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Scientific support regarding hydrodynamics and sand transport in the coastal zone

LITERATURE AND DATA REVIEW COASTAL ZONE ZEEBRUGGE - ZWIN

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waterbouwkundig LABORATORIUM

IMDC International Marine & Dredging Consultants

Vlaamse overheid

Scientific support regarding hydrodynamics and sand transport in the coastal zone

Literature and data review coastal zone Zeebrugge - Zwin

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Abstract

In this report the available literature and data relevant for the coastal zone between Zeebrugge and the Zwin is summarised.

Since the extension of the harbour of Zeebrugge (finalised in 1986) a lot of bathymetrical data are available. With these data the evolution around Zeebrugge (including the Western part, area around the harbour breakwaters, Baai van Heist, the beaches of Knokke and the Appelzak gully) can be reconstructed. But also before this extension some data are available, such that the difference pre and post extension can be compared.

Other data and literature are also described, including numerical modelling of currents and morphology, detailed hydrodynamic and sediment transport measuring campaigns and analysis of the sediment composition.

In front of Knokke-Heist the beaches are eroding due to the presence of the Appelzak-gully. The Appelzak shows a long term landward movement. However the movement and development of the gully seems to slow down during the last 10 years. Although confirmation is needed (both based on further trend analysis and numerical modelling), this might suggest that big scale measures to reduce erosion, might be less effective Possibilities for the slow down are the more equilibrium state of the system after the extension of the harbour of Zeebrugge and the influence of the large nourishments in the last decade .

Consequently, also the erosion in front of Knokke-Heist is clearly slowing down during the last decade.

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1 Introduction

The coastal zone between the Port of Zeebrugge and the Zwin is a complex area. Sediment and water dynamics here are strongly influenced by the presence of the breakwaters of the harbor of Zeebrugge (with e.g. the sedimentation of the Baai van Heist) as well as by the tidal gully Appelzak, located in front of the severely eroding beaches of Knokke-Heist the tidal inlet Zwin and also by the dynamics of the Western Scheldt mouth (see Figure 2.1 and 2.2). This report summarizes and analyses the available information about this area. Firstly, the main features and the history of the area described, using literature and historical maps. A short description is given of available numerical modelling results and the results of measuring campaigns (velocities, sediment concentrations and tracer experiments). The morphological evolution since 1954 (first available data) is described in detail, including the possible influence of the harbor extension of Zeebrugge (finalized in 1986). Possible explanations for the change in morphological trends around 1997-1999 are summarized. Finally the complex pattern of sediment grain sizes is given.

2 Main features

The beaches between Zeebrugge and the Zwin are situated in between the harbor of Zeebrugge (constructed beginning 20th century and extended in 1979-1986) and the mouth of the Scheldt-river (Figure 2-1 and Figure 2-2). The tidal gully Appelzak is located seawards in front of the beaches (about 0.5-1km from the sea wall) resulting in a steep shoreface slope (1:25) in front of Knokke-Zoute. This steep slope and the gully are often cited as a major cause that prevent the restoration of the beaches during calm weather. Here is where the most severe beach erosion along the Flemish coast is found. Just north of the Appelzak gully, the shallow (-3m LAT) Paardenmarkt is situated (up to 5km offshore). At the north western edge of this area the dumping zone “Zeebrugge-Oost” (ZB-Oost in Figure 2.1 and 2.2) is situated, on which mainly the sediments (mainly fines) from the dredging works of the harbor (and access channel) of Zeebrugge is dumped (about 3 million ton dry matter per year). About 10km north of the beaches the important navigation channel Scheur, the access to the Western Scheldt and the port of Antwerp, is situated. Further north, the Vlakte Van de Raan is a shallow area (-3m LAT) in front of the mouth of the Scheldt.

Just east of the harbor of Zeebrugge, the Baai van Heist is receiving sediment, causing a very large beach, with sometimes soft unconsolidated sediments that create dangerous situations for recreation. Ten kilometer more to the east, the tidal marsh “the Zwin” has its entrance. The actual tidal prism at spring tide measures about 250.000m³ and will be extended in the future (scheduled for 2016-2018) up to 1 million m³.

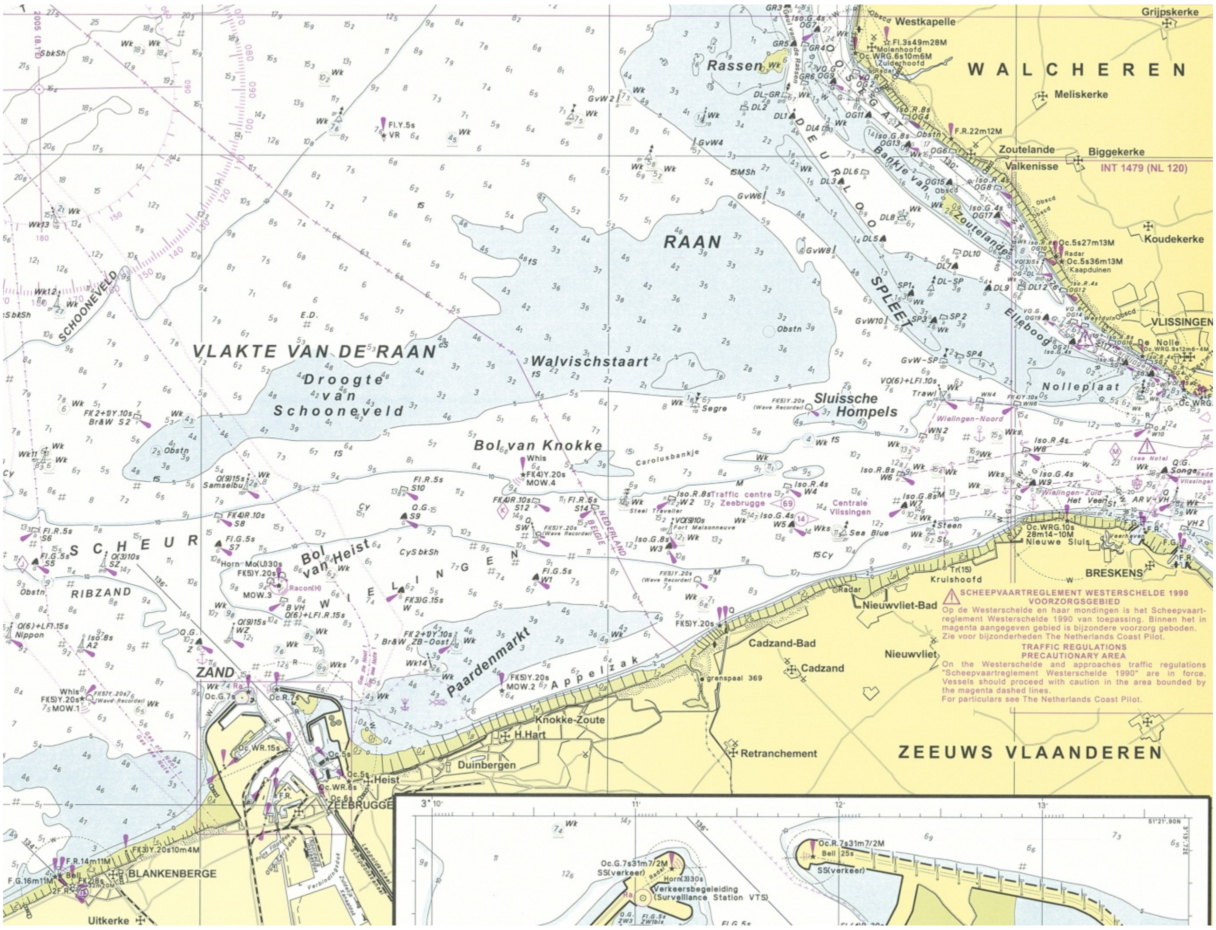


Figure 2-1 Nautical chart of the Scheldt mouth, including the harbour of Zeebrugge (Afdeling Kust)

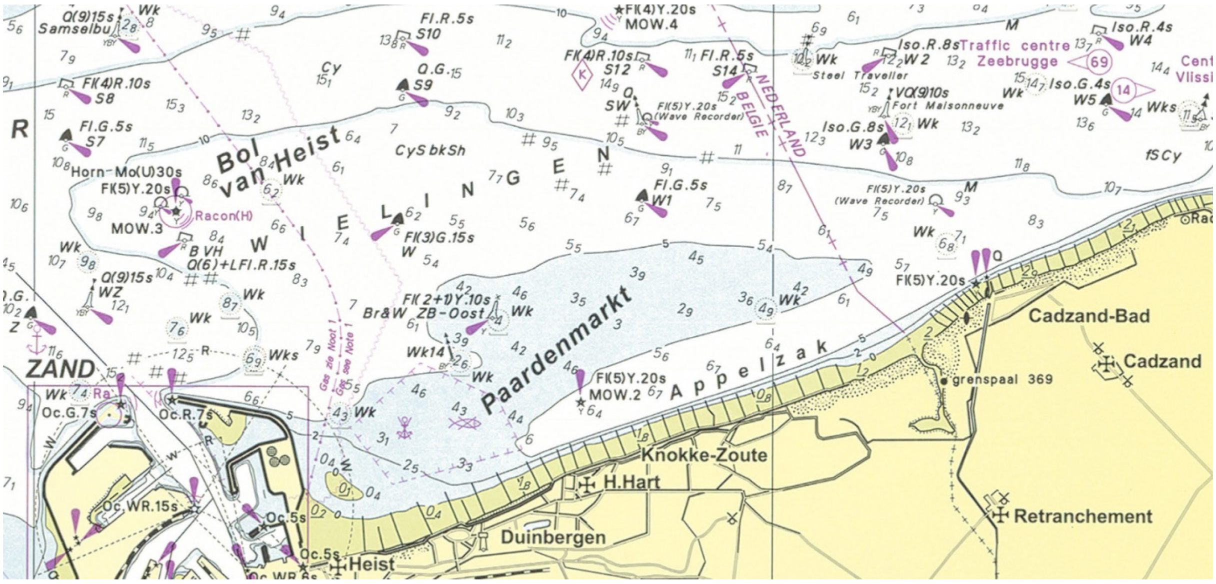


Figure 2-2 Nautical chart – detail between Zeebrugge and Cadzand

The coastline orientation is rather straight (cf. Figure 2-3), with the same orientation as the coastline between Blankenberge and Zeebrugge. Only in front of Knokke Heist and between the Zwin and Nieuwvliet, the coastline is shifted offshore, which can locally influence the sediment transport (e.g. at the Dutch part of the Zwin-entrance, the wave generated transport might be directed more Westwards).

Figure 2-3 Coastline orientation

For management purposes, the coastline is subdivided in numbered sections often defined by groins. An overview of the numbers of the sections in this area, also used in this report, can be found on Figure 2-4.

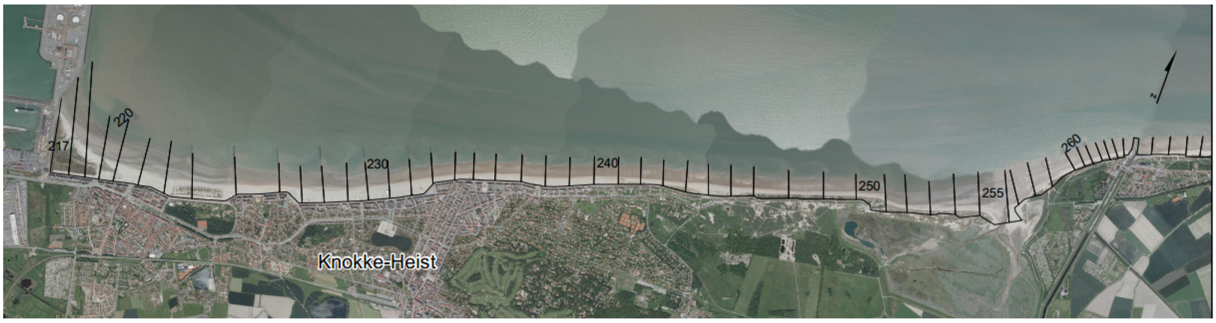


Figure 2-4 Subdivision of the coastline in numbered sections

The groins between Knokke Heist and Zwin are long groins, up to a water depth of -3m LAT, where the groin crest is still at around 0m LAT. Above LW the groins are relatively low crested.

3 History of morphology and human coastal defence measures

De Moor (2002) describes the evolution of the coast between Zeebrugge and Zwin, Houthuys (2012) describes the nourishments (on the beach, mostly extending to the foreshore) since 1977 (trends analysis for the complete Flemish coast grouped in sections after morphological features and calculating and interpreting trends including corrections for nourishments):

- 1848 : first groins
- 1867 : construction of seawalls (at the Flemish coast, often called dikes)
- 1896-1905 : construction of the first outer harbor of Zeebrugge, with a “Claire-voie” (breakwater is very permeable, mainly intended for mooring) to avoid as much as possible the interception of longshore transport
- 1928 :closure of the Claire-voie. Start (?) of erosion near Heist
- 1920 : first nourishment (Heist)
- 1938-1966: 180.000m³/year sand accumulation west of Zeebrugge. After 1966 all longshore transport bypasses the harbor (or sedimentates in the navigation channel) (Delft Hydraulics, 1978)
- 1952 : idea for construction of 25 new groins, because the LW-line approached up to 150m from the sea wall, at HW waves attacked the sea wall
- 1953 : big storm, lot of damage on the dike (including dike erosion)
- 1955-1957 : nourishments over the whole coast east of Zeebrugge (1.25 mill. m³)
- 1955- 1960 : lengthening and strengthening of the groins
- 1968 : nourishment at Heist (0.6 mill. m³)
- January 1976 : severe storms erode the complete beach near Heist
- 1973-1977 dredged material (from Scheur) dumped in the Appelzak, to counter erosion of this gully (BMM, AWZ, 1993, without reporting the volume)
- 1977-1979 : significant nourishments between Heist and Knokke (8.5 mill. m³ supplied, 6.5mill m³ in situ[1]) over 9km)
- 1979-1986 : construction of the new outer harbour of Zeebrugge, extending up to 3km offshore
- since 1987 : natural deepening and landward movement of the Appelzak in front of Knokke
- 1984 : nourishment Heist (mentioned by De Moor (2002) but not confirmed by detailed data)
- from 1985: - dredged material is dumped at the dumping site B&W Zeebrugge-Oost ca. 3 to 6 million ton dry material (TDM)/year (BMM&AWZ, 1993; Lauwaert et al, 2011)
- 1986 : nourishment Heist with sediment from the dredging works in the harbour. A lot of silt goes in suspension and disappears, but the beach volume in sections 217-218 increases with 340.000m³ and the foreshore of sections 218-221 increases with 178.000m³ . Probably the fraction of sand remains on the beach, while the fines are washed out. No quantitative numbers of this wash out are known
- 1986: nourishment of 850.000m³ (in situ) at Knokke-Zoute (sections 232 -243, length 3000m)
- 1992-1993: sand borrowing in sections 217-218 (near LW-line and foreshore) during the construction of the landfall of Zeepipe
- 1993-1995: smaller nourishments in 217-218 (~100.000m³) in compensation for the removal of unwanted mud sedimentation of the borrow
- 1999 : nourishment Knokke-Zoute (sections 233-243 length 2700m) : 410.000m³ in situ
- 2004 : nourishment Knokke-Zoute (sections 232-243 length 2800m) : 330.000m³ in situ

Smaller nourishments (maintenance) for touristic exploitation occur quasi continuously. These numbers are incorporated in the trend analysis presented below.

