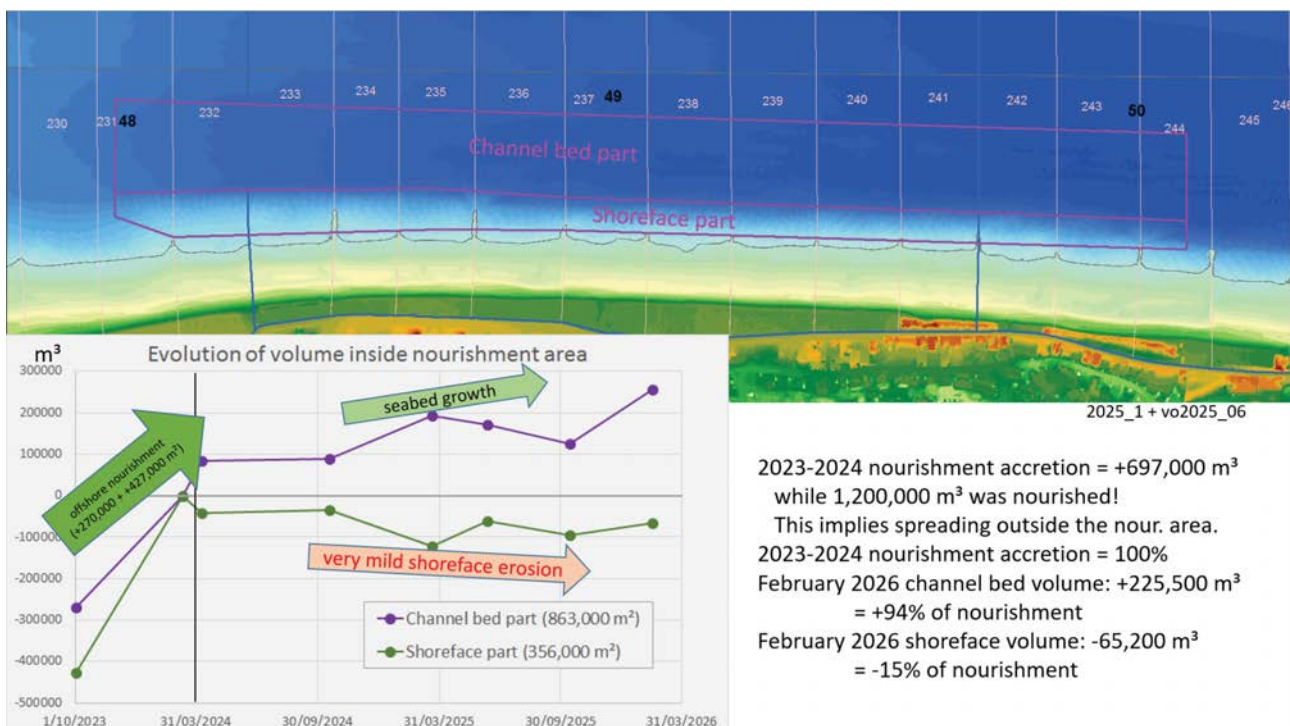


Figure 2-36 – Area of the late 2023 – early 2024 nearshore nourishment off Knokke-Zoute (violet outline), and 2024 – 2026 volume evolution inside it.

Map background: combination of Spring (April) 2025 beach survey and June 2025 MB nearshore survey, supplemented at the seaward side by the March 2025 SB nearshore survey (this explains the offset in bed morphology near the upper side of the map). Lower left inset: 2023 – 2026 volume evolution inside the nourishment area. Final volumes are summarised at the lower right. See section “Description of the morphological evolution following the 2023 beach and 2020-2024 nearshore nourishments” for explanation.

All nearshore nourishments were done using split hopper vessels that dump their load by splitting their hold. For the shallow part of the shoreface, possibly also rainbowing was used.

In the nearshore nourishment area, a MB survey was available just before and just after the late 2023 – early 2024 offshore nourishment operations. The surveys covered the defined nourishment area, but not the surrounding parts of the nearshore. Inside the nourishment area, a volume increase was measured between the two surveys by 697,000 m³. This is a lot less than the nourished 1.2 Mm³. The reason is that even during dumping of the fine sand, spreading occurred in the neighbourhood. Figure 2-37 documents this. This elevation difference map compares two surveys that cover the wider neighbourhood, but the initial survey was conducted a few months before the nourishment while the end survey took place a few months after the nourishment. The elevation difference map shows that widespread accretion occurred also outside the nourishment area. When computing the volume accretion in areas 4, 5 and 6 of Figure 2-37, 1.176 Mm³ volume increase is measured, which matches fairly close the 1.2 Mm³ nourishment volume.

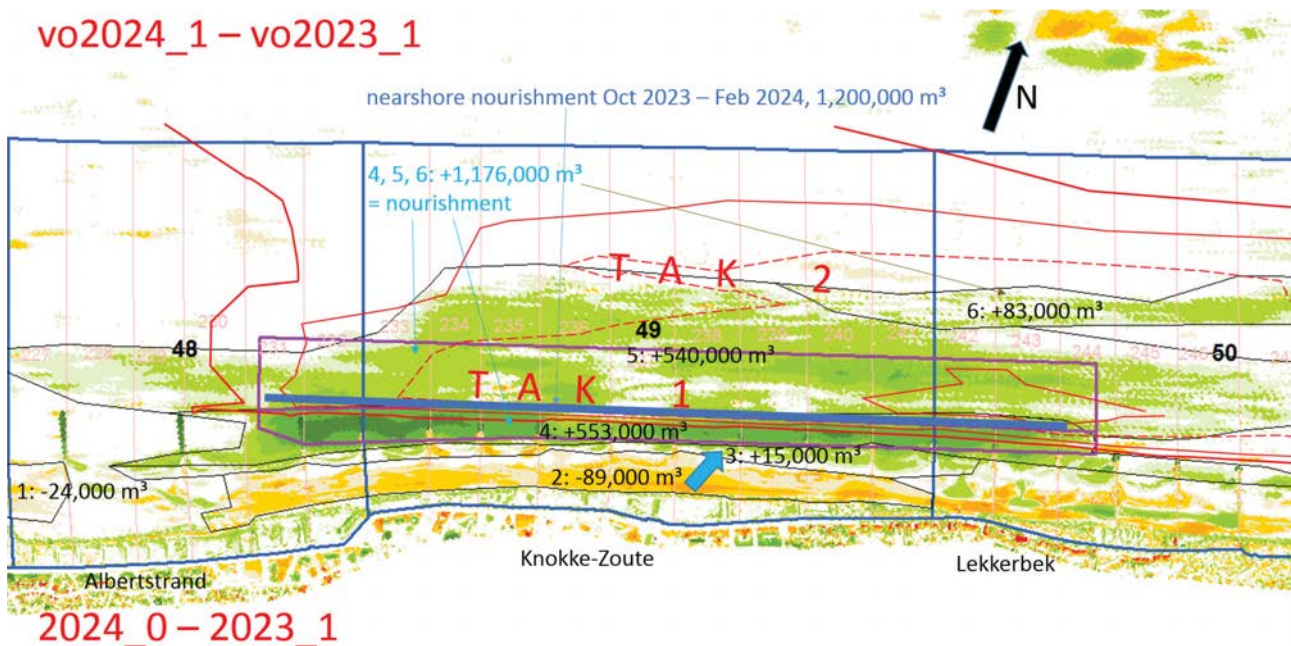


Figure 2-37 – Budget of the late 2023 – early 2024 nearshore nourishment at Knokke-Zoute taken in the wider environment.

Background map is elevation difference between January 2024 (beach) and May 2024 (nearshore) on the one hand, and Spring 2023 (June 2023 for the beach and August 2023 for the nearshore) on the other hand. Violet outline is offshore nourishment area. The measured volume increase of the wider nearshore environment, due to the nourishment, is calculated in specific delimited areas 4, 5 and 6 (thin black outlines). Thick blue arrow indicates net sand transport directions inferred from the morphology.

2.7.3.5 Description of the morphological evolution following the 2023 beach and 2020-2024 nearshore nourishments

Evolution between Spring 2023 and Spring 2024:

- A relatively modest erosion was attested of the 2023 beach nourishment, by -89,000 m³ in zone 2 (Figure 2-37). At least a small part of the eroded sand was found back around the low-water mark: +15,000 m³ in zone 3.

- Like already mentioned in the previous paragraph, shoreface zone 4 accreted by +553,000 m³ while the nearshore channel bed zone 5 showed a volume increase by +540,000 m³. A little more east and offshore, zone 6 increased by +83,000 m³. The three zones total to +1,176,000 m³, which is almost the amount of sand supplied between October 2023 and February 2024. The zones 4, 5 and 6 extend over a larger area than the nourishment area proper (see violet line). This demonstrates that the nourished sand was spread out both alongshore to west and east and offshore to Tak 2.

The 1.2 Mm³ offshore nourishment near Knokke-Zoute was conducted between October 2023 and February 2024. No nourishments were carried out between Spring 2024 and Spring 2025.

Evolution between Spring 2024 and Spring 2025:

- A narrow strip (zone 1 in Figure 2-38) at the backshore slope gained 74,000 m³. There are morphological indications that bulldozing wind-blown sand back from the backshore was carried out.
- The foreshore (zone 2) lost 96,000 m³ while a narrow strip at the low-water mark (zone 3) received 3,000 m³.
- The shoreface zone 4 lost -197,000 m³.
- The adjacent channel floor of Tak 1 in zone 5 accreted by +179,000 m³ while the shallow ridge between Tak 1 and Tak 2 accreted by +177,000 m³ in zone 6. Further offshore, a part of Tak 2 delineated as zone 7, eroded by -135,000 m³, while to the east, sedimentation took place over a wide area delineated by zone 8, by +116,000 m³.

The change is interpreted as follows: the beach erosion after the 2023 beach nourishment is compatible with the expected pattern, with the exception of the restoration of the backshore berm by human action. The shoreface erosion at Knokke-Zoute resumed. The eroded sand was largely kept in the area, mainly on the bed of Tak 1. Due to the shallower water depths in Tak 1, currents were somewhat diverted to Tak 2. This is the probable reason of the erosion in zone 7. The eroded material was redistributed in the area, partly to zone 6 and partly to zone 8.

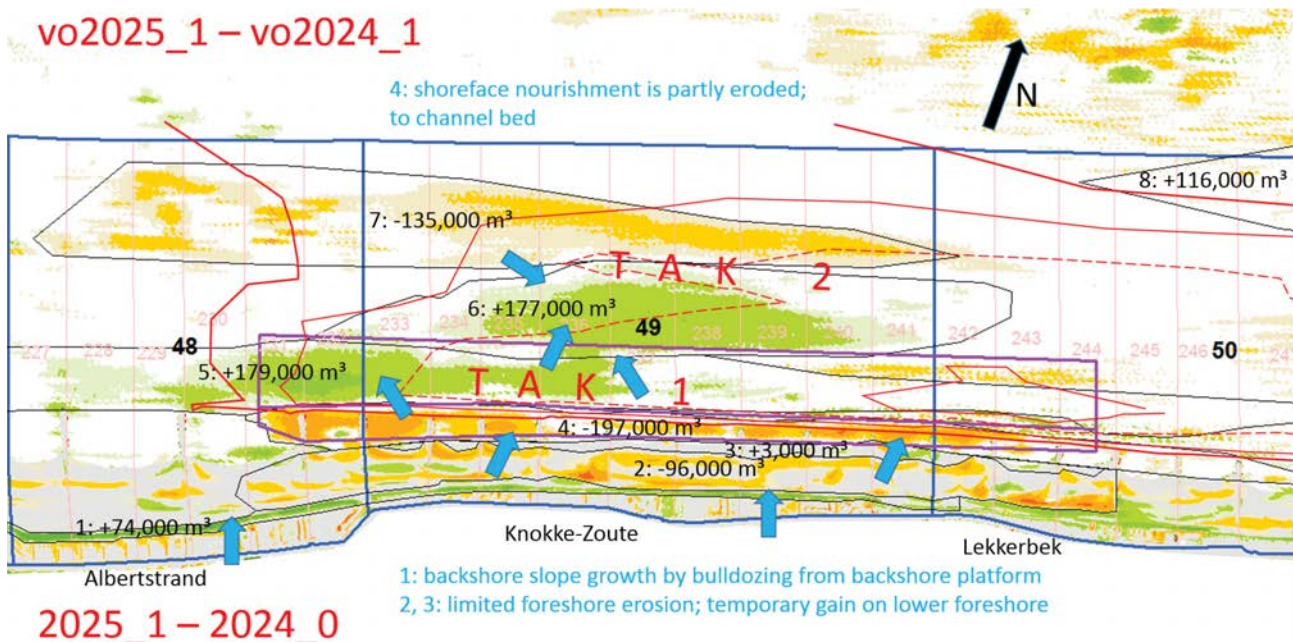


Figure 2-38 - Budget of the first year after the nearshore nourishment at Knokke-Zoute taken in the wider environment.

Background map is elevation difference between April 2025 and January 2024 (beach) on the one hand, and March 2025 and May 2024 (nearshore) on the other hand. Violet outline is offshore nourishment area. The measured volume changes apply to the irregular delimited areas (thin black outlines). Thick blue arrows indicate sand transport directions inferred from the morphology.

Let's look in more detail to the morphological evolution of the late 2023 – early 2024 nearshore nourishment. There are several MB surveys available, with their common area (unfortunately) limited to the proper nourishment area (violet outline in Figure 2-39). However, they allow to calculate volumes inside the two parts of the nourishment area and graph their evolution (see inset in Figure 2-36). The evolution after March 2024 is clear: the shoreface part gradually loses sand, but at a very mild rate. In February 2026, the loss is - 65,200 m³ or 15% of the accretion observed in the same area. The channel bed continued to receive sand and accreted by +225,000 m³ by February 2026. This corresponds to 94% additional increase on top of the volume increase due to the nourishment.

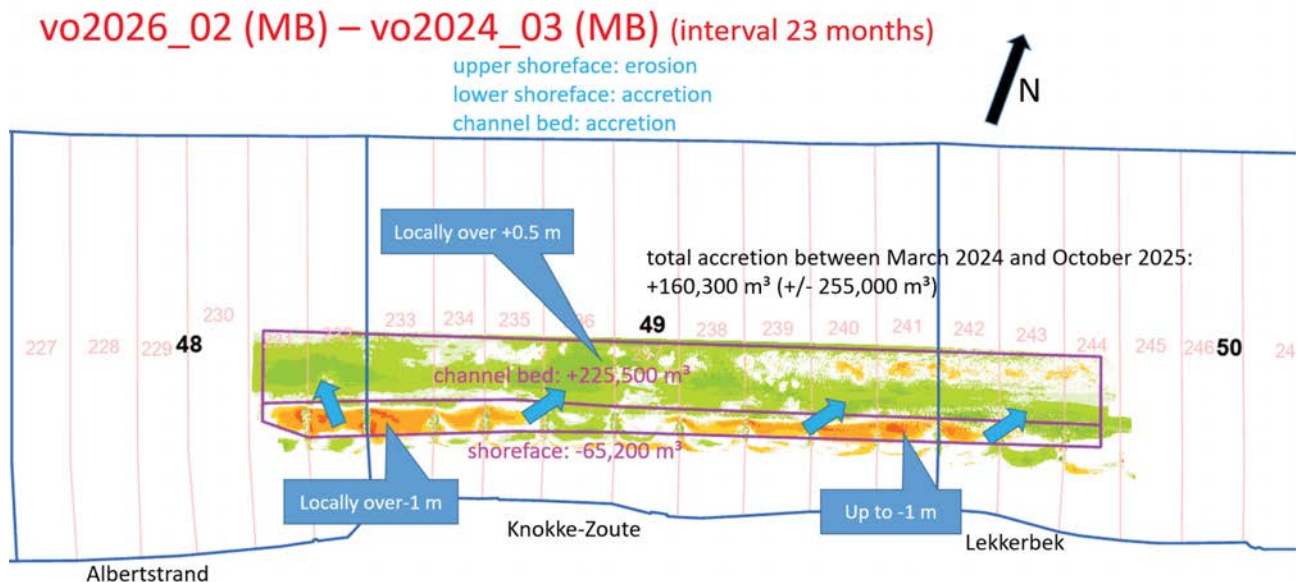


Figure 2-39 – Overall 2024 – 2026 sand budget inside the late 2023 – early 2024 nearshore nourishment area at Knokke-Zoute.

Background map is elevation difference map between MB March 2024 (immediately after the nearshore nourishment) and February 2026 (23 months later).

The overall balance is positive after 23 months (Figure 2-39): 225,500 m³ - 65,200 m³ = +190,300 m³. The channel bed part inside the offshore nourishment area received over 2024 – 2026 more sand than the shoreface part lost. The map also shows that the loss is primarily located on the upper part of the shoreface. This budget only considers the evolution over 2024-2026. In the previous paragraph, it was also observed that more accretion was observed in "Tak 1" than can be explained by nearshore nourishments over 2020-2024.

The supporting material contains detailed profiles of all available surveys between 2018 and 2025 on the two profile lines shown in Figure 2-39. The content of the profiles is schematised in Figure 2-40.

Essentially, the part above +1 m TAW behaves exactly like after the 1999 and 2019 beach nourishments. It implies that there is no direct influence of the nearshore nourishment on the morphological evolution of the beach nourishment. There is no milder erosion or new supply of sand sourced from the nearshore.

Apart from the fact that the upper shoreface was now raised more due to the shoreface nourishment, the after-nourishment evolution is also very similar to the case with a beach nourishment only.

Both morphological changes are thought to reflect dominant wave action.

The shoreface foot area shows a point in the profile of no change at about -5 m TAW.

The channel bed part of the offshore nourishment area clearly received sand and got shallower since the offshore nourishment operations. The same applies for the area surrounding the proper nourishment area. The amounts of accretion exceed the amounts that may have originated from beach erosion at Knokke-Zoute.

Profile development after beach- and offshore nour.

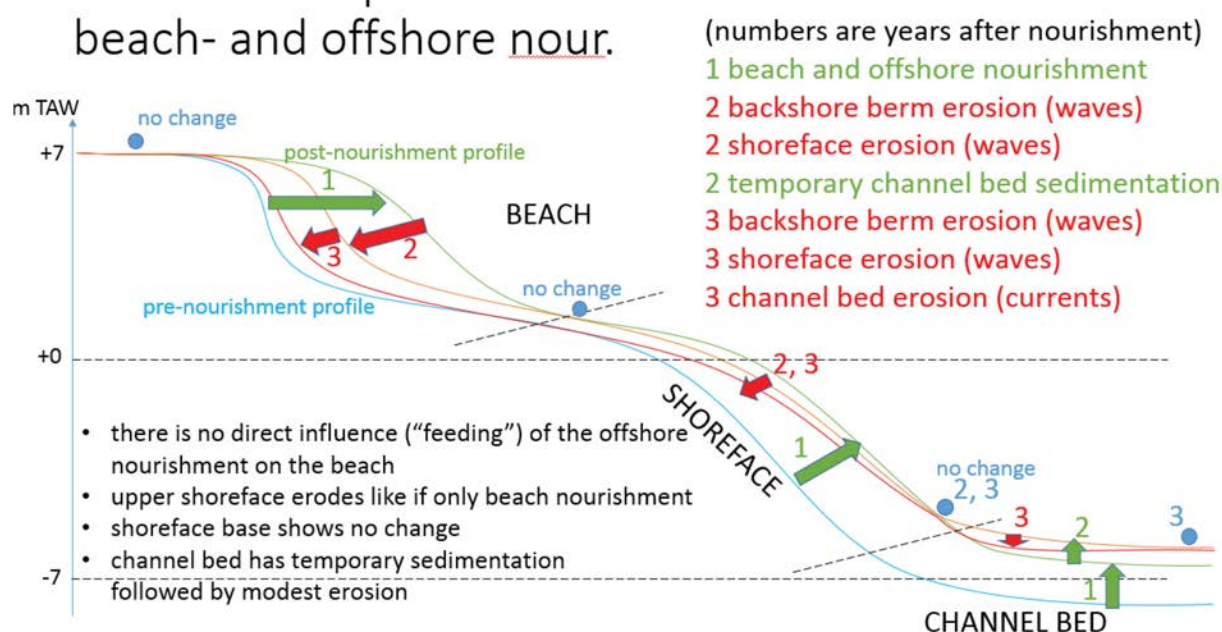


Figure 2-40 – Generalized evolution of the beach and shoreface profile after the 2023 beach nourishment and late 2023 – early 2024 nearshore nourishment at Knokke-Zoute.

It can be concluded that the channel bed nourishment (in successive stages over 2020-2024) successfully created a shallower Tak 1. The latest surveys show some resumed erosion, located on the upper shoreface at Knokke-Zoute. The erosion rates are mild compared to earlier rates. At the current rates, the nearshore nourishment may exist for a long time. In the shoreface part, this may be of the order of 5 to 10 years: measured accretion in the shoreface part of 427,000 m³ would take 6,5 years is the current loss of 65,200 m³ over the first two years is extrapolated) In the channel bed part, at present it appears that the nourishment will not be eroded at all: the area rather attracts sediment from elsewhere. In turn, a shallower channel bed near the shoreface foot may lead to even more reduced shoreface erosion.

In the short time span of almost two years after the nourishment operations, there are no direct indications that the beach nourishment has directly benefited from the nearshore nourishment. However, it is possible that the general morphological configuration in the area will reverse. This is examined next.

2.7.3.6 2018 to 2025 Appelzak sediment budget

The several nourishments are now evaluated in the wider context that also incorporates the neighbouring coastal tracts. For this, areas of sedimentation were outlined on a Spring 2025 – Spring 2018 elevation difference map in the tidal channel Appelzak (fine black lines in Figure 2-41). The specific volumes change areas were limited to the nearshore part.

The following morphological change is observed over 2018-2025:

- Some sedimentation was already observed in the nearshore area before the nourishments.
- The nourishments caused TAK 1 to fill by 0.5 – 1 m; Knokke-Zoute shoreface foot by 2 m.
- An estimated 600,000 m³ from beach nourishments contributed to the channel fill.
- TAK 1's fill shape seems to indicate a dominant net westwards transport. More specifically, there is spreading from the Knokke-Zoute nearshore nourishment both to west and east, but the amounts deposited at the west side are larger.
- Some sediment was also attracted to TAK 2.

Here is the sand balance over 2018-2025:

- Total accretion Appelzak: +3,996,000 m³ (area 4 + 5 + 6 + 7 + 8 + 9).
- Total nourished on shoreface and channel bed: +1,500,000 m³.
- Total nourished on Knokke-Zoute and Duinbergen beach: +1,849,000 m³,
- of which est. 600,000 eroded towards nearshore (475,000 m³ over 2018-2024).
- Balance net sedimentation in Appelzak from unknown source: +1,896,000 m³.

vo2025_1 – vo2018_1

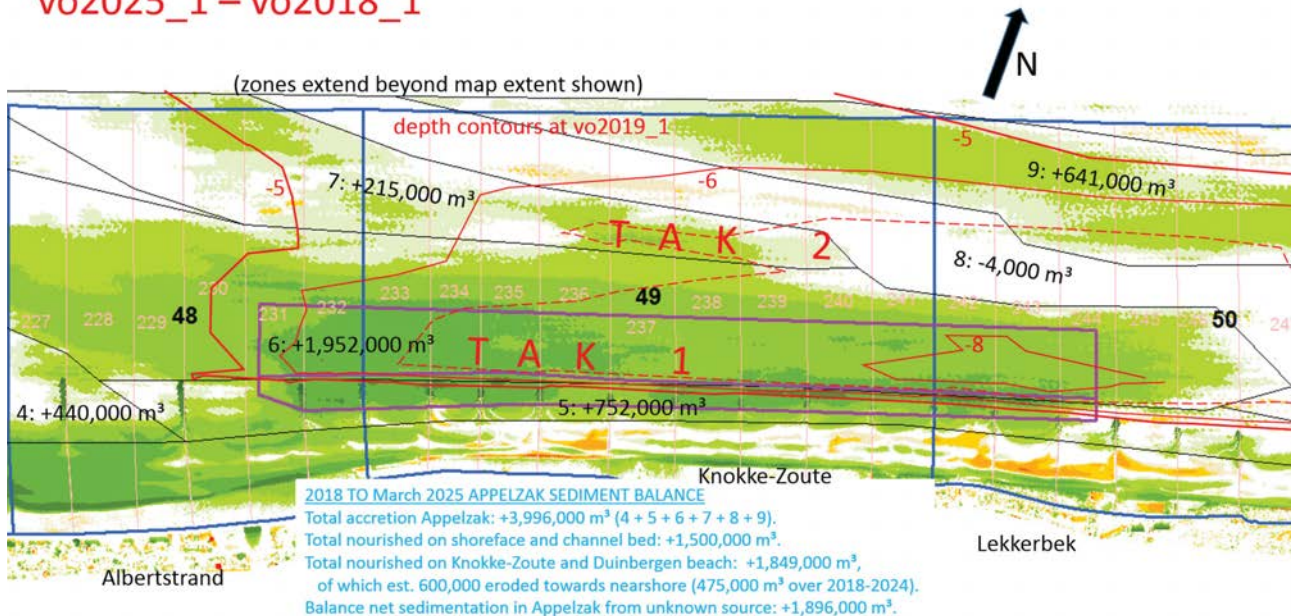


Figure 2-41 – Sand budget of the wider nearshore off Knokke-Zoute over the 7 year period 2018-2025.

Background map is elevation difference map with Initial survey: Spring 2018 (beach: 17 April 2018; nearshore: 28 May-7 July 2018) and end survey: Spring 2025 (beach: 12 April 2025, nearshore: 19-21 March 2025). The areas of volume differences have fine black outlines. They were created specifically for the change over the 7-year period.

Over 2018-2025, the nearshore in the wider area of Knokke-Zoute received more sand than can be explained from the nourishments alone. Almost half of the sediment gain is not accounted for. This question is explored in §2.7.4 over a longer period and an even wider offshore area, as this area must contain the source for the unaccounted sand. First, one local morphological issue is addressed that may help clarify the complete picture.

2.7.3.7 Albertstrand's nearshore: give and take

It was noted earlier (Houthuys et al., 2022, 2026) that the western extremity of Appelzak's Tak 1 shows cyclic fill and scour episodes. The area where this issue happens are sections 230-233 at the boundary of coastal tracts 48 (Albertstrand) and 49 (Knokke-Zoute). In Figure 2-41, the red -5 m and -6 m TAW contour lines (situation Spring 2019) show the western extremity of Tak 1 near the boundary of coastal tracts 48 and 49. Over 2018-2025, this area shows a large net sedimentation.

A sequence spanning 1999 to 2025 using the same depth colours and the same map extent was made of all DEMs of the nearshore (this is available in the supporting material). The movements of the -5 and -6 m TAW depth contours from survey to survey were catalogued as either a shift to east (net sedimentation) or a shift to west (net erosion). These movements were compared with the reported nourishments at Knokke-Zoute. The observations are summarized in Figure 2-42.

Survey Year	Morph. Change	Nour. Knokke-Zoute [Mm ³]	Nourished location
1999	-	0.5	beach+backshore
2000	A		
2003/4	E	0.4	backshore
2007	E	0.1	backshore
2008	E		
2009	A	0.05	backshore
2010	A		
2011	E	0.2	backshore
2012	E	0.1	backshore
2013	A+E		
2014	E	0.1	backshore
2015	E	0.2	beach+backshore
2016	E	0.3	backshore
2017	A		
2018	E		
2019	E	0.3	backshore
2020	A	0.01	channel
2021	A	0.1	channel
2022	A	0.2	channel
2023	A+E	0.5	beach+backshore
2024	A	1.2	channel+shoreface
2025	A+E		

Figure 2-42 – Table relating fill or scour in the western extremity of Tak 1 off Albertstrand with nourishment at Knokke-Zoute.

The second column very schematically describes the observed morphological change between the previous and the current line. A = accretion, E = erosion. In a few cases, partial areas deepened while others accreted (A + E). Column 3 lists the reported nourishments at Knokke-Zoute and the amounts involved. The final column specifies the elevation position of the nourishment at Knokke-Zoute (all nourishments are more or less in the same sections). The green arrows relate the nourishment to the observed morphological changes in the extremity of Tak 1. Dark green arrows denote influence from a channel nourishment, green arrows from a beach and backshore nourishment, pale green arrows from a backshore nourishment. See text for interpretation.

While the relationship can only be established qualitatively, a consistent morphological influence exists between nourishment at Knokke on the one hand and TAK 1 western channel extremity evolution at Albertstrand on the other hand.

The influence is determined by the nourishment size and type:

- Channel nourishment: accretion occurs in the same year.
- Beach + backshore nourishment: accretion occurs next year
- Backshore nourishment: accretion is observed after 2 years.
- No nourishment: the area erodes.

The duration of the influence of nourishment at Knokke-Zoute in Albertstrand is equal to or less than one year.

The location type of the nourishment determines the duration of the interval between nourishment and response in the extremity of Tak 1 at Albertstrand. A nourishment operation in Tak 1 at Knokke-Zoute results in a response in the same year. A beach nourishment takes a year before a morphological response is seen. A backshore nourishment takes two years. This is in agreement with the model of beach erosion after nourishment at Knokke-Zoute: waves act erosively primarily at the backshore slope. Initially, eroded sand is transferred to the low-water mark area and only later on to the tidal channel. Once the sand has been transferred there, it is washed away towards Albertstrand/Heist.

It is concluded that beach nourishment contributes to temporary sedimentation in the western extremity of Tak 1, west of Knokke-Zoute. When no recent nourishment has been carried out, the currents tend to clear the temporary fill.

This morphological influence explains the fluctuating pattern of erosion and accretion of the western tip of TAK 1. The geographical location of this morphological "struggle" makes one thing clear: the sand ultimately contributes to feeding the large sedimentation area off Heist.

2.7.3.8 A granulometric argument

The 1977-1979 large-scale beach and shoreface nourishment from Zeebrugge to Zwin used sand borrowed from the "Wandelaar" shoal and had a mean grain size ranging from 225 to 325 μm . As the more recent, repeated beach nourishments at Knokke-Zoute stand off by their coarse grain size (often 350 – 400 μm), sand redistributed from the nourishment site should contain such coarse grains. A grain-size sampling between the nourishment site at Knokke-Zoute and Zeebrugge East Dam may reveal a suspected western redistribution path. As the redistribution is suspected to occur mainly by flow current transport via Tak 1 of the Appelzak channel, care was taken to carry out the sampling during lower low tide and at the lowest elevations exposed during the low tide. The sampling was carried out on 24 March 2026, when a low tide level was calculated for Zeebrugge of 0.40 m TAW at 11:20h. The median grain size and sorting were estimated in situ. Other characteristics such as admixture of mud or shells were noted. Observations were carried out starting around 10:30h at Knokke and ending around 13:00h at Heist. At the start and end locations, a beach transect was recorded. Between the start and end locations, observations were carried out between the groynes and at the lower edge of the exposed "Plaat van Heist" about every 200 m.

The results are depicted in Figure 2-43.

As expected, coarse grain sizes were present at Knokke, especially on the intertidal part of the beach. Good sorting there attests to the sand being regularly stirred by the waves. Both the grain size and the sorting decreased along the low-water mark in the direction of Heist. The intertidal "Plaat van Heist" was characterised by fine to very fine sand. However, a small admixture of coarse sand was found at all sampling sites, both near the low-water mark as across the shoal, with grains ranging from 275 to 350 μm . Furthermore, at most locations on "Plaat van Heist", an admixture of mud was present. In the swash zone, at the transition from the intertidal part to the backshore part of the beach at Heist, relatively coarse sand measuring up to 300 μm was found. Here, the admixture of coarse, often broken shells was relatively high.

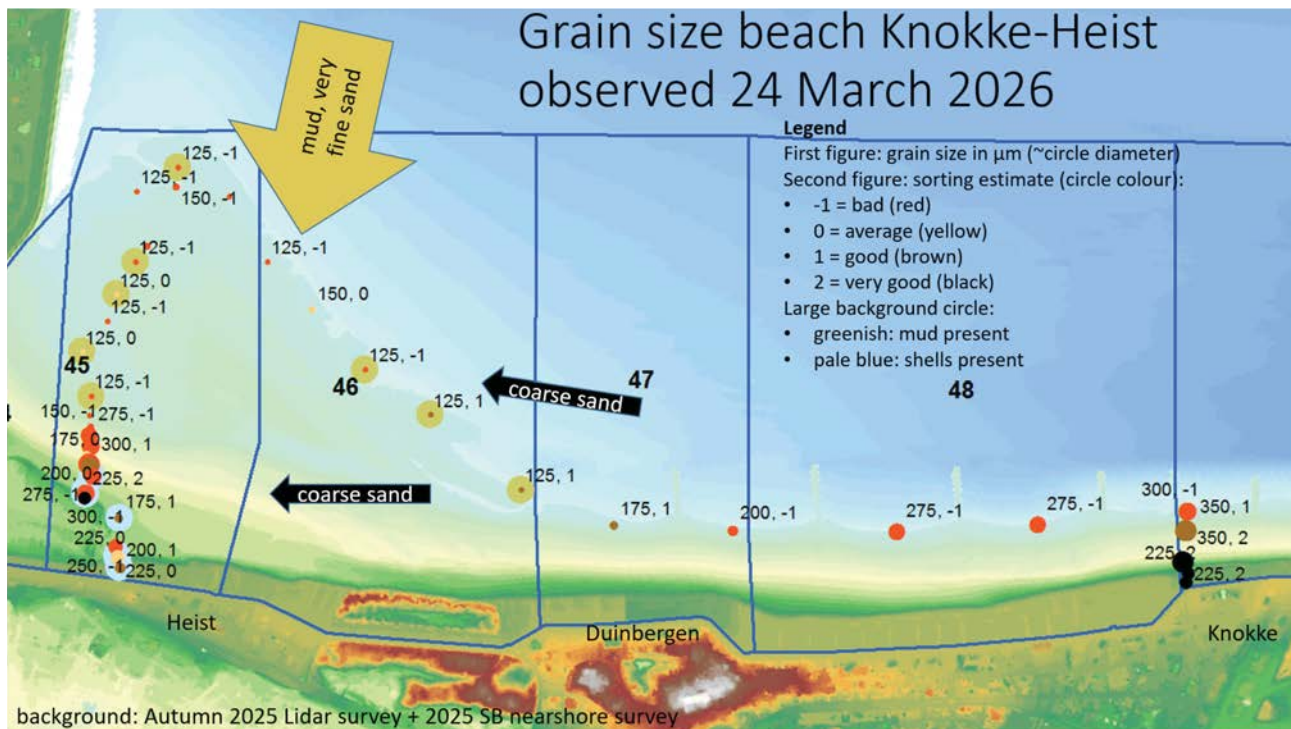


Figure 2-43 - Grain size observed on 24 March 2026 on the beach and near the low-water mark between Heist and Knokke.

Dots represent grain size observation locations. Grain size (in μm) and sorting (4 classes, see legend) are field estimates. Grain size is symbolized by the diameter of the inner dot. The dot in background shows presence of mud or shell (fragment)s at the sample location. Thick arrows are inferred supply directions (see text).

The observations show that most of the sediment found on "Plaat van Heist" is suspension-sized sand and mud. Knowing that the shoal has continually been accreting for decades, the source must be offshore. It is interpreted that continuous advection of suspended very fine sand and mud settles in the relatively sheltered area east of Zeebrugge.

The pervasive presence of a subpopulation of coarse sand indicates a subdominant advection from the nearest source containing such sand: the frequently nourished beach at Knokke-Zoute. As similar coarse sand is also, dominantly, found in the swash zone, additional longshore supply is inferred to occur at swash zone elevations. Both advection processes are schematically depicted in figure by the thick arrows.

The observations presented here are based on a first exploration based on field observations. It is recommended to conduct a more comprehensive grain-size sampling campaign over more sampling locations and to perform a standard laboratory analysis procedure on the samples.

2.7.3.9 Where does the sand nourished on Knokke-Zoute beach end up?

Morphological change is complex and the numerous interactions by humans, mostly by conducting new or maintenance nourishments on the coast and nearshore of Knokke-Heist further complicate nature's response on the nourishments. But taking all the above observations into account, a fairly complete answer can be given to the question "Where does the sand added by a typical beach nourishment at Knokke-Zoute finally ends up?", though it still remains qualitative. Consider a typical beach nourishment at Knokke-Zoute that extends the backshore by a few tens of metres and raises the foreshore by about 1 m. The nourished amount is set to 100%. Then:

- 0 to 5% may contribute to feed the beaches west of Knokke-Zoute.
- About 5% contributes to growth of the backshore (this can be inferred from the volume table of Tract 49 produced by Houthuys et al., 2026).

- About 10% may temporarily feed the beaches east of Knokke-Zoute. Actually, the longer-term evolution shows that these beaches are in equilibrium. It is known since decades that this sand transits and ends up in the mouth area of the Zwin inlet. It is not the only source of sand that fills the Zwin tidal marsh. About an equal amount arrives from the Cadzand beaches (Houthuys et al., 2026). Earlier, it was shown that most of the beach drift happens in stormy periods (Houthuys et al., 2013).
- The remaining part, 80 to 85% is exported to the Appelzak channel's Tak 1. It does not settle off Knokke-Zoute as this channel tended (before 2020) to deepen. The ultimate destinations are
 - o mostly the shallow sedimentation area off Heist
 - o the remaining part (25%?) is carried eastwards. It ends probably up in the Westerschelde estuary.

This budget is still preliminary. More targeted analyses may contribute to settle the budget with more certainty. Note also that a morphological analysis of related erosion and sedimentation areas against the general backdrop of wave, tide and current processes and the grain-size characteristics of the area will only disclose estimates of relative net transport quantities and directions. The actual contribution of the different processes can only indirectly and approximately be assessed.

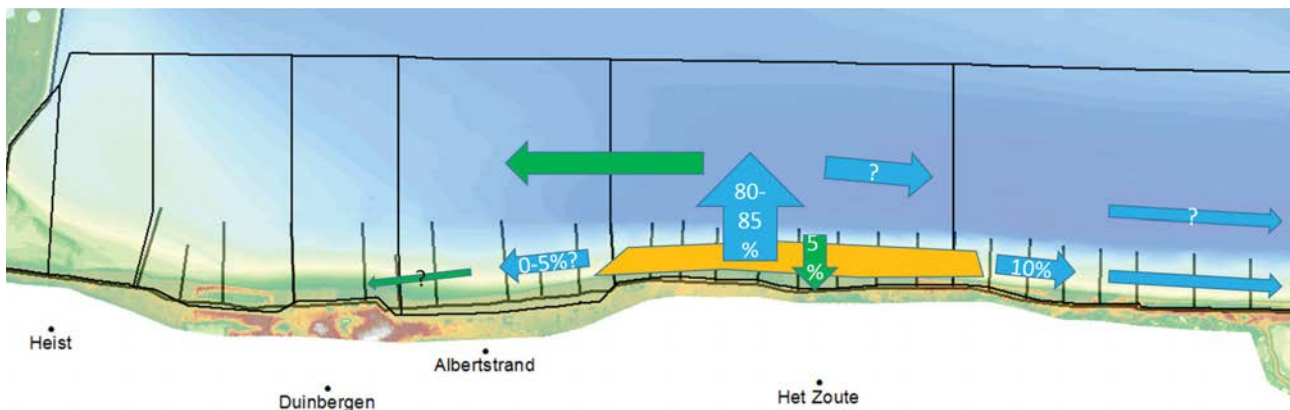


Figure 2-44 – Schematic sediment budget of the 3-4 years after a typical beach nourishment in Knokke-Zoute.

Orange area: beach nourishment at Knokke-Zoute. Thick blue arrows: direction of sand export, blue colour denotes transit. Thick green arrows: direction of sand transport, destination area is known with certainty from the morphological analysis, though the percentage of the original nourished volume cannot be estimated at present.

2.7.4 Longer-term morphological evolution

The sand budgets presented in the previous paragraphs demonstrate that the nearshore zone east of Zeebrugge is, apart from a sedimentation area fed by nourishments, also a net attractor of offshore-sourced sediment. Here, it is attempted to estimate how much sediment is attracted and what the source areas may be. The analysis uses elevation difference maps and selected contour lines shifts, and a sand balance in boxes defined based on the observed morphological change, over the longer-term period 1962-2022.

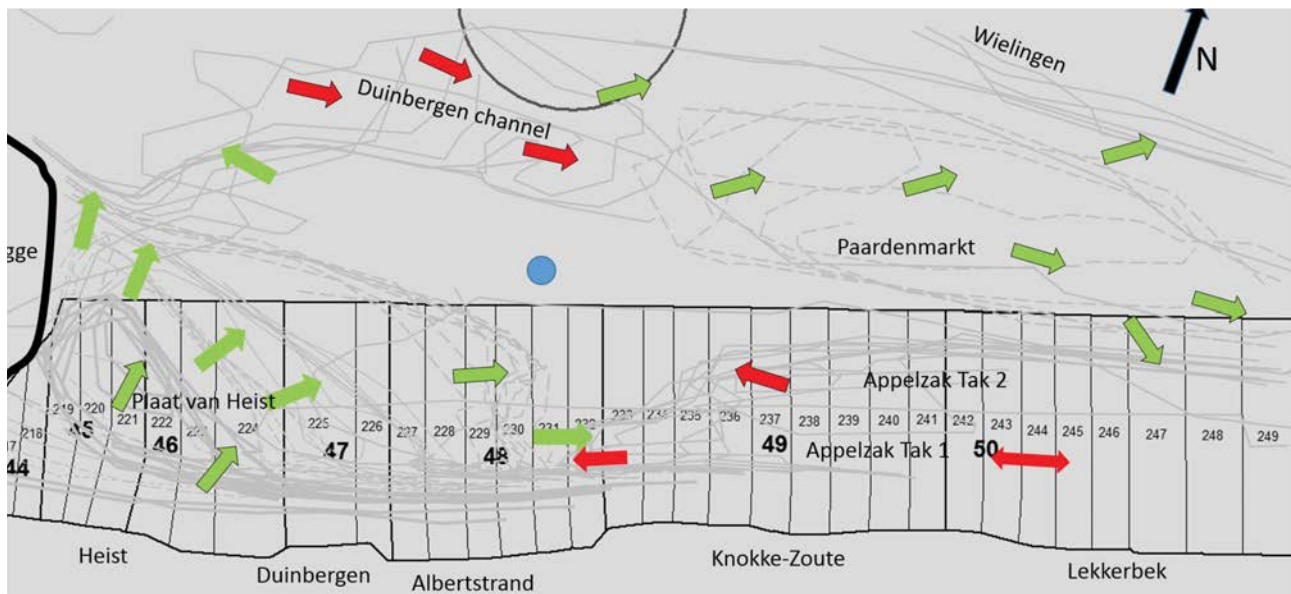


Figure 2-45 – Direction of shift through time of selected contour lines over the period 1962-2022.

Selected contour lines are 0 m (thick lines) -1.5 m (thin dashed lines), -3.0 m (thin lines), -4.5 m (thick dashed lines) and -6.0 m TAW (thick lines). In this figure, the lines are not differentiated for time. Contour line shift over 1962-2022 is shown by thick arrows. Green: shift is accompanied by sedimentation, red: shift is accompanied by erosion. Arrow with black outline: consistent shift through time; no black outline: lines also move back and forth through time. Blue dot: no change.

Figure 2-45 shows the selected depth contour lines (-1.5 m, -3.0 m, -4.5 m and -6.0 m TAW) derived from the 1962, 1976, 1986, 1992, 2000, 2004, 2009, 2013, 2017, 2022 and 2025 nearshore and inner shelf DEMs, all superposed in grey. The supporting material contains all the individual maps underlying this figure. The thick arrows show the movement through time of the contour lines.

There are two important sedimentation areas and two major erosional areas. In the centre is an area without change (blue dot). The first sedimentation area is the wide environment of "Plaat van Heist" (the shallow nearshore off Heist). Accretion occurs in all directions. However, to the north there is a boundary formed by the -4.5 m contour (thick dashed lines) off Duinbergen. This contour does not move through time. It appeared since the construction of Zeebrugge Outer Harbour (1979-1986) and is clearly the prolongation to the east of the straight northern section of Zeebrugge's Eastern Dam. The second sedimentation area is Paardenmarkt and its northern flank bordering the navigation channel Wielingen. The sedimentation shifts through time to northeast and east. The shift is uniform in time.

The first erosional area is Appelzak channel off Knokke-Zoute and Lekkerbek. The undifferentiated channel later (around 2007) developed two deeper sub-channels: Tak 1 and Tak 2. Appelzak tends to extend westwards. In the central part off Lekkerbek, the scour extends the deepest part of the channel bed both to west and to east. The second erosional area is a newly developed channel about 3 km off the seawall at Duinbergen. This channel developed after the construction of Zeebrugge Outer Harbour. The deepening continuous till now. The contour lines shift east. This channel is in this report named "Duinbergen Channel".

The volume change boxes are shown in Figure 2-46. Boxes 1-3 match the area monitored by the yearly morphological surveys. As for the oldest surveys only bathymetries are available, the boxes 1 and 2 are so defined that they do not contain the beach.

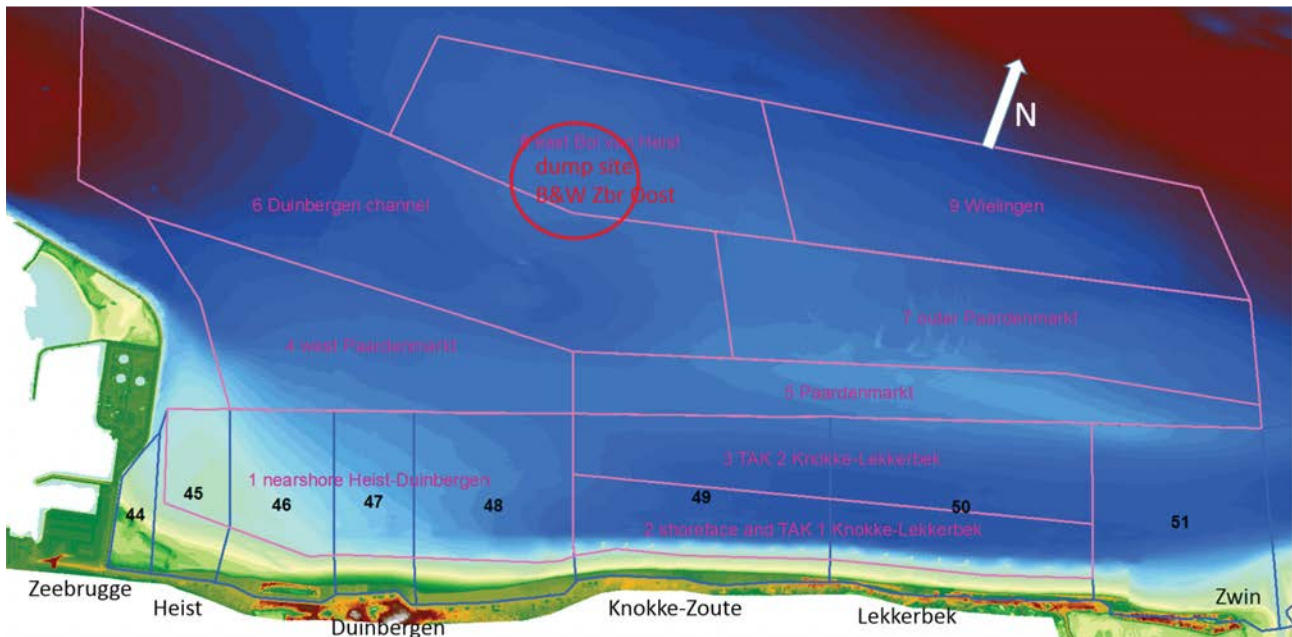


Figure 2-46 _ The wider inner shelf area off the coast east of Zeebrugge.

Background map is 2022 bathymetry of inner shelf. Pink lines delimit boxes defined to study volume change over the longer term. Red circle is dump site Bruggen & Wegen Zeebrugge Oost. Blue boxes 44-51 outline the area surveyed frequently in the coastal morphological monitoring.

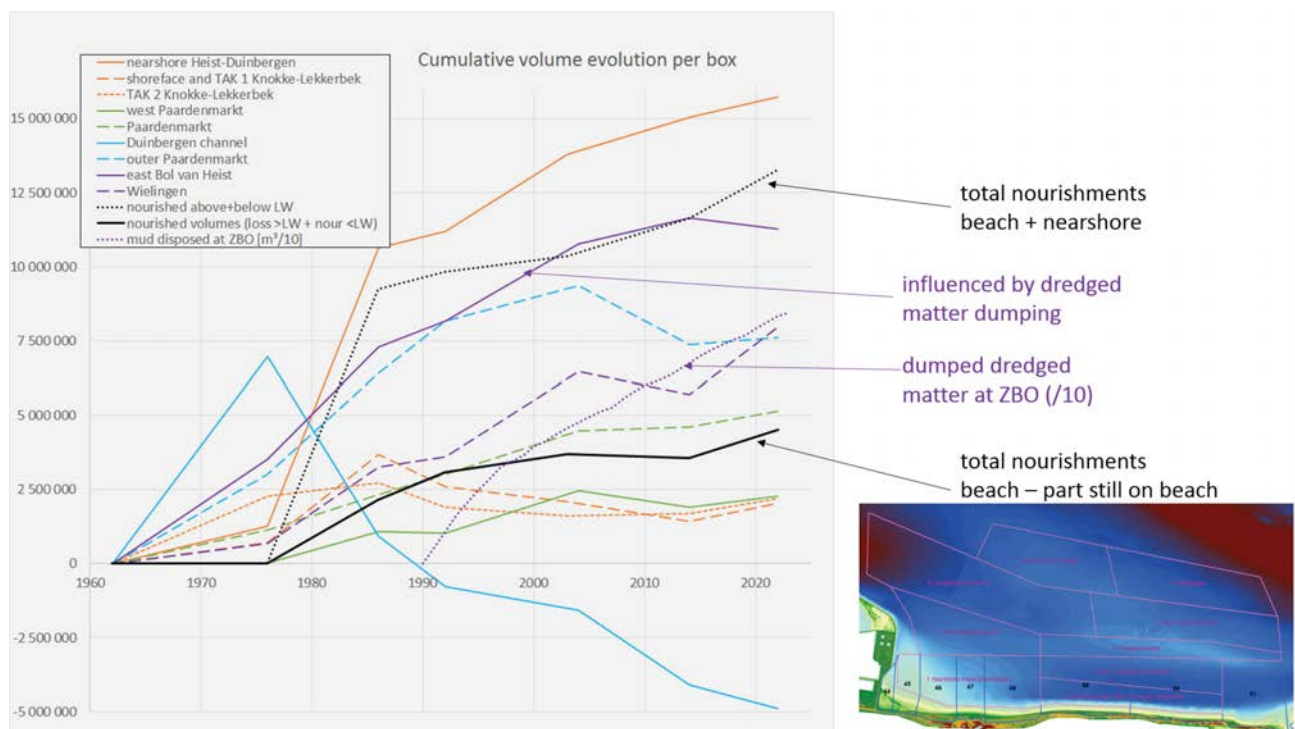


Figure 2-47 – Graph of the volume change over 1962-2022 per box.

The boxes are shown in Figure 2-46 and in the small inset in the lower right. The order of lines in the legend matches the numbers of the boxes. There are three additional graphs: (1) the evolution of nourished volumes on beach and nearshore in this coastal area (thick dotted line); (2) the evolution of the part of the nourished volumes that eroded from the beach nourishments (Houthuys et al.,

2026) + the volumes nourished offshore (thick black line); and (3) cumulative dumped volumes at dump site Bruggen & Wegen Zeebrugge Oost (location: see Figure 2-46) since 1991 (thin dotted line; volumes shown here should be multiplied by 10).

Figure 2-47 summarizes the volume changes over 1962-2022 per box. The coloured graphs are volumes calculated inside the boxes. There are a few additional graphs showing:

- Black dotted line: total volume nourished in the area (beach and offshore nourishments, Houthuys et al., 2026).
- Thick black line: evolution of the nourishment volume losses from the emerged part (assumed to have fed the offshore part) plus the offshore nourished volumes (Houthuys et al., 2026).
- Purple dotted line: cumulative dumped volumes at dump site Bruggen & Wegen Zeebrugge Oost (volumes in graphs must be multiplied by 10) (Fettweis et al., 2024. Note: the data reported start in 1991).

The evolution matches what was observed from the contour line shifts. Delimited areas 1 and 4 accreted since 1976 by over 17 Mm³. The change was fast in the interval 1976-1986, which contains the construction of Zeebrugge Outer Harbour. The evolution is mirrored by the volume change of area 6 (Duinbergen channel): fast erosion between 1976 and 1986, followed by continuing erosion at a slower rate. The total sediment loss over 1976-2022 is 12 Mm³.

Boxes 2 and 3 (Appelzak Tak 1 and Tak 2) accreted by $3.5 + 2.5 = 6$ Mm³ over 1962-1986. Then, the accretion switched to erosion. However, the total erosion over 1986-2014 was smaller than the earlier accretion: $-(1 + 0.5) = -1.5$ Mm³. Over the most recent interval, there was again some accretion.

Box 8 (east Bol van Heist) contains dump site Bruggen & Wegen Zeebrugge Oost. Here, continuous sedimentation by almost 12 Mm³ is observed between 1962 and 2014. There was no further sedimentation in the most recent interval. The three boxes in the northeast (5, Paardenmarkt; 7, outer Paardenmarkt; and 9, Wielingen) all show accretion, which occurred between 1962 and 2014, and totals about $5 + 7.5 + 6 = 18.5$ Mm³. There was further accretion at a lower rate over the last interval, only in boxes 5 and 7, by 2 Mm³.

Over 1962-2022, and summed over the 36 km² of the 9 boxes together, a volume increase of 49.3 Mm³ (+/- 9 Mm³ if a depth uncertainty of 0.25 m is assumed) is observed. The area thus attracted on average 0.82 Mm³ per year. This counts as an important sediment attractor.

The observed changes are summarised here, together with the interpretation of the morphological change:

- before Zeebrugge Outer Harbour construction (1962-1976):
 - Nearshore off Heist, (what will later become) Duinbergen Channel and east Bol van Heist: accretion, most in the later Duinbergen Channel. Interpretation: probably, dredged material was already disposed of in the area back then.
 - Wielingen, outer Paardenmarkt and Paardenmarkt: accretion. Interpretation: mostly supply from dredge disposal site. Apparently, the dump site ZBO was already in use. No information about disposed volumes back then is available in Fettweis et al. (2024).
 - Appelzak channel: accretion, especially in what will later become Tak 2. Local erosion of the shoreface in Knokke-Zoute. Interpretation: morphological adaptation to Leopold II-Dam and probably more importantly, advection from dump site and landward shift of currents.
- during Zeebrugge Outer Harbour construction (1976-1986):
 - An important beach nourishment was carried out involving the placement of about 8.5 Mm³ over a coastal length of about 9 km in 1977-1979. This volume was placed on the beach and the upper shoreface. So, it also contributed an estimated 2.5 Mm³ to the growth of boxes 1 and 2. Until 1986, it can be estimated that another 0.5 Mm³ was eroded from the beach at Knokke-Zoute. This volume can also be considered to end up in boxes 1 and 2. Box 1 gained almost 10 Mm³ over the 10-year survey interval. Box 2 gained about 2.5 Mm³ over the interval. Interpretation: the boxes grew more than can be explained by nourishment.
 - Box 6 (Duinbergen Channel) lost about 6 Mm³. Interpretation: due to the new, large outer harbour of Zeebrugge, a new flow channel developed north of the northeast dam, i.e.

Duinbergen Channel. Much of the sediment eroded here is thought to have ended up in box 2 and especially box 1.

- Boxes 4, 5, 7, 8 and 9 also show accretion. Most accretion is observed in box 7 (outer Paardenmarkt, +4 Mm³) and 8 (east Bol van Heist, +4 Mm³). In the latter lies the dump site ZBO. Unfortunately, the dumped quantities at ZBO are not available. Interpretation: ongoing dump activities at ZBO most probably account for the observed growth in this part.
- since Zeebrugge outer harbour construction (1986-2022):
 - Heist's nearshore continued to accrete, but at less intense rates than before. Duinbergen Channel continued to deepen, at an equally less intense rate. Interpretation: most of the sediment scoured at Duinbergen Channel contributed to sedimentation at Heist's nearshore.
 - East Bol van Heist and the areas east of it continued to accrete. Interpretation: the accretion is mostly due to disposal of dredged matter at Zeebrugge Oost. The sandy fractions are probably sorted out by the currents. Over 1990-2022, about 83 Mm³ has been dumped at ZBO, mostly mud (sand fraction not reported), while boxes 5 and 7, 8, 9 gained about 11 Mm³. Interpretation: the dump activities can explain the observed growth, but as the dumped sediment was mostly mud, there may have been additional sources.
 - The previous report section showed that at least over 2018-2025, about half of the observed growth of about 4 Mm³ in an area that roughly corresponds with boxes 1, 2 and 3 could not be explained by nourishment. It is now clear that erosion in Duinbergen Channel may also be a source for sediment that settled here.

To conclude, it is shown that the construction of Zeebrugge Outer Harbour had a powerful and long-lasting effect on the morphology of the Belgian East Coast; either directly, by blocking the coastal drift and by triggering a sheltered, strongly sedimentary area (Heist's nearshore), and a new tidal current channel, Duinbergen Channel, that is strongly erosional; or indirectly, by dredging and dumping activities. Of the overall 49.3 Mm³ accretion in the complete area of the nine delimited boxes over 1962-2022 (Figure 2-41), about 6.4 Mm³ can be explained by nourishments, and (estimated roughly at 20% sand) 33.2 Mm³ by dumping of dredge spoils. The last quantity is uncertain but is certainly high. The estimation was obtained as follows: over 1990-2022, 83 Mm³ dumped matter was reported. Taken at 20% sand fraction, this provides a source for 16.6 Mm³ sand. No dumped volumes were reported for 1962-1990, but the morphological maps attest that important dump activities were certainly then already going on. The construction dredging work of the harbour, the deeper access channel and some docks took place in that period. Therefore, a same amount is assumed to have been dumped, containing a same sand fraction: another 16.6 Mm³. The new Duinbergen Channel is an important internal source of sediment: about 12 Mm³ was eroded there inside the study area and probably mostly settled inside the study area (it therefore does not interfere with the overall budget). Of the remaining 9.7 Mm³, an unknown part is inferred to have been sourced from other erosional areas around Zeebrugge (scour pit west, scour pit east, part of Duinbergen Channel not included in box 6 because it was not covered by the available surveys). Another unknown part may be fine sand advected in suspension from the coastal and inner shelf areas east of Zeebrugge.

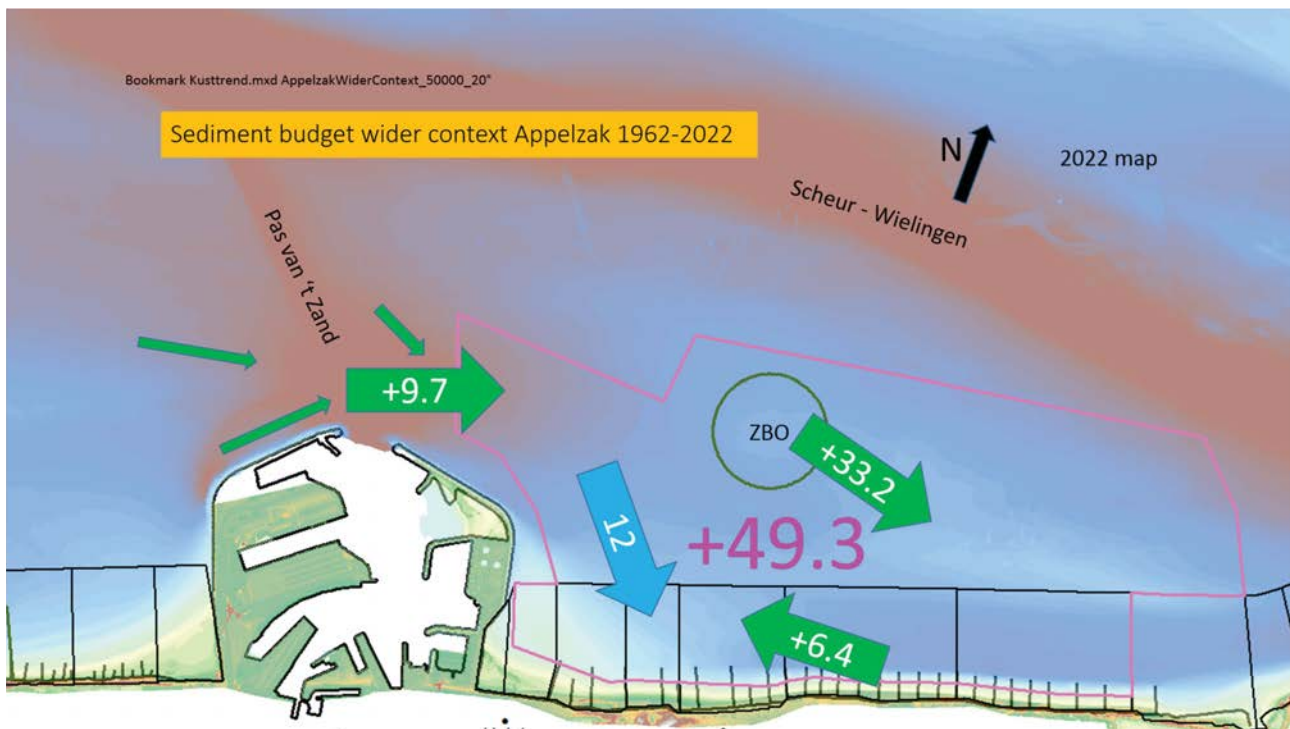


Figure 2-48 – Schematic sediment budget 1962-2022 for the wide nearshore area of the Belgian East Coast. Numbers in millions m^3 .

2.7.5 Summary and morphological inferences

The beaches of the Belgian East Coast are more or less in equilibrium, with the exception of the beach at Knokke-Zoute, which is a protruding part of the local coastline. It has required about 4 Mm^3 nourishments since 1986, of which most was eroded. The end destination of the eroded sand was unravelled in this study. At least a substantial part ended up in the nearshore area west of Knokke-Zoute. It contributed, together with about 2.4 Mm^3 of additional offshore nourishments, to accretion of the wider nearshore area. Most of this happened in the last decades.

That wider area east of Zeebrugge attracted large amounts of sediment since 1962, nearly 50 Mm^3 . An internal source was shown to be the new Duinbergen Channel, eroding since the construction of Zeebrugge Outer Harbour. It is thought that most sediment eroded here ends up in the wide, shallow nearshore off Heist and Duinbergen. The most important external source of sediment are the disposal activities of dredged material at dump site Bruggen & Wegen Zeebrugge Oost, and another one are the repeated nourishments near Knokke-Heist. Allowing for all these known sources, a remaining unknown source of sediment must still account for an estimated 10 Mm^3 of the accretion over 1962-2022. Some source areas may be the scour pit west and the scour pit east of Zeebrugge's harbour dams, and a part of Duinbergen Channel near Pas van 't Zand that is not included in the present sediment budget. Another unknown part may be fine sand advected in suspension from the coastal and inner shelf areas west of Zeebrugge. It is repeated that this budget has some important uncertainties. Raising the sand fraction of the dredged material disposals at the dump site to 25% would result in no remaining unaccounted volume.

Now that a comprehensive picture has been obtained of the short and longer-term morphological changes in the wider nearshore of the Belgian East Coast, and of the sediment budget, some inferences or morphological predictions can be put forward, be it with due caution. When doing this also the recent nearshore nourishments off Knokke-Zoute are kept in mind, which appear to remain largely in the area, at least during the first 2 years after the nourishment.

Plaat van Heist and the wider environment of Heist's nearshore will continue to accrete and is expected to expand eastwards. The sedimentation area will thus intrude into Appelzak, especially Tak 1. This would lead to a shallower nearshore off Knokke-Zoute. While a shallower channel bed and shoreface will probably not directly feed the beach, it may result in reduced erosion in Knokke-Zoute due to milder hydrodynamics. Tak 2 is expected to continue eroding, and this in response to a combination of surrounding squeeze processes (Paardenmarkt moving slowly landward, Heist's nearshore expanding eastwards, nourishments). Tak 2 will eventually connect to Duinbergen Channel and take the role of new main current channel around Zeebrugge. As morphological changes in the offshore domain are slow, these adaptations may take decades.

2.8 Sedimentation in the navigation channel to Oostende harbour as a proxy for longshore transport

2.8.1 Introduction

The old access channel to Oostende Harbour, "Rechtstreekse Kil", was abandoned in 2009. Up to 2009, Rechtstreekse Kil was maintained as a navigation channel by dredging. In 2009-2010, a new and deeper navigation channel to Oostende harbour was created by dredging. This "Pas van Stroombank" crosscuts the Stroombank and Kleine Rede channel. Its floor is 1 to 2 m deeper than the Kleine Rede channel floor and about 4 to 5 m deeper than the generalised crest of Stroombank. The morphological evolution of this channel, at the intersection with Stroombank, in relation to the construction and maintenance dredging work was used to estimate the magnitude of longshore sand transport at that location. In addition, the sanding up after 2009 of the old navigation channel "Rechtstreekse Kil" in the part contained in the yearly nearshore surveys was used to derive a second estimate. Finally, a third estimation was obtained by tracking the morphological recovery of Stroombank by the natural transport processes after the old navigation channel "Rechtstreekse Kil" was abandoned. The investigation sites are shown (pink numbers) in Figure 2-49.

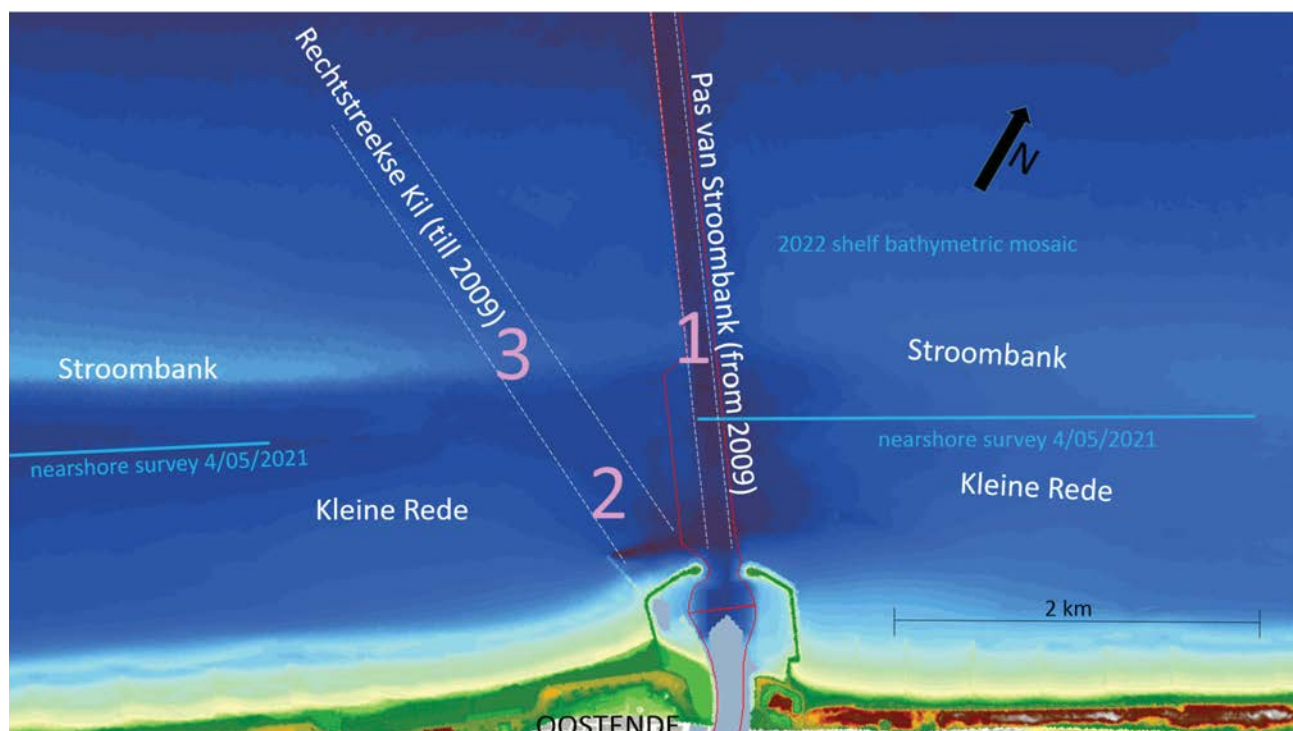


Figure 2-49 - Overview map showing the three sites where fill of the old and new fairways was studied.

This study makes use of all available bathymetric surveys made at the time windows of the morphological analysis. For site 1 also use was made of aggregated spatial output of the "BaggerInformatieSysteem" (BIS) kindly made available for this study by Maritime Access administration. The list of surveys and BIS export data was already reported in the MOZES reports of the second and third working year (Dujardin et al., 2024, 2025). In this report, the actual morphological analysis and the results from these reports are repeated and discussed in the wider context of the coastal system and the inner shelf.

2.8.2 Site 1 and 2

The first site is the point where Pas van Stroombank intersects Stroombank Figure 2-49 The analysis used the frequent bathymetric surveys in relation to the capital and maintenance dredging work of the new navigation channel Pas van Stroombank at the crossing of Stroombank. An observation period covering 2014-2016 was selected. From the numerous bathymetric surveys in the Flemish Bathymetric Database (TRITON), 20 surveys were selected. They define 19 time intervals. The bathymetric datasets, for this study converted to Lambert 72 and TAW, were obtained from Hydrography of the Coastal Division. The conversion WGS84 to Lambert 72 was done in the Caris chart system. The conversion LAT to TAW made use of the conversion grid "LATtoTAW_VlaamseBanken_v2". Depth difference maps were made for all time intervals. Most bathymetric surveys cover the navigation channel and about 100 m east and west of it. The study zone was divided in zones of interest, labelled 1 to 14 (Figure 2-50).

To further visualize the morphological change across the Pas van Stroombank, a time series of cross profiles was made on Profile 1 (Figure 2-50). The evolution is compared with the evolution of the previous navigation channel "Rechtstreekse Kil". This old channel was abandoned in 2010. The evolution of that channel is shown on Profile 2.

Per zone of interest, the sum of DH was obtained using ArcGIS tool "Zonal Statistics as Table". This sum multiplied by the raster cell area is the volume difference (DV) between the initial and final survey of each time interval. It is called in this study the "Survey DV".

Spatial grids containing the BIS parameters "gewicht" (Weight), "volume", "TDS" (Ton Droge Stof, Tons Dry Matter) and "gereduceerd volume" (Reduced Volume), in 5x5m-cells, cumulated over the time intervals between the above surveys, were obtained from Maritime Access. The rasters are geoTIFF files, referenced in ETRS89 UTM31N. The number of intervals is 17, as in some intervals no dredging had taken place. After evaluating the available BIS parameters, the "TDS" was not used in this study. The raster values express the parameters Weight (Mass) in tons, and Volume and Reduced Volume in m³. They are a sum representing the total value in each grid cell of 5 x 5 m².

It was remarked that "volume" from BIS export rasters yielded values per zone, cumulated per analysis time interval, that were often two to four times greater than the observed volume change from the bathymetric surveys. This inconsistency could not be explained. It was subsequently observed that "reduced volume" yielded much better agreement with the observed volume change from the bathymetric surveys. Both volumes are of the same order per zone and per time interval.

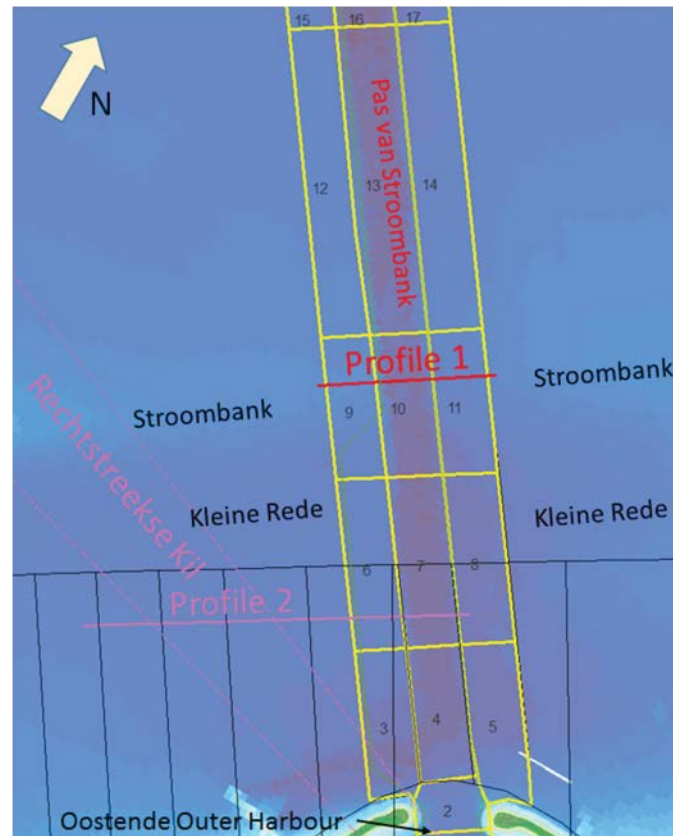


Figure 2-50 – Subdivision of study area in zones (yellow outlines) and location of the profiles. Thin pink dashed line indicates the former navigation channel Rechtstreekse Kil, abandoned in 2010.

2.8.2.1 Evolution of a cross section of Pas van Stroombank

Figure 2-51 displays a time series of cross profiles situated on Profile 1. The profile is located at the intersection of the navigation channel with the shallowest part of Stroombank. Depths are in m TAW and profile distances are in m from the western end of the profile line eastwards. This time series focuses on 2014, featuring more frequent profiles for that year, as it shows the response of the navigation channel morphology on a widening operation created by dredging the western flank of the channel. The profiles after 7/01/2015 were selected each time before a dredging campaign, so that the morphology is shown in its best state of morphological repair after dredging.

The profiles of 3/02/2014 and 2/04/2014 show the channel before widening. It was about 100 m wide then, had its bottom at about -9.2 m TAW and had a steep (about 7.5%) western flank where the channel crosses Stroombank. The eastern flank was less steep (about 1.1%) except for the lower metre which was as steep as the western flank.

Site 1: profile 1

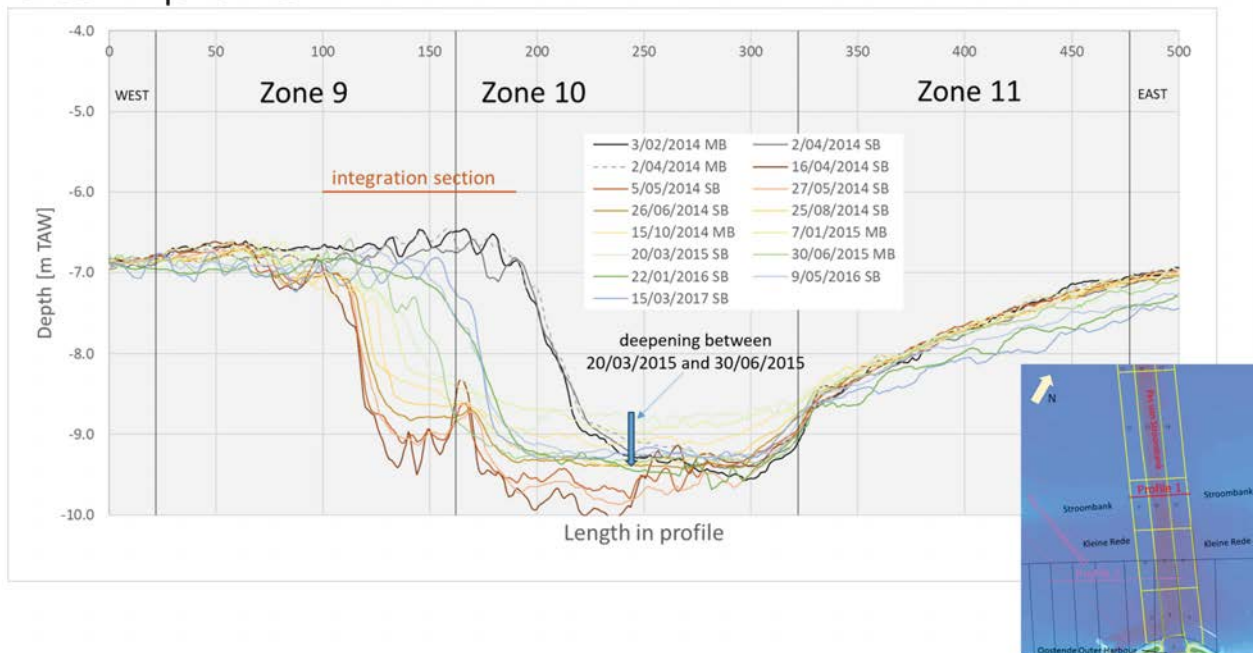


Figure 2-51 – Time series of profile 1 (see location in Figure 2-50).

Between 2/04 and 16/04/2014, the navigation channel was expanded to the west by 90 m and deepened in the centre to -10 m TAW. This was done by dredging.

Over the following months, the western flank gradually and consistently shifted eastwards while the channel bed filled. The small ridges present on the bed of the widened channel, especially in the surveys shortly after the dredging campaign, were most probably due to the morphology created by the dredging activity. The rate of eastern displacement of the channel flank was more or less constant between 16/04/2014 and 7/01/2015. The channel bed shallowed quickly after the deepening and reached its shallowest depth of the study period at between -8.8 and -9.0 m TAW. Between 20/03/2015 and 30/06/2015, both the base of the western flank and the channel bed were deepening due to dredging. The dredging restored 50 m of the earlier 90 m of widening and replaced the bed at about -9.2 m TAW.

The eastward growth of the western channel flank can only be due to sand transport over the top of Stroombank feeding the western channel flank. During the process of flank shift, its slope remained steeper than the initial 7.5%, even up to 10%. Such slopes can only be maintained in sand.

The fill of the channel bed may consist of deposition of suspended fine sand and of mud, as the bed morphology before each dredging campaign is nearly flat.

The eastern channel flank maintained its slope, but it receded also eastward. This may be explained by a lack of sandy sediment available to rebuild the isolated part of Stroombank east of the channel. As a result, the east slope deepened by more than 0.5 m over two years.

2.8.2.2 Transport estimated over the cross-section

Next, an estimation is made of the longitudinal bed transport causing the sedimentation at the western flank of Pas van Stroombank from the time series of bathymetric profiles. The method assumes that the only source of the accretion at the western flank in profile 1 is bed transport of sand over the part of Stroombank west of the navigation channel. This assumption supposes that longitudinal bed transport at the eastern side of the channel is zero and that no sedimentation from suspended sand occurs. Furthermore, it assumes that there is no contribution from east-to-west transport. While these assumptions cannot be proven directly,

there is a strong morphological argument for them. Lacking other data than pure morphology, the result of the estimation must be considered to be within these limitations.

The volume between the successive bed profiles of Figure 2-51 was integrated over the section between distance 100 and 190 m, like indicated in the figure. In this section, the accretion can be interpreted to be natural sedimentation of largely longitudinal bed transport along the crest of Stroombank. When divided by the time interval over which this accretion occurred, it provides a measure for the longitudinal bed transport over Stroombank, per transversal unit metre. The results are listed in Table 2-3.

Table 2-3 – Volume change in the integration section of profile 1 across Pas van Stroombank (see Figure 2-51).

Survey Date	DV [m ³]*	Uncertainty on DV [m ³]	Cum. DV [m ³]	Transport [m ³ /m/year]	Notes
3/02/2014	0		0		
2/04/2014	-1.2	19	-1.2		
16/04/2014	-192.9	19	-194.1		dredging campaign
5/05/2014	11.5	19	-182.6	<i>221</i>	DV < uncertainty
27/05/2014	4.1	19	-178.5	<i>68</i>	DV < uncertainty
26/06/2014	16.5	19	-162.0	<i>201</i>	DV < uncertainty
25/08/2014	13.9	19	-148.1	<i>85</i>	DV < uncertainty
15/10/2014	11.0	19	-137.1	<i>79</i>	DV < uncertainty
7/01/2015	20.4	19	-116.7	<i>89</i>	over four months
7/01/2015	77.5	19	-116.7	106	sum over grey interval
20/03/2015	3.7	19	-113.0		part of section dredged
30/06/2015	0.6	19	-112.4		part of section dredged
22/01/2016	43.1	19	-69.3	76	over half year
9/05/2016	5.0	19	-64.3	<i>17</i>	DV < uncertainty
15/03/2017	-3.4	19	-67.6		part of section dredged

*Volume difference (DV) is each time between the survey and the previous one. For the 7/01/2015 survey, an additional DV is added summarizing all accretion of the lines in light grey, between 16/04/2014 and 7/01/2015. The uncertainty on DV is obtained by multiplying the length of the integration section by $\sqrt{2} \cdot 0.15$. Transport intensity over a year is calculated by $DV \cdot (\text{number of days in a year}) / (\text{survey interval in days})$. If DV is smaller than the uncertainty, the corresponding transport is in italics.

The widening and deepening of the channel between 2/04/2014 and 16/04/2014 involved the removal of almost 200 m³/m. This removal of bed material created an accommodation space for the longitudinal bed transport along the crest of Stroombank.

The calculated transport fluctuates largely. The uncertainty on depth measurement and the sometimes-short time intervals may partly explain the observed fluctuations. When integrated over the interval 16/04/2014 – 7/01/2015, all partial contributions are added to obtain a significant accreted volume, accumulated during more than half a year in a period without dredging. The transport is ~100 m³/m/year. Another value was obtained over the interval 30/06/2015 – 22/01/2016 and was ~76 m³/m/year.

If dredging would be interrupted in the crossing of Pas van Stroombank, the bank morphology can be expected to be restored in a matter of 5 to 10 years, completely closing the navigation channel. The east side of the navigation channel shows erosion, most likely related to depletion of the longitudinal transport (everything is trapped in the channel and removed by dredging). This depletion would be healed.

In order to validate the obtained transport, use was made of the swift natural filling of the abandoned old navigation channel "Rechtstreekse Kil" in 2010 (Houthuys et al., 2022). This navigation channel was a more westerly approach to Oostende harbour and obliquely intersected Stroombank and Kleine Rede (site 2, see approximate location in Figure 2-49 and Figure 2-50). After the creation of the new access channel

Pas van Stroombank, the old channel was just abandoned, i.e. it was not artificially filled but left to fill by natural sedimentation.

The fill was very fast: after one year, the channel that initially had its bed 1.5 m deeper than the Kleine Rede, was filled. A profile line was selected parallel to the coast and the assumed direction of the longitudinal transport (see Figure 2-50). This line crosses the axes of Rechtstreekse Kil obliquely. The profiles are displayed in Figure 2-52. This figure also shows that the creation of the new Pas van Stroombank started before the Spring 2010 survey and created a crossing with a bed about 2 m deeper than Kleine Rede.

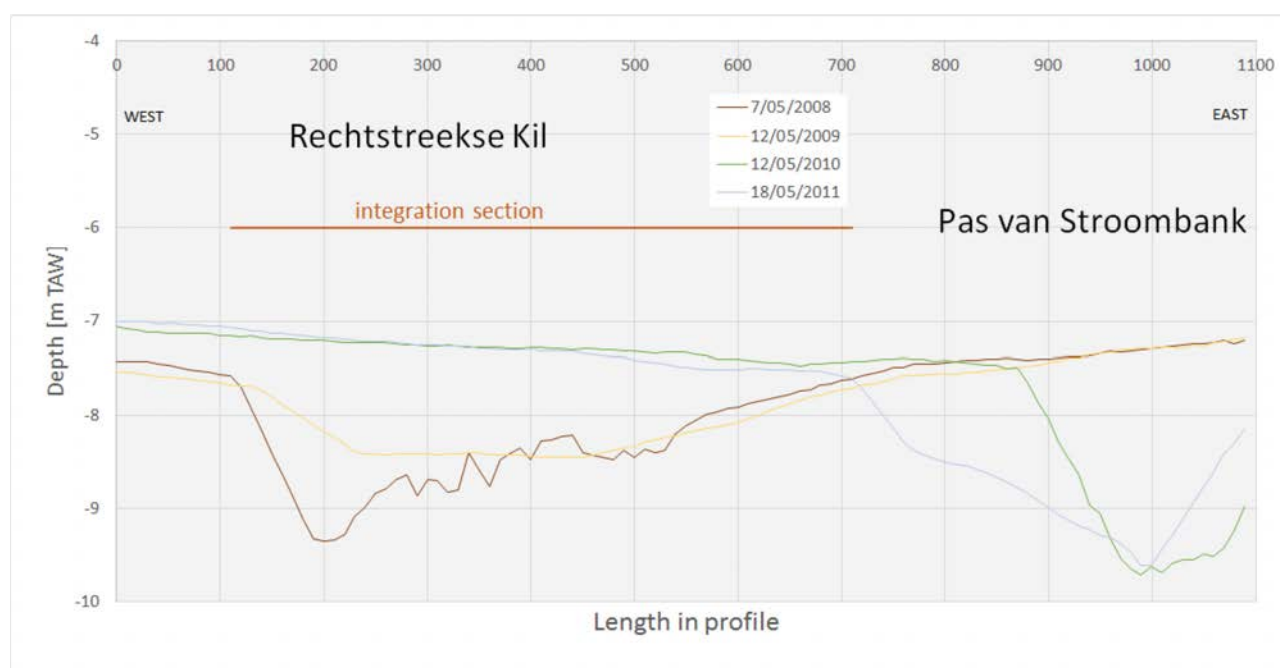


Figure 2-52 – 2008-2011 time series of profile 2 (see location in Figure 2-50).

The eastern slope had in 2008 a gradient of about 3% (perpendicular to the axis of the channel) while the eastern flank was about 0.5%. The channel probably incised in sand, but the fill may also have been muddy, like suggested by the flat section in the top of the channel fill on 12/05/2009.

The calculated volumes and transport values are listed in Table 2-4. The integration section is 600 m long (see Figure 2-52). The precise time of the fill is less well confined than in the above analysis of Pas van Stroombank, as we only have the Spring Nearshore SB surveys with each time a one year interval.

Table 2-4 – Volume change in the integration section of profile 2 across Rechtstreekse Kil (see Figure 2-51).

Survey Date	DV [m ³]*	Uncert. [m ³]	Cum. DV [m ³]	Transport [m ³ /m/year]	Notes
13/05/2008	0		0		
20/04/2009	109.8	126	109.8	<i>117</i>	period unknown, probably only part of year
12/05/2010	538.0	126	647.7	<i>508</i>	good estimate
23/05/2010	647.7	126	647.7	<i>325</i>	good estimate
18/05/2011	-20.8	126	626.9	<i>-20</i>	stability reached

*Volume difference (DV) is each time between the survey and the previous one. For the Spring 2010 survey, an additional DV is added summarizing the accretion of the lines in light grey, from Spring 2008 to Spring 2010. The uncertainty on DV is obtained by multiplying the length of the integration section by $\sqrt{2} \cdot 0.15$. Transport intensity over a year is calculated by $DV \cdot (\text{number of days in a year}) / (\text{survey interval in days})$. If DV is smaller than the uncertainty, the corresponding transport is in italics.

It can be concluded that $\sim 400 \text{ m}^3/\text{m}/\text{year}$ is a good estimate of the longitudinal bed transport in the Kleine Rede. This would be about 4 times greater than on Stroombank. It is probably muddy sand or sandy mud, while most of the transport on Stroombank is thought to be sand.

The results agree well with longitudinal transport modelled in Scaldis-Coast and FlemCo (Dujardin et al., 2024). Transport rates at the Stroombank crossing are about 70 to $145 \text{ m}^3/\text{m}/\text{year}$ in Scaldis-Coast and $95 \text{ m}^3/\text{m}/\text{year}$ in Flemco. Calculations in Kleine Rede are about $120 \text{ m}^3/\text{m}/\text{year}$ in Scaldis-Coast and $185 \text{ m}^3/\text{m}/\text{year}$ in FlemCo. The agreement raises confidence in the modelling of (mainly tidal) longitudinal transport by the models.

2.8.2.3 Summary

The morphological evolution of the dredged navigation channel Pas van Stroombank, created in 2010, was studied in a test case spanning 2014, 2015 and 2016, focused on the navigation channel crossing of Stroombank. On the one hand, a series of 21 SB and MB bathymetric surveys were used to obtain geographic images of bed level change and bed volume differences in a number of zones. On the other hand, 17 BIS export rasters spanning the same time intervals as the bathymetric surveys were obtained. They provide aggregated BIS parameters weight, volume, reduced volume and tons of dry matter over the survey intervals, in $5 \times 5 \text{ m}$ cells.

From the available BIS export rasters, no reliable information on dredged sediment type could be obtained, as sediment density appeared to be equal across all time intervals and zones. While densities suggested all dredged sediment was mud, the morphological analysis implies that often sand has been dredged.

The BIS parameter "reduced volume" gave the best agreement between dredged amounts per time interval and zone, and volumes calculated from successive bathymetric surveys. The agreement is so good that it can be concluded that this parameter can be used to keep stock of sediment volumes removed by dredging, at least in the study environment of Pas van Stroombank.

In the study period and area (excluding the harbour mouth and outer harbour), yearly dredged volumes range from about 100,000 to over 300,000 m^3 .

In the study area, two regimes of sedimentation are active, sometimes simultaneously. One is sandy sedimentation at the western flank of the navigation channel due to trapping of longitudinal bed transport on Stroombank. The other is spatially extensive sedimentation most likely caused by a combination of trapping fine suspended sand and influx of fluid mud.

From successive bathymetric profiles, estimates were obtained of the longitudinal bed transport (from WSW to ENE) over Stroombank and through Kleine Rede: resp. $100 \text{ m}^3/\text{m}/\text{year}$ versus $400 \text{ m}^3/\text{m}/\text{year}$. Based on bed sediment data, the bed transport over Stroombank is fine sand, while the one in Kleine Rede is thought to be muddy sand or sandy mud. Possibly, there also fluid mud transport occurs. The sandy mud or fluid mud could contribute to the fast, spatially expansive fill of Pas van Stroombank that repeatedly occurred in 2014-2016. The results agree well with longitudinal transport rates calculated using Scaldis-Coast and Flemco, especially at the Stroombank crossing.

2.8.3 Site 3

This is the intersection of the former fairway Rechtstreekse Kil with Stroombank. The analysis addresses the fill of the fairway after it was abandoned in 2009 and also describes the evolution of the wider environment where Stroombank restored itself.

2.8.3.1 Visual analysis of successive bathymetries

The abandoned channel "Rechtstreekse Kil" was filled fast, during the first months after abandonment in 2009, but only partially, i.e. until the bed level of the surrounding flow channels was reached. Stroombank rebuilt much slower; this took several years. Up to 2017, a slight depression was visible in the crest of Stroombank.

The crest part of Stroombank situated between the former Rechtstreekse Kil and the new Pas van Stroombank accreted to a depth comparable to the crest west of the abandoned navigation channel but lowered again afterwards. It is thought that sediment is dragged into the new, deeper Pas van Stroombank and removed there by dredging.

2.8.3.2 Longshore transport estimate from volumetric analysis

Four delimited areas (boxes) were defined to study the volume and depth change, under the same limitations as above again taken as proxies for longitudinal sediment transport (Figure 2-53). Box 1 and Box 2 are segments of the former navigation channel "Rechtstreekse Kil". Box 1 is on the intersection of Rechtstreekse Kil with the seaward flank of Stroombank. Box 2 is at the intersection of Rechtstreekse Kil with the crest area of Stroombank. Box 3 is east of Box 1, with about the same alongshore length. This area is likely to recuperate when box 1 is completely sedimented up. Box 4 is east of Box 2, with also about the same alongshore length. In addition, the former crest area is likely to morphologically recover when Box 2 is full.