In Bastin (1974) and Van Cauwenberghe (1966) a description of the historical morphological evolution can be found. Already in 1825 the Appelzak-gully was visible on nautical charts (Figure 3-1). In the absence of the blocking effect of longshore sediment transport by the outer harbor of Zeebrugge, the gully was flood-dominated and situated at a distance of about 1km from the dike. In 1840 the Paardenmarkt was very shallow and protected the coast, but its height started to decrease. Before 1930 (Figure 3-2 and Figure 3-3) the Appelzak was at its offshore side bordered by the Paardenmarkt, which was oblique to the coastline and touched it near Cadzand. After 1930 the Paardenmarkt was no longer connected with the shore and was lower. Along this sand bank sand could migrate towards the shore with the flood currents. Gradually, the

[1] Differences between dumped and in situ due to losses during the dumping process

Paardenmarkt decreased in height and the Appelzak became ebb-dominated and consequently causing erosion of the beaches. After the first construction of the outer harbor of Zeebrugge (around 1900), the currents were redirected around the harbor and may have accelerated this process. However, this is an hypothesis which has never been proven. In 1930 (Figure 3-4) the gully was only at 300m from the dike. The beaches of Knokke were erosive, but the gully could not move much more landward due to the presence of the groins.

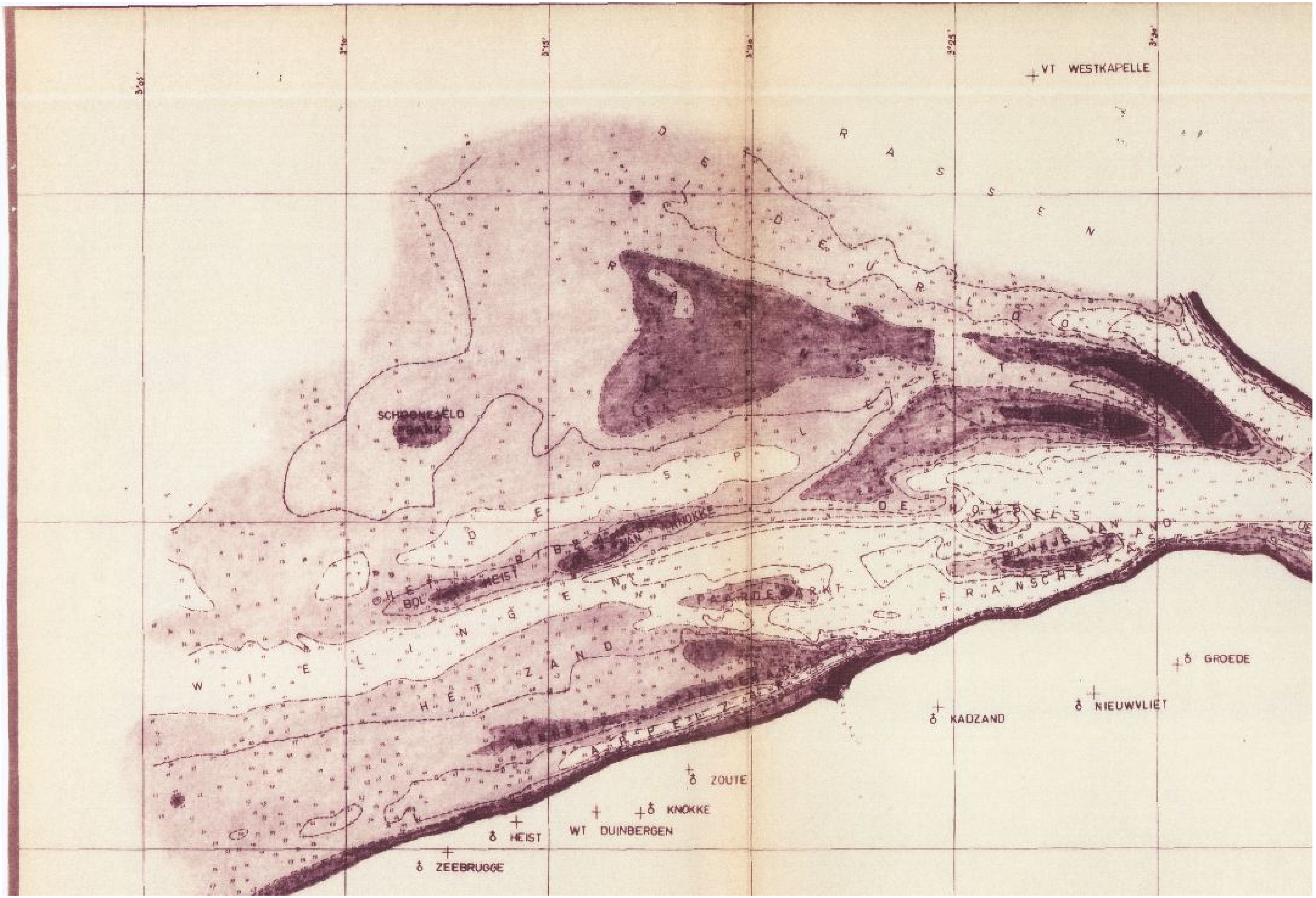


Figure 3-1 Survey 1825 (Van Cauwenberghe, 1966)

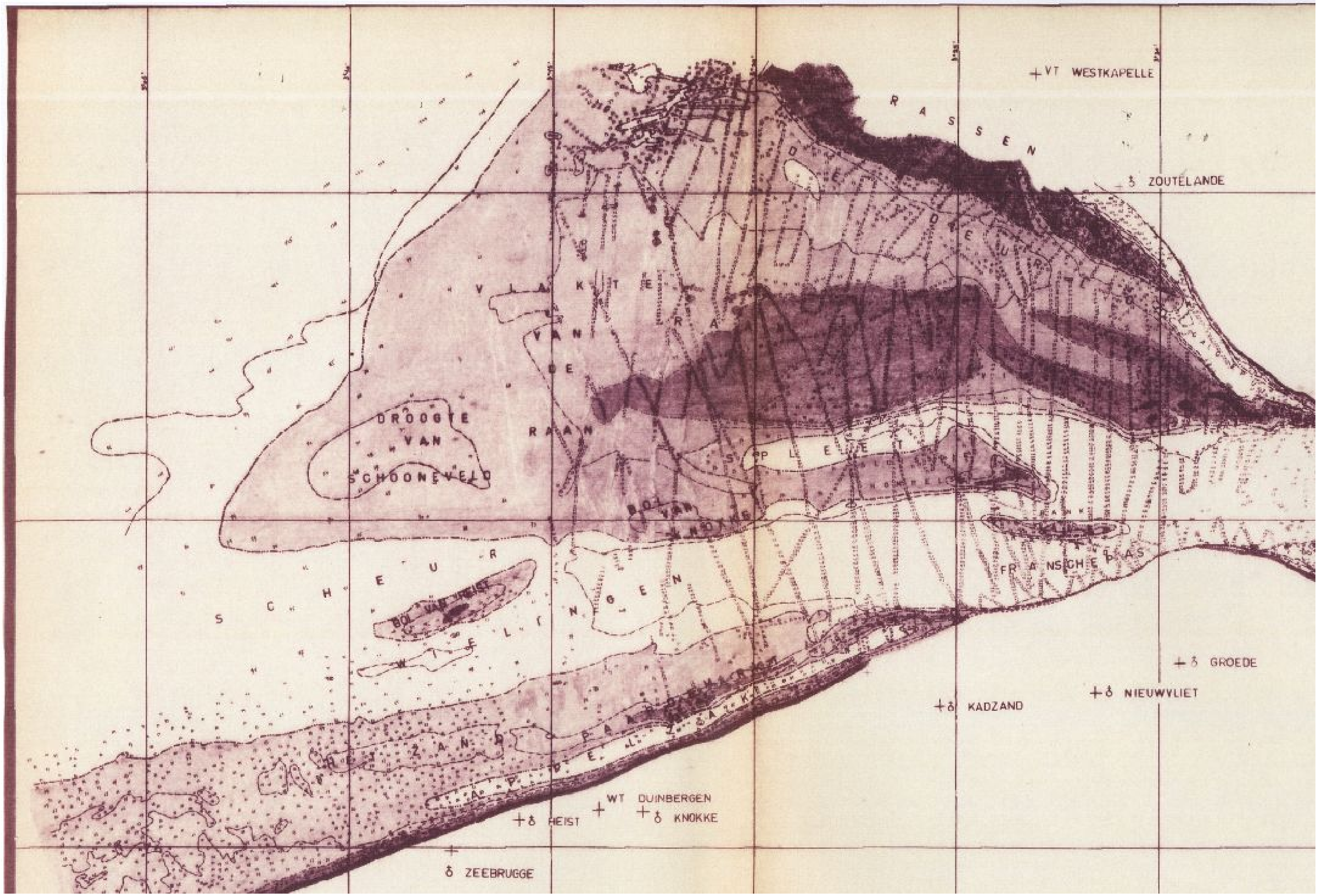


Figure 3-2 Survey 1900/1908 (Van Cauwenberghe, 1966)

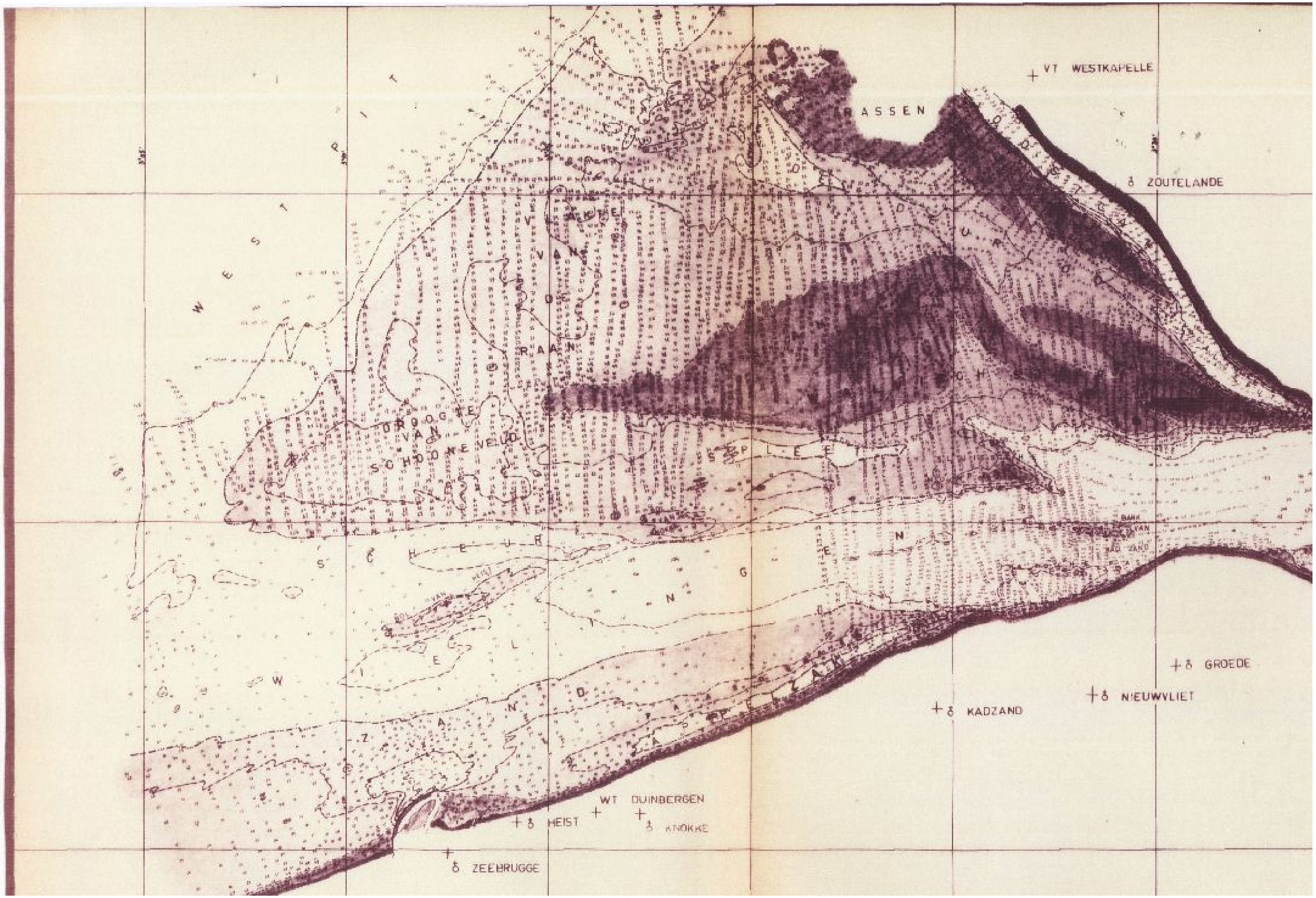


Figure 3-3 Survey 1921/1925 (Van Cauwenberghe, 1966)

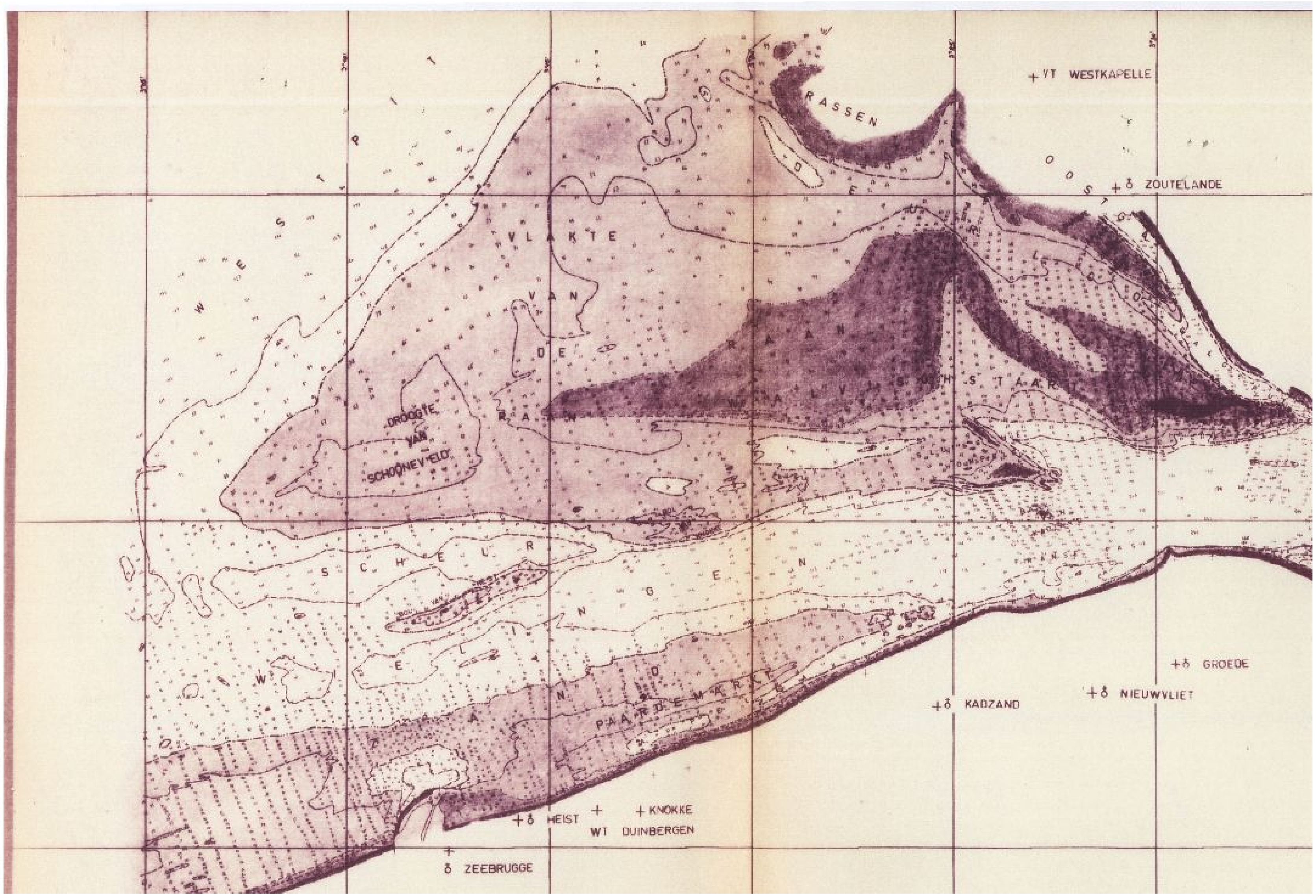


Figure 3-4 Survey 1931/1938 (Van Cauwenberghe, 1966)

In an ebb-gully the residual sediment transport is directed to the southwest. This was confirmed with tracer-experiments (1964, before the extension of the harbor) during 1 year, which also showed that sand bypasses the existing groins. But other tracer-experiments (during some winter-months) between 1977 and 1979 (Bastin et al, 1983) indicate a northeast transport (cf. Figure 3-5). Bastin (1983) suggested that a flood channel may be developing.

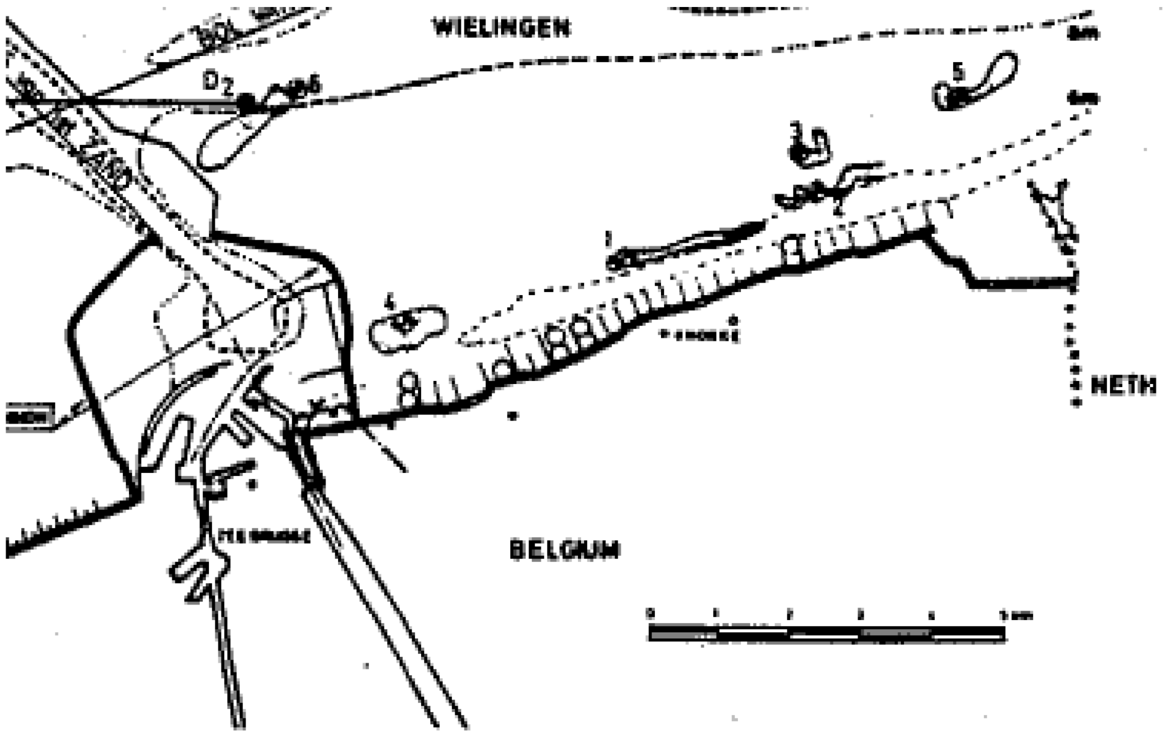


Figure 3-5 Indication of the trajectory of the tracer near Zeebrugge (Bastin et al, 1983)

According to Bastin (1983), the Appelzak may well represent an evacuation gully of water masses piled up during HW. The confinement by the landward moving Paardenmarkt at the seaward side and the groins at the landward side then would force the gully to deepen.

4 Currents and sediment transport

In this chapter results are presented from existing numerical modeling efforts and measurements. The data show that while the residual currents in the area are directed to the West (due to the influence of the Scheldt), the picture is less clear for the residual movement of sand. Modelling by the Management Unit of the North Sea MathematicalModels (MUMM) indicates a net movement to the East, except for a small area (Appelzak), where a net movement to the West is visible (ebb dominated). Tracer experiments (before the harbor extension) did not show this ebb-dominance and also the analyses in the Marebasse project rather show a flood dominance.

4.1 Numerical modeling

At Flanders Hydraulics Research a Delft3D model was set up and used for the simulation of scenarios for the harbor of Zeebrugge. Special attention was paid to the entrance of the harbor. In another project, for the study of the evolution of the Baai Van Heist, detailed Delft3D-modelling was done (Janssens et al, 2009).

MUMM did calculations with the OPTOS-BCZ model (the fine grid 2D sand transport model, including tidal forcing, but without waves) for the Marebasse project (Van Lancker et al, 2007). In the model results, it is visible that there is net transport from the harbor entrance to the Baai Van Heist and also the ebb-dominated (both for currents and sediment transport) Appelzak gully is visible (the grid has about 5 to 8 cells in the gully). However, outside the Appelzak gully, the net transport of water is to the West, while the net sand transport is to the East. The residual sediment transport in Baai van Heist is to the west. The westward oriented residual current is strong, but the transport quantity seems to be low (white color in Figure 4-5, while at Baai van Heist a lot of sand input occurs) . In the Paardenmarkt area, both the residual currents and sediment transport happen eastward. Here, the transport amounts are higher, which is in agreement with the long-term morphological evolution (i.e. landward and eastward shift of Paardenmarkt shoal).

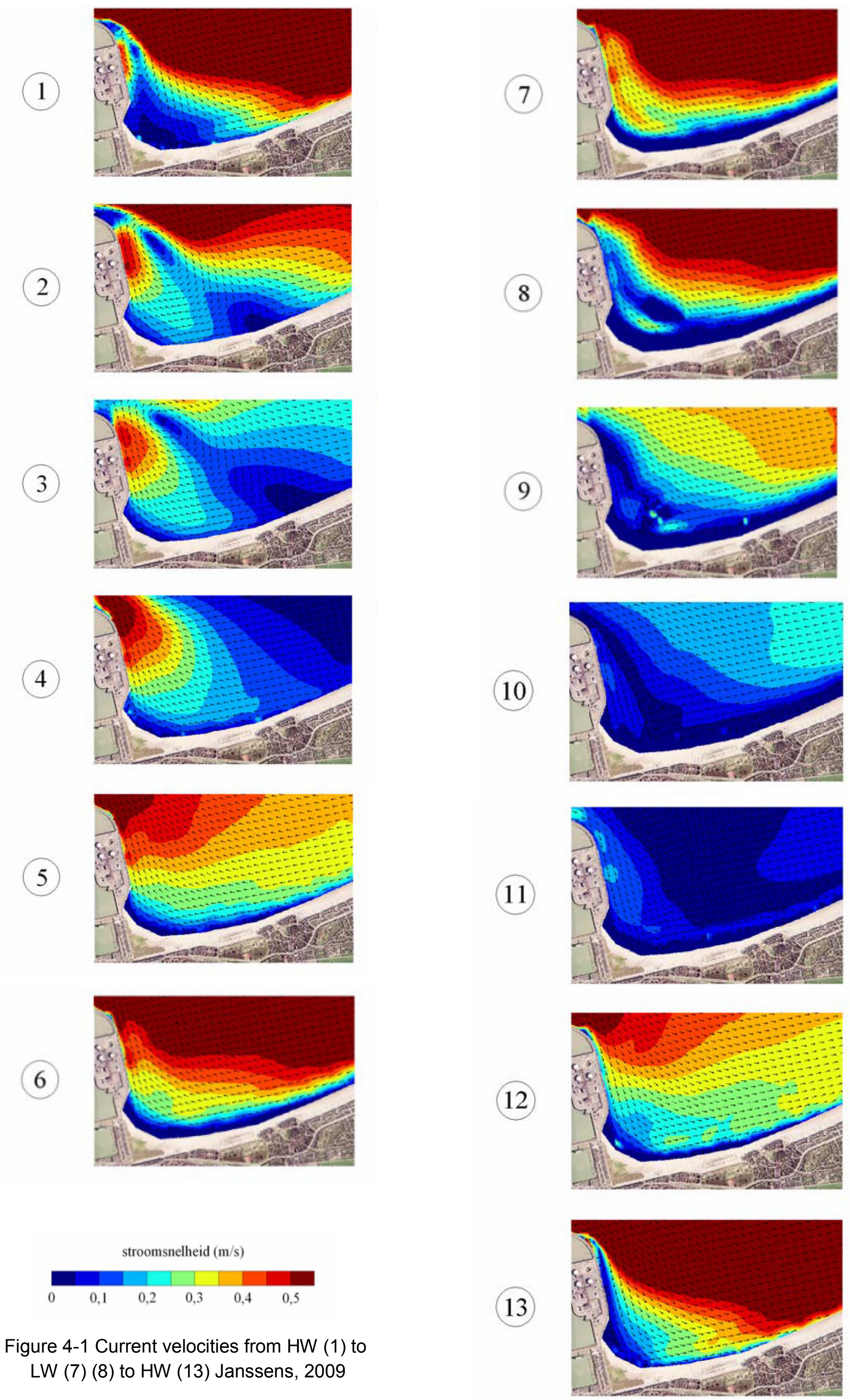


Figure 4-1 Current velocities from HW (1) to LW (7) (8) to HW (13) Janssens, 2009

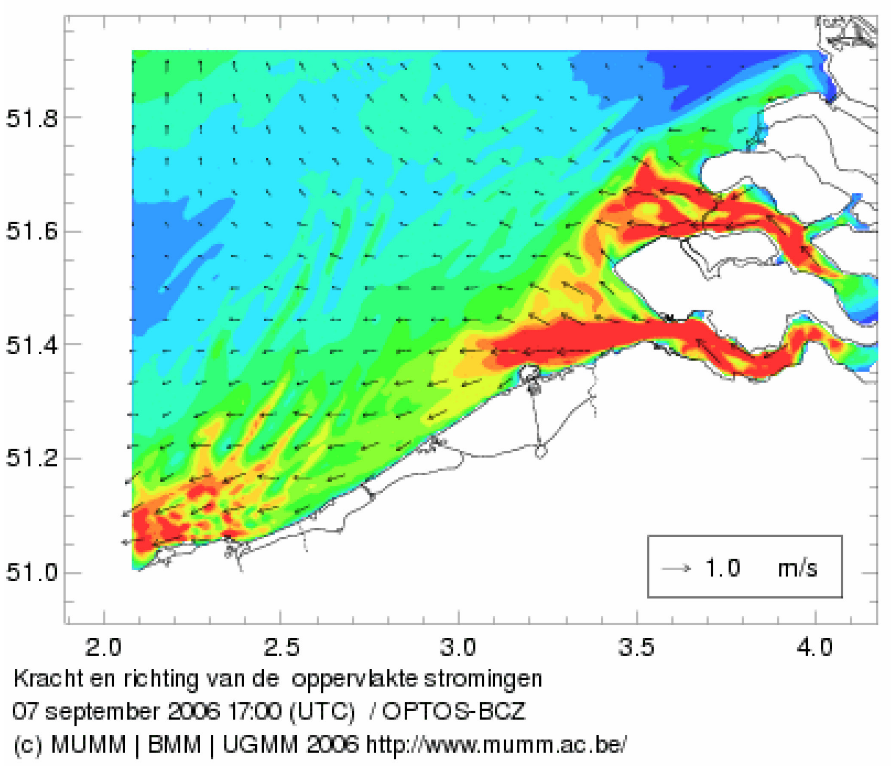


Figure 4-2 Velocity and direction of surface currents during ebb (MUMM – OPTOS-BCZ) (Van Lancker et al, 2007)