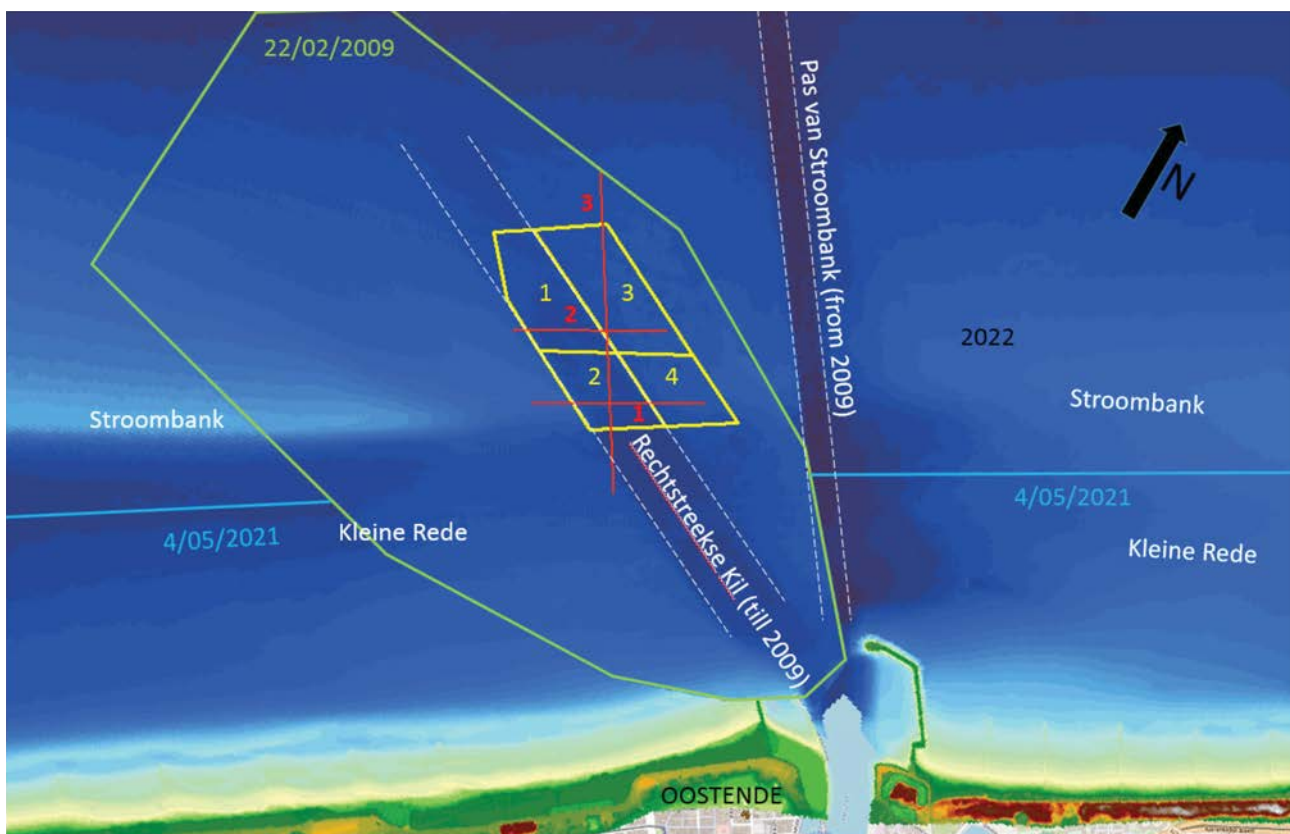


Figure 2-53 – Location of the old navigation channel Rechtstreekse Kil and the new Pas van Stroombank, created in 2009-2010.

Background is 2022 bathymetry mosaic (seaward part). Nearshore bathymetry is from 4/05/2021. The background is covered by the 22/02/2009 bathymetry, inside the green polygon. White dashed lines show the navigation channels. Yellow boxes are areas of volume difference calculation. Red lines are cross profiles.

In Figure 2-54 and Table 2-5, the volume, mean depth and derived alongshore transport are shown over time starting in 2009, the year of the shut-down of dredging maintenance work in the old channel.

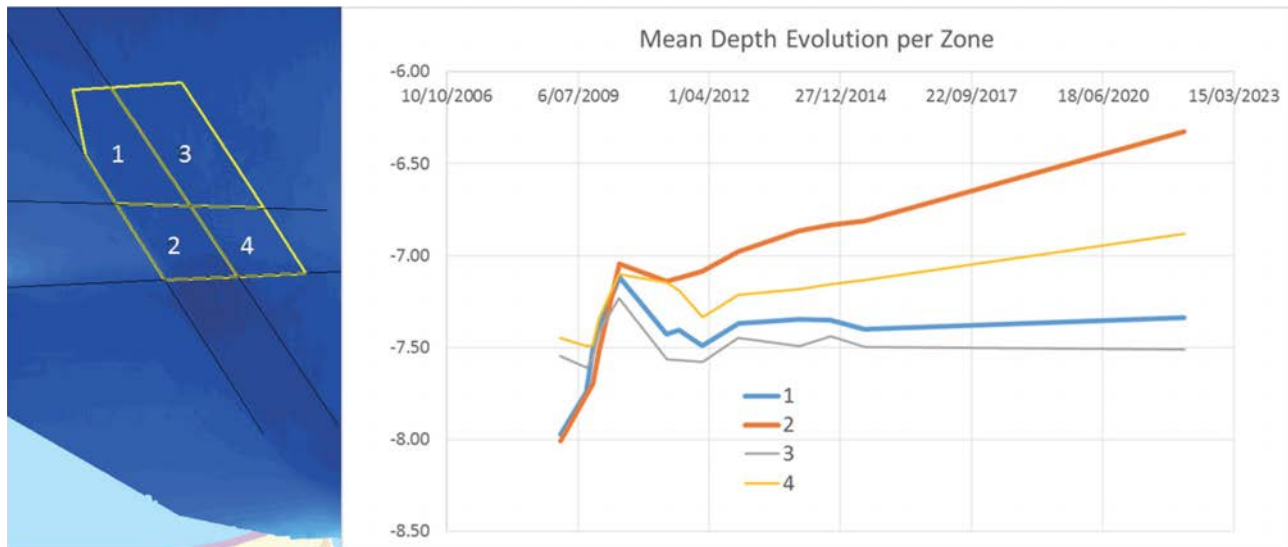


Figure 2-54 – Plot of mean depth versus time, per box.

The volumes and mean depths in Boxes 1 and 2 reached a temporary maximum in May 2010, only 15 months after the first survey. In box 1, the depth increased afterwards by about 0.4 m. This is explained by two events: in May 2010, a medium dune field passed through Box 1, resulting in a temporary supply of sand. Around that time, intensive dredging took place to create and deepen the new Pas van Stroombank. The creation of accommodation space likely has attracted sediment from the environment, explaining the increase in depth seen in all boxes at that time. It can be concluded that the old channel was already filled within 15 months after the first survey. When taking the across-shore width of Boxes 1 and 2 into account (Table 2-5), the alongshore overall sedimentation rate over this period can be estimated: 226 (Box 1) to 285 (Box 2) $\text{m}^3/\text{m}/\text{yr}$. Afterwards, from 2011 to 2022, a slow accretion rate persisted in Box 2: 28 $\text{m}^3/\text{m}/\text{yr}$. This corresponds to the slow but continuing rebuilding of Stroombank's crest area. Possibly, this process will continue after 2022. A similar evolution is observed in Box 4, but at an even lower rate: 11 $\text{m}^3/\text{m}/\text{yr}$. From Box 4, possibly some sediment was attracted into the space of the new Pas van Stroombank.

The initial quick fill of Box 2, by 285 $\text{m}^3/\text{m}/\text{yr}$, is interpreted to reflect trapping of the net longshore transport. Theoretically, the fill can also have trapped longshore transport from the east. However, due to the presence of the new and deeper Pas van Stroombank, it is believed that this channel trapped most of the east-originated longshore transport, also back then. The value is furthermore considered to reflect the net eastwards longshore transport over Stroombank, as the old channel floor was between 0 and 0.5 m above the floor of Kleine Rede, so that an influx of fluid mud from Kleine Rede into this area is unlikely.

Table 2-5 – Volume trends per box. Note different calculation period per box. Box 3 has mostly no change.

	From	To	Trend [m/yr]	Error on trend [m/yr]	Trend [m ³ /yr]	Box across- shore width [m]	Along- shore trend [m ³ /m/yr]	Box area [m ²]	Error on volume [m ³]	Error on along- shore trend [m ³ /m/yr]
box 1	22/02/2009	17/05/2010	0.72	0.09	124280	550	226	172652	36257	54
box 2	22/02/2009	17/05/2010	0.77	0.13	99818	350	285	129485	27192	63
box 2	13/05/2011	2/03/2022	0.08	0.00	9728	350	28	129485	27192	7
box 4	13/05/2011	2/03/2022	0.03	0.01	3639	330	11	115536	24263	7

The error on bed level difference is the standard error on bathymetric depth (0.15 m) x square root of 2 = 0.21 m. The error on volume difference is this value times the box area.

2.8.3.3 Longshore transport estimate from profiles

Three profiles were created to study in more depth the volume and depth change, as proxies for longitudinal sediment transport (Figure 2-53). Profile 1 is coast-parallel and crosses the old navigation channel "Rechtstreekse Kil" at the crest of Stroombank. Profile 2 is also coast-parallel, but it crosses Rechtstreekse Kil at the north flank of Stroombank. Profile 3 is coast-normal and allows visualizing the recovery of Stroombank after the abandonment of Rechtstreekse Kil.

Profile 1 (Figure 2-55) shows the overall Stroombank crest sloping down towards the east. The overall change is a long-term adaptation of the ridge's shape in response to the dredged navigation channels, first Rechtstreekse Kil, then, from 2009 on, Pas van Stroombank (a few 100 metres east of the profile). The floor of Rechtstreekse Kil was about 1.5 m lower than the crest of Stroombank at the west side of the channel, and about 1 m lower at the east side. The profile shows a fast shallowing of the channel, by about 1 m, between 22/02/2009 and 17/05/2010. The unit volume accretion over the 532 m wide channel was 354 m³ in 1.23 year or 288 m³/yr $\pm$ 112 m³/yr (the error estimation uses the error on bed level difference of 0.21 m).

The further evolution shows dynamic beds: all surveys display medium dunes. They are the morphological expression of active bed transport. As the dunes' steepest slope was at their east side, they travelled from west to east, towards Pas van Stroombank. Note that the 2022 profile was derived from a 10 m raster that probably smoothed the dunes out.

Profile 2 (Figure 2-56) shows the old channel to be 1 m deeper than Stroombank's seaward flank at the west and 0.5 m at the east. The profile underwent very fast fill between 22/02/2009 and 17/05/2010. The latter survey is the shallowest bed observed here. The unit volume accretion over the 400 m wide channel is 417 m³ in 1.23 year or 339 m³/yr $\pm$ 84 m³/yr. The May 2010 profile has a peculiar shape. A medium-dune field passed by over the area during that survey. Afterwards, the area lost sediment, likely towards Pas van Stroombank due to the construction at a larger depth and maintenance dredging going on there. The estimate of 339 m³/yr is likely an overestimation of the longshore transport as the May 2010 bed was shallower than any more recent bed.

Interpreting both results, it is concluded that both at the seaward flank and at the crest of Stroombank, the longshore near-bed sediment transport can be estimated at 280 ± 80 m³/m/yr during the initial abandonment stage of Rechtstreekse Kil. The profiles also demonstrate that most (or all) of the sediment that moves through the area is sourced in the west. This is in agreement with the fact that the new and deeper Pas van Stroombank, located east of Rechtstreekse Kil, probably traps most (or all) of the east-sourced longshore transport. It can thus be assumed that the 2009-2010 derived fill rate of the abandoned channel provides a reliable estimate of the net (west to east) longshore transport.

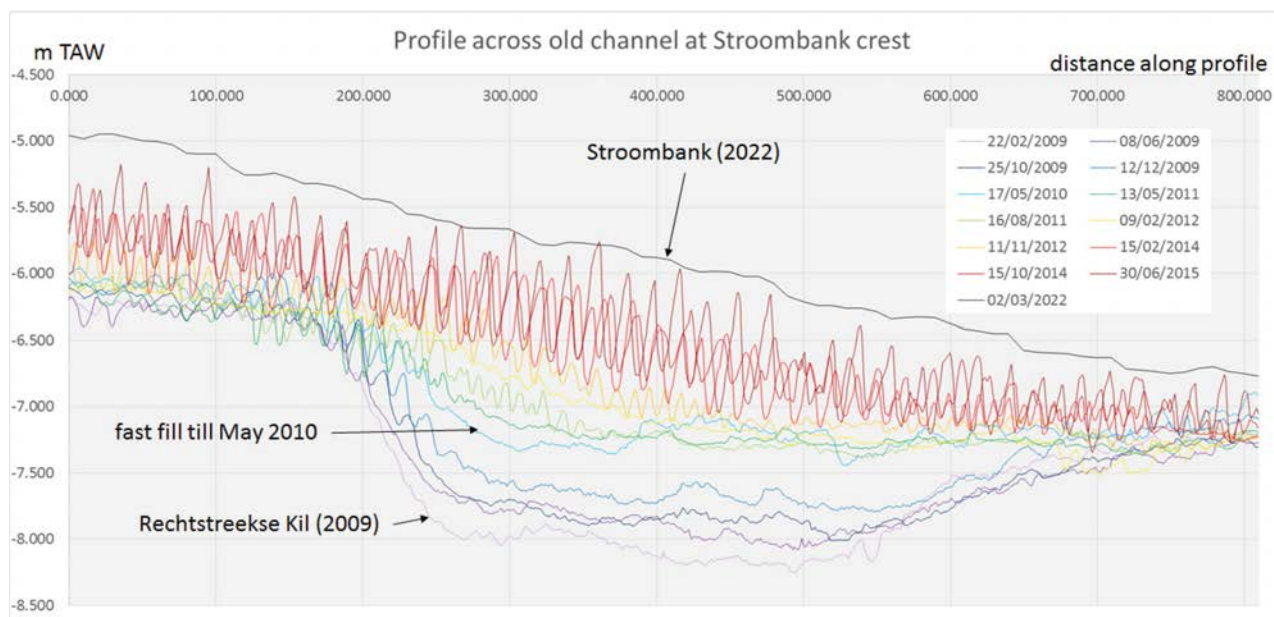


Figure 2-55 – 2009-2022 bed profiles of Profile 1, across Rechtstreekse Kil at crest of Stroombank (west is left).

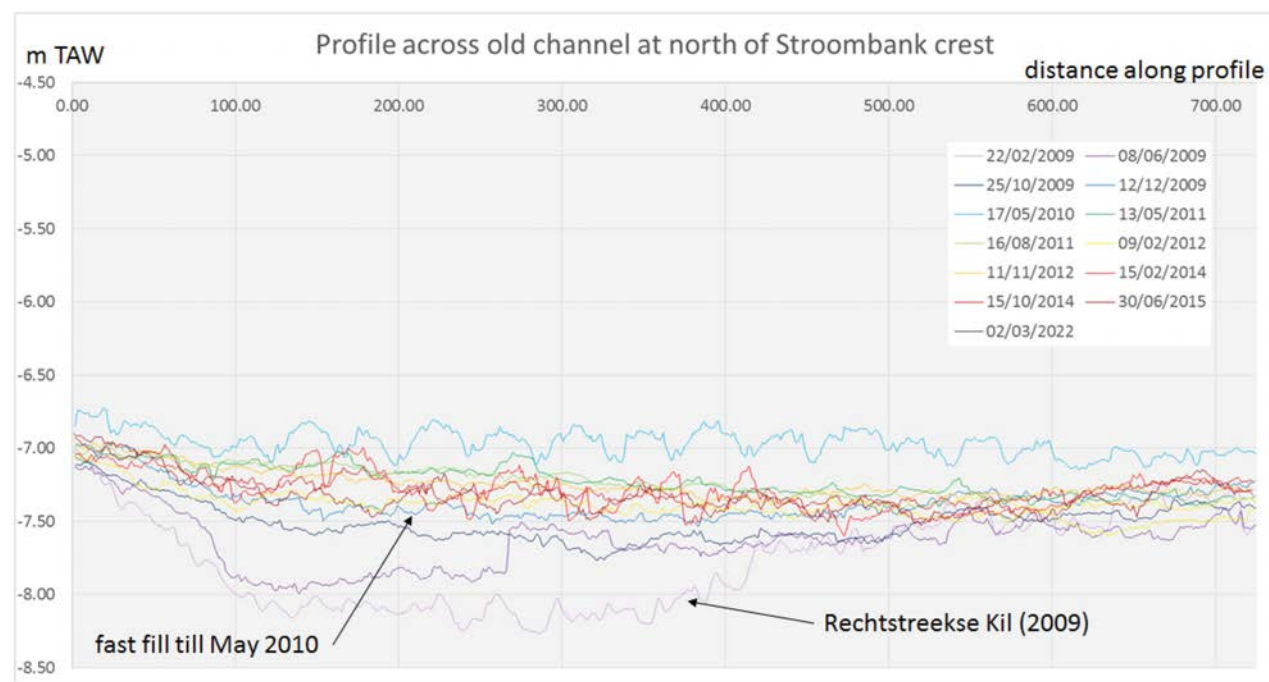


Figure 2-56 – 2009-2022 bed profiles of Profile 2, across Rechtstreekse Kil at north flank of Stroombank (west is left).

Profile 3 (Figure 2-57) illustrates the recovery of Stroombank in a coast-normal profile. This profile cannot be used for longshore sediment estimates, but it shows clearly some important morphological features:

- the fast initial fill of the abandoned channel
- the bed anomaly on the north flank of Stroombank at the May 2010 survey: this is a one-off bed morphology caused by the presence of a medium-dune field over the area. The bedforms prove a high sand mobility. The one-off event may have been triggered both by the local abandonment of the old navigation channel and the creation of a new sink area, i.e. the new navigation channel.
- the subsequent recovery of Stroombank as a positive bed feature. The rebuilding had a stage of medium to large dunes. There is a time gap between 2015 and 2022, but it can be assumed that recovery has been going on steadily over this period., featuring the presence and migration of medium dunes all the time. Note that the 2022 bed is probably smoothed out as it was derived from a 10 m-raster.

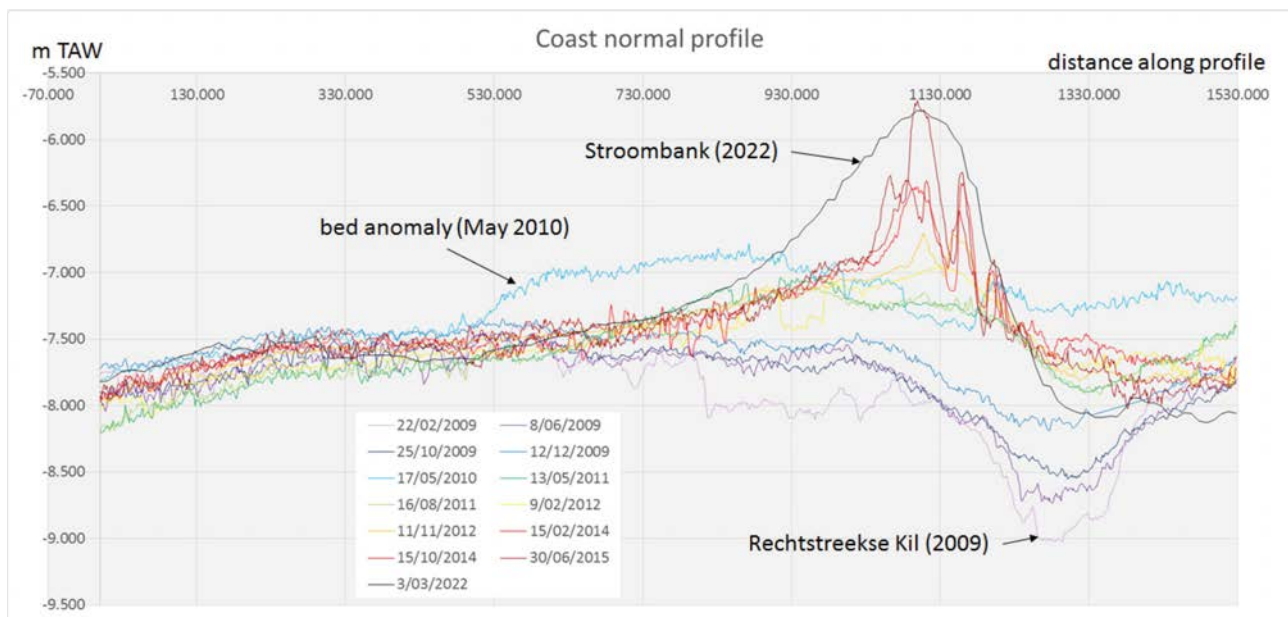


Figure 2-57 – 2009-2022 bed profiles of Profile 3, perpendicular to the coast (north is left) showing the recovery of Stroombank.

2.8.4 Discussion

The first site used the frequent bathymetric surveys in relation to the construction and maintenance dredging work of the new navigation channel Pas van Stroombank at the crossing of Stroombank. The assumed net longshore bed transport was estimated there at about $100 \text{ m}^3/\text{m}/\text{year}$ using a first 9-month period. Another value was obtained over a later 7-month interval and was about $75 \text{ m}^3/\text{m}/\text{year}$. These estimates were obtained from observations from 2014 and 2015.

The second site is the abandoned crossing of Rechtstreekse Kil through the tidal channel Kleine Rede. The fast fill in 2009 to 2010 yielded an estimate of the longitudinal bed transport in Kleine Rede of about 300 to $500 \text{ m}^3/\text{m}/\text{year}$. The large value may contain a substantial contribution of fluid mud, while the transport on Stroombank is thought to be fully sandy.

The third site showed that both at the seaward flank and at the crest of Stroombank, the total longshore near-bed sediment transport can be estimated at $280 \pm 80 \text{ m}^3/\text{m}/\text{yr}$ during the initial abandonment stage of Rechtstreekse Kil, when it can be assumed that most bed transport was trapped in the abandoned channel. As explained above, the 2009-2010 fill of Rechtstreekse Kil in Box 2 is argued to be almost exclusively sourced from the west, along the crest of Stroombank. Therefore, the fill rate is thought to be a good estimate of the net west-to-east longshore transport.

At the level of Stroombank crest, a gradient in longshore transport is observed (see value of 280 versus 75-100 m³/m/year in Figure 2-58). After analysis of the morphological evolution of the repair of Stroombank at the ancient crossing of Rechtstreekse Kil, where it appeared that repair of Stroombank crest was continuing at least until 2022, and thus intercepted a substantial part of the longshore transport over Stroombank crest that can in this period of repair not have contributed to the sand volumes trapped in Pas van Stroombank, the estimates found there in 2014 to 2015 are interpreted as underestimations.

To put the estimates in a wider perspective: under the assumption that they are representative for a 1500 m wide, coast-normal transect spanning the nearshore off Oostende, the values of 280 to 500 m³/m/year would result in a total trapped near-bed longshore transport of 4.2 to 7.5 · 10⁵ m³/year.

It can be concluded that both values found for the fast 2009 to 2010 fill of Rechtstreekse Kil, both in the deepest part of the Kleine Rede crossing and at the crossing of Stroombank crest, are upper estimates of the longshore transport (Figure 2-58). They are roughly double the order of magnitudes found in the transport models. Indeed, the high transport values also include a substantial amount of sand trapping which may also have attracted fluid, suspended and opposite-direction sediment transport.

Houthuys et al. (2026) evaluated the yearly amounts of sediment trapped in Pas van Stroombank where that fairway crosses Kleine Rede inside the coastal monitoring sections (site 4 Figure 2-58). It was found that around 2009-2010, some 80,000 m³ had to be dredged per year in order to keep the designed navigation depth. Over 2012-2018, this amount was found to be around 52,000 m³ per year, while it had further decreased to around 33,000 m³ per year over 2019-2025. The cross-shore length of the dredging area was about 340 m, which allow deriving rates for the longshore transport of 235, 152 and 98 m³/m/year, respectively (Figure 2-58). The orders found at sites 1 to 3 are confirmed. The reason why the rates of site 4 are lower is that more bypass occurs. Indeed, between site 4 and the entrance of the outer harbour, no sedimentation is observed at all and no dredging is needed. Yet, the channel is deep there and has the morphology of a scour trough. Landward of this, quite a lot of sand is trapped in the entrance to the harbour (about 32,000 m³/year over 2019-2025). All observations taken together indicate clearly that in the vicinity of Oostende outer harbour, a strong-current regime exists where sediment bypass is very likely. The nourished beach and shoreface at Oostende are a likely source of sediment to the area of site 4 (Houthuys et al., 2026) and, as currents are high there, transport competence is also high.

As a final conclusion, longshore net transport rates around Stroombank estimated from morphological change are of the order of 200 m³/m/year.

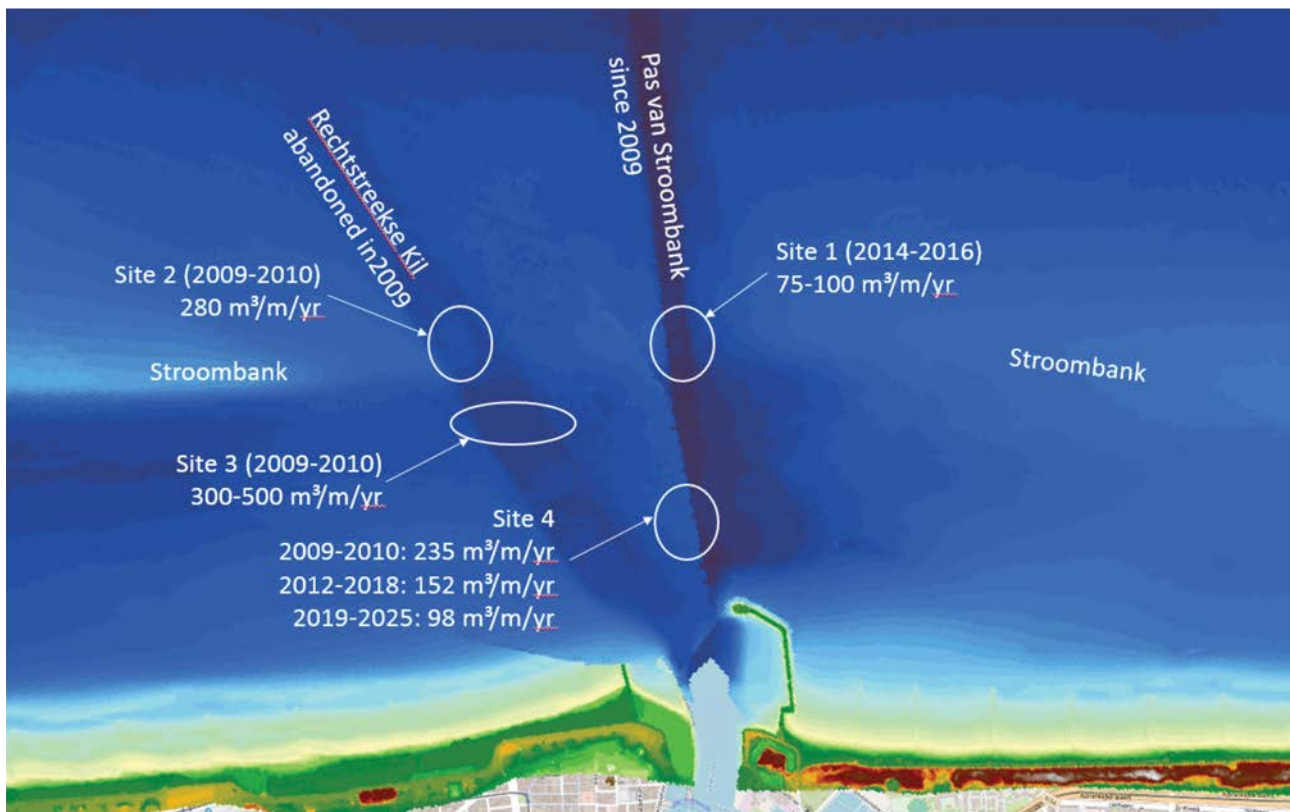


Figure 2-58 – Schematic map of longshore transport estimates (same bathymetry as in Fig. 2-52).

2.9 Exploring why Grote Rede turned erosional

2.9.1 Morphological issue

Houthuys et al. (2026) observed that deepening of the channel bed of Kleine Rede near the coast between Oostende and De Haan can directly be related to the creation around 2009 of the deeper new navigation channel to Oostende Harbour, Pas van Stroombank. However, also a presumed “far field effect” was noted: all of Grote Rede near the coast between De Haan and Blankenberge also started to deepen its bed. It was not understood how this was morphologically possible, as the effects extended over 10 km east of Oostende, beyond Wenduine.

This unanswered morphological question is here considered in a both temporally and spatially wider context.

Due to the available maps representing surveys separated by several years or sometimes decades, and each of them moreover being mosaics surveyed over a multi-year period, the analysis in this paragraph is necessarily qualitative. Nevertheless, it is very clear what actually happens.

2.9.2 Morphological map series analysis

The map series available in Map Series supporting material demonstrates that deepening of Grote Rede east of Oostende probably already occurred before 1969.

The map series illustrates clearly the following points (for locations, see Figure 2-59):

- The dumping site "Bruggen & Wegen Oostende" (BWO) is located in the middle of the about 3 km wide channel. It is a circular site with a diameter of 1.5 km. Over the last decades, three location shifts of the dump site are documented (Van Lancker et al., 2004). Location 1 is between Bredene and De Haan, at about 3.5 km off the dunefoot at Vosseslag ("Old BWO" in Figure 2-63). It was closed on 1/04/2002 because it became too shallow for the vessels that carry out the dredge disposal. Location 2 is off Bredene, about 4.5 km to the west of Location 1, and more seawards, at about 4.5 km off the dunefoot. This location was closed on 1/04/2004 because a telephone cable crosses the area. Location 3 is off Bredene, about 3.5 km to the west of Location 1 and 1 km to the east of Location 2, and at the same offshore distance as Location 2 ("New BWO" in Figure 2-63). The various locations are recognized in the bed morphology of the available surveys.
- Based on the interpretation of the available bathymetric maps, it is possible that some dumping took already place before 1938, near Location 1 but closer to the shoreface at De Haan. Some locations near Oostende and Bredene, on the eastward flank of Stroombank, may also have been dump sites. The dumping activities would have caused deepening of most of Grote Rede north of the dumping area, such as documented by the 1938-1908 elevation difference map.
- There is a low elevated area on the 1969 map at Location 1. This site is surrounded by an extensive area encompassing the complete eastern tip of Grote Rede channel that is in 1969 in its entirety about 1 m shallower than in 1938.
- The 1974 survey shows the beginning of the development of two deeper branches of Grote Rede, on south and one north of the dump site at Location 1. The dump site is only about 0.5 m shallower than the new deeper branches.
- The situation in 1984 pretty much resembles the situation in 1974.
- In 1993, the elevation at the dump site at Location 1 is about 0.5 m shallower than in 1984 while both the channel bed branch north and south of the dump site are about 0.5 m deeper. While the northern branch developed over a longer coast-parallel length before 1993, now the southern branch extends further east and reaches Wenduine.
- The just described development goes on over 2004 and up to 2014.
- In 2014, a first shallow prominence is visible at the new dump site at Location 3.
- In 2022, the new dump site at Location 3 is a bit higher, about 1 m above the surrounding channel bed of Grote Rede. Both the northern and southern branch are a little bit deeper than in 2014 and both extend to Wenduine.
- In Houthuys et al. (2026), it is reported that at least the southern branch stopped deepening since about 2020. This observation is not in contradiction with the previous point, that is based on surveys spaced wider in time.
- Wherever it is located, sedimentation is observed at the dump site and in the residual-downcurrent area east of it. At the same time, erosion is observed both in the part of the channel bed north and the part south of the active dumping site.

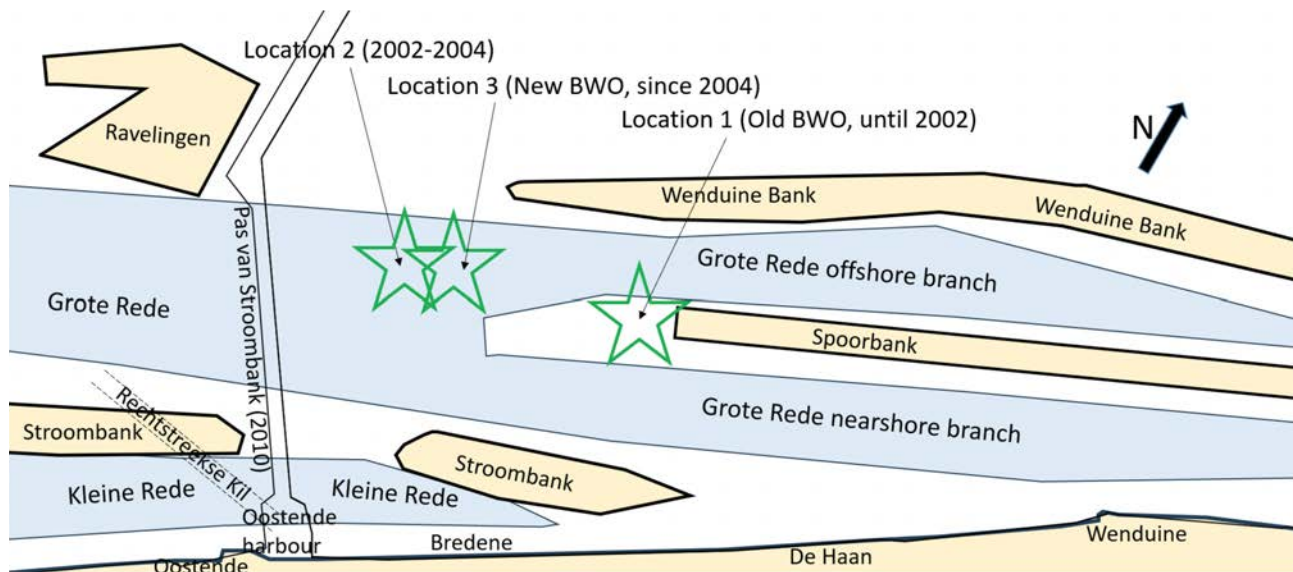


Figure 2-59 – Location map: inner shelf near Oostende – Wenduine and shift of the dump sites.

Apparently, the dump site was situated at Location 1 for several decades. In that period, a new low but long sand ridge developed as a long trace eastward of the location site. This ridge is called in the present study "Spoorbank" (new name; English: "Trace Bank"). Spoorbank is a rectilinear low, narrow sand ridge beginning at and clearly fed by discharged sediment at BWO at Location 1. It is over 12 km long and connects to the wide shoreface east of Blankenberge, near Zeebrugge. It is only about 0.5 km wide and only about 1 m higher than the surrounding channel bed of Grote Rede. It sits in the middle of the channel bed and morphologically splits Grote Rede in two branches.

Both branches have deepened at the same time that Spoorbank developed.

The elevation difference maps document and quantify the above-described evolution. Morphological elevation differences in the area are mostly about 1 to 2 m. In spite of the small elevation differences, the large-scale morphological features are clearly identifiable. The elevation difference between the shallowest point on the dump site in 1997 and the deepest point in the channel branch north of it was about 4 m (Van Lancker et al., 2004). Very widespread sedimentation across all of Grote Rede is observed on the 1969-1938 elevation difference map. Did dumping activities back then occur over the entire area? At least in the years leading to 1969, the dumping must have been concentrated on Location 1 as it is prominent in the 1969 bed morphology. It is possible that temporarily, between 1969 and 1974, dredged material was also dumped at a site west of Location 1. But Location 1 was definitely in use in 1974. Both branches deepened gradually between 1969 and 2022. From Houthuys et al. (2026), it is clear that the deepening of at least the southern branch stopped in 2020.

Finally, the 2022-2004 elevation difference map shows sedimentation at Location 3. Clearly, the new dumping activities there triggered sedimentation in the northern branch of Grote Rede, both in the first about 3 km east of the dump site and about 0.5 km west of it.

2.9.3 Morphological role of dump site BWO (from literature)

Disposal zone BWO has a diameter of 1.5 km and a surface area of 1.8 km². The dredge dump site receives dredged material from the harbour of Oostende and the access channel. This was Rechtstreekse Kil until 2010, followed by the deeper Pas van Stroombank since then (§2.8).

While no data have been retrieved on dumping activities in the area before 1980, it can be inferred from the available maps that apparently, dumping took already place between 1938 and 1969, and possible also already before 1938.

The area of BWO was studied in the MAREBASSE project (Van Lancker et al., 2004). Over 1955-1997, the position and depth of Wenduine Bank stayed more or less the same, though a small coastward progradation was observed. The shallower morphology of the old dumping site (at Location 1) was not yet visible in the first charts. It became clearer in time, while also this shallower zone moved to the east. This was probably caused by the residual currents flowing towards the east. A third remarkable feature was the preservation of the dump site as a morphological entity with reference to the coast. In the beginning the location of the dump site and the shoreface foot were connected, but gradually a channel was formed between both with the result that the old dumping place was in 1997 bordered by two channels, one at the north and one at the south. They were coast-parallel and had a length of several kilometres. Thus, the previously flat and wide Grote Rede was split in two branches separated by the dump site.

The quantitative evolution of the site was also studied in terms of height and volume differences (Van Lancker et al., 2004). A cross-section through the old dumping site from NW to SE (Figure 2-60) confirms the three morphological evolutions already described. Wenduine Bank stayed more or less at the same depth and migrated slightly towards the coastline. The old dumping site rose from 1955 to 1997 by more or less 1.5 m. The channel in between the dumping site and the coast deepened gradually by 1.5 to 2 m. A difference map between the first survey (1955) and the last one (1997) again confirms that Wenduine Bank slightly moved towards the southwest, resulting in accretion. The old dumping site clearly rose with reference to its northern and southern borders where a deepening happened. The net volume difference over the area including and surrounding the dump site, and stretching to the shoreface, shows a negative value, indicating that in spite of (or due to) the dumping activities generally the region became more subject to erosion.

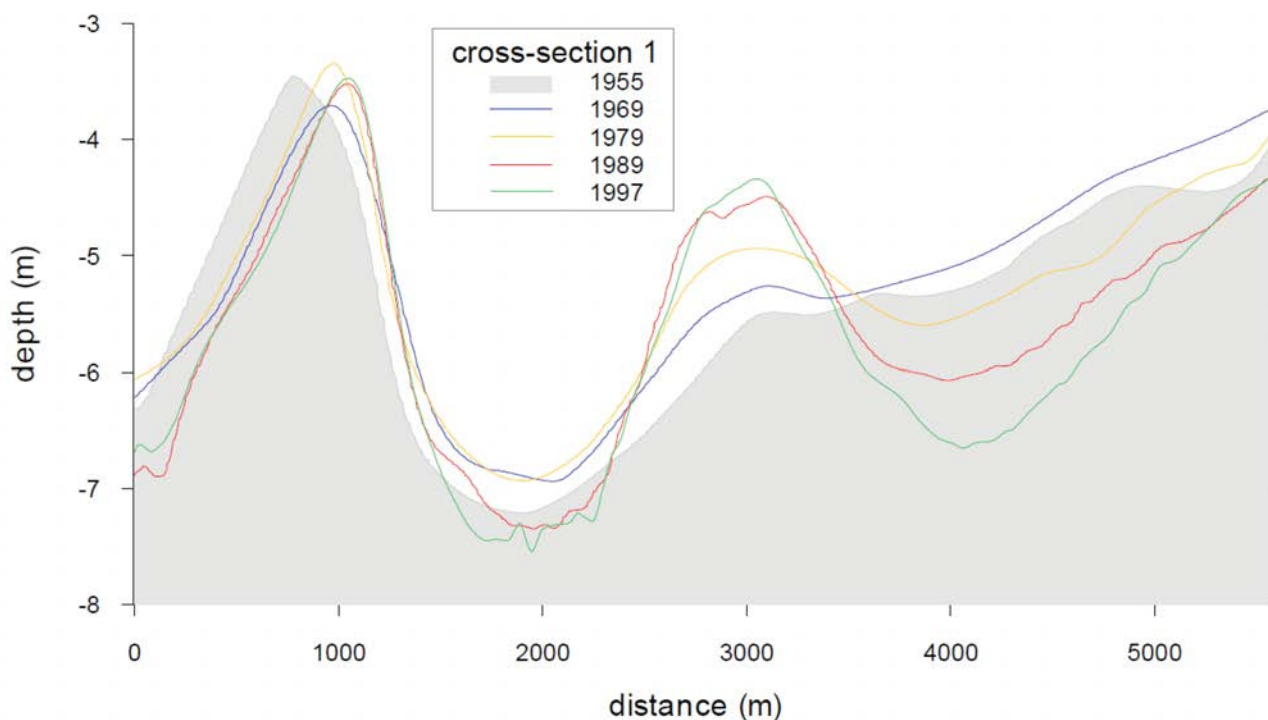


Figure 2-60 – Cross-section NW (left) to SE through the Wenduine Bank, the old dumping site at Location 1 and the two channels. Bredene shoreface at right. Fig. 9a of Van Lancker et al. (2004).

While morphological trends between the available surveys were not uniform, the overall evolution from 1955 to 1997 is clear: continuing sedimentation at the dump site (at Location 1) and continuing deepening of the branch of Grote Rede between the dump site and the coast.

The amounts dumped were approximately 225,000 m³/year in the 1980s while they increased to approximately 350,000 m³/year in the 1990s. More than 2/3 of the dumped material was mud. A large part of the dumped mud was washed away not long after dumping operations, especially in the shallower parts.

Due to this, no direct correlation with the difference maps can be found. But it is nevertheless clear that within the circle of the old dumping site there is relatively more accretion than globally over the whole region.

In the area, residual currents are to northeast. The mud which is deposited during a neap tide can sufficiently consolidate to resist (partly) to the higher bottom stresses occurring during a spring tide. In the neighbourhood of the dump site, especially the deeper parts of Grote Rede contain muddy sediments. Surface morphology was measured using MB in 2002. Areas with small dunes lie to the east in the shallow part of the region and are characterised by sandy sediments. The old dump site has an irregular morphology. Many small, up to 1 m high localized features are found; they don't move position between the surveys. It is assumed that some of them may be waste from demolished harbour constructions; in some samples, bricks were found (Van Lancker et al., 2004).

Anno 2022 (Location 3), sediments from maintenance dredging in the access channels to the port of Oostende and the port itself are not deposited evenly, but the majority is deposited at the southwestern part of disposal ground BWO (Kint & Van Lancker, 2023). Annual deposited tonnes dry matter (TDM) increased from 0.4 million in 2007 to 0.6 million in 2022.

Kint & Van Lancker (2023) made a bathymetric difference map between 2017 and 2021-2022 MB 1 m survey rasters. It showed an elevation rise of up to 2 m in the southwestern part of the disposal zone, while the northeastern part of the disposal zone remained quite stable with locally some slight erosion. The corresponding addition of sediment to the seabed in the disposal zone is 278 602 m³. In comparison, from July 2017 to the end of 2021, 2 567 867 TDM was deposited. It follows that about 10% of the discharged dredged material contributes to in-situ accretion. Another part of the discharged sediment deposited in the vicinity of the dump site (not measured in the study) while the remaining part was suspended and was spread over a wide area. The sediments in the disposal site were mostly sand and mud, either layered or mixed. Medium sand was present.

2.9.4 Morphological role of dump site BWO (update of the literature results)

The morphological maps made in the current MOZES project allow evaluating the morphological evolution and the role of the dump site over a longer time frame and over a wider area, with the restrictions posed by the large time lapse between surveys, the larger uncertainty on depth in older surveys and the mosaic character of all surveys used.

After observing the major change areas, five more or less rectangular areas were defined that display a different morphological evolution (Figure 2-61).

Area 1 is the most landward branch of Grote Rede tidal channel.

Area 2 contains the new dump site (Locations 2 and 3).

Area 3 contains the old dump site (Location 1).

Area 4 contains Spoorbank.

Area 5 contains the most seaward branch of Grote Rede, between Spoorbank and Wenduine Bank.

The volume between the bed surface and the zero-elevation surface was computed for each available DEM. In this analysis, the sea level-rise corrected DEMs were used. The volume of each survey was subtracted from the last one (2022), that was considered a reference. The results are shown in Figure 2-62.

The reported discharges at dumpsite BWO are also represented in Figure 2-62. The older maps make clear that the site was already in use at least in 1961 (Van Lancker et al., 2004). The involved amounts are to our best knowledge not reported. The data for 1980-1989 are from Van Lancker et al. (2004); those for 1991-2023 are from Fettweis et al. (2024). The data for 1989 and 1990 are interpolations. Data for 1980-2006 were reported from 1st of April till the 31st of March of the following year. They are here taken to represent the first year of the dredging period. The data of 1980-1989 were reported in wet volumes: they are taken to represent the dumped volume. The amounts of 1991-1996 were reported in wet tonnes dry matter. They have been converted to in-situ volumes by division by 2. This is a reasonable conversion factor; no precise conversion method has been reported. The amounts since 1997 are in tonnes dry matter. They have been converted to in-situ volumes by division by 1.6.

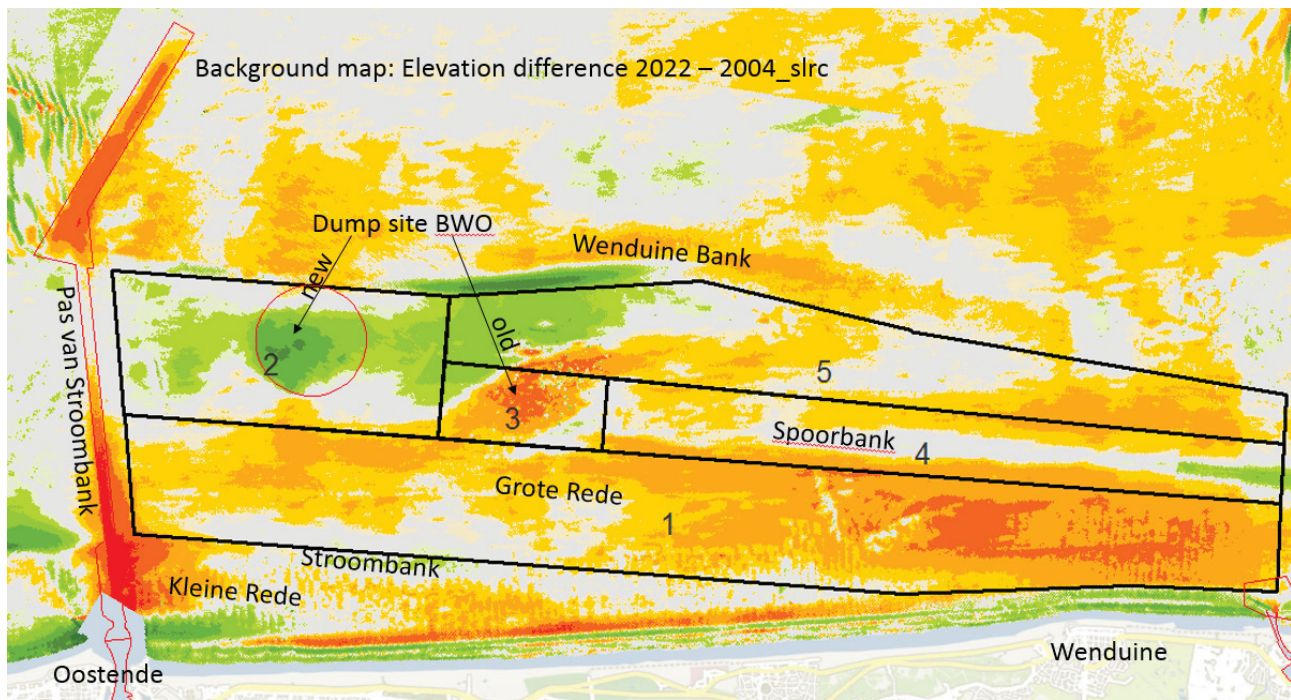


Figure 2-61 – Definition of 5 areas in which the volume difference to 2022 was calculated (black outline).

Background is elevation difference map 2022 – 2004 sea level rise corrected. Green is sedimentation, red is erosion. Old dump site is Location 1; new dump site is Location 3.

As the five defined boxes have different areas, the volume difference to 2022 was divided by the area to obtain the average elevation difference to 2022. The discharged volumes were divided by the area of the dump site, so that also here, average elevation is shown. The yearly elevation changes have been cumulated.

All areas show a significant rise in average elevation between 1938 and 1969 (Figure 2-62). This cannot readily be explained. Therefore, it must be kept in mind that different measurement methods may play a role. However, even allowing for this, the rise of area 1 is significantly smaller (about +0.6 m) and the rise of area 3 is significantly larger (about +1.8 m) than the rise of all the other areas (a little bit over 1 m). It is clear that the dump site was already in use.

The decline of area 1 between 1969 and 2022 is significant and exceeded -1.6 m. Over the same period, area 5 lost 0.5 m. The old dump site (Location 1, area 3) shows a small, non-significant rise over 1969-1984, followed by a decline of about 0.5 m until 2022. The new dump site (Locations 2-3, area 2) rose by about 0.3 m between 2004 and 2022. Finally, area 4 shows no change between 1974 and 2022. The evolution of areas 3 and 4 is probably influenced by internal compensation: the difference maps do show accretion in the centres of the areas.

The discharged volumes before 1980 are missing in the data. The summed volume of discharges over 1980-2023 at BWO totals almost 45 Mm³. The reported yearly volumes between 1980 and 1997 exceed those over 1997-2023 (black curve in Figure 2-62). This may essentially be due to different reporting methods. Apparently, back then some beach nourishments may have been included in the disposal figures thus giving rise to overreporting. Remarkably, the corresponding elevation rise since 1997, calculated from the reported volumes, is nearly linear in time. At least a temporary increase was expected around 2010, when Pas van Stroombank was created. Houthuys et al. (2026) report a gradual decrease in dredged volumes from Pas van Stroombank since 2010. Also this decrease does not show in the graph. It must however be kept in mind that the discharged volumes contain also mud dredged inside the harbour and sediment from the more seaward sections of Pas van Stroombank, that are not taken into account in Houthuys et al. (2026).

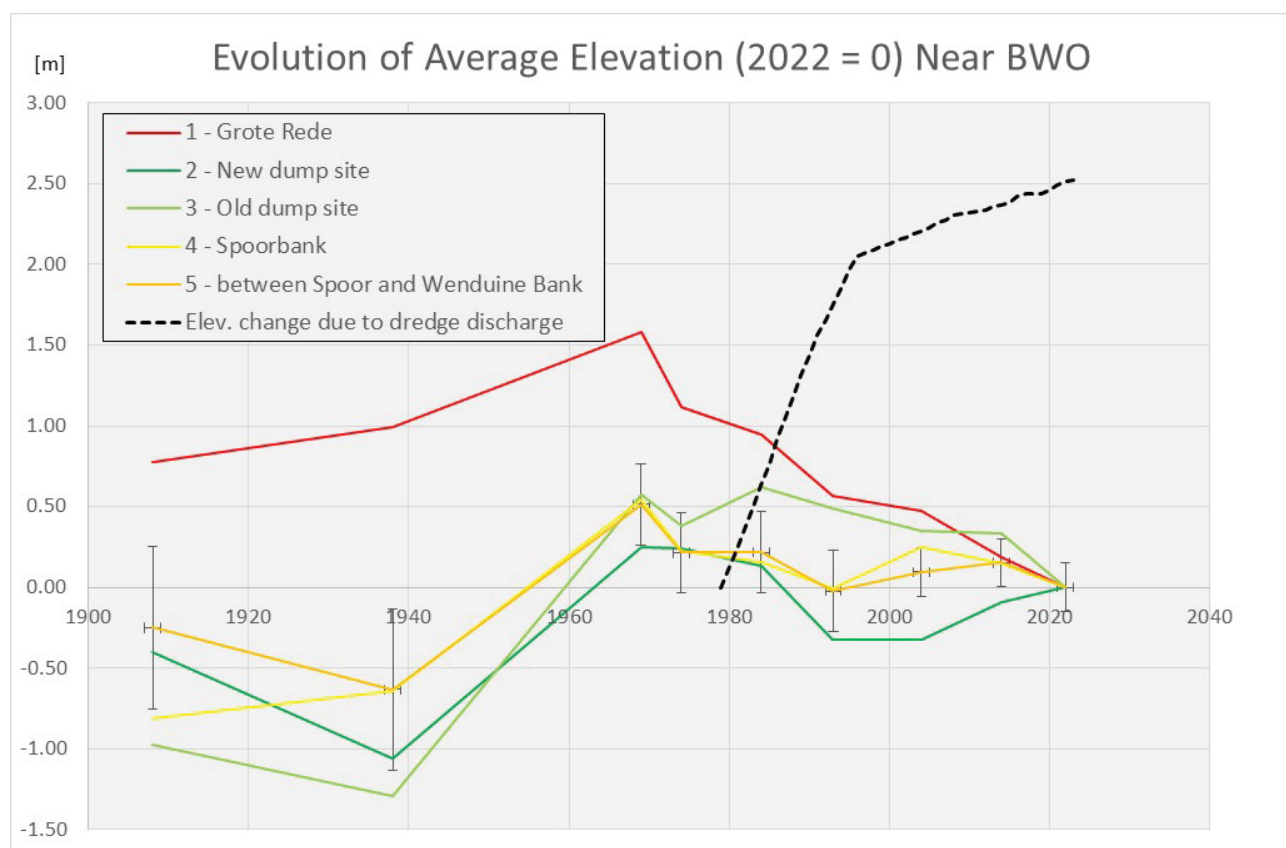


Figure 2-62 – Evolution of average elevation difference (2022 = 0) since 1908 in the 5 areas defined in Figure 2-61.

If only the discharged volumes after 1997 are considered, it is clear that the average elevation contribution of the discharge activities is of the same order of elevation gain in the defined boxes. This may be an indication of the fact that a substantial part of the discharged spoils is sand. Also or additionally, possibly mud was sometimes allowed to deposit.

2.9.5 Interpretation of the observations

The timing and geographical structure of accretion and erosion zones over 1960-2022, considered together with the known tidal current patterns, leaves no doubt on the morphological processes in Grote Rede east of Oostende.

Ever since dredged material has been discharged at Location 1 (Old BWO), severe and continuing erosion has occurred in both the nearshore and offshore branch of Grote Rede. It is inferred that the discharge activities caused a sufficiently high (and sustained) morphological feature, so that the flood current was deflected to both north and south of the site. At the same time, a long low sand ridge, Spoorbank, developed downcurrent of the dump site.

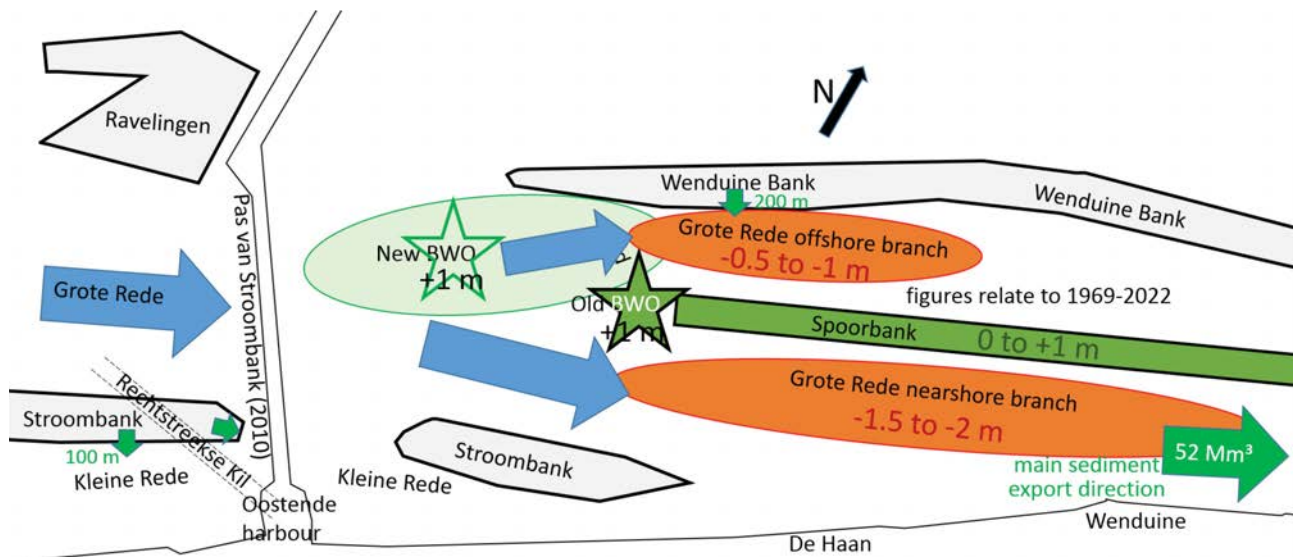


Figure 2-63 – Schematic overview of morphological change between the 1960s and 2022.

Blue arrows: main paths of flood current. Green arrows: coastward movement of shoreface-connected ridges and main evacuation direction of sediment. BWO: dump site Bruggen & Wegen Oostende. Green areas are accretional and red areas erosional. Figures are valid for 1969-2022.

Dredged material disposal probably already affected the area before 1960, possibly even before 1938. The disposal sites were probably more dispersed in the area off Stroombank and De Haan. The induced sedimentation there would have triggered erosion of Grote Rede east of Oostende, especially in the northern part near Wenduine Bank. Later on, around 1960, disposal would have been conducted in dispersed areas in Grote Rede, around Location 1 (Old BWO). This in turn would at first have triggered sediment spreading and fill of the previously erosive Grote Rede. After this, dredge disposal was probably regulated to be inside the 1500 m diameter circle of Location 1 (Old BWO). From then on, two branches developed in Grote Rede north and south of that dump site, the offshore and nearshore branch (Figure 2-63).

The long rectilinear Spoorbank developed mainly after 1993. It is remarked that locally, the crest of this ridge is higher than before 1993, but in general, the ridge stands out mainly because the branches north and south of it gradually deepened.

The shift of the dump site to Location 2 in 2002 and 3 in 2004 (New BWO) caused dispersed sedimentation around the new site. This partly filled the previously deeper northern flow branch.

Remarkably, the southern branch kept deepening out after 2002. Several reasons can be given to explain this:

- the sediment of the old dump site got in time enough consolidated so that the site remained a resistant obstacle to the flow;
- hard elements such as disposed bricks and concrete may also contribute to the resistant nature of the old site;
- the morphological fill at and around the new dump site diminishes the flow section of the northern branch, thus contributing to deflecting the main flow to the southern branch.

As a result, also Spoorbank appears to be a persistent feature.

Everything taken together, the entire balance of the area is sediment loss. Summed over boxes 1-5, the loss between 1969 and 2022 is 52 Mm³ (+/- 26 Mm³). Taking the known residual transport directions into account, most of this must have been exported out of the Grote Rede area to the east. There, it may have contributed to sedimentation in the large nearshore accretion west of Zeebrugge. Part may also have been transported in suspension and have made it to and across Pas van het Zand.

The observed morphological changes reveal the important interaction of dredged material dumping and evolution of nearshore morphology. The deepening of the southern branch of Grote Rede between Oostende and Blankenberge is considered a threat for long-term coastal safety, as it may be a cause of the observed shoreface foot erosion there (Houthuys et al., 2026).

The described system is very similar, be it at a larger scale, to the morphological effects described for the offshore disposal site at Blankenberge, where the concentrated disposals were thought to have triggered a secondary flood channel between the offshore site and the beach (Houthuys et al., 2022).

Houthuys et al. (2026) observed that further deepening of Grote Rede's southern branch stopped in 2020. It is too early to identify a cause for this, but it is now clear that changes in the disposal strategy should be carefully monitored.

It can be considered to adapt the dredged material disposal strategy and to keep more sediment near the coast instead of disposing it offshore. Houthuys et al. (2026) recommended investigating disposal possibilities at the shoreface foot in Bredene. Another approach could consist in more spread-out dumping instead of persistently dumping at the same location.

2.9.6 Conclusion

The Grote Rede case shows the large and geographically extensive consequences of disposing dredged material in a nearshore flow channel. Discharges have been going on for many decades at the dump site Bruggen & Wegen Oostende (BWO). The morphological response of the wide surrounding area was slow but irreversible. Grote Rede was morphologically split into two coast-parallel branches where flow strength was enhanced, separated by a low ridge, Spoorbank. Due to the shifts in location of the dump site, the northern branch partly recuperated while the southern branch continued to deepen. A deeper Grote Rede may contribute to trigger shoreface foot erosion between Oostende and Blankenberge. A change of disposal strategy may be advisable. However, due to the largely qualitative analysis presented here, it is recommended to first explore the full detail of all available surveys conducted in the area over the last decades.

2.10 Conclusion and highlights

This project assembled an impressive uniform and high-quality bathymetric database of the Belgian shelf, inner shelf, nearshore and beach containing surveys from 1804 to the present.

Overall, no significant net sediment loss or gain was observed for the entire region over that long period. However, this is an overall net balance. Sediment is continuously being imported from the adjoining French part of the shelf and exported to the Dutch shelf. Also, there are significant internal rearrangements (Figure 2-64).

Long-term natural morphological change was identified from older maps and in areas without major harbours. Where the more offshore tidal current ridges turn out in general not to have moved, nearshore ridges show significant eastward and shoreward migration, with higher rates tending to be observed in the more inshore areas. Especially in the French-Belgian border area, important alongshore movements of ridges and passes ranging from 5 to 20 m/year are observed. Most nearshore ridges also migrate shoreward, at rates between 1 and 1.5 m/year. Also the nearshore channels and the shoreface base tend to shift landwards. These natural changes are thought to be ultimately driven by the ongoing sea-level rise. On the shoreface-connected ridges, high rates of longshore sand transport are reported. The fill of the fairways to Oostende Harbour allowed us to quantify the longshore net transport rates to be of the order of 200 m³/m/year. These results are in agreement with earlier observations that shoreface-connected ridges act as sand supply paths from the nearshore domain to the beach and the dunes, where the attachment points are the area of entry at the shore.

The height of the nearshore ridges did not change, though often both crest and channel slightly rose over the past two centuries. The crest area of Westerschelde ebb tidal delta shifted landwards, towards the Westerschelde.

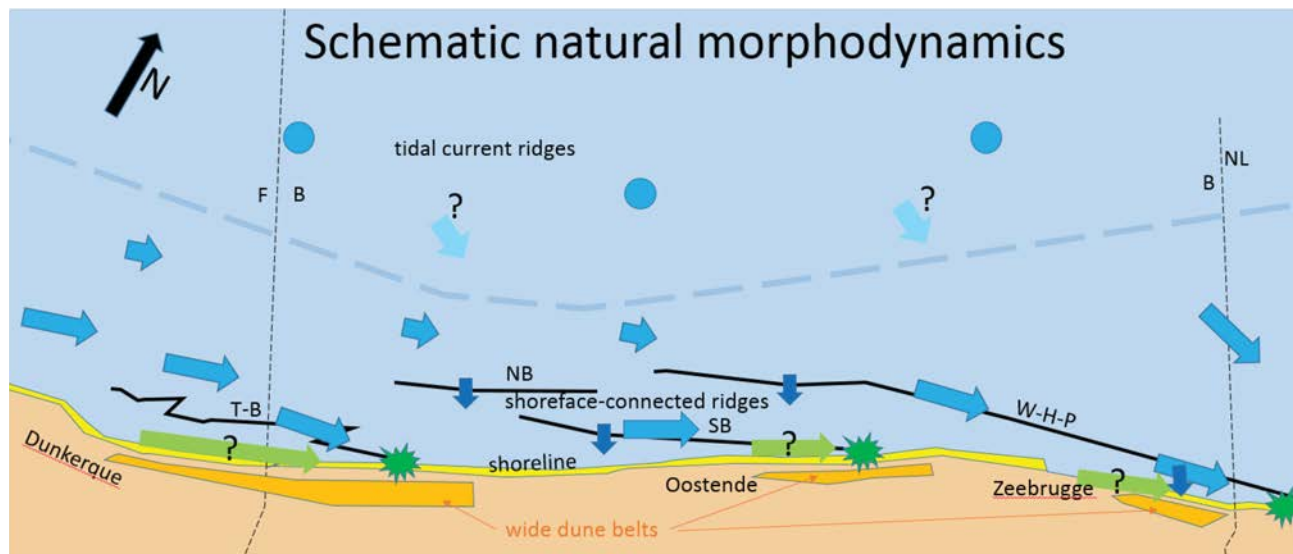


Figure 2-64 - Schematic summary of morphodynamics in the 19th and first half of the 20th century.

Shoreline is the yellow strip near lower edge of figure. State boundaries in fine dashed black lines. Thick black lines are the crests of the shoreface-connected ridge. Pale blue dashed line is approximate boundary between tidal current ridge area and shoreface-connected ridge area. Blue dots indicate no significant morphological change. Thick blue arrows show natural residual longshore sediment transport and movement direction of bedforms on or of extremities of the nearshore sand ridges. Dark blue arrows symbolise landward movement of nearshore sand ridges. Green many-pointed stars show the attachment points as entry points of offshore sand into the coastal barrier system. Thick green arrow is supposed late-Holocene alongshore movement of attachment points (timescale >1000 year), inferred from the presence of wide dune belts; this dynamic remains to be confirmed. Thick pale blue arrows show possible sand transfer from tidal current ridge area to shoreface-connected ridge area; the transfer is inferred but not shown. Abbreviations: F: France, B: Belgium, NL: The Netherlands, T-B: nearshore ridge Trapegeer – Broers Bank, NB: nearshore ridge Nieuwpoort Bank, SB: nearshore ridge Stroombank, W-H-P: nearshore ridge Wenduinde Bank – Hard Zand – Paardenmarkt.

While natural change on the inner shelf and in the nearshore is already considerably affecting the morphological evolution of the beaches, human-induced change has even more powerful effects on nearshore and coastal morphodynamics (Figure 2-65).

There are at least the following five human-induced morphological mechanisms that currently strongly impact on the Belgian coastal morphology:

- The coastal barrier is maintained at its current position and even widened through human interaction. As the nearshore ridges tend to migrate shoreward under natural conditions, as a result, locally, morphological squeeze occurs. This also reduces the flow sections of the inshore tidal channels where they then tend to deepen their bed in order to maintain their flow section. This system also implies that any sand, eroded from the (nourished) beaches and ending up at first in the nearshore channel in front of the beach, is cleared away by the currents.
- The natural sand supply path formed by the shoreface-connected ridge Stroombank is disrupted near Oostende Harbour, depleting the beaches between Bredene and De Haan from the natural offshore sand supply. Further east, the historic shoreface-connected ridge Wenduine Bank / Hard Zand / Paardenmarkt is crosscut by Pas van 't Zand. Sand transported along the ridges is now intercepted in the navigation channels and is removed there by dredging. The dredged material is dumped offshore and thus lost to the coastal system. In addition, the seabed surrounding the frequently dredged fairways shows slow but persistent deepening over extensive areas, suggesting that sediment is attracted into the fairway, and also exported by dredging.

- Dredging activities have a disrupting role on the morphological system. The practice of dumping dredged material at a fixed offshore site in a tidal current channel has the effect of locally plugging up the channel. The currents are diverted around the dump site and the current regime in the diverted branches is reinforced. Under that regime, the morphological response of the channel is deepening its bed next to the dump site. The deepening area extends over many kilometres in the case of dump site Bruggen & Wegen Oostende, where over the recent decades structural deepening of Grote Rede was triggered near the coast between Bredene and Blankenberge Harbour.
- Near Zeebrugge, dump activities at Bruggen & Wegen Zeebrugge Oost have more than compensated the loss of sand advected previously along the shoreface-connected ridge that was cut by Pas van 't Zand. Actually, the wide nearshore area east of Zeebrugge receives large amounts of sediment, triggering both a seaward and eastwards expansion of Paardenmarkt.
- The construction of harbour dams extending deep into the nearshore strongly alters the morphodynamics of the surrounding area. The sheltered areas at the updrift and downdrift sides of the harbour dams attract huge quantities of sediment. The areas just offshore of the harbour dams become exposed to a stronger current regime, and scour troughs develop there. It was shown in this study that morphological adaptations east of Zeebrugge are still going on today, 50 years after the construction of the harbour dams. Sedimentation in the nearshore area off Heist not only receives nourished sand from nourishments at Knokke-Zoute but even larger quantities of sediment derived from a new continuously deepening flow channel north of Zeebrugge, called here "Duinbergen Channel". The overall changed morphological configuration may ultimately benefit Knokke-Zoute: the tidal current channel Appelzak is expected to be diverted more offshore and to link up with Duinbergen Channel, while sedimentation off Heist is expected to expand eastwards to Knokke-Zoute. This may result in milder hydrodynamics at Knokke-Zoute.

This study shows the power of regular morphological monitoring and interpreting morphological change in a coherent and wide context.

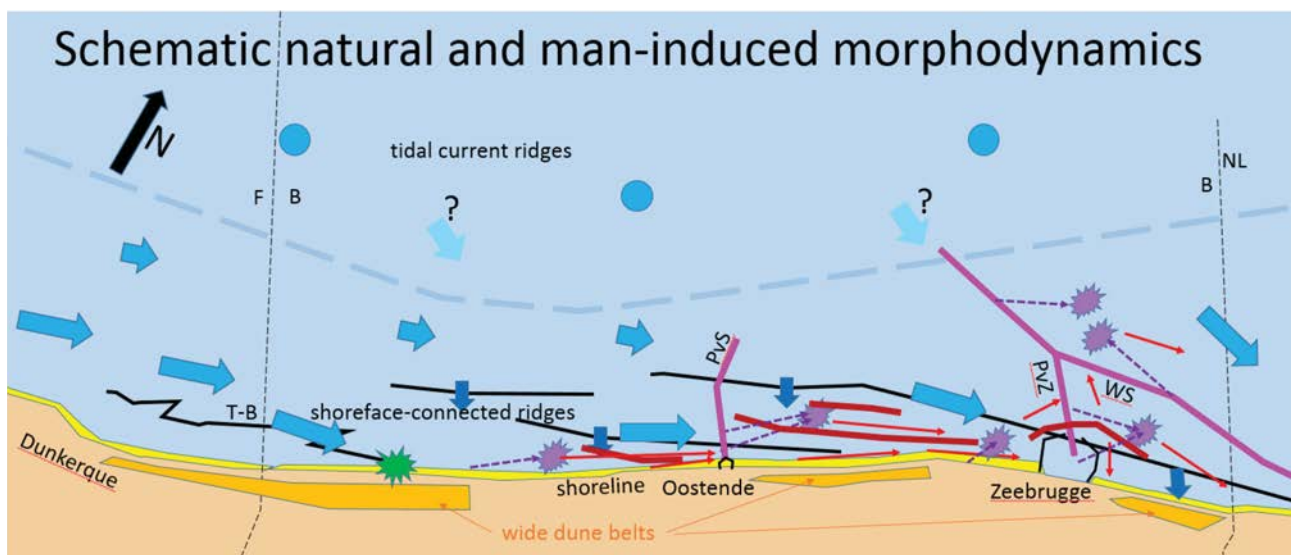


Figure 2-65 – Schematic summary of morphodynamics since about 1950..

Shoreline is the yellow strip near lower edge of figure. State boundaries in fine dashed black lines. Thick black lines are the crests of the shoreface-connected ridge. Pale blue dashed line is approximate boundary between tidal current ridge area and shoreface-connected ridge area. Blue dots indicate no significant morphological change. Thick blue arrows show natural residual longshore sediment transport and movement direction of the nearshore sand ridges. Dark blue arrows symbolise landward movement of nearshore sand ridges. Green many-pointed star shows the attachment point of Broers Bank as entry point of offshore sand into the coastal barrier system. Thick pale blue arrows show possible sand transfer from tidal current ridge area to shoreface-connected ridge area; the transfer is inferred but not shown. Thick pink lines are fairways to the harbours, maintained by dredging. They crosscut the shoreface-connected ridges. Violet dashed arrows symbolise sand transfer from harbour areas to offshore dump sites, which are shown as many-pointed violet stars. Red arrows indicate net sand transport from nourished beaches and dump sites. Thick bordeaux red lines are erosional current channels. Abbreviations: F: France, B: Belgium, NL: The Netherlands, T-B: nearshore ridge Trapegeer – Broers Bank, NB: nearshore ridge Nieuwpoort Bank, SB: nearshore ridge Stroombank, W-H-P: nearshore ridge Wenduinde Bank – Hard Zand – Paardenmarkt.

3 Numerical modelling

3.1 Effects of shelf ridges on decadal morphodynamic evolution of adjacent shorelines using an idealized shelf-shoreline coupled model

Section 3.1 applies an idealized modelling approach to describe the effects of shelf ridges on decadal morphodynamic evolution of adjacent shorelines in the absence of sea level rise (Section 3.1.1) and presence of sea level rise (Section 3.1.2). Section 3.2 describes the shelf morphodynamic on centennial times scales using an idealized morphodynamic shelf model.

3.1.1 Without sea-level rise

3.1.1.1 Model description

This report highlights the key outcomes obtained within this activity, which are presented in this section. Further details and results are available in Nnafie et al. (2024).

The model comprises a shelf model (Delft3D+SWAN) that is coupled to a reduced-complexity nearshore model known as Q2Dmorfo (hereafter referred to as nearshore model). The model has dimensions $x_L \times y_L$, featuring a rectangular shelf ($x_1 \leq x \leq x_L$, $0 \leq y \leq y_L$) and a nearshore domain ($0 \leq x \leq x_1$, $0 \leq y \leq y_L$), where x, y represent the cross-shore and alongshore directions, respectively (Figure 3-1). Furthermore, x_1 is the transition between the shelf and nearshore models. Shoreline position $x_s(y, t)$ is defined as the border between the dry ($z_b > 0$) and wet beaches ($z_b \leq 0$). Here, z_b is the bed level, which is defined with respect to the mean sea level $z = 0$ (MSL), with z the vertical coordinate (positive upward).

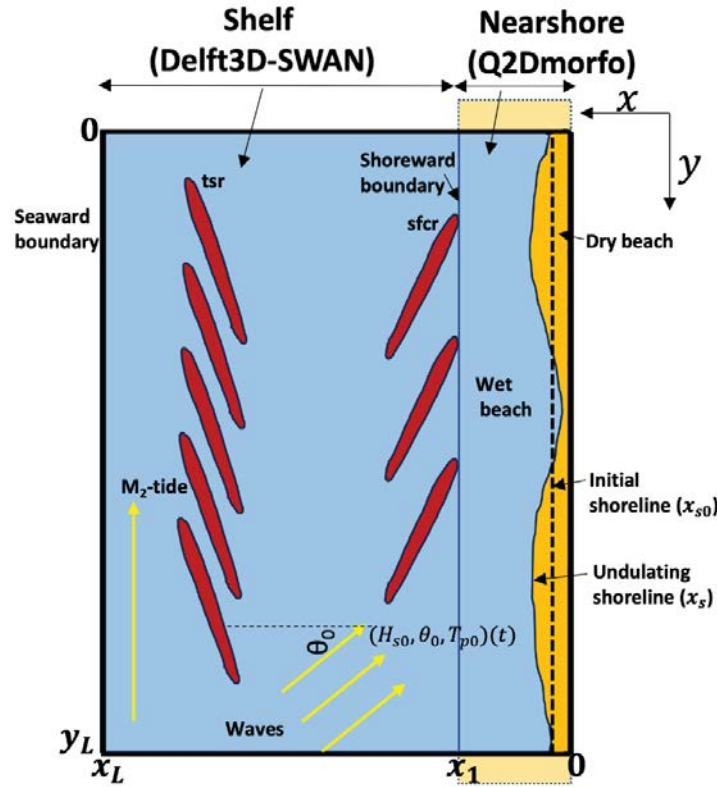


Figure 3-1 – Domains of the shelf model ($x_1 \leq x \leq x_L$, $0 \leq y \leq y_L$) and nearshore model ($0 \leq x \leq x_1$, $0 \leq y \leq y_L$), with x, y pointing in, respectively, the cross-shore and alongshore directions. Shoreline position $x_s(y, t)$ marks the border between the dry ($z_b > 0$) and the wet beach ($z_b \leq 0$). Here, z_b is the bed level, which is defined with respect to the mean sea level $z = 0$ (MSL), with z the vertical coordinate (positive upward). Tidal forcing is imposed at the seaward boundary of the shelf (x_L) as an M_2 wave that propagates from south to north along the coast. Furthermore, a time-varying wave forcing with a significant wave height $H_{s0}(t)$, peak period $T_{p0}(t)$ and wave direction $\theta_0(t)$ (relative to the shore-normal, positive counter-clockwise) is prescribed at the seaward boundary. Wave parameters $H_{s1}(t)$, $T_{p1}(t)$, $\theta_1(t)$, computed by the shelf model at the shoreward boundary (x_1), are subsequently used as a wave forcing for the nearshore model. The orange rectangles at the lateral boundaries of the nearshore model domain indicate the extensions used to compute the waves near these boundaries. The red areas on the shelf are sketches of tsr and $sfcf$.

3.1.1.1.1 Morphostatic shelf model

On the shelf, depth-averaged currents, waves and their interactions are computed with the Delft3D and SWAN models. The bed level in the shelf model is kept fixed (morphostatic) during the simulations, meaning only the FLOW module of Delft3D is used (Lesser *et al.*, 2004; Deltares 2022). Module FLOW computes the water level and currents on the shelf, which are described by the non-linear depth-averaged shallow water equations. This module is forced with sea-level variations at the seaward ($x = x_L$) and lateral ($y = 0, y_L$) boundaries, which mimic a semi-diurnal lunar M_2 tidal wave that propagates in the negative y -direction (Figure 3-1). This tidal wave, characterised by an amplitude $\hat{\zeta}_2$, exhibits a linearly increasing phase from $y = 0$ to $y = L_y$, resulting in a phase difference $\Delta\phi_2$ between the two boundaries. Since the equations of motion are nonlinear, the response to this forcing is an asymmetric tidal motion: it contains the primary constituent (M_2), but also overtones ($M_4, M_6, \dots$), as well as a tidal residual.

The SWAN model simulates the wave propagation on the shelf by solving the spectral wave action balance, which is applied in stationary mode (Holthuijsen 2007; Delft 2024). The default settings are used, as they have been successfully applied by previous studies on coastal morphodynamics (Ridderinkhof *et al.*, 2016; Nnafie *et al.*, 2020). Specifically, dissipation due to whitecapping, depth-induced wave breaking, and bottom friction are considered, utilising the formulations of, respectively, Komen and Hasselmann (1984),

Battjes and Janssen (1978) and Hasselmann et al. (1973). Nonlinear wave-wave interactions, as well as wave growth by wind are neglected. JONSWAP wave spectra are prescribed at the offshore boundaries, with a peak enhancement factor of $\hat{p}$ and directional spreading of $\Delta\theta$.

The waves are considered spatially constant along the seaward boundary and have a time-varying significant wave height $H_{s0}(t)$, a time-varying peak period $T_{p0}(t)$, and a time-varying wave direction $\theta_0(t)$. Additionally, to avoid the formation of shadow zones (i.e., a strong decrease in H_s) near the lateral boundaries ($y = 0, L_y$), periodic boundary conditions are applied at these boundaries. For this reason the original SWAN version was coupled to Delft3D.

Waves influence currents in the FLOW module by introducing additional shear stress at the bed (Soulsby, 1997) and causing a momentum flux through divergence of radiation stresses (Longuet-Higgins and Stewart, 1964). Currents, in turn, affect waves through frequency shifting, refraction and sea level variations. The computed wave time series ($H_{s1}(t)$, $T_{p1}(t)$, $\theta_1(t)$) at the shoreward boundary of the shelf model ($x = x_1$, Figure 3-1) are used as input to drive the nearshore model.

3.1.1.1.2 Nearshore model

In the nearshore area, comprising of the dry and wet beaches (Figure 3-1), the reduced-complexity nearshore model Q2Dmorfo (Arriaga et al. 2017) is used, which simulates the morphodynamic evolution of the nearshore and the changes of its shoreline position $x_s(y, t)$. This model does not explicitly resolve the current field, but it uses empirical formulations to compute the sediment transport directly from the wave field, assuming negligible contribution from the tidal currents. The model consists of three modules: WAVES, TRANSP and BED.

Module WAVES, forced with waves (H_{s1}, T_{p1}, θ_1) at the seaward boundary ($x = x_1$, Figure 3-1), applies the geometrical optics approximation, i.e., linear dispersion relation, irrotationality of the wave vector (also known as the generalised Snell law) and conservation of wave energy, to simulate the wave propagation in the interior of the domain (Arriaga et al. 2017). To define the boundary condition at the up-waves lateral boundary (i.e., the lateral boundary at which wave rays enter) the bathymetry at this boundary is alongshore uniformly extended for a certain alongshore distance (orange rectangle in Figure 3-1). The wave transformation is done in this extended domain, and the transformed waves are then assumed to incise through the lateral boundary.

Module TRANSP calculates the sediment transport vector $\vec{q}_{tot}$ in the nearshore, derived directly from the wave field through empirical formulations, without explicitly resolving the flow field. The used sediment transport formulation does not account tidally-induced transport. To accommodate the curvature of the shoreline represented by $x_s(y, t)$, $\vec{q}_{tot}$ is expressed in a local coordinate system defined by x' and y' . In this system, x' points outward in the direction normal to the local shoreline $x_s(y, t)$, while y' points tangentially along the shoreline. Transport $\vec{q}_{tot}$ is separated into three contributions:

$$\vec{q}_{tot} = \vec{q}_L + \vec{q}_C + \vec{q}_D. \quad (1)$$

The first contribution ($\vec{q}_L$) is the longshore transport vector caused by breaking waves, which is evaluated as a parametrised cross-shore distribution of the total transport rate given by the CERC formula (with coefficient μ that controls the magnitude of this alongshore transport, Komar, 1998). The second contribution ($\vec{q}_C$) represents the cross-shore transport, which is computed as being proportional to the departure of the local bed slope with respect to the slope of an equilibrium profile $z_{b,e}$. Cross-shore sediment transport is the result of several complex processes, mainly including wave nonlinearities, undertow and gravity, which makes it difficult to accurately evaluate this transport. The parametrisation of $\vec{q}_C$ in the model is based on the assumption that, over long time scales (on the order of years to decades), the cross-shore profile of the actual bed level z_b in the nearshore adjusts to the used equilibrium profile $z_{b,e}$. This is consistent with many observations both in nature and in wave flumes. Finally, the third contribution ($\vec{q}_D$) is a bed-slope induced sediment transport. Details on boundary conditions in this module can be found in Arriaga et al. (2017).

The evolution of nearshore bed level z_b is computed in module BED, as a result of the divergence of the sediment transport:

$$\frac{\partial z_b}{\partial t} = -\frac{1}{1-p} \vec{\nabla} \cdot \vec{q}_{tot}, \quad (2)$$

with p the porosity of the bed. The dry beach ($0 \leq x \leq x_s(y, t)$) is part of the computational domain of the nearshore model, meaning that it also experiences erosion and accretion during the simulation. The position of shoreline $x_s(y, t)$ is determined by applying a linear interpolation between the cross-shore locations of the last dry cell and the first wet cell of the nearshore domain.

3.1.1.2 Methodology

3.1.1.2.1 Model configuration

Dimensions of the coupled model domain, bathymetry, tides and waves are based on field data of the Belgian coast, using the "Meetnet Vlaamse Banken" and "Flemish Hydrography" data portals, accessible at <https://www.agentschapmdk.be/en>. Other parameter values are adopted from the work by Arriaga et al. (2017) and Nnafie et al. (2021). A list of all the values of model parameters is provided in Table 3-1. The coupled model domain covers a total area $x_L \times y_L = 50 \times 75$ km. The nearshore zone spans from $x = 0$ and $x = x_1 = 1.5$ km, while the shelf area is between $1.5 < x \leq 50$ km (Figure 3-1).

Table 3-1 – Overview of the physical and numerical parameters of the coupled shelf-nearshore model.

Parameter	Value	Description
<i>Model</i>		
<i>Geometry/bathymetry</i>		
$x_L \times y_L$	$50 \times 75 \text{ km}^2$	Dimensions shelf-nearshore system.
x_{s0}	500 m	Initial shoreline position.
x_1	1500 m	Transition between nearshore and shelf.
$[H_c, w, \alpha]$	[8.2 m, 300 m, -5.23×10^{-4}]	Parameters bathymetric profile (Eqs. 3 and 4).
<i>Shelf model</i>		
$[f, C]$	$[1.43 \times 10^{-4} \text{ s}^{-1}, 65 \text{ m}^{1/2} \text{ s}^{-1}]$	Coriolis and Chézy coefficients.
ν	$1 \text{ m}^2 \text{ s}^{-1}$	Viscosity coefficient.
$[\hat{\eta}_2, \Delta\psi_2]$	[1.8 m, 31.5°]	M_2 -tidal forcing.
σ	$1.405 \times 10^{-4} \text{ s}^{-1}$	Angular frequency M_2 tide.
$[\hat{p}, \Delta\theta]$	[3.3, 25°]	Peak enhancement factor and directional spreading JONSWAP.
<i>Nearshore model</i>		
γ_b	0.5	Breaker index.
d_{50}	0.2 mm	Grain size.
μ	$0.06 \text{ m}^{1/2} \text{ s}^{-1}$	Coefficient CERC formula.
L_2	10 m	Width swash zone.

Parameter	Value	Description
D_c	8 m	Depth of closure with respect to MSL.
<i>Numerics shelf model</i>		
Δt	2 min	Time step (in minutes).
$[\Delta x, \Delta y]$	[250, 250] m	Size grid cells.
<i>Numerics nearshore model</i>		
Δt	0.005 d	Time step (in days).
$[\Delta x, \Delta y]$	[15, 250] m	Size grid cells.
<i>Numerics coupling</i>		
Δt_c	10 days	Coupling time shelf-nearshore model.

3.1.1.2.2 Bathymetry

The present-day bathymetric map of the Belgium coastal zone (Chapter 2) serves as the basis for deriving a representative bathymetry within the model, which is assumed alongshore uniform. In the shelf domain, the following linear bed level profile is used (Figure 3-2, panel a):

$$z_b = \alpha(x - x_1) - H_c, \quad (3)$$

where $\alpha = -5.23 \times 10^{-4}$ is the shelf slope, and $H_c = 8.2$ m is the depth (relative to MSL) at the transition between the nearshore and shelf areas ($x_1 = 1.5$ km). In the nearshore domain (panel b), the bed level profile is approximated by the following (modified) hyperbolic tangent function:

$$z_b = -H_c \left[\frac{\exp(\tilde{x}) - \frac{b}{H_c} \exp(-\tilde{x})}{\exp(\tilde{x}) + \exp(-\tilde{x})} \right], \quad \tilde{x} = \frac{x - \epsilon x_{s0}}{w}. \quad (4)$$

Here, $b = 1$ m is the maximum height of the (dry) beach, which is located at the landward boundary of the nearshore domain ($x = 0$), $w = 300$ m is a characteristic nearshore width and $\epsilon = 1.36$ is a tuning parameter used to smoothly connect the nearshore bathymetry with the shelf bathymetry at the transition x_1 . Furthermore, $x_{s0} = 0.5$ km is the initial shoreline position (vertical dashed line in panel b), which divides the dry beach ($x \leq 0.5$ km, with an onshore increasing height to $b = 1$ m at $x = 0$) and the wet beach ($0.5 < x \leq 1.5$ km). The profile defined in Equation (4) is assumed to be an equilibrium profile $z_{b,e}$, which is needed for calculating the cross-shore sediment transport in the nearshore model.

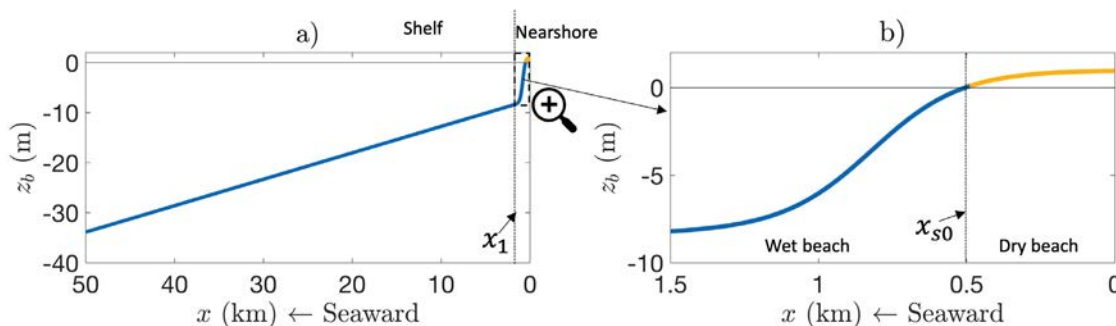


Figure 3-2 – Model bathymetry. a) Shelf and nearshore initial bathymetric profiles used in the model (Eqs. 3 -4). b) A zoom-in view of the bathymetric profile in the nearshore area, which is used as the equilibrium profile $z_{b,e}$. The vertical dashed line in this inset denotes the position of the shoreline ($x = 0.5$ km, $z_b = 0$ MSL), which distinguishes between the dry beach (with an onshore increasing height to 1 m) and the wet beach.

3.1.1.2.3 Tides

In the shelf model, a semi-diurnal lunar M_2 tide forcing (period 12 h 25 min) is applied at the seaward boundary ($x = x_L$), featuring an amplitude $\hat{\eta}_2 = 1.8$ m and a phase difference of $\Delta\psi_2 = 31.5^\circ$ between the lateral boundaries, $y = 0, y_L$. This prescribed tidal forcing simulates a propagating M_2 -tidal wave in the negative y -direction. Tides are not considered in the nearshore model.

3.1.1.2.4 Wave climate

To derive a representative wave climate to force the model, time series of significant wave height (H_s , in m), wave direction (θ , in degrees with respect to North) and peak wave period (T_p , in s) collected at the "Westhinder" wave buoy are used. These time series cover the period from 1990 to 2019. Since these wave time series are not long enough to be used as a forcing in the 100-year model experiments, and given the presence of several data gaps, an alternative wave forcing is derived by constructing synthetic wave time series of H_{s0} , T_{p0} and θ_0 . Further details are provided in Nnafie et al. (2024).

Finally, coefficient μ , which controls the magnitude of the alongshore sediment transport in the nearshore model is set to $0.06 \text{ m}^{1/2} \text{ s}^{-1}$. Using this value yields a total average transport (i.e., integrated over the cross-shore direction and averaged over 10 years) of about $1.1 \times 10^5 \text{ m}^3/\text{yr}$, which is of the same order of magnitude as those found from FlemCo and ScaldisCoast complex models (Section 3.3).

3.1.1.2.5 Numerical aspects

The computation grids in the shelf model (for both wave and flow computations) have sizes of 250 m in the cross- and alongshore directions. The hydrodynamic time step is set at 2 minutes. The alongshore grid size in the nearshore model matches that of the shelf model. However, to capture nearshore processes (e.g., wave refraction and shoaling), the cross-shore grid size in the nearshore model is considerably smaller ($= 15$ m). A time step of 0.005 days is used.

3.1.1.2.6 Coupling aspects

Since the shelf model is morphostatic, a one-way coupling between the shelf and nearshore models is applied, i.e., the bathymetry of the shelf model influences the waves and consequently the evolving bathymetry and the shoreline in the nearshore model, while changes in the latter do not feed back to the shelf morphology. This one-way coupling between the shelf and nearshore models is executed as follows. The two models run separately within time intervals $[t_n, t_{n+1}]$, where $t_n = n\Delta t_c$, $n = 0, 1, 2, \dots$, and Δt_c is the coupling time. During these intervals, the wave forcing of the nearshore model is kept fixed. Only at the end of each interval, this forcing is updated by new wave data (H_{s1} , T_{p1} , θ_1) computed by the shelf model. A coupling time Δt_c of 10 days is used. Test experiments show that, compared with smaller coupling times, a 10-days coupling time yields accurate results, while maintaining reasonable computation durations.

3.1.1.2.7 Model experiments

The bathymetries of the shelf and nearshore domains in the cross-shore direction used in the experiments are given by Equations (3) and (4), respectively, while remaining uniform in the alongshore direction (Figure 3-3). The nearshore zone features an initially straight shoreline situated at $x_s = 0.5$ km.

The first four experiments are named Series S1 (Table 3-2). In the first experiment (referred to as "sfc+tsr (Ref)"), which serves as a reference experiment, synthetic fields of tsr and sfc are imposed onto the shelf bathymetry (Figure 3-3, panel a). These ridges do not move in time. The dimensions, alongshore spacings, and orientations (relative to the shoreline) of these ridges, as well as their heights (crest-to-channel distances), are based on field data of the Belgian shelf (Chapter 2). There are three sfc with alongshore spacings of 15 km and heights of 6 m, which have landward endings positioned at a distance $d_0 = 2$ km from the initially straight shoreline. At approximately 15 km away from the shoreline, five tsr are located, with alongshore spacings of 10 km and heights of 14 m. In the second experiment ("NoRidges", panel b) all ridges are removed. In the third experiment ("sfc only", panel c), only the sfc are introduced onto the shelf, while in the fourth experiment ("tsr only", panel d), the shelf features only tsr.

Impacts of onshore and alongshore displacements of the ridges on the shoreline are addressed by executing three additional series of experiments (S2, S3 and S4 in Table 3-2 and depicted in Figure 3-4). These series simulate the observed onshore and alongshore migrations of the ridges. In all these series, only the sfcir are displaced on the shelf. The tsr are kept fixed, which is supported by the observations presented in Chapter 2.

The four experiments of Series S2 are similar to the reference experiment (Figure 3-3, panel a), with the difference that the sfcir are positioned closer to and farther from the shoreline: $d_1 = 1.5$ km in experiment "Onshore-1" (panel b), $d_2 = 1$ km in experiment "Onshore-2" (panel c), $d_3 = 2.5$ km in experiment "Offshore-1" (panel d) and $d_4 = 3$ km in experiment "Offshore-2" (panel e). In Series S3, besides a shoreward displacement, the sfcir are shifted alongshore to the north by 1000 m ("OnshoreAlong-1", panel f) and by 2000 m ("OnshoreAlong-2", panel g). This northward shift mimics the migration direction of the sfcir on the Belgian shelf.

In reality, the onshore and alongshore displacement of the sfcir is a continuous process, during which sfcir positions change over time. To investigate how existing shoreline profiles respond to these dynamic changes, two additional experiments are carried out: "OnshoreAlong-1-50yrRef" and "OnshoreAlong-2-50yrOA1" (Series S4). These two experiments are similar to experiments "OnshoreAlong-1" and "OnshoreAlong-2", respectively, with the difference that they begin with shoreline profiles obtained at $t = 50$ yr in the reference and "OnshoreAlong-1" cases.

In each experiment, a simulation time of 100 years is used, which is relatively short compared to the time scale over which ridges evolve (Dyer and Huntley 1999), but long compared to that of the shoreline undulations (van den Berg et al., 2012). The experiments are executed on an intel Xeon 2.80 GHz Linux computer, with each experiment requiring approximately 15 days to complete.

Table 3-2 – List of model experiments, organised into four different series: S1, S2, S3 and S4.

Name experiments	Description
S1: "sfcir+tsr (Ref)"	Reference experiment: Both sfcir and tsr present on shelf. Sfcir positioned 2 km from shoreline.
S1: "NoRidges"	No ridges are present on shelf.
S1: "sfcir only"	Only sfcir are present on shelf.
S1: "tsr only"	Only tsr are present on shelf.
S2: "Onshore-1"	As in "sfcir+tsr (Ref)", but sfcir are shifted 500 m shoreward.
S2: "Onshore-2"	As in "sfcir+tsr (Ref)", but sfcir are shifted 1000 m shoreward.
S2: "Offshore-1"	As in "sfcir+tsr (Ref)", but sfcir are shifted 500 m offshore.
S2: "Offshore-2"	As in "sfcir+tsr (Ref)", but sfcir are shifted 1000 m offshore.
S3: "OnshoreAlong-1"	As in "sfcir+tsr (Ref)", but sfcir are shifted 500 m shoreward and 1000 m northward.
S3: "OnshoreAlong-2"	As in "sfcir+tsr (Ref)", but sfcir are shifted 1000 m shoreward and 2000 m northward.
S4: "OnshoreAlong-1-50yrRef"	As in "OnshoreAlong-1", but starting from shoreline profile at $t = 50$ yr of "sfcir+tsr (Ref)".
S4: "OnshoreAlong-2-50yrOA1"	As in "OnshoreAlong-2", but starting from shoreline profile at $t = 50$ yr of "OnshoreAlong-1".

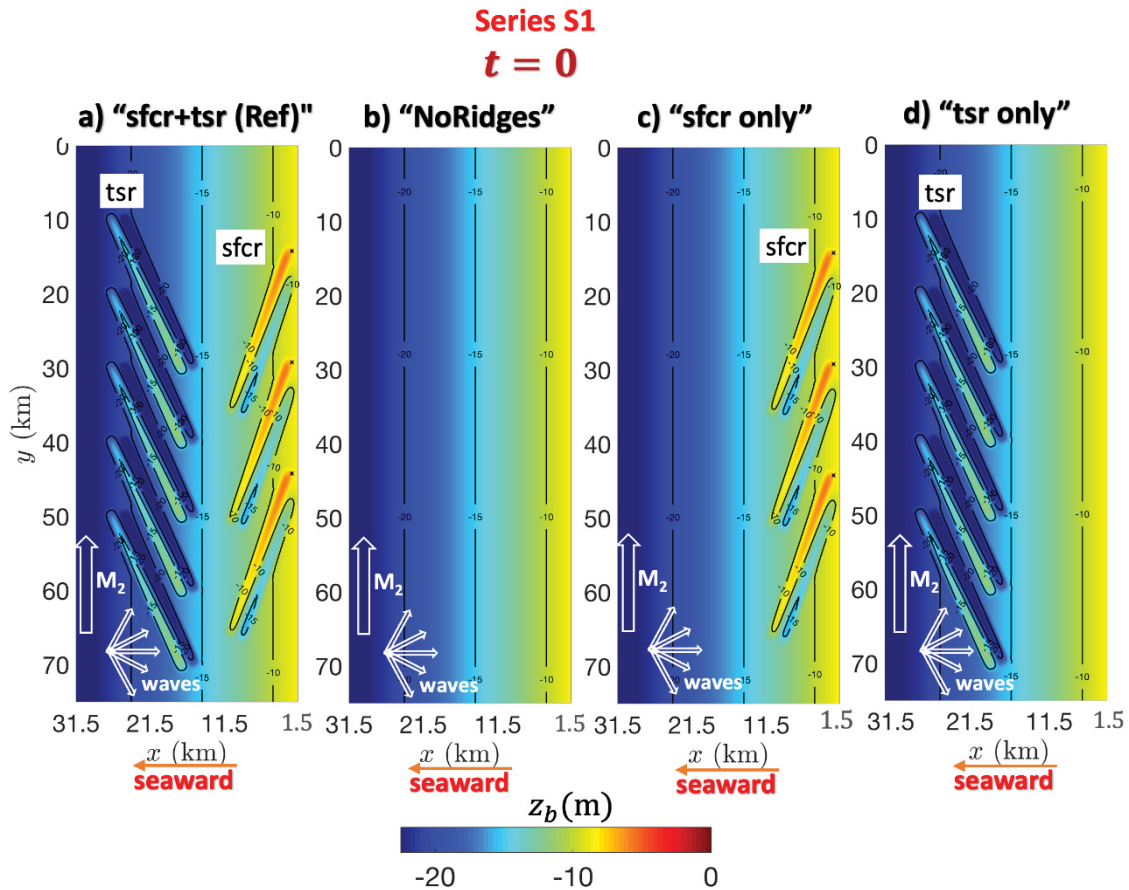


Figure 3-3 – The bathymetric configuration on the shelf used in the experiments of Series S1: Initial bathymetry a) with superimposed fields of synthetic sfc and tsr (reference experiment, referred to as "sfc+tsr (Ref)"), b) without ridges on the shelf ("NoRidges"), c) with a field of synthetic sfc ("sfc only") and d) a field of synthetic tsr "tsr only". The dimensions (width, length and orientation), as well as the distance of the ridges to the shoreline, are based on field data of the Belgian shelf (Chapter 2). Arrows indicate directions of the forcings prescribed at the offshore boundaries (M_2 tidal water level and waves). Note that, for clarity, only a portion of the cross-shore shelf domain is shown ($1.5 \leq x \leq 31.5$ km).

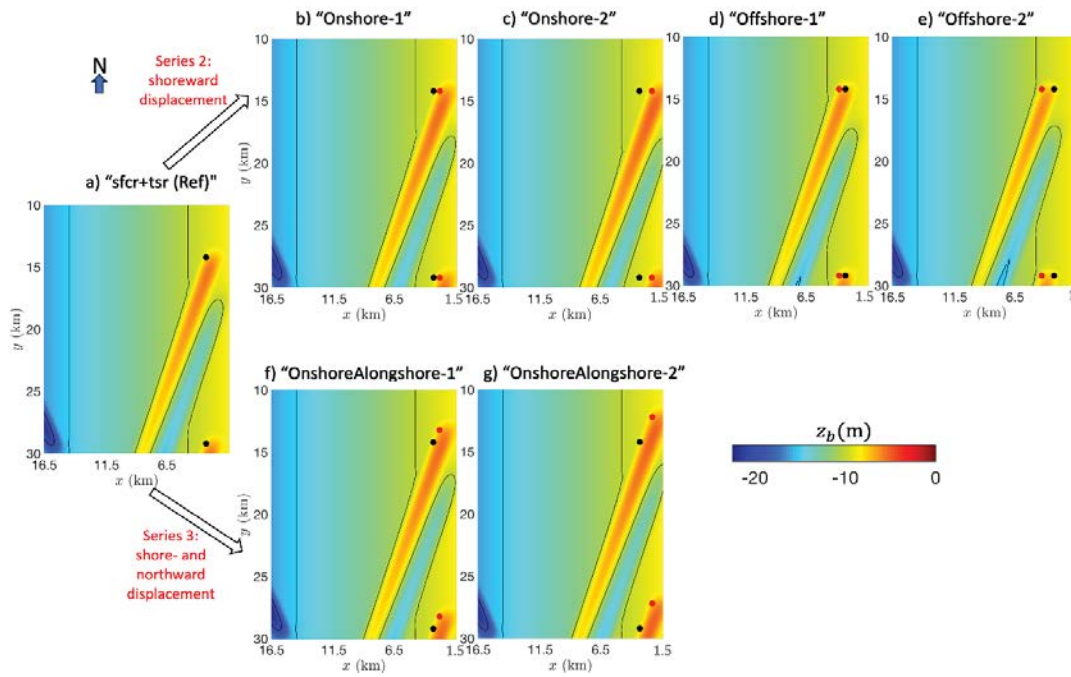


Figure 3-4 – The bathymetric configuration used in the experiments of Series S2 and S3. For clarity, only zoom-ins on the northern-located ridge are displayed for each case. In Series S2, the sfcrtsr are displaced with respect to their locations in the reference experiment (panel a): 500 m shoreward in "Onshore-1" (b), 1000 m shoreward in "Onshore-2" (c), 500 m seaward in "Offshore-1" (d) and 1000 m seaward in "Offshore-2" (e). In the experiments of Series S3, besides a shoreward displacement, the sfcrtsr are displaced 1000 m northward in experiment "OnshoreAlong-1" (f) and 2000 m in "OnshoreAlong-2" (g). As a reference, black dots pinpoint the offshore location of the landward ends of the ridge crests in the reference case at $y = [14.2, 29.2]$ km, while red dots denote their corresponding locations in the other cases. In all cases, the tsr (not visible in the panels) are located offshore.

3.1.1.2.8 Analysis of results

The assessment of the influence of the presence of shelf ridges on the decadal evolution of the nearshore and shoreline involves: 1) identifying areas of progradation and retreat along the shoreline, and 2) evaluating the magnitude of these shoreline undulations. This influence of the ridges are assessed relative to the experiment without ridges ("NoRidges").

The identification of areas of progradation and retreat along the shoreline includes assessing the relative positions of these areas in relation to the adjacent ridge crest and channel between the ridge and the coast. The magnitude of these shoreline undulations is quantified by two quantities: the rate of shoreline change $\partial x_s / \partial t$ (in meters per year) at fixed locations in the proximity of the landward ends of ridge crests and channels; and the root-mean-square (rms) amplitude $\sigma_{x'_s}$ of shoreline undulations, denoted as $x'_s = x_s - \langle x_s \rangle$, where brackets $\langle \rangle$ represent alongshore averaging over length y_L .

3.1.1.3 Results

3.1.1.3.1 Impact of sfcrtsr versus tsr on shoreline dynamics

The outcomes of the full set of experiments of Series S1 are presented in Figure 3-5. Blue, red and green lines denote those of the reference experiment (both tsr and sfcrtsr present), the case with only sfcrtsr, and the case with only tsr, respectively. An animation of the simulated bed levels and shoreline positions x_s between $t = 0$ and $t = 100$ yr is provided in the Supplementary materials of Nnafie et al. (2024) (called movie S1, also available in P:\20_079-MorfoInteract\3_Uitvoering\Final report\AnimationsIdealizedModel)

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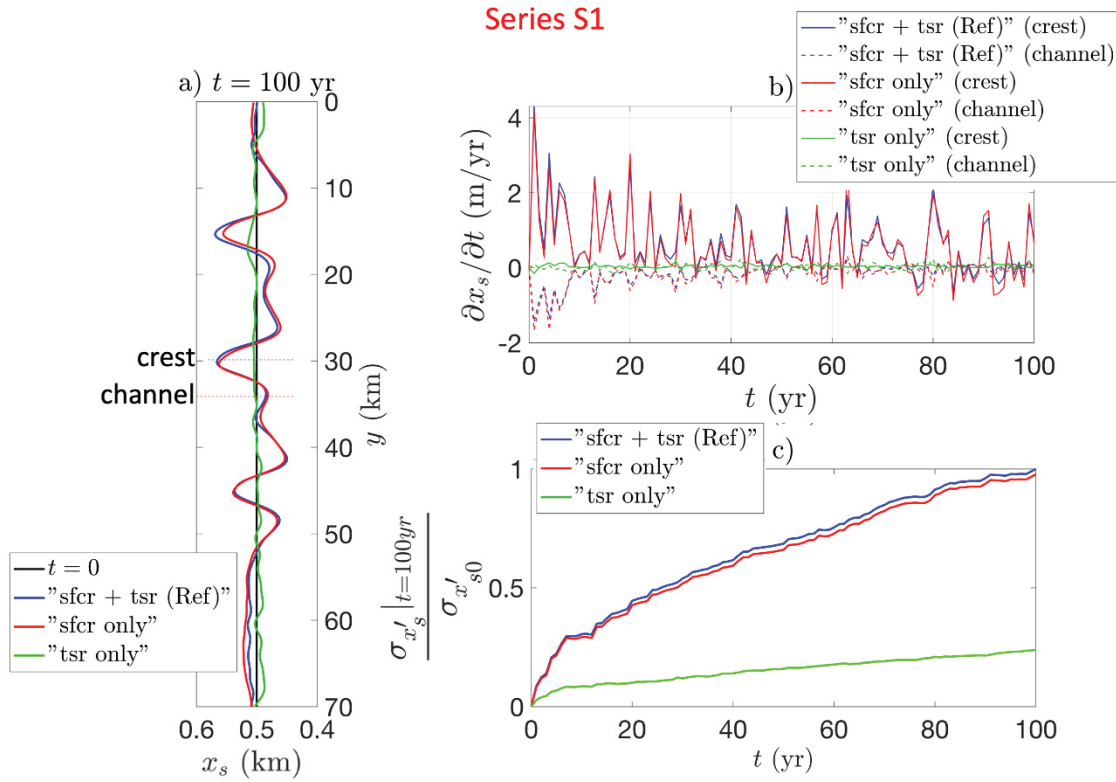


Figure 3-5 – Results from Series S1. a) Simulated shoreline profiles at $t = 100$ yr in the experiments "sfc+tsr (Ref)" (blue line), "sfc only" (red line) and "tsr only" (green line). b) Rate of shoreline change ($\partial x_s / \partial t$) versus time near the crest of the middle sfc (at $y = 30$ km) and near its channel (at $y = 34$ km) in the three cases. c) Root-mean square amplitude $\sigma_{x'_s}$ of shoreline undulations (normalised by its corresponding value at $t = 100$ yr in the reference case, $\sigma_{x'_{s0}}$) versus time in the three cases. The black and red dashed lines in panel a indicate the positions of the landward ends of the crest and channel of the middle ridge, respectively, relative to local positions of the shoreline undulations.

In all three cases, the presence of shelf ridges induces undulations along the shoreline. When only tsr are present, shoreline undulations are weaker ($\sigma_{x'_{s100}} \sim 6$ m after 100 years) compared to the "sfc+tsr (Ref)" and "sfc only" cases, with an rms amplitude $\sigma_{x'_{s100}}$ that is about 24% of that in the reference case. Moreover, unlike the "sfc only" and "sfc+tsr" cases, there is no apparent correlation between the locations of tsr and those of shoreline undulations in the "tsr only" case. Finally, note that the rms amplitude $\sigma_{x'_{s100}}$ of the reference case is approximately 98% of the value in the reference case, indicating that the difference in amplitude between the two cases is smaller than what might be expected based on the sum of $\sigma_{x'_{s100}}$ values from the separate sfc and tsr cases. This aspect is further discussed in Nnafie et al. (2024).

3.1.1.3.2 Different locations of the sfc

3.1.1.3.2.1 Cross-shore displacement

Figure 3-6 shows the results of the experiments in which the sfc are placed at different cross-shore positions on the shelf (Series S2). An animation showing the temporal evolution of bed levels and shoreline positions x_s between $t = 0$ and $t = 100$ yr in the "Onshore-2" case can be found in Nnafie et al. (2024) (Movie S2) (Project folder P:\20_079-MorfolInteract\3_Uitvoering\Final report\AnimationsIdealizedModel\).

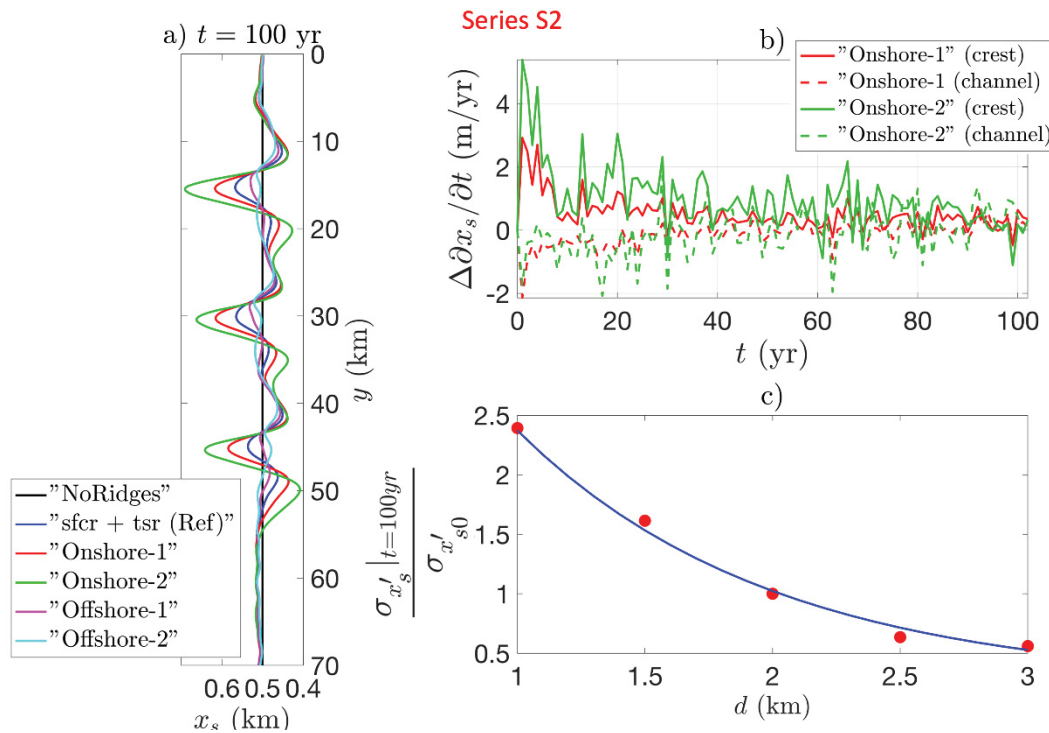


Figure 3-6 – Results of the experiments of Series S2, featuring sfcr with different positions with respect to the shoreline. a) Simulated shoreline profiles at $t = 100$ yr in the different cases (see legend). b) Difference in rate of shoreline change ($\Delta \partial x_s / \partial t$) at fixed locations between the reference case and the "Onshore-1" and "Onshore-2" cases. For the sake of clarity, other cases are omitted. Rates $\partial x_s / \partial t$ are computed near the crest of the landward end of the middle sfcr (at $y = 30$ km) and near its adjacent channel ($y = 34$ km). c) Rms amplitude $\sigma'_{x_s}|_{t=100\text{yr}}$ of shoreline undulations at $t = 100$ yr (normalised by $\sigma'_{x_{s0}}$) versus distance d of the sfcr in the experiments of Series S2. The blue curve represents a fit $\sigma_{\text{fit}} = \sigma_{\text{tsr}} + 5.8 \exp(-2d/d_0)$ through the data, with σ_{tsr} (~ 0.24) the normalised $\sigma'_{x_s}|_{t=100\text{yr}}$ in the case that only tsr are present on the shelf.

From Figure 3-6 (panel a) it is seen that, as the sfcr are positioned more onshore, shoreline progradation and retreat near, respectively, the crests of the landward ends of all three sfcr and the channels between the ridges and the coast become stronger. Conversely, as the sfcr are positioned further offshore, shoreline progradation and retreat in these locations become weaker. This is also evident from panel b, which depicts the time development of the rate of shoreline change $\partial x_s / \partial t$ in the proximity of the crest and channel of the middle sfcr. These rates are initially large, after which they reduce over time. In all cases, shoreline progradation in the proximity of sfcr crests generally exceeds shoreline retreat near the channels (panel a). In the "Onshore-1" and "Onshore-2" cases, the shoreline extends seaward at average rates $\partial x_s / \partial t$ (averaged over the simulation period) of about 1 m/yr and 1.5 m/yr in the proximity of the crests of the landward ends of the sfcr (0.6 m/yr in the reference case), respectively. Meanwhile, near the channels, the shoreline retreats at average rates of approximately 0.5 m/yr and 0.8 m/yr, respectively (0.2 m/yr in the reference case). When the sfcr are displaced further offshore, in the "Offshore-1" case, the shoreline extends seaward (landward) at average rates of about 0.3 m/yr (0.05 m/yr) near the crests (channels). In the "Offshore-2" case, the sfcr still impact the shoreline evolution. However, the manifestation of either progradation or retreat in the proximity of sfcr crests and channels is less evident, indicating that the ridges are situated too far for a notable correlation to emerge between the locations of their landward ends and those of shoreline undulations. Overall, the areas adjacent to all three sfcr undergo qualitatively similar changes in their shoreline. However, in some cases (e.g., "Onshore-2" and "Offshore-1"), rates of progradation and retreat differ quantitatively among these areas.

Panel c of Figure 3-6 shows the rms amplitude $\sigma_{x'_s}|_{t=100\text{yr}}$ of shoreline undulations at $t = 100$ yr (normalised by $\sigma_{x'_s0}$) versus distance d of the sfcr. The blue curve represents a fit $\sigma_{\text{fit}} = \sigma_{\text{tsr}} + 5.8\exp(-2d/d_0)$ through the data, with σ_{tsr} the normalised $\sigma_{x'_s}|_{t=100\text{yr}}$ in the case that only tsr are present on the shelf (experiment "tsr only"). This panel reveals that $\sigma_{x'_s}$ decreases exponentially with distance d from the shoreline. When the sfcr are located far offshore, the influence of the much higher tsr (about 14 m) becomes more significant, with $\sigma_{x'_s}$ approaching $\sigma_{\text{tsr}} = 0.24$.

3.1.1.3.2.2 Shoreward and alongshore displacement

Results from experiments in which the sfcr are positioned more shoreward and northward (Series S3, Figure 3-7) closely resemble those obtained from experiments "Onshore-1" and "Onshore-2" of Series S2. In addition to the observed reinforcement of the shoreline undulations when the sfcr are situated closer to the shoreline, these undulations shift the same distance northward as that of the sfcr (panels a-b).

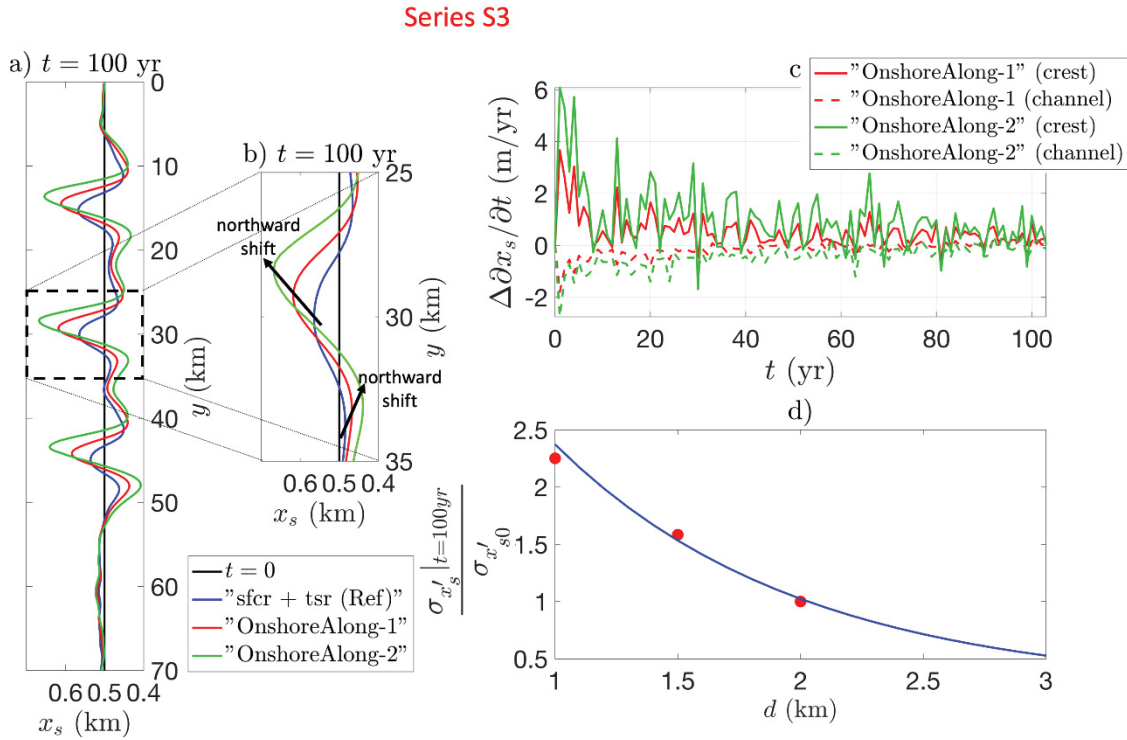


Figure 3-7 – Results of the experiments of Series S3. As in Figure 3-6, but for the experiments of Series S3, where the sfcr are positioned more shore- and northward. A zoom-in on the middle sfcr is also provided (panel b). The thick black arrows indicate the northward shifts of shoreline retreat and progradation areas.

The rates of shoreline progradation and retreat in the "OnshoreAlong-1" and "OnshoreAlong-2" cases are the same as those in the "Onshore-1" and "Onshore-2" cases, respectively. Specifically, the shoreline progrades seaward at an average rate of $\partial x_s / \partial t \sim 1$ m/yr and 1.5 m/yr in the proximity of the crest of landward ends of the ridges in the cases of "OnshoreAlong-1" and "OnshoreAlong-2", respectively. Near the landward ends of the channels, the shoreline retreats at average rates of about 0.5 m/yr and 0.8 m/yr, respectively. Initially, the rate of shoreline change is large, after which it reduces over time (panel c). Similar to the experiments of Series S2, the rms amplitude of the shoreline undulations increases exponentially with decreasing distance of the sfcr to the shoreline (panel d).

Finally, results from experiments of Series S4 (not shown), indicate that, irrespective of whether starting from an initially straight or a pre-existing shoreline profile, the shoreline profiles that eventually develop are nearly identical. Further details are available in Nnafie et al. (2024).

3.1.1.4 Discussion

3.1.1.4.1 Novelty of this study

The novelty of this study is that, for the first time, a coupled shelf-shoreline model was used, which considers the joint effect of tsr and sfc on decadal shoreline dynamics. The model outcomes demonstrate that the presence of sfc on the shelf notably impacts decadal shoreline development, with this impact becoming stronger with decreasing distance of the sfc to the shoreline. Compared to sfc, the impact of tsr on the shoreline development turned out to be weaker but non-negligible, consistent with the findings by Nnafie *et al.* (2021), who obtained similar outcomes when they used conditions of time-varying wave forcing.

3.1.1.4.2 Comparison with observations

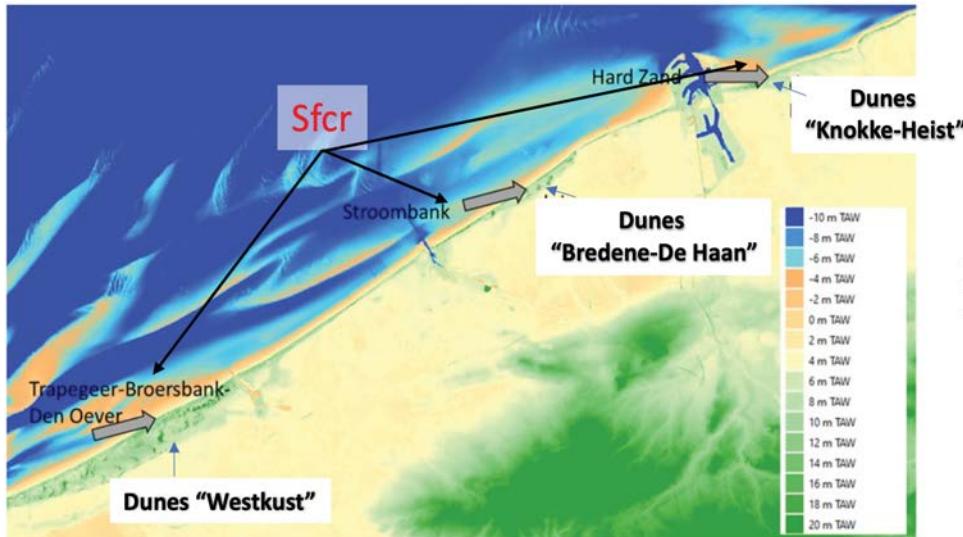


Figure 3-8 – Bathymetric map of the Belgian coastal zone, showing the development of extensive dune areas (green colour) near three offshore located sfc, as indicated by the black arrows. Figure adapted and modified from the work by Verwaest *et al.* (2022).

Figure 3-8, which depicts a bathymetric map of the Belgian coastal zone including locations of dunes, shows that three extensive (aeolian) dunes (green areas) have developed on the upper beach and backshore near three offshore located sfc (indicated by the black arrows), which suggest that shoreline progradation took place in these areas. Verwaest *et al.* (2022), who analysed topographic data for the Belgian west coast between 2000 and 2020, reported the existence of a natural sediment feeding from offshore to the coastline, likely contributing to the growth of dune "Westkust". This natural sediment supply was attributed to the presence of the crest of the offshore located sfc. Coastal volume trends show strong erosion in the proximity of the channel between these ridges and the coast, implying that the shoreline tends to erode at these locations (Dujardin *et al.*, 2023). Similar trends in the shoreline development at decadal time scales were observed by Héquette and Aernouts (2010), who linked the shoreline evolution in the northern coast of France near Calais during the 20th century to offshore changes in bathymetry. They found that eroding (accreting) shorelines generally correspond to areas adjacent to channels (sfc crests).

The results of the present study seem to agree with these observations. However, the Belgian coast zone has experienced intense human activities over the past two centuries, including beach nourishments, construction of groynes, harbours and navigation channels. Whether human activities have also contributed to the observed shoreline progradation and dune growth near the sfc (Figure 3-8) remains unclear. In particular, the "Knokke-Heist" coastal area has experienced an extensive expansion of the Zeebrugge harbour between 1970 and 1985, which impacted the shoreline evolution in this area (Section 2.7). Additionally, the "Knokke-Heist" area may have been significantly influenced by the human activities in the Scheldt estuary and its mouth (e.g., channel deepening, land reclamations), which further complicates the quantification of the relative impact of the shelf ridges on shoreline evolution compared with human-induced evolution.

In addition to shoreline retreat near channels, model results suggest a retreat to the northeast of ridge crests. However, whether such a retreat occurred in the field is currently unknown. Furthermore, observations in the Belgian coastal area show that sfcrcan have an onshore migration (Chapter 2). Based on the model results, it is expected that the zones of shoreline progradation (retreat) will intensify near ridge crests (channels) in case of sfcronshore migration. This is further elaborated in Section 3.1.2.

3.1.1.4.3 Physical interpretation

The emergence of shoreline undulations in the present study is attributed to the forcing template established through the influence of the shelf ridges on the wave propagation towards the shoreline. The basic ingredient of the underlying physical mechanism is wave refraction by the ridges. This gives rise to distinct zones of strong and weak wave energy, as wave energy is focused over the crests of the sfcrcand defocused in the channels between them (Safak et al. 2017). The zones of strong and weak wave energy generate high and low sediment transport in the nearshore zone, resulting in significant gradients along the shoreline. Tsrmodify the wave energy as well, but the corresponding spatial variations in wave energy density are considerably smaller than those induced by sfcrc. When the sfcrcare situated more onshore, focusing or defocusing of wave energy over the sfcrcrests or in the channels becomes stronger. Consequently, larger alongshore gradients in the total sediment transport along the shoreline are created, leading to enhanced shoreline undulations. Further discussion can be found in Nnafie *et al.* (2024).

3.1.1.4.4 Model limitations and potential model improvements

It is important to stress that this model was not designed to perform a reconstruction of the morphodynamic evolution of the Belgian shoreline over recent decades, but rather to gain basic understanding of the effects of onshore migrating ridges towards the shoreline. Therefore, this model was highly idealised, incorporating several simplifications, which are discussed below.

3.1.1.4.4.1 Morphostatic shelf model

The bathymetry of the shelf model, including the tsrand sfcrc, was kept fixed during the simulations. This "freezing" of the shelf bathymetry was done because current existing models (including the present one) are not (yet) capable of self-developing sfcrcand tsrthrough the self-organisation mechanism. The assumption of a morphostatic shelf model implies a one-way coupling between the shelf and nearshore models, meaning that the shelf morphology influences the bed level of the nearshore and its shoreline, but not the other way around. In the present study, amplitudes of shoreline undulations are typically of order 10 to 100 meters, which is much smaller than the width of the nearshore zone (1 km). For these small amplitudes, the one-way approach is considered reasonable. However, in the "Onshore-2" case, where the amplitude of shoreline undulations reached up to 250 m, the validity of the assumption of a morphostatic shelf becomes questionable. In that case, a morphodynamic shelf model where self-developing tsrand sfcrcoccur is necessary to account for the impact of shoreline changes on the shelf evolution. Developing such a morphodynamic shelf model is the topic of Section 3.2.

3.1.1.4.4.2 Wave climate

To mimic the stochastic nature of a realistic wave climate, all the wave events in the applied wave forcing were randomly distributed across the 100-year interval. Only a single realisation of the wave climate was used in the model experiments (one synthetic time series with a certain alternation of wave events). Further information can be found in Nnafie et al, 2021. Ideally, numerous realisations of the wave events should be considered, followed by averaging the ensemble across these realisations. However, due to the long computation times, this approach was not feasible for this study. To explore the sensitivity of model results to the chosen wave climate realisation, two additional experiments were conducted using the setting of the reference experiment, each with a different realisation of the synthetic wave climate. Results (not shown) were nearly identical to those of the reference case, supporting the fact that the choice of a specific realisation of the wave events does not significantly impact the evolution of the shoreline.

However, the wave events within these realisations were treated as statistically independent, while in reality, time series of wave parameters exhibit some degree of correlation, which is linked to the wind. Implementing a correlated wave time series would be a next step, which is considered a topic of future research.

Furthermore, wave growth by wind was neglected in this study. Potential effects of wind on wave growth in the nearshore area were indirectly accounted for through coefficient μ , which controls the magnitude of the alongshore sediment transport in the nearshore model. Using a value of $0.06 \text{ m}^{1/2} \text{ s}^{-1}$, the total average transport (i.e., integrated over the cross-shore direction and averaged over 10 years) was about $1.1 \times 10^5 \text{ m}^3/\text{yr}$, which is of the same order of magnitude as those found from FlemCo and ScaldisCoast complex models (Section 3.3).

3.1.1.4.4.3 Role of tides

Tides in the shelf model are forced by a progressive M_2 tidal wave at the seaward boundary of the shelf. Due to tide-topography interaction, both a tidal residual and higher harmonics of the M_2 constituent are generated, so tidal motion in the domain is asymmetric. Additional tidal asymmetry would result from adding e.g. an M_4 component in the tidal forcing.

The morphodynamics in the nearshore model is only indirectly influenced by tides, in the sense that they only modify the wave motion on the shelf and thereby the wave forcing of and sediment transport in the nearshore zone. This is because the topography of the shelf is kept fixed (morphostatic) and sediment transport in the nearshore model is computed with a bulk transport formula that contains only waves as input. The assumption of a morphostatic shelf is reasonable, as the timescale of shoreline undulations (years to decades) is much shorter (van den Berg et al., 2012) than that of the ridges, which typically evolve on centennial and millennia time scales (Dyer and Huntley 1999). Southgate (1989) and Anthony and Orford (2002) showed that strong interactions between waves and tides occur in the nearshore zone of macro-tidal shelves. More recently, Nnafie et al. (2021) demonstrated that the inclusion of tidal sea-surface variations in the nearshore zone somewhat weakens shoreline undulations, yet the overall trend remains unchanged. However, their results should be interpreted with caution, since they did not consider tidal velocities. Incorporating tides in nearshore modelling is recognized as an important topic of future research.

3.1.1.4.4.4 Role of onshore sediment transport

In the present model, shoreline undulations arise primarily from gradients in the alongshore transport. These gradients are generated by a forcing template that is established through wave refraction over sfcf crests and channels between the ridges and the shoreline, as is illustrated in Figure 3-15. This wave transformation creates gradients in wave energy density, which in turn induce spatial variations in the longshore sediment transport in the nearshore zone. Cross-shore sediment transport $\vec{q}_c$ is represented in the model based on the assumption that the cross-shore profile of the actual bed level z_b adjusts to the used equilibrium profile $z_{b,e}$. In other words, the model accounts for profile adjustment processes but neglects any direct onshore sediment supply associated with the presence of the sfcf. However, analysis of sediment budgets in the Belgian (Verwaest et al., 2022) and northern French coasts (Battiau-Queney et al., 2003), as well as in the Fire Island coastal area (Schwab et al., 2013) indicates the existence of sediment transport from the sfcf towards the shoreline. This suggests that sfcf supply sediment to the nearshore. Especially in the case of sfcf located in relatively shallower waters, as studied in the present work, these ridges can contribute substantial amounts of sediment to the beach through shoreward-directed wave asymmetry-induced transport or other mechanisms (Anthony and Aagaard 2020). Héquette and Aernouts (2010) argued that wave-related transport significantly contributed to the formation of the shoreline progradation observed near the ridge in the Calais coastal area, northern France. Similarly, Schwab et al. (2013) provided evidence for the existence of onshore directed sediment transport from the sfcf towards the adjacent shoreline of Fire Island, USA. In the present study, an onshore-directed sediment transport is anticipated to further enhance shoreline progradation in the proximity of the ridge crest, particularly in the case of sfcf located close to the shoreline. Investigation of ways to incorporate onshore-directed sediment transport is considered a key topic for future model improvements.

3.1.1.4.4.5 Migrating vs displacing sfc

In the present study, sfc were displaced cross- and alongshore on the shelf. In reality, however, the sfc migrate on the shelf, leading to continuous adjustments of the shoreline over time. Model results indicated that regardless of whether starting from an initially straight or a pre-existing shoreline profile (run series S3 and S4 in Table 3-2), the shoreline goes towards the same equilibrium shoreline profile. Therefore, the static positioning of the sfc on the shelf in this study, rather than applying a dynamic movement, is not expected to change the outcomes of this study.

3.1.1.4.5 Relevance of model results

Sea level rise might have caused the observed onshore migration of sfc in the Belgian coastal area (as detailed in section 3.1.2). Given the reported acceleration of sea level rise in these coastal areas over recent decades (Wahl et al., 2013; Steffebauer *et al.* 2022), this onshore migration could intensify, potentially amplifying shoreline changes near these ridges. This topic is discussed in Section 3.1.2. Furthermore, the increasing demand for sand extraction from shelf ridges and construction or deepening of navigation channels (Van Lancker *et al.* 2010; Wyns *et al.* 2021) could significantly impact ridge evolution, potentially leading to additional changes along the adjacent shoreline. Continuous monitoring of bathymetric changes and shoreline evolution in these areas is therefore essential to determine whether the onshore movement of shelf ridges and the associated shoreline changes are accelerating.

3.1.1.5 Summary and Conclusions

The model results show that sfc and tsr on the Belgian shelf act as a forcing template for the decadal evolution of the shoreline. This template is established through wave refraction over sfc crests and channels between the ridges and the shoreline. This creates gradients in wave energy density, which induce spatial variations in the longshore sediment transport in the nearshore zone. Consequently, shoreline progradation occurs in the proximity of crests of landward ends of the sfc, while shoreline retreat appears adjacent to the channels in between the ridges. Compared to sfc, the impact of tsr on the shoreline development turns out to be smaller, but significant.

When the sfc are positioned more onshore, both shoreline progradation and retreat become stronger. The root-mean square amplitude after 100 years of simulation time of these shoreline undulations appears to strongly increase with decreasing distance of the sfc to the shoreline. These shoreline undulations shift in conjunction with the alongshore displacement of the sfc. Based on these outcomes, it is expected that the observed onshore migration of sfc on the Belgian continental shelf will lead to increased shoreline retreat near the channels and progradation near the crests of the sfc, with these changes moving with the alongshore movement of the ridges.

3.1.2 With sea-level rise

3.1.2.1 Introduction

Shoreline erosion threatens many coastal areas. Addressing this issue requires a thorough understanding of the underlying processes for effective mitigation (Vousdoukas et al. 2020). Previous studies that focused on the analysis of field data (W. C. Schwab et al. 2000; Héquette and Aernouts 2010) as well as model studies (Safak et al. 2017; Nnafie et al. 2024) have demonstrated that large-scale sand ridges on continental shelves significantly influence shoreline evolution on decadal scales. These ridges, known as shoreface-connected sand ridges (sfc) and tidal sand ridges (tsr), are spaced 2–15 km apart, have lengths of 10–50 km, widths of 1–10 km, heights of 5–25 m, and evolve on centennial time scales (Dyer and Huntley 1999). There are three major differences between the two types of ridges, which concern their formation mechanism, locations and the orientation of their crestlines. Regarding their formation, tsr are generated by tides (Huthnance, 1982),

whilst sfcir are generated by storm-driven currents (Trowbridge, 1995). Furthermore, tsr occur on the shelf, whilst sfcir are found closer to the coast. Finally, the crests of tsr are rotated anticlockwise with respect to the tidal current, whereas the crests of sfcir have seaward ends that, with respect to their landward ends, are shifted against the dominant storm-driven current.

A limitation of the model studies cited above is their assumption of a constant mean sea level (MSL), albeit that other studies (Swart and Yuan 2019; William C. Schwab et al. 2013) have highlighted that sea level rise (SLR) plays an important role in ridge evolution and, consequently, shoreline morphodynamics. SLR is also believed to be the driver of the onshore migrating sfcir observed on many shelves (Swift and Field 1981; Antia 1996), including the Northern French and Belgian shelves (Héquette and Aernouts 2010; Dujardin et al. 2023). In particular, it is expected that due to climate change rates of global mean sea level rise will rapidly increase in the near future (IPCC 2022). This raises concern about their increasing impact on decadal shoreline morphodynamics. Another limitation is the neglect of anthropogenic influences, such as sand nourishments and the construction of ports, which are widely implemented along shorelines and can significantly influence shoreline evolution (Del Río et al., 2013).

These considerations motivated the objective of this study, which is to quantify the impact of SLR and sand nourishments on the long-term shoreline evolution of an idealized coastal system relative to the situation without SLR and nourishments. The Belgian coast is used as a suitable study area (Figure 3-9), as it provides an ideal test case due to the presence of both sfcir and tsr, its history of shoreward ridge migration, and its extensive nourishment programme. It is important to emphasise that the goal of this study is not to reconstruct the morphodynamic evolution of the Belgian shoreline over recent decades, but rather to gain fundamental insights into the effects of onshore migrating sfcir on the shoreline. To this end, an idealised modelling approach is employed, in which the tides, waves, bathymetry and ridge configuration are schematised and serve as first-order approximations of reality.

To meet this objective, the following activities were carried out:

- A review of the literature on historical rates of sea-level rise (SLR) from 1800 onward along the Belgian and Dutch coasts;
- For the same period, landward migration rates of sfcir were retrieved from bathymetric data;
- This information was used to run the model described in Section 3.1.1 to simulate the morphological evolution of the nearshore zone, including undulations of the shoreline, subject to sea level rise, while maintaining a fixed shoreline position (the so-called 'hold the line' strategy);
- Finally, the model was applied to estimate required future annual nourishment volumes for a period of 50 years for different rates of sea level rise.

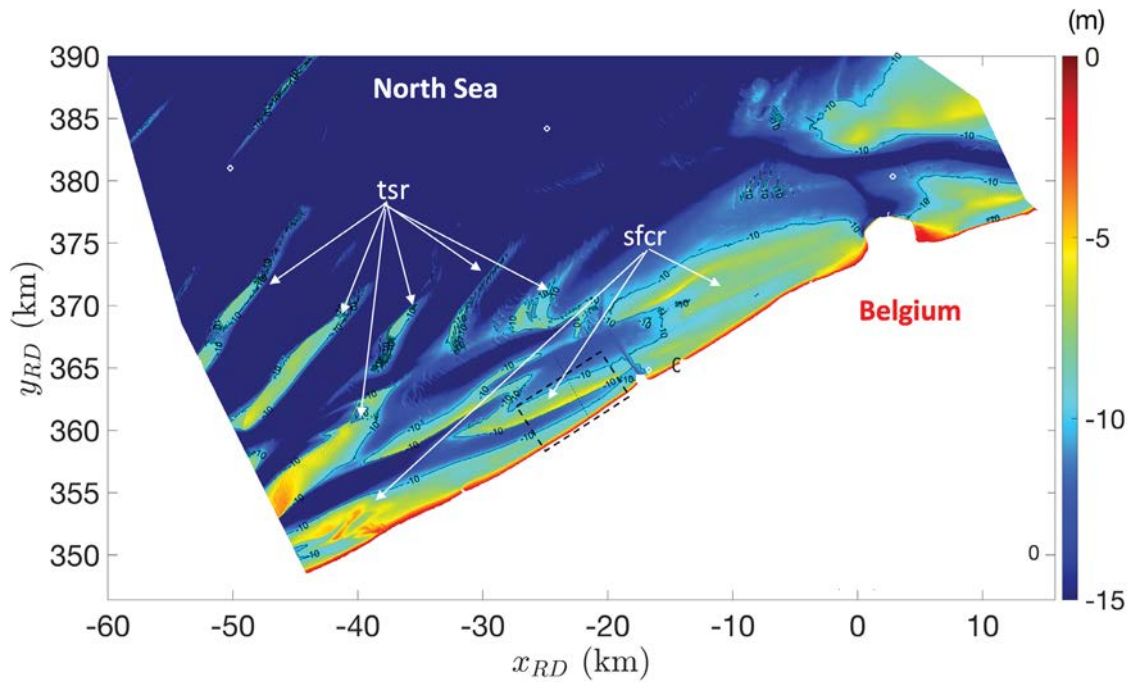


Figure 3-9 Present-day bathymetric map (in meters NAP, Dutch equivalent for mean sea level = MSL) of the Belgian shelf, showing sfc and tsr.

3.1.2.2 Study area

The Belgian coast is located along the southern margin of the North Sea basin between the borders of France and the Netherlands (Figure 3-9). The coast extends for approximately 65 km, from De Panne in the southwest to Knokke-Heist in the northeast (De Clercq et al. 2016). The present-day shoreline, oriented roughly 240° clockwise relative to geographic north (Figure 3-9), is believed to have formed during the Holocene period (Houthuys et al.; 1995). The nearshore zone is typically characterized by sandy beaches, with widths (i.e., the distance between mean low-water level and the dune foot) of ~ 200-250 m and a beach slope of ~ 0.02 (Deronde et al., 2008; Strypsteen et al., 2019).

3.1.2.2.1 Sea level rise

Like many coastal regions worldwide, the Belgian coast is exposed to sea-level rise. In the 19th century, modest rates of SLR of, on average, ~ 0.5–1 mm yr⁻¹, increasing in the latter half of the century (Mörner 1973; Van Cauwenberghe 1999; Mortari 2004; Walker et al. 2022). In the 20th century, rates roughly doubled to ~ 1.5–2.0 mm yr⁻¹ (Van Cauwenberghe 1999; Stolte et al. 2023; Pereira et al. 2023; Wahl et al. 2013). Since the 1990s, acceleration to ~ 3 mm yr⁻¹ has been observed along the Belgian coasts (Stolte et al. 2023), although Keizer et al. (2023) reported that the acceleration of sea-level rise in the southern North Sea began already in the 1960s. Further details are given in Appendix B.

According to the latest IPCC assessment (AR6, Working Group I, Chapter 9) (Lee et al. 2023), climate change is expected to induce higher rates in the near future, with values up to 8 mm/yr in scenario (SSP5-8.5). Such an increase is anticipated to strongly impact the coast. The Belgian coast is already experiencing increased coastal erosion. The shoreline management along much of the Belgian coast has followed a hold-the-line approach, aiming to maintain the existing shoreline position, at places resulting in seaward progradation. This strategy has been implemented by a combination of hard-engineering structures such as groynes and sea dykes and beach nourishment campaigns. In recent decades nourishments were the main measure of coastal protection. Typical averaged nourishment volumes along the Belgian coast in recent decades are $[5 - 6] \times 10^5 \text{ m}^3/\text{yr}$ (see Chapter 2).

3.1.2.2.2 Tides, waves and sediment characteristics

The tidal regime along the Belgian coast is dominated by the semi-diurnal lunar constituent M_2 , which is the principal tidal component in the southern North Sea. The Belgian coast experiences a meso- to macrotidal environment, with a typical tidal range of approximately 3–5 m, depending on location and tidal phase. Along the Belgian coast, the M_2 constituent generally exhibits amplitudes on the order of 1.5–2.0 m. The phase of the M_2 constituent increases progressively from southwest to northeast, with a typical phase difference of approximately 35° along the coast. This reflects the progressive nature of the tidal wave in the region. Nonlinear processes in the shallow coastal zone generate overtides, among which the M_4 constituent is the most significant. The M_4 amplitude is typically around 0.1 m along the Belgian coast. Its phase also varies alongshore, with a difference of approximately 140° between the southwestern and northeastern parts of the coast.

The Belgian shelf is exposed to a moderate to energetic wave climate typical of the southern North Sea. Wave conditions are predominantly from the south-south-west (SSW) and north-north-west (NNW) directions. Significant wave heights during normal conditions are typically in the range of 0.5–1.5 m, while winter storm events can produce significant wave heights exceeding 3–4 m in offshore areas. Wave periods are generally short to moderate, with peak periods of 4–8 s under average conditions and up to 8–10 s during storms. Due to the relatively shallow water depths of the Belgian shelf, wave transformation processes such as shoaling, refraction, and bottom friction strongly influence nearshore wave conditions. These processes result in a gradual reduction of wave energy toward the coast.

The seabed of the Belgian shelf is predominantly composed of sandy sediments, with spatial variations linked to hydrodynamic conditions and morphological features such as sand ridges (Figure 3-9) and tidal channels. Typical median grain sizes (d_{50}) range from approximately 200 to 350 μm , corresponding to fine to medium sand.

3.1.2.3 Material and Methods

3.1.2.3.1 Historical bathymetric data

To quantify the effects of sea-level rise on the long-term morphological evolution of the Belgian coast, the multi-century bathymetric datasets presented in Chapter 2 are used. These datasets represent conditions on the Belgian shelf and in the nearshore zone for the years 1804, 1866, 1938, 1962 and 2022. The datasets are processed to extract cross-shore profiles in the area of the Stroombank ridge (black rectangle in Figure 3-9). For each dataset, an alongshore-averaged profile is constructed by averaging 100 individual cross-shore profiles within this area.

3.1.2.3.2 Model

The model as described in Section 3.1.1 is adapted for modelling sea level rise, onshore migrating sfc and the 'hold-the-line' using nourishments coastal protection policy. In case there is no change in mean sea level, the model is closed once the bed level $z_b(x, y)$ on the shelf and an equilibrium profile $z_{b,eq}(x)$ in the nearshore zone are defined. This setting was used in Section 3.1.1 to study the evolution of the nearshore bathymetry and shoreline undulations at fixed time slices. This model setting will also be used in the present study to spin up the model, albeit with a different $z_b(x, y)$ on the shelf and a different $z_{b,eq}(x)$ in the nearshore zone (see later).

Once there is sea level rise, the sea surface $z = z_s$ will not only change due to internal hydrodynamics, but also experiences an additional increase as a result of SLR, which has to be prescribed. Furthermore, the values of x_L and H_c are kept fixed, but H_o, x_c, x_1 (with x_c the position of the ridge crest), as well as z_b on the shelf and $z_{b,eq}$ in the nearshore zone become time dependent, as they respond to both sea level rise and nourishments. The varying quantities are computed using the following equations.

The direct impact of SLR in the model is that

$$\frac{\partial z_s}{\partial t} \Big|_R = \frac{\partial z_s}{\partial t} \Big|_{R=0} + R, \quad (2)$$

with R the rate of SLR. Furthermore, the seaward depth (H_o) at location x_L changes according to:

$$\frac{dH_o}{dt} = R. \quad (3)$$

This equation can be solved once an initial depth $H_o(t = 0)$ is specified.

As sfcir migrate landward, the value of x_c will change. The migration rate of these ridges, $\frac{dx_c}{dt}$, is determined from the longshore averaged bathymetric profiles at different years. A linear fit is subsequently applied, such that

$$\frac{dx_c}{dt} = -aR(t), \quad (4)$$

with a a parameter.

Furthermore, it is assumed that location $x = x_1$ of the transition shelf-nearshore zone migrates at the same rate as that of the sfcir, so

$$\frac{dx_1}{dt} = \frac{dx_c}{dt}, \quad (5)$$

where the right-hand side is retrieved from field data. Once initial values for $x_1(t = 0)$ and $x_c(t = 0)$ are given, Eqs. (4-5) can be straightforwardly integrated. Note that H_o, x_c, x_1 are assumed alongshore uniform, i.e., they do not depend on the y -coordinate.

Finally, the choices of $z_b(x, y, t)$ on the shelf and $z_{b,eq}(x, t)$ in the nearshore zone are described. In the shelf domain, the bed level is defined as $z_b(x, y, t) = \langle z_b \rangle(x, t) + h(x, y, t)$, where $\langle z_b \rangle$ denotes the mean (i.e., alongshore-averaged) bed level and $h(x, y)$ represents bottom perturbations with respect to $\langle z_b \rangle$. The latter is approximated by a linear

cross-shore profile (dashed yellow line in Figure 3-10, panel a):

$$\begin{aligned} \langle z_b \rangle &= \alpha(x - x_1) - H_c, \\ \alpha &= \frac{H_c - H_o}{x_L - x_1}. \end{aligned} \quad (6)$$

where α is the mean shelf slope, H_c is the water depth at the transition between the nearshore and shelf domains (x_1), and H_o is the depth at the offshore boundary (x_L). Thus, with imposed values H_o , H_c , x_1 and x_L at time $t = 0$, the initial shelf bathymetry is known (see Figure 3-10, panel a). Note that α , x_1 and H_o are time-dependent and known once Eqs. (4-5) are solved. Bottom perturbations $h(x, y, t)$ represent a field of tsr and sfcir, which are superimposed on the mean bed level $\langle z_b \rangle$. Only the field of sfcir is assumed to migrate landward with the same rate as the observed onshore migration rate of the sfcir (1-4 m/year). The position of tsr is assumed to be fixed in time. This means that $h(x, y, t + \Delta t)|_{\text{sfcir}} = h(x - \Delta x_c, y, t)|_{\text{sfcir}}$ (horizontal shift over distance Δx_c during a small time Δt , see panels a,b of Figure 3 10). Using Eq. (4), this can be rewritten as

$$h(x, y, t + \Delta t) = h(x - aR\Delta t, y, t),$$

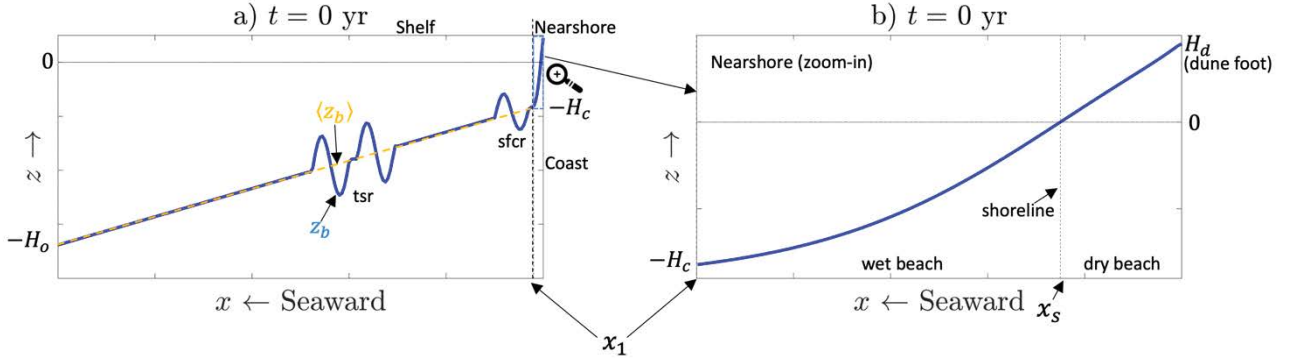


Figure 3-10. a) Shelf and nearshore initial bathymetric profiles at $t=0$ (blue lines) used in the model (Eq. 8). The dashed yellow line indicates the mean shelf bed level, $\langle z_b \rangle$. b) Zoomed-in view of the nearshore bathymetric profile. The vertical dashed line marks the shoreline position, which separates the dry beach (with rises landward to the dune foot height H_d at $x = 0$) from the wet beach. Water depths at the shelf-nearshore transition (H_c) and at x_L (H_o) are also indicated. Note that the nearshore profile used here, which is based on the 1866 bathymetry, differs from the profile used in Section 3.1.1, which was derived from the present-day bathymetry.

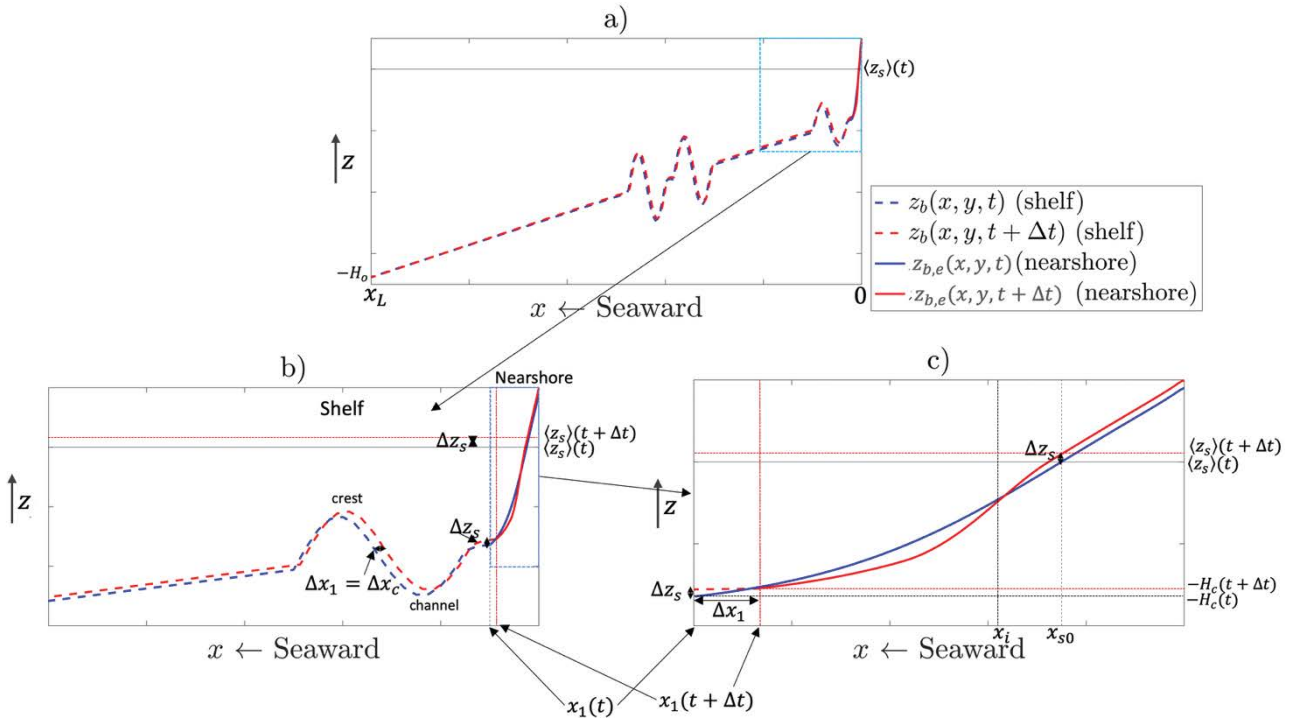


Figure 3-11. Schematic illustration of changes in shelf (dashed lines) and nearshore (solid lines) bed levels z_b under SLR and hold-the-line management measures over a small time increment Δt . Zoom-ins are provided in panels b and c. The ridge crests and adjacent channels of the sfc migrate landward by a distance Δx_c , accompanied by an increase in the mean bed level slope α (i.e., without superimposed ridges; Eq. 6, such that the shoreward depth at $x_1(t)$ remains equal to H_c . Ridge characteristics (heights, lengths and widths) are assumed constant. The position of tsr is assumed to be fixed in time. In the nearshore seaward part ($x_i < x < x_1(t)$), bed level $z_{b,e}$ retreats by Δx_1 , shifts upward by Δz_s , and steepens according to Eq. (9). Shoreline fixation at x_s is achieved through the upward translation of $z_{b,e}$ by Δz_s .

so in the limit $\Delta t \rightarrow 0$:

$$\left. \frac{\partial h}{\partial t} \right|_{\text{sfc}} = aR \left. \frac{\partial h}{\partial x} \right|_{\text{sfc}}. \quad (7)$$

In the nearshore domain (Figure 3-10, panel b), the initial bed level profile $z_b(x, t = 0)$, which is assumed to represent the initial equilibrium profile $z_{b,e}(x, t = 0)$, is chosen to be a Yu & Slinn (2003) profile:

$$z_b(x, t = 0) = z_{b,e}(x, t = 0) = -a_1 \left[1 - \frac{\beta_2}{\beta_1} \right] \tanh \left[\frac{\beta_1(x-x_s)}{a_1} \right] - \beta_2(x - x_s). \quad (8)$$

Here, a_1 , β_1 and β_2 are tuning parameters that are obtained by fitting the profile of Eq. (8) to the bathymetric profile of 1866.

A schematic illustration of changes in nearshore equilibrium bed level $z_{b,eq}$ under SLR and hold-the-line using nourishments coastal protection policy over a small time increment Δt is depicted in Figure 3-11 (panel c). A position $x - x_i$ inside this area is defined, where x_i separates the landward, gently sloping part of the equilibrium profile ($0 \leq x \leq x_i$) from the steeper seaward part ($x_i < x \leq x_1$). Location x_i is to be determined from field data. The steeper seaward part is obtained by shifting this part horizontally and vertically with Δx_1 and Δz_s , respectively. The landward part of the profile ($0 \leq x \leq x_i$) is shifted only vertically with Δz_s , thereby maintaining the profile shape of Eq. (8). Mathematically, this is expressed as follows

$$\frac{\partial z_{b,eq}}{\partial t} = \begin{cases} R, & 0 \leq x \leq x_i, \\ aR \frac{\partial z_{b,eq}}{\partial x} + R, & x_i < x \leq x_1. \end{cases} \quad (9)$$

In the seaward part ($x_i < x \leq x_1$), the landward and upward shift of the profile implies that deeper sections of the previous profile are assigned to more landward locations within the new profile (Figure 3-11, panel c). Together with the landward movement of the offshore boundary x_1 , this leads to a continuous steepening of the offshore part of the equilibrium profile over time. In the landward part of equilibrium profile ($0 \leq x \leq x_i$), the upward shift means that the total water depth remains unchanged, and that the position of the mean shoreline ($\langle x_s \rangle$) does not shift in response to changes in mean sea level, consistent with the hold-the-line measure. The sand required to achieve the vertical translation of the equilibrium bed level in the landward part is assumed to be supplied solely by nourishments.

To avoid a discontinuity in bed level and its slope at the interface between the onshore and offshore parts of the nearshore profile, a transition zone of width L_b is introduced,

$$x_i \leq x \leq x_i + L_b.$$

Within this transition zone, the equilibrium profile is constructed as a weighted average of the onshore and offshore mappings, using a smooth weighting function $w(\eta)$ defined by

$$w(\eta) = 3\eta^2 - 2\eta^3, \quad (10)$$

where the non-dimensional transition coordinate η is given by

$$\eta = \frac{x-x_i}{L_b}, \quad 0 \leq \eta \leq 1. \quad (11)$$

The weight function $w(\eta)$ satisfies $w(0) = 0$, $w(1) = 1$, and has zero slope at both endpoints of the transition zone, ensuring continuity of both the equilibrium bed level and its first derivative across this zone. In this way, artificial kinks in the equilibrium profile at the interface between the onshore and offshore regions are avoided.

3.1.2.4 Methodology

3.1.2.4.1 Model configuration

The model configuration of Section 3.1.1 is adopted here, but with the following changes. Shelf dimensions do not change in time, whereas the nearshore offshore extent (x_1) decreases in time according to Eqs. (4-5).

The bathymetric map of 1866 is now used to derive a representative bathymetry within the model. In the nearshore area, the tuning parameters in Eq. (8) are obtained by fitting this equation to the alongshore-averaged 1866 profile. Based on the work of Strypsteen et al. (2019), the dry beach has an initial width of 250 m ($x_s = 250$ m at $t = 0$, vertical dashed line in Figure 3-10, panel b), and rises landward to approximately $H_d = 4.5$ m at the dune foot ($x = 0$).

Besides tides and waves, the shelf model is also forced by sea level rise. To this end, a spatially uniform sea level rise according to Eq. (2) is imposed in both the shelf and nearshore domains, with different values of R considered. In addition to the M_2 component, the tidal forcing now includes the quarter diurnal lunar M_4 component, with amplitudes $\hat{\eta}_4 = 0.1$ m and phase differences $\Delta\psi_4 = 140^\circ$ between the lateral boundaries, $y = 0, y_L$.

3.1.2.4.2 Numerical experiments.

Table 3-3. Overview of numerical experiments.

Run	Description
Exp-SpinUp	Spin-up run without SLR and without nourishments.
Exp-Series	Four experiments with nourishments and different SLR rates: Exp1–1.5 mm/yr, Exp2–3.0 mm/yr, Exp3–5.0 mm/yr, and Exp4–8.0 mm/yr.

To quantify the impact of sea-level rise (SLR) and sand nourishments on the long-term shoreline evolution of an idealized coastal system, relative to a scenario without SLR and nourishments, four experiments are conducted (Table 3-3). In the first experiment ("Exp1-3.0mm/yr"), a rate of $R = 1.5$ mm/yr is applied, representing the observed rate along the Belgian coast during the 20th century (Fig. B1 in Appendix B). The second experiment ("Exp2-3 mm/yr") uses a rate of $R = 3$ mm/yr, representative of the SLR rate over the past 30–40 years. The remaining experiments ("Exp3-5.0mm/yr" and "Exp4-8.0mm/yr") correspond to two IPCC projection scenarios with SLR rates of 5.0 mm/yr and 8.0 mm/yr, respectively.

All experiments start from an initially developed shoreline position $x_s(y, t)$, obtained from an additional spin-up simulation ("Exp-SpinUp") without SLR or nourishments, in which the shoreline evolves freely. This spin-up run is initialized with a straight shoreline ($x_s = 250$ m). The simulated nearshore bathymetry and shoreline ($x_s(y, 50)$) after 50 years are subsequently used as initials conditions for the four experiments. In each experiment, a simulation period of 50 years is used, which is short relative to the timescale of ridge evolution (Dyer & Huntley, 1999), but long compared to that of shoreline undulations (van den Berg et al., 2012). All experiments are executed on a Linux-based Intel Xeon 2.80 GHz system, with an average runtime of approximately 10 days per simulation.

Hold-the-line by nourishments management is implemented by continuously monitoring the evolving shoreline position $x_s(y, t)$ and comparing it with the reference shoreline position $x_s(y, t = 50 \text{ yr})$ at the start of the simulations ($t = 50 \text{ yr}$) (i.e., after the 50-years spin-up run). At locations experiencing erosion, defined by $x_s(y, t) < x_s(y, 50 \text{ yr})$, the nearshore bed level z_b is artificially raised to match the equilibrium profile $z_{b,e}(x, t)$ in the onshore part of the nearshore domain. This adjustment is applied from the shoreline up to a seaward depth of -0.33 m (relative to MSL, equivalent to 2 m TAW), within the cross-shore range $0 \leq x \leq x_i$. In doing so, the local shoreline position is restored to its reference location $x_s(y, 50 \text{ yr})$. This bed level restoration mimics the way beach nourishments are being implemented along the Belgian coast. The model keeps track of the nourishment volume Q_s required to achieve these bed-level adjustments.

3.1.2.5 Results and discussion

3.1.2.5.1 Historical morphological evolution

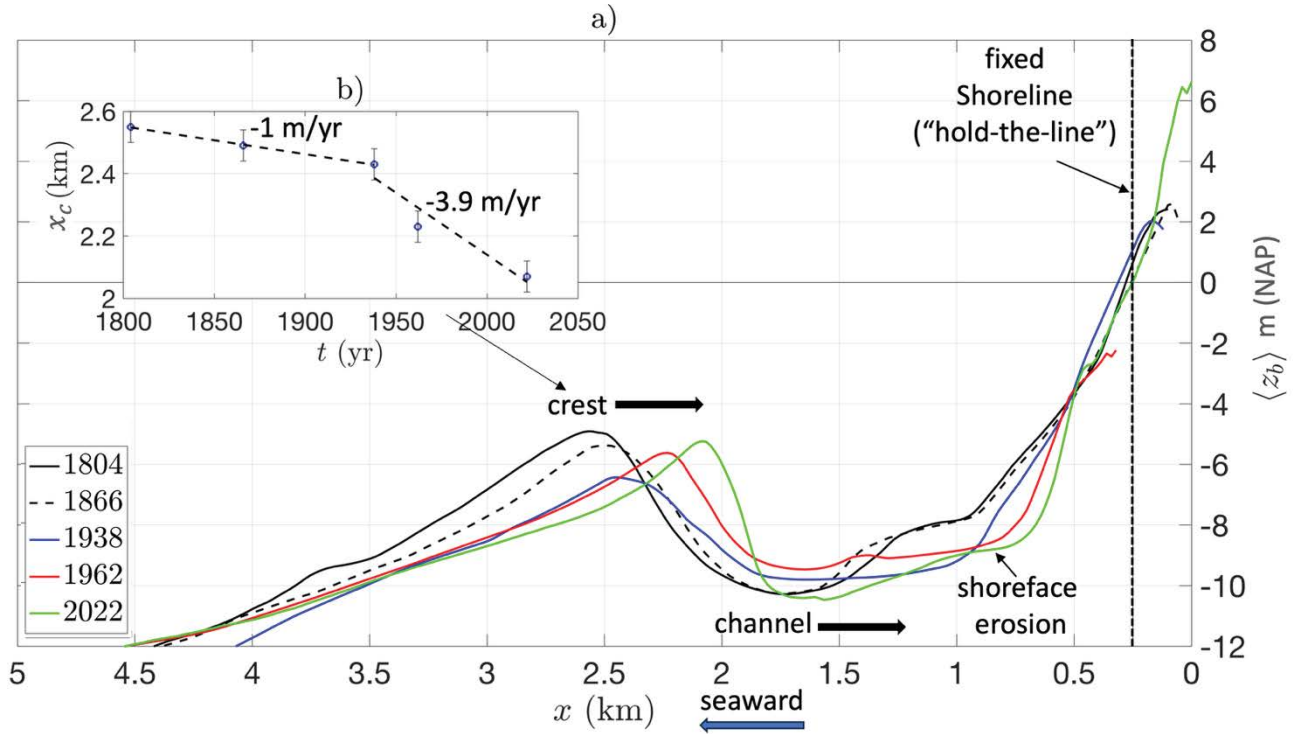


Figure 3-12. a) Historical evolution of alongshore-averaged cross-shore profiles in the coastal region of the "Stroombank" ridge (indicated by the black rectangle in Figure 3-9). The profiles are obtained by averaging 100 cross-shore profiles alongshore for the years 1804, 1866, 1938, 1962, and 2022. Here, z_b is the bed level relative to the 2022 vertical datum, defined as $z = 0$ m NAP (equivalent to MSL). The historical MSL curve between 1800 and 2022 presented in Appendix B (Figure B1) was used to correct for the differences in MSL among the different years. Coordinate x measures the offshore distance to a fixed horizontal point $x = 0$. b) Time evolution of the location of the ridge crest x_c of the "Stroombank" ridge

Longshore averaged bed level profiles for the years 1804, 1866, 1938, 1962, and 2022 are used to determine landward migration rates of sfcf in the coastal region of the "Stroombank" ridge (indicated by the black rectangle in Figure 3-9). The results of this analysis, presented in Figure 3-12, reveal major changes in the shelf and nearshore cross-shore profiles over the past two centuries (panel a). The ridge crest, adjacent channel and lower shoreface migrated shoreward at rates of about 1 m/yr during the 19th century, increasing to about 4 m/yr over the past 100 years (see also panel b). This onshore migration was accompanied by erosion of the lower shoreface and a landward retreat of the offshore nearshore profile at comparable rates. Together with hold-the-line management measures that maintain a fixed shoreline position through groynes and nourishments, this process has reduced the width of the nearshore zone and steepened its profile, a phenomenon referred to in this study as coastal squeeze.

Based on Figure 3-12 (panel b) and Fig. B1 of Appendix B, parameter a in Eq. (4) is estimated as $a = 1.27$ m/mm (see Figure 3-13, panel a). Here, it is assumed that in the absence of sea-level rise ($R = 0$), the migration rate is zero ($dx_c/dt = 0$). Furthermore, based on Figure 3-12 (panel a), location x_i between the landward and seaward parts of the nearshore area, marked by a change in bathymetric slope, is estimated to be about 500 m.

3.1.2.5.2 Initial bathymetry

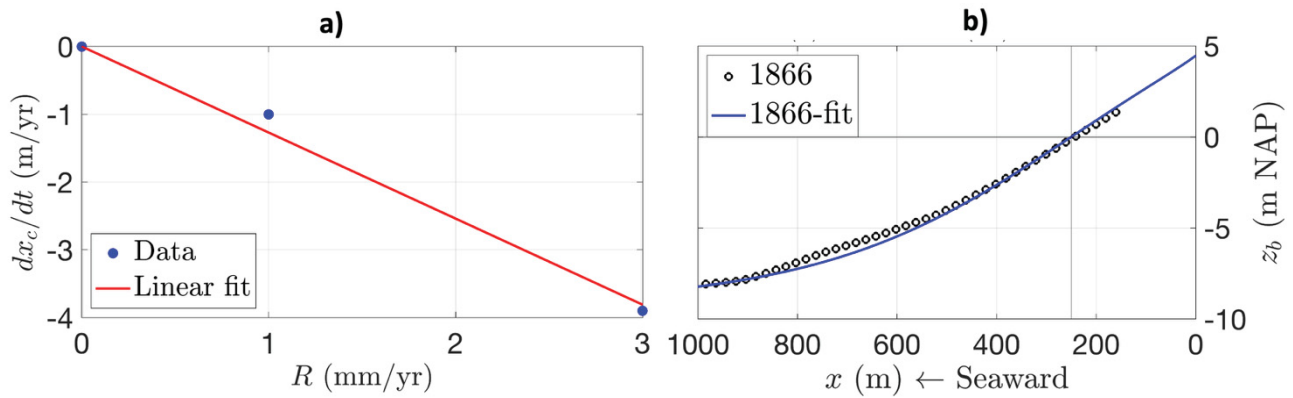


Figure 3-13. a) Ridge crest migration rate dx_c/dt (in m/yr) versus sea level rise rate R (in mm/yr). This plot is constructed from the mean sea-level curve shown in Fig. B1 of Appendix B, assuming that in the absence of sea-level rise ($R = 0$), the migration rate is zero ($dx_c/dt = 0$). b) The fit of the profile of Eq. (8) (blue line) to the alongshore-averaged cross-shore profile of 1866 (black circles).

The bathymetric map of 1866 in the area of the "Stroombank" ridge is used to derive a representative bathymetry within the model. In the nearshore area, this bathymetry is obtained by fitting Eq. (8) to the alongshore-averaged 1866 profile shown in Figure 3-12. Results from this fit, shown in Figure 3-13 (panel b), yield the following tuning parameters: $a_1 = 8.86$ m, $\beta_1 = 0.0181$, and $\beta_2 = 5 \times 10^{-4}$. The water depth at the nearshore-shelf transition ($x_1 = 1$ km) is $H_c = 8.2$ m.

In the shelf area, a representative mean bed level $\langle z_b \rangle$ (Eq. 6) is obtained by fitting linear profiles to 11 observed 1866 bathymetric profiles along cross-shore transects extending 50 km offshore and averaging the results. Here, depth H_c at the transition shelf-nearshore is fixed to $H_c = 8.2$ m. This fitting yields a mean shelf slope of $\alpha = -5.2 \times 10^{-4}$ and an offshore depth $H_o = 34.3$ m.

3.1.2.5.3 Spin up case

Model results from the spin-up experiment ("Exp-SpinUp") are displayed in (Figure 3-14). Panel (a) shows the initial shelf bathymetry (left) and nearshore bathymetry (right) used in the experiments, while panel (b) displays the simulated shoreline position x_s . The dashed and solid black lines show the initial ($t = 0$) and the shoreline position at $t = 50$ yr.

From this figure it is seen that with a free evolving shoreline, progradation occurs near the crests of the sfcr, while retreat is observed near the channels and to the north of the ridges. These patterns are supported by field observations of the Belgian coastal zone, where extensive dune development is found near three offshore located sfcr, indicating shoreline progradation at these locations. Further discussion is provided in Section (3.1.1).

As described in Section (3.1.1), the sfcr on the Belgian shelf act as a forcing template for the decadal evolution of the shoreline. This template is established through wave refraction over sfcr crests and channels between the ridges and the shoreline, as is illustrated in Figure 3-15. This creates gradients in wave energy density, which induce spatial variations in the longshore sediment transport in the nearshore zone. Consequently, shoreline progradation occurs in the proximity of crests of landward ends of the sfcr, while shoreline retreat appears adjacent to the channels in between the ridges.

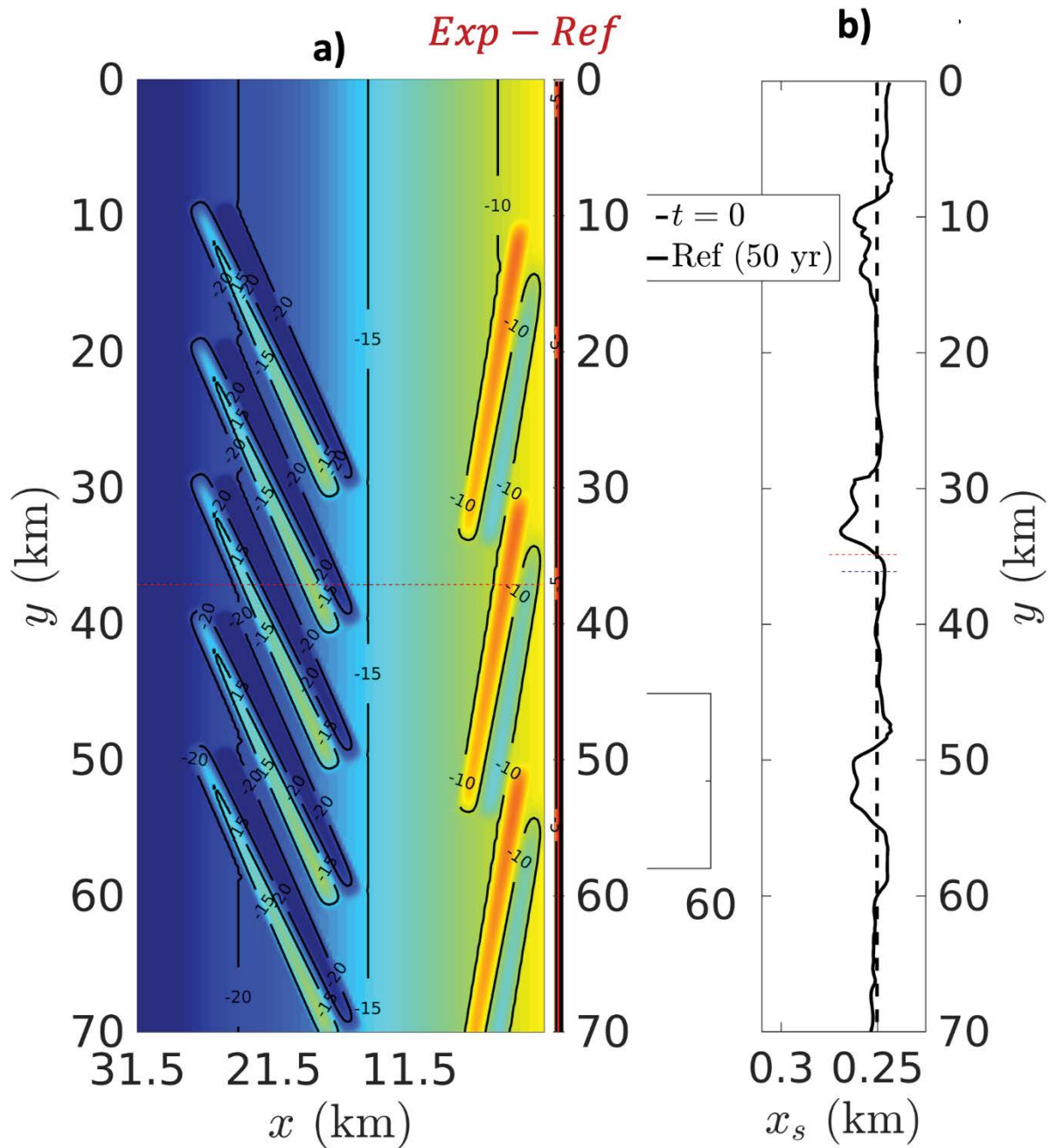


Figure 3-14. Results from "Exp-SpinUp" experiment. a) Initial bathymetry used in the experiments. b) Simulated shoreline position x_s at $t = 50$ yr in the spin-up experiment ("Exp-SpinUp"). The dashed and solid black lines show the initial ($t = 0$) and the shoreline position at $t = 50$ yr.

3.1.2.5.4 Effects of sea level rise and hold-the-line by nourishments

Rate $R = 1.5$ mm/yr

Snapshots of the shoreline evolution x_s for the case $R = 1.5$ mm/yr at $t = 60, 75$, and 100 years are presented in Figure 3-16a. Initially, shoreline progradation in the vicinity of the ridges increases over time, which is the result of the decreasing distance between the ridges to the shoreline as a result of the onshore migration of these ridges. This is also evident from panel (b), which shows the root-mean-square (rms) amplitude $\sigma_{x'_s}$ of shoreline progradation (defined as $x'_s = x_s - \langle x_s \rangle > 0$, where $\langle x_s \rangle$ represents the alongshore averaged profile, see also Section 3.1.1). The rms amplitude increases until approximately $t = 75$ years, after which it decreases.

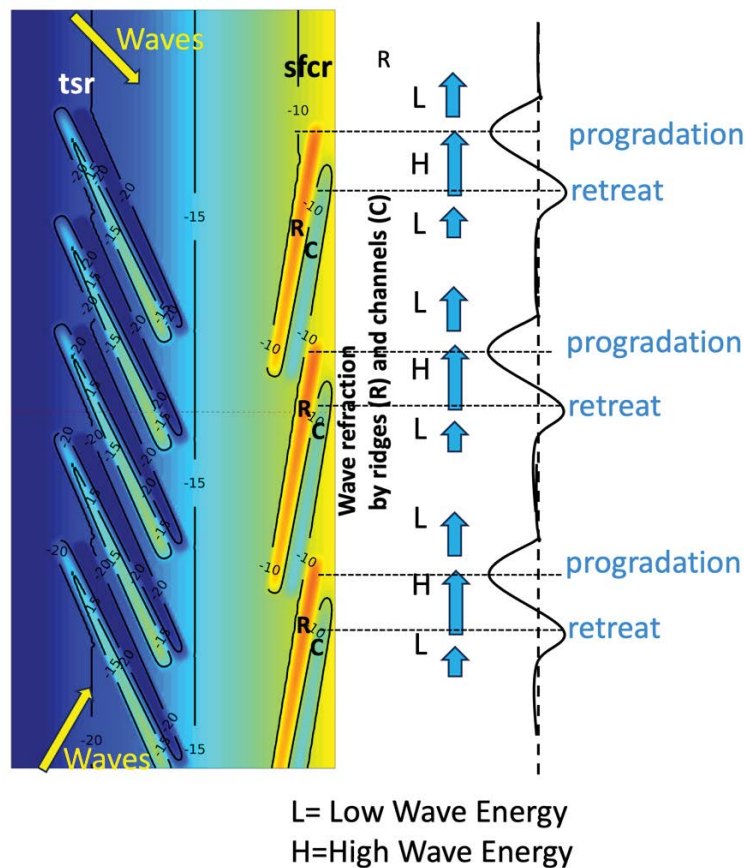


Figure 3-15. Schematic view of the forcing template in the coupled shelf-shoreline morphodynamic system: wave refraction over ridges (R) and channels (C) produces alternating high- (H) and low-energy (L) zones, driving alongshore variations in sediment transport and causing shoreline progradation (retreat) near landwards ends of ridges (channels)

From the rightmost snapshot in panel (a) of this figure, it appears that the entire shoreline tends to retreat over time and is continuously restored to the $t = 50$ year profile to implement the hold-the-line strategy. Note that, due to discretization effects, the profile can only be maintained at the $t = 50$ year shape within the accuracy of the grid resolution (15 m).

The initial growth of shoreline progradation and its decay over longer time scales can also be seen from Figure 3-17, which shows that most nourishments are initially applied near the channels and to the north of the ridges. Over time, however, the entire beach requires nourishment to maintain the hold-the-line shoreline position (panels b-c). Panel (d), which displays the annual nourishment volumes over time, indicates that the nearshore profile requires about 10 years to adjust to the imposed SLR rate. During this adjustment period, only limited nourishment is required.

After this initial phase, however, the nourishment demand increases steadily, occasionally showing a weak tendency towards saturation. By the end of the simulation ($t = 100$ years), the required annual nourishment volume reaches approximately $Q_s = 6.0 \times 10^5 \text{ m}^3/\text{yr}$

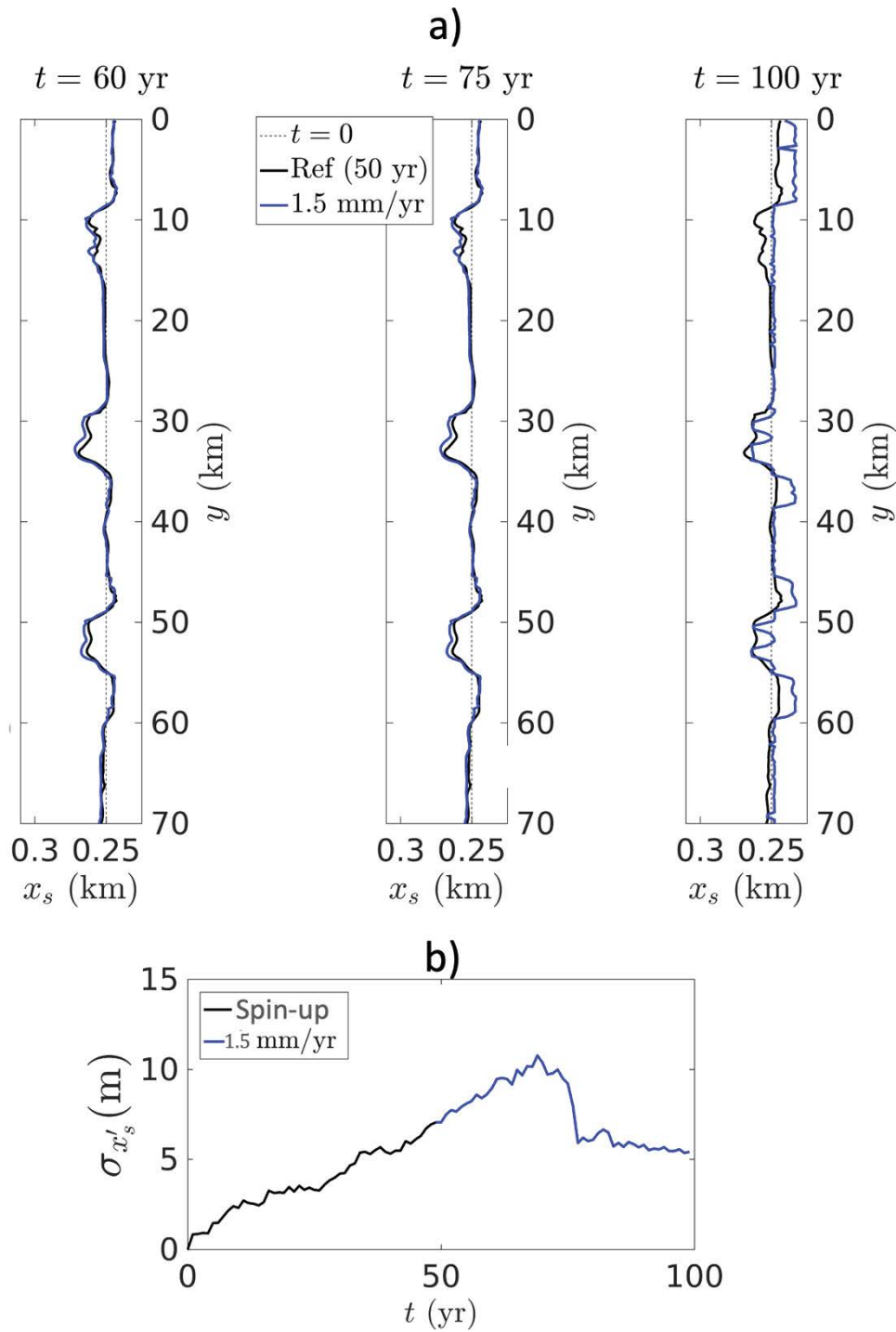


Figure 3-16 a) Results from run “Exp1–1.5 mm/yr”. Simulated shoreline profiles in the case of $R = 1.5$ mm/yr (blue lines) at $t = 60$ yr, 75 yr and 100 yr. Black lines represent the initial profile ($t = 50$ yr) used to start this experiment. Note that, because of discretization effects, the ($t = 50$)-year profile can only be preserved to within the grid resolution (15 m). Consequently, the blue profile does not perfectly coincide with the initial profile. b) the root-mean-square (rms) amplitude $\sigma_{x'_s}$ of shoreline progradation (defined as $x'_s = x_s - \langle x_s \rangle > 0$) versus time in the “Exp1–1.5 mm/yr” case (blue line). Here, $\langle x_s \rangle$ represents the alongshore averaged shoreline profile. The black line shows the rms amplitude $\sigma_{x'_s}$ of the spin-up experiment.

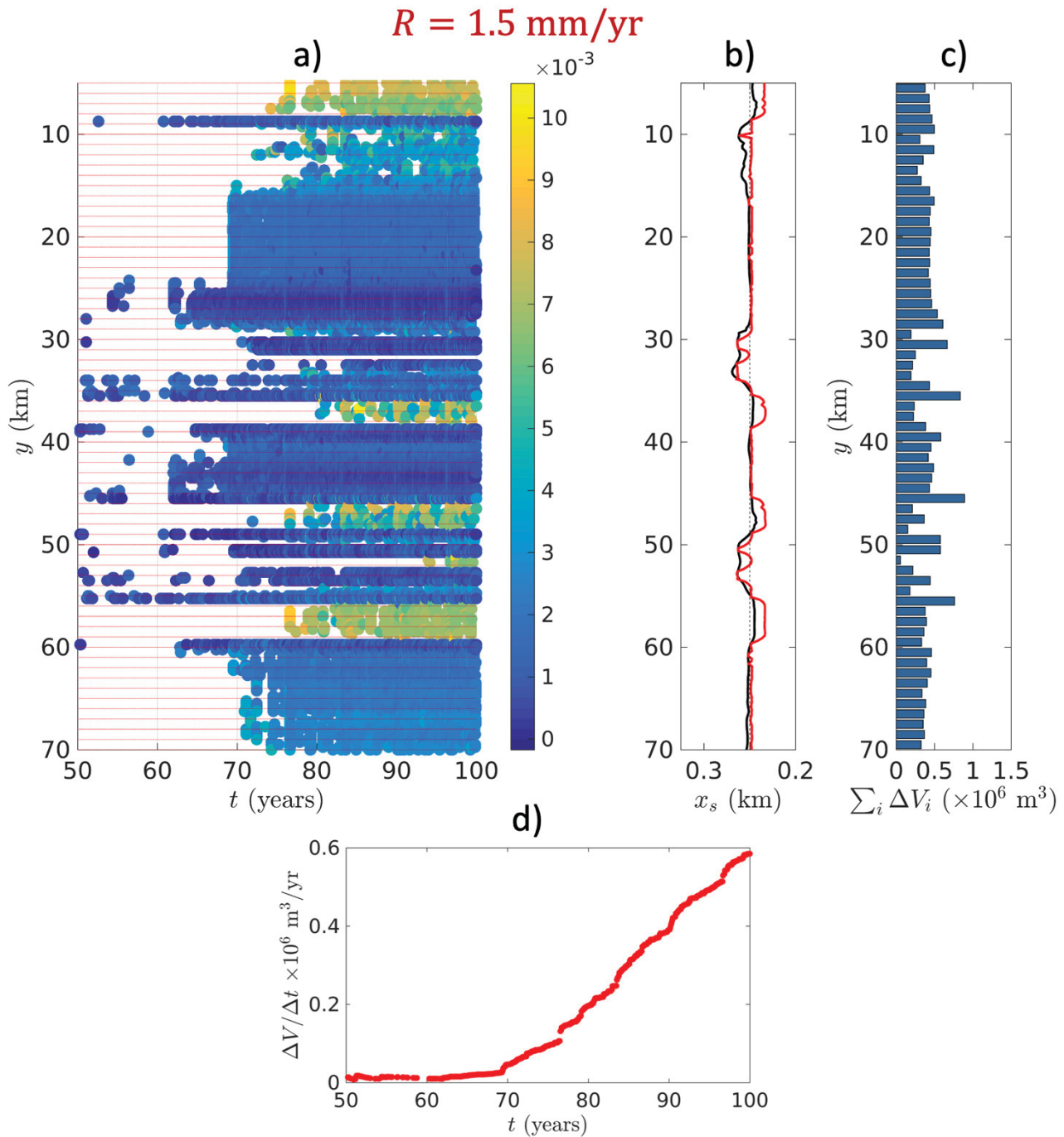


Figure 3-17. Results from run “Exp1–1.5 mm/yr”. a) Time evolution of the alongshore distribution of nourishment volumes (in 10^6 m^3). Alongshore profile at $t = 100$ yr is also depicted (red line in panel b). c) Alongshore distribution of the total nourishment volumes (in 10^6 m^3) during the entire simulation period (50 yr). d) Annual nourishment volumes (in $10^6 \text{ m}^3/\text{yr}$) versus time.