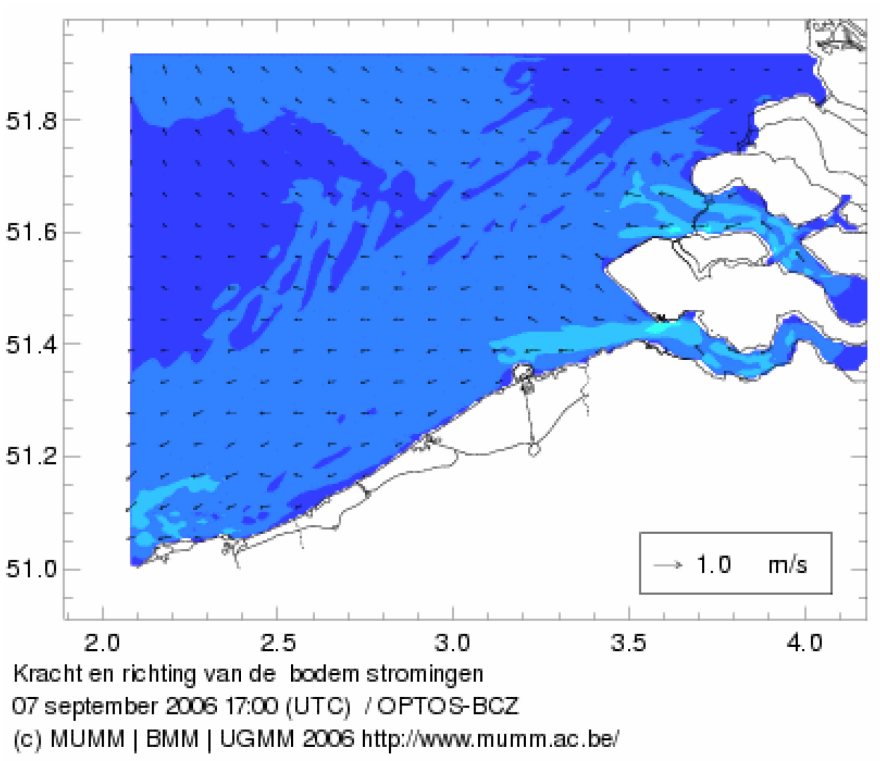


Figure 4-3 Velocity and direction of bottom currents during ebb (MUMM – OPTOS-BCZ) (Van Lancker et al, 2007)

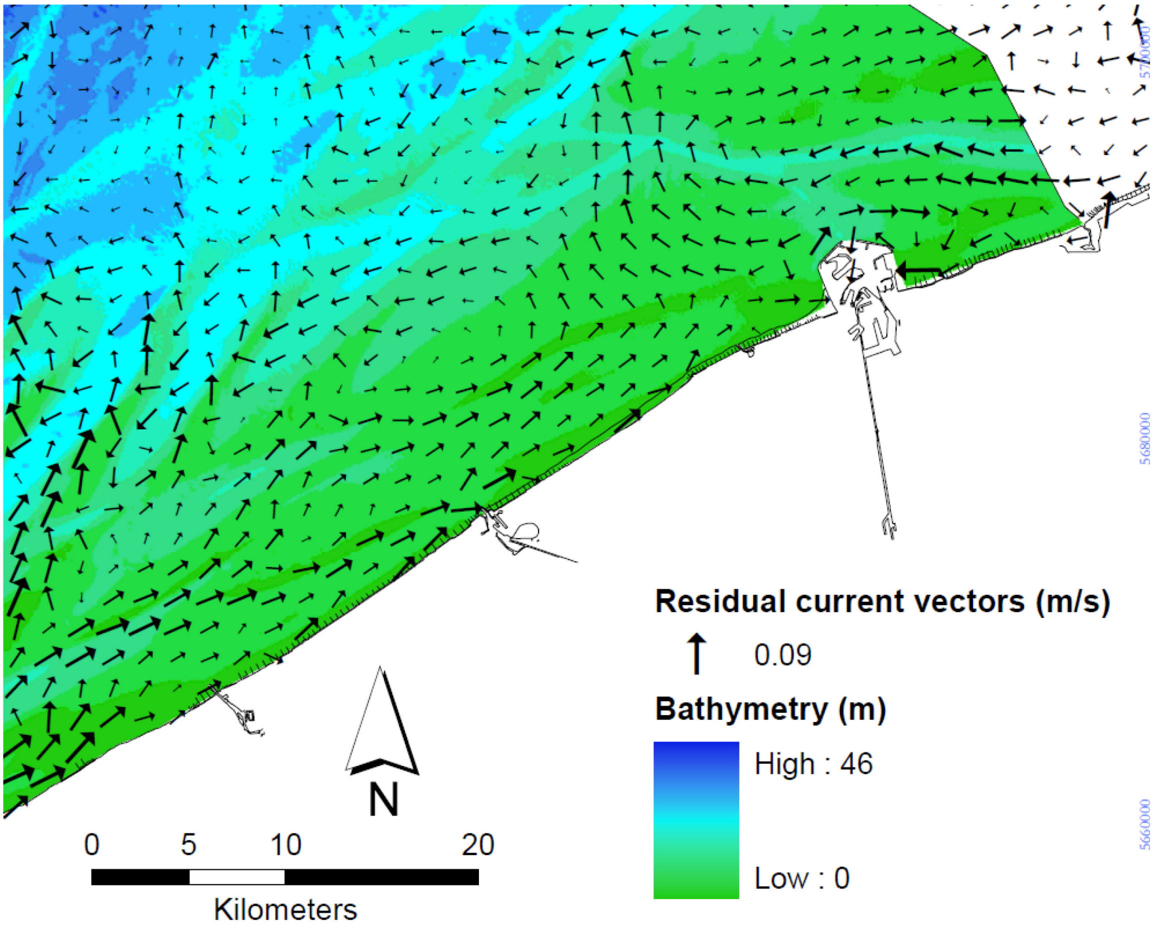
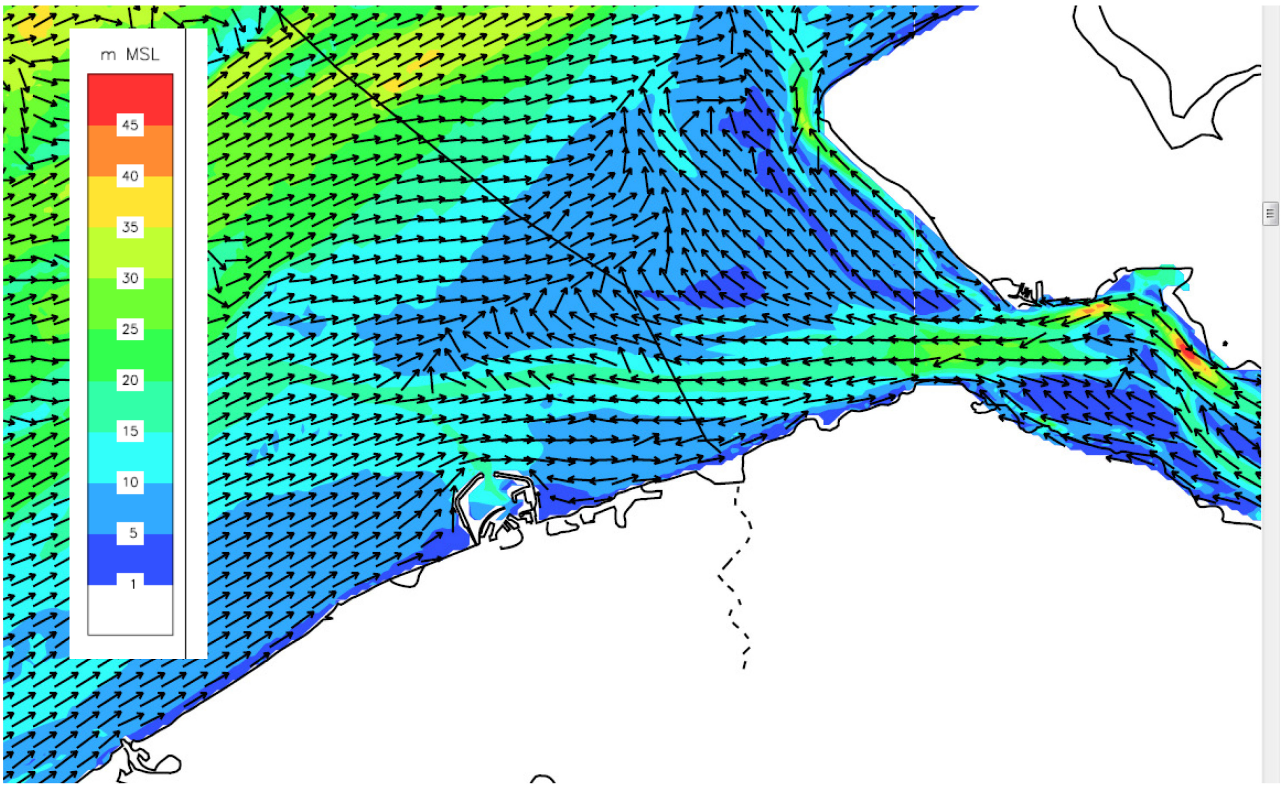


Figure 4-4 Residual currents (Van Lancker et al, 2007)



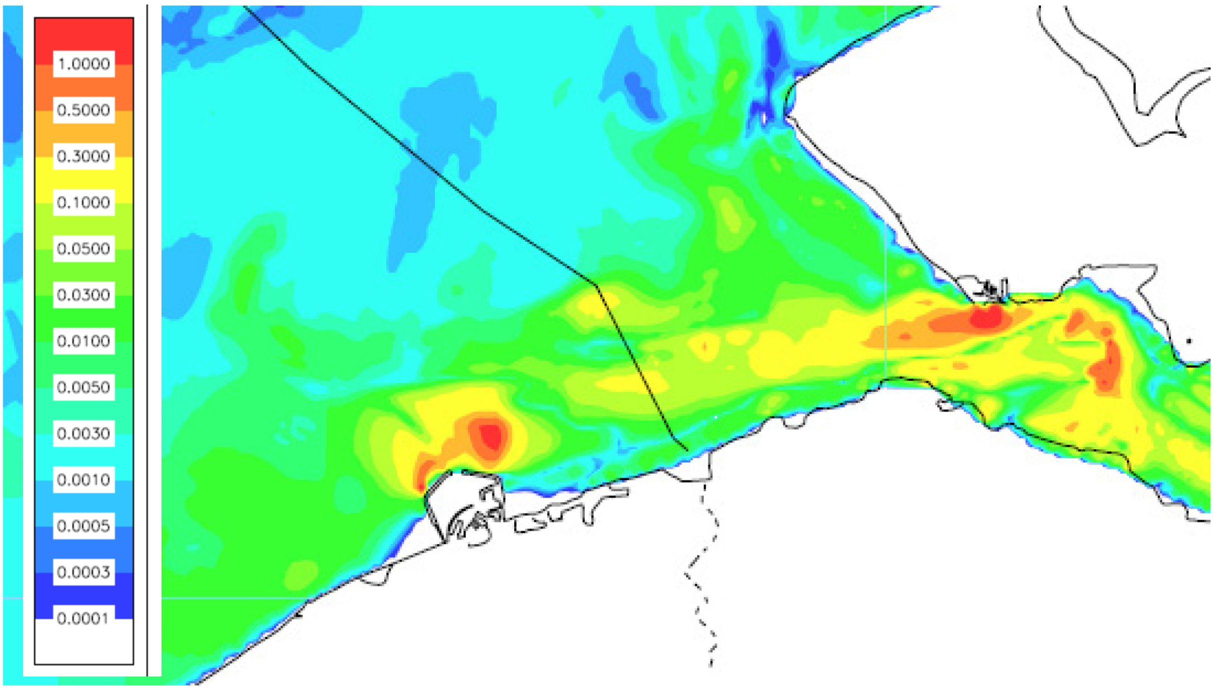


Figure 4-5 Residual sand transport direction (above) and magnitude (kg/m²s) of residual sand transport (below). The sand transport has been simulated over 14 days using the fine grid 2D sand transport model, including tidal forcing, but without waves. (Van Lancker et al, 2007)

Van den Eynde et al. (2006) describes the modelling of the morphological evolution of the Baai van Heist.

The numerical model had following characteristics:

- No waves
- Coherens model (version of 1999) (precede or equal to the OPTOS-BCZ model)
- Original: Grid size nested model : 250x250 – 10 vertical layers, specific for project location:: 50x50m
- Boundary conditions Q1, O1, P1, K1, N2, M2, S2, K2 + wind velocities
- Wetting and drying scheme
- Bathymetry: 2005
- Time step: 1s
- MU-SEDIM and MU-STM (resp. sand and mud transport model)
- MU-SEDIM: Ackers-White (1973) (not corrected): problems for fine sediment/strong currents ->for this reason the MU-STM was used instead of MU-SEDIM.
- D50=110µm
- MU-STM: mud model (using advection diffusion, with source and sink terms with critical shear stresses for resp. erosion and deposition, but not including bedload transport.
- Diffusion constants for the sedi-model 10m²/s
- Erosion rate M=0.00012kg/m²/s
- Critical bottom shear stress for deposition: 0.5 Pa
- Critical bottom shear stress for erosion: 0.5 – 0.8 Pa, depending on consolidation

Figure 4-6 and Figure 4-7 show some typical current patterns (resp. residual over neap-spring cycle and max velocity at HW. The authors mention that the measured velocities at their measuring station (3km offshore, just east of the harbor moles) give higher velocities than modelled. However, it is indicated that in this area velocities are very sensitive to the exact location and the local bathymetry.

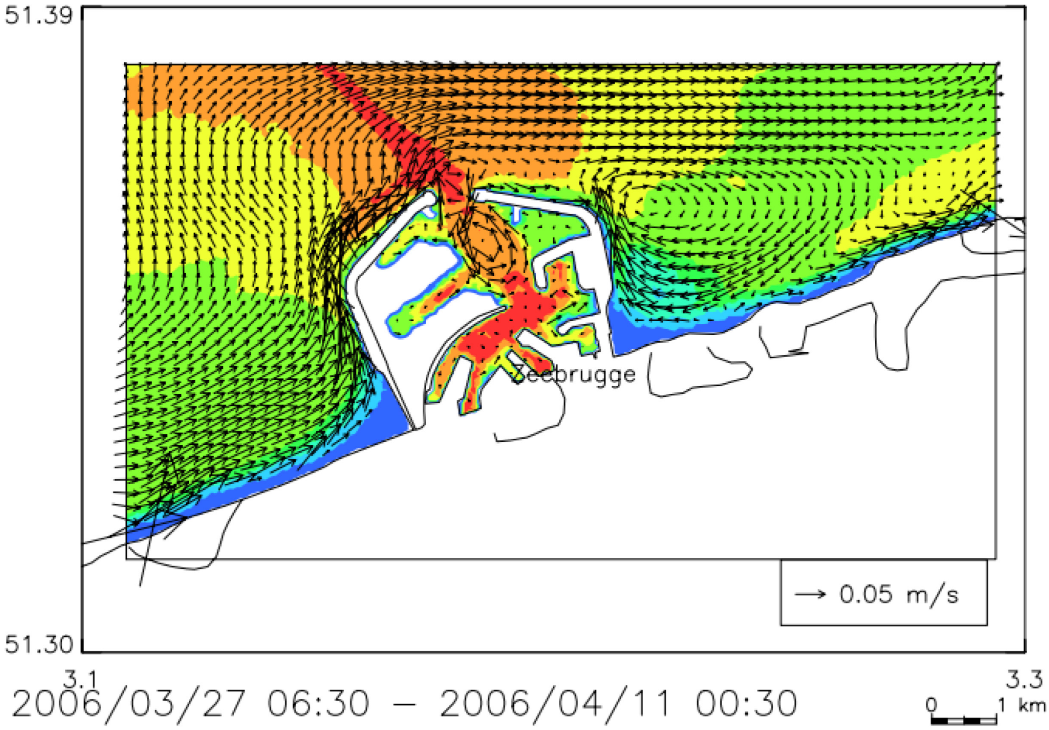


Figure 4-6 Residual current for a neap-spring tide
(Van den Eynde et al. (2006))

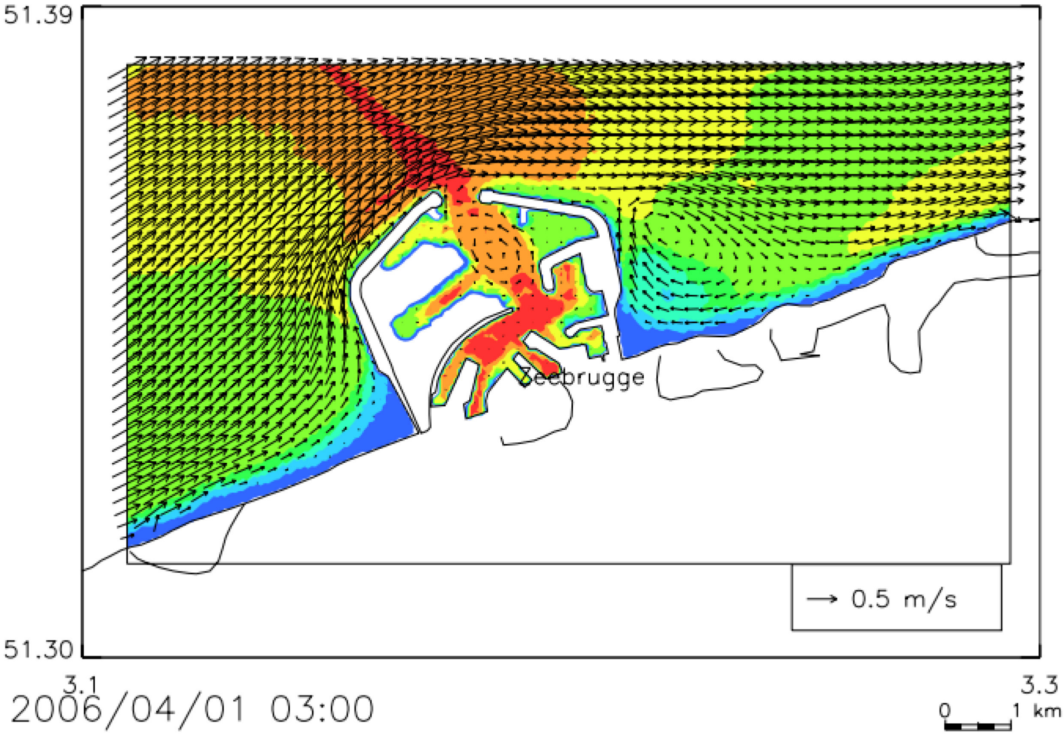


Figure 4-7 Depth averaged current at HW
(Van den Eynde et al. (2006))

Figure 4-8 and Figure 4-9 show the erosion/sedimentation pattern for a typical spring tide. The settling velocity is chosen resp. 1cm/s (=settling velocity of sand with d50 of 0.1mm) and 0.01cm/s. Although the very low settling velocity, the results with the finest material predict the sedimentation at the crest of Baai van Heist in the best way, due to the fact that more sediment remain in suspension during the tidal cycle. Thus, when the shear stress is low, more sediment can settle. The unrealistic low settling velocity might be a compensation for the absence of waves (and thus the shear stress and turbulence is underestimated).

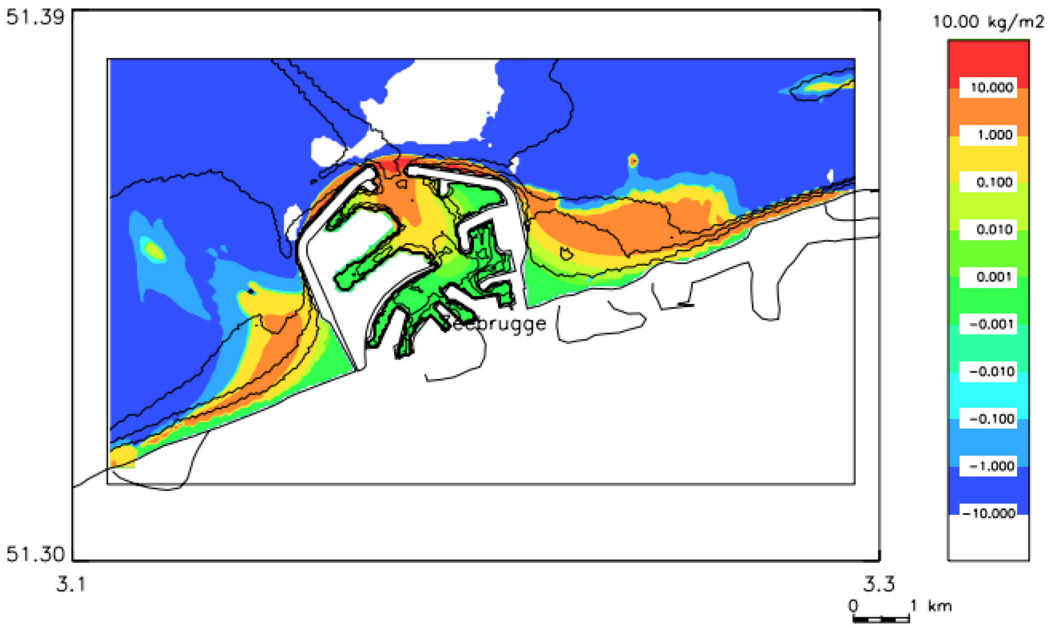


Figure 4-8 Erosion/sedimentation during the spring tide of 18/04/2006, with a settling velocity of 1cm/s (Van den Eynde et al. (2006))

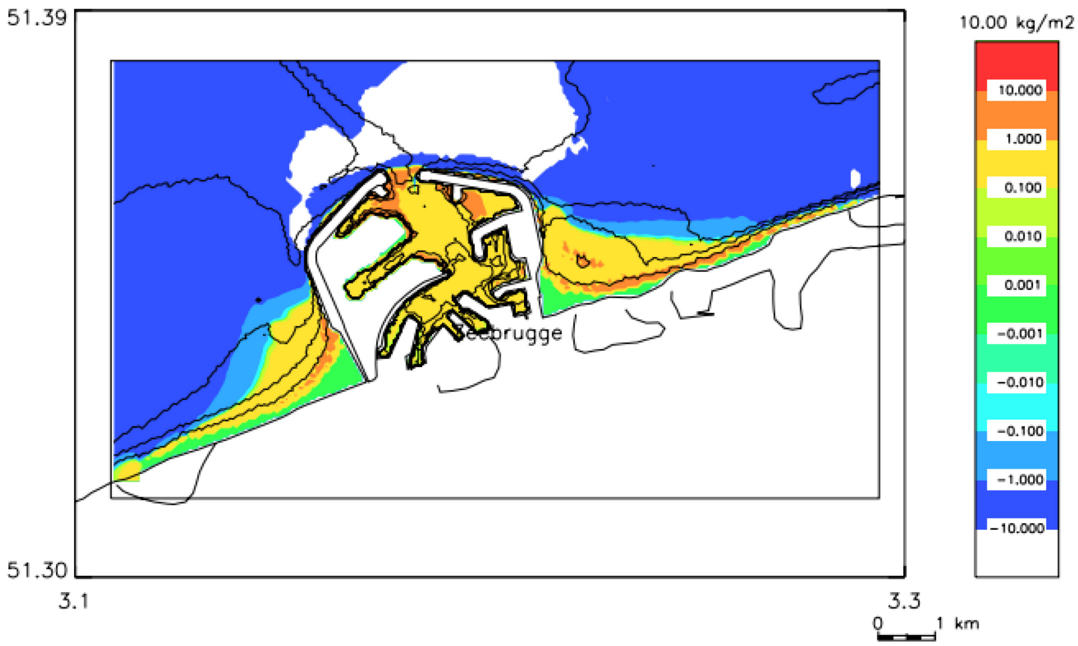


Figure 4-9 Erosion/sedimentation during the spring tide of 18/04/2006, with a settling velocity of 0.01cm/s (Van den Eynde et al. (2006))

Svasek (2012) reports, based on applying the CERC-formulae on the modelled wave climate a net sediment transport of 200.000m³/year eastward (gross: 400.000 E, 200.000W) near Cadzand. They also applied their Finel model (waves + currents). Results are shown below. They are only partially representing the morphological evolution.

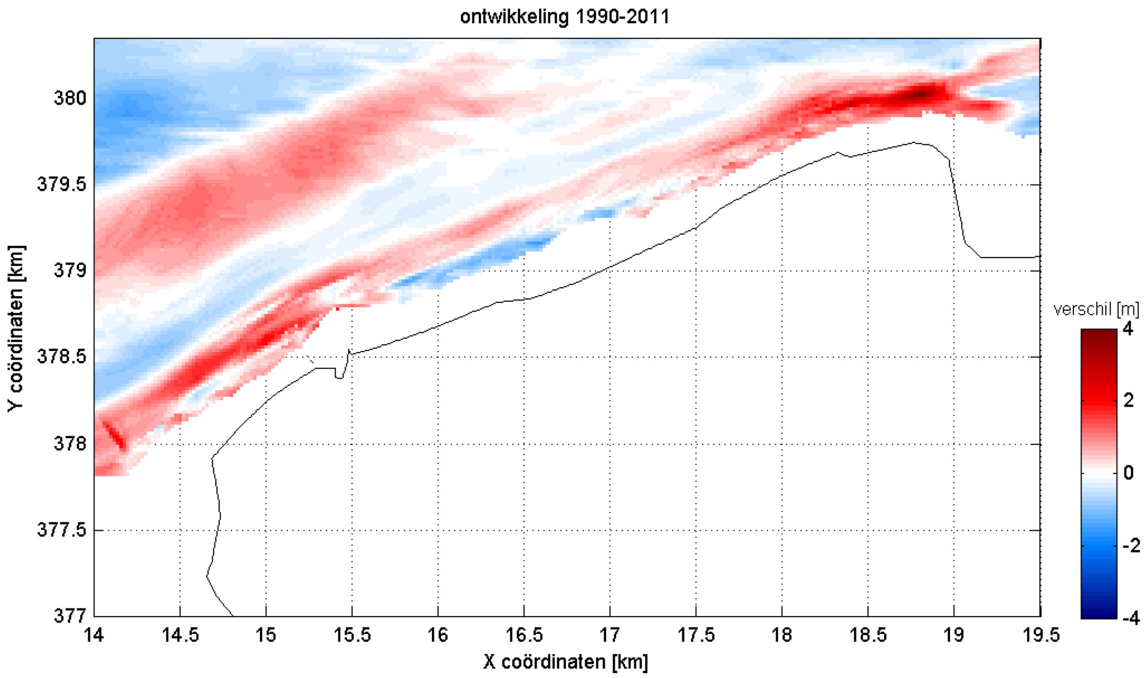


Figure 4-10 Measured morphological evolution between Zwin and Zwarte Polder between 1990 and 2011 (Svasek, 2012) (red: sedimentation, blue: erosion)

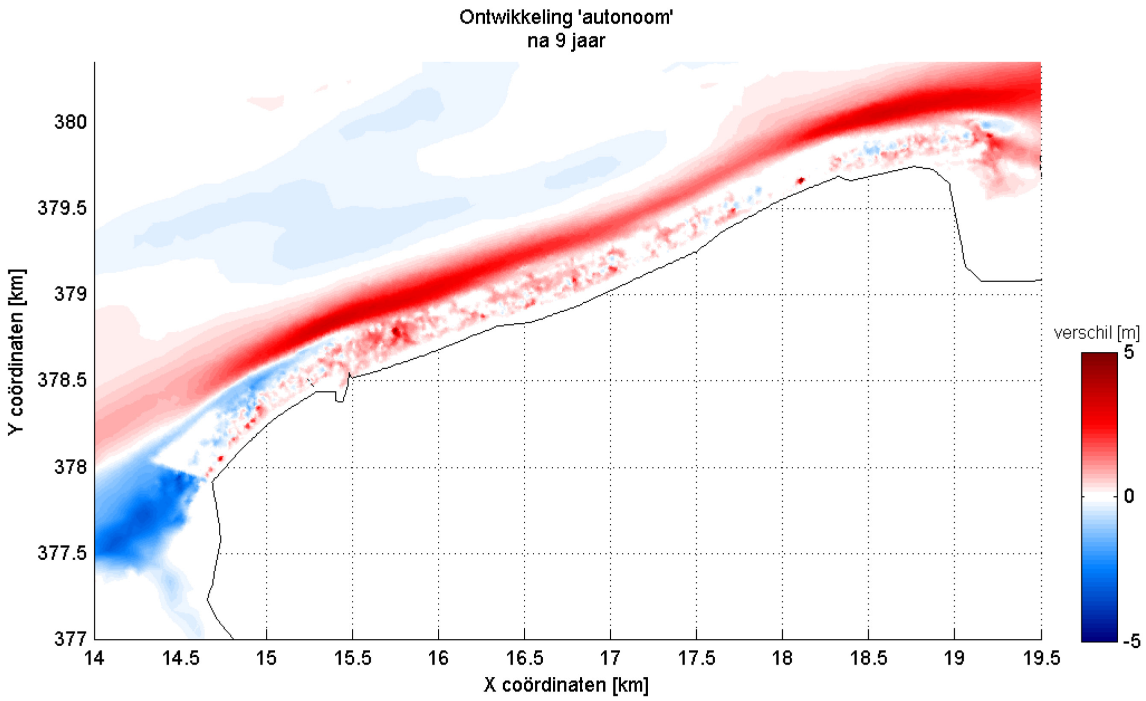


Figure 4-11 Modelled (Finel) morphological evolution between Zwin and Zwarte Polder between 1990 and 2011 (Svasek, 2012) (red: sedimentation, blue: erosion)

4.2 Measurements

In 1990, 1991 and 1993 detailed velocity and sediment concentration measurements near Knokke (Baai Van Heist) and the Zwin were performed by Eurosense (1991a,b and c, 1994 a and b). Data are reported (in tables and figures) both for calm and storm weather conditions. The following conclusions were drawn:

- Velocities increase strongly with distance from the shore line
- At all locations, the flow was flood dominated, the closer to the coast, the more the tide is asymmetrical (flood dominated)
- Sediment concentration is related to the velocity, with a time lag of 0.5 – 1 hour
- The peaks in concentration are short (less than 1 hour)
- During calm weather conditions, near flow reversal all sediment is settled.
- The sediments in suspension (from 0.25m to 1.5m above the bottom) consist for roughly 33% of sand (cf. Figure 4-13 to Figure 4-15)
- During storm conditions the sediment concentration increases significantly, especially during ebb, as shown in Figure 4-15.