Other rates R

Results for higher rates of SLR R are presented in Figure 3-18a, which show the time evolution of the root-mean-square (rms) amplitude $\sigma_{x'_s}$ of shoreline progradation. This figure reveals that progradation near the ridge crests initially becomes stronger as R increases. This results from a greater reduction in the distance between the shoreline and the sfc, caused by enhanced onshore migration of the ridges (dx_c/dt , Eq. 4) at higher rates of sea-level rise. However, the subsequent decay of the shoreline progradation area also

becomes stronger with increasing R . The stronger shoreline erosion with increasing R , and the more nourishment demands needed to maintain hold-the-line shoreline positions, is also reflected in the annual nourishment volumes curves displayed in Figure 3-19 (panel a). Furthermore, from panel c, which displays the maximum annual nourishment volumes $Q_{s,max}$ during the simulation period versus rate R (red dots), it is seen that, relative to the reported sea-level rise rate over the last century (≈ 1.5 mm/yr, see Appendix B), $Q_{s,max}$ becomes a factor of about 2.5, 3.3 and 4.1 for rates $R = 3, 5$ and 8 mm/yr, respectively. Note that, due to the large retreat of the shoreface in the cases of $R = 5$ and 8 mm/yr, the seaward part of the nearshore area becomes so steep that model instabilities start to occur, leading eventually to model blow-up.

To quantify the relative impact of nearshore profile steepening and retreat (i.e., width reduction) of the nearshore zone, additional experiments were conducted without these processes. Consequently, in the latter experiments, both the nearshore equilibrium profile and the width of the nearshore zone remain constant throughout the simulation. As in the experiments with full coastal squeeze enabled, the evolving profile is continuously monitored and, if necessary, restored to its initial 50-year configuration. Results are presented in Figure 3-18 (panel b), which shows the rms amplitude $\sigma_{x'_s}$ for the case without nearshore steepening and retreat. These results indicate that shoreline progradation continues to increase throughout the simulation period, although with a tendency toward saturation near the end. These outcomes demonstrate that nearshore steepening and retreat enhance shoreline erosion. The effects of these two processes are further illustrated in Figure 3-19, which shows that the annual nourishment volumes required to maintain the hold-the-line measure increase strongly with the SLR rate R (panel a), without any sign of saturation. In contrast, saturation is reached in the case without nearshore steepening and retreat (panel b). In this case, the required annual nourishment volumes are comparable to those predicted by a Bruun-type response, in which the nearshore profile is translated upward by an amount Rt . The corresponding annual nourishment volume can be approximated as $Q_s = x_L y_L R$.

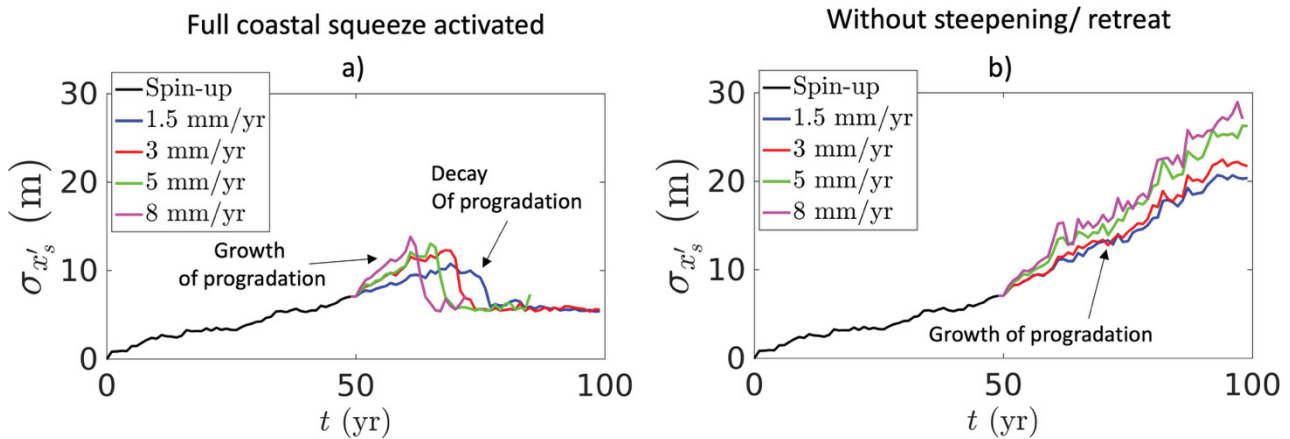


Figure 3-18 Results from all experiments "Exp1–1.5 mm/yr", "Exp2–3 mm/yr", "Exp3–5 mm/yr" and "Exp4–8 mm/yr". a) Time evolution of the root-mean-square (rms) amplitude $\sigma_{x'_s}$ of shoreline progradation for different rates R of sea level rise. Same as panel (a), but for the case without steepening of the nearshore profile and retreat of the nearshore zone.

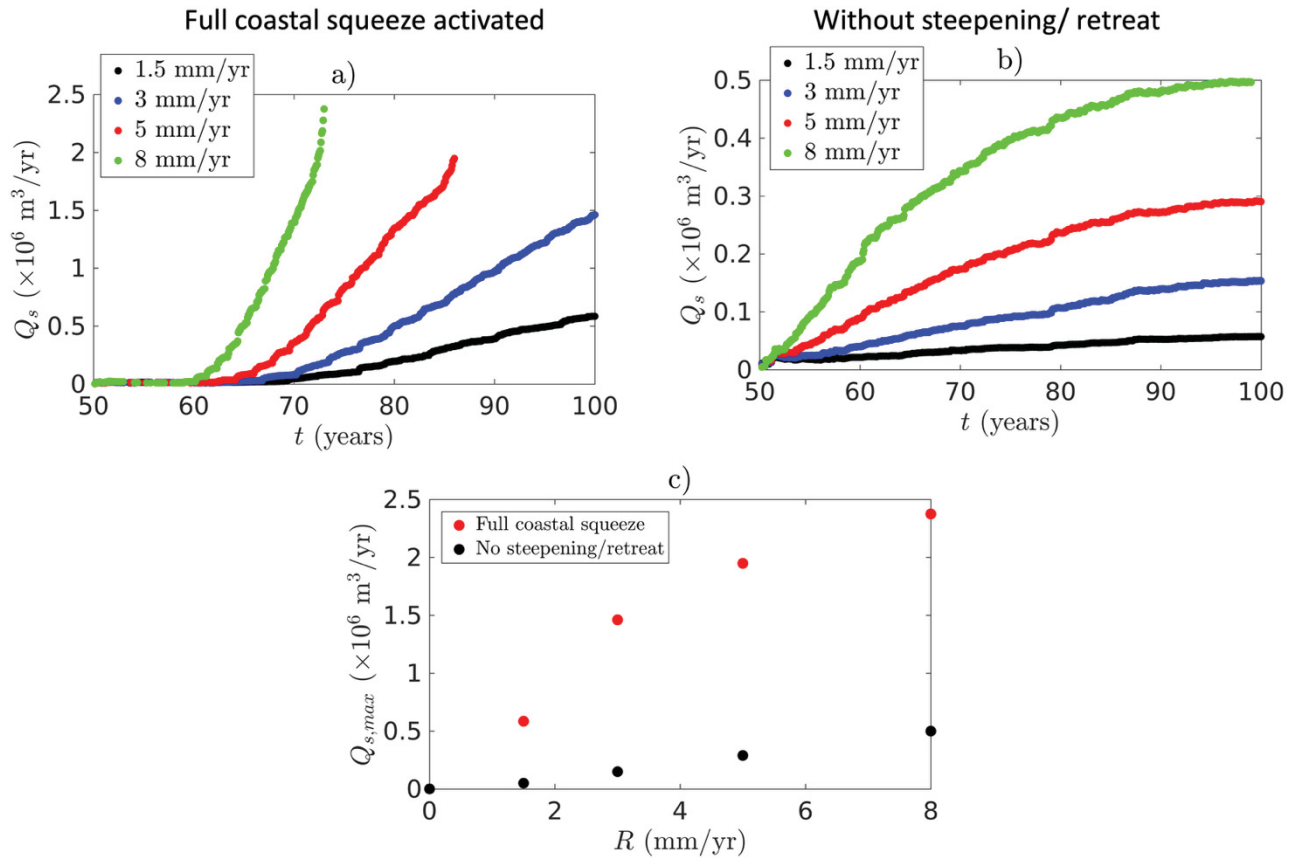


Figure 3-19 a-b) Time evolution of the annual nourishment volumes (in 10^6 m³) for different rates R of sea level rise in the cases with (a) and without (b) profile steepening and retreat of the offshore nearshore boundary. C) Maximum nourishment volumes during the simulation period versus rate R in the two cases.

To quantify the sensitivity of model results to some of the model parameters, additional experiments were conducted for different values of ν_b , μ and parameter a in Eq. (4). Coefficients of ν_b and μ control the magnitude of cross-shore and alongshore sediment transport, respectively. The used sea level rise rates $R = 1$ and 5 mm/yr. Figure 3-20, which shows the results with different values of ν_b and μ for $R = 5$ mm/yr, reveals that the required nourishment volumes to maintain the hold-the-line shoreline position are related with cross-sediment transport (panel a). The larger ν_b , the larger Q_s . Alongshore sediment transport hardly affects model results (panel b). Figure 3-21 compares the annual nourishment volumes for different parameters a in Eq. 4 and different parameters ν_b , for rates $R = 1$ and 5 mm/yr. This figure demonstrate that, relative to the default parameters values used in this study, the ratio in Q_s between the two SLR rates do not change significantly when a smaller a or larger ν_b is used.

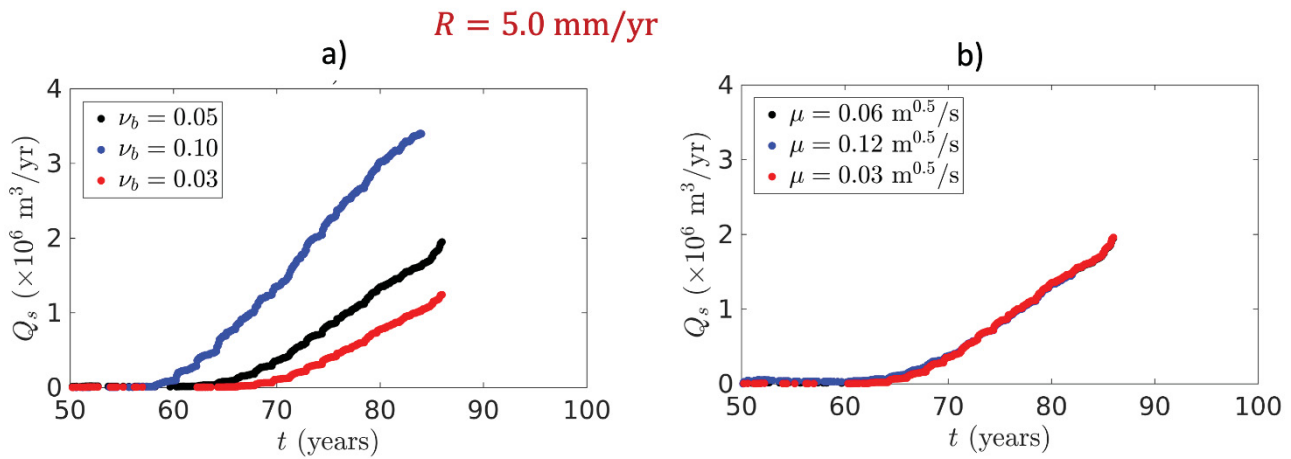


Figure 3-20 Results from the additional experiments for rate $R = 5 \text{ mm/yr}$. a-b) Time evolution of the annual nourishment volumes (in 10^6 m^3) larger and smaller values of ν_b (a) and μ (b), which control the magnitude of cross-shore and alongshore sediment transport, respectively.

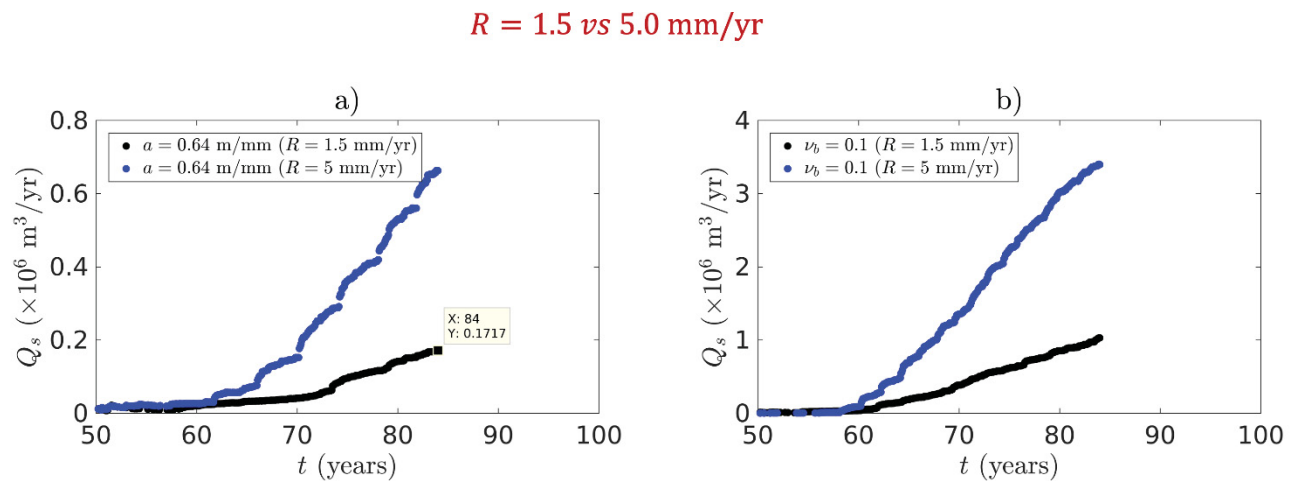


Figure 3-21. Results from the additional experiments for different parameters a in Eq. 4 (a) and different parameters ν_b for $R = 1.5 \text{ mm/yr}$ (black) and 5 mm/yr (blue).

3.1.2.6 Conclusions and outlook

Historical bathymetric analyses of the Belgian coast reveal a persistent onshore migration of ridge crests, adjacent channels, and the lower shoreface, with migration rates over the past 100 years exceeding those observed during the 19th century. This migration, combined with hold-the-line coastal management through beach nourishment, has led to a narrowing of the nearshore zone and a consequent steepening of the coastal profile, referred to as coastal squeeze.

Based on model results, the following new insights are obtained regarding effects of sea level rise on decadal shoreline morphodynamics. Two competing mechanisms appear to govern shoreline evolution under SLR and the hold-the-line strategy in the vicinity of ridges. On the one hand, the onshore migrating ridge caused by SLR promotes shoreline progradation. On the other hand, coastal squeeze (shoreface retreat and profile steepening) counteracts this progradation. Over time, coastal squeeze becomes the dominant mechanism, leading to the disappearance of shoreline progradation, particularly for higher rates of SLR. Near channels,

shoreline erosion increases due to both the onshore migrating channels and coastal squeeze, requiring more nourishment than in cases without coastal squeeze. This decay in progradation and increase in erosion seem to be caused by increased offshore-directed sediment transport, caused by narrower and steeper nearshore profiles.

Compared with the reported sea-level rise rate over the last century (≈ 1.5 mm/yr), model results indicate that the future annual nourishment volumes needed to maintain the hold-the-line shoreline position under higher rates of sea level rise may increase by a factor of approximately 2-5 in areas where coastline erosion is determined by the channel-ridge morphology.

Significant progress has been made with the development of the present model to assess the effects of future sea-level rise and the hold-the-line strategy on shoreline position and the associated nourishment intensities. However, it is important to emphasize that the results should be interpreted qualitatively rather than as precise quantitative predictions. More reliable projections will require improvements in the following areas:

- The representation of coastal squeeze along the Belgian coast. In the present study, this process is based on the Stroombank area and assumed to be representative of the entire Belgian coastline, which in reality includes many human constructions such as groynes and harbours.
- Refinement of model parameters and the underlying assumptions in the coastal squeeze model.
- Improvement of the nearshore model to account for morphological interactions with dunes, which are not included in the present model.

3.2 Shelf morphodynamic evolution on centennial times scales using an idealized morphodynamic shelf model

The shelf model in the coupled shelf–shoreline modelling system described in Section 3.1.2 was quasi-morphostatic. Apart from the prescribed onshore migration of the synthetic sfc, the shelf bathymetry, including the tsr, was kept fixed throughout the simulations. This simplified treatment was adopted because the coupled shelf–shoreline model is not (yet) capable of simulating the self-organized development and evolution of sfc and tsr. Consequently, the imposed sfc migration represented an external forcing rather than a morphodynamic response of the shelf system. The assumption of a quasi-morphostatic shelf model implies a one-way coupling between the shelf and nearshore models, meaning that the shelf morphology influences the bed level of the nearshore and its shoreline, but not the other way around. The amplitudes of shoreline undulations were found to be typically of order 10 to 100 meters, which were much smaller than the width of the nearshore zone (1 km). For these small amplitudes, the one-way approach is considered reasonable. However, in the "Onshore-2" case, where the amplitude of shoreline undulations reached up to 250 m, the validity of the assumption of a morphostatic shelf becomes questionable. In that case, a morphodynamic shelf model where self-developing tsr and sfc occur would be necessary to account for the impact of shoreline changes on the shelf evolution. In Section 3.2 such a morphodynamic shelf model is developed. This model will account for waves, wind and tides.

3.2.1.1 Model description

The morphostatic shelf model used in Section 3.1 is extended into a morphodynamic version by incorporating sediment transport and bed level update. The shelf model assumes a rectangular shelf with dimensions $L_x \times L_y$, where the x and y represent the cross- and alongshore directions, respectively (Figure 3-22a).

Coordinate z denotes a vertical position, while $z_b(x, y, t)$ (defined with respect to the undisturbed water level $z = 0$) marks the position of the bed level, positive upward. Perturbations in bed-level $z_b(x, y, t)$ with respect to its initial value ($z_b(x, y, 0)$) are represented by h (positive upward), i.e., $h(x, y, t) = z_b(x, y, t) - z_b(x, y, 0)$.

Sediment transport, assumed to be non-cohesive and characterized by a spatially uniform d_{50} , is calculated according to the formulations of Van Rijn (1993). These formulations included both bedload and suspended load transport under the joint action of waves and currents. The time evolution of the shelf bed level ($\partial z_b / \partial t$) is determined by the net exchange of sediment between the water column and the bed, as well as the spatial gradients in the bedload sediment transport vector $\vec{q}_b$. Further details are available in Appendix A.

A view of the structure of the new morphodynamic shelf model is depicted in Figure 3-22b. Waves exert a shear stress at the bottom, thereby eroding sediments from this bottom. Subsequently, these sediments are transported by current $\vec{v}$, which is induced by wind and tide. The divergence or convergence of sediment transport $\vec{q}_{tot}$ determines changes in bed-level z_b , which influence the current and the waves. Waves affect also the currents and vice versa. At the offshore boundary, obliquely incoming waves and a wind forcing pointing in the negative y -direction are prescribed. The waves are characterized by a significant wave height H_{s0} , angle of wave incidence θ_0 (with respect to the negative x -axis, positive counterclockwise) and peak period T_{p0} . These waves are assumed to have a JONSWAN shape.

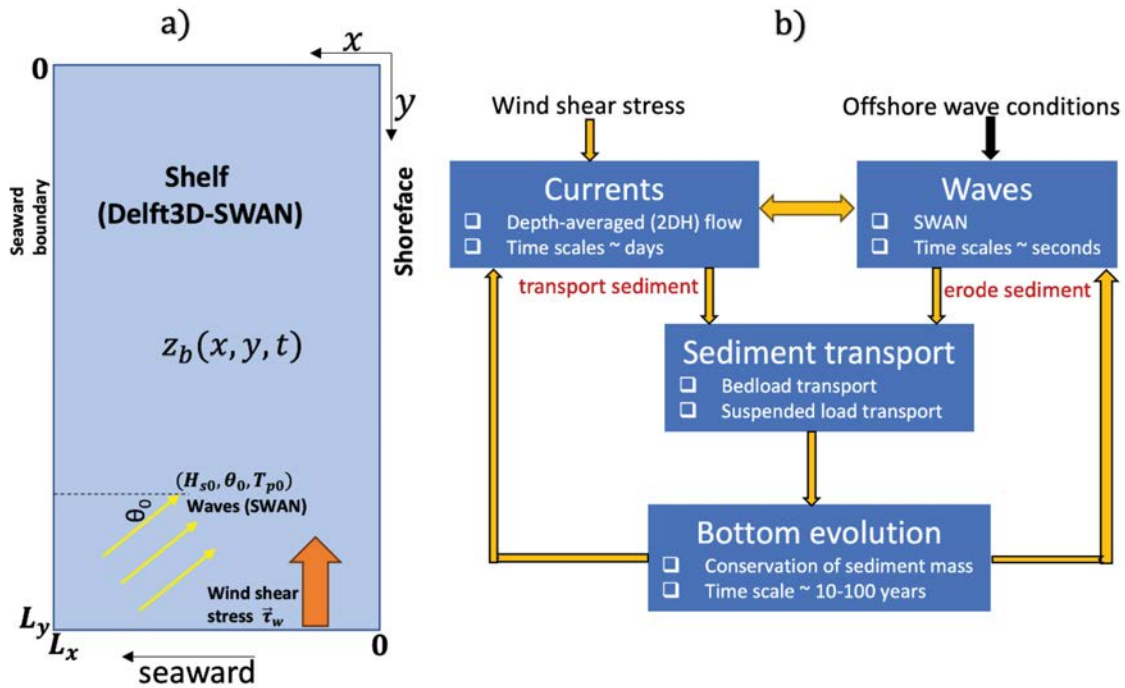


Figure 3-22 – Schematisation of the morphodynamic shelf model. a) Top view of the rectangular model domain, with dimensions $L_x \times L_y$, where the x and y represent the cross- and alongshore directions, respectively. The model, comprising of a coupled Delft3D-SWAN modelling system, is driven by time-varying wave and wind forcings. Currents and sediment transport and resulting bed level changes are simulated using Delft3D, while waves are computed using SWAN. Waves are characterized by a time-varying significant wave height $H_{s0}(t)$, angle of wave incidence $\theta_0(t)$ (with respect to the negative x -axis, positive counter-clockwise), and peak period T_{p0} . These waves are assumed to have a JONSWAP shape. Wind forcing is represented by a time-varying wind stress $\vec{\tau}_w$ directed alongshore the negative y -axis. b) Structure of the morphodynamic shelf model: Waves erode sediment from the seabed, which is subsequently transported by wind-induced currents. Divergence or convergence of sediment transport leads to bed level changes, which, in turn, influence both currents and waves. Additionally, waves affect currents and vice versa, creating a dynamic feedback loop.

3.2.1.2 Methodology

The morphodynamic shelf model has the same dimensions as the morphostatic shelf model in the coupled shelf-shoreline modelling system. Tidal forcing, comprising M_2 and M_4 components, are prescribed at the seaward boundary ($x = x_L$). Amplitudes and phases of these components are derived from the harmonic analysis described in Section 3.1). Specifically, at the southern boundary ($y = 0$), the M_2 and M_4 tidal components have amplitudes $\hat{\eta}_2 = 1.67$ m and $\hat{\eta}_4 = 0.1$ m, with phase differences of $\phi_2 = 73^\circ$ and $\phi_2 = 94^\circ$. At the northern boundary (y_L), the amplitudes remain the same, but the phase differences are $\phi_2 = 96^\circ$ and $\phi_2 = 187^\circ$. This prescribed tidal forcing simulates a tidal wave moving in the negative y -direction. As a first step, southwesterly stormy waves are considered, which are assumed to remain constant during the model simulations, with $H_s = 3.5$ m, $T_p = 11$ s and $\phi_w = 110^\circ$. A wind forcing is prescribed, having the a time-varying wind velocity. Since wind blows predominantly from the southwest (almost parallel to the Belgian shoreline), the wind forcing imposed in the model is directed in the negative y -axis (Figure 3-22a).

To address the first objective within Activity 2, two experiments are carried out: one with a constant wind velocity of $V_w = 20$ m/s (experiment "Reference", Table 3-4) and another with a time-varying wind velocity ("Time-varying wind"). In both experiments, the waves, with $H_s = 3.5$ m, $T_p = 11$ s and $\phi_w = 110^\circ$, represent stormy conditions. For the second objective, which examines the effects of tides on ridge evolution on the shelf, two additional experiments are conducted: "OnlyTide" and "TideWavesWind". In "OnlyTide", the model is forced with tides only (M_2 and M_4), excluding waves and wind. In "TideWavesWind", the model forcing is similar to that in the "Time-varying wind" experiment, with the difference that tides are included in the model forcing

The simulations start from small-scale random bottom perturbations (with a root-mean square height of 10 cm) superimposed on the bathymetry. The principle is that these perturbations contain all kinds of patterns with different length scales. The formation mechanisms of (sfc) and (tsr) will subsequently cause the bottom pattern that initially has the fastest growth rates to dominate after some time. After that stage, when ridges have attained considerable height, they will nonlinearly interact with each other and typically saturated towards finite heights. To reduce computation time, a morphological amplification factor of 400 is used. This is justified because the morphodynamic timescale is much longer (order of years) than the hydrodynamic timescale (order of hours to days). Test experiments confirm that using smaller amplification factors does not alter the model outcomes. Experiments were conducted for a maximum duration of 2000 years. The characteristics of the simulated bedforms are analysed in terms of their average height H_{av} (crest-to-trough distance), global migration speed V_m and their longshore dominant spacing λ . Migration V_m and spacing λ (i.e., alongshore crest-to-crest distance) are defined as follows:

$$V_m = - \frac{1}{\left(\frac{\partial h}{\partial y}\right)^2} \frac{\partial h}{\partial y} \frac{\partial h}{\partial t}. \quad (5)$$

In these expressions, the overbar indicates averaging over the entire model domain, i.e.,

$$\frac{1}{L_x L_y} \int_0^{L_y} \int_0^{L_x} dx dy.$$

The longshore dominant spacing of the sand ridges (λ_d) is computed using the discrete Fourier transform of the bottom perturbations h at the longshore section $x = 2.2$ km. This dominant spacing is defined as the longshore spacing between ridges for which the modulus of the Fourier coefficients is maximum:

$$F(x_t, k_l, t) = \sum_{j=1}^{N_y} h(x_t, y_j) e^{-i \frac{2\pi}{N_y} (j-1)(l-1)}, k_l = \frac{2\pi(l-1)}{L_y}, l = 1:N_y, y_j = j\Delta y. \quad (6)$$

Here, $F(x_t, k_l, t)$ is the Fourier coefficient that corresponds to the topographic wavenumber k_l and N_y is the number of grid points in the longshore direction (y). The wavenumber for which the modulus of the Fourier coefficient ($|F(x_t, k_l, t)|$) is maximum for a given time t and longshore position x_t defines the dominant mode, which is used to compute the longshore dominant spacing λ_d .

Table 3-4 – List of model experiments conducted within Activity 2.

Name experiments	Description
"Reference"	Reference experiment: Constant waves and wind (stormy conditions), no tide.
"Time-varying wind"	Constant (stormy) waves and time-varying wind velocity, no tide.
"OnlyTide"	Only tides (M_2 and M_4), no waves and wind.
"TideWavesWind"	Tides (M_2 and M_4), constant (stormy) waves and time-varying wind velocity.

3.2.1.3 Results and discussion

3.2.1.3.1 Reference case: only waves and wind

Figure 3-23 (panel a) shows snapshots of the simulated bed level z_b at different points in times ($t = 0$ yr, $t = 50$ yr, $t = 100$ yr and $t = 175$ yr) in the case that only waves and wind are considered ("Reference" experiment). These snapshots illustrate the evolution of randomly imposed bottom perturbations on the initial bathymetry over time, which evolve into large-scale, elongated, and oblique ridges on the shelf. Initially, a mode scale selection process takes place, where the bottom mode with the most-preferred topographic wavelength (alongshore spacing) grows over time, while other modes decay. Over time, coast-oblique ridges resembling shoreface-connected sand ridges (sfcr) manifest on the shelf, maintaining a connection to the shoreface. These sfcr originate close to the shoreface and gradually extend offshore. Eventually, these sfcr exhibit widths of approximately 5 km, with lengths spanning between 15 and 25 km (panel b). From Figure 3-23c and Figure 3-24, it is seen that 1) the sfcr attain heights of about 5 m over time (panel a), 2) they migrate downstream (negative y direction) at rates V_m of roughly -55 myr^{-1} , as a result of the storm-driven currents (Figure 3-24, panel b), and 3) they have alongshore spacings of roughly ~ 12 km (panel c). Initially, ridge height grows exponentially, eventually saturating towards the end of the simulation period (panel a).

Furthermore, Figure 3-24 (panel d), which displays the time evolution of the bed level along the alongshore transect depicted in panel b of Figure 3-23 (red dashed line), reveals that as the ridges develop on the shelf, smaller ridges gradually merge into larger-scale bedforms with larger alongshore spacings.

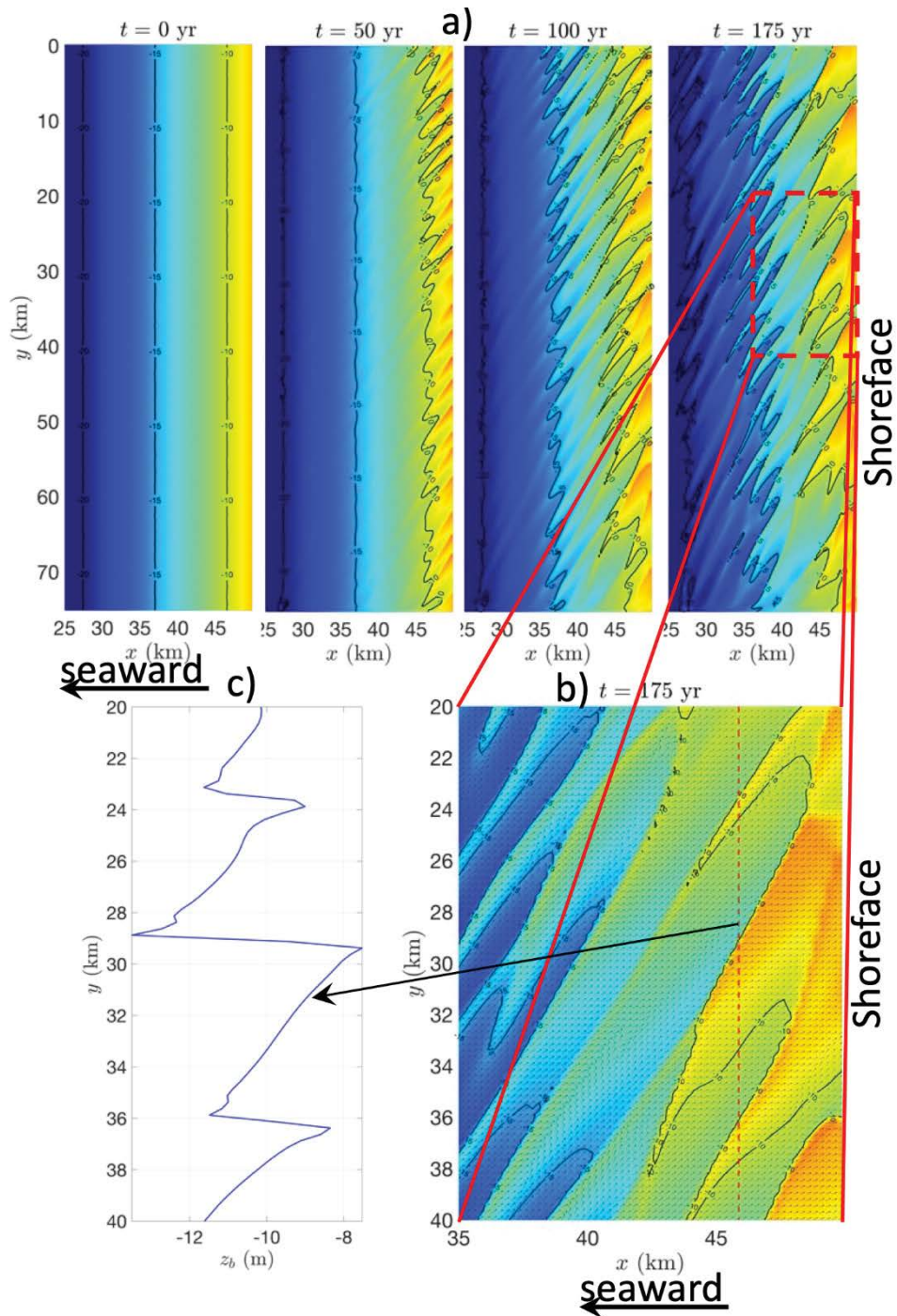


Figure 3-23 – Morphodynamic shelf model results. a) Snapshots of the simulated bed level z_b at times $t = 0$ yr, $t = 50$ yr, $t = 100$ yr and $t = 175$ yr. A zoom-in at $t = 175$ yr is displayed in panel b, while panel c shows the bed level profile along the alongshore transect depicted in panel b (dashed red line).

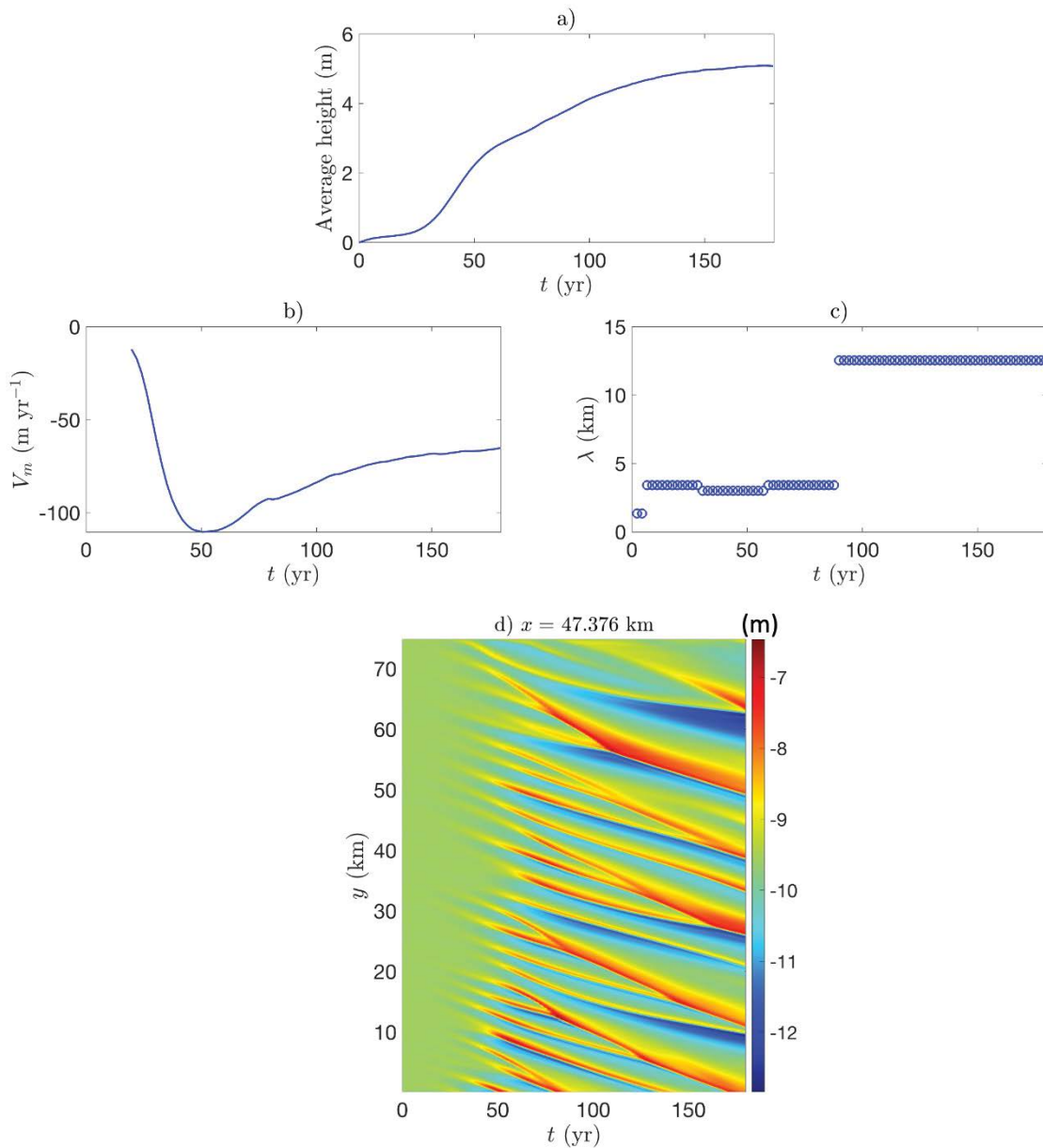


Figure 3-24 – Average height of the ridges H_{av} (a), their migration speed V_m (b) and their dominant longshore spacings λ_b versus time.

The height, dimensions (width and length) and alongshore spacing of the simulated sfcf described above are similar to those observed on the Belgian shelf (Section 3.1.2, see also Chapter 2). However, a notable difference is that the observed ridges on the Belgian shelf are more oblique than the simulated ones. This discrepancy in ridge orientation may arise from the absence of tides and the use of constant wave and wind forcing in this experiment. Another notable difference is the migration rate of the ridges: the simulated ridges migrate significantly faster than the observed ones, which migrate at approximately 10 to 20 m/yr alongshore in the northeastern direction (Chapter 2). This discrepancy is attributed to imposing continuous stormy conditions in the "Reference" experiment, whereas in reality, the wind climate alternates between fair and stormy conditions. When a time-varying wind velocity and direction that alternate between these conditions is prescribed, as is the case in the "Time-varying wind" experiment, the (average) migration rate is reduced by a factor of ~ 2 , as shown in Figure 3-25 (panel c). Note the fluctuating migration rate between larger and smaller values,

reflecting the time-varying wind velocity. Figure 3-25 further demonstrates that incorporating a time-varying wind velocity significantly reduces the growth rate of the ridges (panels a and b). The use of a time-varying wave climate is expected to further reduce the growth and migration rates of the ridges, which is a topic of future research.

Finally, we would like to highlight an important novelty of this study: for the first time, a morphodynamic model is established in which sfc develop on the shelf in the case of using a sediment formulation other than the traditional formulations employed in previous models (see the review by Ribas et al., 2015). Specifically, this study uses the formulations of Van Rijn (1993) (see Appendix D), in contrast to the widely used Bailard (1981) sediment formulations. Results from additional experiments (not shown) show that, besides the Van Rijn (1993) formulations, sfc also develop when using other transport formulations, such as the Soulsby-van Rijn (Soulsby 1997) and Van Rijn (2007) formulations. Thus, the occurrence of sfc on the shelf is not limited by the type of sediment transport formulation employed in the model, unlike in previous studies (Calvete et al. 2001; Vis-Star et al., 2007; Nnafie et al. 2014). The reason why sfc develop on the shelf irrespective of the type of transport formulation used is believed to lie in the use of SWAN (for the first time!) to model waves in the morphodynamic shelf model.

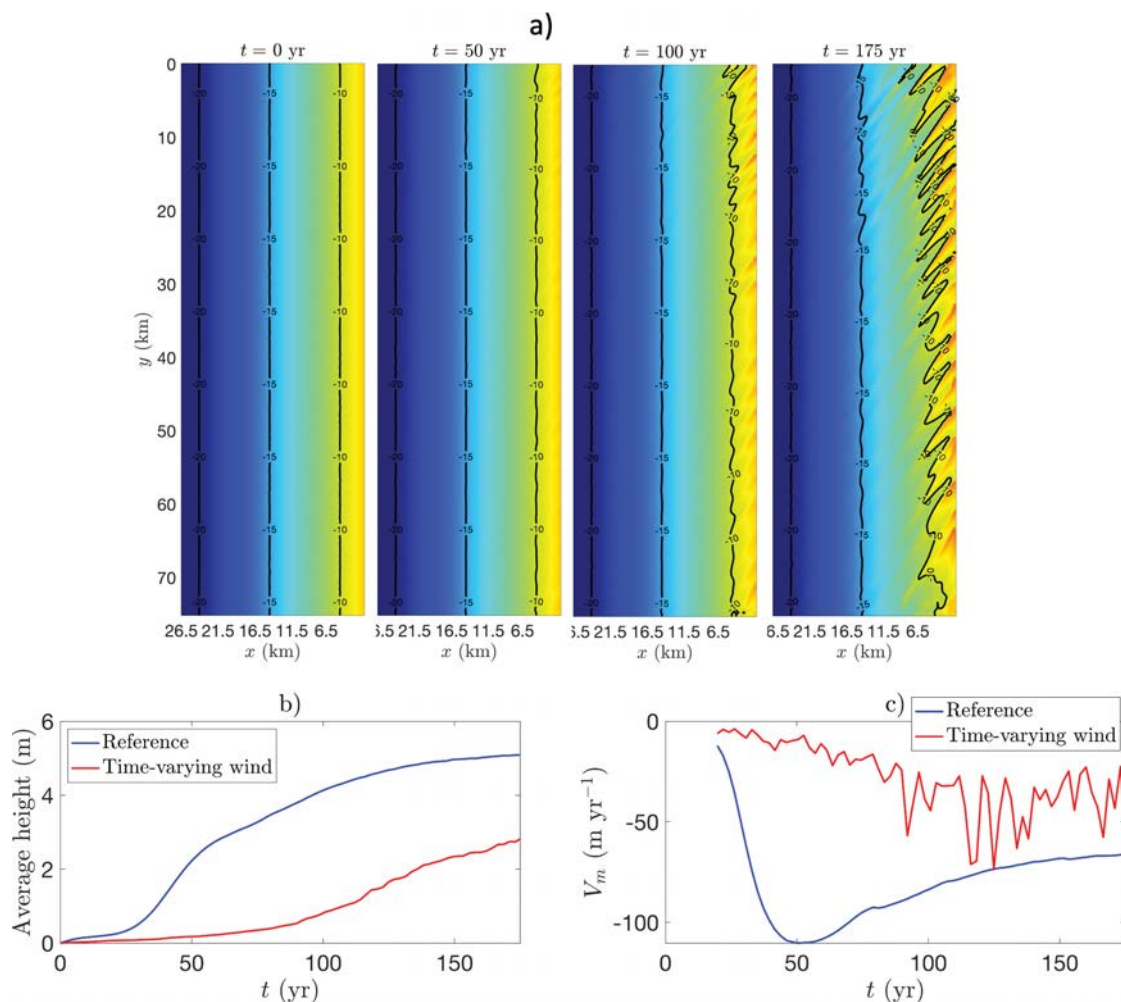


Figure 3-25 - Snapshots of the simulated bed level z_b at times $t = 0$ yr, $t = 50$ yr, $t = 100$ yr and $t = 175$ yr in the "Time-varying wind" case. b-c) Average height of the ridges H_{av} (b) and their migration speed V_m (c) versus time in the "Reference" and "Time-varying wind" cases (blue and red lines, respectively)

3.2.1.3.2 Only tides

Figure 3-26 presents snapshots of the simulated bed level z_b at times $t = 0$ yr, $t = 300$ yr, $t = 600$ yr and $t = 900$ yr (panel a) in the case that the shelf model is forced only by tides (so no waves and wind forcing, experiment "OnlyTide"). A zoom-in at $t = 300$ yr is displayed in panel b, while panel c shows the bed level profile along the alongshore transect indicated by the dashed red line in panel b. From the snapshots in panel a it appears that the random bottom perturbations imposed on the initial bathymetry evolve on a centennial time scale into large-scale elongated bedforms on the shelf. These bedforms initially form close to the shoreward boundary and gradually extend to the offshore area. Panel c shows that the ridges reach heights (crest-to-trough distances) up to 25 m, with lengths on the order of tens of kilometres, and wavelengths of about 6 km. Crests of the ridges are rotated counterclockwise by up to 30° relative to the main south–north direction of the tidal current. These bottom patterns resemble tidal sand ridges observed on the Belgian shelf (Section 3.1.2).

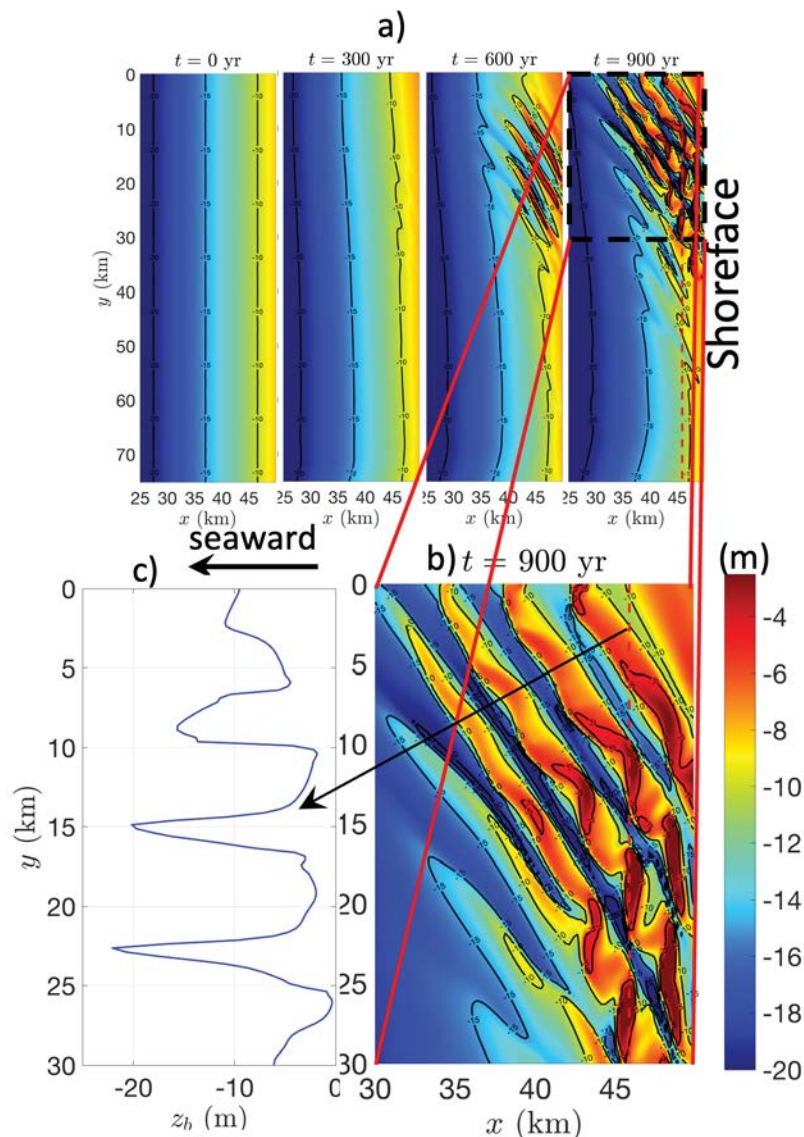


Figure 3-26 – Morphodynamic shelf model; results for only tides. a) Snapshots of the simulated bed level z_b at times $t = 0$ yr, $t = 300$ yr, $t = 600$ yr and $t = 900$ yr in the case of only tides (no waves and wind). A zoom-in at $t = 900$ yr is displayed in panel b, while panel c shows the bed level profile along the alongshore transect depicted in panel b (dashed red line).

3.2.1.3.3 Waves, wind and tide

Results in the case that all three forcings (waves, wind and tides, experiment "WavesWindTides") are imposed in the shelf model are presented in Figure 3-27, which shows Snapshots of the simulated bed level z_b at times $t = 0$ yr, $t = 100$ yr, $t = 150$ yr and $t = 200$ yr in the case of constant (stormy) waves, time-varying wind velocities and tides (experiment "WavesWindTides"). A zoom-in at $t = 200$ yr is displayed in panel b. From panel a it is seen that a complex bottom pattern develop on the shelf over time, comprising of a mix of ridges that resemble sfcrr and tsr (indicated in panel b).

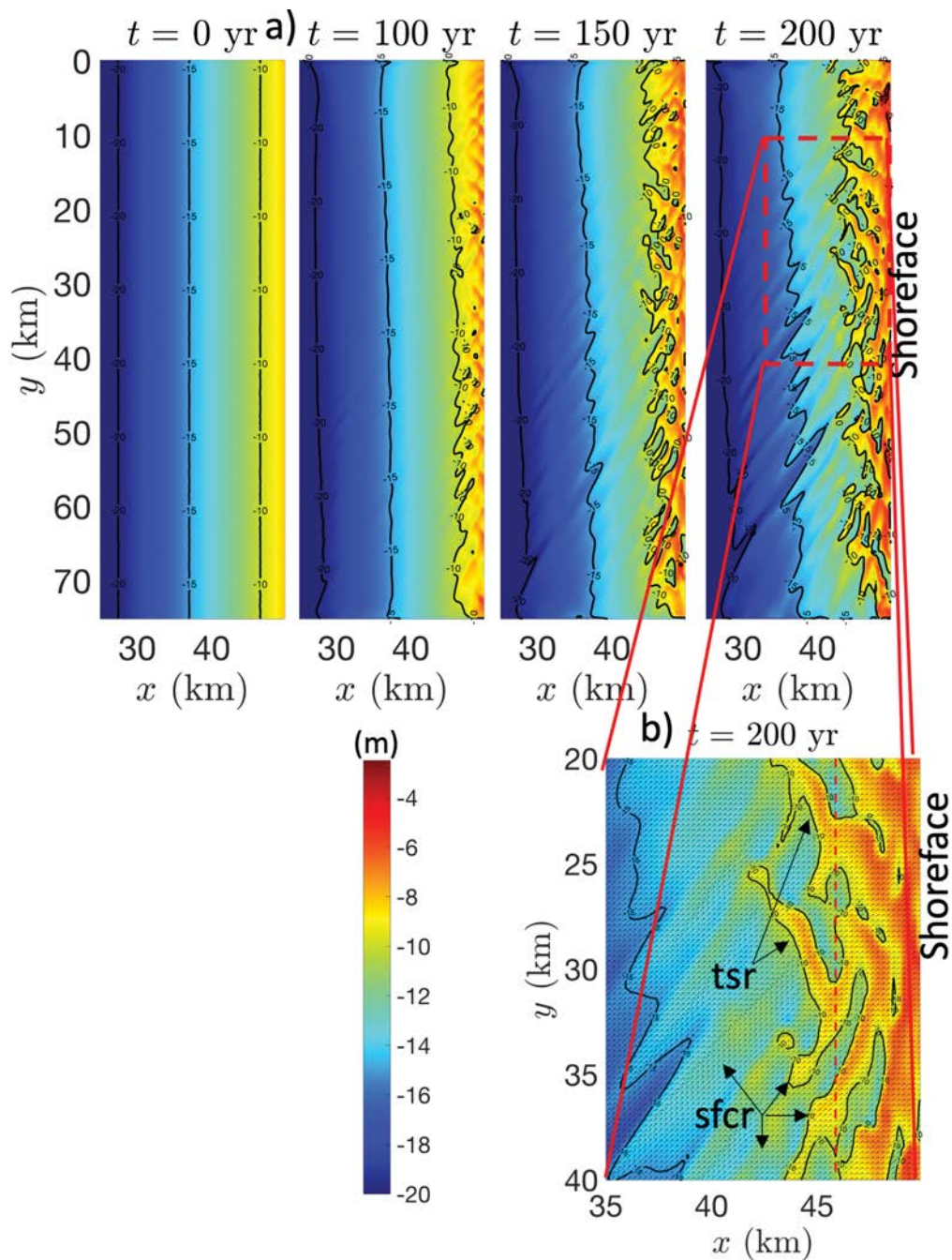


Figure 3-27 – Morphodynamic shelf model; experiment "WavesWindTides" a) Snapshots of the simulated bed level z_b at times $t = 0$ yr, $t = 100$ yr, $t = 150$ yr and $t = 200$ yr in the case of constant (stormy) waves, time-varying wind velocities and tides (experiment "WavesWindTides"). A zoom-in at $t = 200$ yr is displayed in panel b..

These results indicate that the formation mechanisms of sfc and tsr proposed by, respectively, Trowbridge (1995) and Huthnance (1982) are both active on the shelf. Results from additional experiments (not shown) reveal that reducing the significant wave height weakens the growth of sfc. Under fair weather wave conditions ($H_s < 1$ m), the sfc do not develop, while tsr dominate on the shelf. Results from these additional experiments also show that decreasing tidal amplitude weakens the formation of tsr. When tidal currents are too weak, only sfc form on the shelf. This competition between the formation mechanisms of sfc and tsr can be characterised by the ratio R of bottom shear stresses related with waves ($\sim \frac{0.018}{c_D} U_w^2$) and currents ($\sim |\vec{v}|^2$) according to the Soulsby-van Rijn sediment formulation (Soulsby 1997). In these expressions, c_D ($= 4$ mm) is a morphodynamic drag coefficient, typically ranging from 1 to 10 mm (Damgaard et al. 2002), U_w represents the magnitude of the near-bed peak wave orbital velocity (computed by SWAN) and $|\vec{v}|$ is the magnitude of current velocities resulting from tide and wind. By plotting ratio $R = \frac{\frac{0.018}{c_D} U_w^2}{|\vec{v}|^2}$, it appears that the wave related shear stress dominate ($R \geq 1$) during stormy conditions (Figure 3-28, panel a). Under calm conditions, the current related shear stress dominate $R < 1$ (panel b).

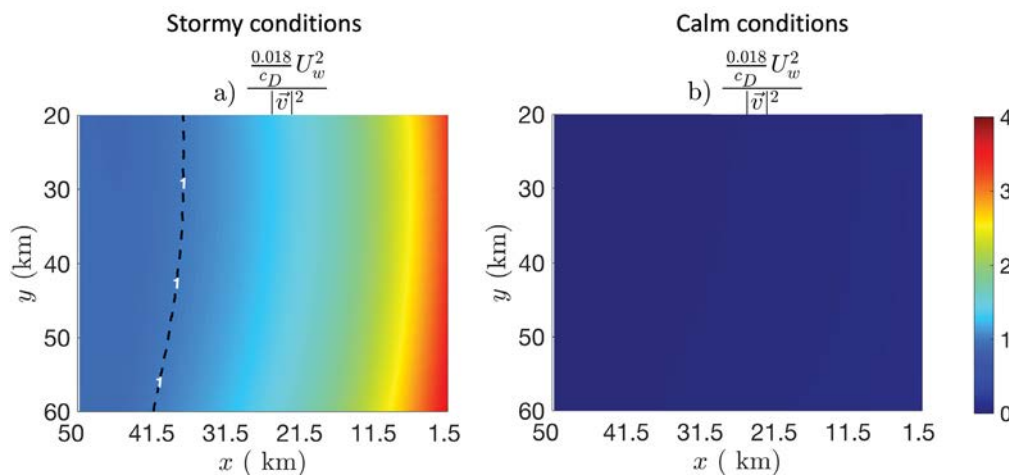


Figure 3-28 – Ratio R of the bottom shear stresses related with waves ($\sim \frac{0.018}{c_D} U_w^2$) and currents ($\sim |\vec{v}|^2$) according to the Soulsby-van Rijn sediment formulation (Soulsby 1997) in the cases of stormy (a) and calm conditions (b). In these expressions, c_D ($= 4$ mm) is a morphodynamic drag coefficient, typically ranging from 1 to 10 mm (Damgaard et al. 2002), U_w represents the magnitude of the near-bed peak wave orbital velocity (computed by SWAN) and $|\vec{v}|$ is the magnitude of current velocities resulting from tide and wind. For stormy conditions, the wave and wind forcings of the "Reference" experiment are applied, while for calm conditions, values $H_s = 0.5$ m and $V_w = 5$ m/s are used.

A notable difference between model results and observations is the location of tsr on the Belgian shelf. Observations indicate that the tsr are situated further offshore, while the sfc are located on the shoreward part of the shelf. In contrast, the tsr and sfc that form in the model are both located on the shoreward part of the shelf (Figure 3-27). This difference in tsr location between model results and observations may be caused by the use of constant (stormy) waves in experiment "WavesWindTides". Incorporating tides along with alternating stormy and fair wave conditions is anticipated to cause the tsr to form further offshore, as reported in the study by Walgreen et al. (2002). Investigating the effects of alternating fair and stormy wave conditions on the evolution of the shelf ridge evolution remains a topic of future research.

3.2.1.4 Summary and Conclusions

Efforts were concentrated on developing a morphodynamic shelf model by 1) incorporating a wind climate more representative for the Belgian shelf and 2) including tides in the model.

The morphodynamic shelf model successfully simulate sfcrl with characteristics (height, width, length and alongshore spacings) similar to those observed on the Belgian shelf. However, the observed sfcrl on the Belgian shelf are more oblique and their migration rates are slower than the simulated ridges. Incorporating a time-varying wind velocity alternating between stormy and fair weather reduces both migration rates and sfcrl growth. Further reduction is expected by including a time-varying wave climate.

When only tides are included, large-scale, elongated, counterclockwise-rotated bedforms resembling tsr evolve. With waves, wind and tides active, a complex mix of sfcrl and tsr emerges on the shelf, indicating that both formation mechanisms of these ridges are active on the shelf. A key discrepancy is the tsr location: observed tsr occur offshore, while modelled tsr are situated more shoreward. This mismatch likely stems from the use of stormy waves and the absence of sea level rise in the model.

Furthermore, we would like to highlight the novelty of this study: the morphodynamic shelf model is the first to simulate sfcrl on the shelf using sediment formulations other than those used in traditional models. These results demonstrate that sfcrl formation is not constrained by a specific sediment transport formulation, unlike in earlier studies.

3.3 Longshore and cross-shore sand transport processes along the Belgium coast simulated with 2 complex process-based 2DH models

3.3.1 Introduction

This section presents the findings gained with two available complex process-based numerical models for longshore and cross-shore sediment transport processes along the Belgium coast. These models are the earlier developed Telemac Scaldis-Coast (Figure 3-29) and the Delft3D Flexible Mesh FlemCo models (Figure 3-30), which – for the current study – were fine-tuned and applied with respect to the following research questions:

- 1) What is the order of longshore sediment transport along the Belgian coast and what is the relevance of tides, waves and wind for this transport (Section 3.3.2)?
- 2) Are the beaches at the Belgian coast naturally fed by the shoreface connected ridges and what are the driving mechanisms for this feeding (Section 3.3.3)?
- 3) What are the effects of nearshore tidal channels on the beach erosion at the Belgian coast (Section 3.3.4)?
- 4) Morphological hindcast and forecast simulations for Knokke-Zoute considering various beach nourishment scenarios (Section 3.3.5)

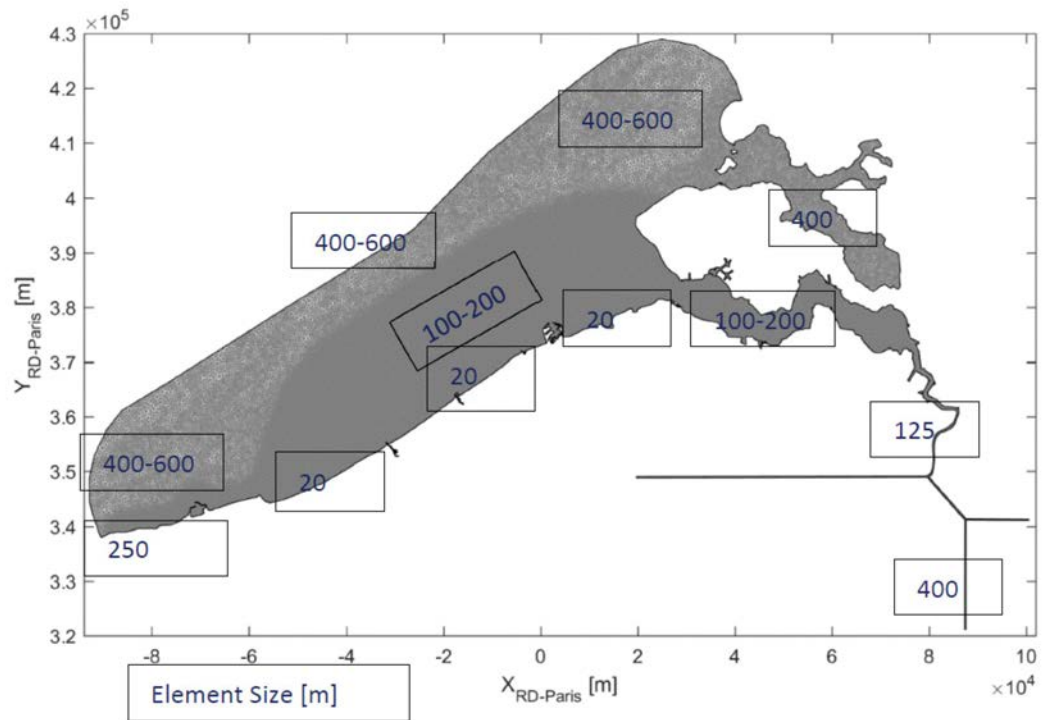


Figure 3-29: Computational grid and domain of the Telemac Scaldis-Coast model. For more detailed information on the model setup see Smolders et al. (2016), Kolokythas et al. (2021) and Dujardin et al. (2023).

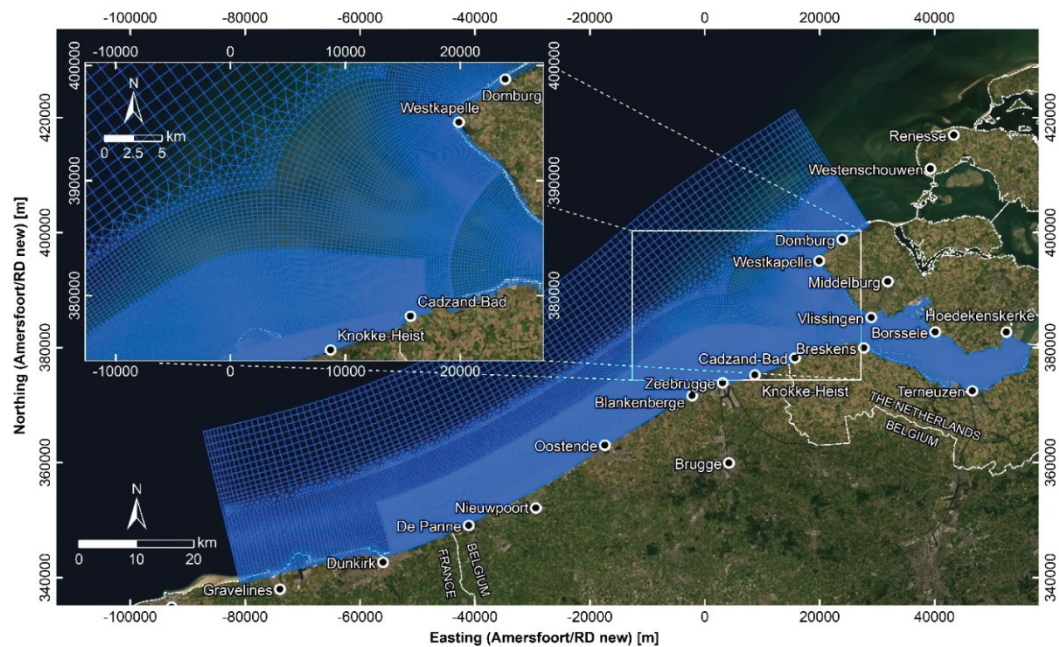


Figure 3-30: Computational grid and domain of the Delft3D Flexible Mesh model. For more detailed information on the model setup see R  bke et al. (2020), Grasmeier et al. (2020) and Dujardin et al. (2023).

The general setups of both applied models are described in detail by Dujardin et al (2023). For research question 1) (Section 3.3.2), modified model settings were applied and for question 3) (Section 3.3.4) both models were further developed/fine-tuned compared with the original model versions described by Dujardin et al. (2023). These model modifications/fine-tuning steps are described below in the corresponding sections.

3.3.2 Longshore sediment transport along the Belgian coast and the relevance of tide, waves and wind

3.3.2.1 Introduction and methodology

The longshore sediment transport is a crucial process for understanding the morphodynamic behaviour of the Belgian coast including its shoreface connected ridges and nearshore tidal channels. Several studies exist that estimate the longshore sediment transport based on i) observed bed level changes (e.g. Section 2.8 Verwaest et al. 2010, Trouw et al. 2015), ii) empirical analyses (e.g. Vandebroek et al. 2017) and iii) numerical simulations (e.g. Wang et al. 2013, 2015). In the current study, we simulated the longshore sediment transport (both suspended and bedload transport) with the Scaldis-Coast and FlemCo models for the ca. 350 m to 750 m wide nearshore zone (between the beach and ca. the -5 m TAW/-7.33 m NAP contour) of the Belgian coast. This zone is indicated by the black cross-sections in Figure 3-31 and is believed to be a good approximation of the average wave breaker (surf) zone at the Belgian coast (cf. Dujardin et al. 2023).

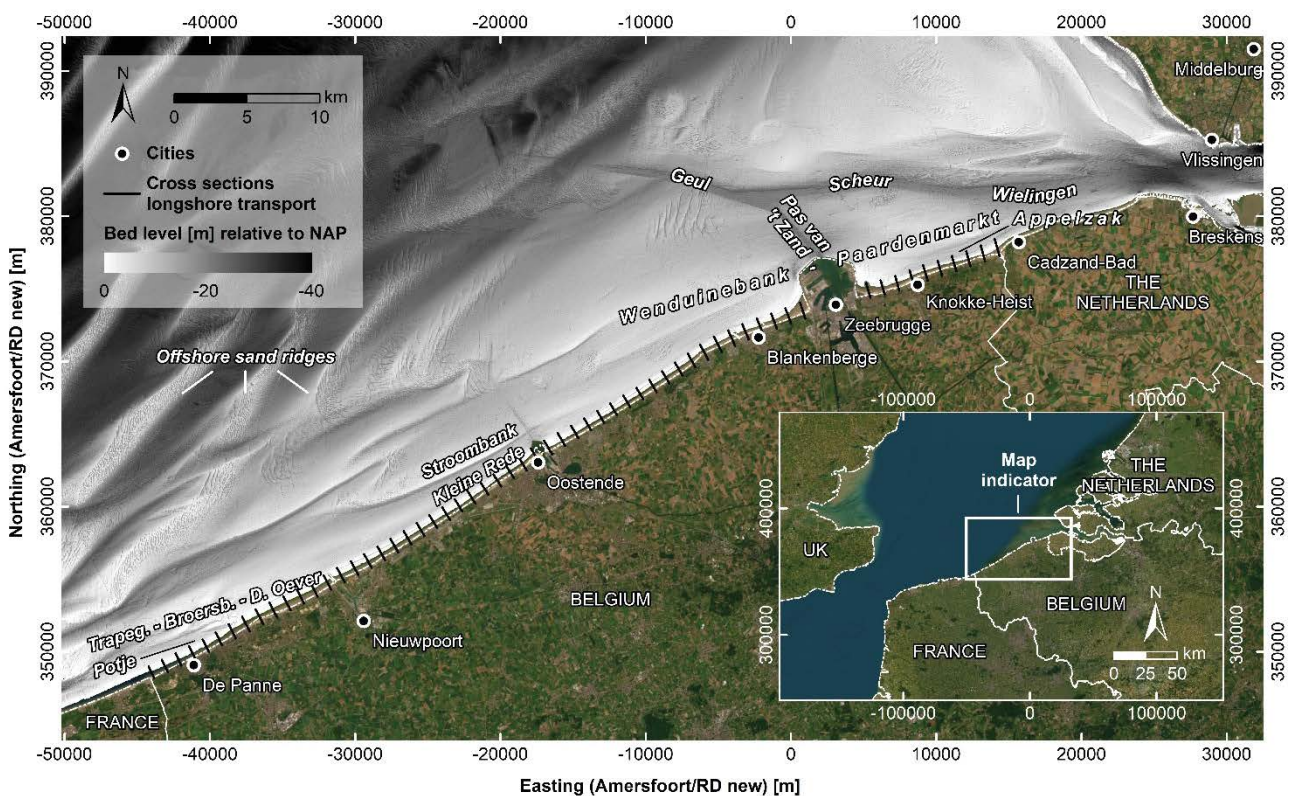


Figure 3-31: Satellite image (Esri 2022) and bathymetry of the Belgian (Flemish) coast and the Western Scheldt mouth including the main navigation channel Geul-Scheur-Wielingen and the connecting channel Pas van 't Zand to Zeebrugge harbour as well as the sand ridges in the western part of the study area. The coastal bathymetry is derived from several sources of data according to Dujardin et al. (2023). The black lines indicate cross sections based on which the longshore sediment transport along the Belgian coast was simulated.

The coordinates are given in km according to Amersfoort/RD New.

Longshore sediment transport simulations were performed based on two different setups of the Scaldis-Coast and FlemCo models (for more details on the approach and results see Dujardin et al. 2024):

- 1) Original model settings according to Dujardin et al. (2023) and realistic wave and wind boundary conditions (i.e. measured time series at Westhinder station for the representative period from 14 March 2014 to 13 May 2014, see R bke et al. 2018) with various model forcing combinations (tide only, waves only, wind only and all possible combinations) in order to:
 - a) make estimates on the absolute longshore sediment transport along the Belgian coast,
 - b) study the relevance of tide, waves and wind on the longshore transport and
 - c) investigate the cross-shore distribution (along the 750 m cross-sections) of the longshore transport.
- 2) Identical wave model settings (the original wave model settings according to Dujardin et al. (2023) differ between the Scaldis-Coast and FlemCo models) and non-realistic constant wave and wind boundary conditions with various model forcing combinations (tide only, waves only, wind only and all possible combinations) in order to get a better understanding of model prediction differences between Scaldis-Coast and FlemCo.

3.3.2.2 Longshore sediment transport and role of tide, waves and wind

Based on the original model settings and the realistic wave and wind boundary conditions (see bullet point 1) above) the fully forced (tide, waves and wind) Scaldis-Coast and FlemCo models predict a similar longshore transport pattern along the Belgian coast, although the Scaldis-Coast model generally shows a larger transport (often factor two) compared to FlemCo (Figure 3-32; for more details see Dujardin et al. 2024):

- Both models indicate a significant spatial variability of the longshore sediment transport along the Belgian coast (between De Panne and Zwin) from slightly negative values (i.e. westward transport east of Zeebrugge) to almost 300,000 m³/year (i.e. eastward transport near Blankenberge).
- Three outstanding transport peaks are predicted – i) in the area of the Trapegeer-Broersbank-Den Oever sand ridge (east of De Panne), ii) west of Blankenberge where the coastline has a convex shape and iii) toward the Belgian-Dutch border near Zwin.
- Between Nieuwpoort and Blankenberge, the longshore sediment transport continuously increases (only interrupted by the navigational channel of Oostende harbour) and subsequently drops significantly towards Zeebrugge harbour. Here, the longshore sediment transport of the coast is interrupted due to the presence of the two large harbour breakwaters.
- Directly east of Zeebrugge harbour, the longshore transport changes its direction from earlier eastward to westward but subsequently becomes eastward orientated again (at a distance of about 58 km/4 km along the coastline to the French boarder/the eastern breakwater of Zeebrugge harbour) and increases significantly towards the Belgian-Dutch border near Zwin.

Both models generally reproduce the range and the spatial variability of longshore sediment transport according to earlier studies, although significant differences can be observed in specific areas. These differences are at least partly related to i) different nearshore zones (due to different applied maximum water depths) that are applied in the various studies, ii) different processes (tides, waves and/or wind) that are considered and iii) different grain sizes that are assumed. These difference clearly hamper a one-by-one comparison between the earlier studies and the Scaldis-Coast and FlemCo predictions.

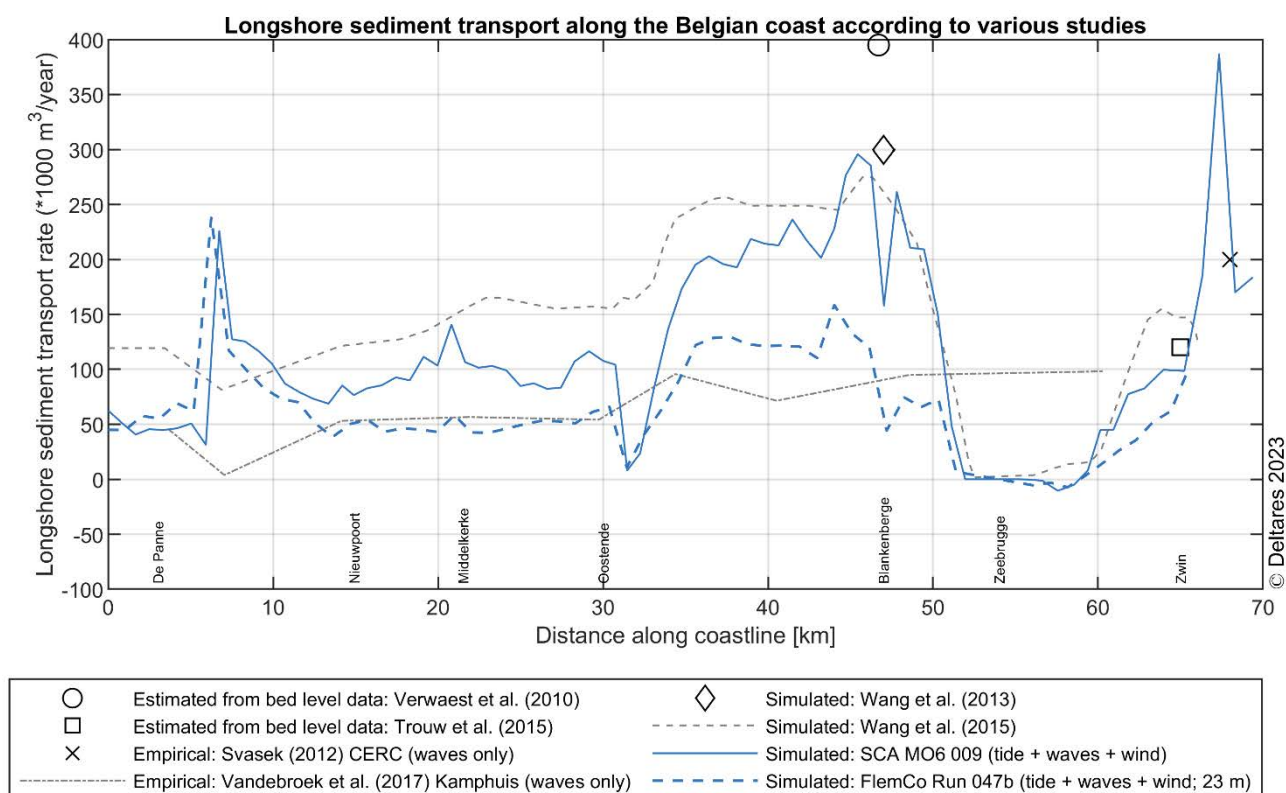


Figure 3-32: Longshore sediment transport simulated with the Scadis-Coast and FlemCo model based on tide + wave + wind (blue lines) forcing and comparison with the longshore sediment transport according to earlier studies. Both models were run for the representative period from 14 March to 13 May 2014. Note that among the earlier studies, the considered coastal zones have different widths, hindering a one by one comparison. This particularly applies to the estimated longshore transports derived from bed level data, which generally consider wider zones.

In a next step and still based on the original model settings and the realistic wave and wind boundary conditions (see bullet point 1) above) the Scadis-Coast and FlemCo models were run with different forcing combinations to determine the relevance of tide, waves and wind for the longshore sediment transport along the Belgian coast in the approximate 750 m nearshore zone. These additional sensitivity model runs reveal that, in this zone, the wave-induced longshore transport clearly dominates the total longshore transport (often about 2/3 or 3/4 of the total) and that wind has a minor impact on the tide-induced longshore transport but a major impact on the wave-induced longshore transport (cf. Figure 3-33 and Figure 3-34). The latter is due to the fact that the wind compensates for wave dissipation in coastal waters and by this results in clearly higher waves in the nearshore zone, which causes a larger wave-induced longshore drift and associated sediment transport.

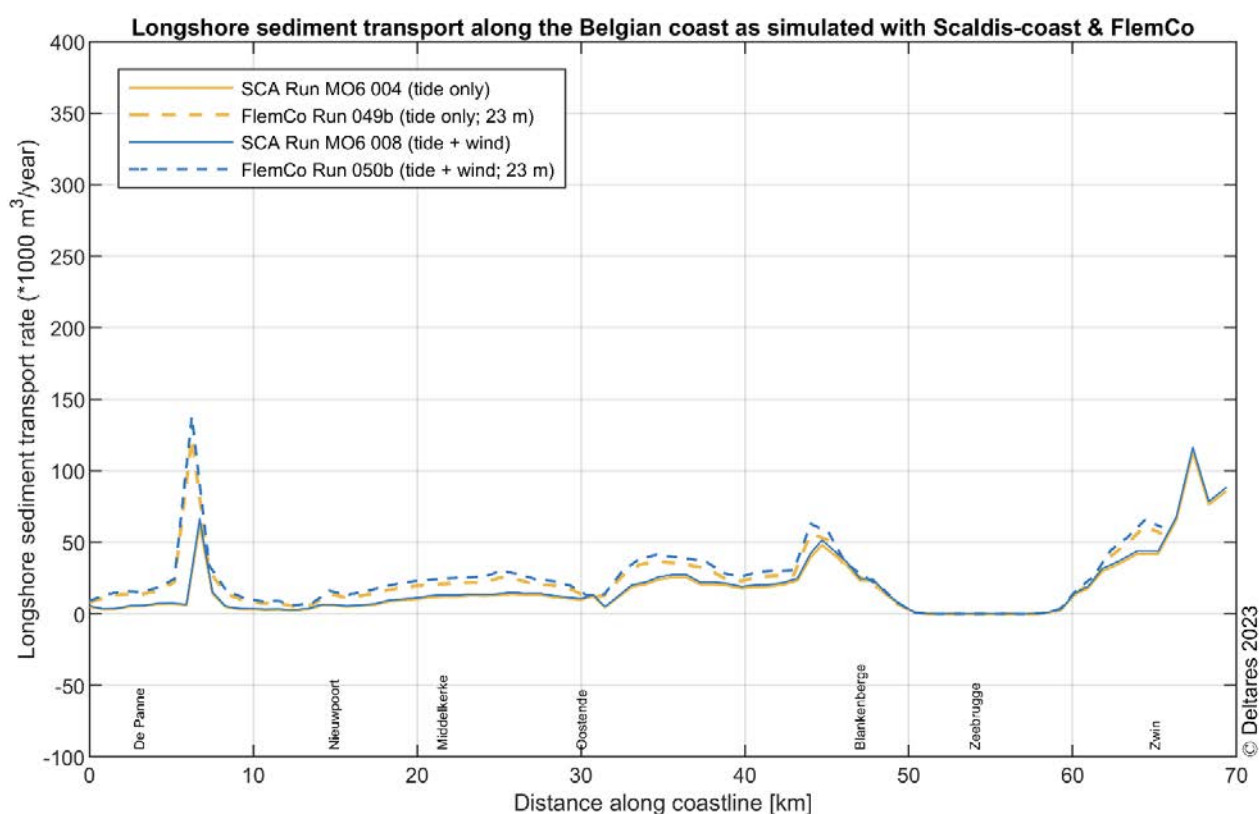


Figure 3-33: Longshore sediment transport as simulated with the Scaldis-Coast and FlemCo model based on tide only (yellow lines) and tide + wind (blue lines) forcing. Both models were run for the representative period from 14 March to 13 May 2014.

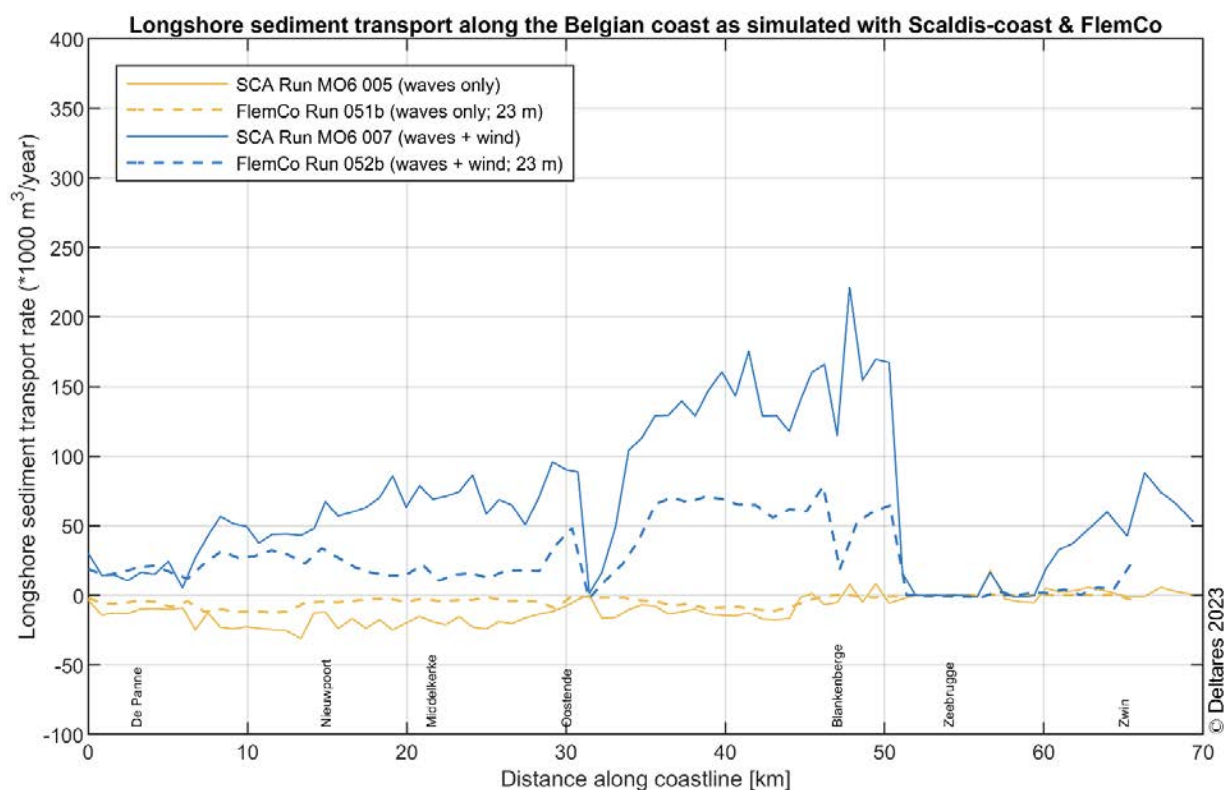


Figure 3-34: Longshore sediment transport as simulated with the Scaldis-Coast and FlemCo model based on wave only (yellow lines) and wave + wind (blue lines) forcing. Both models were run for the period from 14 March to 13 May 2014.

3.3.2.3 Cross-shore distribution of longshore sediment transport

The above mentioned Scaldis-Coast and FlemCo model simulations based on the original model settings and the realistic wave and wind boundary conditions were also used to analyse the cross-shore distribution of the predicted longshore sediment transport (for more details see Dujardin et al. 2024). Figure 3-35 exemplarily illustrates the longshore transport along two cross-shore transects running across the Stroombank/Kleine Rede ridge-channel system near Oostende and the Paardenmarkt/Appelzak ridge-channel system near Knokke-Zoute. Both transects show a similar cross-shore distribution of the longshore sediment transport that is representative for the Belgian coast. Regardless of the discrepancy of the predicted absolute longshore sediment transport between the Scaldis-Coast and the FlemCo models, they both indicate dominating wave-induced longshore transport in the first few hundred metres seawards the coastline (breaker zone), followed by dominating tide-induced longshore transport further seawards. While both models suggest a considerable but narrow peak for the wave-induced transport, they show a much wider but flattened peak (numerous hundreds of meters wide) for the tide-induced transport. According to both models, the tide-induced transport is still significant even numerous kilometres offshore.

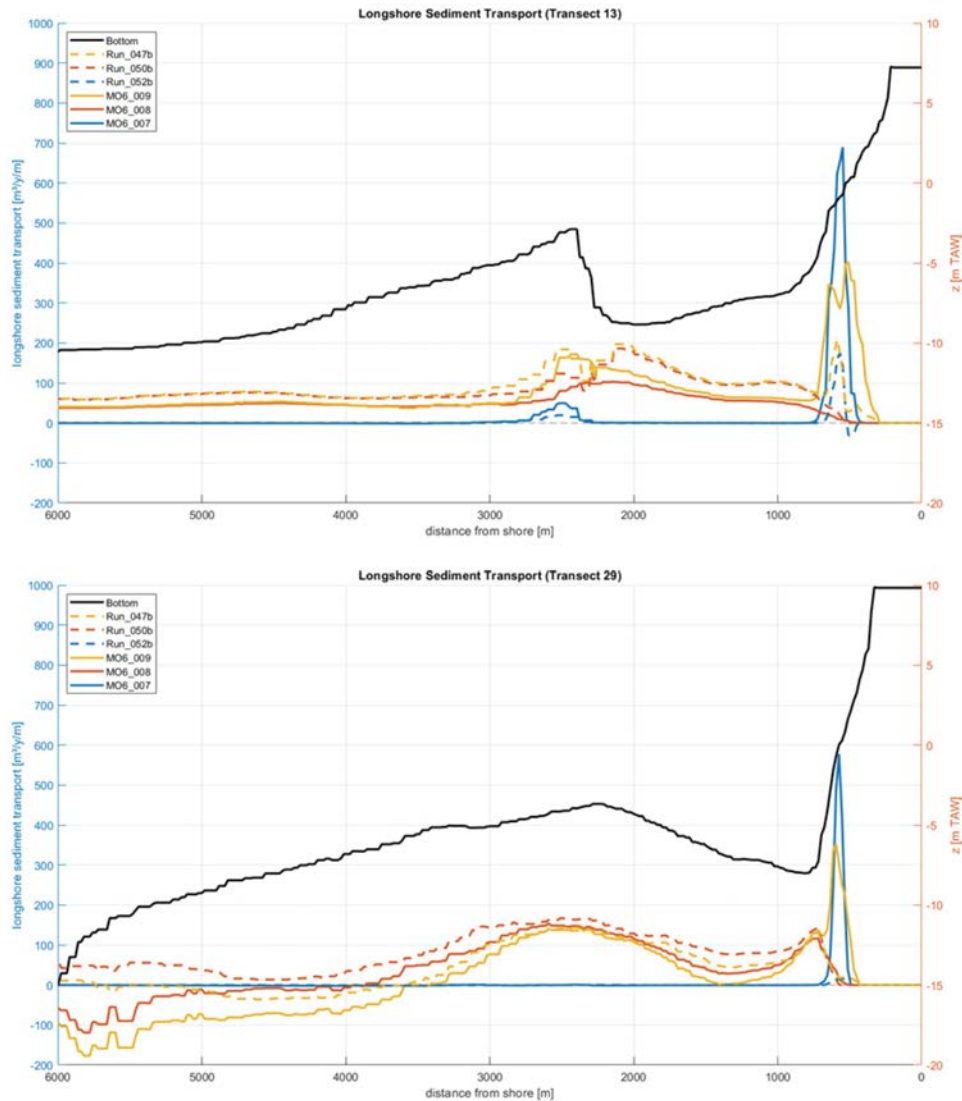


Figure 3-35: Cross-shore distribution of the longshore sediment transport as simulated with the Scaldis-Coast (solid lines) and FlemCo (dashed lines) models based on the full model forcing (orange lines), tide + wind forcing (red lines) and wave + wind forcing (blue lines). Top: transect over the Stroombank and Kleine Rede, ca. 5 km west of Oostende; bottom: Full lines show Scaldis-Coast results; dashed lines show FlemCo results. Top panel: based on tide + wind (red lines) and waves + wind (blue lines) forcing. Bottom panel: transect over the Paardenmarkt sand ridge and Appelzak channel at Knokke. Both models were run for the representative period from 14 March to 13 May 2014.

3.3.2.4 Explaining differences in Scaldis-Coast and FlemCo model predictions on the longshore transport

The Scaldis-Coast and FlemCo sensitivity runs based on the original model settings/realistic wave and wind conditions and with the different model forcing combinations (tide, waves, wind) indicate that it is mainly the wave-induced longshore sediment transport that differs between the two models, while the tide related transports show a much closer match (cf. Figure 3-33 and Figure 3-34). This is confirmed by additional sensitivity runs using identical Scaldis-Coast and FlemCo wave model settings and non-realistic constant wave and wind boundary conditions (see bullet point 2) in the [Introduction and methodology](#) section). Analyses of the whole set of performed sensitivity runs (for more details see Dujardin et al. 2024) reveal that the observed discrepancy in predicted wave-induced longshore transport between Scaldis-Coast and FlemCo is – apart from the different applied modelling software (Telemac/TOMAWAC in Scaldis-Coast and Delft3D Flexible Mesh/SWAN in FlemCo) – related to:

- different settings used in the two wave models, especially the applied bed friction coefficient (lower in Scaldis-Coast) and breaker index (higher in Scaldis-Coast),
- the fact that groynes in the Scaldis-Coast model are smaller in dimension (interpolated as bathymetry on the computational grid) in the FlemCo model (fixed weirs with specified elevations), and therefore block the wave-induced longshore current to a smaller degree than in the FlemCo model,
- less spreading of the wave directions in the nearshore zone in the Scaldis-Coast model resulting in a more peaked dominant wave direction and by this stronger wave-induced longshore current than in the FlemCo model.

This altogether favours higher wave energy and more pronounced wave-induced longshore currents in the nearshore zone causing a higher longshore transport in the Scaldis-Coast than in the FlemCo model.

Since the wave predictions for the nearshore zone clearly differ between the Scaldis-Coast and FlemCo model, we compared both the predicted significant wave heights and wave directions with measurements taken at various wave buoys spread over the model domains, including two nearshore buoys, i.e. the MP2 Appelzak and the Blankenberge buoys (for more details see Dujardin et al. 2025). The comparison shows that both models accurately reproduce the measured nearshore wave height time series (Figure 3-36), while the Scaldis-Coast model predicts clearly less and the FlemCo slightly more spreading of the wave directions compared to the measurements (Figure 3-37). This can also be derived from the wave roses depicted in Figure 3-38. At MP2 Appelzak, waves from western to north-western directions are dominant and show a relatively pronounced spreading within this sector according to the measurements. This spreading is well captured by the FlemCo model (although the spreading is slightly overestimated for the south-western and northern sectors), while the Scaldis-Coast model predicts a significant single peak for waves from the north-west. The same observation can be made at Blankenberge, where the Scaldis-Coast underestimates the spreading of the wave directions, although to a smaller degree compared to MP2 Appelzak.

The comparison of the simulated and measured wave directions confirm the earlier observation that the Scaldis-Coast model generally predicts a more peaked dominant wave direction in the nearshore zone than the FlemCo model. Given the orientation of the Belgian coastline from generally WSW to ENE, the overestimated peaked westerly wave direction in the Scaldis-Coast model in the nearshore zone results in a stronger wave-induced longshore current and by this a stronger wave-induced and total longshore sediment transport compared with the FlemCo model.

Comparison of the measured and simulated significant wave height MP2 - Appelzak

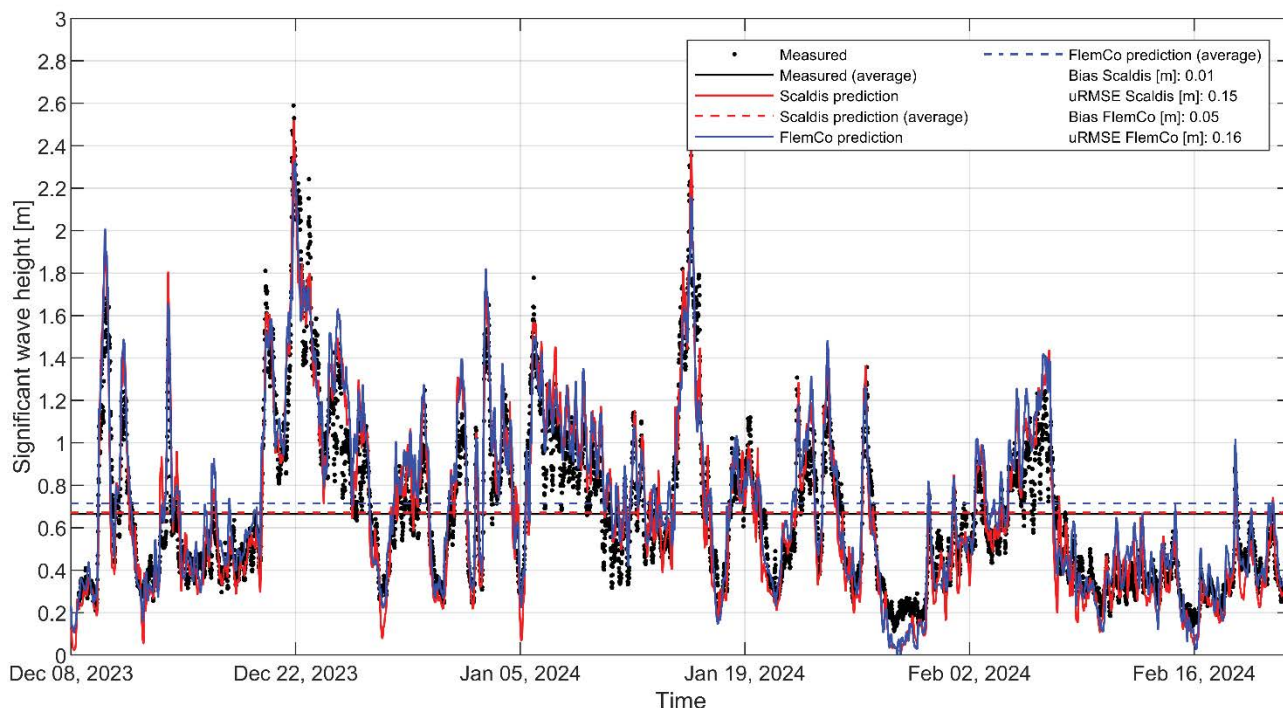


Figure 3-36: Comparison of the measured and simulated significant wave height at wave buoy MP2 – Appelzak, based on Scaldis-Coast model reference Run MO6_207 and on FlemCo model reference Run 35. The measured significant wave height is derived from Meetnet Vlaamse Banken (2024).

Comparison of the measured and simulated wave direction MP2 - Appelzak

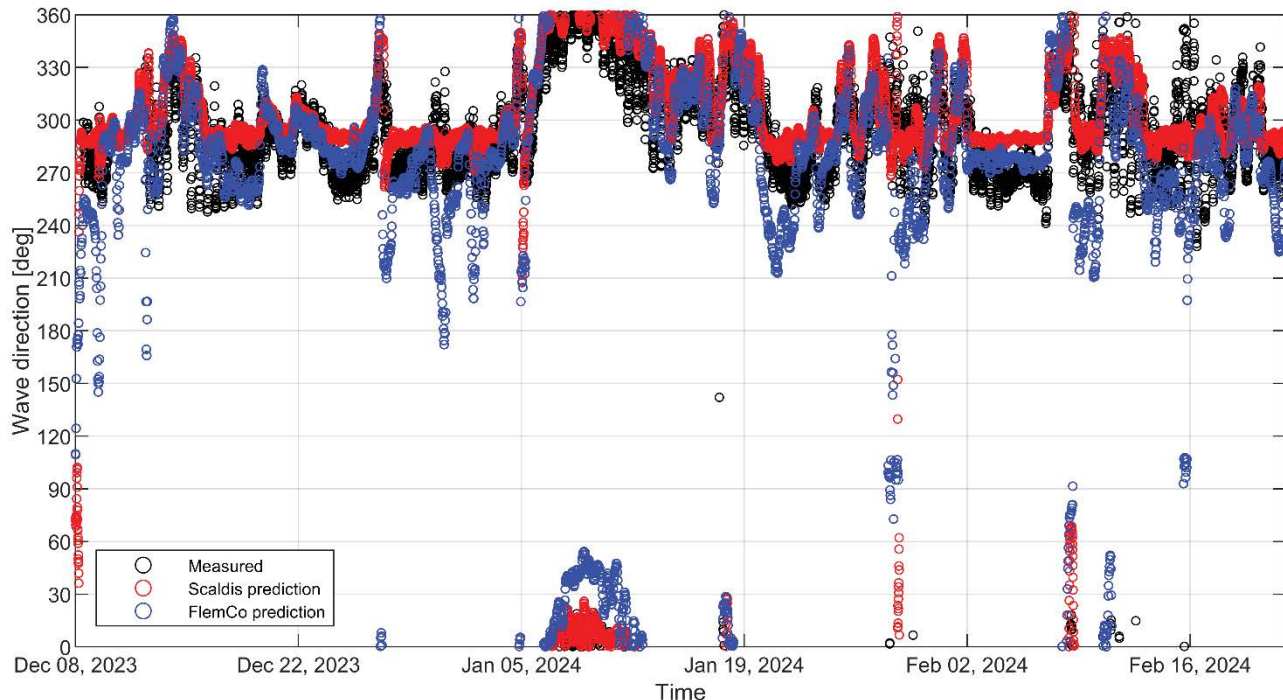


Figure 3-37: Comparison of the measured and simulated wave direction (= direction associated with the maximum wave energy) at wave buoy MP2 – Appelzak based on Scaldis-Coast model reference Run MO6_207 and on FlemCo model reference Run 35. The measured wave direction is derived from Meetnet Vlaamse Banken (2024).

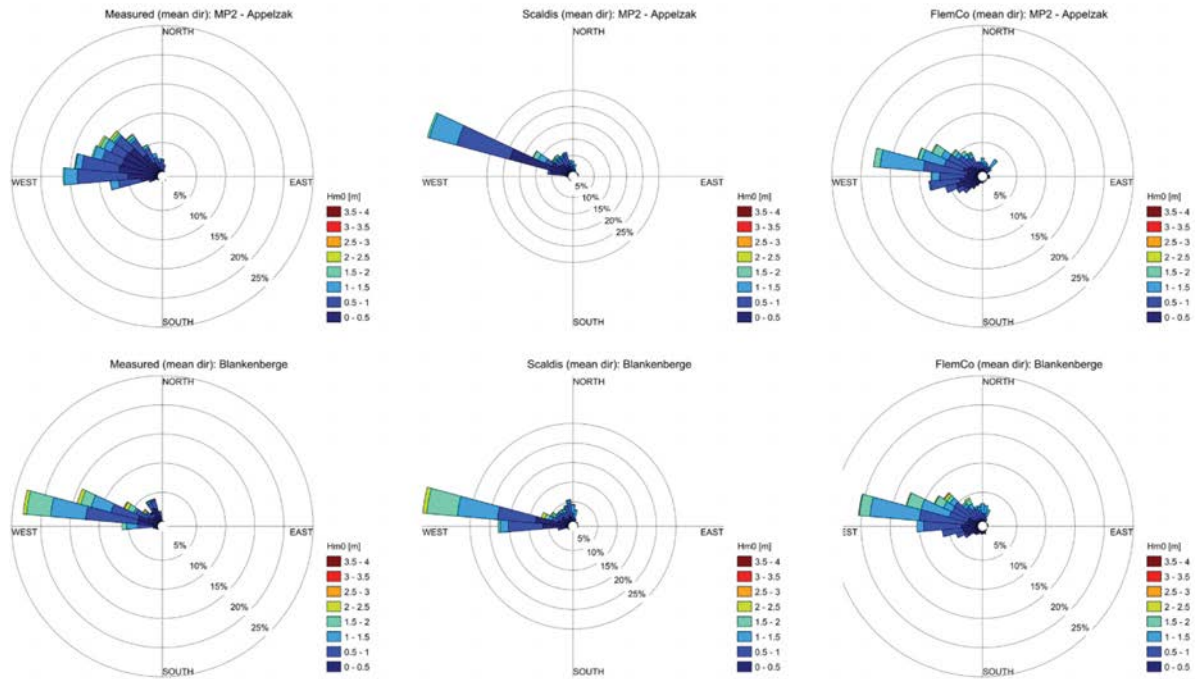


Figure 3-38: Wave roses of the measured (left) and simulated Scaldis (centre) and FlemCo (right) significant wave height and wave direction (= direction associated with the maximum wave energy) at wave buoys MP2 – Appelzak and Blankenberge based on Scaldis-Coast model reference Run MO6_207 and on FlemCo model reference Run 35. The measured significant wave height and wave direction is derived from Meetnet Vlaamse Banken (2024).

3.3.2.5 Modelled wave fields and the influence of tidal currents

To better understand the wave-propagation patterns and assess the influence of currents on wave propagation, the wave vector fields are plotted for the Knokke-Zoute area and its surroundings during flood and ebb tidal conditions, based on the results of the Scaldis-Coast model (Figure 3-39). The selected tide represents the averaged tidal condition in the area with slightly stronger peak flood current (0.58 m/s) than peak ebb (0.52 m/s), based on the model results at Bol van Heist (Figure 3-39). The figure shows that the wave propagation directions are generally similar for the two tidal phases, with waves approaching the coast and gradually refracting as they propagate into shallower water. Only minor differences in wave height and direction between the flood and ebb moments are observed in channels (port access channel and the one along northern limit of the figure) where current velocities are relative high, and along the beach where waves break.

For both flood and ebb tidal conditions examined, the offshore wave direction is west-southwest. The presence of the Zeebrugge port induces a sheltering effect in the lee side of the eastern breakwater with reduced wave heights and local modification of wave directions.

Overall, the model results indicate that the bathymetric refraction governs the spatial pattern of wave propagation in the Knokke-Zoute area. Under the considered conditions (averaged tide and west-southwest-directed incoming waves), tidal currents have a limited influence on the wave field. However, it is noted that this behaviour might change under strong currents and/or with different combinations of current and incident wave directions.

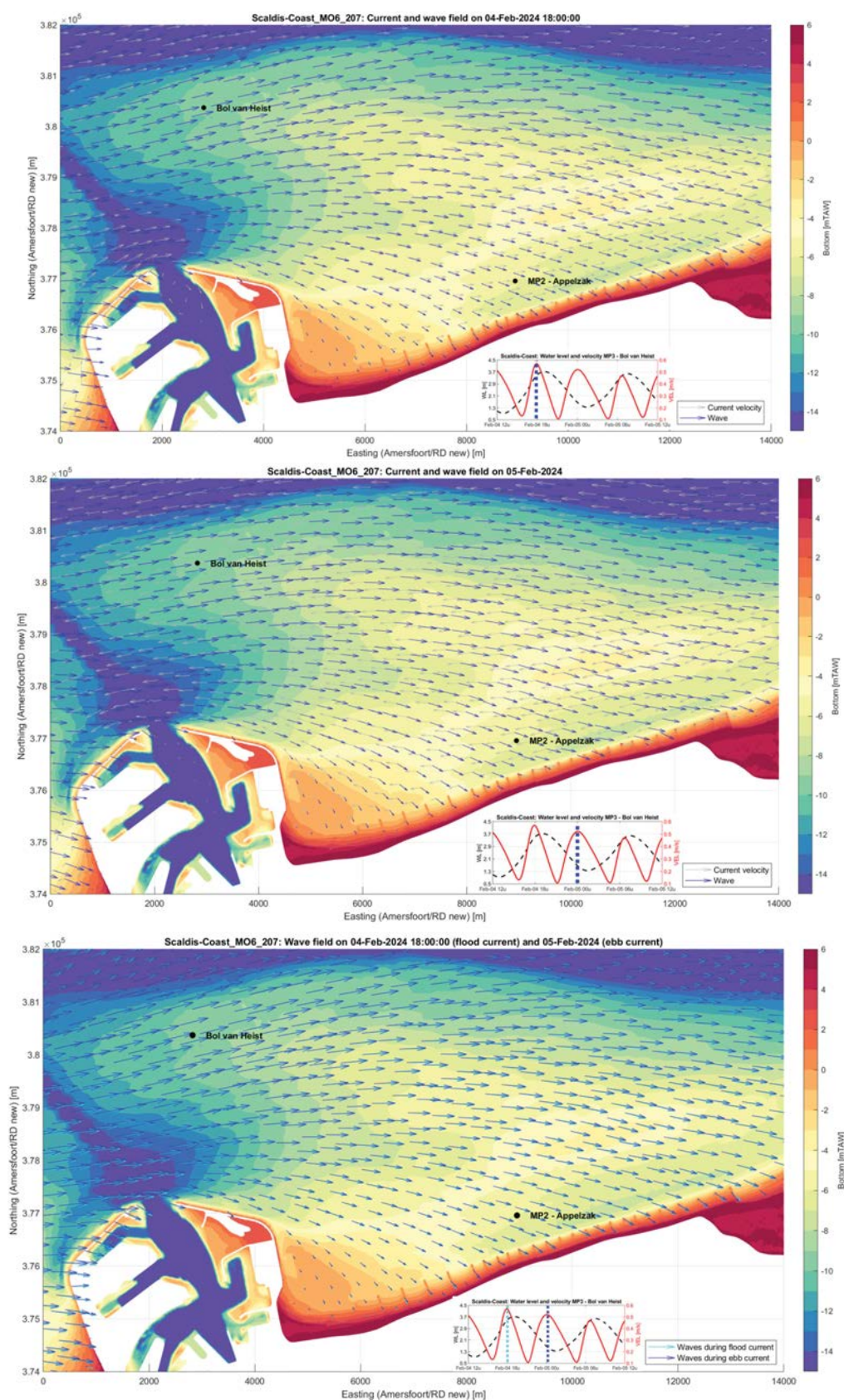


Figure 3-39: Current and wave field in the Knokke-Zoute and surrounding area simulated by the Scaldis-Coast model. Upper: current and wave field during flood current; middle: current and wave field during ebb current; lower: wave field during flood and ebb current

3.3.3 First steps towards the simulation of the natural feeding of the beach via shoreface connected ridges

Aside from longshore sediment transport simulations (previous section), the Scaldis-Coast and FlemCo models were also applied with regard to the research question whether the shoreface-connected sand ridges (Trapegeer-Broersbank-Den Oever, Stroombank and Wenduinebank-Paardenmark; Figure 3-31) naturally feed the Belgian beaches. For this, the original model setups with realistic representative wave and wind boundary conditions as described by Dujardin et al. (2023) were used. In order to get more insight into the potential natural feeding process, we visualised the sediment pathways based on the simulated sediment transport in the two models (for more details on this analysis see Dujardin et al. 2023). In the case of the FlemCo model, this was done by means of a SedTRAILS analysis, which visualises the Lagrangian sediment pathways, i.e. fictive pathways of hypothetical sediment particles. For the Scaldis-Coast model, we performed a streamline analysis, which indicates the relative residual sediment transport directions and intensities. Despite technical differences between both approaches, both the SedTRAILS and the streamlines analyses can be used to visualise the morphodynamic connectivity between different morphological features, such as the sand ridges and the adjacent beaches (cf. Dujardin et al. 2023).

Figure 3-40 show the results of the FlemCo SedTRAILS analysis in the area of the Trapegeer-Broersbank-Den Oever and Stroombank sand ridges. Based on the flow-wave coupled FlemCo model, the analysis demonstrates that the fictive pathways run generally parallel to the coast, while a cross-shore/landward component can only be observed when waves are added in the FM-FlemCo model (cf. top with bottom figure panels). This effect is particularly obvious in the areas, where the sand ridges merge into the adjacent beach. In contrast, the pathways at the Paardenmarkt sand ridge are mainly parallel to the coastline even when waves are considered in the model (see Figure 54 in Dujardin et al. 2023).

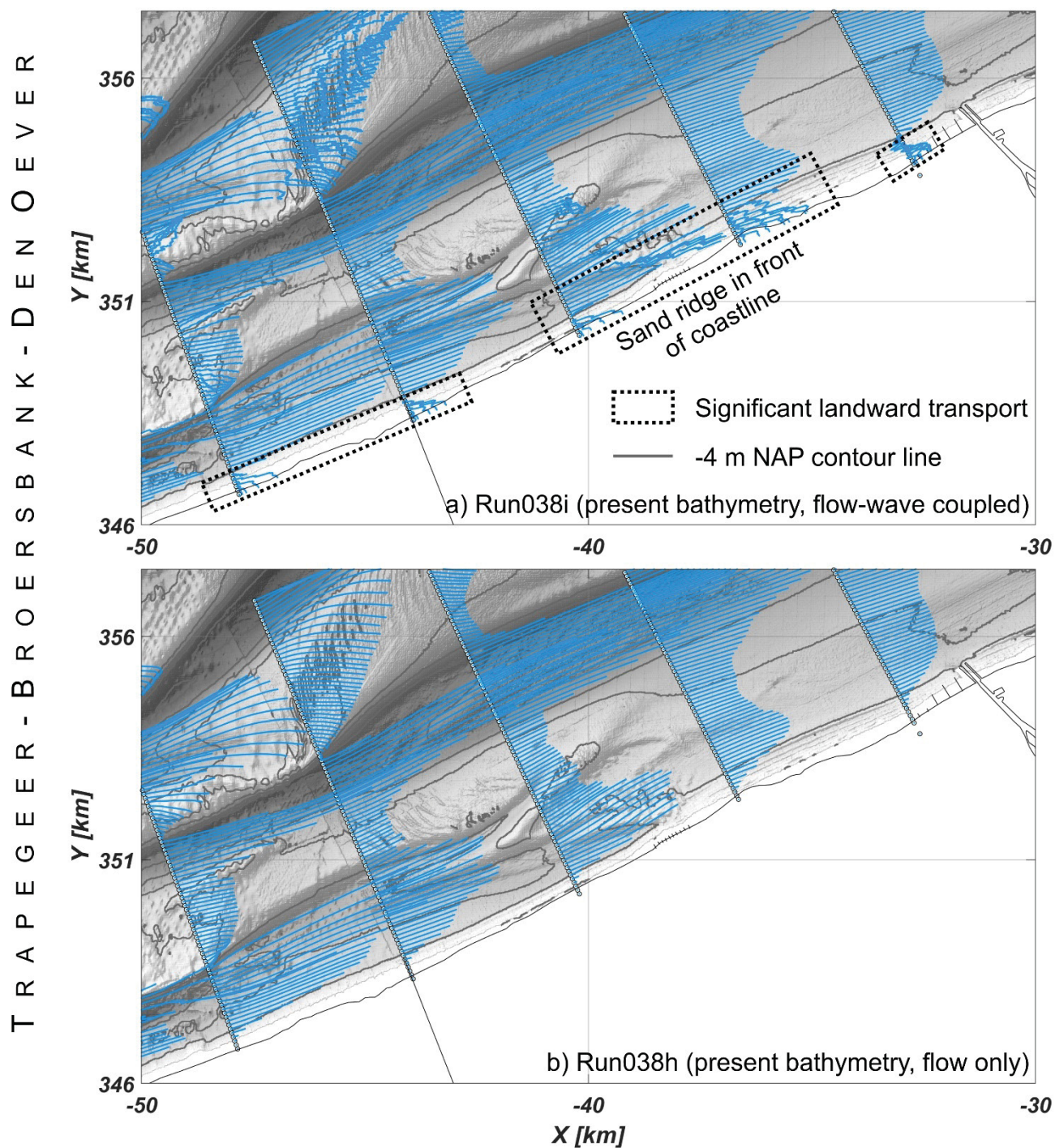


Figure 3-40: Results of a preliminary SedTRAILS analysis for the area of the sand ridge Trapegeer-Broersbank-Den Oever performed for FM-FlemCo model with flow-wave coupling (top) and with flow/tide only forcing (bottom). The blue lines indicate the fully developed pathways based on the representative period from 14-03-2014 to 13-05-2014 for 100 fictive sediment particles along each transect. The dotted boxes indicate the areas where significant landward sediment transport can be observed. The coordinates are given in km according to Amersfoort/RD New.

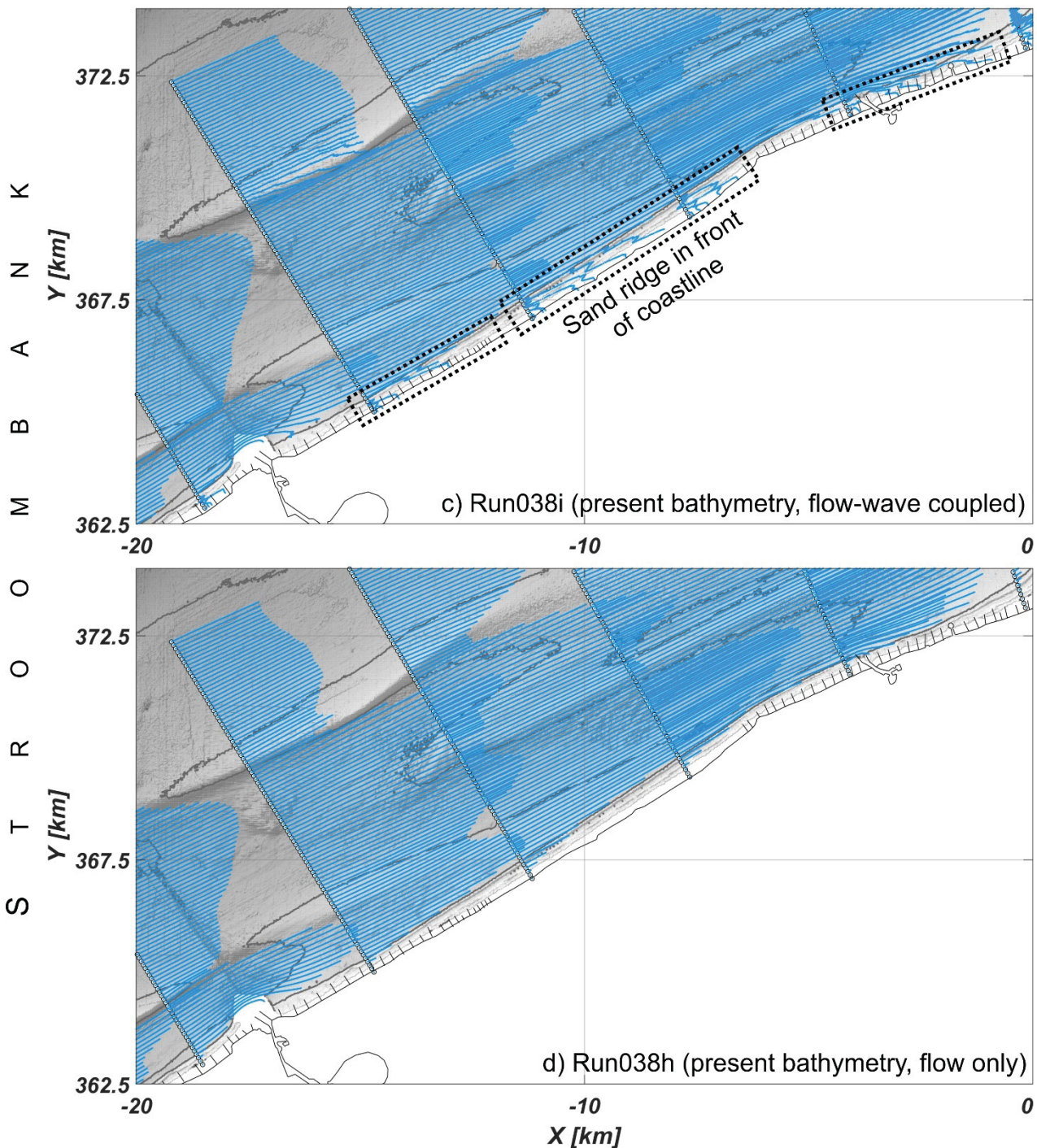


Figure 3-41: Results of a preliminary SedTRAILS analysis for the area of the sand ridge Stroombank performed for FM-FlemCo model with flow-wave coupling (top) and with flow/tide only forcing (bottom). The blue lines indicate the fully developed pathways based on the representative period from 14-03-2014 to 13-05-2014 for 100 fictive sediment particles along each transect. The dotted boxes indicate the areas where significant landward sediment transport can be observed. The coordinates are given in km according to Amersfoort/RD New.

The comparison of the hypothetical pathways between the flow-wave coupled and flow only/tide FlemCo simulations implies that sediment is transported along the sand ridges Trapegeer-Broersbank-Den Oever and Stroombank and then – due to the presence of the waves – reaches the beach in those areas, where the sand ridges meet the coastline. Deposition of sediment near Den Oever is also indicated by the significant gradient of the longshore sediment transport as shown in Figure 3-32. In the case of the Paardenmarkt sand ridge, the landward transport component can hardly be observed, which might be due to the facts that (i) in contrast to the other two sand ridges the Paardenmarkt is clearly separated from the coastline by a distinct tidal channel,

i.e. the Appelzak channel and (ii) the wave heights at the Paardenmarkt are lower due to the protecting breakwaters of Zeebrugge harbour, the different coastline orientation and the smaller water depths in this area. The strong tidal flow in the Appelzak channel therefore seems to dominate the longshore sediment transport at the Paardenmarkt in a way that the local wave related cross-shore/landward transport is limited and cannot contribute to significant landward orientated sediment transport. The clear dominance of the tide related longshore transport in the area of the Paardenmarkt/Appelzak is also indicated by Figure 3-32 and Figure 3-33, which show that the simulated longshore transport is almost the same in both the flow-wave coupled and the flow only simulation.

The residual sediment transport streamlines as calculated for the Scaldis-Coast model (Figure 3-42) do not show the same cross-shore deflection of the sediment trajectories on the shoreface as indicated by the SedTRAILS analysis of the FlemCo model. Only along the central axis of the sand ridges, a significant landward deflection of the streamlines can be observed, while they align again with the dominant tidal flow direction (i.e. parallel to the coastline) near the coastline. The observed differences between the SedTRAILS and streamline sediment pathways might be an indication of a lack of cross-shore wave induced processes in the openTELEMAC modelling suite (Scaldis-Coast model), since the SedTRAILS analysis revealed that these deflections can be attributed to wave action by comparing FlemCo simulations with and without wave forcing.

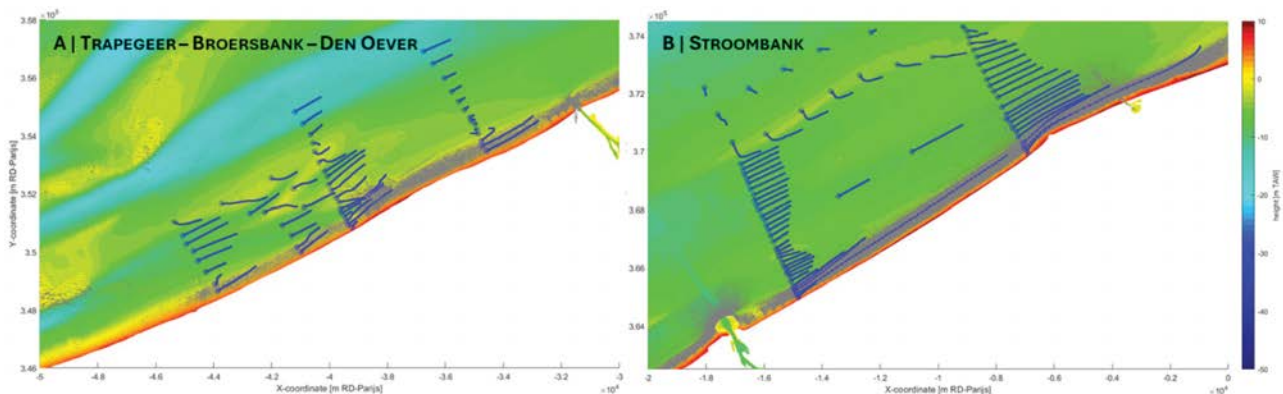


Figure 3-42: Streamline analysis showing the relative residual sediment transport directions and intensities as simulated with the Scaldis-Coast model for the sand ridges Trapegeer-Broersbank-Den Oever (A) and Stroombank (B). Starting position of the fictive particles is indicated by a circle. Grey vectors show the cumulative sediment transport after one year. The spatial density of the vectors is defined by the (varying) spatial density of the unstructured computational mesh of the model.

The above described evaluation of the FlemCo and Scaldis-Coast model results and sediment pathways analyses indicate that at the sand ridges Trapegeer-Broersbank-Den Oever and Stroombank landward directed sediment transport occurs, which potentially nourishes the adjacent coastline. On the shoreface, this landward directed transport is particularly associated with wave related sediment transport, while the tide related sediment transport mainly occurs parallel the coastline. At the Paardenmarkt, no significant landward directed transport and by this no natural feeding of the coastline can be observed due to the dominance of tide related longshore transport even close to the coastline in the Appelzak channel.

Although the current study implies landward directed sediment transport from the sand ridges towards the coast and by this indicates a potential natural feeding of the adjacent coastline, further research has to be carried out whether the landward transported sediment indeed feeds the beaches. Moreover, it has to be investigated what are the exact processes that lead to wave related landward directed sediment transport and in how far the interaction of tide and waves is relevant for this transport. A more in-depth comparison of both process based numerical models should be conducted, to better understand the differences in the results. At this point it is not yet clear how much of these differences is induced by (i) parameter settings, (ii) the implementation of the physical processes in the model code (see e.g. potential lack of cross-shore wave induced processes in the Scaldis-Coast model) and (iii) post-processing routines used.

3.3.4 Impact of nearshore channels on the beach erosion

Literature overview and data analysis on the influence of deepening nearshore channels on coastline maintenance

In order to study the effects of the observed gradual deepening of nearshore tidal channels on beach erosion and beach nourishments, a concise literature review and analysis of bathymetric data and of the nourishment intensities between 1979 and 2019 along the Belgian coast were performed as a first working step (for a more detailed description of this study see Dujardin et al. 2023). While the literature review and bathymetric data analysis provide an initial assessment of the morphological evolution of the nearshore tidal channels and shoreface-connected sand ridges on a time scale of decades to centuries, the analysis of the nourishment intensities indicates hotspots in shoreface and beach nourishment locations. Based on the results of these analyses additional insight might be gained on the effects of the gradual deepening of the nearshore tidal channels on the intensity of nourishments needed to sustain the coastline at its present location.

Detailed analysis of bathymetric data from the period 1986 to 2022 revealed that all nearshore tidal channels have deepened, and all macroforms (ridges and channels) along the Belgian shore migrate alongshore to the east and cross-shore to the coast. Morphological migration rates vary between 3 m/y and 20 m/y. The morphological migration rates appear to decrease in offshore direction. The influence of offshore dredge disposal on bed morphology extends a few hundred metres in cross-shore and a few kilometres in longshore direction. These sites are important supply points for the local area. It is clear that tidal currents rework and redistribute the disposed sediment to the east in the longshore direction. Zeebrugge's outer dams have significantly changed the surrounding morphology over several kilometres in all directions. While sedimentation characterizes the sheltered areas west and east of the dams, strong erosion is found in a wide area at the offshore side of the harbour. A similar response, but at the correspondingly smaller scale of that harbour, is found after the construction of Oostende's outer dams around 2010.

The analysis of the nourishment intensities since 1979 (Figure 3-43 and Figure 3-44), showed how coastal authorities have a long history of elevating the beaches (and touristic sand platforms) along the Belgian coast, either by moving sand from the upper shoreface to the beach (beach scraping) or by nourishing the beach with marine sands. The former was mainly used in the 1980's and 1990's until it was completely replaced by nourishing with marine sands in the years 2000. Only since 2011, after the introduction of the *Masterplan Kustveiligheid*, this methodology of annual assessment was abandoned. This is related to the increased safety levels defined by the Masterplan, the accompanying large nourishments carried out between 2011 and 2014, and the renewal/maintenance of the nourishments in 2017–2018; eliminating the need for annual maintenance. This shift in maintenance strategy can be observed in 5 coastal town areas: Sint-Idesbald – Koksijde, Bredene, Mariakerke – Oostende, De Haan and Blankenberge. At the east coast this pattern of small annual nourishments only started in 1997, probably because there was less need for sand after the large nourishments of 1977–1979 and 1986, related to the extension of the Zeebrugge breakwaters. Large nourishments can be related either to storm impacts (e.g. shoreface and beach in De Haan after 1990 or beach in Blankenberge after storms in 1990, 1993 and 1995), or – more recently – to the increased safety level defined by the *Masterplan Kustveiligheid*.

Detailed analysis of bed level cross-shore profiles indicated a clear deepening of the Potje, Grote Rede and Appelzak tidal channels (see example of Potje in Figure 3-45). In the Kleine Rede, from the beach until 1500 m offshore, sedimentation occurred between 1999 and 2011, thereafter the same amount of sediment was eroded again. The analysis on the inner shelf maps however showed that most of the erosion occurred in the deeper part of the Kleine Rede channel, further offshore and thus can't be seen in the (semi-)annual beach and shoreface profiles. The profile at Sint-Idesbald (Potje channel) shows a stable lower shoreface, as does the profile at Middelkerke (Kleine Rede). In Oostende the seaward movement of the lower shoreface is caused by shoreface nourishments, while the retreat of the lower shoreface at De Haan is probably a return to the natural beach profile after the large shoreface nourishments in 1990–1991 and 2000.

In Wenduine, where the Grote Rede approaches the shoreline, and where the Belgian coastline changes orientation, erosion can be observed at the base of the shoreface. Also in the Appelzak channel the lower shoreface is eroding.

None of the profiles analysed by Dujardin et al. (2023) shows a natural growth of the beach and (upper) shoreface, except for the one at Sint-Idesbald on the western part of the Belgian coast and the one in front of the Zwin at the easternmost part of the Belgian coast. For all other locations there is a clear relation between nourishments and the evolution of the beach and upper shoreface profiles. Fresh beach nourishments erode first at their highest point, thereafter erosion continues gradually until the low water line.

We can thus conclude that storm events, changes in (safety) policy or nourishment method and other human factors (e.g. building the breakwaters of Oostende, excavating works at the Zwin) are the main drivers behind nourishment intensity and obscure the possible relation with the deepening of nearshore tidal channels. This human influence is further illustrated by the Dutch Oostgat case study: traditional beach nourishments proved insufficient to stop coastline retreat at the west coast of Walcheren. Large scale channel-slope nourishments were introduced, and these have proven effective in maintaining the coastline position. However, now the channel-slope on the seaward side is also eroding.

The lack of sustained periods without changes in the nourishment method during the last decades – be it due to storm events, changes in policy or construction works – made it difficult to directly correlate nourishment intensity to the gradual deepening of the tidal channels. It is therefore suggested to further study the effects of the observed gradual deepening of nearshore tidal channels on beach erosion and required beach nourishments by means of complex process-based numerical models such as the Scaldis-Coast and FlemCo models (see following section).

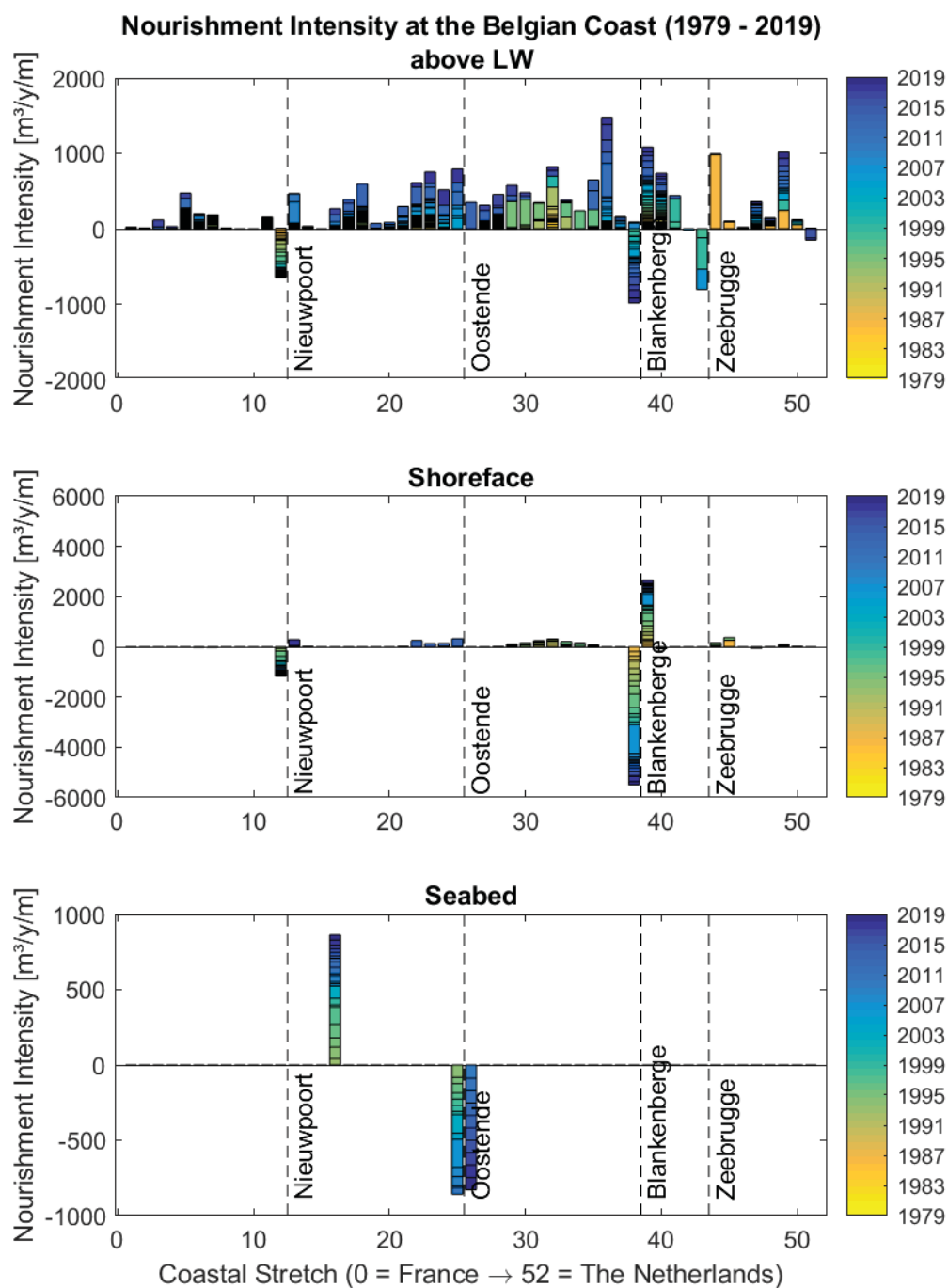


Figure 3-43: Nourishment intensity at the Belgian coast, per stretch from 1979 until 2019. Three vertical layers were defined: above Low Water (+1.39 m TAW), the shoreface between Low Water and -4.11 m TAW and the seabed below -4.11 m TAW. Negative values are related to dredging works. Please note the difference in scale on the y-axis.

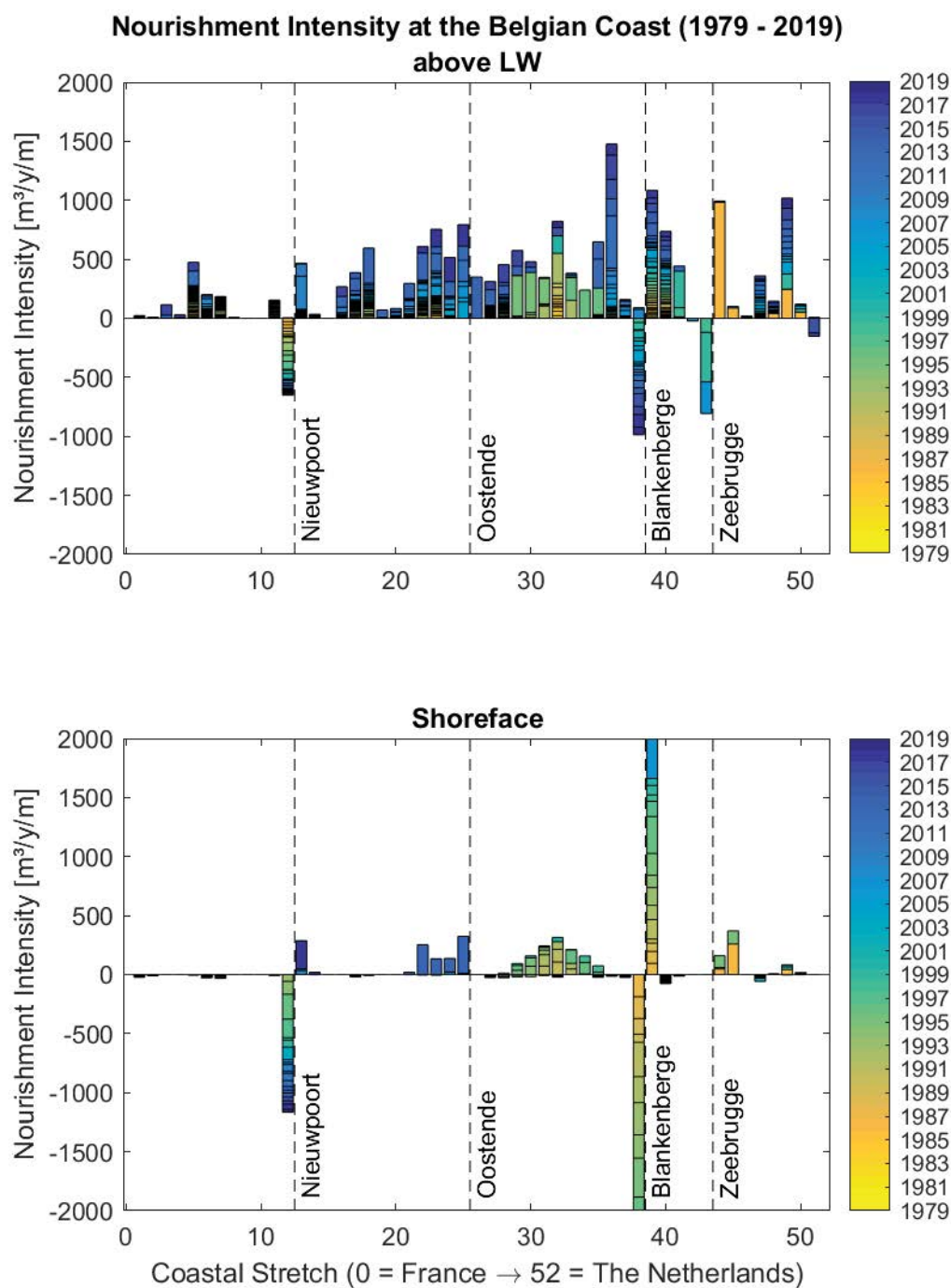


Figure 3-44: Nourishment intensity at the Belgian coast, per stretch from 1979 until 2019. Three vertical layers were defined: above Low Water (+1.39 m TAW), the shoreface between Low Water and -4.11 m TAW and the seabed below -4.11 m TAW (not shown here). Negative values are related to dredging works. Dredging and dredged sediment disposal at Blankenberge are out of range in the lower panel, but can be observed in the central panel of Figure 3-43.

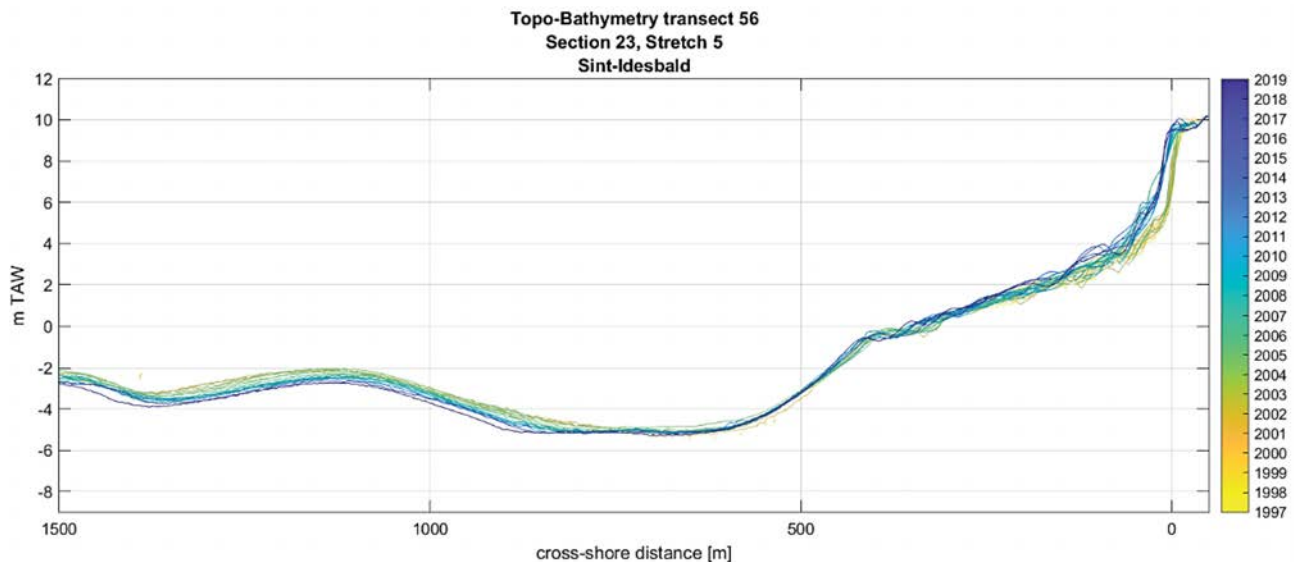


Figure 3-45: Morphological evolution of a cross-shore bed level profile through the Potje channel and the adjacent shoreface located directly to the west of Koksijde.

3.3.4.1 Scenario modelling study on the effects on a deepened Appelzak channel on the beach erosion

In order to further investigate the hypothesis whether a deeper/wider nearshore tidal channel causes an increased erosion of the adjacent beach and by this larger nourishment volumes, a scenario modelling study for the Appelzak channel at Knokke-Zoute was performed (for a more detailed description of this study see Dujardin et al. 2024). For this study, we applied the Scaldis-Coast and FlemCo models using the original 2020 and two synthetic model bathymetries for the coast between Zeebrugge harbour and the Belgian-Dutch border. Based on these model bathymetries we particularly investigated how the longshore sediment transport changes in the case of a shallower Appelzak channel and a deeper Paardenmarkt ridge (as it was the case in 1986). The two synthetic model bathymetries are as follows (cf. Figure 3-46):

- *Appelzak 1986*: For the first synthetic model bathymetry, the 2020 measured bathymetry was replaced by the 1986 measured bathymetry inside the 0 m depth difference contour polygon (grey dotted polygon in Figure 3-46) of the bed level differences between 2020 and 1986 in the area of the Appelzak channel.
- *Appelzak + Paardenmarkt 1986*: For the second synthetic model bathymetry, the 2020 measured bathymetry was replaced by the 1986 measured bathymetry inside the 0 m contour polygon (black solid polygon in Figure 3-46) of the bed level differences between 2020 and 1986 in the area of both the Appelzak channel and the Paardenmarkt ridge. Note that north of the Paardenmarkt ridge, there is no continuous contour line that indicates 0 m bed level changes between 2020 and 1986. Here, the polygon therefore follows the area with the smallest observed bed level changes.

Based on these two synthetic bathymetries and the original 2020 bathymetry (reference), three basic simulations were performed with each the Scaldis-Coast and FlemCo models (Table 3-5).

Table 3-5: Overview of the Scaldis-Coast and FlemCo runs performed to investigate the impact of the deepening of the Appelzak channel on the longshore sediment transport and on the beach erosion.

Scaldis-Coast Run ID	FlemCo Run ID	Bathymetry
MO6_009	047b	2020
MO6_030	60	2020 (Appelzak 1986)
MO6_033	61	2020 (Appelzak + Paardenmarkt 1986)

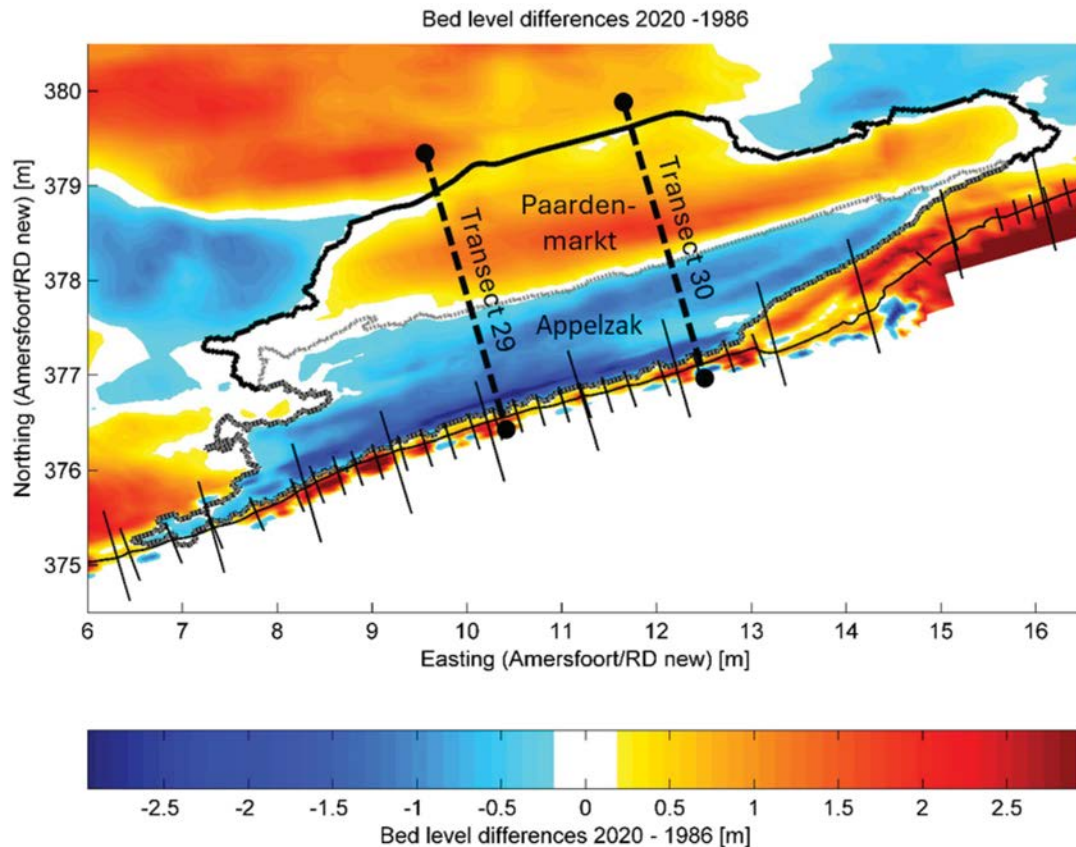


Figure 3-46: Differences between the 2020 and the 1986 measured bathymetries in the area between Zeebrugge harbour and Cadzand. The two polygons indicate the 0 m contour lines of the bed level differences for the area of the Appelzak channel (grey dotted polygon) and for the Paardenmarkt ridge (black solid polygon).

Figure 3-47 and Figure 3-48 illustrate the cross-shore distribution of the total longshore sediment transport simulated with the Scaldis-Coast and FlemCo models for two transects over the Paardenmarkt sand ridge and Appelzak channel based on the three different bathymetries. As a result of a large shoreface nourishment conducted in 1986, the lower beach and the shoreface are positioned further seawards in 1986 than nowadays (cf. grey dotted with black lines in Figure 3-47 and Figure 3-48). Therefore, the peak of the wave-induced longshore sediment transport (between the beach and ca. the -5 m TAW/-7.33 m NAP contour; cf. Figure 3-35) is either shifted seawards (transect 29) or slightly reduced (transect 30) compared with the 2020 situation. The two scenarios based on the synthetic bathymetries (*Appelzak 1986* and *Appelzak + Paardenmarkt 1986*; see bullet points above) show similar results for the wave-induced longshore sediment transport on the shoreface. We can therefore conclude that the considered bed level difference of the Paardenmarkt sand ridge has little influence on the nearshore wave climate in the models. The tide related longshore sediment transport (mainly seawards of the ca. the -5 m TAW/-7.33 m NAP contour) is clearly effected by the different applied bathymetries. In the western part of the deepened Appelzak, the longshore sediment transport decreases, while the elevated Paardenmarkt ridge leads to a transport increase (Figure 3-47). In the eastern part of the Appelzak these trends are inverse: the deepened channel shows more longshore transport, while the flood-directed longshore sediment transport decreases at the elevated Paardenmarkt ridge and even becomes ebb-directed. The inverse responses of the longshore transport in the western and eastern Appelzak channel (see also Figure 3-49) may be caused by less funnelling and associated lower flow velocities of the tidal flow in the western Appelzak due to the increased cross-section and more funnelling and associated higher flow velocities of the flow in the eastern Appelzak due to the more distinct channel, which is clearly confined by the Paardenmarkt ridge in the 2020 situation. Moreover, changes in the local tidal asymmetry may play a role.

Based on the model results, there is no direct evidence that a deepened Appelzak channel leads to more erosion of the beaches at Knokke-Zoute since the nearshore peaks of the wave-induced longshore sediment transport mainly show a landward shift/only slight increase in the case of a deeper channel. Nevertheless, models show that deepening of the channel results in changes of the distribution of the longshore sediment transport in the profile (cf. Figure 3-49)..

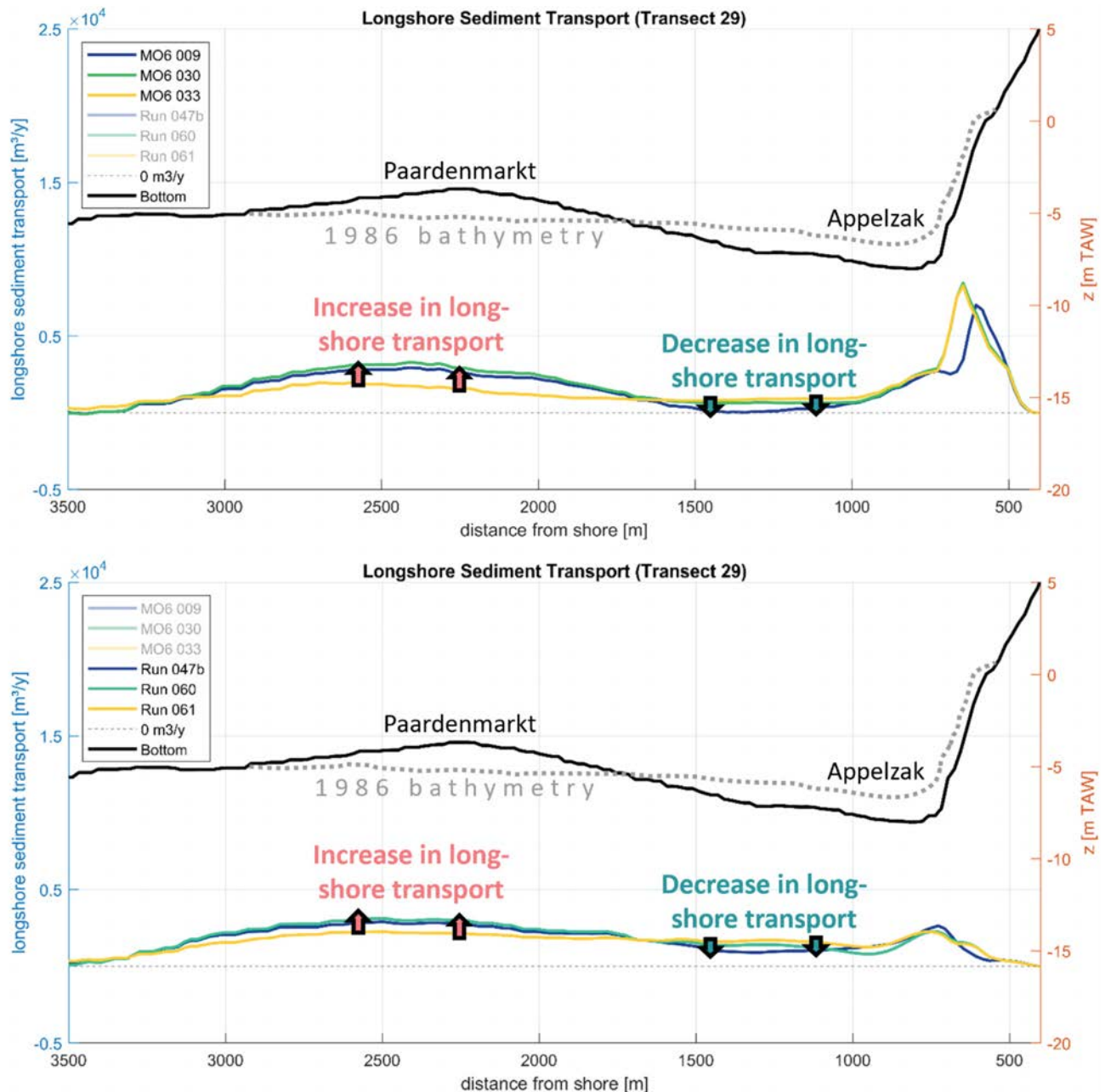


Figure 3-47: Cross-shore distribution of the total longshore sediment transport simulated with the Scaldis-Coast (top) and FlemCo (bottom) for transect 29, running over the Paardenmarkt sand ridge and Appelzak channel at Knokke-Zoute.

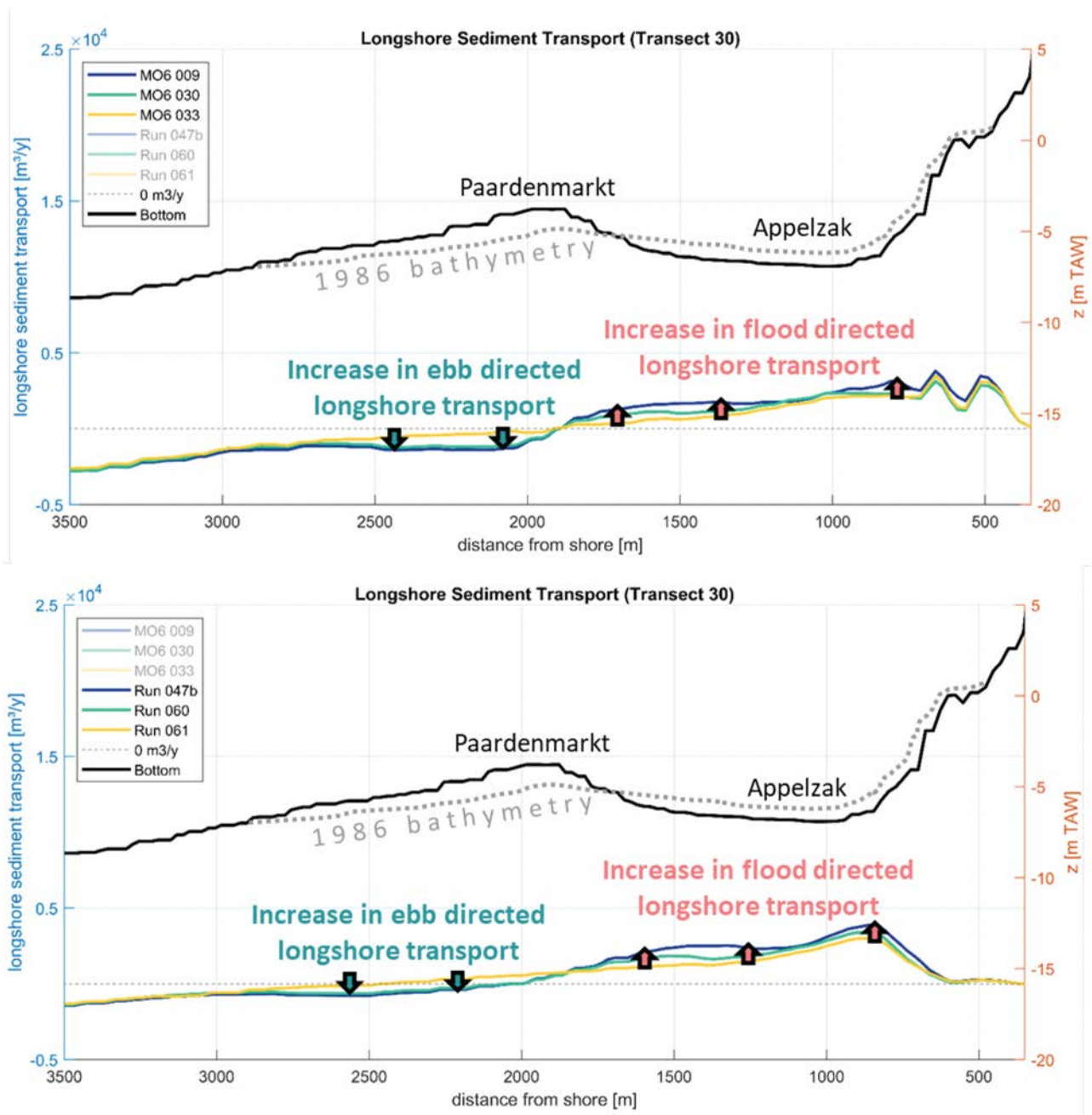


Figure 3-48: Cross-shore distribution of the total longshore sediment transport simulated with the Scaldis-Coast (top) and FlemCo (bottom) for transect 30, running over the Paardenmarkt sand ridge and Appelzak channel at the Zwin.

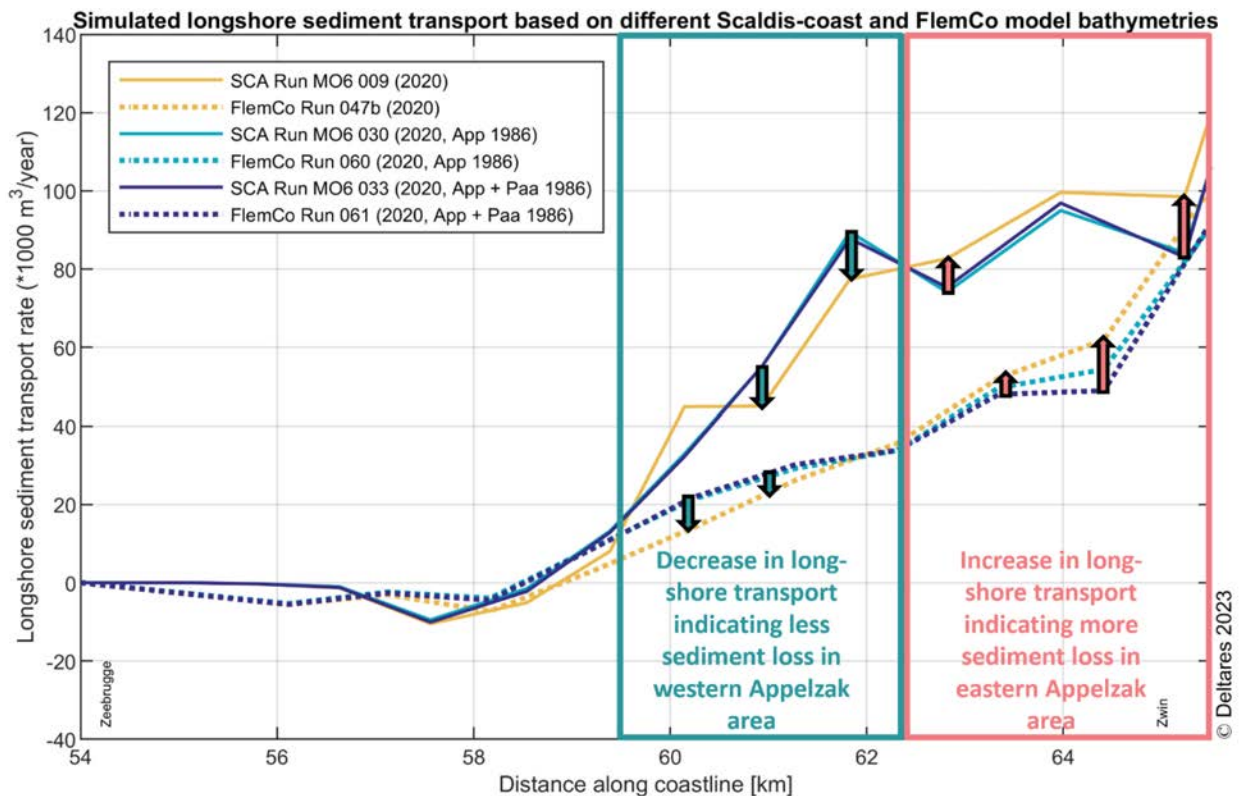


Figure 3-49: Sediment longshore transport as simulated with the Scaldis-Coast (full lines) and FlemCo (dashed lines) model with full hydrodynamic forcing based on realistic 2020 bathymetry and synthetic bathymetries for Appenzak and Paardenmarkt 1986.

3.3.5 Morphological hindcast and forecast simulations for Knokke-Zoute considering various beach nourishment scenarios

3.3.5.1 Introduction

In Dujardin et al., (2025), a first attempt was made to hindcast the morphological changes in the Knokke-Zoute area for the period 1999-2003 (just after a beach nourishment carried out in 1999) using the two models Scaldis-Coast (model settings version described in Wang et al., 2025) and FlemCo models. The models were improved and calibrated through fine-tuning of the model settings to achieve the best possible agreement with observed sedimentation and erosion patterns over the period 1999 to 2002/2003. The models were further validated for another period (2019-2022) (just after a beach nourishment carried out in 2019) to evaluate their performance. Finally, the two models were used to study the morphodynamic behaviour of the Knokke-Zoute area in two beach nourishment scenarios: (i) Albertstrand beach nourishment (straightening the Albertstrand coast) (simulation period: 2022-2025) and (ii) Knokke-Zoute beach nourishment (simulation period: 2025-2029). The implementation of the model runs and the results are presented in the following sections.

3.3.5.1.1 Model settings

After model calibration and improvement, several changes were made to the physical model parameters and settings of the two models as below:

For the Scaldis-Coast model:

- Erosion on the seawards part of the groynes is restricted by setting the erosion layer to zero.
- The minimum water depth below which the bed is considered as dry was reduced from 0.1 m to 0.01 m.
- Bottom smoothing is set to 2 instead of 0.

Table 3-6 presents the main model settings of the Scaldis-Coast model. Details of other model parameters can be found in Wang et al., (2025).

Table 3-6: Overview of selected parameter settings of the Telemac Scaldis-Coast model used in the study

Effect of waves	Yes
Minimum water depth	0.01 m
Number of sediment fractions	2
Classes sediment diameters	200; 500 μm
Layers initial thickness	100; 0 m
Bed-load transport formula for all sands	4: Bijker (total transport)
Layers non cohesive bed porosity	0.4; 0.4
Slope effect	Yes
Formula for slope effect	1: Koch and Flokstra
Sediment slide	Yes

For the FlemCo model:

For the transverse bed gradient factor for bedload transport – the so-called AlfaBn parameter – we applied a reduced value of 5 (earlier 10) in order to avoid overexaggerated downslope sediment transport in the model. The wave-related suspended and bedload sediment transport factors – the so-called SusW and BedW parameters – were lowered to 0.1 (earlier: 0.2) to avoid too much landward directed wave-related sediment transport, since depth-averaged models cannot solve the wave-related undertow current in the beach zone. For the wave velocity asymmetry in the model (Wform parameter) we applied the more advanced description according to Boechat Albernaz et al. (2019) (earlier: Isobe & Horikawa 1982).

3.3.5.1.2 Simulation period and morphological scale factors

Both Scaldis-Coast and FlemCo models apply the same hydrodynamic simulation period as applied in the 1999-2002/2003 hindcast (Dujardin et al., 2025), i.e. representative half-year (07-11-2013 to 07-05-2014) for the Scaldis-Coast and 82 days (5 January 2024 to 27 March 2024) for FlemCo. Different morphological scale factors were used to extent the hydrodynamic period to the corresponding morphological periods.

Table 3-7: Overview of morphological simulation period and morfac used.

Simulation period	Morphological scale factor	
	Scaldis-Coast model	FlemCo model
1999-2002/2003 – Hindcast	7	15.67
2019-2022 – Hindcast	6	13.44
2022-2025 – Scenario	6	13.44
2024-2029 – Scenario	10	22.39

3.3.5.1.3 Bathymetry data used

For each morphological period/model application, i.e. i) hindcast 1999–2002/2003, ii) hindcast 2019–2022, iii) nourishment scenario Albertstrand starting from 2022 and iv) nourishment scenario Knokke-Zoute starting from 2024, different initial and for the two hindcast periods final bathymetries were prepared according to Table 3-8.

Table 3-8: Overview of the various sources of data used to create the initial and final bathymetries for the various morphological period/model application, i.e. i) hindcast 1999–2002/2003, ii) hindcast 2019–2022, iii) nourishment scenario Albertstrand starting from 2022 and iv) nourishment scenario Knokke-Zoute starting from 2024.

Year	Inside the study area		Outside the study area	
	Beach	Nearshore incl. shoreface	JarKus	Vaklodingen
1999	Jun 1999 (g_vo_vj1999)	Jun 1999 (g_vo_vj1999)	Summer 1999	Summer 1998 & 1999
2002/2003	Dec 2002 (g_2002_2e)	Apr 2003 (g_vo_vj2003)	Summer 2003	Summer 2003
2019	Jun 2019 (g_2019_1e_10)	Jun 2019 (g_vo2019_1E)	Summer 2020	Summer 2020
2022	Jun 2022 (g_vo2022_1liE)	Jun 2022 (g_vo2022_1liE)	Summer 2020	Summer 2020
2024	Mar 2024 (g_2024_03ap_E)	Mar 2024 (g_2024_03ap_E)	Summer 2020	Summer 2020

3.3.5.2 Hindcast 1999–2002 (model calibration)

In this hindcast period, the model simulations start after a large beach nourishment of about 413,000 m³ of the profile. Note that 15 % of this volume was nourished below the low water line (Houthuys et al., 2022). No additional nourishment took place during the considered period.

Figure 3-50 compares the bed level changes according to the measurements and the two models Scaldis-Coast and FlemCo for the period 1999 to 2002/2003. The red polygon indicates the area of the nourishment performed in May 1999, excluding the area that lies above the high water level (approximately 5.33 m TAW/3 m NAP), for which no morphodynamics are calculated because these are associated with aeolian sediment transport which is not considered in both models. The red polygon was used to calculate the bed volume changes in the period 1999-2002/2003 based on the measurements and the two models.

The measurements show that the bed level changes in the observed period typically range between -0.5 m to +0.5 m, with local changes reaching up to -1.5 m to +1.5 m. In the area of the 1999 nourishment (red polygon), the beach strip above 0 m NAP is characterised by significant, relatively uniform erosion of about 1.5 m. Also the adjacent shoreface (between the beach and ca. -8 m to -9 m NAP) show dominant erosion, although to a smaller degree compared with the beach. The shoreface only shows local sedimentation adjacent to the groynes. The area seawards of the red polygon (i.e. the western part of the Appelzak channel) is characterised by erosion of up to 0.5 m. West of the Appelzak channel, dominant sedimentation is observed during the considered period.

The Scaldis-Coast and FlemCo models generally reproduce the overall erosional trend as derived from the measured bed level changes in the study area. However, both models underestimate the erosion along the beach in the zone above mean sea level (above 0 m NAP), probably due to aeolian transport processes which are not considered by the models. Moreover, wave related cross-shore transport – which may contribute to the beach erosion – is not considered (Scaldis-Coast) or only parameterised (FlemCo) in the models due to the applied depth-averaged (2DH) computational mode. Also the observed shoreface erosion is underestimated by both models which both – but especially the Scaldis-Coast model – indicate a sedimentation zone directly seawards of the groynes. The sedimentation is most probably associated with an exaggerated sediment relocation from the beach and upper shoreface to the lower shoreface in the two models. This is indicated by the converging residual sediment transport vectors in the sedimentation zone as exemplarily depicted for the FlemCo model in Figure 3-51. The convergence is the result of seaward directed residual transport predicted for the areas between the groynes, due to the clockwise and counterclockwise flow vortices that can be observed in this area during ebb and flood (Figure 3-52).

Outside the red polygon (i.e. seawards of the -8 m NAP contour line), both models predict dominant erosion which is consistent again with the observed bed level changes. However, the predicted erosion reaches too far westwards, which is in contrast to the observed sedimentation in this area. This mismatch might be related to the role of erosion resistant layers in the bed, which are not considered in the two models.

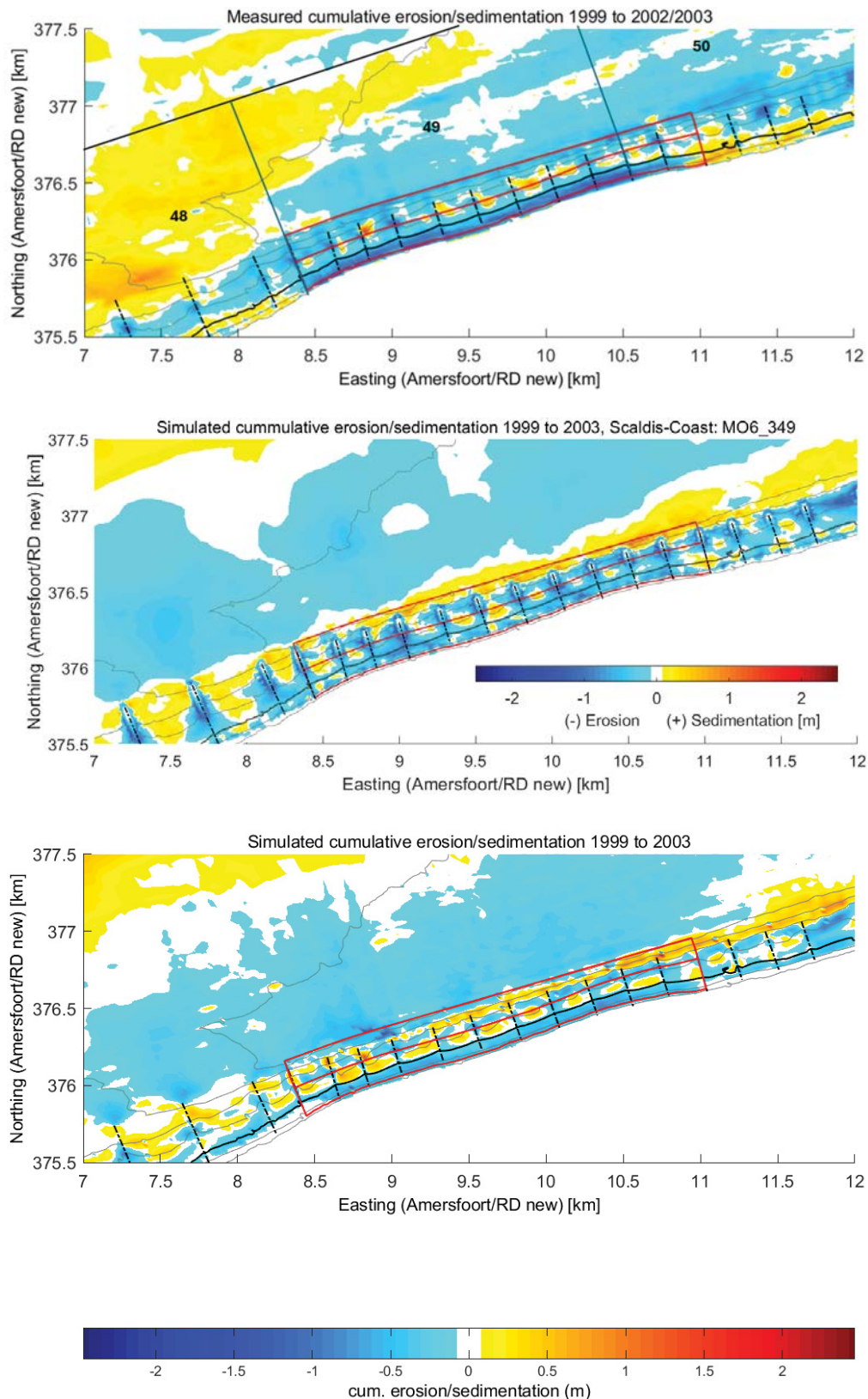


Figure 3-50: Bed level differences between 1999 and 2003 in the Knokke-Zoute area: measured (top), Scaldis-Coast model (centre) and FlemCo model (bottom). The grey contour lines have an interval of 2 m. The black line indicates the coastline (0 m NAP). The black dashed lines show the groynes. The red polygon indicates the zones used for calculating bed volume changes (area of nourishment performed in May 1999 excluding dry part).

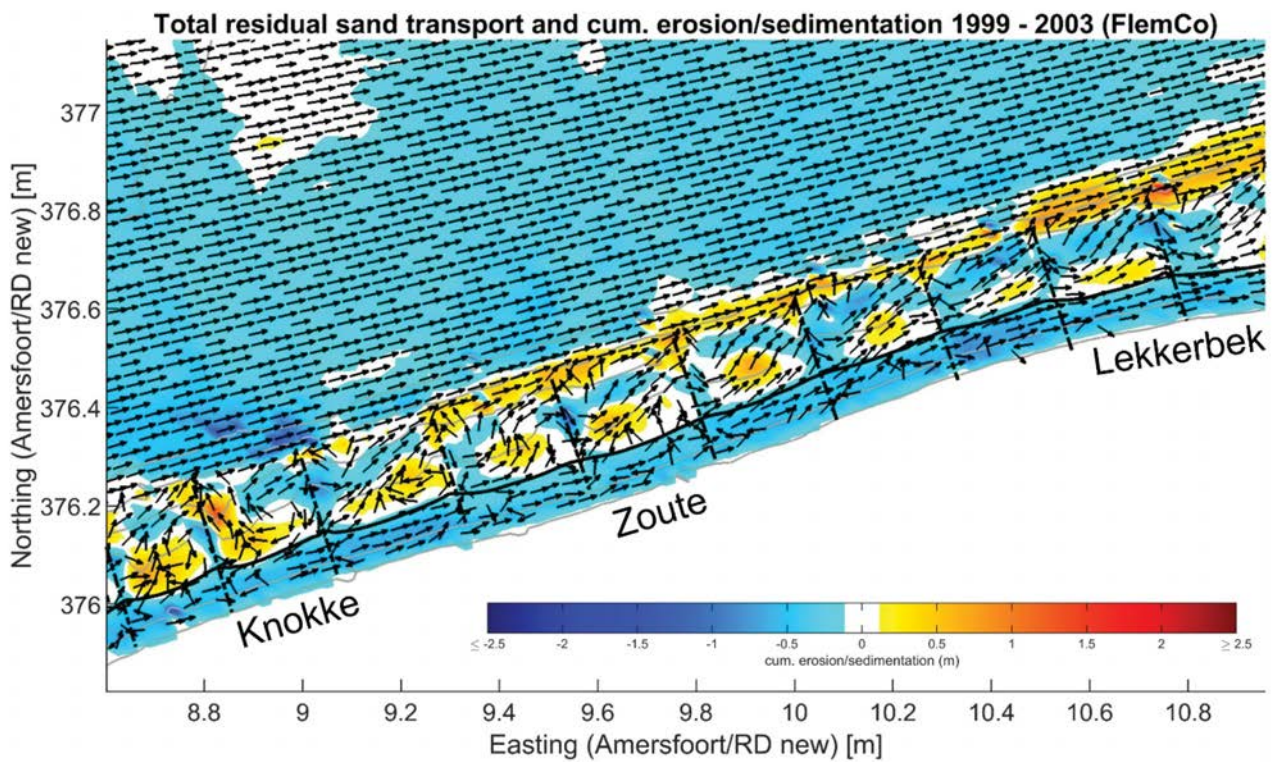


Figure 3-51: Total (bedload and suspended load) residual sand transport and associated cumulative erosion/sedimentation in the hindcast period 1999 and 2003 in the Knokke-Zoute area according to the FlemCo model. The grey contour lines have an interval of 2 m. The black line indicates the coastline (0 m NAP). The black dashed lines show the groyne.

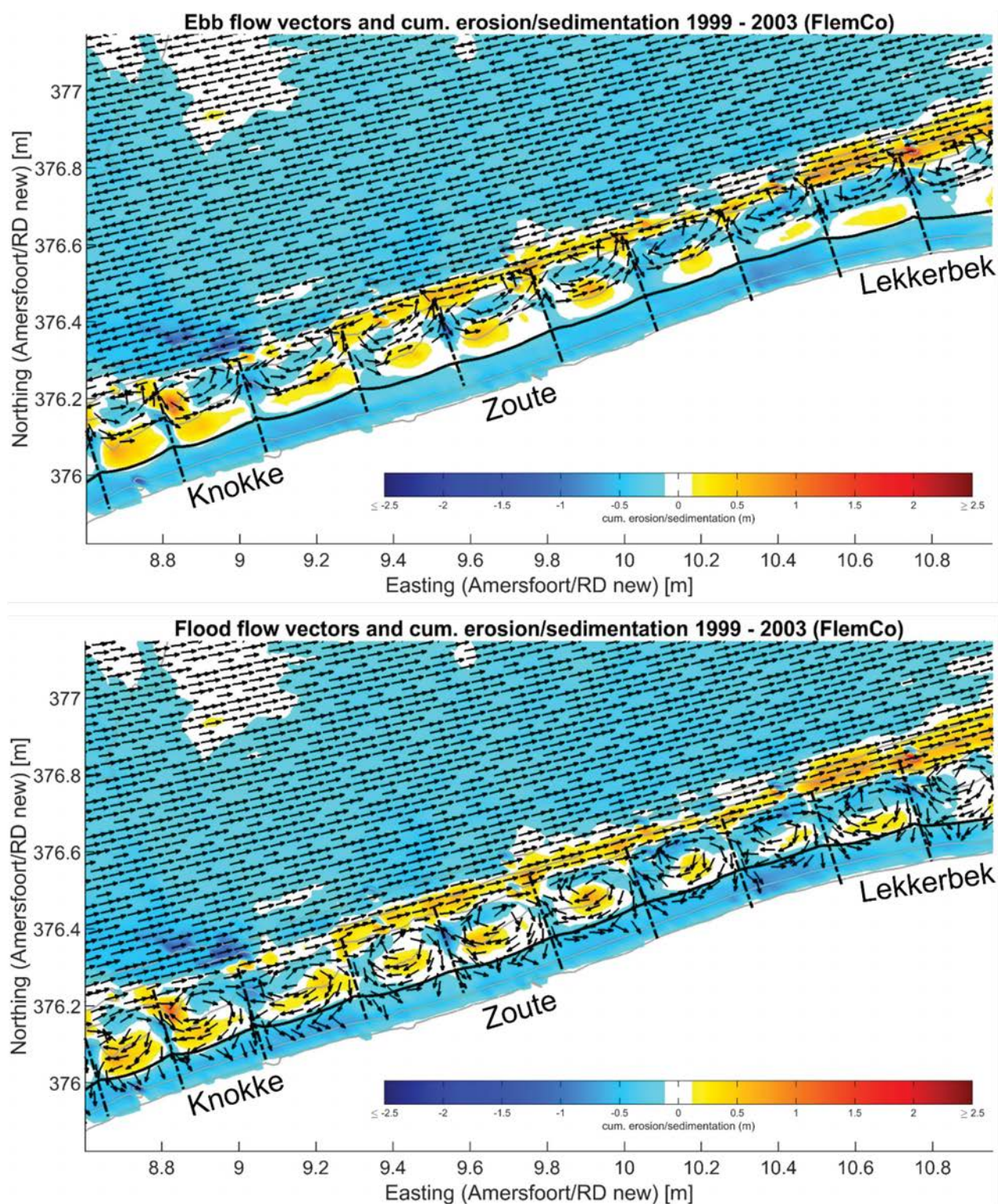


Figure 3-52: Typical instantaneous ebb flow (top) and flood flow (bottom) vectors and cumulative erosion/sedimentation in the hindcast period 1999 and 2003 in the Knokke-Zoute area according to the FlemCo model. The grey contour lines have an interval of 2 m. The black line indicates the coastline (0 m NAP). The black dashed lines show the groynes.

The morphological model results are further evaluated by comparing the bed volume changes in the period 1999-2002/2003 derived from the measurements and the two models (Table 3-9) for the area of the nourishment performed in May 1999 (excluding the dry area above 3 m NAP). The analyses were performed for two distinct zones (see Figure 3-53):

- Shoreface: ca. -8 m NAP to -2 m NAP
- Wet beach: ca. -2 m NAP to +3 m NAP

Note that for the area of the dry beach (ca. +3 m NAP to +6 m NAP), only the measured volume changes were analysed, while the simulated volume changes could not be considered because this area lies above the high water level, meaning that no morphodynamics are predicted by the two models.

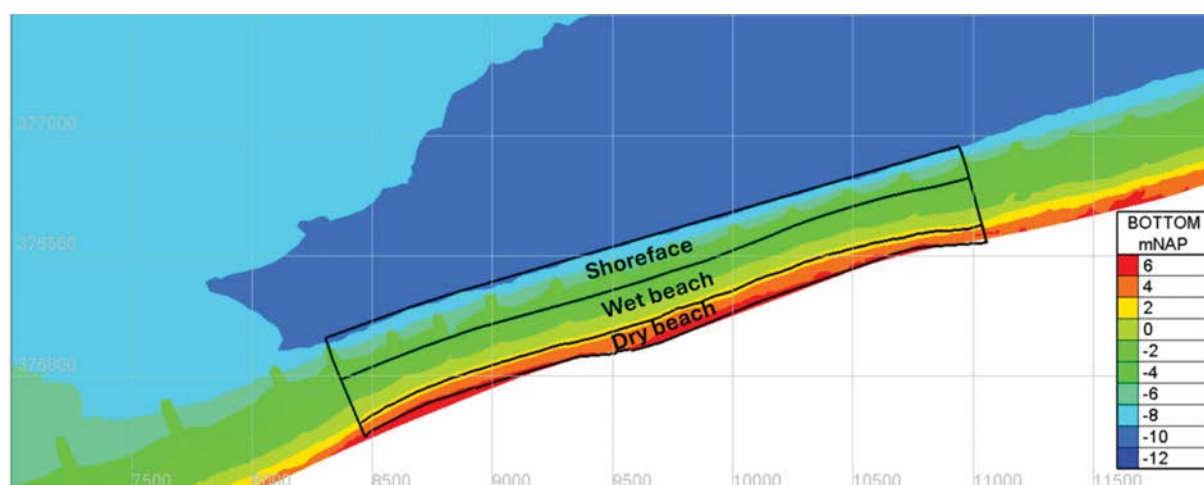


Figure 3-53: Three zones in the Knokke-Zoute nourishment area used for the calculation of bed volume changes 1999-2002/2003.

Table 3-9: Bed volume changes in the nourishment area at Knokke-Zoute in the period 1999-2002/2003 derived from measured bed levels and from the Scaldis-Coast and FlemCo models. Negative values indicate sediment loss.

Bed volume changes 1999-2003 [$\times 10^3 \text{ m}^3$]			
Polygons	Measurements	Scaldis-Coast	FlemCo
Dry beach	-28.1	n.a	n.a
Wet beach	-169.8	-136.5	-78.2
Shoreface	-122.6	-53.4	-17.6
Wet beach + Shoreface	-292.3	-189.9	-95.8

The measurements indicate erosion in all three zones in the calibration period (Table 3-9). The erosion volume in the dry beach area is rather small ($28,100 \text{ m}^3$) while a significant sediment loss is observed for other two zones: beach ($169,800 \text{ m}^3$) and shoreface ($122,600 \text{ m}^3$). The total volume loss in these two zones during the period 1999-2002/2003 amounts to $292,300 \text{ m}^3$.

Both models capture the overall erosional trend but underestimate the magnitudes. The Scaldis-Coast model calculates slightly lower volume changes for the beach compared to the data (136,500 m³ vs. 169,800 m³) and underestimates the volume loss for the shoreface by a factor of 2. Overall, the Scaldis-Coast model predicts about 65% of the total observed volume loss.

The FlemCo model underestimates the observed volume loss in the shoreface zone (almost by factor 7) and in the beach (by factor 2). Altogether, the FlemCo model predicts about 33 % of the total observed volume loss within the considered area.

3.3.5.3 Hindcast 2019–2022 (model validation)

The two models were run using the same settings as applied during the calibration period to validate the models. A three-year period (2019-2022) is selected for the validation runs. In contrast to the calibration period described above, nourishments were carried out during the validation period, providing a suitable case for assessing the model performance under nourishment conditions.

During the period 2019-2022, nourishments were carried out at two locations, i.e. the Appelzak channel and the Duinbergen area, both in 2021 (see Figure 3-54):

- Sand nourishment of 293,000 m³ in the Appelzak channel
- Sand nourishment of 982,000 m³ in the Duinbergen area, about 3 km west of Knokke-Zoute.

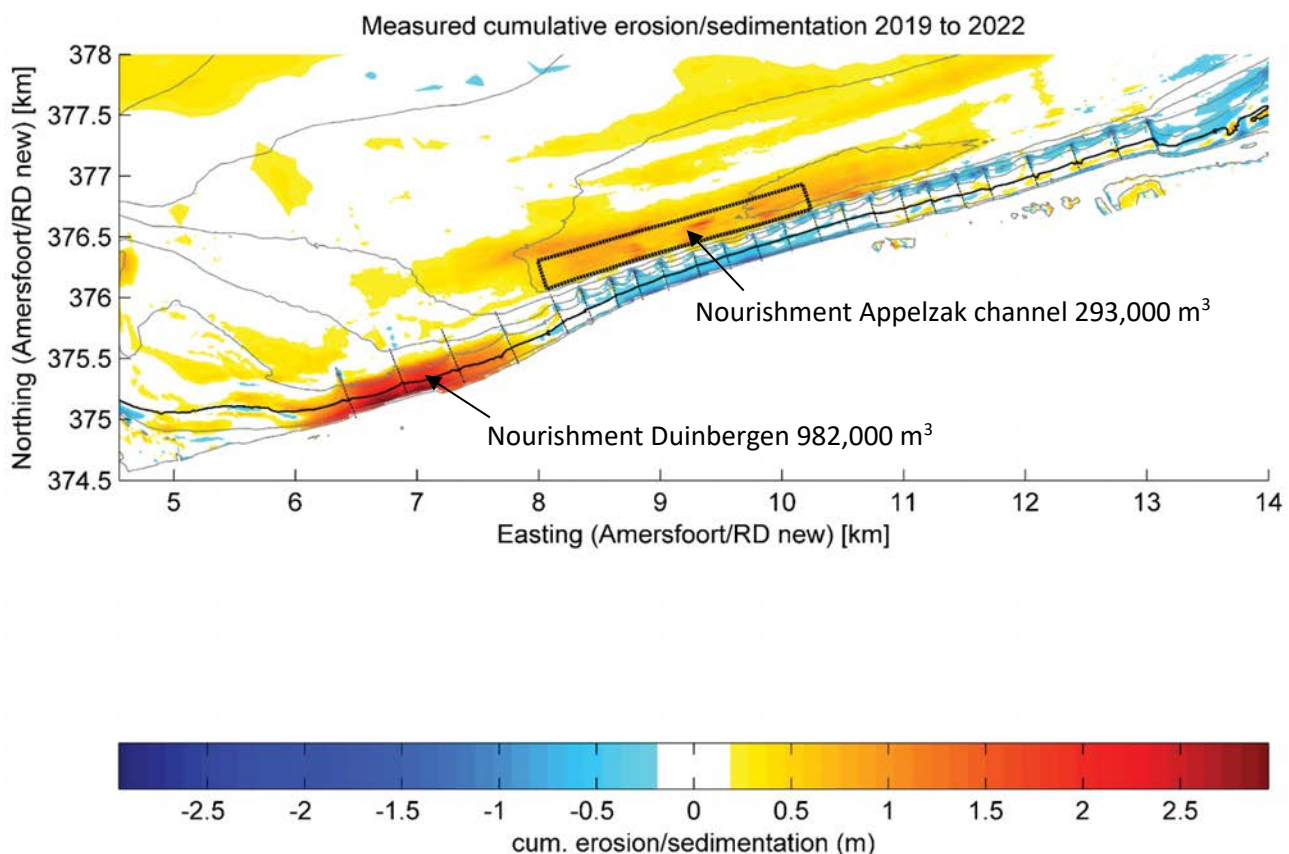


Figure 3-54: Measured cumulative erosion and sedimentation in the model validation period 2019 to 2022 and areas in which sand nourishments were carried out in this period.

Figure 3-55 shows the bed level changes according to the measurements and the two models Scaldis-Coast and FlemCo for the second hindcast period (2019-2022). The red polygons indicate the two areas at Knokke-Zoute (beach and shoreface) for which bed volume changes are calculated and evaluated.

The measurements indicate dominant erosion of the beach and the upper shoreface at Knokke-Zoute. This erosion is generally well reproduced by both models. Due to the sand nourishment carried out in the Appelzak channel in 2021, vast sedimentation can be observed in the hindcast period, which is also predicted by both models. However, the measured bed level changes indicate sedimentation also for the area seawards of the nourishment, while the models predict erosion or no bed level changes. This discrepancy can partly be explained by the immediate spreading of sediment during the execution of sand nourishments, a process not considered by both models, where the nourished sand is directly added to the bed and not disposed at the water surface.

Table 3-10 compares the bed volume changes derived from the data and the two models for the period 2019-2022 in the two zones beach and shoreface. The measured bed volume changes for the period 2019-2022 indicates net erosion of 117,000 m³ on the beach and net accretion of 38,000 m³ on the shoreface, resulting in a net erosion of 79,000 m³ for the combined area.

Both models reproduce the observed erosional trend on the beach and sedimentation on the shoreface. The Scaldis-Coast model shows stronger beach erosion and weaker shoreface sedimentation compared to the measurements, leading to an overestimation of the total erosion by a factor of 1.7. The FlemCo model simulates beach erosion closer to the measured value (122,000 m³) and gives stronger shoreface accretion (67,000 m³). In both areas together, the FlemCo model underestimates the measured volume loss by a factor of 1.4. Both models are unable to reproduce observed erosion on the dry beach (above 3 m NAP) since this erosion is associated with aeolian sediment transport, which is not considered by the models.