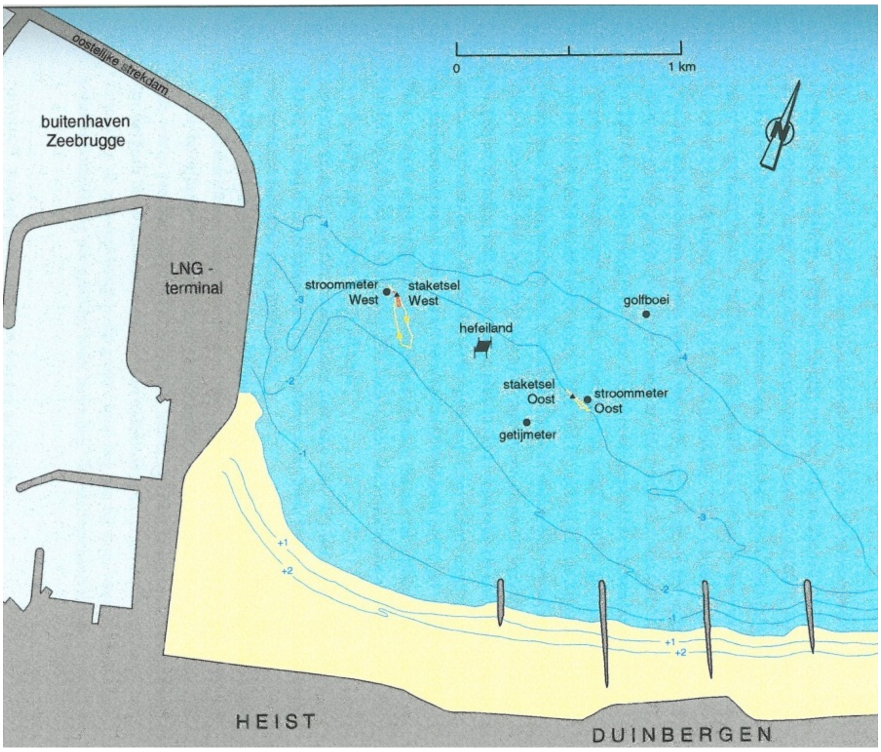


Figure 4-12 Measuring locations (Eurosense, 1991 and 1994)

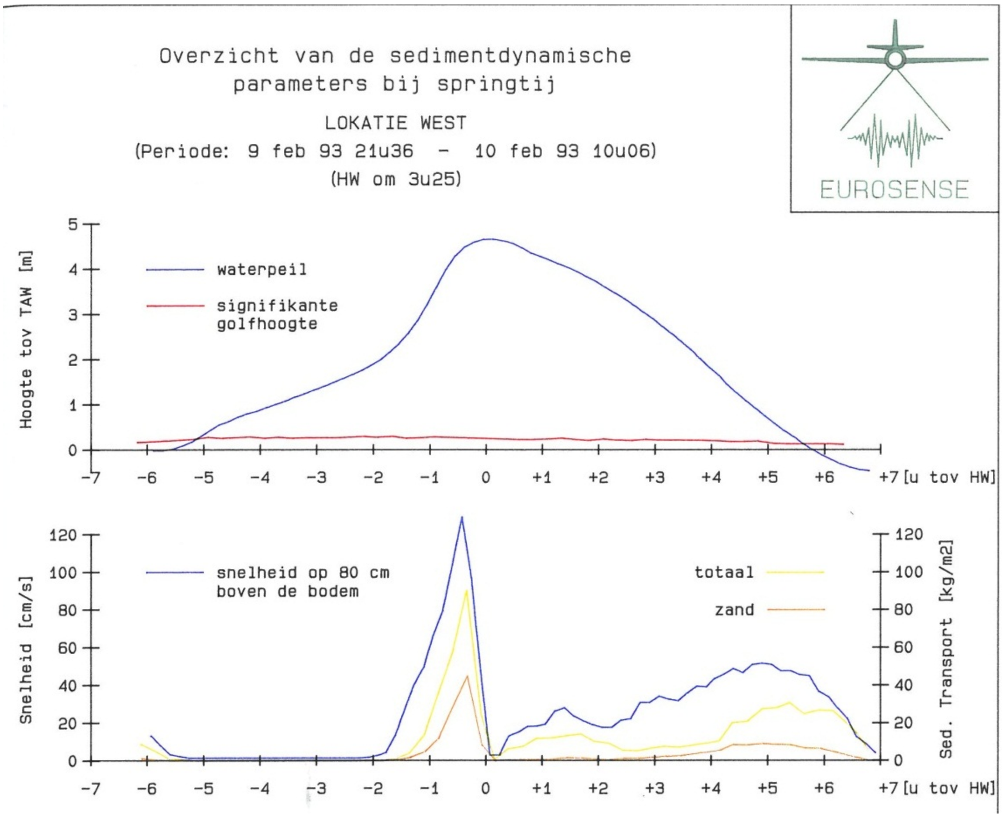


Figure 4-13 Currents and sediment transport during spring tide at location West (Eurosense, 1991 and 1994)

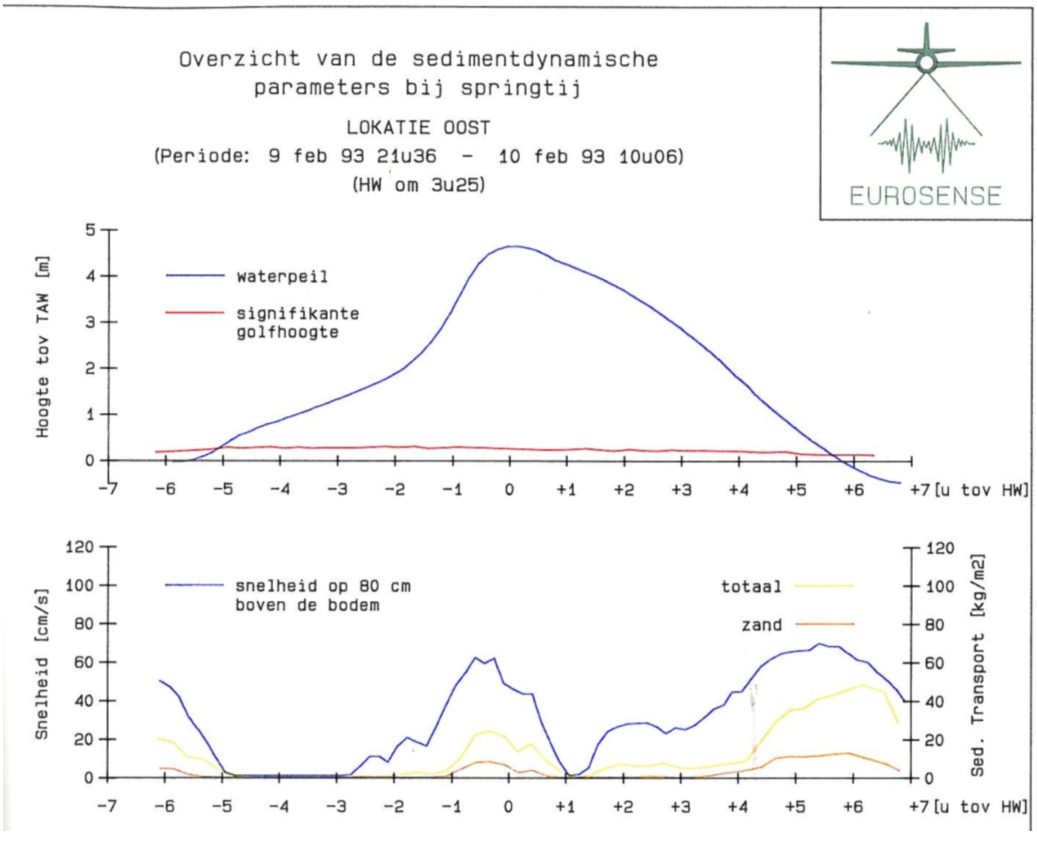


Figure 4-14 Currents and sediment transport during spring tide at location Oost (east) (Eurosense, 1991 and 1994)

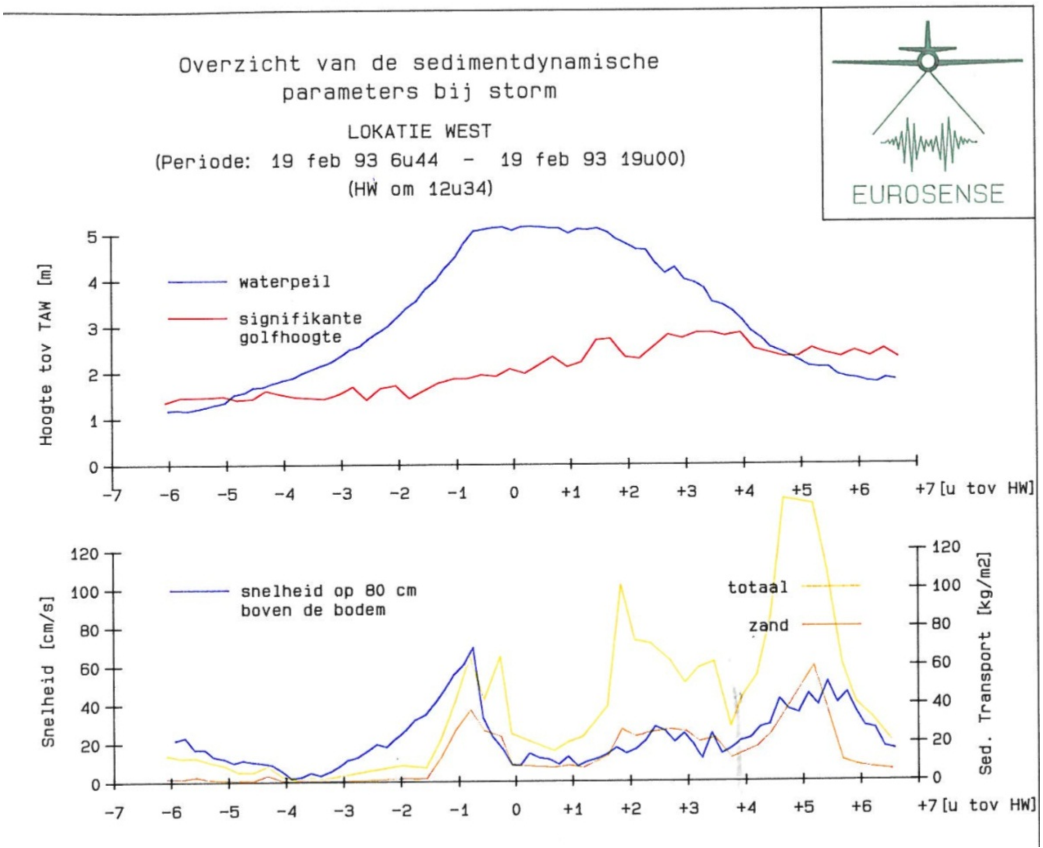


Figure 4-15 Currents and sediment transport during a storm location West
(Eurosense, 1991 and 1994)

Based on these measurements and on a numerical model of the velocities (KULeuven, Yu, 1993) a sediment balance (calculation of the net input/output in the area of Baai van Heist) was made for a normal tide on 13 February 1993 and for the storm of 19 February 1993. During a normal tide during calm weather about 800 ton of sediment (probably 300 ton sand, 500 ton fines) sedimented in the (large) zone of Baai van Heist. During the storm, sediment left the area, probably because the storm was much stronger during the ebb phase. Extrapolation of the normal tide sediment input to a full year gives a total sedimentation of 340.000m³.