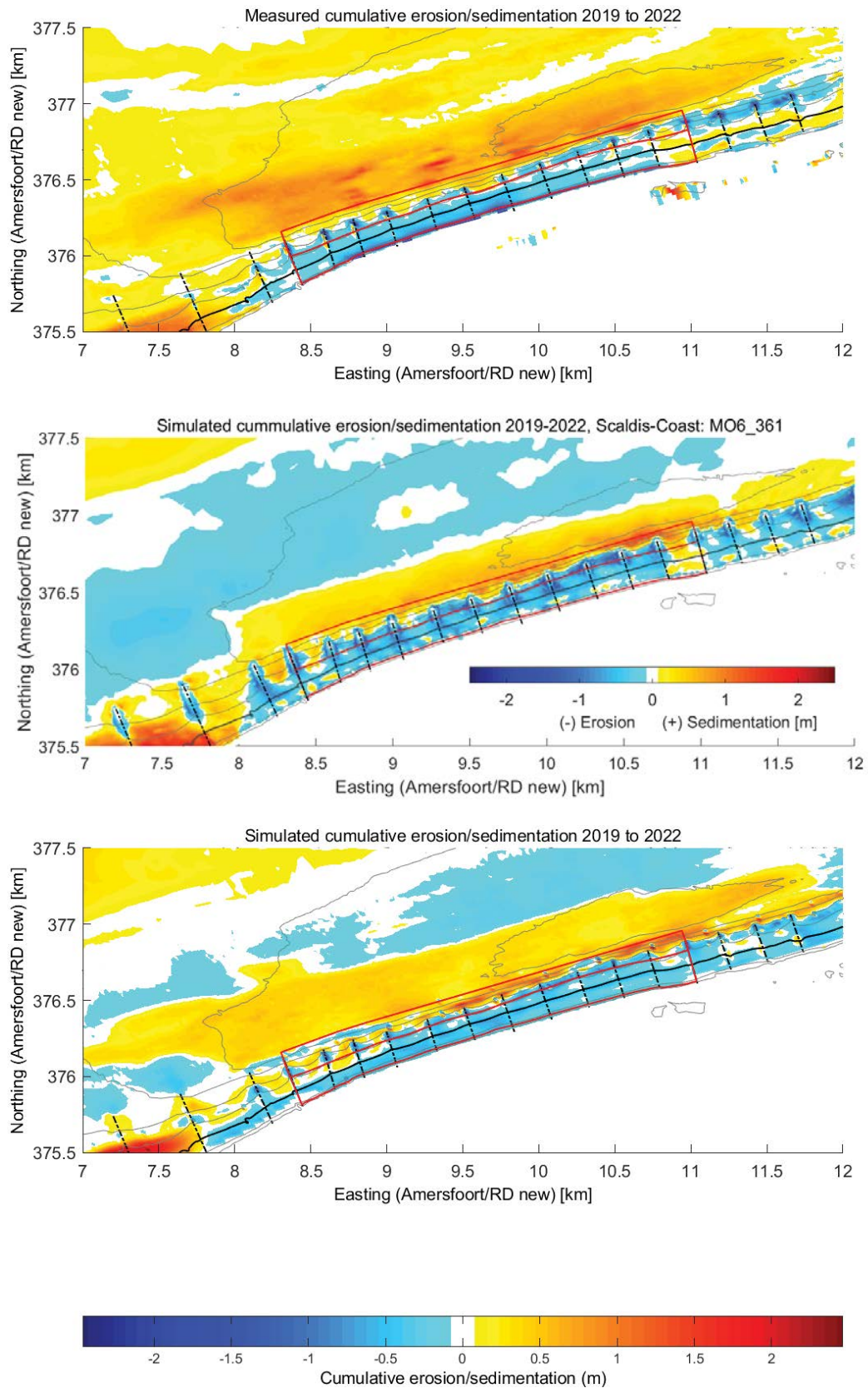


Figure 3-55: Bed level differences between 2019 and 2022 in the Knokke-Zoute area: measured (top), Scaldis-Coast model (centre) and FlemCo model (bottom). The grey contour lines have an interval of 2 m. The blackline indicates the coastline (0 m NAP). The black dashed lines show the groyne.

Table 3-10: Bed volume changes in the nourishment area at Knokke-Zoute in the period 2019-2022 derived from measured bed levels and from the Scaldis-Coast and FlemCo models. Negative values indicate sediment loss and positive values show sediment gain.

Bed volume changes 2019-2022 [$\times 10^3 \text{ m}^3$]			
Polygons	Measurements	Scaldis-Coast	FlemCo
Beach	-117.2	-155.4	-122.3
Shoreface	38.3	22.2	66.5
Beach + Shoreface	-78.9	-133.2	-55.8

3.3.5.4 Beach nourishment scenario Albertstrand – straightening the Albertstrand coast

The objective of this model scenario is to investigate the influence of straightening the adjacent Albertstrand coast on the morphodynamics in the Knokke-Zoute area (see Figure 3-56 for the location). The Albertstrand coast, located west of Knokke-Zoute, has a curved shoreline. In this scenario, the curved coast of Albertstrand is straighten based on the bathymetry measured in 2022. The models run for three years for the two cases, with and without straightening of the Albertstrand coast. The model results are then compared to assess how changes in the nearby coast affect the morphological behaviour of the Knokke-Zoute area.

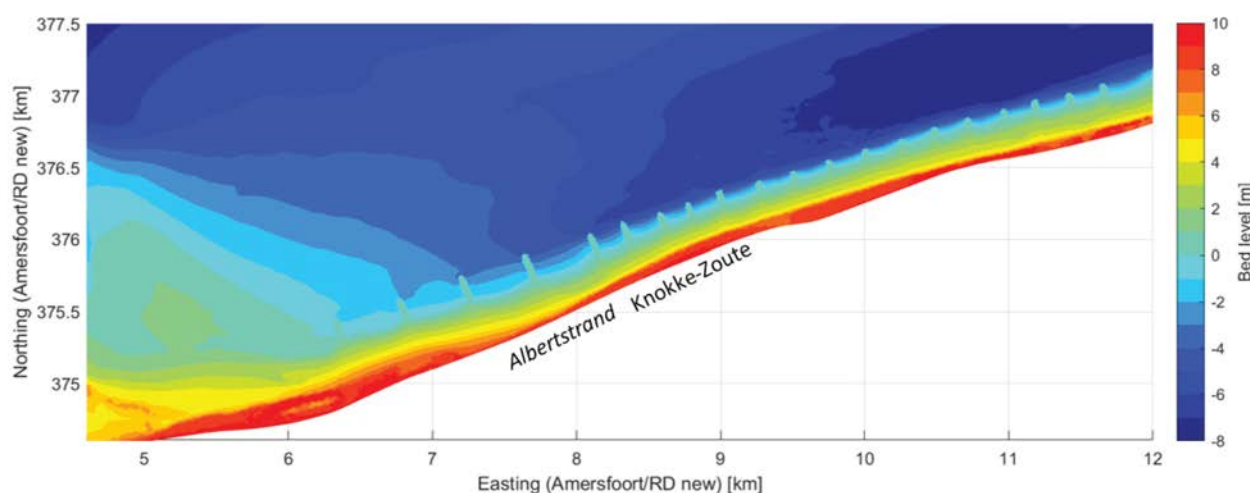


Figure 3-56: Location of Albertstrand and Knokke-Zoute area.

Figure 3-57 shows the bathymetry of the Albertstrand area in 2022, the designed straight coast and the bathymetric difference between the two cases. Several representative cross-sections are plotted in Figure 3-58. To achieve the designed bathymetry, sediment nourishment is required with nourishment volume of approximately $1,050,000 \text{ m}^3$. The bed level is raised by up to 4 m.

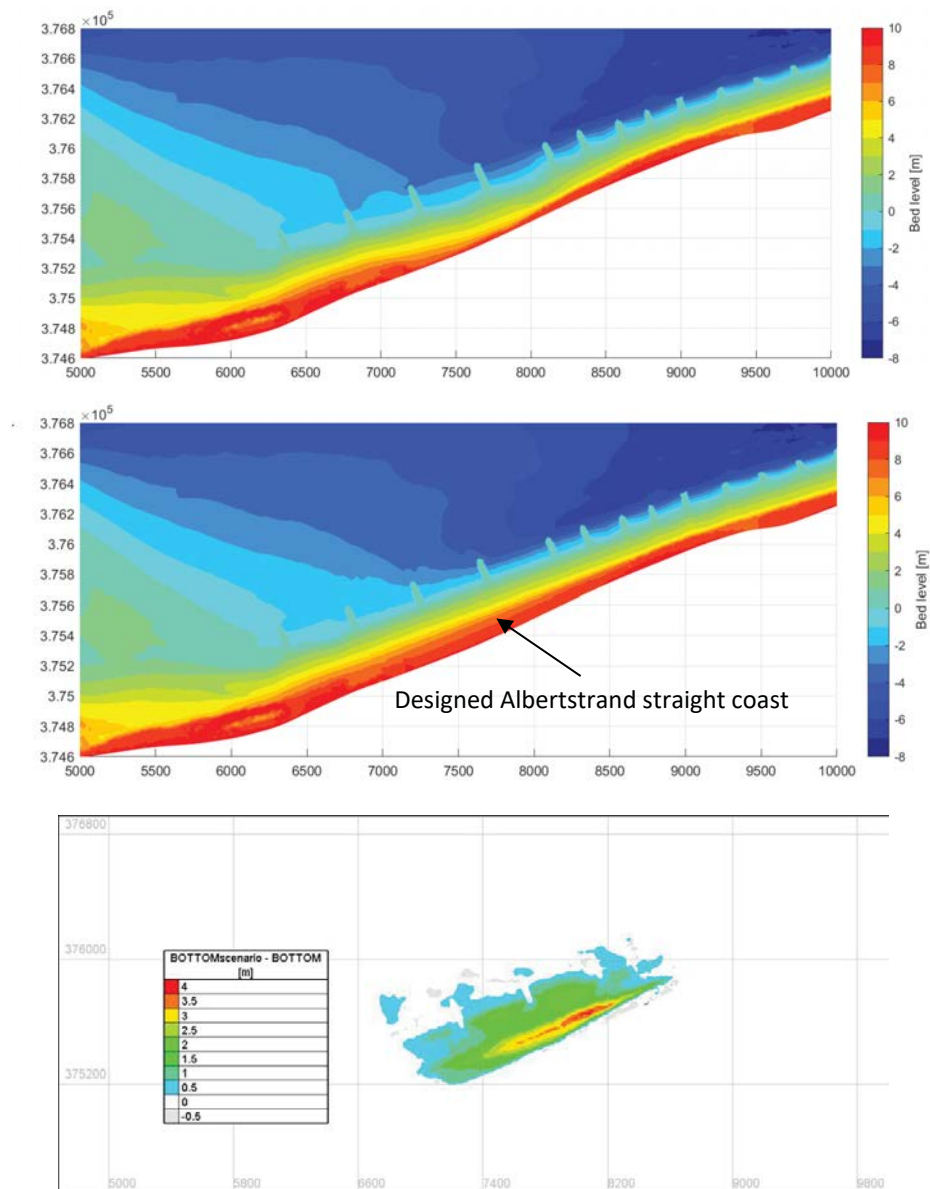


Figure 3-57: Straightening Albertstrand coast: measured bed level 2022 (upper), designed straight coast (centre) and bathy difference (2022 scenario – 2022) (lower).

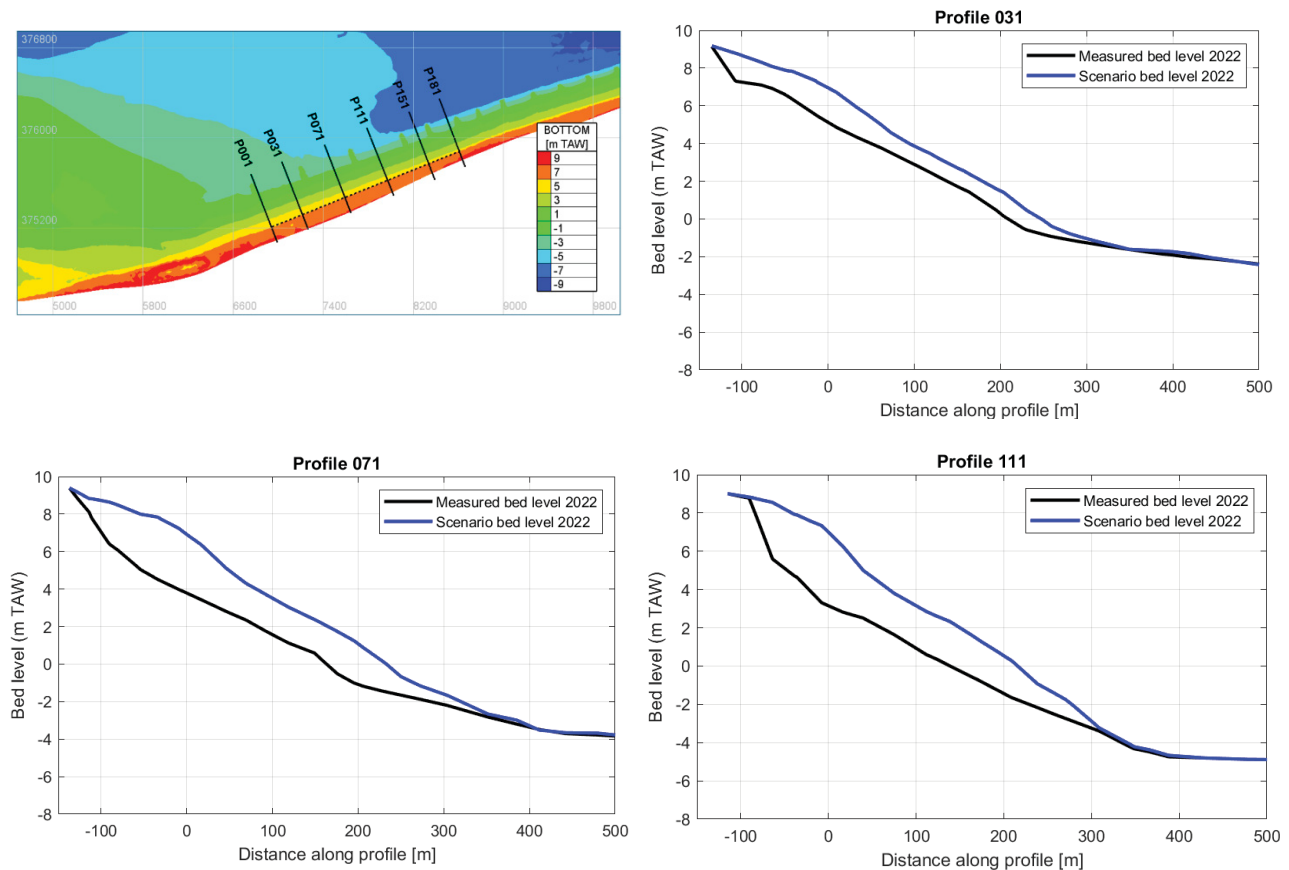


Figure 3-58: Beach profiles at Albertstrand area: measured 2022 (black) and Albertstrand straight coast scenario (blue).

Figure 3-59 presents a comparison of bed level changes over three years between the reference case and scenario case computed from Scaldis-Coast model. The results obtained from the FlemCo model are illustrated in Figure 3-60. Both models show that the straightening of the Albertstrand coast hardly causes changes of the predicted coastal morphology in the study area, except for the Albertstrand coast where the nourishment is performed. The nourished sediment remains relatively stable in the simulation period. This stability is mainly attributed to the location of the Albertstrand coast within the sheltered zone of the Zeebrugge port where wave energy and longshore sediment transport are significantly reduced, resulting in minor sediment redistribution (cf. Section 3.3.2).

The effect can be further explained by examining the residual sediment transport from the Scaldis-Coast model over the entire three-year simulation period 2022-2025 for the reference and scenario cases (Figure 3-61). The transport pattern shows nearly identical sediment transport magnitudes and directions between the two cases, except in the straightened section. Within the modified area, the sediment transport becomes more aligned with the straight shoreline. These are also confirmed in Figure 3-62 which shows the difference in the residual sediment transport between the two cases computed using the FlemCo model. Except for the altered area at Albertstrand, the difference in residual sediment transport is zero across the domain.

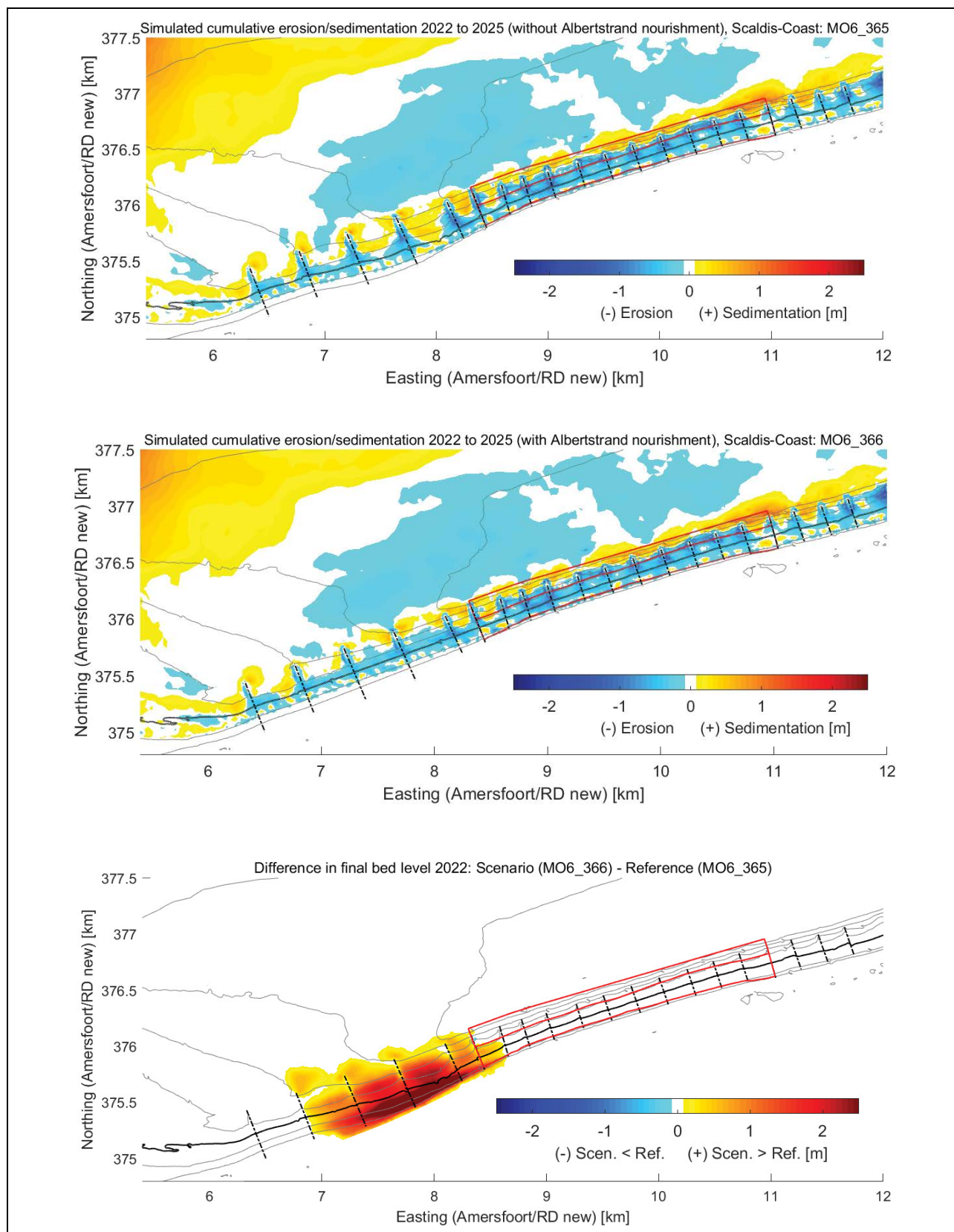


Figure 3-59: Scaldis-Coast model: bed level differences between 2022 and 2025 in the Knokke-Zoute and Albertstrand area for the case of without (upper), with (centre) Albertstrand nourishment and the difference of modeled bed level 2025 between the two cases. The grey contour lines have an interval of 2 m. The blackline indicates the coastline (0 m NAP). The black dashed lines show the groynes.

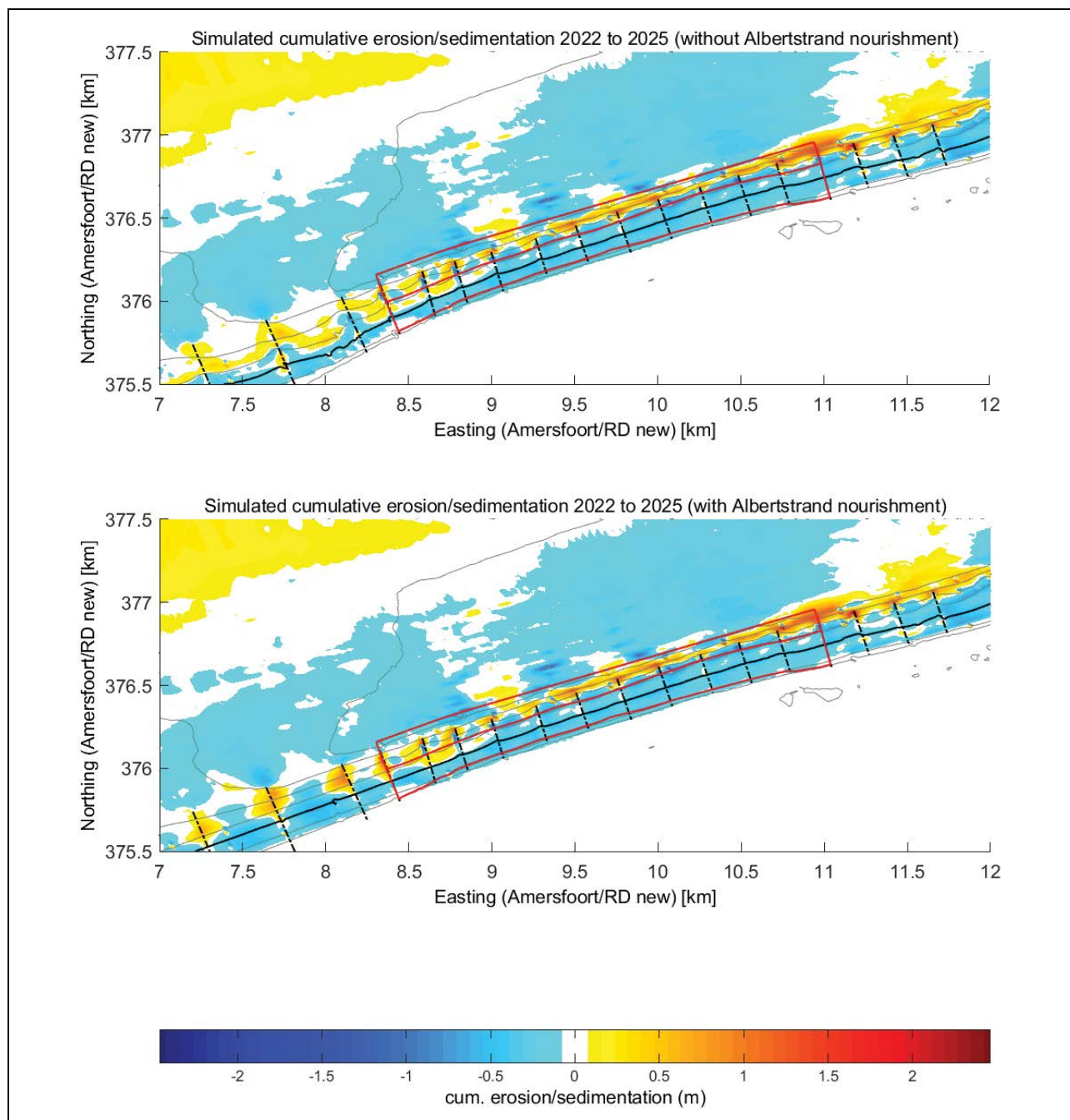


Figure 3-60: FlemCo model: bed level differences between 2022 and 2025 in the Albertstrand and Knokke-Zoute area for the case of without (upper), with (lower) Albertstrand nourishment. The grey contour lines have an interval of 2 m. The blackline indicates the coastline (0 m NAP). The black dashed lines show the groynes.

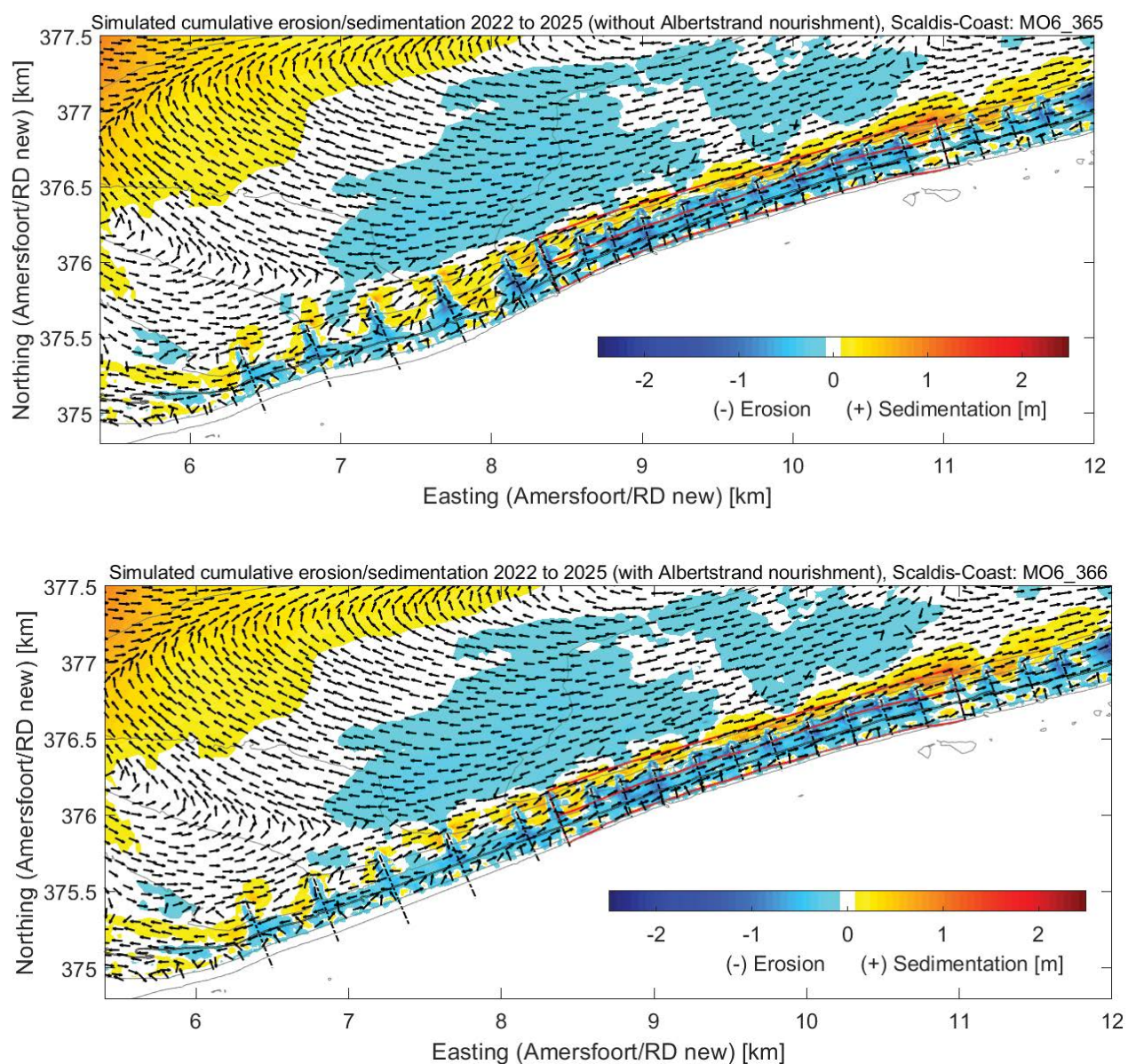


Figure 3-61: Scaldis-Coast simulated bed level differences between 2022 and 2025 and associated total transport vectors in the Albertstrand and Knokke-Zoute area.

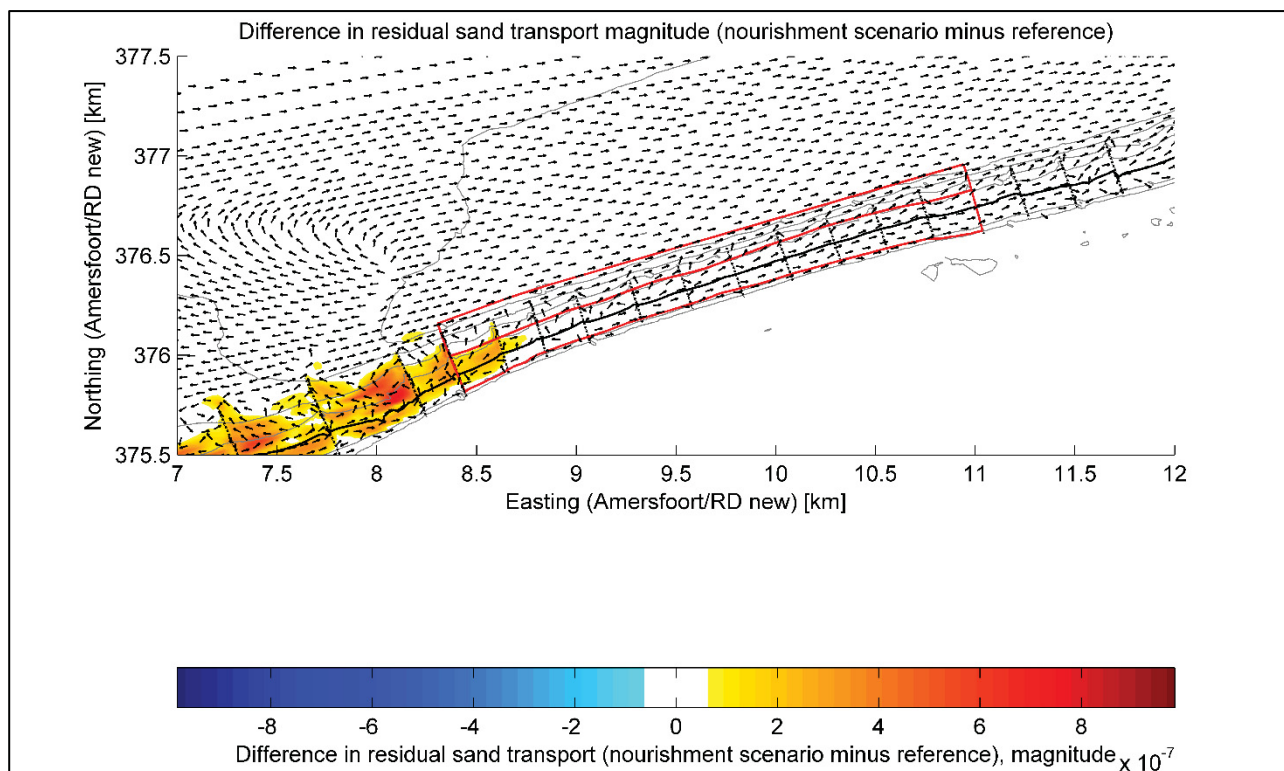


Figure 3-62: Difference in residual sediment transport between the two cases (with-without straightening Alberstrand coast) computed from the FlemCo model.

3.3.5.5 Beach nourishment scenario Knokke-Zoute

This model scenario was developed based on a conceptual design proposed by Coastal Division as illustrated in Figure 3-63. Using the 2024 topo/bathymetric data, the nourishment was designed according to a pre-designed profile as shown in Figure 3-64 and Figure 3-65. The beach profile incorporates different slopes across the cross-section (Figure 3-63). The proposed nourishment requires the placement of approximately 425,000 m³ of sediment.

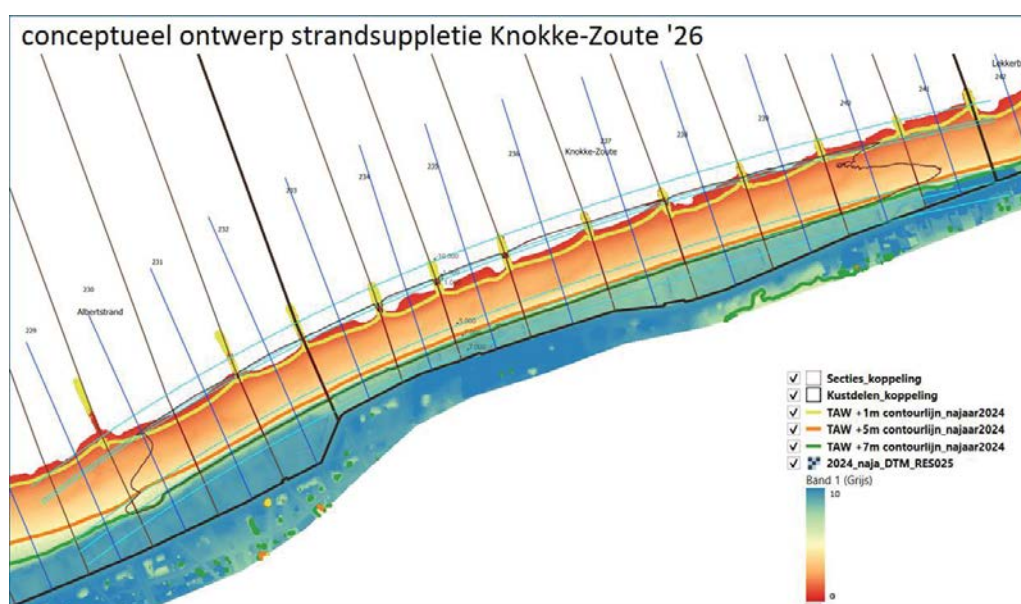


Figure 3-63: Conceptual design idea of Coast Division for beach nourishment at Knokke-Zoute.

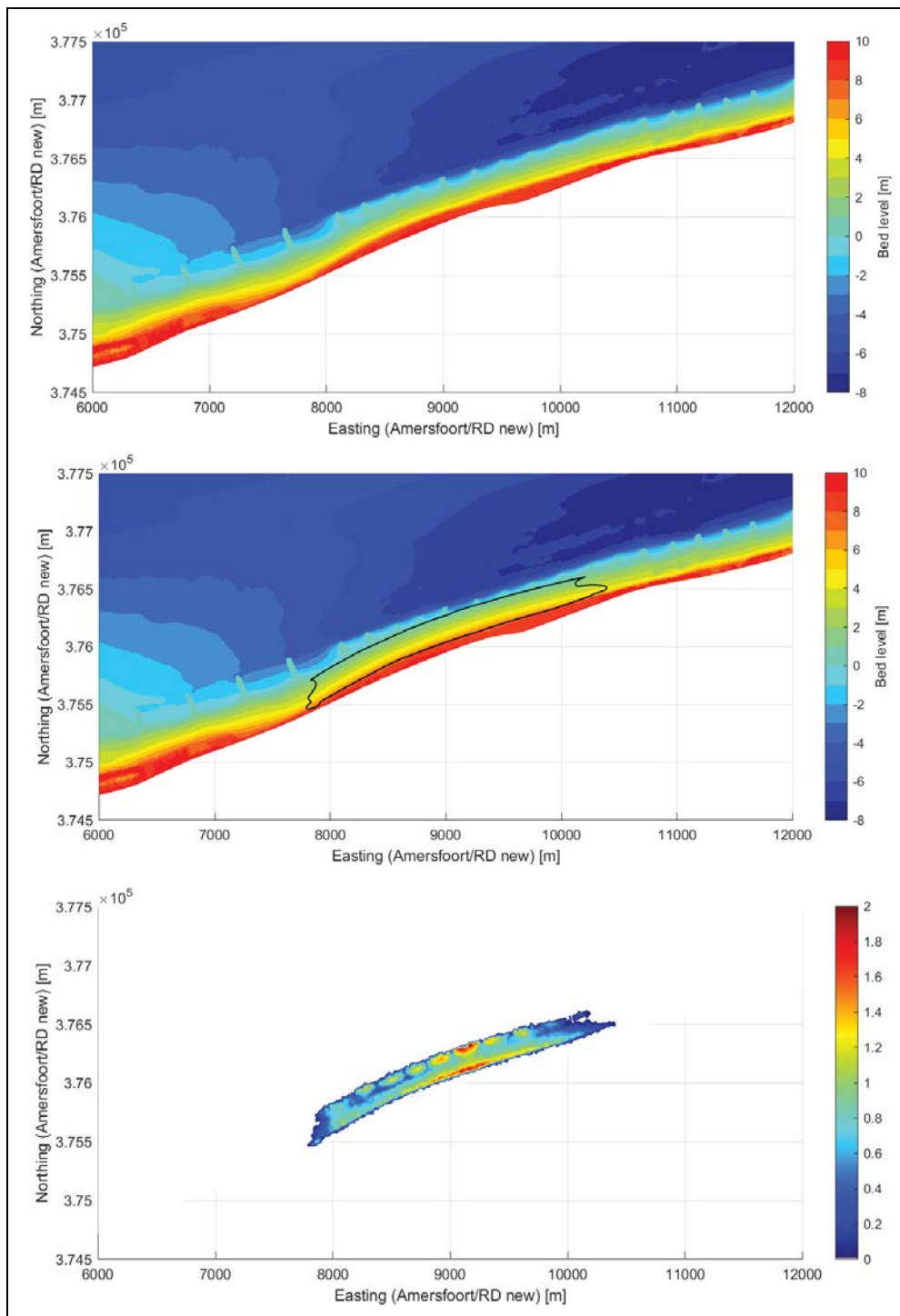


Figure 3-64: Scenario beach nourishment at the Knokke-Zoute: measured bed level 2024 (upper), bed level with nourishment (middle) and bathy difference (2024 scenario – 2024 reference) (lower). Black polygon shows the sand nourishment area.

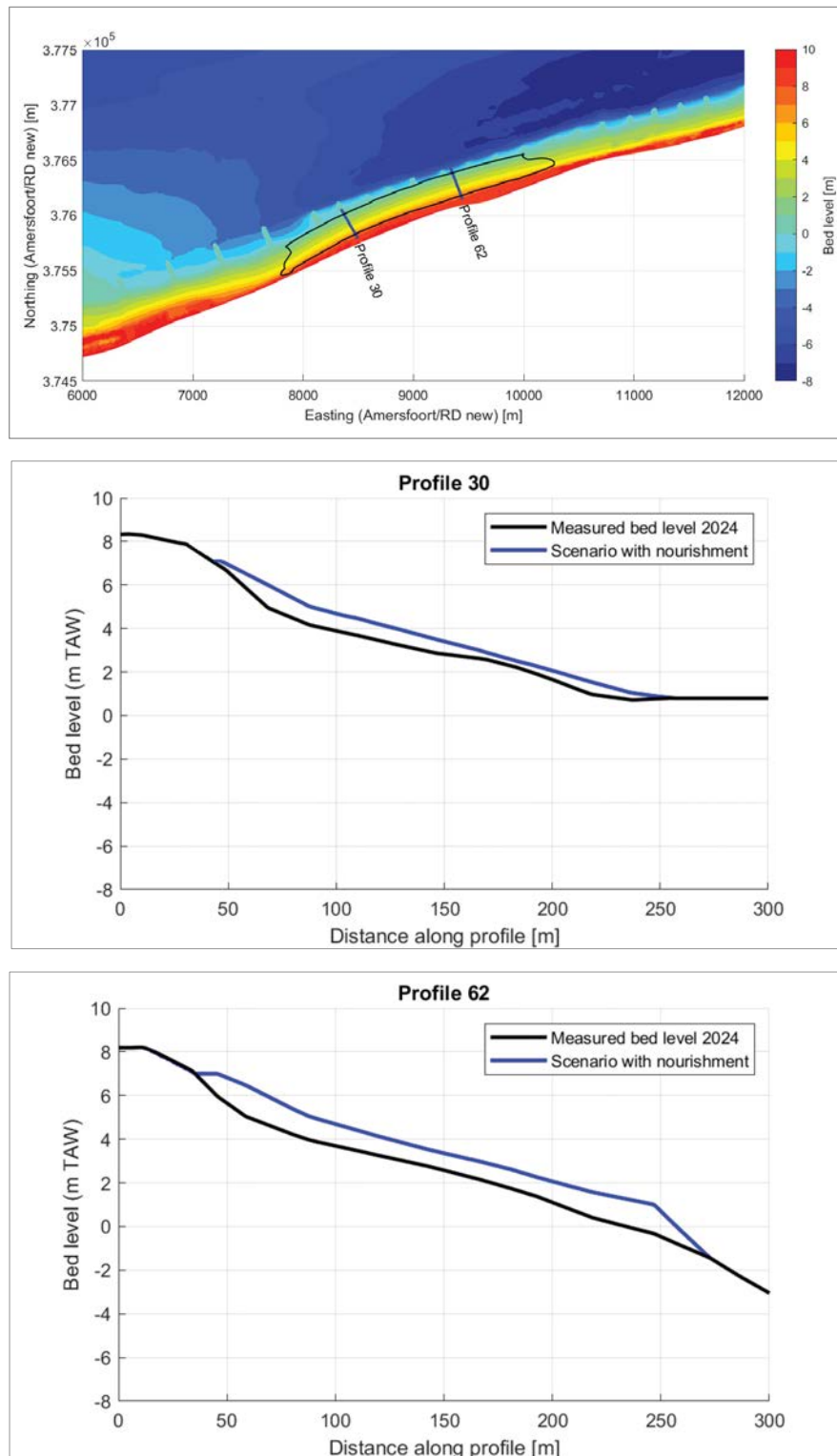


Figure 3-65: Beach profiles at Knokke-Zoute area: measured 2024 (black) and beach nourishment scenario (blue).

Figure 3-66 presents a comparison of bed level changes over five years between the reference case (without Knokke-Zoute nourishment) and scenario case (with Knokke-Zoute nourishment) computed using the Scaldis-Coast model. The corresponding results obtained from the FlemCo model are illustrated in Figure 3-67. Both models simulate the erosion in the beach area for both reference and nourishment scenario. Erosion is also predicted along the landward part of the shoreface while sedimentation occurs on the seaward side. The Scaldis-Coast model shows stronger sedimentation compared to the FlemCo model.

Compared with the reference run (i.e. without Knokke-Zoute nourishment), both models predict more erosion along the transition between the beach and the shoreface. The FlemCo model also indicates an increased erosion on the beach. In contrast, the Scaldis-Coast model predicts reduced erosion, or even no bed level changes along the upper beach (landward part) for the nourishment scenario.

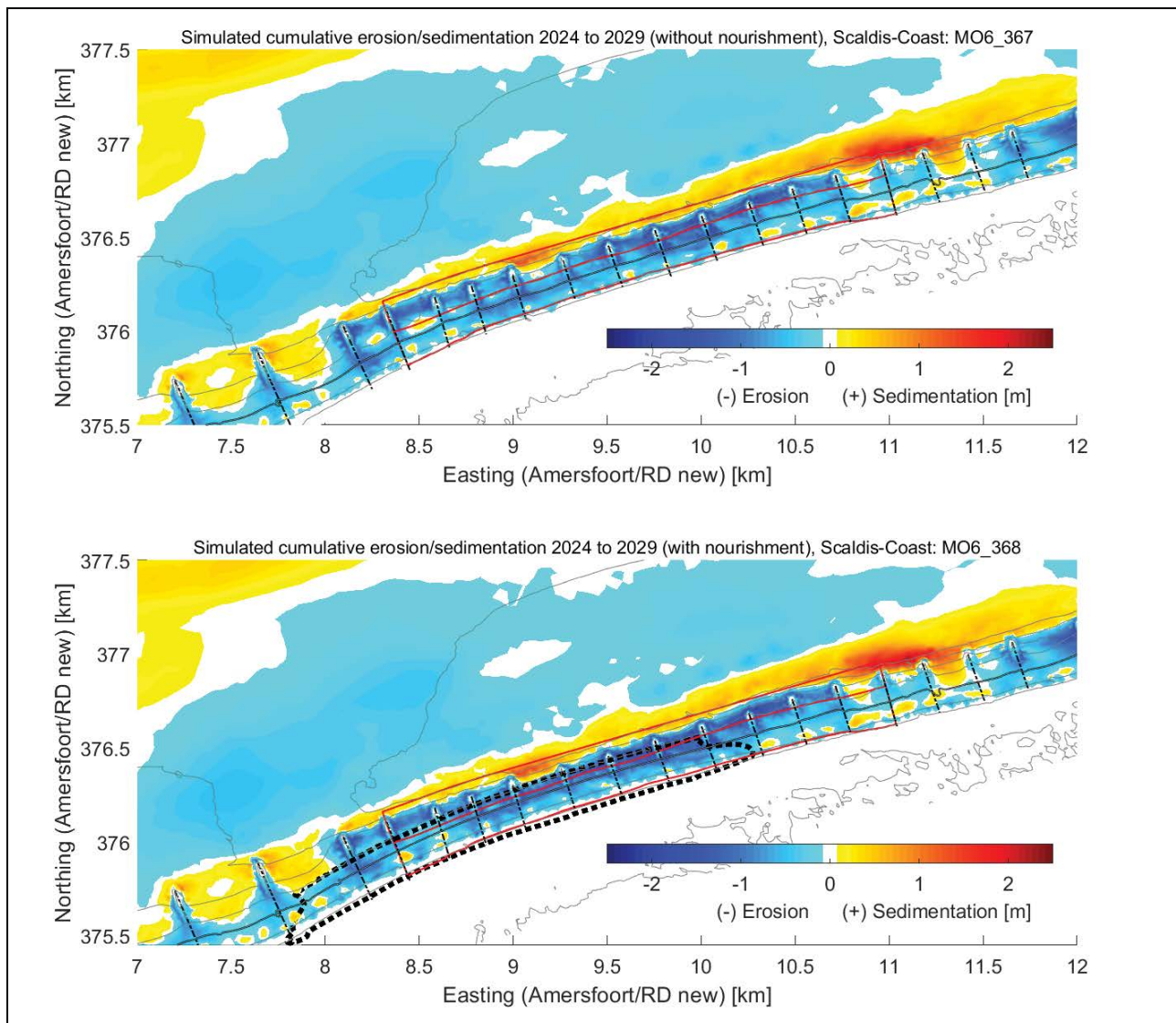


Figure 3-66: Scaldis-Coast model: bed level differences between 2024 and 2029 in the Knokke-Zoute area for the reference case (upper) and Knokke-Zoute nourishment scenario (lower). The grey contour lines have an interval of 2 m. The black line indicates the coastline (0 m NAP). The black dashed lines show the groynes. Red polygons show the zones used for the volume calculation. Black dotted polygon indicates the sand nourishment area in the scenario.

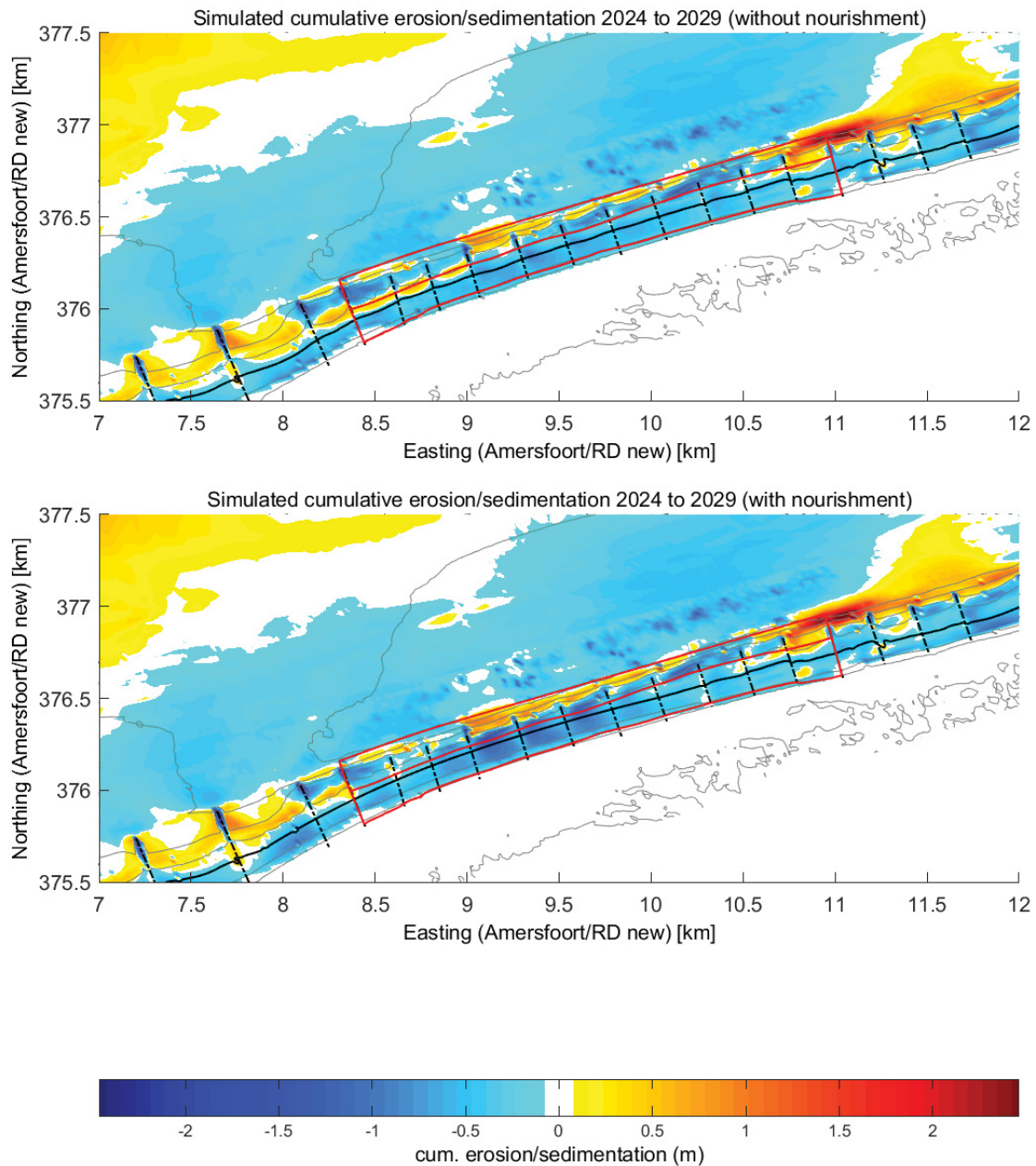


Figure 3-67: FlemCo model: bed level differences between 2024 and 2029 in the Knokke-Zoute area for the case of without (upper), with (lower) Knokke-Zoute nourishment. The grey contour lines have an interval of 2 m. The black line indicates the coastline (0 m NAP). The black dashed lines show the groynes. Red polygons show the zones used for the volume calculation.

In the nourishment scenario, sediment is placed in the designated Knokke-Zoute area just prior to the start of the modeling exercise. As a result, the modeled initial bed levels in the nourished zone are higher for the nourishment case than for the no-nourishment reference case (see Figure 3-64 and Figure 3-65). To investigate the influences of these two initial bed levels on the cross-shore morphodynamics, bed profiles within the Knokke-Zoute nourishment area are plotted, including initial and final profiles computed by the Scaldis-Coast and FlemCo model for the two cases over the period 2024-2029 (Figure 3-68 and Figure 3-69). The models predict beach erosion for both initial bed level conditions. However, the landward erosion limit shifts seaward in the nourishment scenario as observed in the blue profiles. This is also observed in the simulated sedimentation and erosion patterns in Figure 3-66 (Scaldis-Coast) and Figure 3-67 (FlemCo). The Scaldis-Coast simulation shows negligible bed level changes along the landward beach strip within the nourishment area (lower panel) where erosion is predicted for the reference case (upper panel).

The FlemCo simulation indicates erosion along the beach strip landward of the red polygon for the reference case, while almost no erosion is computed for the nourishment scenario. It is due to the higher and wider beach created by sand nourishment which causes wave breaking farther seawards, resulting in reduced wave energy reaching the upper beach area.

For the shoreface, erosion is predicted in the area adjacent to the beach, while sedimentation develops farther out across the shoreface.

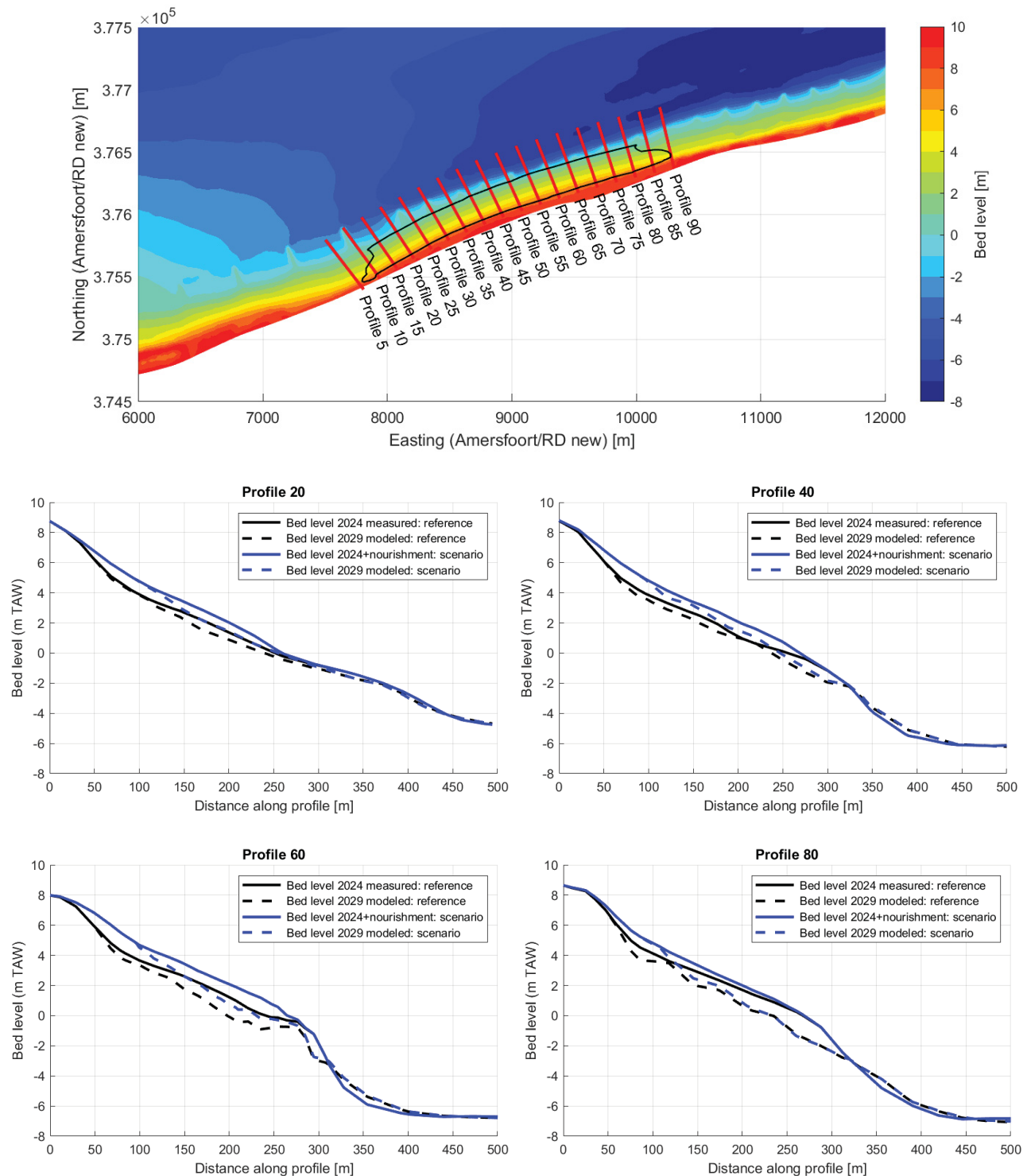


Figure 3-68: Scaldis-Coast initial (2024) and final (2029) bed levels at representative cross-shore profiles within the designed nourishment in Knokke-Zoute (black polygon) for the reference case and Knokke-Zoute nourishment scenario.

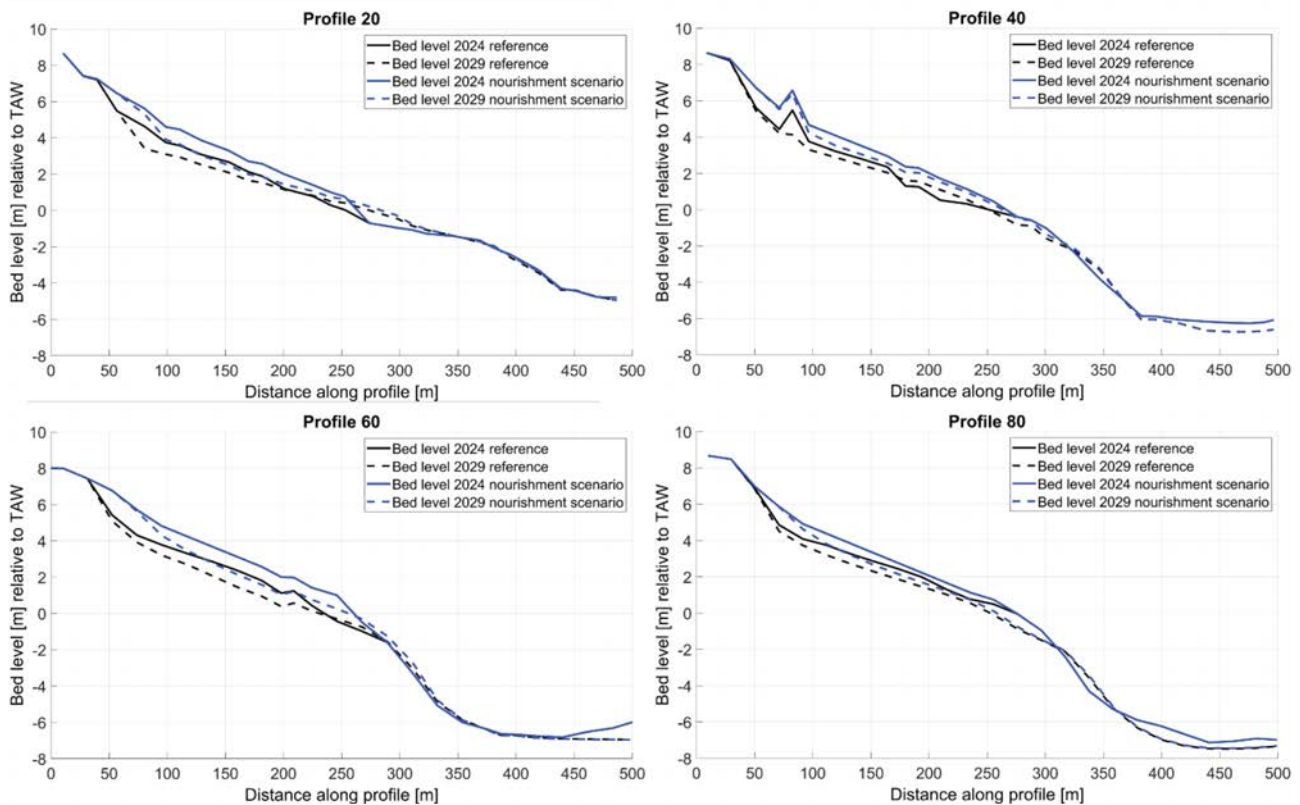


Figure 3-69: FlemCo model initial (2024) and final (2029) bed levels at representative cross-shore profiles within the designed nourishment in Knokke-Zoute (see black polygon in Figure 3-66) for the reference case and Knokke-Zoute nourishment scenario.

To quantitatively assess the effect of sand nourishment on the morphological development in the area, volume changes are compared. Figure 3-68 shows the temporal variation of the simulated bed volume changes for the two cases (reference and scenario) during the 2024-2029 period. The analysis is done for the beach, shoreface and the combined beach-shoreface, which are identical to those used in the above scenario (see also the red polygon in Figure 3-59). It should be noted that the simulated bed volume changes over time are presented only to illustrate the overall trend in bed volume variation predicted by the models. Only volume changes at the end of simulations should be considered for the quantitative assessment. This is due to the fact that both models use MORFAC approach, which is not intended to provide accurate intermediate results during the simulation period.

In general, both models predict continuous sediment loss throughout the considered period for both cases, except for the shoreface where FlemCo shows several fluctuations of the bed volume. The Scaldis-Coast model predicts higher volume than the FlemCo model for all areas and for both cases.

Although the nourishment scenario case shows higher volume loss compared to the reference case, the difference is small: $-334,400 \text{ m}^3$ vs. $-352,300 \text{ m}^3$ for Scaldis-Coast and $-212,500 \text{ m}^3$ vs. $-232,100 \text{ m}^3$ for FlemCo, considering the combined zone (see Table 3-11). When the volume changes are calculated within the area designated for sand nourishment in the scenario (black polygon in Figure 3-66, top panel), the difference in volume (reference vs. scenario) is larger ($-223,000 \text{ m}^3$ vs. $240,400 \text{ m}^3$ for Scaldis-Coast and $-165,700 \text{ m}^3$ vs. $-233,200 \text{ m}^3$ for FlemCo), but remains insignificant.

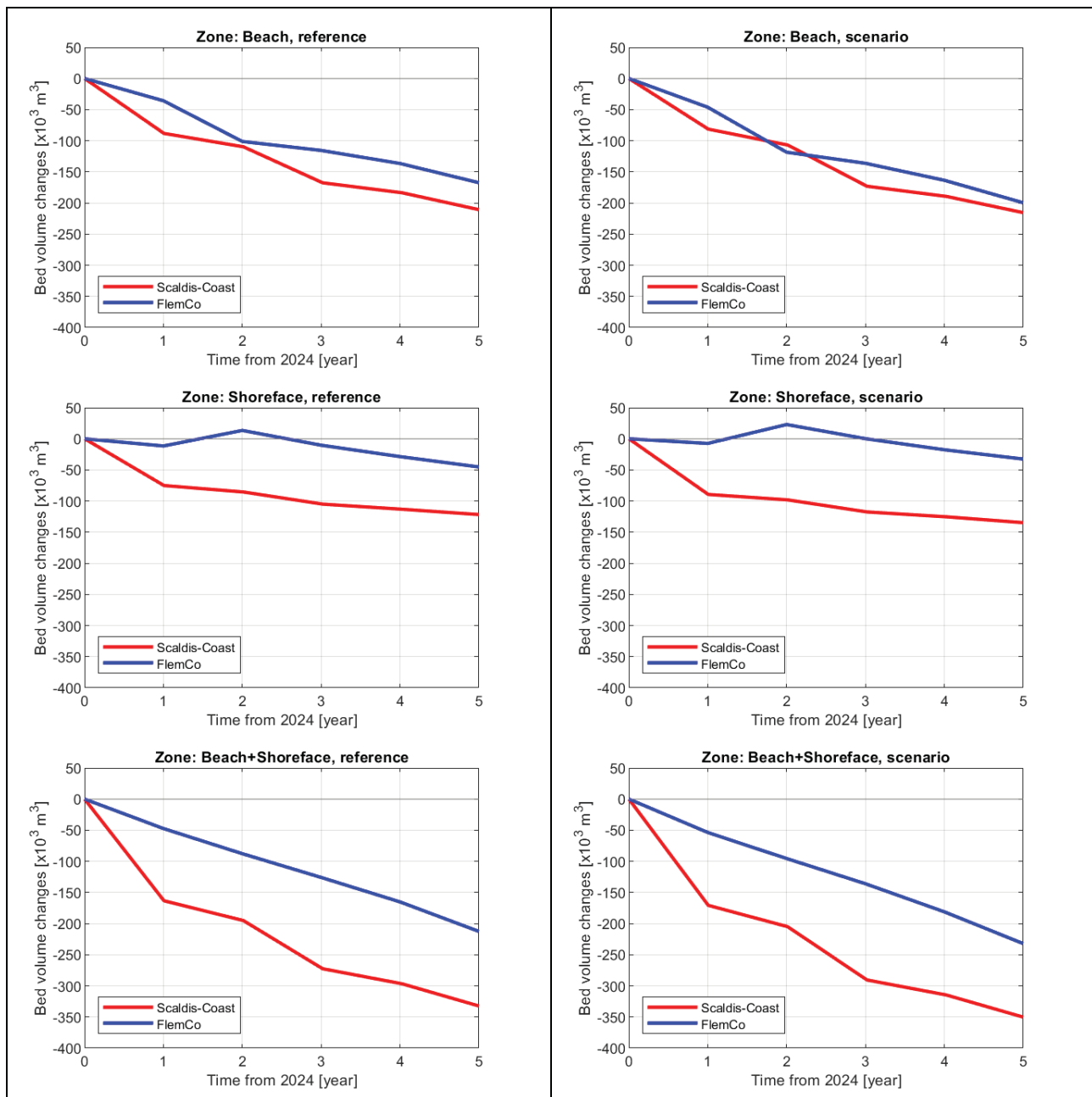


Figure 3-70: Bed volume changes in the Knokke-Zoute in the period 2024-2029 for different moments in time predicted by the Scaldis-Coast and FlemCo models for the reference case (left) and Knokke-Zoute nourishment scenario (right). Negative values indicate sediment loss and positive values show sediment gain.

Table 3-11: Bed volume changes in the Knokke-Zoute area in the period 2024-2029 predicted by the Scaldis-Coast and FlemCo models for the reference case and Knokke-Zoute nourishment scenario. Negative values indicate sediment loss and positive values show sediment gain.

Bed volume changes 2024-2029 [$\times 10^3 \text{ m}^3$]				
Polygon	Scaldis-Coast		FlemCo	
	Reference	Nourishment scenario	Reference	Nourishment scenario
Beach	-212.1	-216.9	-167.3	-199.6
Shoreface	-122.3	-135.4	-45.2	-32.5
Beach + Shoreface	-334.4	-352.3	-212.5	-232.1
Nourishment area (black polygon in Figure 3-64)	-223.0	-240.4	-165.7	-233.2

Conclusions.

In this section, the two morphodynamic models, Scaldis-Coast and FlemCo were calibrated for the period 1999-2002/2003 and validated for the period 2019-2022, with a particular focus on the Knokke-Zoute area. Both periods directly begin after beach nourishments performed at Knokke-Zoute. During the validation period from 2019 to 2022, a shoreface nourishment was carried out.

The two models generally show similar erosion/sedimentation patterns for the study area. Comparisons with the measurements indicate that both models capture the dominant morphological responses: beach erosion in both periods and erosion in the Appelzak channel during 1999-2002/2003 (i.e. the case without shoreface nourishment).

Quantitatively, both models simulated sediment loss in the combined beach and shoreface area. For the calibration period 1999-2002/2003, the Scaldis-Coast model underestimated the erosion by a factor of 1.5 and FlemCo model by a factor of almost 3. In the validation period with shoreface nourishment, the FlemCo model underestimated the erosion by factor 1.4, whereas the Scaldis-Coast model showed an overestimation by factor 1.7. The clear overestimation of the sediment loss in the Scaldis-Coast model can be attributed to the fact that the model version applied here does not include the relevant cross-shore processes. As a result, the Stokes drift and undertow are not considered in the Scaldis-Coast model. This probably leads to an underestimation of the onshore sediment transport from the nourished shoreface towards the beach, contributing to the overestimation of sediment loss in the model results.

The two calibrated and validated models were further used to simulate two beach nourishment scenarios: (i) Albertstrand beach nourishment of $1,050,000 \text{ m}^3$, designed to straighten the Albertstrand beach (simulation period: 2022-2025) and (ii) Knokke-Zoute beach nourishment of $425,000 \text{ m}^3$ (simulation period: 2024-2029). For each scenario, the model results were compared with the corresponding no-nourishment case (reference) to assess the influence of the proposed measures on the morphodynamical evolution in the Knokke-Zoute area. The models indicate that straightening the Albertstrand coastal area has a local impact on the sediment transport with negligible influence on the Knokke-Zoute area. This limited response is primarily due to the sheltered position of the Albertstrand coast east of the Zeebrugge port where reduced wave energy and mainly westward directed longshore sediment transport lead to minimal sediment redistribution towards the Knokke-Zoute area.

For the cases Knokke-Zoute with and without nourishment, the two models predict erosion in both cases, with slightly higher erosion in the nourished case, although the difference is insignificant.

3.4 Hindcast of 40 years of coastline maintenance using coastline model ShorelineS for Knokke-Heist

3.4.1 Introduction

3.4.1.1 Background

The MOZES project focusses on the understanding of the morphological interaction between the sea bottom and the Belgian coastline. One of the focus areas for the numerical modelling work packages is the Knokke-Heist coastal area, as it has been a hotspot for structural coastal erosion since the major port and beach expansion works carried out in the late 1970s and early 1980s, especially the Knokke-Zoute stretch (Trouw et al., 2024).

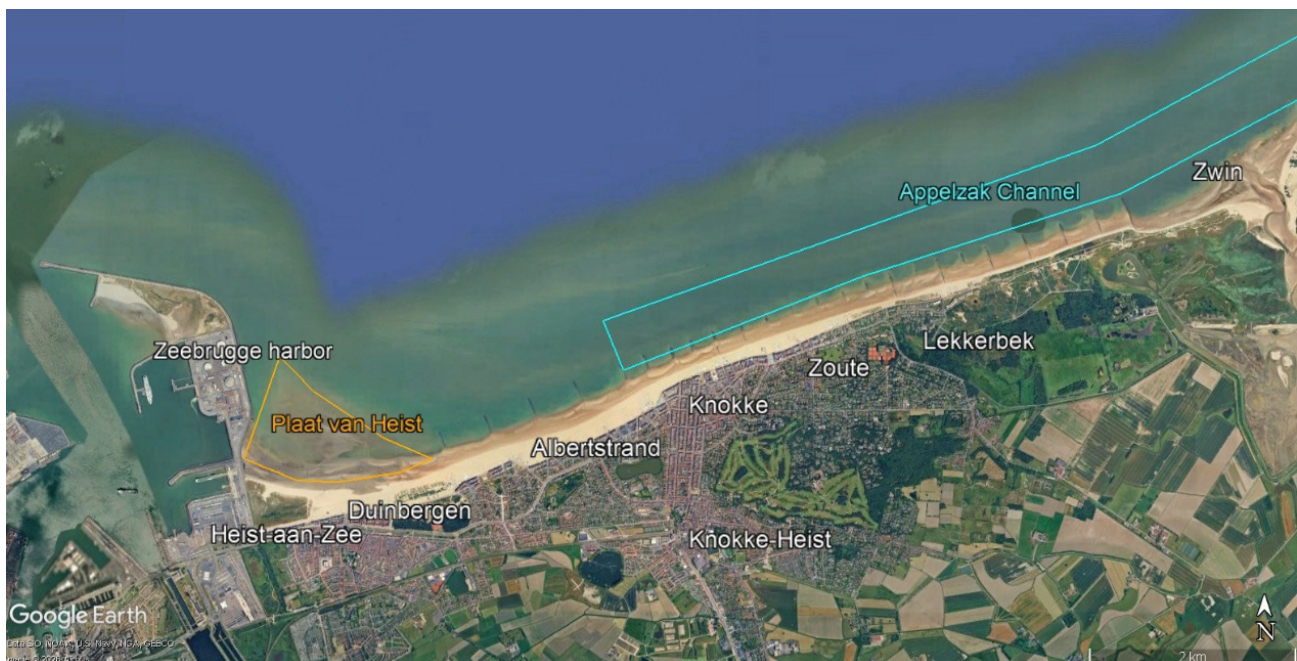


Figure 3-71: The study area is the coastal area bordered by the harbour of Zeebrugge in the west and the nature reserve het Zwin in the east. The focus in the analyses is on Knokke-Zoute stretch.

This coastal area is strongly influenced by the harbour moles, that create a blockage of the alongshore sediment transports as well as shielding of the waves and tidal currents. This leads to strong alongshore gradients in sediment transport in the area close to the breakwater, which drives local sedimentation near the harbour mole (i.e. in the bay at Heist), forming the Plaat van Heist and erosion for the beaches at Knokke-Zoute (i.e. where the sediment transport is picking up again). Several other processes play a role too. First of all, the locally protruding coastline at Knokke experiences enhanced erosion due to its curvature, which enhances local transport gradients. Another, though seemingly more secondary cause, is the occurrence of cross-shore sediment transport from the active zone towards the sea, which is caused by the proximity of the Appelzak channel (Trouw et al. 2024). This channel has disrupted the beach and foreshore profile, leading to a steepening of the deeper foreshore. The ongoing deepening of the Appelzak channel (linked to a landward trend of the Paardenmarkt ridge) reinforces both of the above processes. It is expected that this will increase the need for nourishments in the coming decades, in addition to what will be needed to keep pace with sea level rise (following Bruun's rule). To counter the coastal erosion, numerous beach and foreshore nourishments have been placed during the past decades (Houthuys et al., 2020).

Further information on the long-term morphological evolution of the seabed and Appelzak channel can be found in Section 2.7.4 of the current report.

3.4.1.2 Objectives

In 2025 it was decided to complement the other work packages in the MOZES project, by developing a coastline model (reduced complexity model) that can be used to gain further insight into the coastline development of the Knokke-Heist coastal zone on larger timescales. More specifically, this model can be used to assess the coastal changes during the past 40 years, and predict and study future developments or maintenance strategies for this coastline which was created in 1977-79 by a mega nourishment ($\sim 8,5 \text{ Mm}^3$) establishing a progradation of $\sim 80 \text{ m}$ over a length of almost 10 km .

3.4.1.3 General approach

The choice was made to use the recently developed numerical coastline model ShorelineS for this task (Roelvink et al., 2020), and more specifically to build further on the existing ShorelineS model application Knokke-Heist for the period for 1999-2004, developed by *Trouw et al. (2024)*.

As a first step, the existing ShorelineS model for Knokke-Heist is tested and slightly adapted to the new functioning of the ShorelineS TKI code. Furthermore, the new code development of *Trouw et al. (2024)* to account for submerged groynes has been merged with the newest model code of ShorelineS.

In parallel, the measured volume changes in the area between the Zeebrugge harbour and het Zwin are prepared and studied for the use of model calibration and validation.

Using the adapted model, and the information on measured volume changes in the area over the past decades, the model is calibrated (years 1983-1999) and validated (2000-2023). During the calibration process, following several recommendations of *Trouw et al. (2024)*, the model sensitivity to wave forcing is tested, as well as the sensitivity to initial coastline, profile shape, and various sediment transport formulations.

Next, the model has been used for evaluation of the effect of groynes, predicted future coastline development and a specific nourishment scenario.

3.4.1.4 Readers guide

In Section 3.4.2 the ShorelineS model setup is described. The volume analyses and processing steps are described in Section 3.4.3. In Section 3.4.4 the model calibration and validation results are shown, as well as future predictions and a specific nourishment scenario. In Section 3.4.5 is reflected on the model capabilities and limitations to the current approach. In Section 3.5.3 the main results are summarized, and recommendations are given.

3.4.2 ShorelineS model setup

ShorelineS is an open-source numerical model for coastal planform evolution. It uses one-dimensional equations for alongshore sediment transport and mass conservation, on a free-form grid that may consist of several coastal sections represented as strings of coastline points.

A range of hard elements or coastal structures are supported, such as groynes, T-groynes, offshore breakwaters and revetments; processes simulated include bypassing and diffraction. A range of longshore (bulk) transport formulas is available and soft engineering measures such as beach- and nearshore nourishments can be simulated.

For more background information, please refer to the ShorelineS manual (Deltares, 2024) and Roelvink et al. (2020).

Here below information on the needed information for model setup is briefly described. For a complete overview of the model parameter settings that are different from the default settings, please see the shared model setup files.

3.4.2.1 Coastline

Relevant shorelines at mean sea level (2.33 TAW) were extracted from digital elevation models (cf. Section 2.5.3) and used as start coastline for the simulations. The date of the available coastlines is shown in Table 3-12. In the Baai van Heist (Stroken 44-46), in the sheltered zone next to the Zeebrugge harbour, the beach has accreted considerably over time, and dune growth was substantial. The exact location of the shoreline position is, however, quite sensitive to variations in the 3D morphology of the intertidal area of the rather mildly sloping beaches. This holds especially for the beaches directly next to the harbour breakwaters of Zeebrugge, while also the beaches which were nourished show quite some variability of the waterline position.

The waterline position by itself is therefore not one-on-one representative of the natural trends in this zone. Therefore, it was chosen to calibrate and validate the model predictions not based on coastline position but based on measured volume changes (as recommended by *Trouw et al. 2024*). The measured volume changes were earlier determined by *Houthuys et al. (2019)* based on available digital elevation models. See for more information on the volume data analyses Section 3.4.3 of this report.

For calculation time purposes, the used dx grid spacing was 150 m in most simulations, resulting in a timestep of about 12 hours to a day. To verify whether this choice in dx would not considerably affect the results, a similar reference run was performed for a dx grid spacing of 50 m, with a corresponding smaller timestep of ~2 hours.



Figure 3-72: Coastline position over time of the 2.33 TAW depth contour corresponding to mean sea level.

Table 3-12: Date of the available coastlines

Available volume estimations per coastal section
1983 (may 18th)
1986 (may 26th)
1989 (april 9th)
1999 (june 6th)
2004 (september 2nd)
2019 (april 20th)
2023 (june 17th)

3.4.2.2 Cross-shore profile

In the 1D-coastline models, the shoreward/seaward movement of the shoreline represents the average change in the active part of the cross-shore profile, which may move forward and backward depending on the gradients in longshore sediment transport. This active profile has been defined from the dunefoot down to the depth of closure for the Knokke-Heist study. A single representative cross-shore beach profile was used in the model, which was already defined by *Trouw et al. (2024)*. Cross-shore beach profiles every km along the study area are shown in Figure 3-71. This means that variability over the study area is not taken into account, but overall, the profiles are still reasonably similar. The most relevant profiles (between x coordinate 74.000 till 78.000) can be represented by a profile with slope 1/35 between +5 and -2 m TAW, a slope 1/25 between -2 and -6 m TAW, and slope 1/300 between -6 and -7 m TAW.

The depth of closure for wave action is determined around -6 m TAW. The high-water level is at 4.5 m TAW, so to include maximum setup/run-up levels, a total active height of 12 m is defined for the ShorelineS model setup along the entire domain.

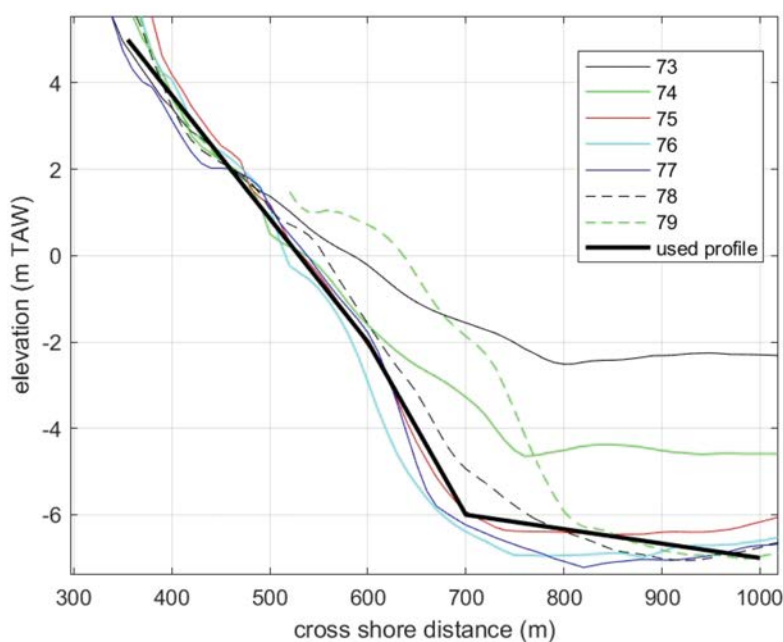


Figure 3-73: Cross-shore beach profiles every kilometre, for Lambert x coordinates 73.000 to 79.000 m, with the used profile represented by the thick black solid line. Source: *Trouw et al. (2024)*.

3.4.2.3 Wave conditions

Sediment transport in the nearshore and on the beach is driven by wind, waves, tidal currents, and differences in salinity and/or river discharges. Especially in shallow water, near the coast, the transport is dominated by waves. The wave conditions are therefore one of the most important model forcings for the ShorelineS model. They are generally determined using a separate detailed wave model like SWAN, where wave conditions are extracted at around the depth of closure, so that they can be imposed on the ShorelineS offshore model boundary. In the current study, to test the sensitivity and improve ShorelineS predictions during the calibration phase, much attention has been paid to the available detail (locations / timespan / accuracy) in wave forcing.

In the earlier study of *Trouw et al. (2024)*, the wave climate is defined at five locations. These locations are situated around the -5 m TAW line (see their Figure 7). The climates are obtained from the project “Golfklimaat Vlaamse Kust” (IMDC, 2009), where they conducted detailed research using SWAN to translate the wave climate at sea to the coast. The period they modelled is 1996-2005. The study of *Trouw et al. (2024)* showed that variability in wave boundary conditions between years has a major impact on long-range transport. Therefore, for the current hindcast from 1983 to the present, it would be of great added value to have a longer time series on wave boundary conditions. In addition, the available extracted locations of this model show limitations for the ShorelineS modelling of the coast near Zeebrugge harbour, which has a negative effect on the more easterly focus areas of Mozes.

Therefore, it was chosen to compare the existing approach of *Trouw et al. (2024)* with another approach, using the transformation matrix of *Huisman et al. (2019)*. This second approach offers the availability of the complete time period of interest, from 1983 to the present, and to have the possibility to refine the location choice of the wave boundary conditions for the ShorelineS model, particularly useful for better representing the coastline around Zeebrugge harbour. It is important to note that this transformation matrix has not been specifically validated for the Knokke-Heist coastal zone, but that it shows robust and accurate validation results for comparisons at other locations along the Dutch coast. The approach is described in *Grasmeijer et al. (2022)* and *Huisman et al. (2019)*. Locations where wave conditions are extracted vary slightly, with on average -9 m with respect to MSL (Figure 3-72). In the shadow zone behind Zeebrugge harbour arm, the water is shallower, so to extract conditions close to the coast, the wave conditions are extracted around -3 m with respect to MSL. A comparison for the wave roses of the two approaches is shown in Appendix 0, as well as for the new extraction points of the timeseries of wave conditions following the wave transformation matrix approach of *Huisman et al. (2019)*.

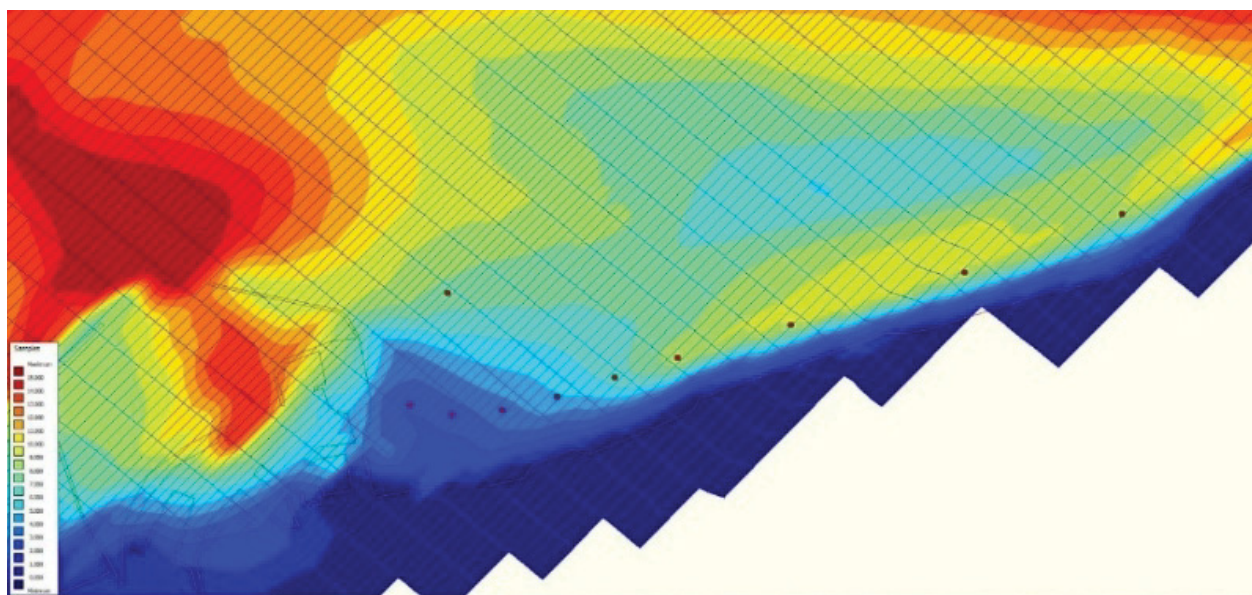


Figure 3-74: Location of extraction points of timeseries of wave conditions following the wave transformation matrix approach of Huisman et al. (2019). Please note that bed levels are with respect to Mean Sea Level (+2.33 TAW).

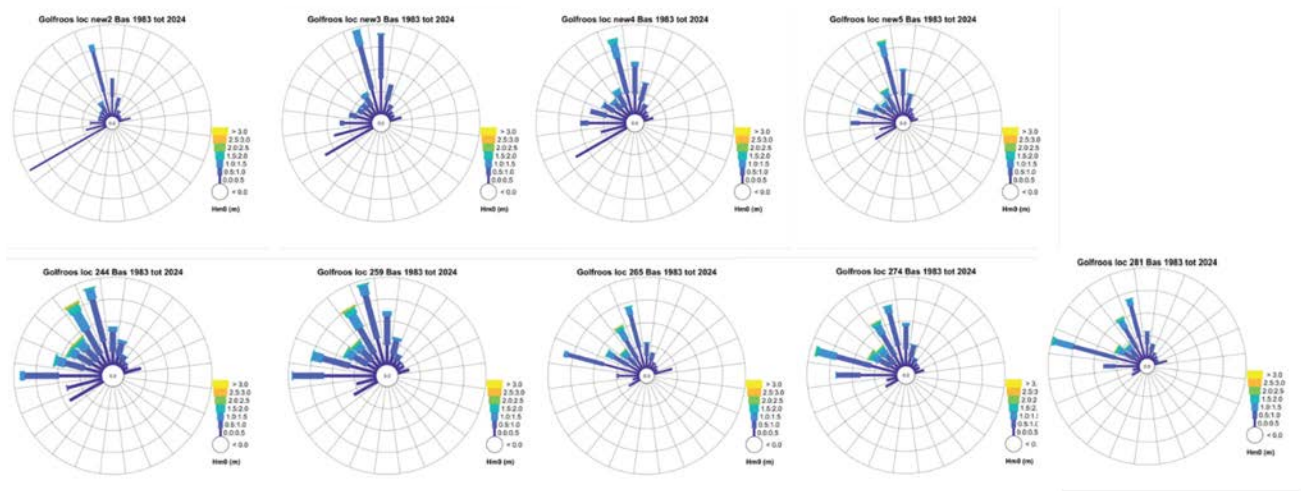


Figure 3-75: Wave roses for the wave conditions spanning the years 1983-2023, for the selected locations from the transformation matrix approach of Huisman et al. (2019), from west to east.

To speed up calculation time about an order of magnitude, wave timeseries (see example in Figure 0-1), were binned into 82 corresponding wave climates, that are repeated in a random order during the simulations. In this way, a larger timestep can be used without a measurable impact on the long-term coastal evolution predictions.

3.4.2.4 Tidal conditions

Tidal currents and water-levels can be added in the ShorelineS model at discrete number of nearshore locations. The tidal conditions that are imposed here are the same as used by *Trouw et al. (2024)*. Tidal information was extracted from a Delft3D model at several locations around 5 meter water depth. For each location where the input of the tide is specified, a table with the necessary coefficients (e.g. amplitude of M2 and M4, phase differences, longshore slope) are given. For detailed explanation on the used tidal forcing, please refer to *Trouw et al. (2024)*.

3.4.2.5 Sediment transport formulations

Two sediment transport formulations are tested. The one of *Van Rijn (2014)*, where tide and wave-driven longshore transport are calculated using nearshore waves. And secondly, the “*tideprof*” formulation where wave transformation and transports are computed over the whole cross-shore profile for the *Soulsby-VanRijn* formulation with tide.

3.4.2.6 Submerged groynes

In the study zone, numerous submerged groynes are present in the intertidal area. These groynes are intermittently submerged or emerged, and therefore affect the waves and tidal currents varyingly depending on the phase of the tide. As the original ShorelineS code could only handle fully emerged groynes (with a height extending above the high water level), *Trouw et al. (2024)* have therefore developed a new specific model function within the ShorelineS numerical model to account for these submerged groynes. In the current study, this development has been merged into the latest ShorelineS model code, but the implementation process into the code is not reported here.

3.4.2.7 Nourishments

To counter the coastal erosion east of Zeebrugge, numerous beach and foreshore nourishments have been placed during the past decades (*Houthuys et al., 2020*). Information on these nourishments has been extracted per Strook, and is therefore in the current study also applied into the ShorelineS code for those specific Strook coordinates. It is noted that this does not always reflect reality of the placement accurately. Shoreface nourishments were added as regular nourishments of which the feeding takes place over a 3-year period. This resembles not the actual construction time but rather the approximate time before the nourished sediment would lead to a coastline progradation. The nourishments that were carried out in the study area since the year 1986 are presented in Table 0-1 (Appendix E), of which a summary is described here below per Strook.

The calibration and validation periods are predominantly simulated without taking the nourishments into account, and removing their volumes from the measured data that was combined on Strook “level”. This was done as the available information on their exact location, shape and timing is limited to the information on Strook level from *Houthuys et al. (2019)* and has not been assessed in more detail due to time constraints. This is therefore the cleanest comparison to the measured data volumes that is corrected based on that same nourishment information.

Strook 44 Heist, Oostdam (Secties 217-218); 340.000 m³ was placed as beach nourishment in 1986. Below the low water line 35.000 m³ was nourished in 1995. In the following decades, only minor nourishments were placed. In total 350.000 m³ has been nourished above the low water line since 1986, and 55.000 m³ below the low water line.

Strook 45 Heist, Heldenplein (Secties 219-221); in 1986, 55.000 m³ was placed as beach nourishment and 160.000m³ as shoreface nourishment. In the decades after that, only minor nourishments were placed on the beach in the order of 25.000 m³, and one underwater nourishment in the order of 70.000 m³. In total 80.000 m³ has been nourished above the low water line since 1986, and 230.000 m³ below the low water line.

Strook 46 Duinbergen (Secties 222-224); since the year 2008 in total some 155.000 m³ has been nourished on the dry part of the beach, of which 130.000 m³ was placed in 2021, accompanied by 10.000 m³ as shoreface nourishment.

Strook 47 Duinbergen zeedijkzone (Secties 225-226); since 2003 yearly nourishments in the order of ~15.000 m³ have been placed above the low water line, with a mega nourishment of 350.000 m³ in 2021 above the low water line, and about 90.000 m³ below the low water line. In total 600.000 m³ has been nourished above the low water line since 1986, and 50.000 m³ below the low water line.

Strook 48 Albertstrand (Secties 227-232); was nourished in 1986 with about 55.000 m³ above the low water line, followed by several localized small nourishments (<10.000 m³) since the year 2000. The nourishment volumes have increased over time, with as largest nourishment 250.000 m³ in 2021 above the low water line in 2021, and 100.000 m³ below the low water line. In 2023 a nourishment of 125.000 m³ was placed above low water, and in 2024 a nourishment of the same order was placed below the low water line. In total 580.000 m³ has been nourished above the low water line since 1986, and 250.000 m³ below the low water line.

Strook 49 Knokke-Zoute (Secties 233-241); has been nourished numerous times since 1986. In 1986 a nourishment of 500.000 m³ was placed above low water. Since the year 1999, this was regularly followed by nourishments in the order of 50.000-200.000 m³, with the largest underwater nourishment placed in 600.000 m³ in 2024. In total 2.500.000 m³ has been nourished above the low water line since 1986, and 940.000 m³ below the low water line.

Strook 50 Lekkerbek (Secties 242-249); was nourished in 1986 with 120.000 m³, above the low waterline. Some localized nourishments followed sporadically, with the largest nourishment of 135.000 m³ in 2024. In total 300.000 m³ has been nourished above the low water line since 1986, and 175.000 m³ below the low water line.