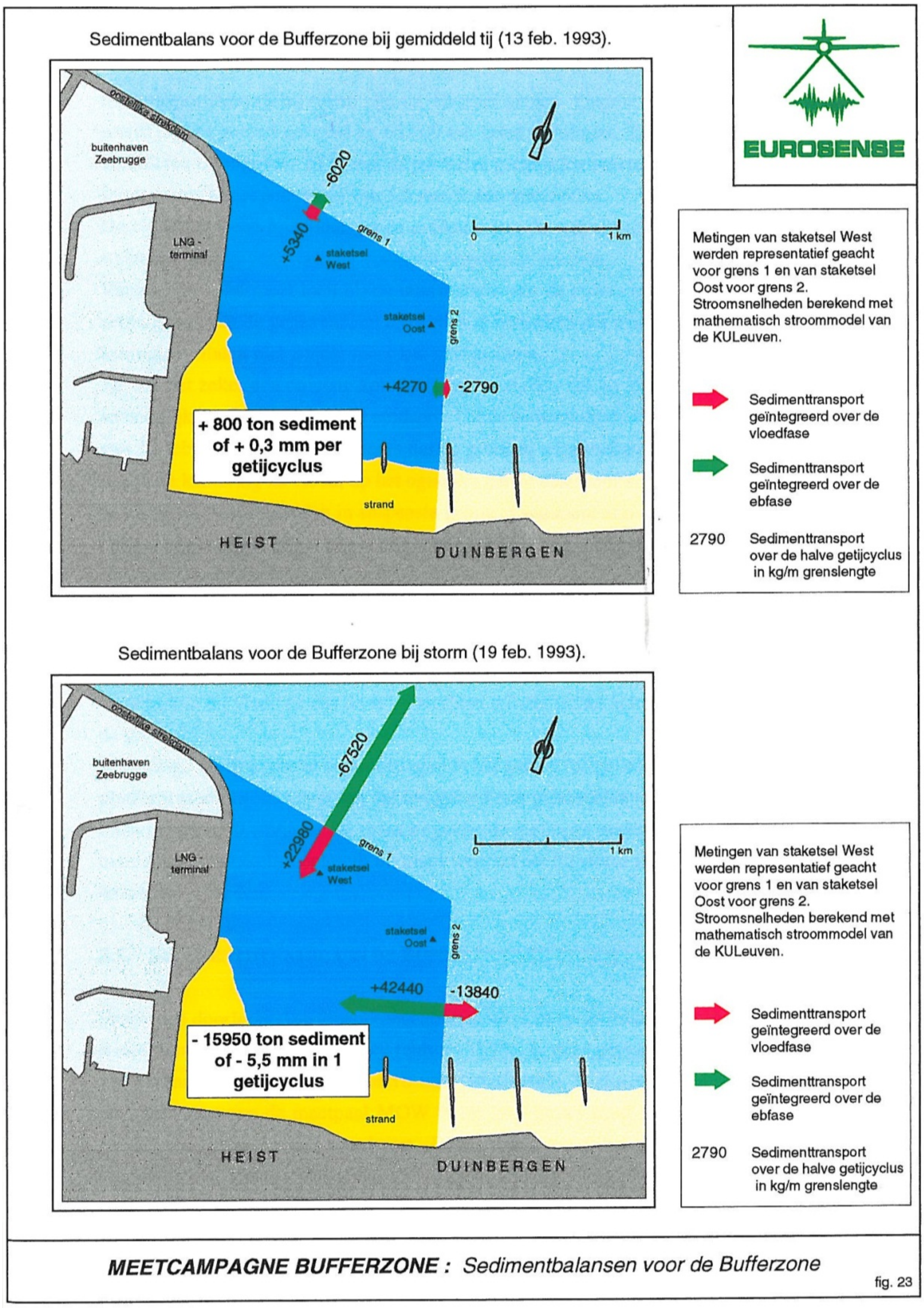


Figure 4-16 Sediment balance for a normal tide without storm (above) and a storm (below) (Eurosense, 1991 and 1994)

Comparable measurements have been carried out at the eastern boundary of the Appelzak gully (in front of the Zwin)(Eurosense, 1994), on the shoreface (at -3m TAW) (cf. Figure 4-17). Following interpretation of the test results can be made: During calm weather, the net transport was directed to the West (ebb dominated), but once the local wave height increased to values higher than 0.5 m, the net transport was to the East. The amount of sand in suspension is smaller than 10% of the total amount of sediment in suspension (for the lowest measurement point at 25 cm above the bottom). Sediment transport is estimated at 3000 kg/m during flood and 4000 kg/m during ebb (of which resp. 240kg/m and 260kg/m sand) for conditions with wave heights smaller than 0.5m. (longshore transport over a unit length in cross shore direction). For the other conditions (much influenced by the waves this is 6000kg/m during flood and 5000kg/m during ebb (of which resp. 1000 and 500kg/m sand) (sand is the fraction with grain sizes >63µm). It is remarkable that the percentage of sand is smaller than at Baai van Heist. It should also be noted, that if the figures are extrapolated to a full year (assuming that the 13 measured tides are representative), the transport of sand amounts (over a cross shore length of 1000m (using for simplicity the very rough assumption of a uniform distribution of transport over the cross shore) to about 280.000m³/year to the East and 160.000m³ to the West. These values are of the order of magnitude of the expected longshore transport. This indicates that even in the nearshore zone the transport of cohesive material is considerable. During other measurements (project SCHERMEN) the sand fraction was “less than 50%” at 50cm above the bottom and 30 to 90% in water pumped near the bottom.

Figure 4-17 Measurement location

4.3 Analysis

In the Budget-project (Lanckneus et al, 2001) an analysis is made of the sediment transport direction and magnitude. The results are summarized in the map below.

Figure 4-18 Synthesis map of sediment dynamics (from the BUDGET-project (Lanckneus et al, 2001))

Figure 4-18 indicates that 0.05m^3/m/day of sand is transported as bedload from the North towards Baai van Heist (based on measurements)

The suspended transport (mud ?) in front of Knokke is flood dominated (based on measurements)

The Mobag, 2000 report (Magelas, 2001) mentions that about 4 million m^3 sediment per year is dumped at B&W Zeebrugge Oost (near Paardenmarkt). It consists for more than 50% of mud (sediment smaller than 63µm), however, a fraction of fine sand (up to 250 micron) is also present. At the dumping site, the median grain size varies between 50 micron in the western control points and 400 micron in the northern control points.

In the report is also indicated that based on measurements of currents and sediment concentrations at 4 locations during a spring-neap tide cycle near the dumping zone B&W Zeebrugge Oost, a residual sediment transport (in suspension) of the order of magnitude of 10 ton/m/day in NE direction occurs.

5 Sediments

Sediments are very heterogeneous. They vary from mud, to silt (e.g. erosive zone around Zeebrugge and Baai van Heist, where also samples of coarser sand are observed) to very coarse sand due to beach nourishments with d50>300mu. Figure 5-1 and Figure 5-2 give an overview of available data. Van Lancker (pers. comm.) indicates that at many locations the sea bottom is covered with a thin layer of sand above a clay layer. The presence of silt/mud on the bottom will also depend on the hydrodynamic conditions (tide, waves).

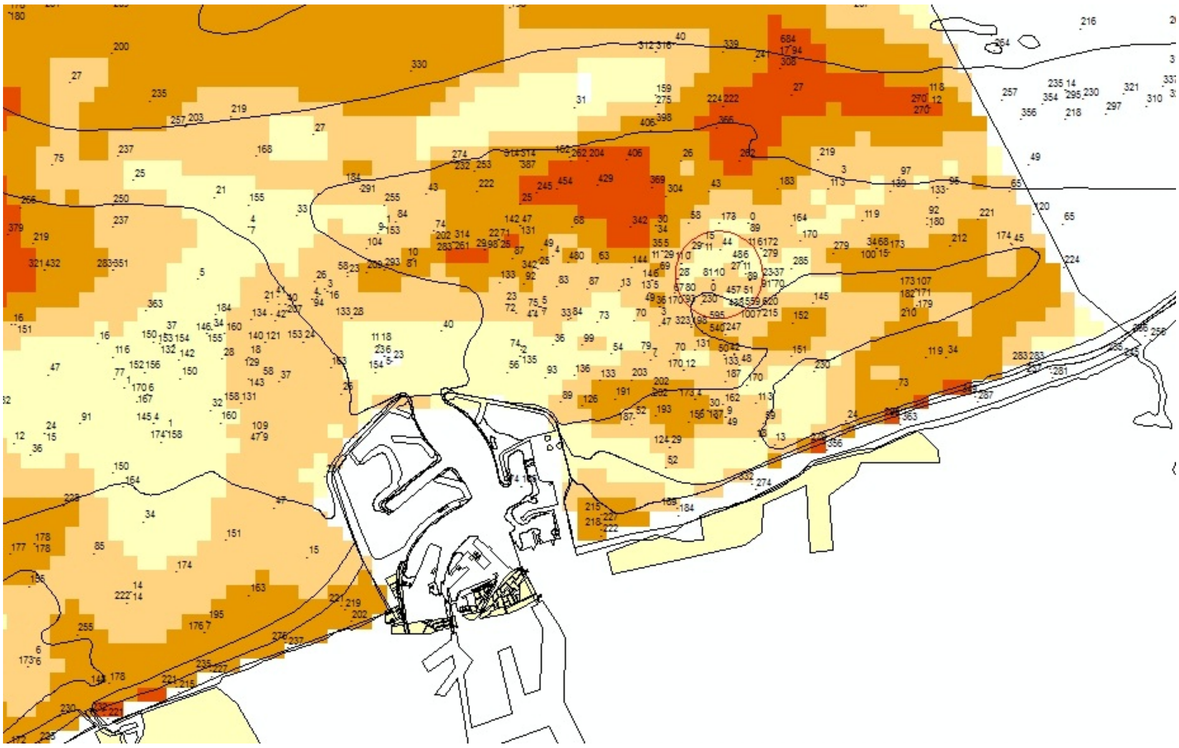


Figure 5-1 Grain sizes near Zeebrugge
(Van Lancker (pers. comm.) – Quest4D-project)

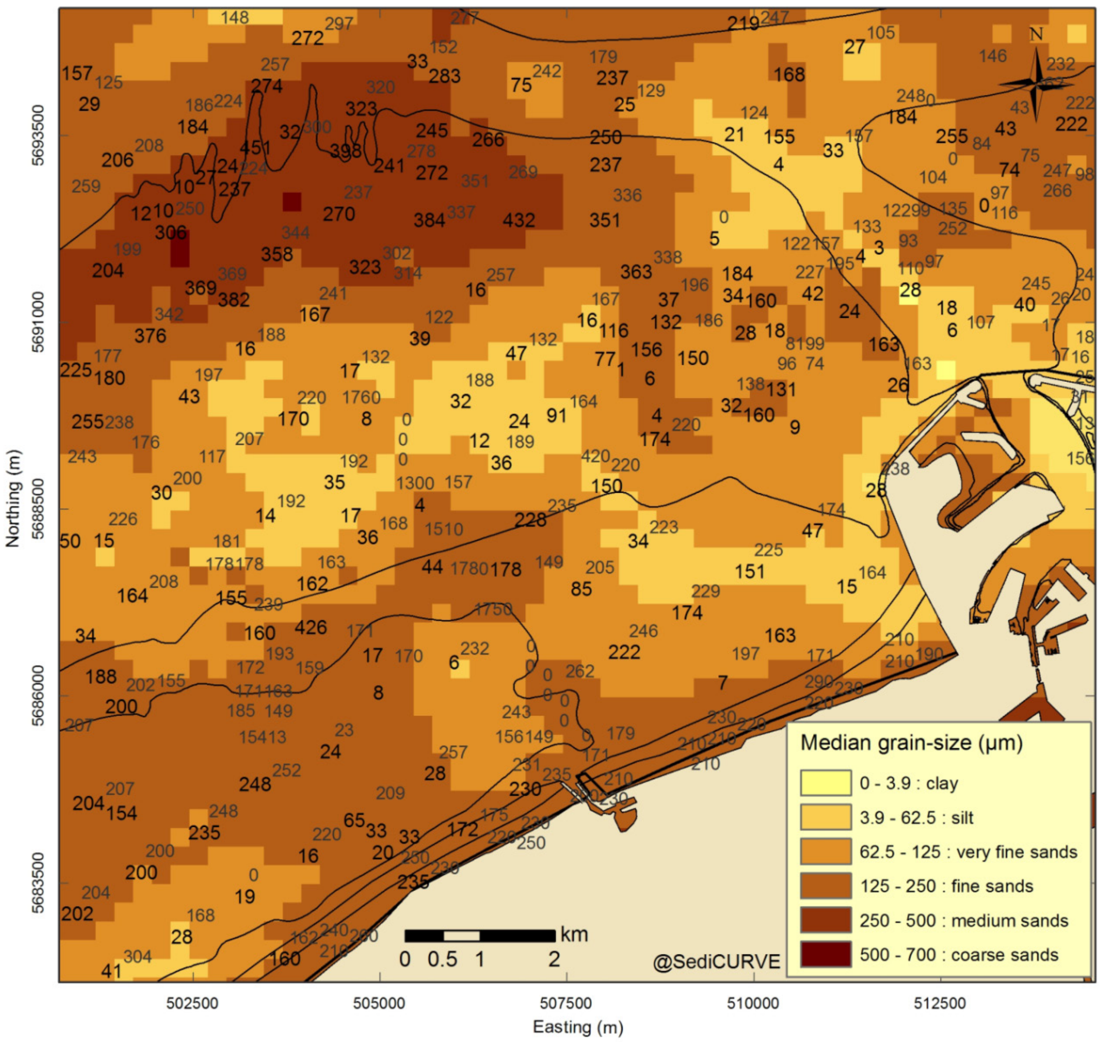


Figure 5-2 D_{50} bed sediment grain size map (Du Four et al., 2006) with superposition of number values in µm from sediSURF@SEA (gray, Van Lancker et al., 2007) and sediCURVE@SEA (black, Van Lancker et al., 2009).

MUMM uses a grain size of 110mu in their sand transport models of this area (pers. comm.). MUMM also analysed some extra samples at Baai van Heist (Figure 5-3).

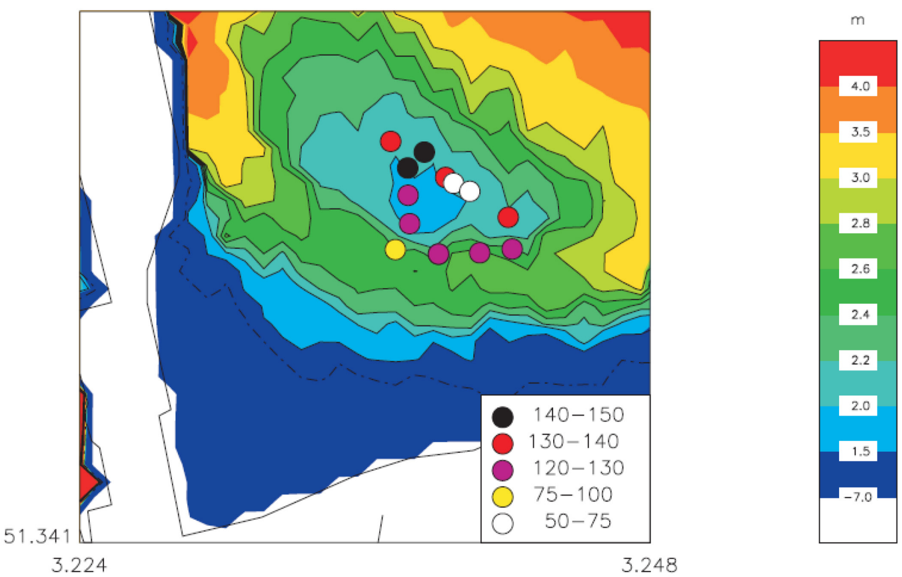


Figure 5-3 Sediment samples from MUMM (Van den Eynde et al, 2006)

Comparing Figure 5-1 with Figure 6-17 indicates that the erosion around Zeebrugge occurs in an area covered with very fine sand (West part)/silt (east part). It is remarkable that the erosion does not cause coarsening of the sediments. But it should be remarked that the density of the measuring points is limited. The maps only give the median grain size. In general, the area is characterised as “sandy silt (25%<sand<80%; d50=25-170µm” (Charlet, 2001). Van den Eynde et al (2006) describes that on top of the bank, sand with only a small amount of mud (<10%) is found (cf. Figure 5-3) but they mention that also mud is observed at the northern flank of the Bank van Heist. Also the transport of sediments entering the area is described (based on measurements of MUMM) as a mixture of mud and sand transport. The detailed measurements described in chapter 4.2 indicate that at a height of 80cm above the bottom about 33% of the sediment consists of sand.