3.4.2.8 Overview simulations

An overview of the most relevant simulations that were carried out is given in Table 3-13. Used settings for the reference run are:

- a longshore grid resolution of 150 m
- sediment transport formulation tideprof
- wave climate using the Huisman et al. (2019) approach with a calibration of the most western wave climate next to Zeebrugge harbour (wave energy reduced to 0.4 the original value, and clockwise turning of wave direction with +12 degrees).
- submerged groynes
- coastline representative of mean sea level
- including diffraction
- excluding nourishment information

Table 3-13: Overview of the realized relevant simulations for this report

Number	Type	Specifics
#1	Calibration	Reference run
#2	Calibration	Reference run with dx = 50m
#3	Calibration	Reference run with calibrated 2 most eastern wave locations
#4	Calibration	Reference run including nourishments
#5	Calibration	Reference run with forcing Trouw et al. (2024)
#6	Calibration	Reference run with calibrated 2 most eastern wave locations with emerged groynes using tideprof formulation
#7	Calibration	Reference run with calibrated 2 most eastern wave locations with emerged groynes using VanRijn14 formulation
#8	Calibration	Reference run with calibrated 2 most eastern wave locations without groynes
#9	Calibration	Reference run using low water coastline as start
#10	Calibration	Reference run without diffraction
#11	Validation	Simulation with calibrated model for period 1999-2023
#12	Validation	Simulation with calibrated model for period 1999-2023, including nourishments
#13	Validation	Simulation with wave climate Trouw et al. (2024)
#14	Validation	Simulation with calibrated model for period 1983-2023
#15	Future predictions	Simulation with calibrated model for period 2023-2050

#16	Future predictions	Simulation for period 2023-2050 with wave climate Trouw et al. (2024)
#17	Albertstrand nourishment	Simulation with calibrated model for period 2022-2032
#18	Albertstrand nourishment	Simulation with calibrated model for period 2022-2032 including nourishment scenario Albertstrand
#19	Albertstrand nourishment	Simulation with calibrated model for period 2022-2032 including nourishment scenario Albertstrand with emerged groynes
#20	Albertstrand nourishment	Simulation with calibrated model for period 2022-2032 including nourishment scenario Albertstrand without groynes
#21	Albertstrand nourishment	Simulation with calibrated model for period 2022-2032 including nourishment scenario Albertstrand without tide

3.4.3 Volume data-analyses

The model predictions for coastal evolution over the past decades are compared to measured volume changes for predefined sections (called *Stroken* in Dutch), as reported by *Houthuys et al. (2020)*.

The volume analyses per Strook (or substrook) in *Houthuys et al. (2019)* was performed using specific horizontal discs, spanning from the dune (3), to the dry part of the beach (2), the wet part of the beach (1) to the foreshore (4) and the seabed (5) (see Figure 3-76).

The active height of the ShorelineS model extends from around the dune foot (+6.89 m TAW) down to the depth of closure (-6 m TAW). Therefore, the most logical comparison between the model predictions and the measured volumetric changes corresponds to horizontal volume discs 1, 2 and 4.

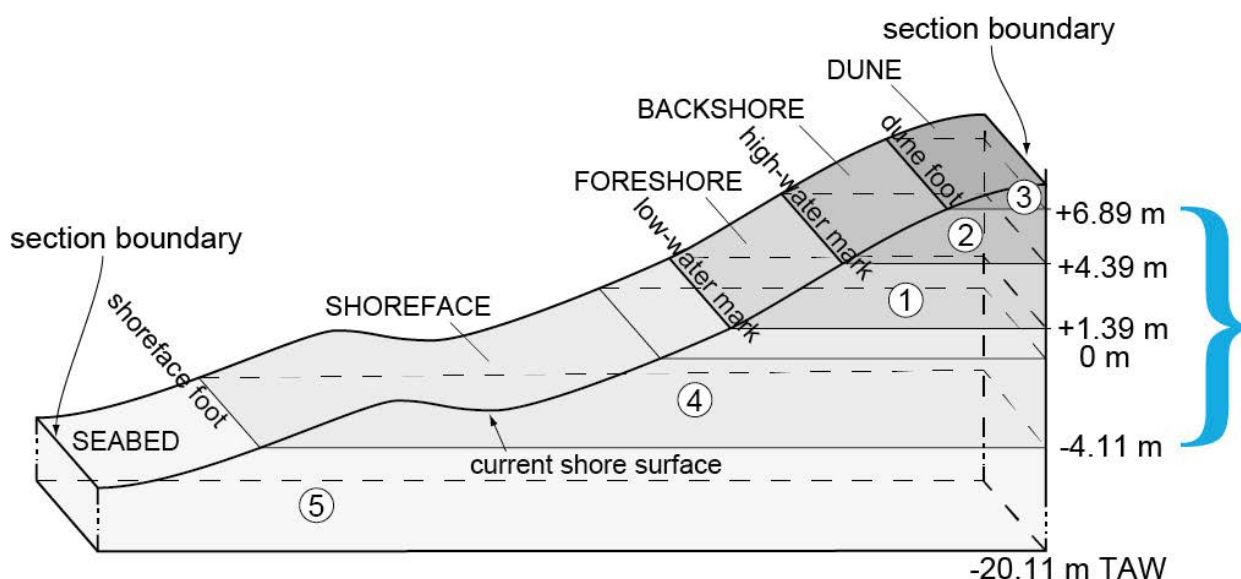


Figure 3-76: Method in which the volume was determined in *Houthuys et al. (2020)*, and in blue the selected horizontal discs to compare with the model predictions. TAW 0 m, is representative of lowest low water, and TAW = +5 m is representative of highest high water, with +2.3 m TAW corresponding to mean sea level.

The ShorelineS model is a 1d-coastline model that represents the “active zone” of the beach (from about dune foot to depth of closure of wave action) and not the deeper shoreface with shoals and channels. For this reason, the seaward limit of the horizontal integration zones was chosen in the middle of the Appelzak channel (for 49a and 50a) at the foot of the most seaward underwater bank (subscript a), to avoid that the seaward shoal is part of the volume balance. This is around -6 to -7m TAW (see Figure 3-71). For sections 45, 46 and 47, the differentiation between the nearshore section of the profile (that is directly affecting shoreline behaviour) and the profile changes of the sandbank next to the harbour mole are at a shallower depth. The behaviour of the sandy shoal called *Plaat van Heist* in 45b and 46b is not simulated by ShorelineS, therefore in this report is focused on subsections a only.

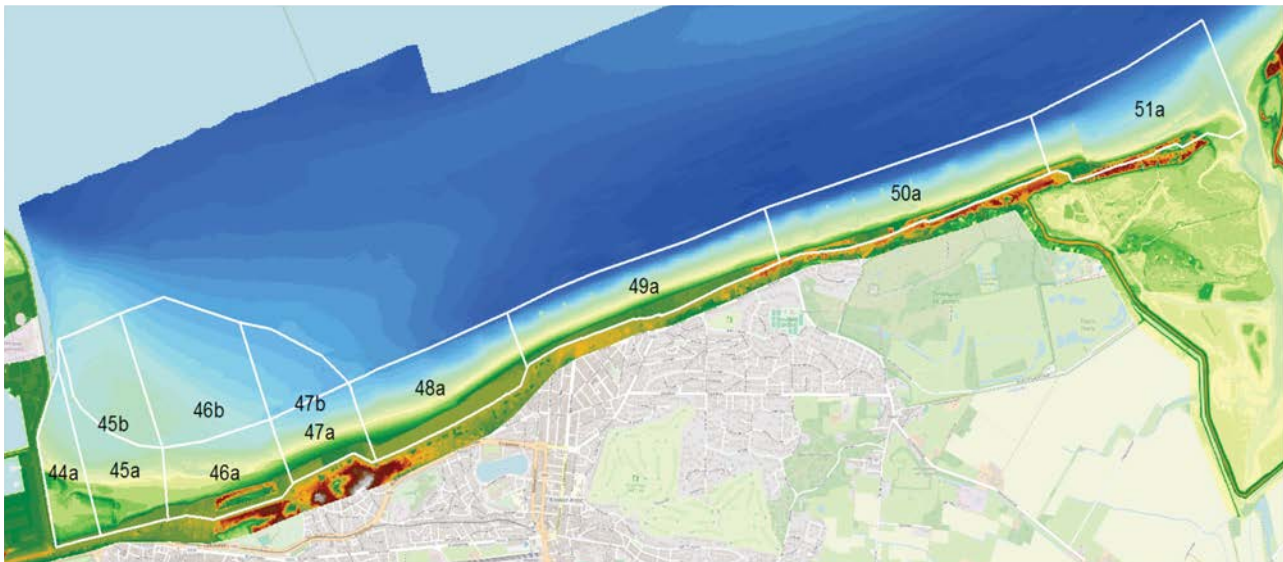


Figure 3-77: Volume data analysis is based on the above zones (Stroken). In this study we focus on strook 44 Heist (just east of Zeebrugge) up to strook 50, just west of the Zwin.

The volumetric changes have been analysed for the same years in which the bathymetric surveys were taken (as shown in Table 3-14). The first available bathymetric datasets are from 1983 for the beach and 1986 for the foreshore, we have here taken 1983 as starting point, assuming no change between 1983 and 1986. The last year that was selected was 2023 just before a large underwater nourishment was placed at Knokke at the end of 2023.

Table 3-14: Date of the available volume estimations per coastal sections A and B

Available volume estimations per coastal section
1983 (may 18th)
1992 (april 8th)
2000 (september 11th)
2007 (june 3rd)
2015 (may 17th)
2023 (june 17th)

An indication of the total measured volume changes over time between the available years are shown in Figure 3-78, where only the nearshore part of the integration areas (with suffix ‘a’) is shown. The volume changes of the horizontal discs wet beach, dry beach and foreshore (i.e. elements 1, 2 and 4 in Figure 3-74) were added up. In Figure 3-77, the same trends are shown but corrected for the placed nourishments on Strook level. The reference year here is taken as 1983.

The following can be observed:

- A volume increase in Stroken 44, 45 and 46. This is linked to the harbour moles, that create blockage and gradients in wave energy and tidal currents in the area, leading to strong gradients in sediment transport along the coast. Those gradients result in local sedimentation near the harbour mole in the baai van Heist. The interaction between the harbour moles and the tidal wave creates also local circulation patterns that promote westward transport (see e.g. Figure 3-32 and Figure 3-33).
- An erosive trend in Stroken 48, 49 and 50 in the years after the construction of the harbour moles of Zeebrugge. This is linked to the longshore gradients in sediment transport, that is picking up again further east towards Knokke, resulting in erosion. Several other processes play a role too, such as the locally protruding coastline at Knokke-Heist that leads to additional gradients in longshore transport and thereby enhanced erosion. The largest erosion occurs in Knokke-Zoute (Strook 49a), with up to 100.000 m³ per year in the first period (1983-1992).
- Beach and foreshore nourishments partly compensated erosion for Knokke-Zoute Strook 49a (Figure 3-78).
- Evidence of erosion (at the seabed) in Strook 49a and 50a that can be related to the morphodynamics of the Appelzak channel. This is illustrated in Figure 3-78 wherein the volume change with and without seabed layer/disc is shown for Strook 49a. Cross-shore sediment transport from the active zone towards the sea could be linked to the proximity of the Appelzak channel (for more information please refer to section 2.7). This channel has disrupted the beach and foreshore profile, leading to a steepening of the deeper foreshore. The ongoing deepening of the Appelzak channel (linked to a landward moving trend of the seaward lying Paardenmarkt ridge) reinforces both of the above processes.
- A potential change in the trend of erosion due to the Appelzak channel after the year 2004 in Strook 49, as the volume in this Strook has been increasing since then even after correction for the nourishments according to Houthuys et al. (2019) (purple and green line Figure 3-78). This may be either a natural trend reversal or an indication of missing information on the location/volume of the placed nourishments. Due to lack of time, no further research into the source(s) of this trend change could be made here.
- The volume changes over time for subsections A are considerably different than the volume changes determined for the entire Strook (please refer to Houthuys et al. 2019 for analyses of total volume changes in the entire Strook).

For a more detailed analyses of the volume changes in the larger area refer to *Houthuys et al. (2019)*. However, please do note that their analyses are focused on a larger seaward stretching zone then is considered here.

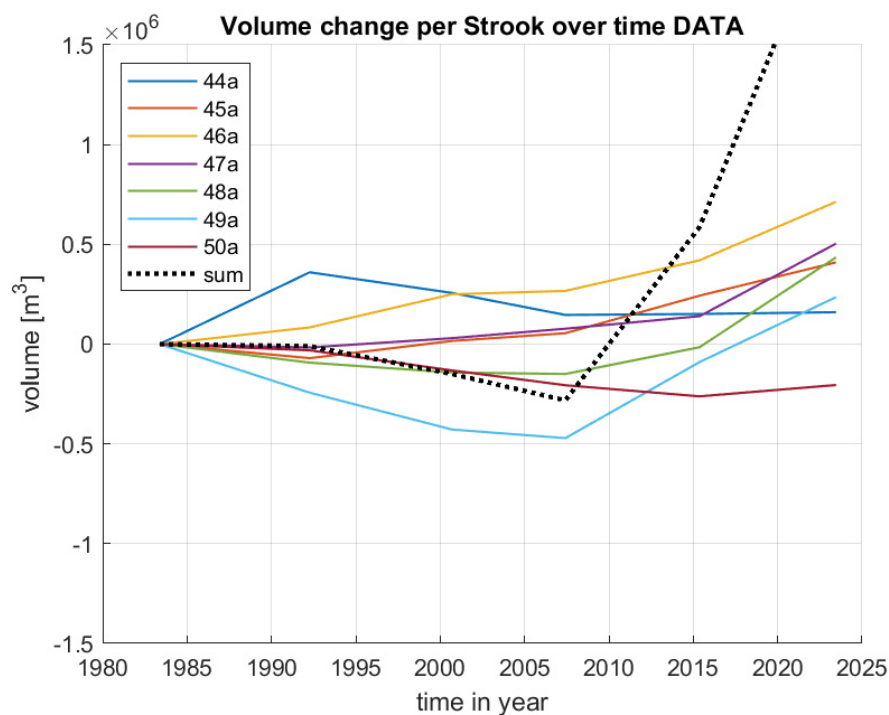


Figure 3-78: Total measured volume change between 1983 and 2023 for all Stroken in subsections a, for the horizontal discs 1 wet beach, 2 dry beach and 4 foreshore combined, see Figure 3-74 for definition of the discs.

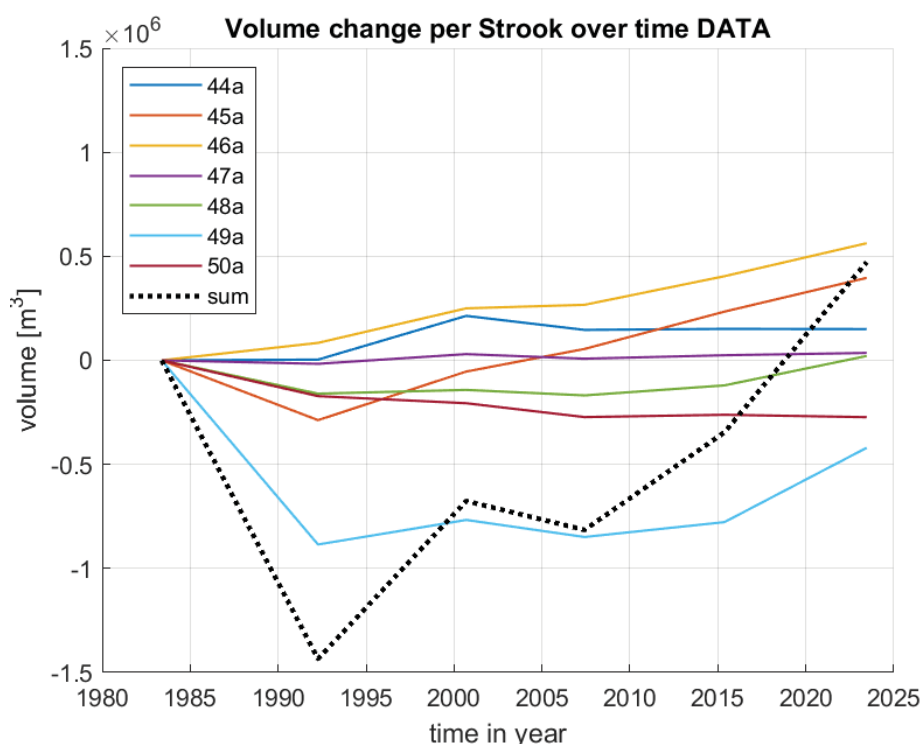


Figure 3-79: Total measured volume change corrected for nourishments (no nourishments in the current graph), between 1983 and 2023 for all Stroken in subsections a, for the horizontal discs 1 wet beach, 2 dry beach and 4 foreshore combined.

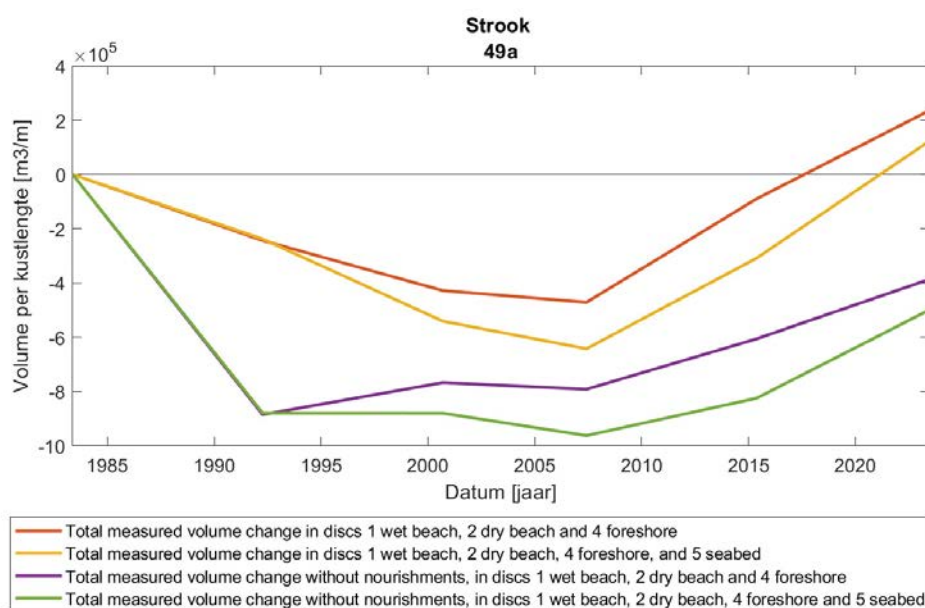


Figure 3-80: Total measured volume change for strook 49 subsection a, between 1983 and 2023, with and without including the seabed disc (5) and with and without nourishments included.

3.4.4 Results

ShorelineS was calibrated for the period 1983-1999 and subsequently used to assess the performance for the validation period 2000-2023. In addition, the impact of the groynes in this area are evaluated, expected future coastline development until 2050 is studied, and a potential nourishment strategy is assessed.

3.4.4.1 Calibration period 1983-1999

As explained above, the calibration and validation periods are predominantly simulated without taking the nourishments into account, and removing their volumes from the measured data that was combined on Stroom “level”. This was done as the available information on their exact location, shape and timing is limited to the information on Stroom level from Houthuys et al. (2019), and has not been assessed in more detail due to time constraints. This is therefore the cleanest comparison to the measured data volumes that is corrected based on that same nourishment information.

An impression of the predicted coastline position in 1999 by ShorelineS is given in Figure 3-79. On the left figure the what is here called “reference run” (simulation #1); on the right the calibrated model results.

The model, also after calibration, has difficulty to represent the volume changes adjacent to the Zeebrugge harbour (Stroom 44), which is likely due to the limitations of the model to represent the offshore circulation patterns in the area, that enhance westward sediment transport and sedimentation of especially fine material.

The model does generally succeed to hindcast the erosive tendency in the focus area of the MOZES project, Stroom 49 Knokke-Zoute (Figure 3-79), and corresponding erosion volumes in this period (Figure 3-80).

The model with uncalibrated settings has difficulty to represent coastline evolution in Strook 50 Lekkerbek. This could be due to several factors. First of all, the offshore bathymetry is relatively complex (please refer to Section 2.6) and dynamic with channels and shoals and furthermore, tidal currents affecting wave propagation. Furthermore, the bathymetry that has been used in the wave model approach of *Huisman et al. (2019)* is not the most recent nor detailed for this area, it could be that the wave climates are therefore not accurate enough. In an attempt to improve the hindcast for that zone, a calibration factor has therefore been imposed on the two most eastern wave climates, resulting in a better reproduction of the measured volume changes in Strook 50 (Figure 3-80, right). It has however to be noted, that further investigation is required.

When forcing the model with the wave climate used by *Trouw et al. (2024)* (deduced for the period 1999-2004), overall, this gives similar trends, though the extend of sedimentation or erosion is smaller using the wave forcing of *Trouw et al. (2024)* (see Figure 0-2 and Figure 0-3, appendix E). This is more clearly visible when compared to the measured volume changes.

When testing the simulations without adding tidal velocities (not shown here), this does not affect the results considerably, indicating that wave action is the dominant process causing coastline changes. The use of the low water coastline (1.39 TAW) instead of the mean water level (2.33 TAW), does not result in considerable improvement of the hindcast (not shown here).

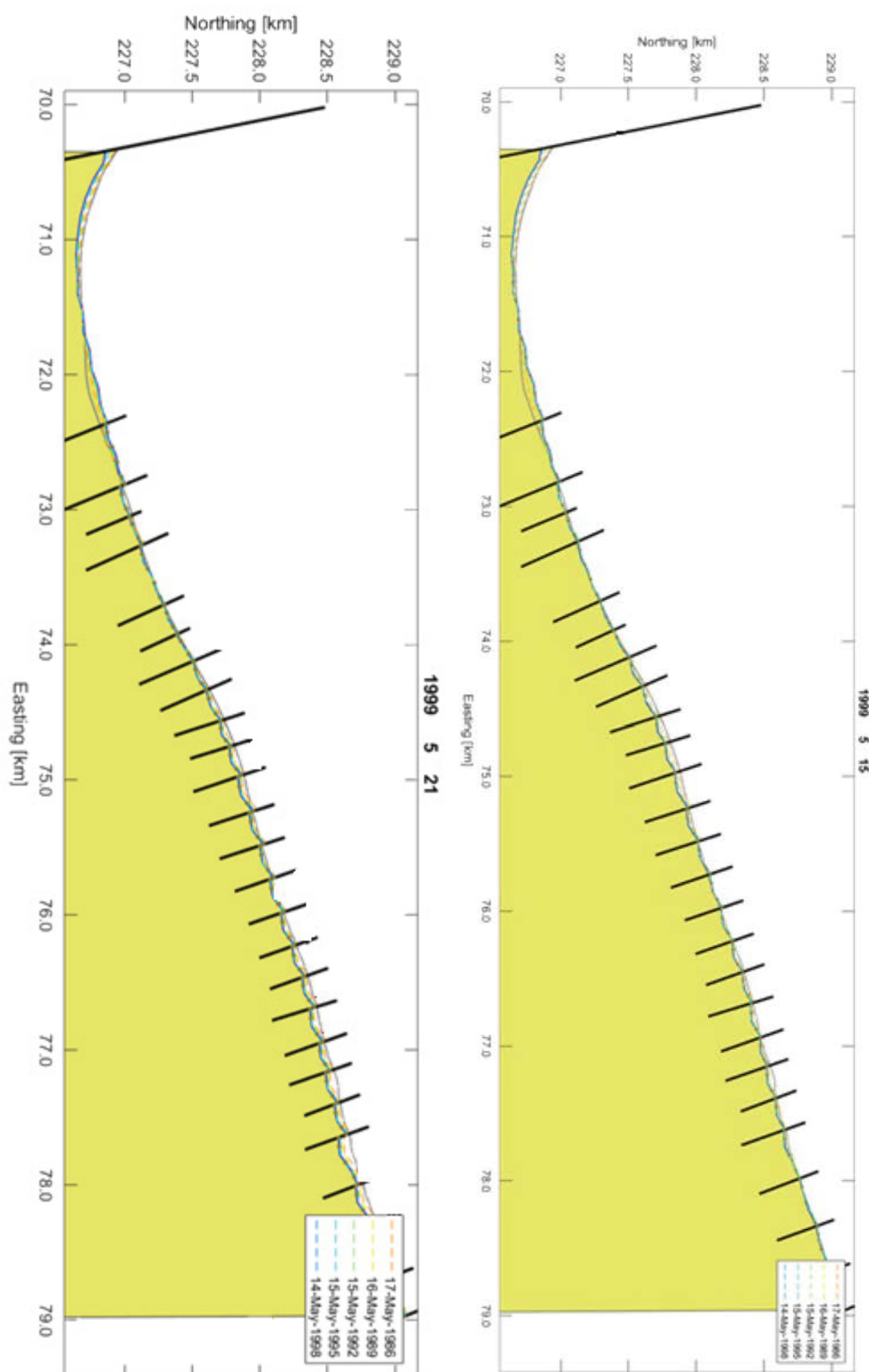


Figure 3-81: Hindcast simulation for the period 1983 to 1999, start coastline indicated by the grey line. (left) reference run, with wave forcing based on wave transformation matrix approach of Huisman et al. (2019), with minor calibration on the most westerly wave location. (right) simulation #3, with calibration of the two most eastern wave climates (wave energy times 0.875(0.75) and clockwise turning of wave direction of +5(10) degrees).

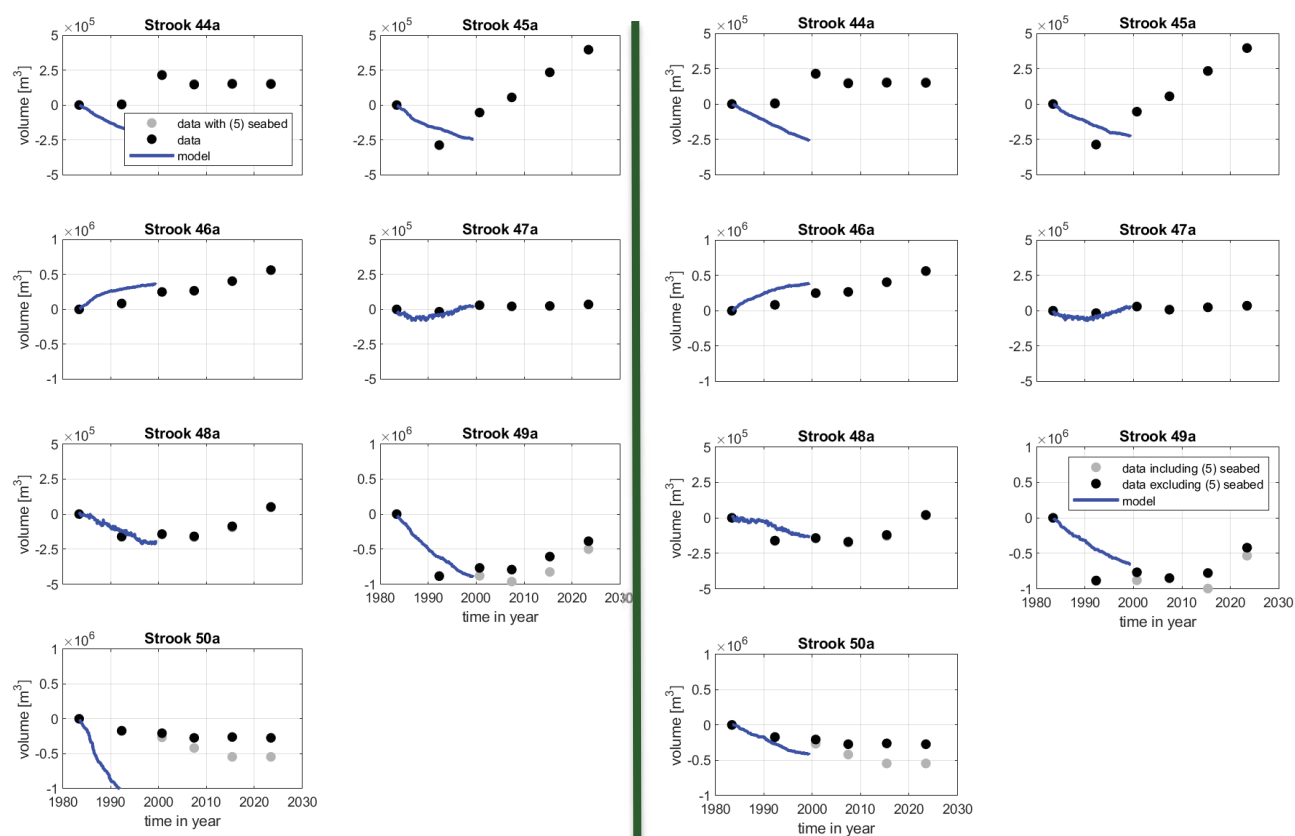


Figure 3-82: Comparison of measured volume changes per Strook, subsection A, with model predictions for the period 1983-1999.

Nourishment volumes are not taken into account in this figure. On the left, results for reference run #1. On the right, results for simulation #3 with calibration of the two most eastern wave climates (wave energy times 0.875(0.75) and clockwise turning of wave direction of +5(10) degrees).

The calibrated model predicts increasing longshore sediment transport from the Albertstrand (Strook 48, 6.000 m³/year) to Knokke-Zoute (Strook 49, 15.000 m³/year) and further east to Lekkerbek (Strook 50, 22.000 m³/year) (Figure 3-81). Increasing transport towards the east translates into an erosive trend in Knokke-Zoute. The predicted longshore transport in this area has a similar order of magnitude compared with other studies, for instance Figure 3-32 from Scaldis/Flemco. Close to the harbor mole the direction and order of transport is not correctly modelled by ShorelineS due to the 3D flow / eddies present in this region that are not represented in the model.

When forcing the model with the wave climate of *Trouw et al. (2024)* the model predicts similar trends, though magnitude of the longshore transport is slightly varying (Figure 0-4).



Figure 3-83: Longshore sediment transport magnitude and dominant direction per Strook over the calibration period 1983-1999, for the calibrated model, simulation #3 (with wave calibration of the eastern two locations).

3.4.4.2 Validation period 1999-2023

The calibrated model is mobilized for the period of 1999-2023 as validation step, using as start coastline the measured coastline of the year 1999, with corresponding wave climates for this specific period.

Predicted coastline evolution trends for the validation period are seen to be very similar to the calibration period. However, there should be noted that for Strook 49 Knokke-Zoute, a clear trend reversal can be observed in the measurements, starting in the nineties, from strongly erosive to mildly accretive conditions. This is likely related to a change of nourishment activities that seem to lead here to an accretive trend (though natural tendency is erosive), which might not be represented well in the simulations. In the current simulation no nourishment volumes have been added. It is assumed that nourishments have been subtracted from the total measured volume changes per Strook. However, this might be prone to limitations on nourishment information and the translation of that to Strook level. In Figure 0-5 (appendix E) results are shown of a simulation where nourishments are added, and compared to the total measured volume changes. This would still result in similar trends, and might still contain a bias on nourishment information.

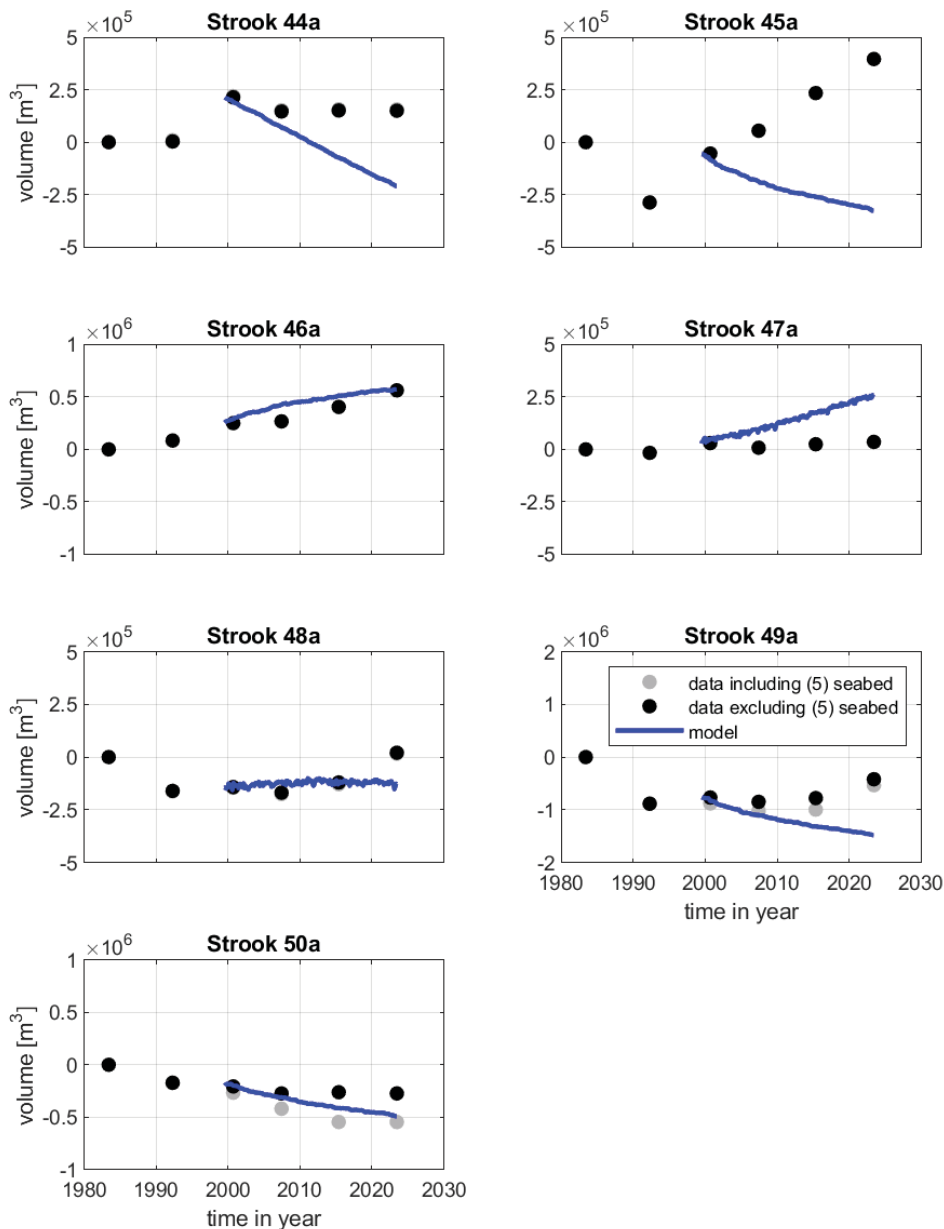


Figure 3-84: Volume changes over time per Strook, for model simulation # and data for the validation period 2000-2023.

When running a simulation from 1983-2023 in one go, predictions for the period 1999-2023 improve slightly (Figure 0-4), as “spin-up” type artifacts to the coastline position are smoothed out.

3.4.4.3 Evaluation of the effect of groynes

To evaluate the effect of groynes on the coastline evolution, additional simulations have been realized for the same calibration period 1983-1999; 1) without groynes and 2) with emerged groynes and 3) emerged groynes with the Van Rijn 2024 sediment transport formulation (latter not shown here). When comparing the coastline without groynes to the reference run with submerged groynes (Figure 3-79 – left figure), a coastline retreat up to ~150 m is visible for the Knokke-Zoute area (Figure 3-83 – left figure), indicating the added value of the submerged groynes to maintain the coastline position.

When the groynes are specified as fully emerged (Figure 3-83 – right figure), the coastline position is maintained without the current need for nourishments. This is also verified with the Van Rijn 2014 transport formulation, which shows similar results, though the tidal currents are not considered here.

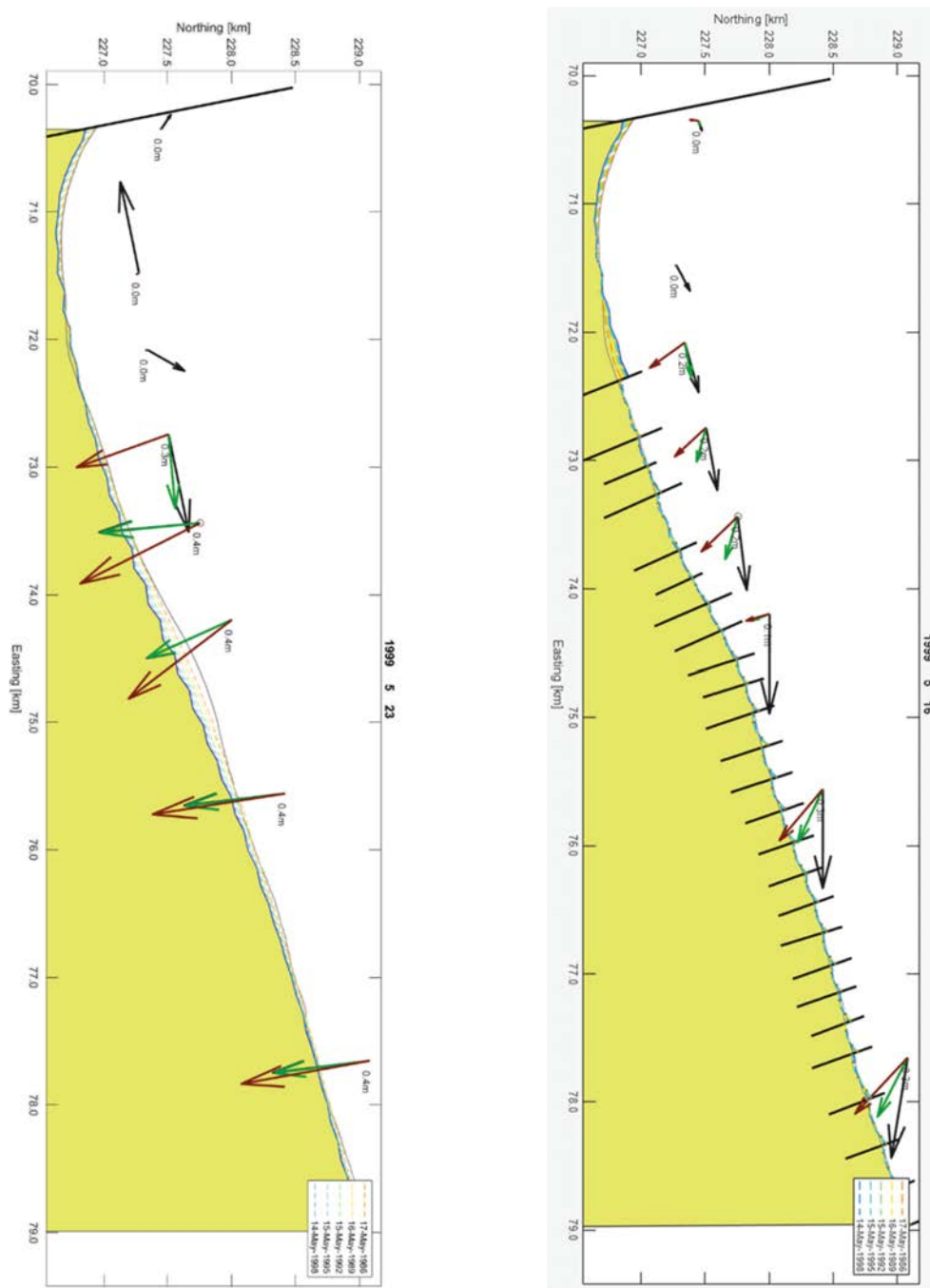


Figure 3-85: Hindcast simulation for the period 1983 to 1999 with same settings as the reference run (left) but without groynes and (right) with emerged groynes. The start coastline is indicated by the grey line. The arrows are less relevant here, but are automatically generated output that show the applied offshore (wave) conditions and the local wave directions at the coast (for the nearshore in green and poin-of-breaking in red-brown) at the indicated final timestep.

When the groynes would be fully emerged, almost no net sediment transport occurs between the Stroken (Figure 3-84). On the contrary, without groynes, the sediment transport would increase an order of magnitude compared to the reference run, up to $\sim 200.000 \text{ m}^3/\text{year}$ at Knokke-Zoute (Figure 3-85).



Figure 3-86: Longshore sediment transport magnitude and dominant direction per Strook over the calibration period 1983-1999, for simulation #6 with emerged groynes.



Figure 3-87: Longshore sediment transport magnitude and dominant direction per Strook over the calibration period 1983-1999, for simulation #8 without groynes.

3.4.4.4 Evaluation of predicted future coastline development

Based on the calibrated model, forecasts for future coastline development demonstrate that especially for Knokke-Zoute the erosive tendency is expected to continue (Figure 3-86 and Figure 3-87), when assuming that wave forcing stays similar to the past decades. The figure shows the results for the wave forcing of *Huisman et al. (2019)* on the left, and *Trouw et al. (2024)* on the right. In Strook 49 Knokke-Zoute, up to 1.6 million m³ (Trouw) to 1.8 million m³ (Huisman) million m³ of volume is predicted to be eroded until 2050.

However, please note that in the validation period a discrepancy has been observed between the model predictions and the measured volume changes. It could therefore be the case that the here predicted erosive trend is too negative. Further analyses are therefore recommended (see Section 3.4.5).

Please note that sea level rise has not been included in the current simulations, but is expected to result in an additional retreat of the coastline of ~ 7 m when following the Bruun rule (considering a sea level rise of about 20 cm, and a beach slope of $\sim 1/30$). This would result in an additional beach volume loss of 150.000 m³ for Knokke-Zoute alone (retreat = 6m x active height = 12 m x longshore length = 2000 m).

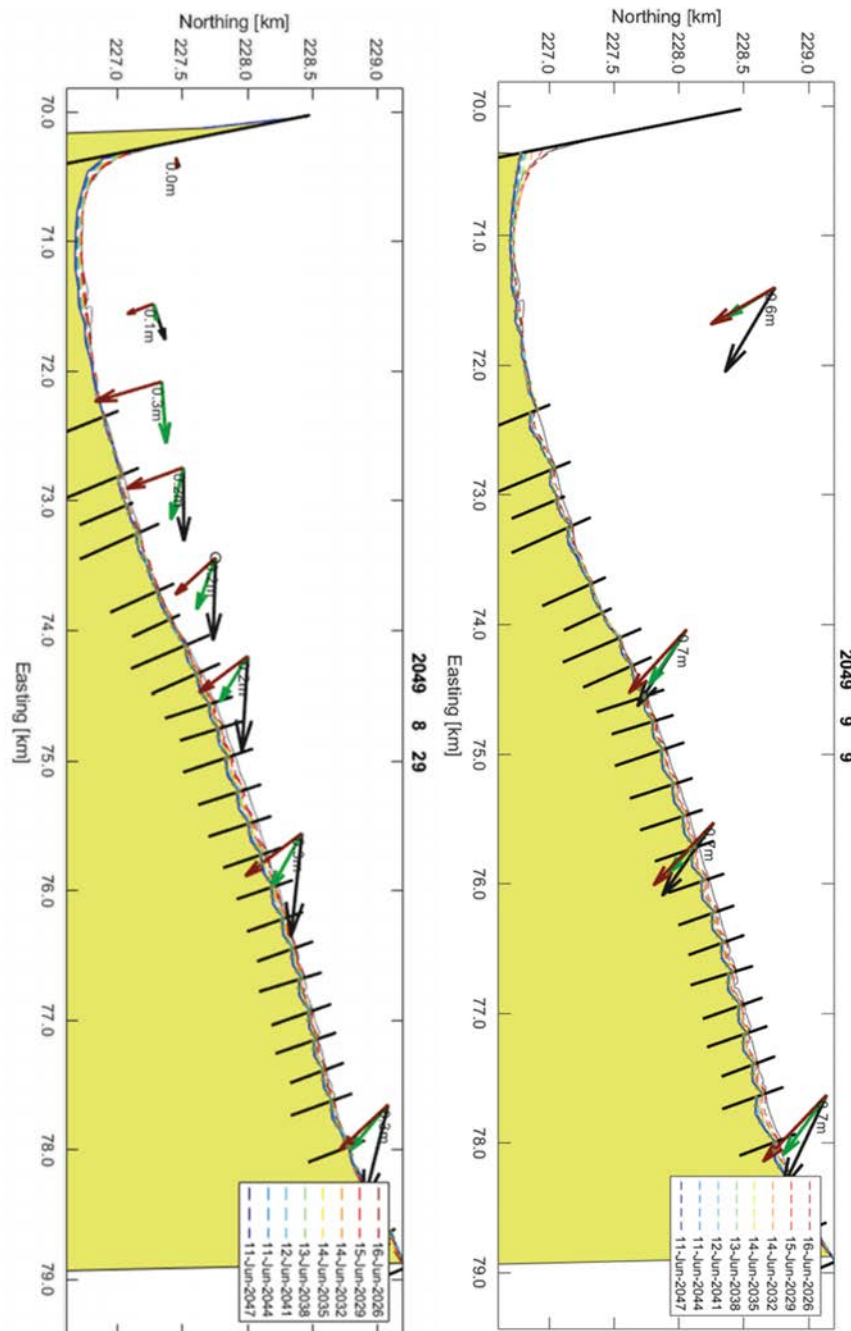


Figure 3-88: Forecast simulation for the period 2023 to 2050. On the left, simulation #15 with wave forcing based on wave transformation matrix approach of Huisman et al. (2019), with wave climates based on 1983-2023 and calibration of the two most easterly wave climates (most eastern location not visible here), (right) simulation #16, similar settings, but then using the wave climate of Trouw et al. (2024) for the period 1999-2024. Start coastline in grey. The arrows are less relevant here, but are automatically generated output that show the applied offshore (wave) conditions and the local wave directions at the coast (for the nearshore in green and point-of-breaking in red-brown) at the indicated final timestep.

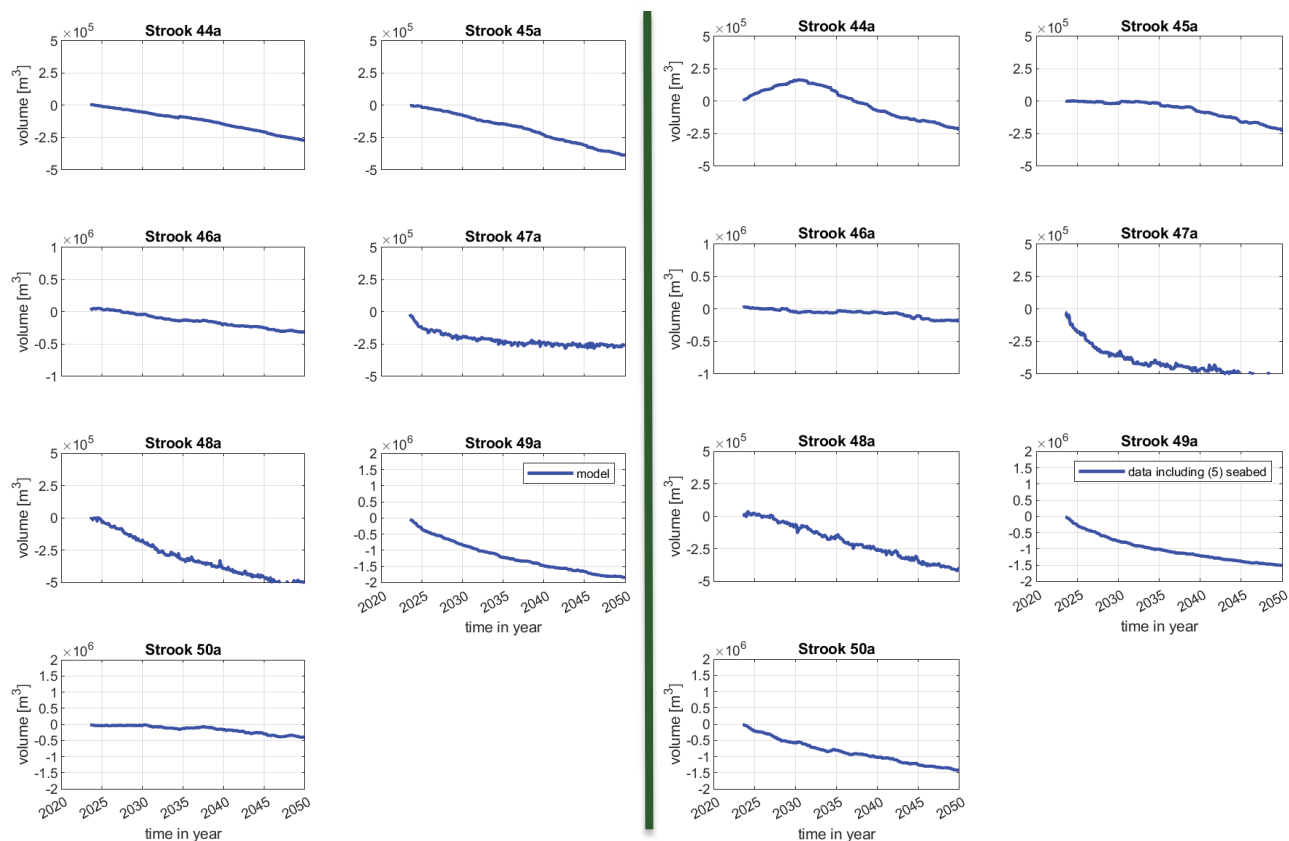


Figure 3-89: Forecast for volume changes over time per Strook for the period 2023-2050. On the left, simulation #15 with wave forcing based on wave transformation matrix approach of Huisman et al. (2019), with wave climates based on 1983-2023 and calibration of the two most easterly wave climates (most eastern location not visible here), (right) simulation #16, similar settings, but then using the wave climate of Trouw et al. (2024) for the period 1999-2024.

3.4.4.5 Evaluation of nourishment scenario Albertstrand

The locally protruding coastline at Knokke-Zoute leads to gradients in longshore sediment transport, and thereby enhanced erosion. Similar to the study of Flemco and Scaldis coast described in Section 3.3.5, ShorelineS is used here to assess the hypothesis whether straightening the coastline of the neighbouring Albertstrand with a large nourishment could:

- reduce sediment transport gradients along the coast
- thereby reduce erosion in Knokke-Zoute.
- reduce nourishment requirements for the area of Knokke-Zoute on the longer term.

The Albertstrand coastline and beach volume appear relatively stable over time. Nourishment volumes are relatively limited in this area (Table 0-1, appendix E). Also the model hindcasts (see above section) demonstrate a rather stable coastline position for this Strook 48.



Figure 3-90: Coastline position for Albertstrand, Stroom 48, over time of the 2.33 TAW depth contour corresponding to mean sea level.

When including the straightening of the coastline, model simulations show that after ten years, considerable coastal erosion occurs at Albertstrand, particularly during the first few years. This is likely due to transport gradients in this zone. Sedimentation is observed to both the west of this zone and predominantly towards the east, due to wave and tidal currents picking up eastwards of the shadow zone created by the Zeebrugge harbour mole. When performing a similar simulation without including tide results are the same, indicating that wave forcing is the dominant process in this area.

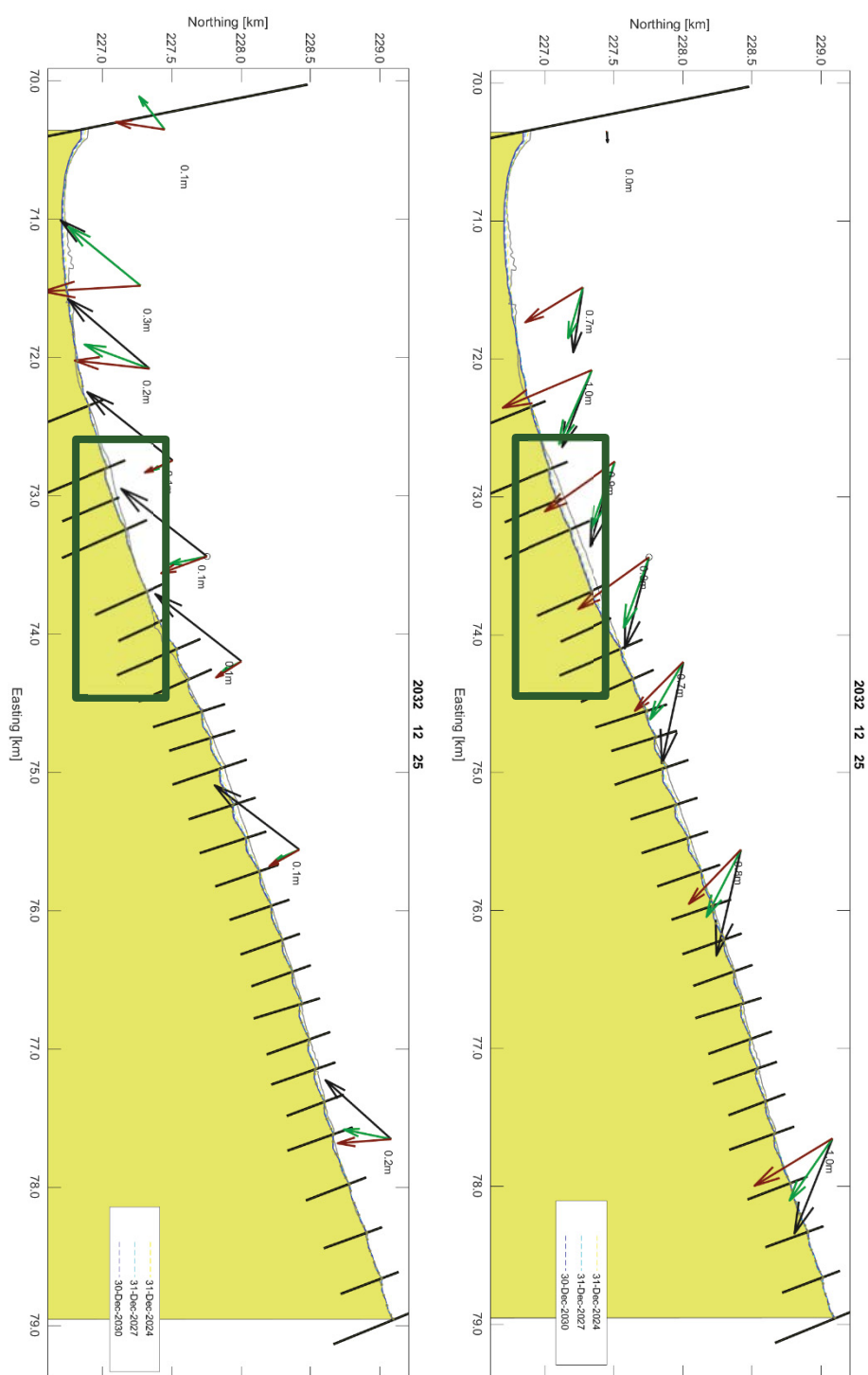


Figure 3-91: Coastline evolution predicted for ten years with calibrated settings. (left) simulation #13, with reference coastline in 2023, (right) simulation #14, coastline in 2023 including Albertstrand nourishment scenario with straightening of the coastline. Start coastline in grey. The arrows are less relevant here, but are automatically generated output that show the applied offshore (wave) conditions and the local wave directions at the coast (for the nearshore in green and poin-of-breaking in red-brown) at the indicated final timestep.

Longshore sediment transports for the reference coastline of 2023 show a decrease in sediment transport from Strook 47 ($45.000 \text{ m}^3/\text{year}$) to 48 ($38.000 \text{ m}^3/\text{year}$), and small decrease in sediment transport from Strook 48 to 49 ($33.000 \text{ m}^3/\text{year}$), leading to sedimentation at Albertstrand.

Longshore sediment transports for the straightened coastline show an increase in sediment transport gradient from Strook 47 (42.000 m³/year) to 48 (62.000 m³/year), and coastline retreat at Albert Strand. Transport decreases between Albertstrand (Strook 48), and Knokke-Zoute (37.000 m³/year Strook 49) leading to relative sedimentation in Knokke-Zoute, when compared to the reference run.



Figure 3-92: Longshore sediment transport magnitude and dominant direction per Strook for the calibrated model settings, for (top) simulation #13, reference coastline in 2023, (bottom) simulation #14, coastline in 2023 including Albertstrand nourishment scenario with straightening of the coastline.

Based on the above analyses, straightening the coastline of Albertstrand does not seem like a sustainable solution to reduce erosion (and thereby nourishment requirements) for Knokke-Zoute. Especially differences (gradients) in wave forcing along the coastline impose shoreline changes. Variability in wave energy occurs due to the presence of the harbour moles of Zeebrugge as well as bathymetric features on the seafloor. A potential solution to create a more stable coastline position at Knokke-Zoute could be to accompany the nourishment by a change in groyne configuration (lengthening groynes or increasing their height, tested but not shown here). More model assessments and detailed volume analyses are required to confirm this.

3.4.5 Discussion

Overall, the calibrated and validated ShorelineS model can serve as a useful tool to support future management decisions for this area. In the conclusions section, the main findings are summarized. Here below a short reflection is given on the limitations of the study approach.

3.4.5.1 Limitations of the current volume analyses

There are a few important limitations to the use of the Houthuys et al. (2019) approach for a one-on-one comparison with the ShorelineS predictions. First of all, the volume analyses by Houthuys et al. (2019) uses specific horizontal discs for their analyses. These do not correspond with the representative active height (12 m) used by ShorelineS. Furthermore, the coastal Stroken as defined by Houthuys et al. (2019) includes channels and shoals present in the nearshore, which the ShorelineS model does not represent. The seaward polygon extend was therefore adapted to the averaged location where a change in slope occurs between the seafloor and shoreface slope, to create a better match with the ShorelineS approach, but this remains an averaged arbitrary limit applied to all Stroken. A detailed analyses based on the bathymetries and/or the digital elevation models would likely provide improved data for a comparison with ShorelineS.

The current analyses were using integrated volume changes of 6 bathymetric surveys, based on the Houthuys et al. (2019) approach, for the period 1983 and 2023 as a reference to the model predictions. Analysing more available bathymetric surveys will likely lead to more robust information on the actual volume changes of the coast and therefore improve the reference dataset on the basis of which the model can be calibrated.

Furthermore, more precise information on nourishments would be very relevant for better understanding of the development of the coast, and for the ability to accurately hindcast its changes. Information on the nourishments is now available per Strook, which is a quite large area. Meaning that the current ShorelineS model uses nourishments that are spread over this whole strook area, while they may in reality be placed in only a section of the Strook. It is therefore recommended to impose the actual nourishments coordinates in the model, which is information that is likely available at the contractors or can be obtained from available bathymetric surveys.

All these factors make it difficult to perform detailed model calibration at these beaches and should therefore be investigated before doing further studies with the models.

3.4.5.2 Limitations of the ShorelineS model approach

The ShorelineS model is following a coastline approach, with one representative cross-shore profile extending to the theoretical depth of closure for wave action. This means that the effect of the 3D variations in the seabed is considered in the separate wave model. In many cases this is an assumption that can be made, but for this case it may be difficult for very steep local beach profiles. Here sediment may move offshore into the channel.

The wave forcing is based on a transformation matrix approach, where only one single bathymetry was included. However, the offshore channels (Appelzak) and shoals are changing in morphology over the last decades, which may lead to some inaccuracies in the wave climate. Though overall, the effect on nearshore wave characteristics is expected to be minor, the wave conditions may therefore change to some extent over time. This imposes some inherent uncertainty on the predicted longshore sediment transport and coastline evolution. Besides these uncertainties also the possibility of complex bi-directional wave conditions (i.e. at the same time from SW and NW) may be relevant for the morphological development of the Knokke-Heist beaches, as the dominant winds are from SW while swell waves originate from NW. A check of 2D wave spectra would be needed to investigate the relevance of this.

The presence of the Zeebrugge harbour creates large-scale eddies, which may influence the alongshore velocities in the nearshore (i.e. close to the beaches). The actual alongshore velocities may therefore deviate to some extent from the computed tides. This may have a (small) effect on the sediment transports along the coast. The relevance of the eddies may be investigated.

Spatial variations in grainsize may affect the transport (rates) along the coast of Knokke-Heist. The actual beach and underwater sediments may be sampled and interrelated with local conditions.

Furthermore, also the profile shape varies in the alongshore. The cross-shore profile is now uniform in the model, as spatially varying characteristics cannot yet be represented. The beach slope varies across the area and is steepest at the border between the Knokke-Zoute and Lekkerbek coastal areas. These steep beaches likely have greater cross-shore losses from the beach towards the Appelzak channel.

3.5 Conclusion/highlights

3.5.1 Idealised modelling of shelf-nearshore coupling

An idealized coupled shelf-nearshore model (Delft3D+SWAN+Quasi2Dmorfo) was used to improve fundamental understanding of the impact of shelf ridges and adjacent channels on the decadal nearshore and shoreline morphodynamics. The observed large-scale bathymetric changes over the past 200 years were incorporated in a schematized form. Sea level rise (also including future IPCC projections), the hold-the-line strategy to maintain shoreline position and coastal squeeze were also accounted for in the model. The main lessons learned from this study are summarized below.

- Model results in the case without sea level rise (SLR) show that shoreface-connected sand ridges (sfc) and tidal sand ridges (tsr) on the Belgian shelf act as a forcing template for the decadal evolution of the shoreline. This template is established through wave refraction over sfc crests and channels between the ridges and the shoreline. This creates gradients in wave energy density, which induce spatial variations in the longshore sediment transport in the nearshore zone. Consequently, shoreline progradation occurs in the proximity of crests of landward ends of the sfc, while shoreline retreat appears adjacent to the channels in between the ridges. Compared to sfc, the impact of tsr on the shoreline development turns out to be smaller, but significant. These results show that, in addition to acting as natural sediment feeders for nearby beaches, shoreface-connected sand ridges also influence shoreline morphodynamics by altering waves propagating onshore across these ridges.
- Model results using sea-level rise rates from the IPCC scenarios for the next 50 years (> 3 mm/yr), combined with a hold-the-line strategy to maintain shoreline position and the associated coastal squeeze (i.e., shoreface retreat and nearshore profile steepening), indicate that future annual nourishment volumes in areas where coastline erosion is determined by the channel-ridge morphology may need to be about 2–5 times larger than those under the sea-level rise rates over the last 50 years (≈ 1.5 -3 mm/yr).
- Based on model results, the following new insights are obtained regarding effects of sea level rise on decadal shoreline morphodynamics. Two competing mechanisms appear to govern shoreline evolution under SLR and the hold-the-line strategy in the vicinity of ridges. On the one hand, the onshore-migrating ridge induced by SLR promotes shoreline progradation. On the other, coastal squeeze (shoreface retreat and profile steepening) counteracts this progradation. Over time, coastal squeeze becomes the dominant mechanism, leading to the disappearance of shoreline progradation, particularly for higher rates of SLR. Near channels, shoreline erosion increases due to both the onshore migrating channels and coastal squeeze, requiring more nourishment than in cases without coastal squeeze. This decay in progradation and increase in erosion seem to be caused by increased offshore-directed sediment transport, caused by narrower and steeper nearshore profiles.

3.5.2 Longshore and cross-shore sand transport processes along the Belgium coast simulated with 2 complex process-based 2DH models

- The Scaldis-Coast and FlemCo sensitivity runs based on different model forcing combinations (tide, waves, wind) revealed that the wave-induced longshore transport clearly dominates the total longshore transport (often about 2/3 or 3/4 of the total) and that wind has a minor impact on the tide-induced longshore transport but a major impact on the wave-induced longshore transport (cf. Figure 3-33 and Figure 3-34). The latter is due to the fact that the wind reduces wave dissipation in coastal waters and by this results in clearly higher waves in the nearshore zone, which causes a larger wave-induced longshore drift and associated sediment transport.
- Regardless of the discrepancy of the predicted absolute longshore sediment transport between the Scaldis-Coast and the FlemCo models, they both indicate dominating wave-induced longshore transport in the first few hundred metres seawards the coastline (breaker zone), followed by dominating tide-induced longshore transport further seawards. While both models suggest a considerable but narrow peak for the wave-induced transport, they show a much wider but flattened peak (numerous hundreds of meters wide) for the tide-induced transport. According to both models, the tide-induced transport is still significant even numerous kilometres offshore.
- Analyses of the whole set of performed sensitivity runs reveal that the observed discrepancy in predicted wave-induced longshore transport between Scaldis-Coast and FlemCo is – apart from the different applied modelling software (Telemac/TOMAWAC in Scaldis-Coast and Delft3D Flexible Mesh/SWAN in FlemCo) – related to
 - different settings used in the two wave models, especially the applied bed friction coefficient (lower in Scaldis-Coast) and breaker index (higher in Scaldis-Coast),
 - the fact that groynes in the Scaldis-Coast model are smaller in dimension (interpolated as bathymetry on the computational grid) in the FlemCo model (fixed weirs with specified elevations), and therefore block the wave-induced longshore current to a smaller degree than in the FlemCo model,
 - less spreading of the wave directions in the nearshore zone in the Scaldis-Coast model resulting in a more peaked dominant wave direction and by this stronger wave-induced longshore current than in the FlemCo model.

This altogether favours higher wave energy and more pronounced wave-induced longshore currents in the nearshore zone causing a higher longshore transport in the Scaldis-Coast than in the FlemCo model.

- The evaluation of the FlemCo and Scaldis-Coast model results and sediment pathways analyses indicate that at the sand ridges Trapegeer-Broersbank-Den Oever and Stroombank landward directed sediment transport occurs, which potentially nourishes the adjacent coastline. On the shoreface, this landward directed transport is particularly associated with wave related sediment transport, while the tide related sediment transport mainly occurs parallel the coastline. At the Paardenmarkt, no significant landward directed transport and by this no natural feeding of the coastline can be observed due to the dominance of tide related longshore transport even close to the coastline in the Appelzak channel. Although the current study implies landward directed sediment transport from the sand ridges towards the coast and by this indicates a potential natural feeding of the adjacent coastline, further research has to be carried out whether the landward transported sediment indeed feeds the beaches. Moreover, it has to be investigated what are the exact processes that lead to wave related landward directed sediment transport and in how far the interaction of tide and waves is relevant for this transport. As a first follow-up step, it is suggested to apply the more recent Scaldis-Coast and FlemCo model versions that have been further developed and fine-tuned (including longshore and cross-shore sediment transport processes) based on the morphological hindcast study presented in Section 3.3.4.

- The analysis of beach and shoreface nourishment intensity showed that storm events, changes in (safety) policy or nourishment method and other human factors are the main drivers behind nourishment intensity and obscure the possible relation with the deepening of nearshore tidal channels. It is therefore suggested to further study the effects of the observed gradual deepening of nearshore tidal channels on beach erosion and required beach nourishments by means of complex process-based numerical models such as the Scaldis-Coast and FlemCo models.
- The scenario modelling study performed for the Appelzak channel at Knokke-Zoute does not directly indicate that a deeper Appelzak channel leads to more erosion of the adjacent beaches since the peaks of the wave-induced longshore sediment transport mainly show a landward shift/only slight increase in the case of a deeper channel and the residual transport direction remains parallel to the coastline. However, the general increase of the tide related and by this total longshore sediment transport in the eastern deepened Appelzak channel indicates an increased sediment loss in this area, which may also affect the beaches provided that waves transport sediment from the beach in cross-shore direction towards the shoreface (cf. Figure 3.20 and Section 2.7.3). At the same time, the general decrease of the tide related and by this total longshore sediment transport in the western deepened Appelzak channel indicates a decreased sediment loss in this area.
- The two morphological models, Scaldis-Coast and FlemCo were further improved through fine-tuning of the model settings based on the model version presented in Dujardin et al., (2025). The calibrated models are subsequently validated for an independent period. The models were then applied to investigate the influence of the two different beach nourishment scenarios on the morphodynamic development in the Knokke-Zoute area. Altogether, both models were used to simulate four simulation periods (two hindcasts and two scenarios), which cover a wide range of practical application: beach nourishment within/outside the area, shoreface nourishment during the simulation period. The following conclusions are made:
 - The Scaldis-Coast and FlemCo models generally show quite similar erosion/sedimentation patterns in the Knokke-Zoute area, although Scaldis-Coast predicts more erosion on the beach and the shoreface. This can be explained by various reasons presented above. Compared with the measurements for the two hindcast periods 1999-2002/2003 and 2019-2022, the two models capture the main morphological features in the area: erosion on the beach and Appelzak channel for the case without shoreface nourishment. Some model shortcomings were observed, among others probably due to wave related cross-shore processes in the nearshore zone due to the depth-averaged (2DH) approach of both models. While these processes are parametrised in the FlemCo model, the Scaldis-Coast model version used in this study, does not consider wave-related cross-shore transport associated with Stokes drift and undertow.
 - Conducting the model scenarios together with the reference cases allows for a relative comparison, thereby reducing model uncertainty. Analysis of the scenario designed to alter the Albertstrand coast indicates that straightening the coastal area (requiring sand nourishment) have a local impact on the area itself but nearly no protective effect on the adjacent area, Knokke-Zoute. This is primarily attributed to the location of the Albertstrand coast within the sheltered zone of the Zeebrugge port where wave energy and longshore sediment transport are significantly reduced, resulting in minimal sediment redistribution.
 - The scenario modelling study on beach erosion at the Knokke-Zoute area shows that a proper study on beach nourishment design can result in an effective reduction of sand loss. Optimizing parameters, e.g. nourishment shape, beach slope, grain size, nourished volume is essential to ensure effective beach stability.
- The usage of two complex process-based 2DH models significantly contributed to a better understanding of the models' sensitivity and uncertainties with regard to the predicted sediment transport and morphodynamics in the study area. The comparison of both models in particular demonstrated

- o the high sensitivity of the predicted longshore sediment transport – and by this of the resulting morphodynamics – to the predicted wave directions,
- o the relevance of the technical implementation of groynes in the model (either implemented in the model bathymetry or as 2D fixed weir structures) for longshore sediment transport predictions,
- o that model calibration based on longshore sediment transport is not sufficient for reliable morphodynamic hindcast modelling,
- o the relevant cross-shore sediment transport processes – although simplified – can be captured by the models provided that more complex sediment transport formulations and descriptions for the wave asymmetry velocity are used.

Based on these findings, we suggest the following for the future development of the applied models:

- o Use more complex sediment transport formulations such as van Rijn (2004) instead of more simplified formulations such as Bijker (1971), which have their limitations for wave related and cross-shore transport processes nearshore.
- o Rather focus on morphological hindcasting than on the longshore sediment transport during the model calibration in order to account for both cross-shore and longshore sediment transport processes and to avoid over-calibration of the model based on the longshore transport.
- o Further improve the nearshore wave direction predictions by means of fine-tuning of the wave model settings and/or the usage of alternative wave modelling software (e.g. SWAN or similar).

3.5.3 ShorelineS model application

3.5.3.1 Conclusions

In this study, we further refined the reduced-complexity ShorelineS model for the Knokke-Heist coastline, originally developed by *Trouw et al. (2024)*. The model was calibrated and validated over a 40-year period using measured volume-change data from *Houthuys et al. (2019)*, which were adapted to align with the ShorelineS modelling approach. A brief system analysis was carried out, and the influences of the (submerged) groynes, wave forcing, tides, future coastline development, and a selected nourishment strategy were assessed.

Model results show that wave forcing is the dominant driver of coastal change in this area, outweighing the influence of tidal currents. Spatial variability in wave forcing—caused by the sheltering effect of the Zeebrugge harbour mole and the complex nearshore bathymetry of channels and shoals—creates strong longshore sediment-transport gradients, with additional secondary gradients in the cross-shore direction. These gradients lead to pronounced erosion in Knokke-Zoute (strook 49) and Lekkerbek (strook 50). Furthermore, the locally protruding coastline at Knokke-Heist itself induces additional longshore sediment-transport gradients, which further enhance erosion in this zone.

The submerged groynes currently present in the study area play an important role in supporting coastline stability. However, they are not sufficient on their own to maintain the coastline position, which has required numerous nourishments over recent decades. Model results indicate that if the groynes would be fully emerged, the coastline would require less maintenance nourishments, but this is a complex work and may introduce other complexities such as stronger rip-currents.

Based on the calibrated model, projections of future coastline development indicate that erosion at Knokke-Heist is likely to continue, assuming wave forcing remains comparable to that of recent decades and that sea-level rise is excluded. In Knokke-Zoute (strook 49), up to 1.8 million m³ of sediment is predicted to be eroded by 2050. It is important to note, however, that starting in the nineties a clear trend reversal can be observed in the measurements, from strongly erosive to mildly accretive conditions. The ShorelineS model does not capture this trend reversal. As a result, the projected erosion rates presented here may be a high estimate of the losses. Additional analyses are therefore recommended.

Similar to the Scaldis-Coast/FlemCo study, the ShorelineS model is used here to assess whether straightening the coastline at the adjacent Albertstrand through a large nourishment could reduce alongshore sediment-transport gradients and thereby mitigate long-term erosion in Knokke-Zoute. Based on the analyses above, straightening the Albertstrand coastline does not appear to reduce the sediment demand at Knokke-Zoute, meaning that nourishing this beach section with similar volumes will remain a necessity also in the future. The main reason is that the harbour of Zeebrugge blocks the wave energy and therefore interrupts the net north-eastward directed alongshore sediment transport at this beach section, driving ongoing erosion. An approach that may be considered is to combine a nourishment with adjustments to the groyne configuration to enhance local coastline stability, but a dedicated technical study and (societal) cost-benefit assessment would be required to weigh the pros and cons of such a strategy against a strategy with just nourishments. Additional model simulations and more detailed volume analyses are needed to confirm this.

Overall, the calibrated and validated ShorelineS model can serve as a useful tool to support future management decisions for this area, although additional verification and further model improvements are recommended.

3.5.3.2 Recommendations

Several recommendations are listed below:

- As mentioned in more detail in the discussion section, the approach used by *Houthuys et al. (2019)* to determine volume changes in the area incorporates several assumptions (strook/discs/dates) and thereby limitations for a robust comparison to the ShorelineS model predictions. Detailed analyses of the local bathymetry and/or the digital elevation models themselves are required, with further research into the observed change in trend at Knokke-Zoute (strook 49). Comparing the observed coastlines (e.g. at every 50 to 100 meter) will provide more information than an assessment of the ability to predict the Strook volumes.
- It is recommended to investigate the precise locations, sediment properties and volumes of the nourishments that have been carried out in the study area. For example, applying the exact locations of the nourishments in the model (and not on the 'Strook' level) will already improve the ability of the model to hindcast the local coastal changes.
- The wave forcing is based on a transformation matrix approach, where only one single bathymetry was included. However, the offshore channels (Appelzak) and shoals are changing in morphology over the last decades, which leads to inaccuracies in the wave climate. It is recommended to investigate the influence of updating the bathymetry in the wave model used for the wave transformation matrix approach. Especially, detailed analyses of the wave extraction locations near the Appelzak channel and Zwin are recommended, to obtain more robust wave forcing conditions in this area.
- The groyne dimensions could be further improved in the model as already mentioned in *Trouw et al. (2024)*. Also, the physics of the bypassing of the submerged groynes will need to be investigated. Possibly, both detailed numerical studies and field measurements are needed to improve the knowledge of the submerged groynes.

- It would be particularly valuable to examine the coastline evolution of the past 40 years in greater temporal and spatial detail, including the influence of the numerous nourishments, in order to improve future maintenance strategies. This analysis could be carried out using the available wave time series, rather than relying on a derived wave climate that is then randomly varied throughout the simulation. At present, this is not yet feasible with the *tideprof* sediment transport formulation used for submerged groynes. A logical first step would be to apply the Van Rijn (2014) sediment transport formulation instead.

4 Conclusions and lessons learned for coastal protection

4.1 Introduction

The Belgian inner shelf along with the adjacent French and Dutch shelves form a geomorphologically complex coastal system characterized by tidal sand ridges offshore and shoreface-connected ridges closer to the coast, as well as channels in between the ridges. Understanding their long-term evolution is critical for assessing sediment budgets, coastal resilience, and the cumulative effects of sea-level rise and human intervention. This study reconstructs and analyses largescale seabed changes from 1804 to 2022 to quantify natural morphological trends, identify connectivity between offshore and nearshore sedimentary environments, and evaluate the influence of anthropogenic activities such as dredging, navigation channels, and harbour construction. In addition, two types of numerical models (complex and idealized process-based models) were applied to better understand effects of the seabed changes on decadal shoreline evolution, as well as the influence of the anthropogenic activities.

4.2 Data-analysis of the channels-ridges morphology

A multi-century bathymetric dataset was developed by vectorizing and harmonizing historical navigation charts from 1804, 1866, 1908, 1938, the 2000s, 2010s and 2020s, supplemented by inner-shelf surveys from the 1960s, 1970s, 1980s and 1990s. Widely spaced historical soundings were interpolated using knowledge of present-day morphology to obtain realistic bedform geometry. In addition, a number of coastal topobathymetric datasets from the late 20th century were vectorized, including beach topographies for spring 1983 and spring 1992 as well as shoreface bathymetries for spring 1986 and spring 1992.

The morphological evolution was analysed across three zones: (1) the offshore shelf containing tidal sand ridges, (2) a ~7 km wide nearshore zone with shoreface-connected ridges, and (3) a ~4 km wide transition zone between them. Using difference maps, contour line shift maps and volumetric analyses bedform migration, elevation change, sediment gain/loss, and channel dynamics were quantified and human-induced changes were interpreted.

Overall, no significant net sediment loss or gain was observed across the entire region (boxes in Figure 2-29) over that long period. However, this is an overall net balance. Sediment is continuously being imported from the adjoining French part of the shelf and exported to the Dutch shelf. Also, there are significant internal rearrangements (Figure 4-1, top panel).

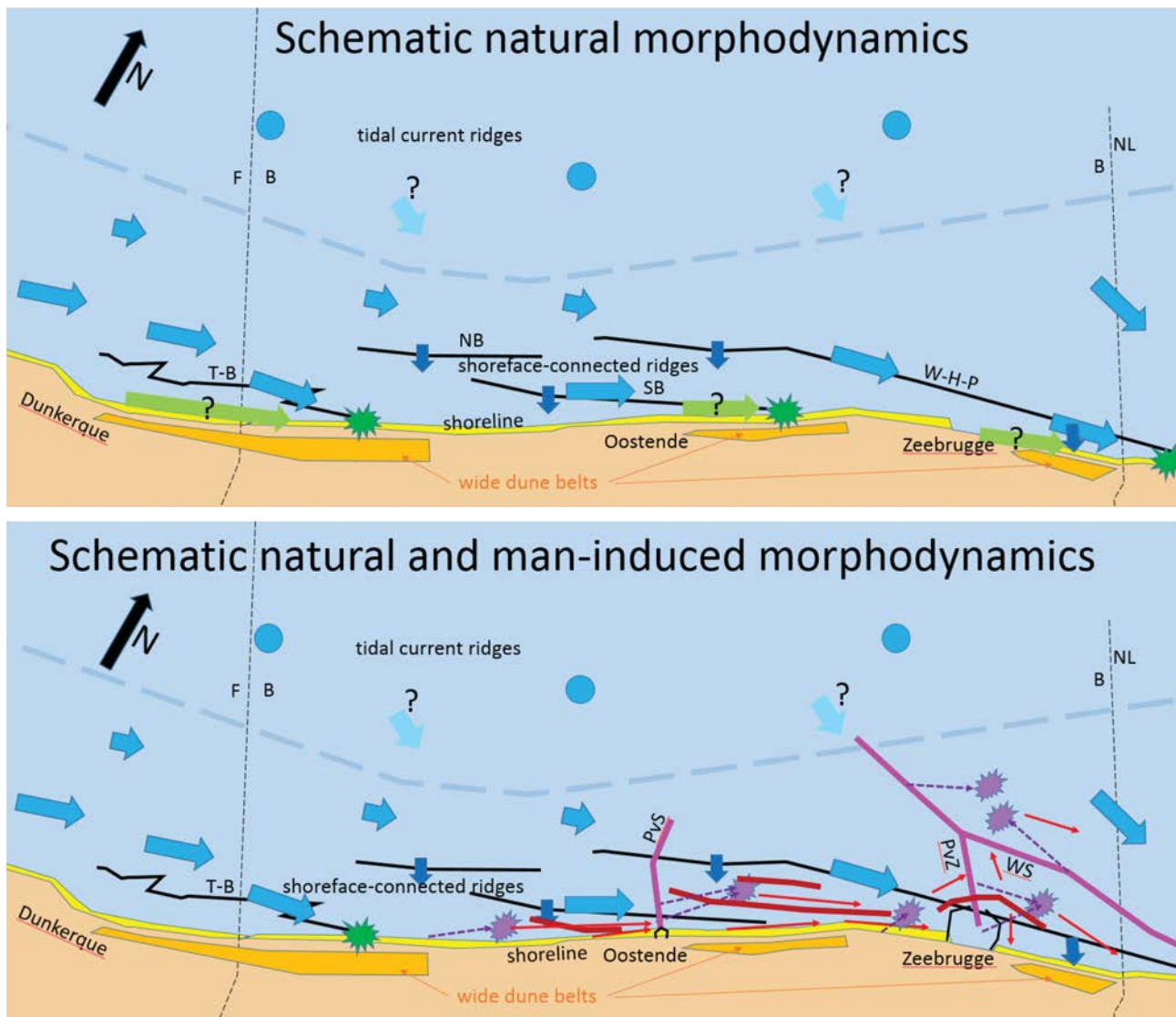


Figure 4-1 - Schematic summary of natural and man-induced morphodynamics. Top: in the 19th and first half of the 20th century. Bottom panel: since about 1950. Legend: cf. Section 2.10

Long-term natural morphological change was identified from older maps and in areas without major harbours. Where the more offshore tidal sand ridges turn out in general not to have moved, the more nearshore located shoreface-connected sand ridges show significant eastwards and shorewards migration, with higher rates tending to be observed in the more inshore areas. Especially in the French-Belgian border area, important alongshore movements of ridges and passes ranging from 5 to 20 m/year are observed. Most shoreface-connected sand ridges also migrate shorewards, at rates between 1 and 1.5 m/year. This is also seen from Figure 4-2, which shows the evolution of historical bathymetric profiles in the area of Stroombank, and the associated large-scale morphological changes. The migration rates of the ridges over the past 100 years in this area are even larger (3-4 m/year) than those observed during the 19th century. Also the nearshore channels and the shoreface base tend to shift landwards. These natural changes are thought to be ultimately driven by the ongoing sea-level rise. The coastal barrier is maintained at its current position (the hold-the-line strategy) and even widened through human interaction, which is believed to have led to steepening of the shoreface. As a result, morphological squeeze pushes the nearshore tidal channels to deepen their bed in order to maintain their flow section. This system also implies that any sand, eroded from the (nourished) beaches and ending up at first in the nearshore channel in front of the beach, is cleared away by the currents. On the shoreface-connected ridges, high rates of longshore sand transport are reported.

The fill of the fairways to Oostende Harbour allowed us to quantify the longshore net transport rates to be at least of the order of 200 m³/m/ year. These results show an intense transport along the ridge which may in turn contribute to sand supply from the nearshore domain to the beach and the dunes, where the attachment points are the area of entry at the shore.

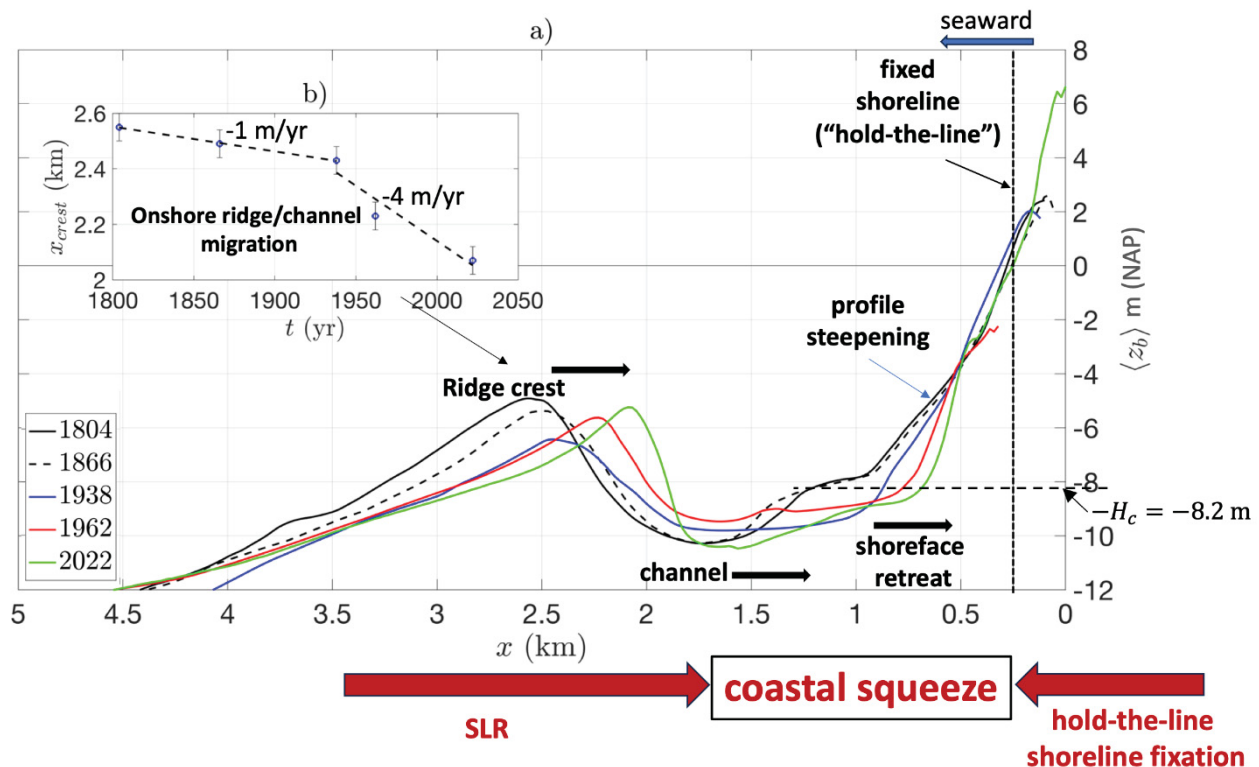


Figure 4-2 Schematic view of coastal squeeze: nearshore zone is trapped in between onshore migrating ridges and channels driven by sea level rise (SLR) and shoreline fixation under the hold-the-line strategy.

The height of the shoreface-connected sand ridges did not change over the past 200 years, though often both crest and channel slightly rose over the past two centuries. The crest area of Westerschelde ebb tidal delta shifted landwards, towards the Westerschelde.

While natural change on the inner shelf and in the nearshore is already considerably affecting the morphological evolution of the beaches, also human-induced change locally affects nearshore and coastal morphodynamics substantially (Figure 4-1, bottom panel).

There are at least the following four human-induced morphological mechanisms that strongly impact on the Belgian coastal morphology:

- The natural sand supply path formed by the shoreface-connected ridge Stroombank is disrupted near Oostende Harbour, depleting the beaches between Bredene and De Haan from the natural offshore sand supply. Further east, the historic shoreface-connected ridge Wenduine Bank / Hard Zand / Paardenmarkt is crosscut by Pas van 't Zand. Sand transported along the ridges is now intercepted in the navigation channels and is removed there by dredging. The dredged material is dumped offshore and thus lost to the coastal system. In addition, the seabed surrounding the frequently dredged fairways shows slow but persistent deepening over extensive areas, suggesting that sediment is attracted into the fairway, and also exported by dredging.
- Dredging activities have a disrupting role on the morphological system. The practice of dumping dredged material at a fixed offshore site in a current channel has the effect of locally plugging up the channel. The currents are diverted around the dump site and the current regime in the diverted branches is reinforced.

Under that regime, the morphological response of the channel is deepening its bed. The deepening area extends over many kilometres in the case of dump site Bruggen & Wegen Oostende, where over the recent decades structural deepening of Grote Rede was triggered between Bredene and Blankenberge Harbour.

- Near Zeebrugge, dump activities at Bruggen & Wegen Zeebrugge Oost have more than compensated the loss of sand advected previously along the shoreface-connected ridge that was cut by Pas van 't Zand. Actually, the wide nearshore area east of Zeebrugge receives large amounts of sediment, triggering both a seaward and eastwards expansion of Paardenmarkt.
- The construction of harbour dams extending deep into the nearshore strongly alters the morphodynamics of the surrounding area. The sheltered areas at the updrift and downdrift sides of the harbour dams attract huge quantities of sediment. The areas just offshore of the harbour dams become exposed to a stronger current regime and scour troughs develop there. It was shown in this study that morphological adaptations east of Zeebrugge are still going on today, 50 years after the construction of the harbour dams. Sedimentation in the nearshore area off Heist not only receives nourished sand from Knokke-Zoute but even larger quantities of sediment derived from a new continuously deepening flow channel north of Zeebrugge, called here "Duinbergen Channel". The overall changed morphological configuration may ultimately benefit Knokke-Zoute: the tidal current channel Appelzak is expected to be diverted more offshore and to link up with Duinbergen Channel, while sedimentation off Heist is expected to expand eastwards to Knokke-Zoute. This may result in milder hydrodynamics at Knokke-Zoute.

A new hypothesis on the mechanism of natural feeding of sand from the seabed towards the coastline is obtained from the data-analysis of bathymetric maps from the past ~200 years. Namely that the shoreface-connected ridges along the Belgian coast act as carriers of smaller seabed forms that migrate along their axes, which are slightly angled relative to the coastline. When these bed forms reach the coast, they deliver substantial quantities of sand to the active coastal zone (shoreface, beach, dunes).

This data-analysis shows the power of regular morphological monitoring and interpreting morphological change in a coherent and wide context.

4.3 Numerical modelling

Two types of numerical models (complex and idealized process-based models) were applied to better understand the effects of seabed changes on shoreline evolution, as well as the influence of the anthropogenic activities. Below is a summary of the main lessons learned from these models.

Alongshore sand transport (i.e. parallel to the coastline), was simulated with two state-of-the-art complex 2DH models, namely Scaldis-Coast (Telemac software) and FlemCo (Delft3D Flexible Mesh software). The main finding with respect to the alongshore sand transport from this work is that, in most parts of the Belgian shore, wave-induced alongshore transport is the dominant process in the active zone landward of the depth of closure, typically contributing about 65–75% of the total transport. Tides and wind-induced currents are of less importance in this zone. However, tide-induced transport becomes more dominant east of Zeebrugge harbour and further offshore. Differences between Scaldis-Coast and FlemCo longshore transport predictions are relatively large and can be attributed to a combination of software and model set-up configuration aspects mainly related to the different applied wave models, transport formulations and also to the implementation of the groynes in the two models. Substantially larger wave-induced longshore sand transport is simulated by Scaldis-Coast compared to what is simulated by FlemCo. Given the uncertainty on longshore transport estimates from data, it remains unclear which model predicts the longshore transport more accurately. However, FlemCo wave climate results near the coastline are more representative of real wave climate statistics along the coastline at the Appelzak channel based on in-situ wave measurements analyses.

Scaldis-Coast and FlemCo 2DH model results were also analysed with respect to cross-shore sand transport in the nearshore to investigate natural feeding processes from the shoreface-connected sand ridges to the coastline. Some indications of natural feeding processes on the shoreface were found in the FlemCo model at the ridges Trapegeer-Broersbank-Den Oever and Stroombank. However, wave related cross-shore transport on the beaches is not (Scaldis-Coast) or only simplified (FlemCo) simulated by the two applied 2DH models. Further research has to be carried out on what are the exact processes that lead to landward directed sand transport from the sea to the coastline and in how far the interaction of waves, wind and tide are drivers of this transport.

The nourishment needs for coastline preservation at the erosional hot-spot of Knokke-Zoute were investigated with both 2DH models Scaldis-Coast and Flemco, and with a third and different type of model namely a ShorelineS coastline model developed for the east coast domain (from Zeebrugge harbour to Zwin). A set of selected historical nourishments were hindcasted for calibration and validation of these models. Results showed that these models can all reproduce the high erosion rates of beach nourishments at Knokke-Zoute as volumetric losses of the active profile (m^3/year) after calibration. Most importantly it was shown that the main driver of this erosion is the large gradient of alongshore sand transport in the active zone which is caused by the harbour of Zeebrugge blocking alongshore transport from the southwest coastline. Appelzak channel migration and local protrusion of the coastline are secondary drivers of erosion of the beaches in Knokke-Zoute (Figure 4-3). Sensitivity analysis based on a deepened Appelzak channel configuration in both 2DH models indicated that a deeper Appelzak channel or a steeper shoreface does not directly imply increased erosion on the beaches of Knokke-Zoute. This finding, however, must be considered cautiously due to the missing or only simplified wave-related cross-shore processes (see above) in the models, which may have significant impact on the beach erosion processes. Regarding the larger scale sediment transport patterns, the predictions by both models are generally in line with the transport patterns as derived from the historical bed level changes analysed in Section 2.7.4 (cf. Figure 2-45 with Figure 4-3). Note that applying the presented Scaldis-Coast and FlemCo predictions should also allow for the simulation of longer term large-scale morphological changes near Zeebrugge that were induced by the extension of the harbour in 1980's and that is still continuing today.

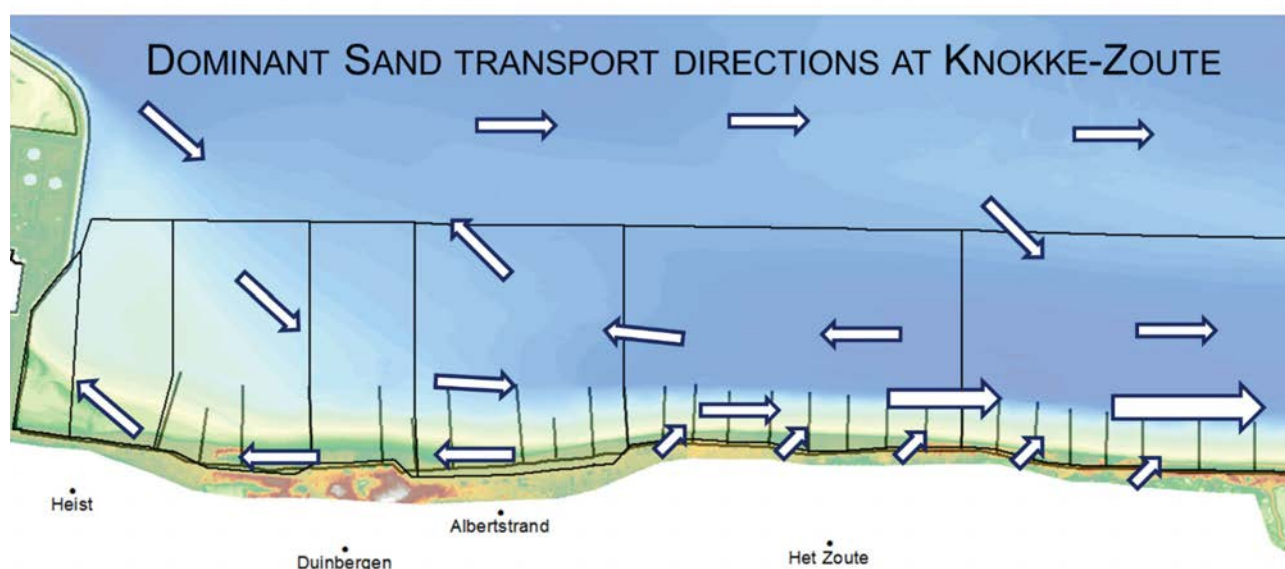


Figure 4-3: Dominant sand transport directions in the area of Knokke-Zoute according to the residual transport predictions by the Scaldis-Coast and FlemCo models (see Section 3.3.5). In general, the simulated transport directions are in good agreement with the transport patterns as derived from the historical bed level changes (cf. Figure 2-44).

An idealized coupled shelf-nearshore model (Delft3D+SWAN+Quasi2Dmorfo) was used to improve fundamental understanding of the impact of shelf ridges and adjacent channels on the decadal nearshore and shoreline morphodynamics. The observed large-scale bathymetric changes over the past 200 years were incorporated in a schematized form. Sea level rise (also including future IPCC projections), the hold-the-line strategy to maintain shoreline position and coastal squeeze were also accounted for in the model. The main lessons learned from this study are summarized below.

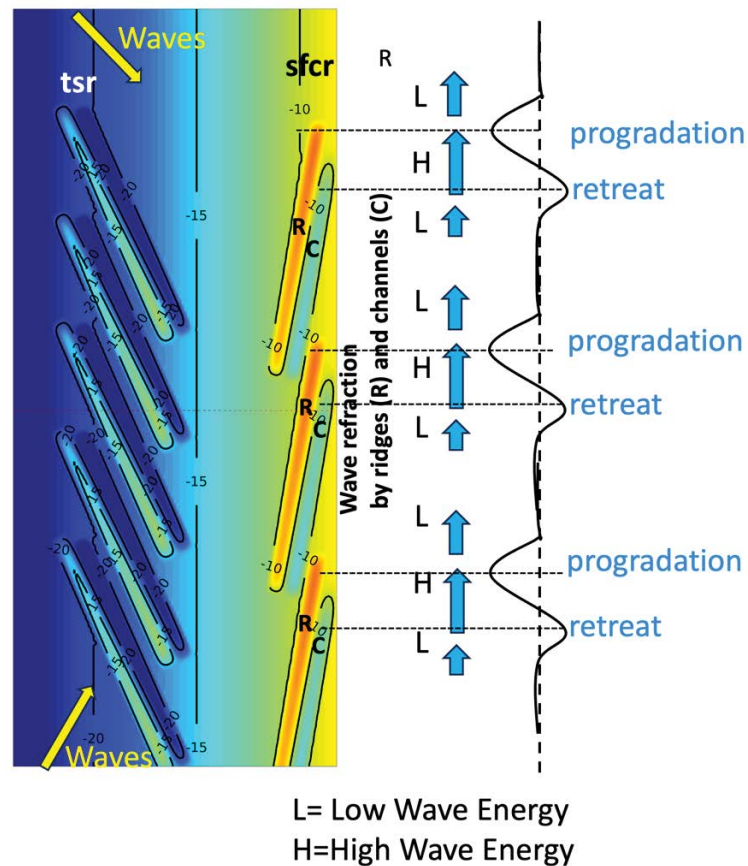


Figure 4-4. Schematic view of the forcing template in the coupled shelf-shoreline morphodynamic system: wave refraction over ridges (R) and channels (C) produces alternating high- (H) and low-energy (L) zones, driving alongshore variations in sediment transport and causing shoreline progradation (retreat) near landwards ends of ridges (channels).

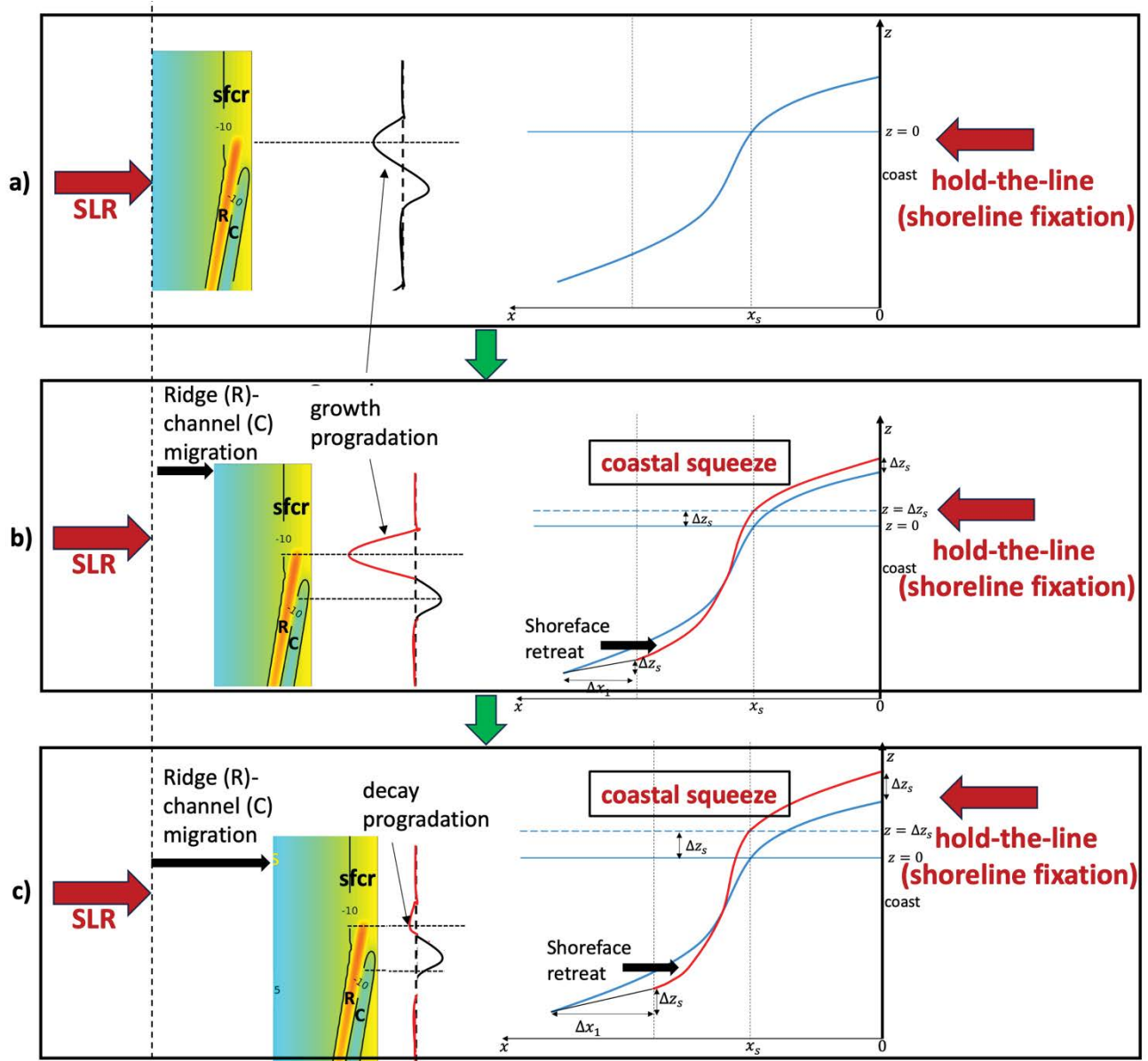


Figure 4-5. Sketch of the evolution of the nearshore bathymetric profile and shoreline under sea level rise (SLR) and the hold-the-line strategy to maintain shoreline position, leading to coastal squeeze (shoreface retreat and profile steepening). a-b) Growth of shoreline progradation driven by the onshore migrating ridge (R). c) Area of shoreline progradation reduces as result of coastal squeeze.

- Model results in the case without sea level rise (SLR) show that shoreface-connected sand ridges (sfcr) and tidal sand ridges (tsr) on the Belgian shelf act as a forcing template for the decadal evolution of the shoreline. This template is established through wave refraction over sfcr crests and channels between the ridges and the shoreline. This creates gradients in wave energy density, which induce spatial variations in the longshore sediment transport in the nearshore zone. Consequently, shoreline progradation occurs in the proximity of crests of landward ends of the sfcr, while shoreline retreat appears adjacent to the channels in between the ridges. Compared to sfcr, the impact of tsr on the shoreline development turns out to be smaller, but significant. These results show that, in addition to acting as natural sediment feeders for nearby beaches, shoreface-connected sand ridges also influence shoreline morphodynamics by altering waves propagating onshore across these ridges. A schematic view of the forcing template established through wave refraction over the ridges is shown in Figure 4-4.

- Model results using sea-level rise rates from the IPCC scenarios for the next 50 years (> 3 mm/yr), combined with a hold-the-line strategy to maintain shoreline position and the associated coastal squeeze (i.e., shoreface retreat and nearshore profile steepening), indicate that future annual nourishment volumes in areas where coastline erosion is determined by the channel-ridge morphology may need to be about 2–5 times larger than those under the sea-level rise rates over the last 50 years (≈ 1.5 -3 mm/yr). It is important to note that these annual nourishment volumes are larger than those estimated based on a Bruun-type response (see Section 3.1.2).
- Based on model results, the following new insights are obtained regarding effects of sea level rise on decadal shoreline morphodynamics. Two competing mechanisms appear to govern shoreline evolution under SLR and the hold-the-line strategy in the vicinity of ridges (Figure 4-5). On the one hand, the onshore-migrating ridge induced by SLR promotes shoreline progradation. On the other, coastal squeeze (shoreface retreat and profile steepening) counteracts this progradation. Over time, coastal squeeze becomes the dominant mechanism, leading to the disappearance of shoreline progradation, particularly for higher rates of SLR. Near channels, shoreline erosion increases due to both the onshore migrating channels and coastal squeeze, requiring more nourishment than in cases without coastal squeeze. This decay in progradation and increase in erosion seem to be caused by increased offshore-directed sediment transport, caused by narrower and steeper nearshore profiles.

Note that cross-shore sediment transport is represented in the idealised model based on the assumption that the cross-shore profile of the actual bed level z_b adjusts to the used equilibrium profile. In other words, the model accounts for profile adjustment processes but neglects any direct onshore sediment supply associated with the presence of the sfc. In the present study, an onshore-directed sediment transport is anticipated to further enhance shoreline progradation in the proximity of the ridge crest, particularly in the case of sfc located close to the shoreline. Investigation of ways to incorporate onshore-directed sediment transport is considered a key topic for future model improvements.

4.4 Lessons learned for coastal protection

From detailed morphological analysis of sand nourishments carried out at the Knokke-Zoute beach erosion hot spot in the past, different stages in the nourishment erosion process could be distinguished, both for a beach nourishment configuration as for a shoreface nourishment configuration. The results of the research in the Mozes project indicate that the main driver of coastline erosion in this area is the blockage of alongshore sand transport by the harbour of Zeebrugge, possibly supplemented by wave-related cross-shore transport. In addition, the locally protruding coastline at Knokke-Zoute leads to gradients in longshore transport, and Appelzak channel encroaching the shoreface leads to cross-shore losses in Knokke-Zoute and Lekkerbek; both enhance coastline erosion in these areas. Straightening the coastline by a large beach widening at Albertstrand would not reduce the erosional character at Knokke-Zoute. The shallowing of the nearshore Appelzak-channel is not expected to reduce the beach erosion at Knokke-Zoute too much either. Beach nourishments at Knokke-Zoute set-back the coastline erosion process a number of years, but do not stop it.

The nearshore sea bottom morphology, consisting of a sequence of shoreface-connected ridges and channels close to the coastline, influences the morphology of the active coastal zone (shoreface, beach, dunes). One can summarise this influence to be a gift and a challenge for coastal protection. The gift for coastal protection is the natural feeding process by which sand is delivered from the sea bottom to the coastline, concentrated in the regions where the ridges connect to the shoreface. The challenge for coastal protection is the coastal squeeze of the shoreface profile between on the one hand beach nourishments and on the other hand deepening and landward movement of channels close to the coastline, which is probably driven by sea level rise.

Sediment dredged from the access channels to the harbours of Oostende, Blankenberge and Nieuwpoort contain a significant proportion of sand. This dredged material would be more beneficial for coastal protection if dumping would be realised in the active zone, landward of the depth of closure (ca. the -5 m TAW depth contour), instead of dumping this sediment at the dumping sites located more off-shore. Research on such alternative sediment management is proposed combining several points of view: innovative dredging-dumping techniques (cost- effective combination of dredging and dumping), morphological monitoring and modelling (to investigate effectiveness of alternative dumping strategies), legislation and permits (federal as well as Flemish competences).

The natural feeding from the sea to the coastline was active for centuries at 3 locations along the Belgian coastline. This process resulted in 3 areas with relative wide coastal dune belts, namely De Panne – Koksijde – Nieuwpoort, Bredene – De Haan and Knokke-Heist. Dune belts in Middelkerke-Oostende and Blankenberge-Zeebrugge are much more narrow. The development of the coastal harbours of Oostende and Zeebrugge cut through the shoreface-connected ridges around the year 1900, resulting in a cessation of the natural feeding process in 2 of the 3 locations. The natural feeding process remaining active nowadays is situated at the west coast with the attachment point in Koksijde. Around 100.000 m³/year is supplied to the beaches of the west coast from the sea (cross-shore). Numerical modelling of this natural feeding process is challenging due to the complexity of 3D cross-shore processes that need to be represented by the models. More in-situ measurements of bedform propagation may contribute to better unravel the natural feeding process, e.g. to better understand how the dynamics of different types of bed forms contribute to a net sand transport from the ridge to the coastline.

The coastal squeeze of the shoreface profile is a challenge for coastal protection because a steeper shoreface induces a higher erosion potential of the beaches. A new insight in the mechanism of coastal squeeze is obtained from the data-analysis of bathymetric maps from the past ~200 years and correlating it with the sea level rise observations during this period. Namely that the ridges close to the coastline migrate landward at a rate that is proportional to sea level rise rate. And the channels close to the coastline move landward and/or deepen synchronous with the landward movement of these ridges. Acceleration of sea level rise as well as increasing the intensity of sand nourishments during the past decades has resulted in a retreat and steepening of the shoreface (coastal squeeze). In the past 40 years the average width of the shoreface, between the low water line and the depth of closure, has decreased by 50-100 m. A typical shoreface slope that was 1/45 in the 1980s has steepened to a slope of 1/30. These slopes are still mild but one has to monitor this evolution closely because it can undermine beach stability. Sea level rise is expected to accelerate, which will necessitate increased nourishment intensities for coastline preservation in the coming decades. This will also be the case in areas where progradation of the coastline is the result of widening the (dry) beach. This is supported by results of the idealized model, which indicate that higher rates of sea-level rise, and the resulting stronger coastal squeeze, will substantially increase future nourishment demands for coastal protection. However, the precise values of this idealized model should be regarded as qualitative indicators rather than exact quantitative values. It is recommended that more information on nourishment works are collected systematically as well as analysed from time to time e.g. as part of 6-yearly cycle to update morphological trends.

In coastal morphology research, one should always start with observed phenomena from morphological analyses before attempting to create numerical models. If numerical models can successfully simulate observed morphological changes based on hydrometeorological drivers and sediment properties, they deepen understanding and support predictions. If not, researchers must rely on trend extrapolations from topobathymetric data series, conceptual models derived from data-analysis relating evolution of morphological characteristics with influencing factors and/or expert judgment.

The idealized coupled shelf–nearshore model developed in the MOZES project is currently the best available tool to assess the effects of future sea-level rise and the hold-the-line strategy to maintain shoreline position (including the associated shoreface erosion and nearshore profile steepening) on decadal shoreline evolution. Based on this model, annual nourishment intensities in areas where coastline erosion is determined by the channel-ridge morphology are estimated to increase by a factor of 2–5 compared with conditions under sea-level rise rates over the past 50 years ($\approx 1.5\text{--}3\text{ mm/yr}$). This raises concerns for future coastal protection. However, these results should be interpreted qualitatively rather than as exact quantitative estimates. More reliable projections will require improvements in (1) SLR scenarios, (2) the representation of coastal squeeze along the Belgian coast, and (3) model parameters and underlying assumptions. One of these assumptions is the absence of an onshore sand transport from the ridges towards the nearshore in the model, which is considered an important topic for future model improvements.

The results of the MOZES project therefore have direct implications for present-day coastal management, as well as for the long-term implementation of Coastal Vision. The observed coastal squeeze will affect the required sand volumes for the realisation (including maintenance) of the seaward advancement ($\sim 100\text{ m}$) as proposed in Coastal Vision, more than was anticipated before.

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Appendix A: outsourced vectorisation

During the MOZES project, old 1980s-1990s beach and inner shelf maps were vectorised by an external partner. The outsourcing specifications, the georeferenced plan packages, vectorisation work deliveries and the acceptance reports can be found here:

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in subfolders "plannen" (georeferenced plan packages sent out) and "lev" (delivery and report). The inspection and acceptance of each delivery of the vectorisation work was done according to section 5 of the work specifications. Table 0-1 lists the outsourced work per partial assignment (deelopdracht):

Table 0-1 – History of the outsourced vectorisation work.

Work package	Sheets	Date of acceptance	Delivered files
Selection stage	A typical beach map: SIT_1985_1_OOST10.jpg (1 sheet) A typical nearshore map: VO_1986_1_8616.jpg (1 sheet) A typical inner shelf map: wie-sch1986.jpg (1 sheet)	12/07/2022	SIT_1985_1_HL.shp SIT_1985_1_HP.shp SIT_1985_1_SD.shp VO_1986_1.shp wie-sch1986.shp
Deelopdracht 1	SIT_1985_1_OOST05 – 09, OOST11; SIT_1983_1_OOST05 – 08 (10 sheets) and ZUYWE_1987 en west-dh1984 (2 sheets)	29/08/2022	SIT_1983_1_OOST05_08_HL(HP, SD).shp SIT_1985_1_OOST05_11_HL(HP, SD).shp west-dh1984.shp zuywe_1987.shp
Deelopdracht 2	SIT_1983_1_OOST09 – 11; OOST03 – 04; MIWE28 – 32 (10 sheets)	11/10/2022	SIT_1983_1_OOST09_11_HL(HP, SD).SHP SIT_1983_1_MIWE28_31_HL(HP, SD).SHP SIT_1983_1_MIWE31_OOST04_HL(HP, SD).SHP
Deelopdracht 3	SIT_1983_1_MIWE01 – 09; VO_1987_2_87130	16/11/2022	SIT_1983_1_MIWE01_09_HL(HP, SD).SHP VO_1987_2_87130.shp
Deelopdracht 4	SIT_1983_1_MIWE10 – 20	5/01/2023	SIT_1983_1_MIWE10_20_HL(HP, SD).SHP
Deelopdracht 5	SIT_1983_1_MIWE21 – 27	7/02/2023	SIT_1983_1_MIWE21_27_HL(HP, SD).SHP

Deelopdracht 6	<p>ZuyWe1967.jpg (locally the first survey)</p> <p>wie-sch1962.jpg (the 1968 sheet was originally selected, but it covers only a small part of the inner shelf. Priority was given to a complete coverage of the inner shelf, for which 1962 was the closest in time)</p> <p>WestDH1969.jpg (locally the first survey)</p> <p>ZuyWe1991.jpg</p> <p>WestDH1993.jpg</p> <p>WieSch1992.jpg</p>	27/04/2023	<p>wie-sch1962.shp</p> <p>ZUYWE_1967.shp</p> <p>west-dh1969.shp</p> <p>Zuywe_1991.shp</p> <p>wie-sch1992.shp</p> <p>west-dh1993.shp</p>
Deelopdracht 7	8 nearshore plans of the Spring 1992 survey which was the first to cover the complete Belgian coast	15/06/2023	<p>KOPP_1992_1_B12.shp</p> <p>Vo1992_1.shp</p>
Deelopdracht 8	SIT_1992_1_MIWE21-30	2/08/2023	SIT_1992_1_MIWE21_30_HL(HP, SD).shp
Deelopdracht 9	SIT_1992_1_OOST05-11	29/09/2023	SIT_1992_1_OOST05_11_HL(HP, SD).shp
Deelopdracht 10	SIT_1992_1_OOST01-04	26/10/2023	SIT_1992_1_OOST01_04_HL(HP, SD).shp
Deelopdracht 11	SIT_1992_1_MIWE01-09	26/12/2023	SIT_1992_1_MIWE01_09_HL(HP, SD).shp
Deelopdracht 12	SIT_1992_1_MIWE10-20	3/05/2024	SIT_1992_1_MIWE10_20_HL(HP, SD).shp
Deelopdracht 13	3 nearshore plans of the Autumn 1989 survey and the corresponding 3 nearshore plans of the March of Spring 1990 survey	3/06/2024	<p>VO_1989_2_89146_147_158.shp</p> <p>VO_1990_1_mrt90_90106_108.shp</p>
Deelopdracht 14	<p>ZUYWE_1978.jpg</p> <p>ost-dh74-75.jpg (in two parts)</p> <p>wie-sch1976.jpg</p>	27/06/2024	<p>ost_dh74-75.shp, ost_dh74-75 plan2.shp</p> <p>wie-sch1976.shp</p> <p>ZUYWE_1978.shp</p>
Deelopdracht 15a	SIT_1989_2_MIWE01-07	28/08/2024	SIT_1989_2_MIWE01_07_HL(HP, SD).shp
Deelopdracht 15b	SIT_1989_2_MIWE24-30, SIT_1989_2_OOST01-04	2/11/2024	1989_2_MIWE24_30_OOST01_04_HL(HP, SD).shp
Deelopdracht 15c	SIT_1989_2_OOST05-11	22/01/2025	1989_2_OOST05_11_HL(HP, SD).shp

Deelopdracht 16a	SIT_1990_0_OOST05-11.jpg	8/04/2025	SIT_1990_0_OOST05_11_HL(HP, SD).shp
Deelopdracht 16b	SIT_1990_0_OOST01-04.jpg	8/05/2025	SIT_1990_0_OOST01_04_HL(HP, SD).shp
Deelopdracht 16c	SIT_1990_0_MIWE20-30.jpg	21/06/2025	SIT_1990_0_MIWE20_30_HL(HP, SD).shp
Deelopdracht 16d	SIT_1990_0_MIWE10-16.jpg	31/07/2025	SIT_1990_0_MIWE10_16_HL(HP, SD).shp
Deelopdracht 16e	SIT_1990_0_MIWE01-09.jpg	4/09/2025	SIT_1990_0_MIWE01_09_HL(HP, SD).shp
Deelopdracht 17	SIT_1989_1_MIWE08-09.jpg SIT_1989_1_MIWE20-23.jpg	28/10/2025	SIT_1989_1_MIWE08_09_HL(HP, SD).shp SIT_1989_1_MIWE20_23.HL(HP, SD).shp
Deelopdracht 18	SIT_1989_1_MIWE10-16.jpg	11/02/2026	SIT_1989_1_MIWE10-19.HL(HP, SD).shp
Deelopdracht 19	SIT_1989_1_MIWE18-19.jpg SIT_1990_0_MIWE17-19.jpg SIT_1988_1_MIWE17.jpg	11/02/2026	SIT_1989_1_MIWE10-19.HL(HP, SD).shp SIT_1990_0_MIWE17-19.HL(HP, SD).shp SIT_1988_1_MIWE17.HL(HP, SD).shp

The DEMs of Table 0-2 were made from the vectorised maps and are available on [P:\20_079_MorfoInteract\3 Uitvoering\Deeltaak1_DataAcquisition\DEMs](#). The rasters are in ESRI raster format. They are referenced in Lambert72 and, while the source maps were either in Z MOW or MLLWS, they have been converted to TAW before making the DEMs. For the datum conversion MLLWS to TAW, use was made of *gllws_to_taw_vlaamsebanken_l72.tif*, a conversion raster borrowed from aMT available at FH on [G:\Masterarchief\cnv](#). The same raster was used for all surveys. This means that, assuming that the maps were made in contemporary MLLWS, the conversion to TAW does not correct for sea-level rise.

Table 0-2 – DEMs made of vectorised data.

Topic	Source of data	DEM	Area
Beach and dune foot maps (cell size 2 m)	SIT_1983_1_MIWE01-09.jpg	G_1983_1A	De Panne to Nieuwpoort
	SIT_1983_1_MIWE10-20.jpg	G_1983_1B	Nieuwpoort to Oostende
	SIT_1983_1_MIWE21-31.jpg	G_1983_1C	Oostende to Wenduine
	SIT_1983_1_MIWE31-OOST04.jpg	G_1983_1D	Blankenberge to Zeebrugge
	SIT_1983_1_OOST05-11.jpg	G_1983_1E	From Heist to Zwin

	SIT_1985_1_OOST05-11.jpg	G_1985_1E	From Heist to Zwin
	SIT_1989_1_MIWE08-23.jpg	G_1989_1AB	Oostduinkerke to Bredene
	SIT_1989_2_MIWE01-07.jpg	G_1989_2A	De Panne to Oostduinkerke
	SIT_1989_2_MIWE24-30.jpg	G_1989_2C	Bredene to Wenduine
	SIT_1989_2_OOST01-04.jpg	G_1989_2D	Blankenberge to Zeebrugge
	SIT_1989_2_OOST05-11.jpg	G_1989_2E	Zeebrugge to Zwin
	SIT_1990_0_MIWE01-09.jpg	G_1990_0A	De Panne to Nieuwpoort
	SIT_1990_0_MIWE10-20.jpg	G_1990_0B	Nieuwpoort to Oostende
	SIT_1990_0_MIWE21-31.jpg	G_1990_0C	Oostende to Wenduine
	SIT_1990_0_MIWE31-OOST04.jpg	G_1990_0D	Blankenberge to Zeebrugge
	SIT_1990_0_OOST05-11.jpg	G_1990_0E	Zeebrugge to Zwin
	SIT_1992_1_MIWE01-09.jpg	G_1992_1A	De Panne to Nieuwpoort
	SIT_1992_1_MIWE10-20.jpg	G_1992_1B	Nieuwpoort to Oostende
	SIT_1992_1_MIWE21-31.jpg	G_1992_1C	Oostende to Wenduine
	SIT_1992_1_MIWE31-OOST04.jpg	G_1992_1D	Blankenberge to Zeebrugge
	SIT_1992_1_OOST05-11.jpg	G_1992_1E	From Heist to Zwin
Nearshore maps (cell size 10 m)	VO_1986_1_8616.jpg	G_vo1986_1	From Heist to Zwin
	VO_1987_2_87130	G_vo1987_2	De Panne to Oostduinkerke
	VO_1989_2_89158.jpg VO_1989_2_89147.jpg VO_1989_2_89146.jpg	G_vo1989_2	From Bredene to Zwin
	VO_1990_0_maart1990.jpg VO_1990_1_90106.jpg VO_1990_1_90108.jpg	G_vo1990_0_1	From Bredene to Zwin
	VO_1992_1 (8 sheets)	G_vo1992_1	Complete coast
Inner shelf maps (cell size 10 m)	ZuyWe1967.pdf	G_ZW1967_taw	Inner shelf western part

	WestDH1969.pdf	G_WD1969_taw	Inner shelf central part
	wie-sch1962.pdf	G_WS1962_taw	Inner shelf eastern part
	Mosaic 1962-1969	G_BS62_69_taw	Complete inner shelf
	Wie-sch1986.pdf	G_WS1986_TAW	Inner shelf eastern part
	West-dh1984.pdf	G_WD1984_TAW	Inner shelf central part
	ZUYWE_1987.pdf	G_ZW1987_TAW	Inner shelf western part
	Mosaic 1984-1987	G_BS84_87_TAW	Complete inner shelf
	ZuyWe1991.pdf	G_ZW1991_taw	Inner shelf western part
	WestDH1993.pdf	G_WD1993_taw	Inner shelf central part
	WieSch1992.pdf	G_WS1992_taw	Inner shelf eastern part
	Mosaic 1991-1993	G_BS91_93_taw	Complete inner shelf
	ZuyWe1978.pdf	G_ZW1978_taw	Inner shelf western part
	Ost-dh74-75.pdf	G_WD1974_taw	Inner shelf central part
	wie-sch1976.pdf	G_WS1976_taw	Inner shelf eastern part
	Mosaic 1974-1978	G_BS74_78_taw	Complete inner shelf

Appendix B: Historical sea level rise in the southern North Sea: A literature review

This section summarizes key findings from a review of the literature on historical rates of sea-level rise (SLR) from 1800 onward along the Belgian and Dutch coasts, and compares them with records from the southern UK coastline and global IPCC assessments. Reported estimates are derived from long tide-gauge records and proxy reconstructions.

B.1 Belgium and Dutch coasts

Table B 1. Overview of sea level rates along the Belgian and Dutch coasts since the 1800.

Period	rate of SLR (mm/yr)
19th century	~ 0.8 – 1.0
1900–1993	~ 1.5 to 2.0
1993–2022	~ 3

Belgian observations of relative sea-level rise (SLR) over the past two centuries are primarily based on historical tidal elevation data recorded by early tide gauges along the Belgian coast. These include annual records of High Water (HW), Mean Sea Level (MSL), and Low Water (LW) for Oostende, Zeebrugge, and Nieuwpoort. However, water-level data from the 19th century are scarce (Wahl et al. 2013); the only available series for this period originates from Oostende, covering 1835–1852 (Van Cauwenberghe 1999). Based on this record, relative rates of SLR during the 19th century are estimated to be on the order of ~ 0.5 – 1 mm yr⁻¹, notably lower than those observed throughout the 20th century (Van Cauwenberghe 1999; Pereira et al. 2023).

A comparable pattern is observed along the neighbouring Dutch coast, where early instrumental records from Vlissingen (from the 1860s) and Amsterdam (from the 1700s) indicate similarly low rates of rise during the 19th century, typically ~ 0.8–1 mm yr⁻¹ (Mörner 1973; Mortari 2004). According to these studies, rates of sea level rise began to increase around the 1840s, consistent with global analyses indicating that modern rates of sea-level rise started to emerge above pre-industrial variability by about 1863 CE (Walker et al. 2022).

During the 20th century, Belgian and Dutch rates of SLR increased to approximately 1.5–1.8 mm yr⁻¹ (Van Cauwenberghe 1999; Stolte et al. 2023). Stolte et al. (2023) identified a clear shift, with trends of about 1.8 mm yr⁻¹ up to ~ 1990 and roughly 3 mm yr⁻¹ thereafter. Keizer et al. (2023) reported that the acceleration of sea-level rise along the Dutch coast started already in the 1960s.

The values presented in Table B.1 summarizes the findings above.

B.2 Comparison: UK southern North Sea

To provide a broader regional context, long salt-marsh reconstructions and tide-gauge series from the UK south and east coasts indicate a comparable temporal evolution (see Table B. 2):

- **19th century:** Salt-marsh proxy data from the Isle of Wight show relative sea-level (RSL) rise at rates of roughly 0.5–0.8 mm yr⁻¹ (Long et al. 2014).

- **20th century (pre-1990):** National tide-gauge compilations report average rates of 1.5–2.0 mm yr⁻¹ (P. L. Woodworth et al. 1999; Philip L. Woodworth 2017).
- **Recent decades (post-1993):** Accelerations to 3–3.5 mm yr⁻¹ have been observed since 1993 (Hogarth et al. 2020).

These results indicate that SLR along the southern UK coastline mirrors the evolution observed along the Belgian and Dutch coasts: a slow rise during the 19th century ($\sim 0.5\text{--}0.8\text{ mm yr}^{-1}$), increasing to 1.5–2.0 mm yr⁻¹ during most of the 20th century, and an acceleration to about 3–3.5 mm yr⁻¹ after the early 1990s.

Table B 2. Overview of sea level rates along UK coast since the 1800.

Period	rate of SLR (mm/yr)
19th century	$\sim 0.5 - 0.8$
1900–1993	$\sim 1.5 \text{ to } 2.0$
1993–2022	$\sim 3.0 - 3.5$

B.3 Global sea level change

According to the latest IPCC assessment (AR6, Working Group I, Chapter 9) (Lee et al. 2023), global mean sea-level rise (GMSL) has accelerated markedly since 1900. Tide-gauge reconstructions indicate a global mean rate of $\sim 1.3\text{ mm yr}^{-1}$ over 1901–1990, while satellite altimetry observations show rates of 3–3.5 mm yr⁻¹ since 1993. Historical sea-level changes in the southern North Sea region closely mirror these global trends.

Table B 3. Overview of global sea level rates since the 1800.

Period	rate of SLR (mm/yr)
19th century	~ 0.4
1900–1993	~ 1.2
1993–2022	$\sim 3.0 - 3.5$

B.4 Summary

- **19th century:** Modest rates of SLR of, on average, $\sim 0.5\text{--}1\text{ mm yr}^{-1}$, increasing in the latter half of the century (Mörner 1973; Van Cauwenberghe 1999; Mortari 2004; Walker et al. 2022).
- **20th century:** Rates roughly doubled to $\sim 1.5\text{--}2.0\text{ mm yr}^{-1}$ along both the Belgian and Dutch coasts (Van Cauwenberghe 1999; Stolte et al. 2023; Pereira et al. 2023; Wahl et al. 2013).
- **Since the 1990s:** Acceleration to $\sim 3\text{ mm yr}^{-1}$ along the Belgian and Dutch coasts (Stolte et al. 2023), although (Keizer et al. 2023) reported that the acceleration of sea-level rise began already in the 1960s.
- **Regional context:** Salt-marsh reconstructions and tide-gauge series from the UK south and east coasts indicate broadly consistent temporal patterns in the sea level evolution (Long et al. 2014; P. L. Woodworth et al. 1999; Philip L. Woodworth 2017; Wahl et al. 2013).

- **Global context:** Rates of sea level rise since 1900 aligns closely with global assessments reported in the IPCC Sixth Assessment Report (AR6) (Lee et al. 2023).

Based on these outcomes, a reconstruction of the cumulative mean sea level (MSL) is conducted, which is presented in Figure B-1.

B.5 IPCC projections

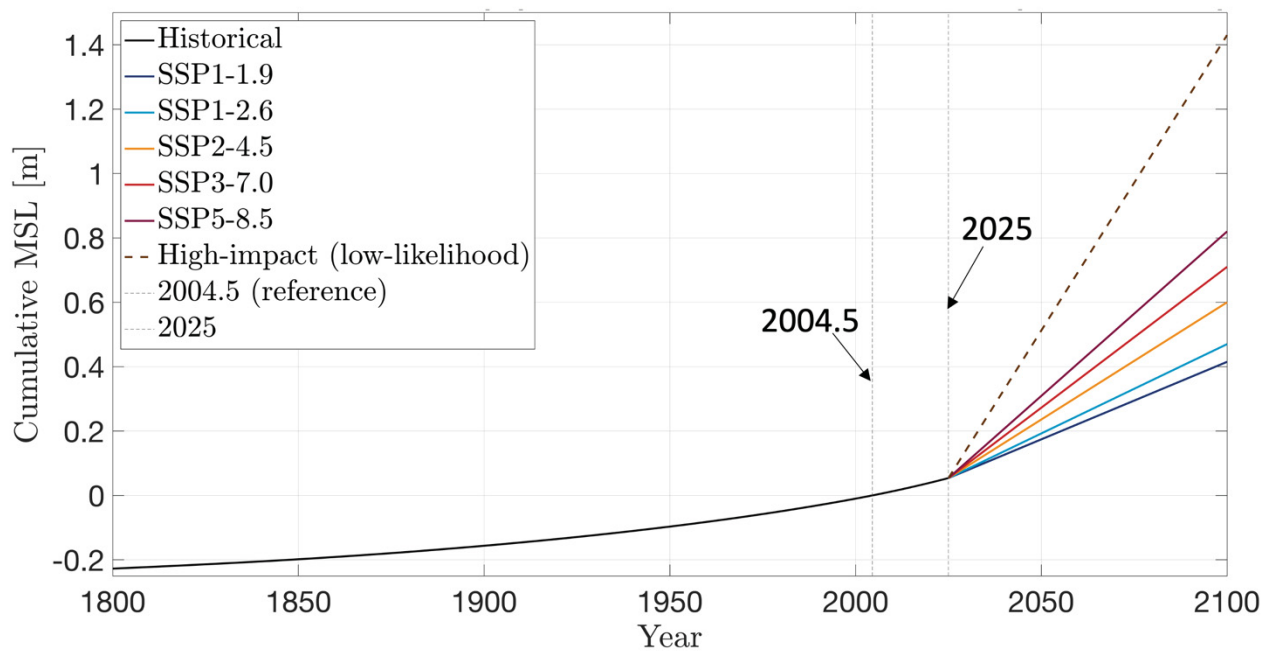


Figure B 1. Historical mean sea level (MSL) development between 1800 and present (black line). The coloured lines show projected SLR under different IPCC scenarios (see legend, Lee et al. 2023). Following the IPCC conventions, the year 2004.5 is used as the baseline (i.e., MSL = 0).

Projected sea level rise (SLR) under different IPCC scenarios (Lee et al. 2023) are presented in Figure B-1. The names of the different scenarios are shown in the legend.

Appendix C

Coupled shelf-nearshore model

5.1.1.1 Shelf model: Delft3D-Flow + SWAN

The hydrodynamics and wave propagation on the shelf are simulated using the Delft3D numerical model in its depth-averaged mode (2DH), coupled with the SWAN wave model. In this study, only the FLOW module of Delft3D is employed, which serves the purpose of generating a wave forcing to drive the nearshore model (Q2Dmorfo). The governing equations are given below, with further details and specifications available in and the Delft3D user manual (Deltares 2022).

5.1.1.1.1 Delft3D-FLOW:

This module calculates the hydrodynamics on the shelf, which are governed by the nonlinear depth-averaged shallow-water equations

$$\begin{aligned} \frac{\partial \eta}{\partial t} + \frac{\partial(Du)}{\partial x} + \frac{\partial(Dv)}{\partial y} &= 0, \\ \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} - f v &= -g \frac{\partial \eta}{\partial x} - \frac{\tau_x}{\rho D} + \frac{\nu}{D} \left[\frac{\partial}{\partial x} \left(D \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left(D \frac{\partial u}{\partial y} \right) \right] + \frac{1}{\rho D} F_x, \\ \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + f u &= -g \frac{\partial \eta}{\partial y} - \frac{\tau_y}{\rho D} + \frac{\nu}{D} \left[\frac{\partial}{\partial x} \left(D \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left(D \frac{\partial v}{\partial y} \right) \right] + \frac{1}{\rho D} F_y. \end{aligned}$$

In these equations, t represents time, η denotes the water level relative to the mean sea level $z = 0$ (MSL), and $D = -z_b + \eta$ denotes the water depth, where z_b is the bed level relative to MSL ($z = 0$). Additionally, u and v represent the cross- and longshore components of the depth-averaged velocity vector $\vec{v}$. The parameters f and g denote the Coriolis parameter and the acceleration due to gravity, respectively. The bed shear stress components τ_x and τ_y represent the combined effects of currents and waves (Soulsby 1997). The variables ρ and ν stand for water density and horizontal eddy viscosity, respectively, with ν assumed to be constant. Finally, F_x and F_y are the components of the wave-induced force per unit surface area, calculated from the divergence of the radiation stress tensor $\bar{\bar{S}}$ (Longuet-Higgins and Stewart 1964):

$$\begin{aligned} F_x &= - \left[\frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y} \right], \\ F_y &= - \left[\frac{\partial S_{yx}}{\partial x} + \frac{\partial S_{yy}}{\partial y} \right]. \end{aligned}$$

The components of the tensor $\bar{\bar{S}}$ (S_{xx} , S_{xy} , S_{yx} , and S_{yy}) are computed by the SWAN wave model, as is detailed in the subsequent section.

5.1.1.1.2 SWAN:

SWAN, a third-generation wave model, is utilized in this study for the computation of random, short-crested wind-generated waves. The model employs the spectral wave action balance, applied in stationary mode (Booij, Ris, and Holthuijsen 1999; Holthuijsen 2007):

$$\vec{\nabla} \cdot [(\vec{c}_g + \vec{v})N] + \frac{\partial c_\sigma N}{\partial \sigma} + \frac{\partial c_\theta N}{\partial \theta} = \frac{S_{tot}}{\sigma}.$$

In this equation, $N = \mathcal{E}/\sigma$ denotes the spectral action density, where $\mathcal{E}$ represents the spectral energy density, and σ is the frequency. The first term in the equation accounts for the propagation of action density in geographical space, incorporating wave shoaling, with a group velocity denoted by $\vec{c}_g = \partial \sigma / \partial \vec{k}$, where $\vec{k}$ is the wave vector. The second term considers the effect of frequency shifting due to variations in depth and currents. The third term describes depth- and current-induced refraction. The quantities c_σ and c_θ represent the propagation velocities in spectral space (σ, θ) , and these velocities are calculated based on linear wave theory. The right-hand side of the equation (S_{tot}/σ) accounts for all physical processes that either generate, dissipate, or redistribute wave energy. In this study, dissipation due to whitecapping, depth-induced wave breaking, and bottom friction is considered, utilising the formulations described in . Non-linear wave-wave interactions are disregarded, and only swell waves are taken into consideration, implying no wave growth by wind.

5.1.1.1.3 Boundary conditions:

To compute the currents in the Delft3D model, sea surface elevations are prescribed at both the seaward ($x = x_L$) and lateral ($y = 0, y_L$) boundaries, simulating a tidal wave propagating in the alongshore direction with the coast to its right. This tidal wave, characterized by an amplitude $\hat{\eta}_2$, exhibits a linearly increasing phase from $y = 0$ to $y = L_y$, resulting in a phase difference $\Delta\psi_2$ between the two boundaries. With regard to waves (SWAN model), JONSWAP spectra are specified at the offshore boundaries, with a peak enhancement factor of $\hat{p}$ and directional spreading of $\Delta\theta$. The waves have a time-varying significant wave height $H_{s0}(t)$, a time-varying peak period $T_{p0}(t)$, and a time-varying wave direction $\theta_0(t)$. Additionally, to avoid the formation of shadow zones (i.e., strong decrease in H_s) at the lateral boundaries ($y = 0, L_y$), periodic boundary conditions are applied at these boundaries. Shadow zones arise due to the directional spreading of waves, a phenomenon that becomes prominent when introducing obliquely incident waves at the offshore boundaries, as is the case in the present study. In principle, the wave forcing at the southern boundary is determined by waves that enter the nearshore zone further south of this boundary. By applying periodic boundary conditions in SWAN, this wave forcing is reconstructed from waves at the northern boundary. As long as those waves have not been significantly affected by topographic undulations (sand ridges), which is the case in this study, no conflicts between Delft3D and SWAN arise due to the use of non-periodic boundaries in the former model and periodic boundaries in the latter.

5.1.1.2 Nearshore model

The morphodynamic changes in the nearshore zone, including the shoreline, are simulated with the reduced-complexity numerical nearshore model Q2Dmorfo, which comprises three modules, i.e., WAVES, TRANSP and BED. The governing equations are summarized below, with additional details available in Arriaga et al. (2017).

5.1.1.2.1 WAVES:

Waves with a narrow frequency-direction spectrum, but random in wave height are assumed, which are described using linear theory (Holthuijsen 2007). The wave field is characterized by four main parameters: 1) the radian frequency σ , 2) the wavenumber k , 3) the angle of wave incidence θ (respect to the negative x -axis, positive anti-clockwise), and 4) the significant wave height H_s . Note that the x -axis points from land to sea (i.e., in Fig. 2 of the main text from right to left). These wave characteristics are determined by solving the dispersion relation, the equation for wave number irrotationality, and the conservation of wave energy density, which are expressed as follows:

$$\begin{aligned}\sigma^2 &= gk \tanh(k|z_b|), \\ \frac{\partial(k \sin \theta)}{\partial x} + \frac{\partial(k \cos \theta)}{\partial y} &= 0, \\ \vec{\nabla} \cdot (\vec{c}_g H_s^2) &= 0.\end{aligned}$$

Equation [eq:wave equation] considers stationary conditions and does not incorporate the dissipation of wave energy caused by bottom friction and wave breaking. The latter is omitted because the empirical sediment transport formulations used in this study (described in the next section) rely on wave conditions at the breaker point $x = x_b$. These conditions are influenced by events further offshore ($x < x_b$). The breaker point x_b is established through the relationship $z_b(x_b) = -\frac{H_{s,b}}{\sqrt{2}\gamma_b}$, where $H_{s,b}$ represents the significant wave height at $x = x_b$ and γ_b is the breaker index.

5.1.1.2.2 TRANSP:

The TRANSP module calculates the sediment transport vector $\vec{q}_{tot}$ in the nearshore, derived directly from the wave field through empirical formulations, without explicitly resolving the flow field. To accommodate the curvature of the shoreline represented by $x_s(y, t)$, the sediment transport vector $\vec{q}_{tot}$ is expressed in a local coordinate system defined by x' and y' . In this system, x' points outward in the direction normal to the local shoreline $x_s(y, t)$, while y' points tangentially along the shoreline. Transport $\vec{q}_{tot}$ is separated into three contributions:

$$\vec{q}_{tot} = \vec{q}_L + \vec{q}_C + \vec{q}_D.$$

The first contribution ($\vec{q}_L$) is the longshore transport vector caused by breaking waves, which reads

$$\vec{q}_L = Q(y')f(x')\hat{t},$$

where Q is the cross-shore integrated sediment transport, calculated based on the CERC formula (Komar 1998)

$$Q(y') = \mu \left(\frac{H_{s,b}}{\sqrt{2}} \right)^{5/2} \sin[2(\theta_b - \phi)].$$

In this expression, the parameter μ governs the magnitude of transport Q , while θ_b represents the wave angle at the breaker point (x_b). Additionally, $f(x')$ denotes a normalized shape function responsible for redistributing transport Q across an area with a cross-shore width L :

$$f(x') = \frac{4}{\sqrt{\pi}L^3} x'^2 e^{-\left(\frac{x'}{L}\right)^2}.$$

The shape function $f(x')$ is assumed to exhibit a profile similar to typical alongshore current profiles observed in the nearshore. The width L , dependent on y and t , is defined as $L(y, t) = 0.8L_1(y, t) + L_2$, with $L_1(y, t) = x_b(y, t) - x_s(y, t)$ representing the surf zone width and L_2 as the constant width of the swash zone.

The second contribution ($\vec{q}_C$) is a parametrisation of the cross-shore transport. This is based on the assumption that over long time scales (on the order of years to decades), the cross-shore profile of the actual bed level z_b in the nearshore adjusts to the used equilibrium profile $z_{b,e}$ (as given by Eq. 1 in the main manuscript). Mathematically, $\vec{q}_C$ is computed as follows:

$$\vec{q}_C = -\gamma_C [\nabla z_b \cdot \hat{n} - \nabla z_{b,e} \cdot \hat{n}] \hat{n}.$$

Here, γ_C represents a spatially and time-varying cross-shore diffusivity coefficient, estimated from the momentum mixing expression and scaled by a power of the significant wave height at the breaker point x_b :

$$\gamma_C = \nu_b g^{1/2} \gamma_b^{-1/6} H_{s,b}^{11/6} L_1^{-1/3} \Psi,$$

with ν_b a non-dimensional parameter and Ψ a shape function that is based on the cross-shore distribution of the wave orbital motion. This shape function is assumed to reach its maximum at the shoreline ($\Psi = 1$ at $x = x_s$) and decay to 0 in both the offshore ($x < x_s$) and onshore ($x > x_s$) directions. In the wet cells ($z_b < 0$), the following expression for Ψ is used as a function of z_b :

$$\Psi(z_b) = \frac{1 + b + \tanh\left[\frac{\alpha D_c + z_b}{L_d}\right]}{1 + b + \tanh\left[\frac{\alpha D_c}{L_d}\right]}.$$

In this expression, α and b are non-dimensional parameters, D_c represents the depth of closure and L_d is the decay distance, defined as $L_d = 0.5\alpha D_c$. In the dry cells ($z_b > 0$), function Ψ decays in the onshore direction according to

$$\Psi(x - x_s) = \exp\left[-\left(\frac{x - x_s}{L_2}\right)^4\right],$$

where $x - x_s$ is the distance to the shoreline. The width of the swash zone L_2 determines the decay distance.

Finally, the third contribution ($\vec{q}_D$) is a diffusive transport that tends to flatten bumps by breaking waves. Moreover, it helps to prevent the occurrence of numerical instabilities by suppressing small scale noise. The following formula is applied:

$$\vec{q}_D = -\gamma_D (\vec{\nabla} z_b \cdot \hat{t}) \hat{t},$$

with γ_D an alongshore diffusivity coefficient, which is set equal to the cross-shore diffusivity coefficient ($\gamma_D = \gamma_C$).

5.1.1.2.3 BED:

The computation of the evolution of bed level z_b is conducted in the BED module, relying on the principle of conservation of sediment mass:

$$\frac{\partial z_b}{\partial t} = -\frac{1}{1-p} \vec{\nabla} \cdot \vec{q}_{tot},$$

with p is the bed porosity. The dry beach ($0 \leq x \leq x_s(y, t)$) is included in the computational domain, experiencing erosion and/or accretion during the simulation. The position of the shoreline $x_s(y, t)$ is determined through linear interpolation between the cross-shore locations of the last dry cell and the first wet cell in the nearshore domain.

5.1.1.2.4 Boundary conditions:

Regarding waves, the time-varying significant wave height $H_s(t)$, peak period $T_p(t)$, and wave direction $\theta(t)$ computed by the shelf model at $x = x_1$ (the seaward boundary of the nearshore model) serve as boundary conditions to drive the nearshore model. As for bed level z_b , at the the seaward boundary ($x = x_1$), a linear extrapolation of the inner bathymetry is imposed. Along the lateral boundaries ($y = 0, L_y$), the profile gradually relaxes to the equilibrium profile ($z_{b,e}$), with an exponential decay characterized by the decay distance λ ,

$$\frac{\partial(z_b - z_{b,e})}{\partial y} = \pm \lambda^{-1} (z_b - z_{b,e}),$$

Once a bed level is imposed outside the boundaries is prescribed, the alongshore, cross-shore and diffusive transports are calculated in the same manner as at any other point in the computational domain. At the shoreward boundary ($x = 0$), the cross-shore sediment component of $\vec{q}_{tot}$ vanishes.

In the TRANSP module, the seaward boundary ($x = x_1$) and lateral boundaries ($y = 0, y_L$) are open, allowing sediment to enter or exit through these boundaries. At the shoreward boundary ($x = 0$), the cross-shore sediment component of $\vec{q}_{tot}$ vanishes.

Appendix D

Morphodynamic shelf model: Sediment transport and morphology

In the morphodynamic shelf model, sediment transport, assumed to be non-cohesive and characterized by a spatially uniform d_{50} , is calculated according to the formulations of Van Rijn (1993). These formulations included both bedload and suspended load transport under the joint action of waves and currents, i.e.,

$$\vec{q} = \vec{q}_b + \vec{q}_s. \quad (A1)$$

The magnitude of bedload transport, $|\vec{q}_b|$, is expressed as

$$|\vec{q}_b| = 0.006w_s d_{50} M^{0.5} M_e^{0.7}. \quad (A2)$$

Here, w_s represents the sediment setting velocity, which is computed using the following expression

$$w_s = \frac{10\nu_k}{d_{50}} \left[\sqrt{1 + \frac{0.01(s-1)gd_{50}}{\nu_k^2}} - 1 \right], \quad (A3)$$

in which ν_k is the kinematic viscosity of water ($1 \cdot 10^{-6} \text{ m}^2\text{s}^{-1}$). Furthermore, M and M_e denote the sediment mobility numbers:

$$M = \frac{|\vec{v}|^2 + U_w^2}{(s-1)gd_{50}},$$

$$M_e = \begin{cases} \frac{[\sqrt{|\vec{v}|^2 + U_w^2} - v_{cr}]^2}{(s-1)gd_{50}} & \text{if } \sqrt{|\vec{v}|^2 + U_w^2} \geq v_{cr}, \\ 0 & \text{if } \sqrt{|\vec{v}|^2 + U_w^2} < v_{cr}. \end{cases} \quad (A4)$$

In these expressions, U_w represents the magnitude of the near-bed peak wave orbital velocity (computed by SWAN), $s = \rho_s/\rho$ (with ρ_s the sediment density) is the relative density, and v_{cr} is the critical depth-averaged velocity for the initiation of motion. Critical velocity v_{cr} comprises a component due to currents ($v_{cr,c}$) and another due to waves ($v_{cr,w}$):

$$v_{cr} = \Gamma v_{cr,c} + (1 - \Gamma) v_{cr,w}, \quad \Gamma = \frac{|\vec{v}|}{|\vec{v}| + U_w}. \quad (A5)$$

These critical velocities are computed using the following formulations:

$$v_{cr,c} = \begin{cases} 0.19(d_{50})^{0.1} \log\left(\frac{12D}{3d_{90}}\right) & \text{for } 0.1 < d_{50} < 0.5 \text{ mm}, \\ 8.5(d_{50})^{0.6} \log\left(\frac{12D}{3d_{90}}\right) & \text{for } 0.5 < d_{50} < 2 \text{ mm}, \end{cases} \quad (A6)$$

and

$$v_{cr,w} = \begin{cases} 0.24[(s-1)g]^{0.66} (d_{50})^{0.33} T_p^{0.33} & \text{for } 0.1 < d_{50} < 0.5 \text{ mm}, \\ 0.95[(s-1)g]^{0.57} (d_{50})^{0.43} T_p^{0.14} & \text{for } 0.5 < d_{50} < 2 \text{ mm}, \end{cases} \quad (A7)$$

where d_{90} is the sediment diameter corresponding to the 90% cumulative percentile value, while T_p is the peak wave period.

The suspended load transport ($\vec{q}_s$) is calculated by solving the depth-averaged advection-diffusion equation, expressed as

$$\frac{\partial(Dc)}{\partial t} + \frac{\partial(Duc)}{\partial x} + \frac{\partial(Dvc)}{\partial y} - \epsilon_H \left[\frac{\partial}{\partial x} \left(D \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left(D \frac{\partial c}{\partial y} \right) \right] = \frac{w_s(c_{eq} - c)}{T_{sd}}, \quad (A8)$$

where c is the depth-averaged sediment volume concentration, and ϵ_H is the horizontal eddy diffusion coefficient, which is calculated using the following expression

$$w_s = \frac{10\nu_k}{d_{50}} \left[\sqrt{1 + \frac{0.01(s-1)gd_{50}}{\nu_k^2}} - 1 \right], \quad (A9)$$

in which ν_k is the kinematic viscosity of water ($1 \cdot 10^{-6} \text{ m}^2\text{s}^{-1}$), T_{sd} represents a dimensionless adaptation time scale, determined using the following empirical function (Galappatti 1983):

$$T_{sd} = \widetilde{w}_s \exp[(1.547 - 20.12\widetilde{u}^*)\widetilde{w}_s^3 + (326.832\widetilde{u}^{*2.2047} - 0.2)\widetilde{w}_s^2 + (0.1385\ln(\widetilde{u}^*) - 6.4061)\widetilde{w}_s + (0.5467\widetilde{u}^* + 2.1963)]. \quad (A10)$$

Here, $\widetilde{w}_s \equiv w_s/u^*$ is the dimensionless fall velocity, where u^* is friction velocity, and $\widetilde{u}^* \equiv u^*/\sqrt{u^2 + v^2}$ represents the dimensionless friction velocity. Finally, c_{eq} is the depth-averaged equilibrium sediment concentration as defined by Van Rijn (1993).

Bed slope effects on sediment transport, considered only on for bedload transport, are calculated with the formulations of Bagnold (1966) and Ikeda (1982). These effects are incorporated both in the direction of the local flow and perpendicular to it, with coefficients α_{BS} and α_{BN} , respectively (Dissanayake et al., 2009).

The time evolution of the shelf bed level ($\partial z_b / \partial t$) is determined by dynamically updating z_b based on the net exchange of sediment between the water column and the bed, as well as the spatial gradients in the bedload sediment transport vector $\vec{q}_b$, i.e.,

$$\frac{\partial z_b}{\partial t} = -\frac{1}{1-p} \left[\vec{\nabla} \cdot \vec{q}_b + \frac{w_s(c_{eq} - c)}{T_{sd}} \right], \quad (A11)$$

with $p(= 0.4)$ the porosity of the bed.

Appendix E: additional figures ShorelineS application

Wave forcing

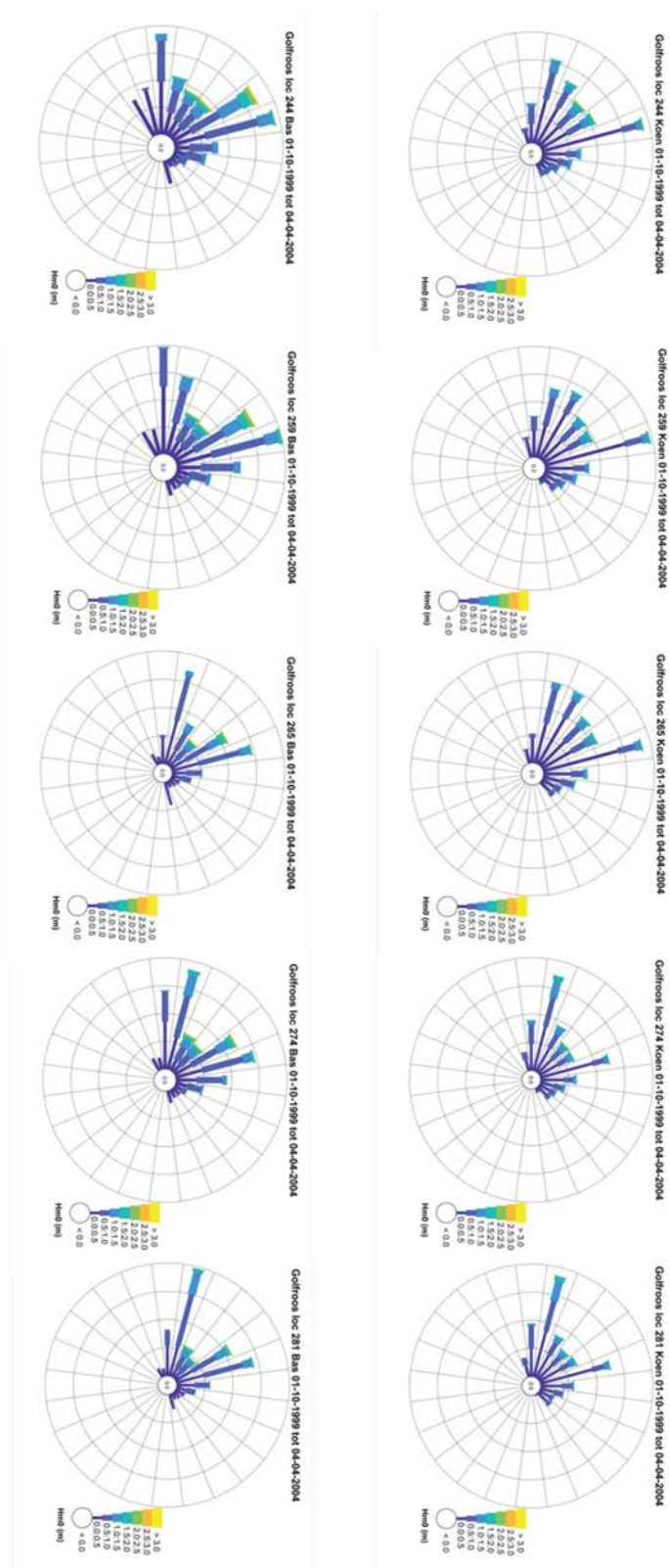


Figure 0-1: (top) Wave roses as used in Trouw et al. (2019) for the period 1999-2004, from west to east, and (bottom) wave roses for the same period, based on Huisman et al. (2019), from west to east.

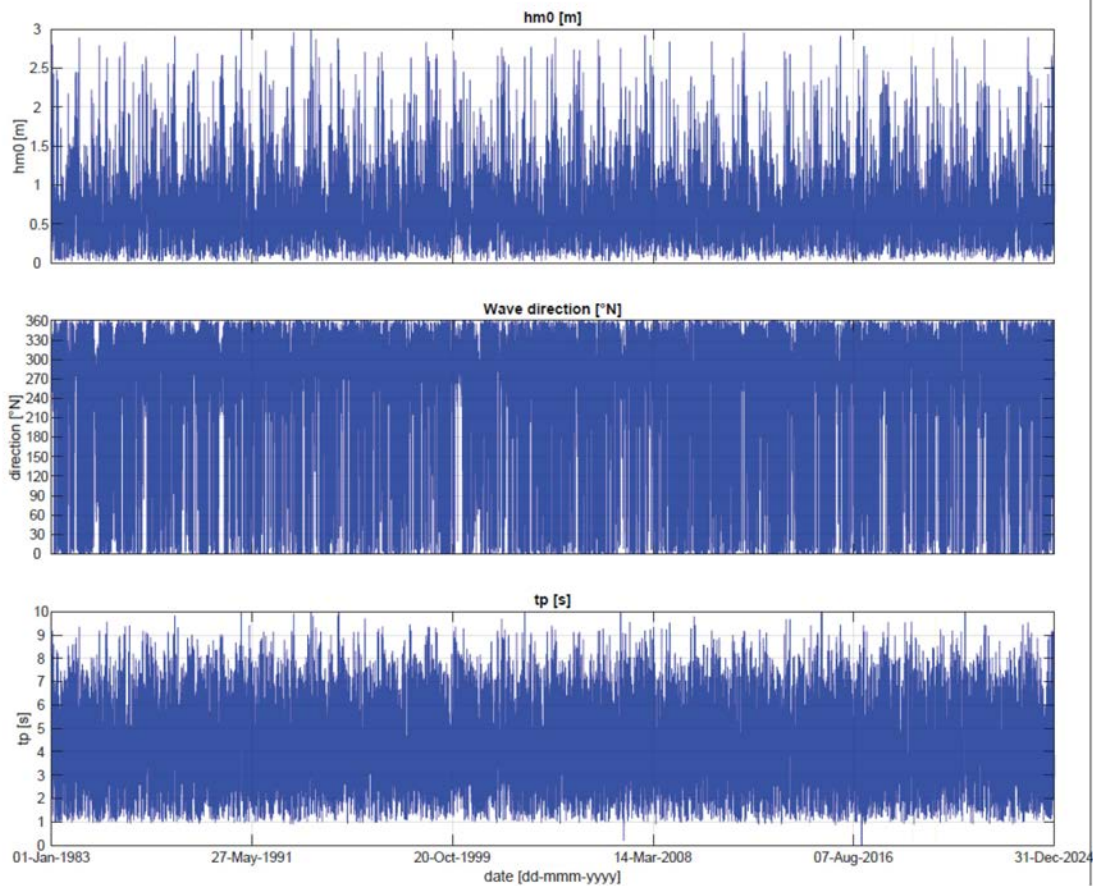


Figure 0-1: Wave timeseries for the extracted location offshore of Knokke-Heist, coordinates $x = 740400$; $y = 228059$ Lambert [m].

Nourishment volumes per Strook

Table 0-1: Nourishment volumes over the past decades per strook, separated in above and below low water.
Source: Houthuys et al. (2019).

Above low water		Below low water	
Date	m ³	Date	m ³
Strook 44			
26/09/1986	340.000	07/10/1986	16.600
30/04/1993	-26.600	07/05/1993	-26.600
07/01/1994	30.600	04/12/1993	30.600
17/04/2022	5.500	16/05/1995	35.100
08/02/2023	4.500		
Total:	350.000		55.000
Strook 45			
26/09/1986	55.000	07/10/1986	162.100
07/05/2012	8.800	16/05/1995	70.000
17/04/2022	4.500		
08/02/2023	9.100		
Total:	80.000		230.000
Strook 46			
19/06/2008	3.200	12/05/2021	10.800
24/05/2009	2.200		
28/05/2010	4.200		
17/04/2011	6.200		
26/05/2017	3.100		
28/04/2021	130.000		
08/02/2023	6.400		
Total:	155.000		11.000
Strook 47			
25/05/1997	3.500	26/04/1997	-3.500
29/04/1998	5.300	04/04/1998	-5.300
06/06/1999	6.200	18/04/1999	-6.200
16/06/2000	6.000	07/04/2000	-6.000

10/05/2001	6.000	14/04/2003	-18.800
12/05/2002	6.000	12/05/2021	92.600
14/04/2003	11.700		
17/04/2004	13.100		
23/08/2005	18.100		
18/04/2006	19.400		
03/06/2007	14.000		
19/06/2008	11.400		
24/05/2009	7.800		
28/05/2010	14.700		
17/04/2011	21.600		
07/05/2012	31.300		
29/04/2013	22.600		
15/04/2014	6.300		
27/10/2015	10.000		
26/05/2017	16.900		
28/04/2021	348.700		
Total:	600.000		50.000
Strook 48			
26/05/1986	57.300	10/05/2007	1.400
23/08/2005	7.700	12/05/2021	12.300
03/06/2007	9.900	02/07/2024	83.500
24/05/2009	14.800		
28/05/2010	7.300		
17/04/2011	3.600		
07/05/2012	23.300		
10/12/2013	11.800		
15/04/2014	10.900		
17/05/2015	33.200		
26/05/2017	24.600		
28/04/2021	251.100		
17/06/2023	126.000		
Total:	580.000		97.200
Strook 49			
26/05/1986	545.400	26/04/1997	-6.200

18/10/1997	6.200	18/04/1999	50.900
06/06/1999	288.200	06/04/2004	39.700
23/08/2005	225.100	02/07/2024	401.800
18/04/2006	55.500		
03/06/2007	57.600		
24/05/2009	41.000		
17/04/2011	108.100		
07/05/2012	126.000		
10/12/2013	100.500		
15/04/2014	140.200		
17/05/2015	171.700		
26/05/2017	218.600		
20/04/2019	194.200		
17/06/2023	242.900		
Total:	2.500.000		486.200
Strook 50			
26/05/1986	119.800	20/05/1986	21.100
14/01/1997	2.500	05/10/1996	-2.500
06/06/1999	63.200	18/04/1999	11.200
23/08/2005	58.100	06/04/2004	8.700
26/05/2017	10.000	02/07/2024	89.800
20/04/2019	24.700		
28/04/2021	33.500		
Total:	300.000		128.300

Additional model figures for the calibration period

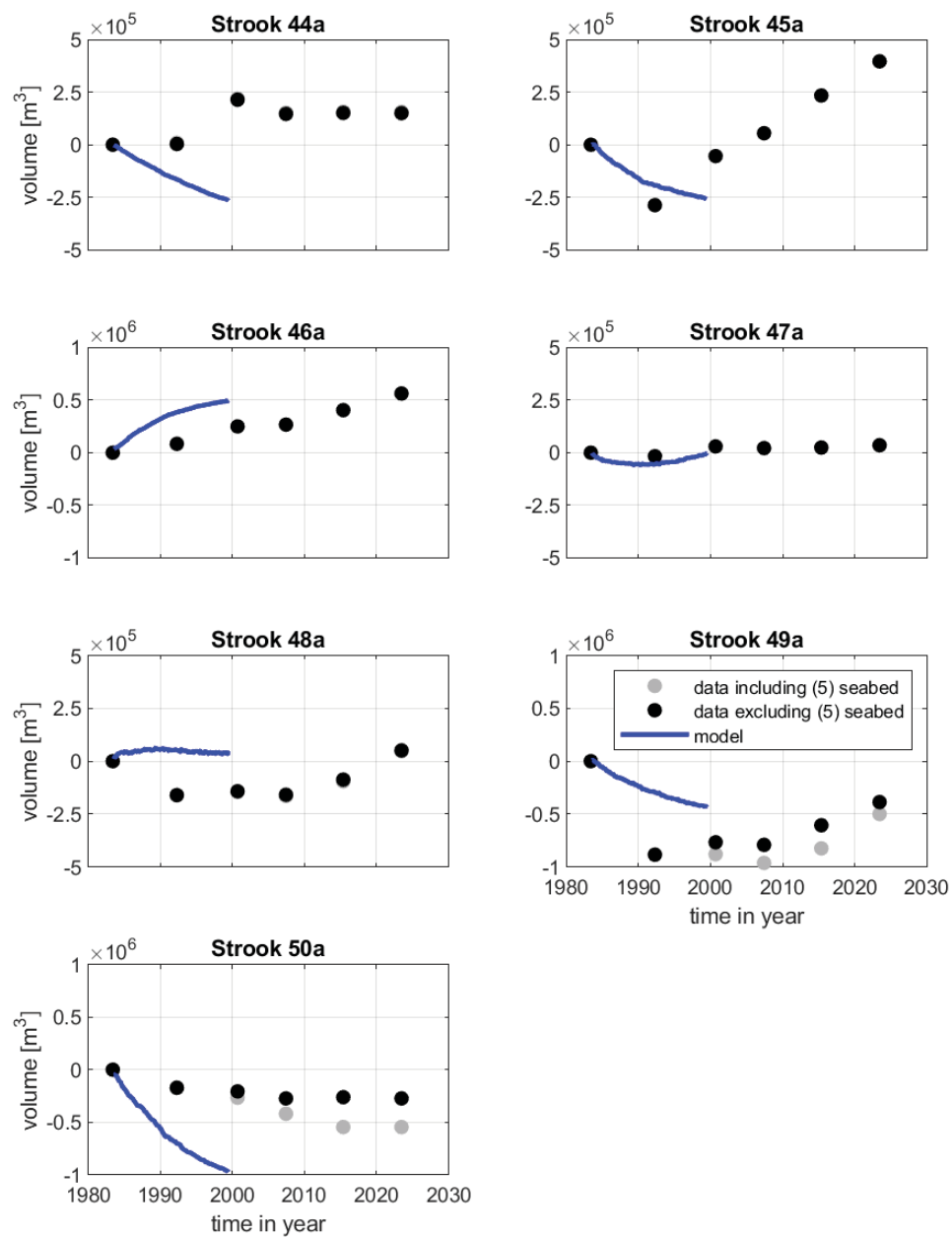


Figure 0-1: Comparison of measured volume changes per Strook, subsection A (Figure 3-75), with model predictions for the period 1983-1999, for simulation #2, which is similar to the reference run, but with a cross-shore grid resolution of 50 m. Nourishment volumes are not taken into account in this figure.

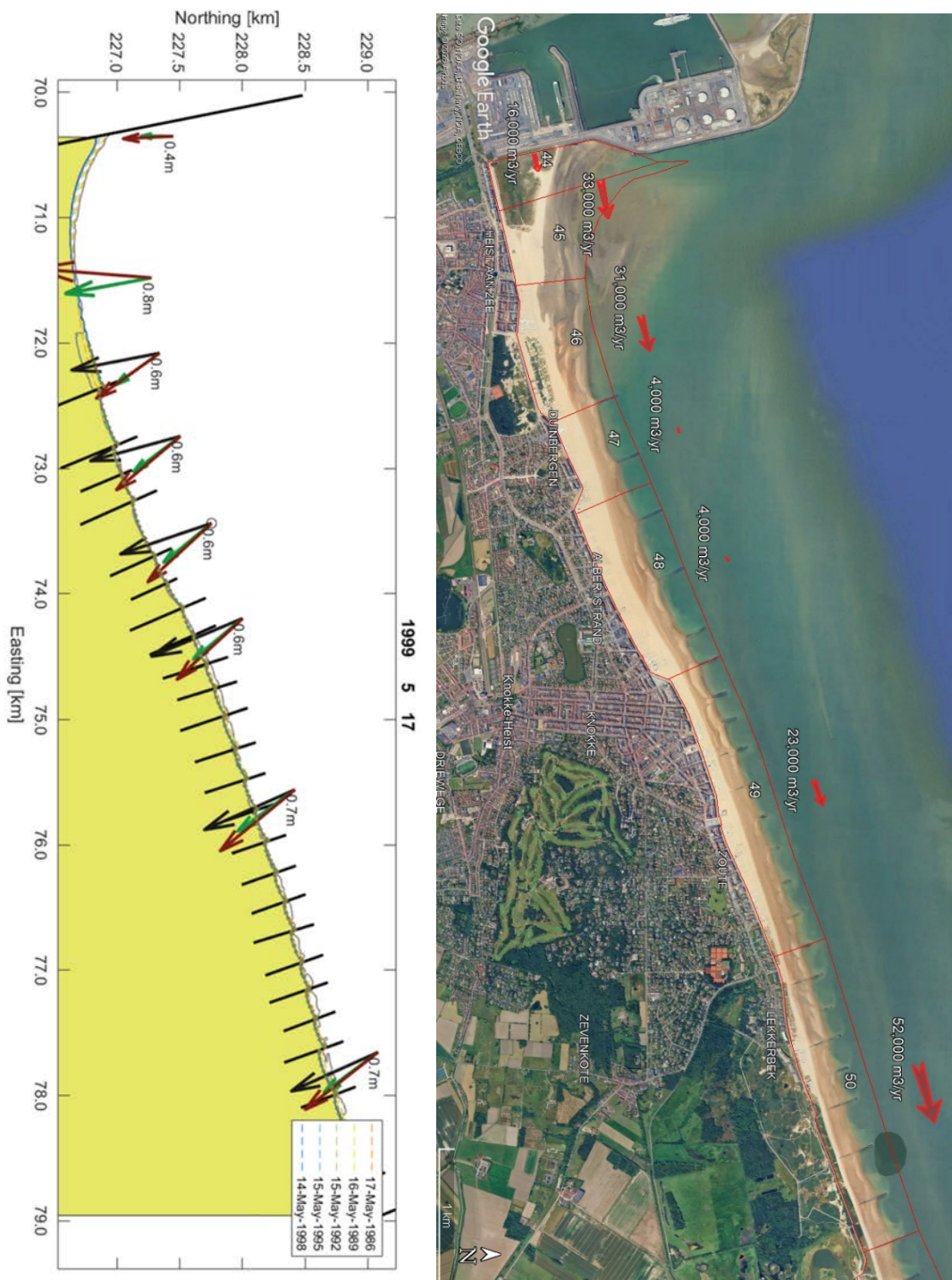


Figure 0-2: Hindcast simulation for the period 1983 to 1999. Simulation #2, with a cross-shore grid resolution of 50 m. The arrows are less relevant here, but are automatically generated output that show the applied offshore (wave) conditions and the local wave directions at the coast (for the nearshore in green and poin-of-breaking in red-brown) at the indicated final timestep.

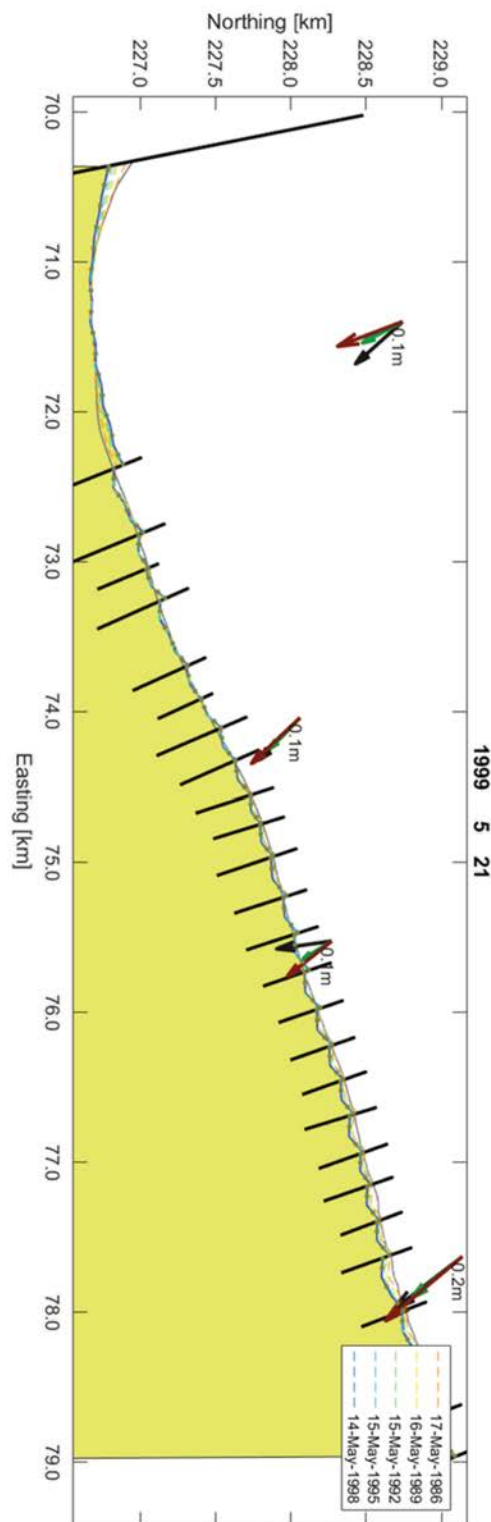


Figure 0-2: Hindcast simulation for the period 1983 to 1999 for simulation #5, using the wave climate of Trouw et al. (2024) for the period 1999-2024. Start coastline in grey. The arrows are less relevant here, but are automatically generated output that show the applied offshore (wave) conditions and the local wave directions at the coast (for the nearshore in green and poin-of-breaking in red-brown) at the indicated final timestep.

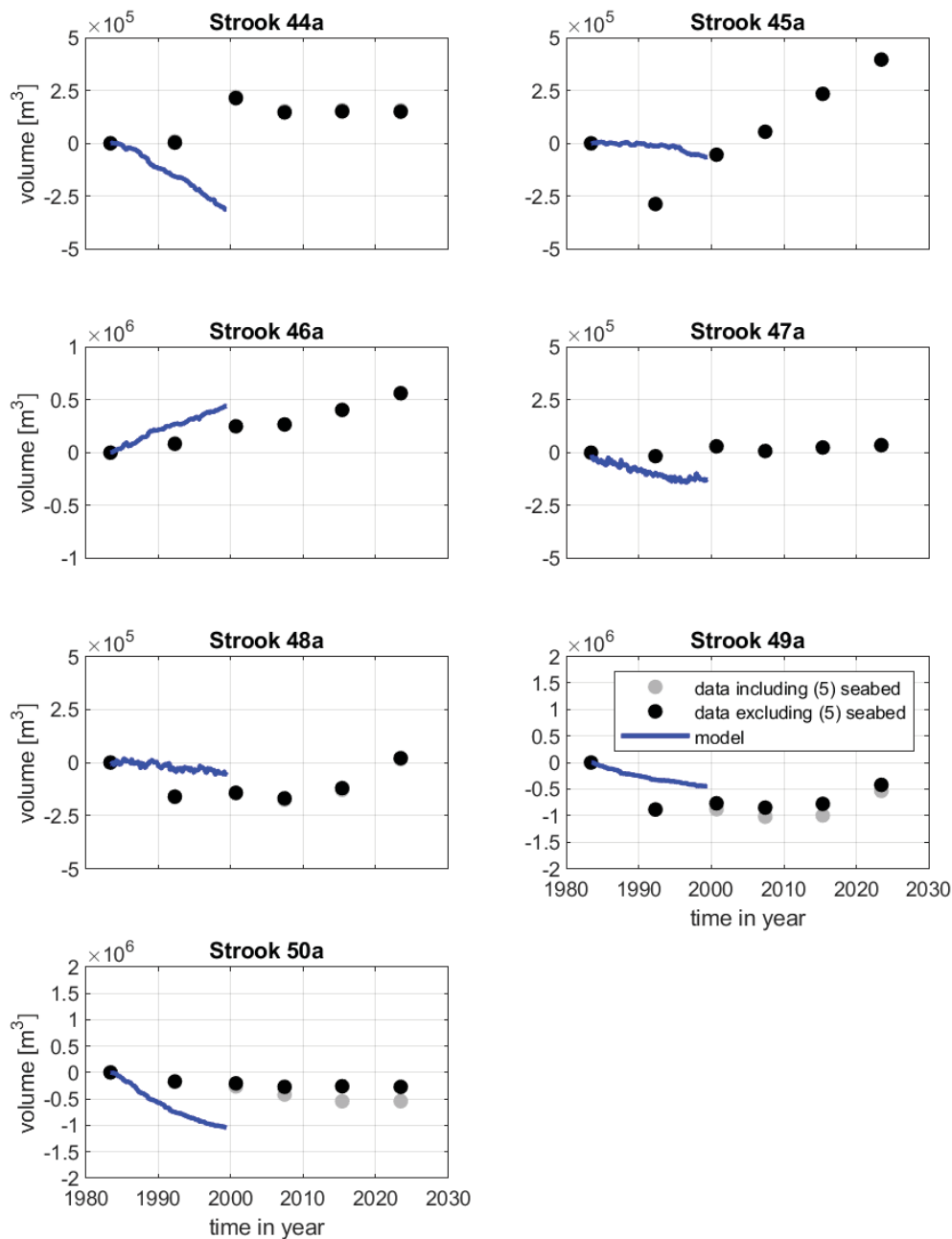


Figure 0-3: Comparison of measured volume changes per Strook, subsection A (Figure 3-75), with model predictions for the period 1983-1999, for simulation #5. Nourishment volumes are not taken into account in this figure. Wave forcing is imposed using the wave climate for 1999-2004 as determined by Trouw et al. (2024).



Figure 0-3: Longshore sediment transport magnitude and dominant direction per Strook over the calibration period 1983-1999, for simulation #1.



Figure 0-4: Longshore sediment transport magnitude and dominant direction per Strook over the calibration period 1983-1999, for simulation #5 with wave climate of Trouw et al. (2024).

Additional figures validation period

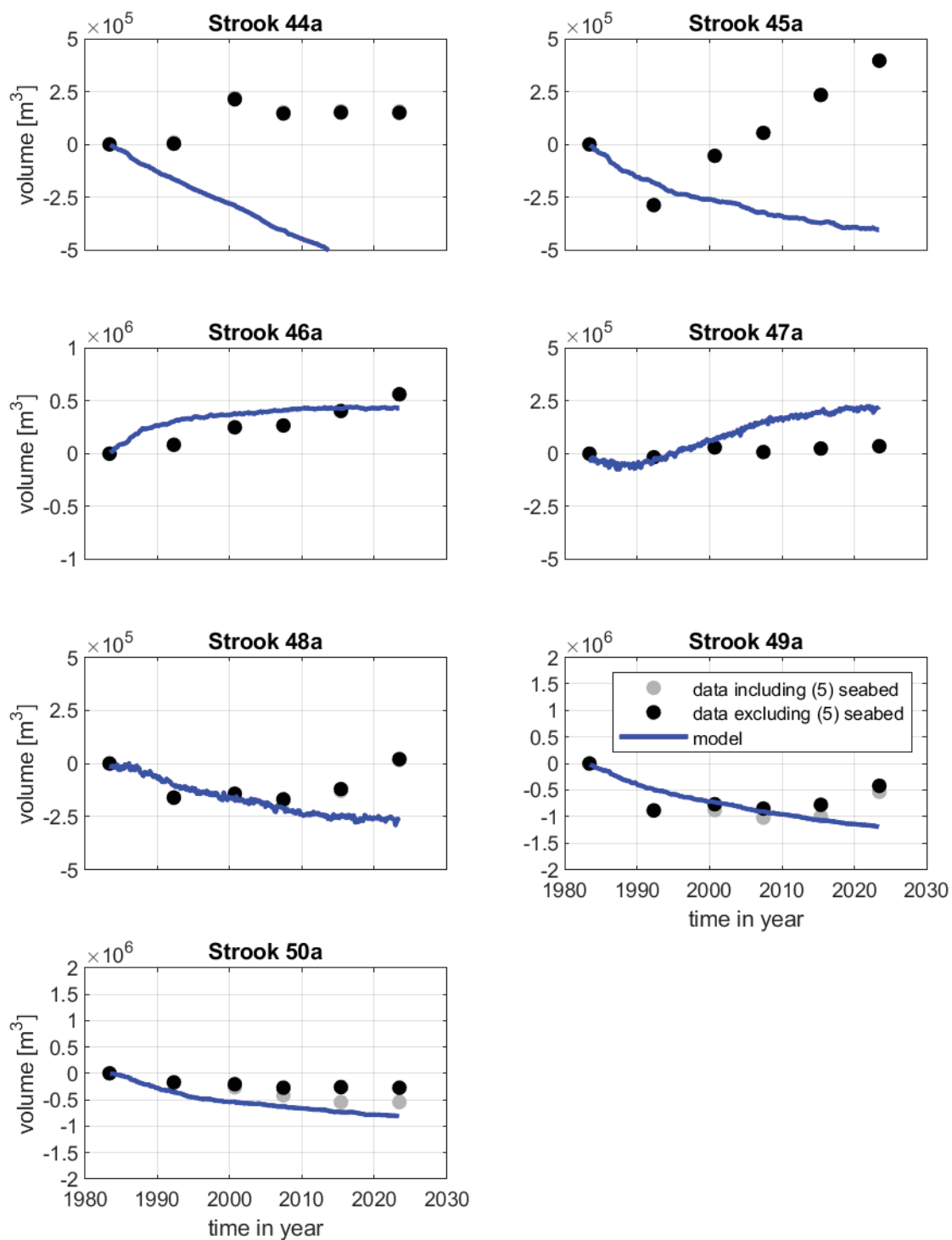


Figure 0-4: Comparison of measured volume changes per Strook, subsection A (Figure 3-75), with model predictions for the period 1983-2023, simulation #14. Nourishment volumes are not taken into account in this figure.

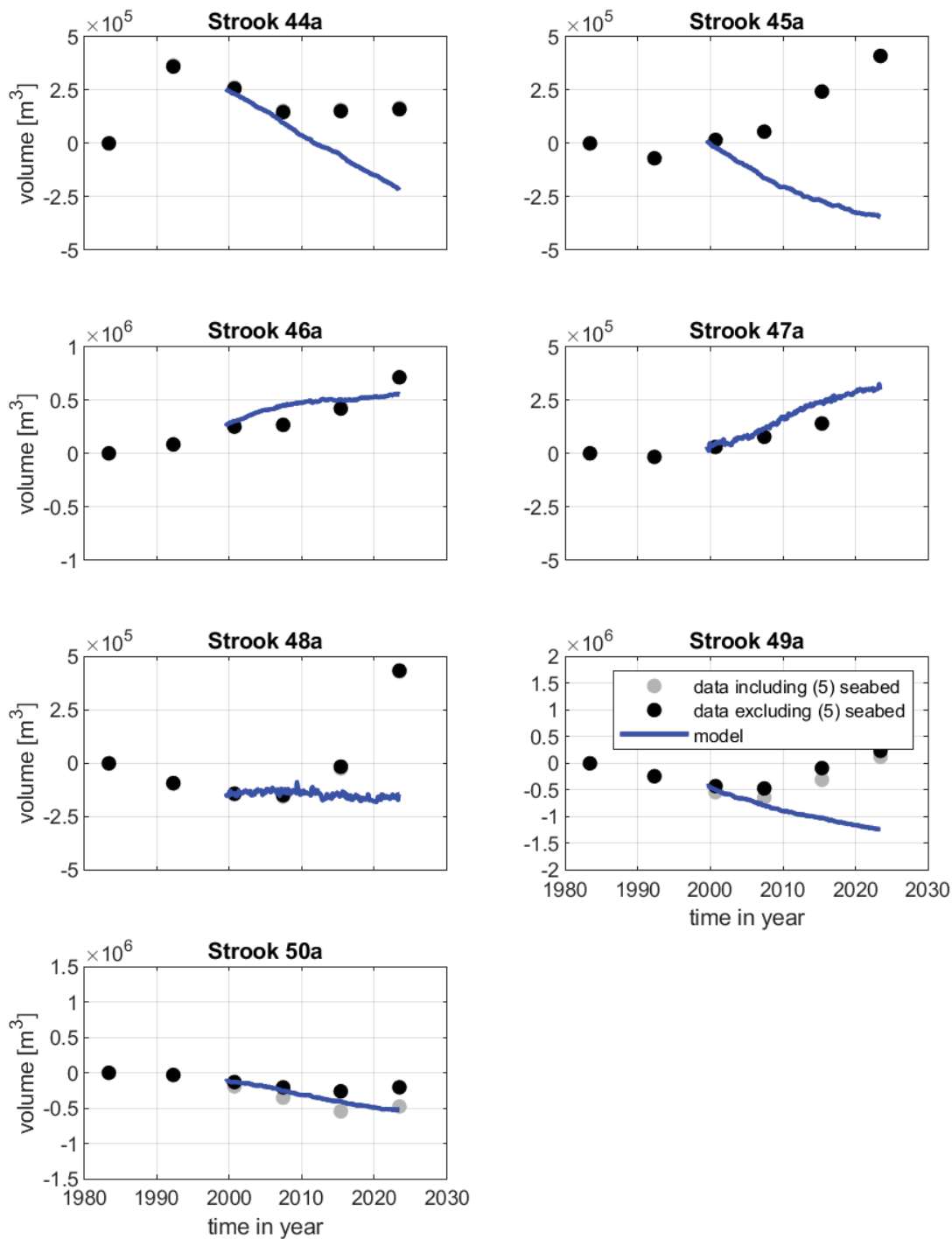


Figure 0-5: Comparison of measured volume changes per Strook, subsection A (Figure 3-75), with model predictions for the period 1999-2023, simulation #12 including nourishments in the model, and the uncorrected data.

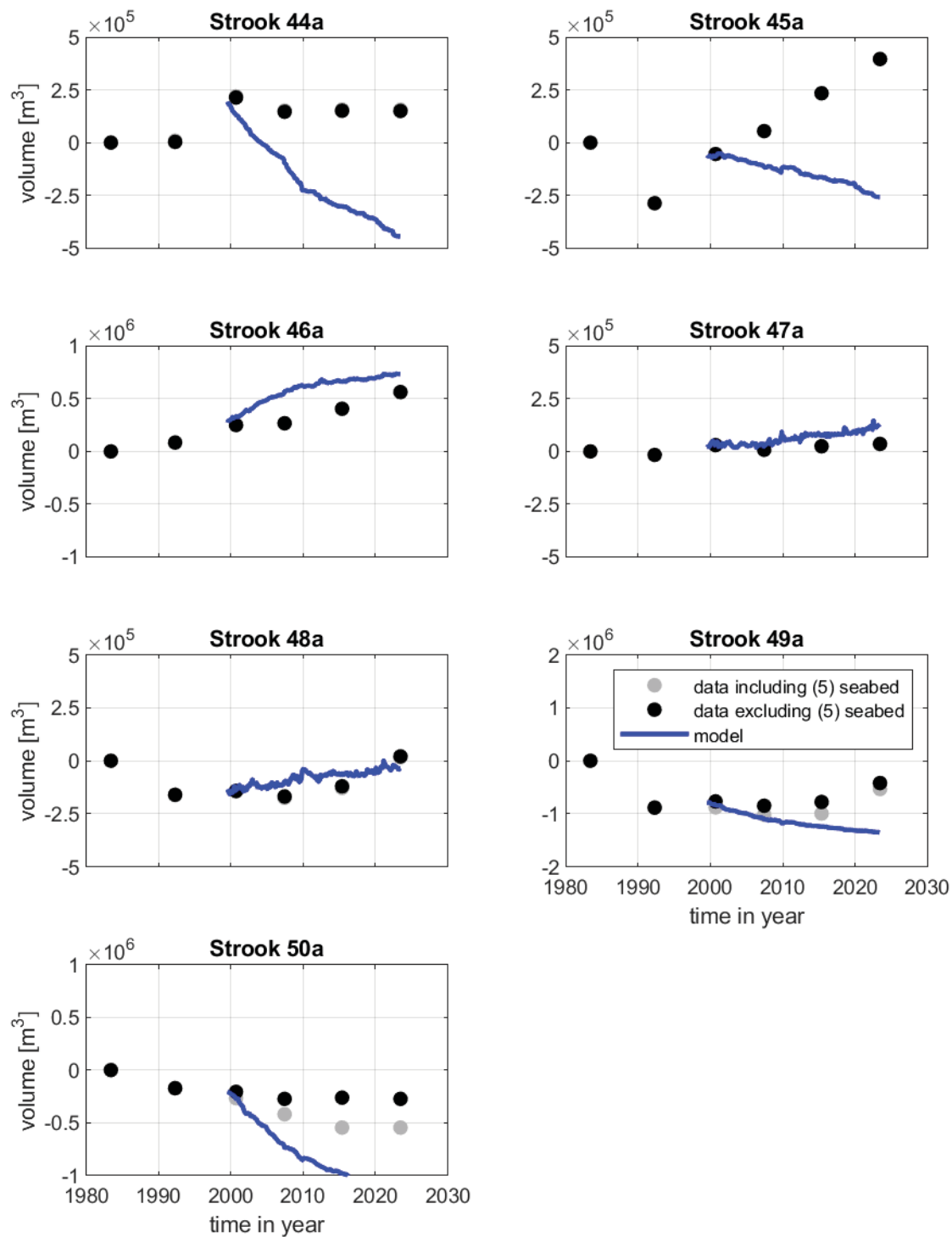


Figure 0-6: Comparison of measured volume changes per Strook, subsection A (Figure 3-75), with model predictions for the period 1999-2023, for simulation #13 with wave climate of Trouw et al. (2024).

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