Figure 5-4 shows the percentage of material finer than 63 µm in the bottom sediments.(not representative for the beaches).

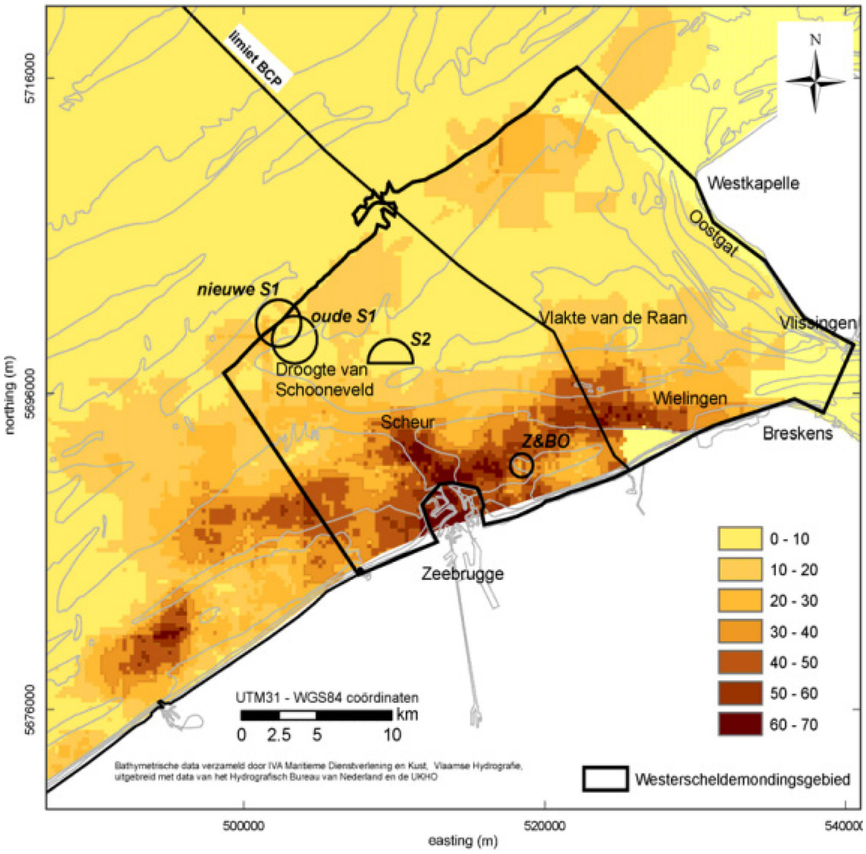


Figure 5-4 Occurrence of material finer than 63 µm in the bottom sediments (in %) (Van Lancker, 2007)

De Ronde (2007) analysed in detail the beach sediment characteristics (Figure 5-5). The nourishments in Knokke are with coarse sand (0.35mm).

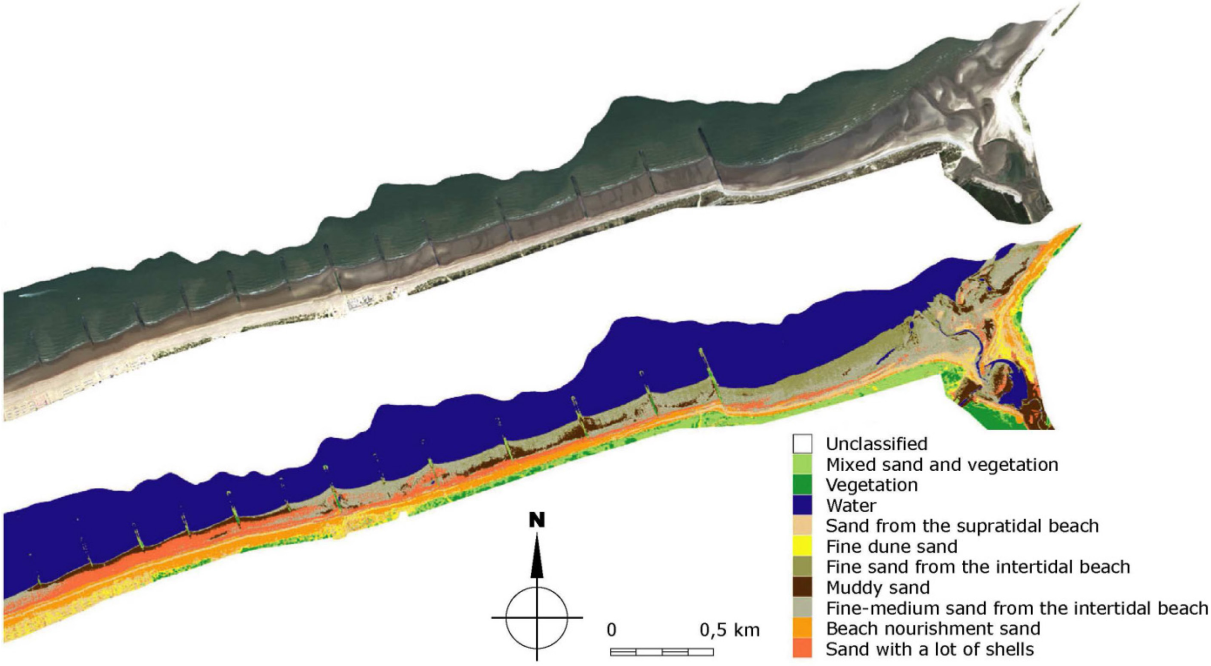


Figure 5-5 Classification of the shoreline in Knokke-Heist. 7 sand type classes could be distinguished, applying a Linear Discriminant Classifier and feature selection on wavelet transformed bands.

The results show a lot of variation, which are not necessarily due to spatial differences, but maybe also due to temporal differences (e.g. different values if measured after a storm or after a long period of calm weather). It is strongly recommended to have more detailed results, measuring at least up to a depth of half a meter below the seabed.

6 Morphological evolution of the coastal zone

6.1 Beach and shoreface

6.1.1 Long term morphological trend

To investigate the morphological evolution of the coastal zone, following information is available:

- Houthuys (2012): describes the evolution of the beach (dunes, dry and wet beach) and the shoreface/sea bottom (up to1500m offshore the dikes) since resp. 1979 - 1986 including the influence of human intervention (nourishments, dumping of dredged material, sand extraction), based on the yearly bathymetrical and topographical surveys
- Eurosense (1998): averaged profiles for coastal zones (cluster of ±5 sections, longshore length of ±1000m) : from 1954 till 1979, only data below LW (more recent profiles available, but not used)
- Janssens et al. (2013): trend analysis between 1997 and 2010 (used for the offshore part)

In this chapter the evolution of the coastal zone around Zeebrugge is investigated , including the zone West of Zeebrugge. Since there exists clear evidence that the sediment transport in the coastal zone (first 1500m) is dominated by the wave-driven longshore transport (e.g. ratio of 4:1 of eastward to westward transport is obtained from numerical modeling in Blankenberge, Wang et. al, 2012), the ratio of sedimentation West of Zeebrugge to the sedimentation East of Zeebrugge can give indications of the sediment input into the eastern zone, coming from offshore along the eastern harbor mole of Zeebrugge.

The sediment budget is analysed in coastal units (=cluster of cells) (cf. Figure 6-1) as used in Eurosense (1998). 6 measurements are used: 1954 – 1966 – 1976 – 1986 – 1997 – 2010. The first 4 are based on (limited) availability of data, 1997 – 2010 are in correspondence with the time period used by Janssens et al (2013), for these 2 years digital data exists, for 1986 a digital DTM is drafted up by digitization of existing bathymetrical and topographical charts. Up to 1986 no tabled/complete information is available about human interference. Probably (cfr. history in chapter 3), this interference is small, except for the large beach nourishment of the East Coast during the construction of the new harbor of Zeebrugge. Measurements from the beach (above LW) are only available from 1979 on (although measurements before 1979 have been done by the University of Ghent, but they are not available).

Figure 6-1 Definition of coastal units

Appendix 1 summarises the available information. Graphical output and conclusions are presented below.

An indication of the errors on the reported values is given in Table 6-1 (for the measurements since 1979).

It should be kept in mind that for all considered periods harbor moles were present, but that they were extended in the period 1979-1986.

In Figure 6-2 the cumulative erosion and sedimentation, corrected for nourishments, east and west of Zeebrugge are presented for the period 1986-1997 and 1997-2010 (so the erosion at a given distance is the total erosion between the harbor and this point). The cumulative volume change at a distance x is calculated by integration of all volume changes between the harbor mole and x m more to the East/West, over a cross shore distance of 1500m (the coastal cells used for measurements). Error bars are rough estimates based on a vertical measuring accuracy of 25cm before 1986 and 10cm after 1986. The figure indicates that in the first 10 years after the lengthening of the harbor moles, severe erosion occurred between x=4000 (where the blue line starts to decrease, i.e. erosion starts) and x=8000m (i.e. from Knokke-Zoute to Lekkerbek). Between 1997 and 2010 some stabilization occurred (partly because the beach volume in 1997 was exceptional low; below the general trend), but also because of a clear change in trend, which is mainly visible in Lekkerbek, but also in front of Knokke-centrum (change in trend since 1992) (cf. Figure 6-9 and Figure 6-10).

Near the harbor moles no real change in trend is visible. It can also be concluded that if the whole area between Zeebrugge and the Zwin is taken into account, the area is rather stable, even slightly accretive, despite the interruption of the eastward longshore transport. At the Westside more sedimentation occurs, and only near Wenduine significant differences between the two decades can be seen, which might be a local phenomenon.. (The erosion in Wenduine is visible by the decrease of the curves between x=7000m and x=9000m, in the period 1997-2010 this is smaller, mainly due the erosion at the shoreface/sea bottom is disappeared (while the erosion at the beach increased, partly due to the effect of nourishments, which tend to erode faster).

In the last decade the total sedimentation West of Zeebrugge is about 300.000 m³/year, East of Zeebrugge about 200.000m³/year.

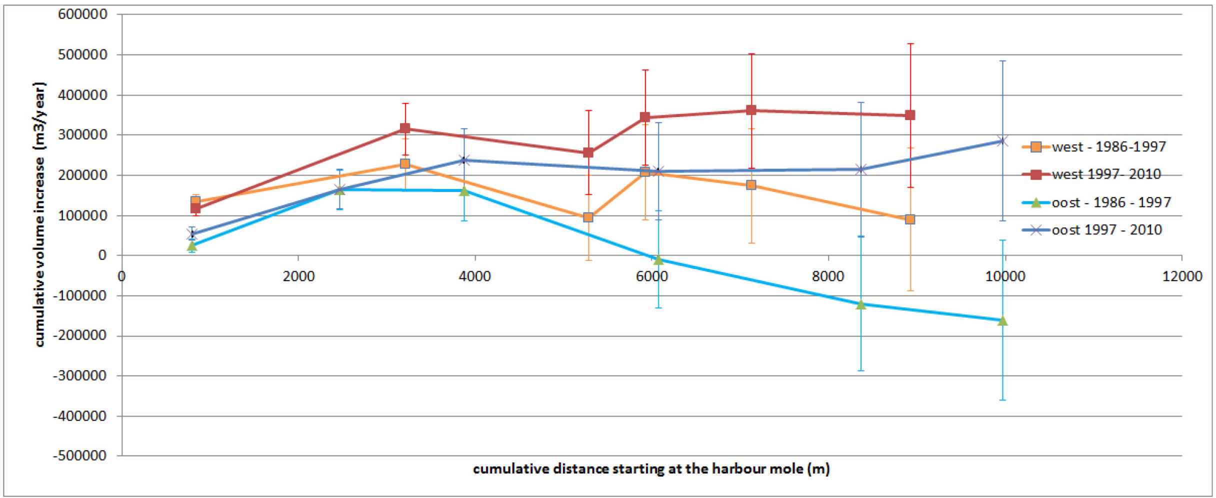


Figure 6-2 Cumulative yearly erosion (-) / sedimentation (+) East and West of Zeebrugge for the last 2 decades

It is obvious that in the first period after the construction a lot of erosion occurred (over the complete zone up to the Zwin), but in the second decade, the eastern zone accreted already (if the whole zone between Zeebrugge and Zwin is considered, erosion at Knokke-Zoute and Lekkerbek continues). Looking to the last period (1997-2010) the accretion rate at respectively the western and eastern side is comparable, despite the fact that the westward directed longshore sediment transport is quasi negligible compared to the eastward transport. This means that the 200.000 m³ sedimentation eastward of the harbor of Zeebrugge should come from offshore, assuming that near the Zwin, the eastward transport is comparable with the eastward transport near Blankenberge (and thus smaller than 100.000 m³/year) . Figure 4-5 indicates that most of the offshore transport is probably coming from near the erosion zone in front of the harbor of Zeebrugge In this area, the erosion trend is about 400.000 m³/year of which 150.000 m³/year settles offshore Baai van Heist (e.g. Figure 6-17). This is import of very fine sediments, contrary to the coarse sediments that would be imported by longshore transport in the absence of the harbor of Zeebrugge. So, although sedimentation occurs, the harbor has still an influence (on the grain size). Figure 6-3 shows that West of Zeebrugge the erosive behavior in the period 1954-1976 (before the start of the extension of the harbor) was changed to an accretional behavior afterwards (1986-2010). While for the east part, close to the harbor mole, the stable behavior transformed in an accretional behavior and also for the whole area, there is no evidence that the behavior changed. It is suggested that the blocked west-east transport of sand has been replaced by the input of sand in the system from offshore (e.g. from the erosion near the north of the eastern mole). Also the transport coming from the East still continuous. It should be taken into account that before the harbour extension the uncertainty on the data (and especially human interference) is higher. It should also be taken into account that already since the beginning of the 20th century (smaller) harbor moles were present.

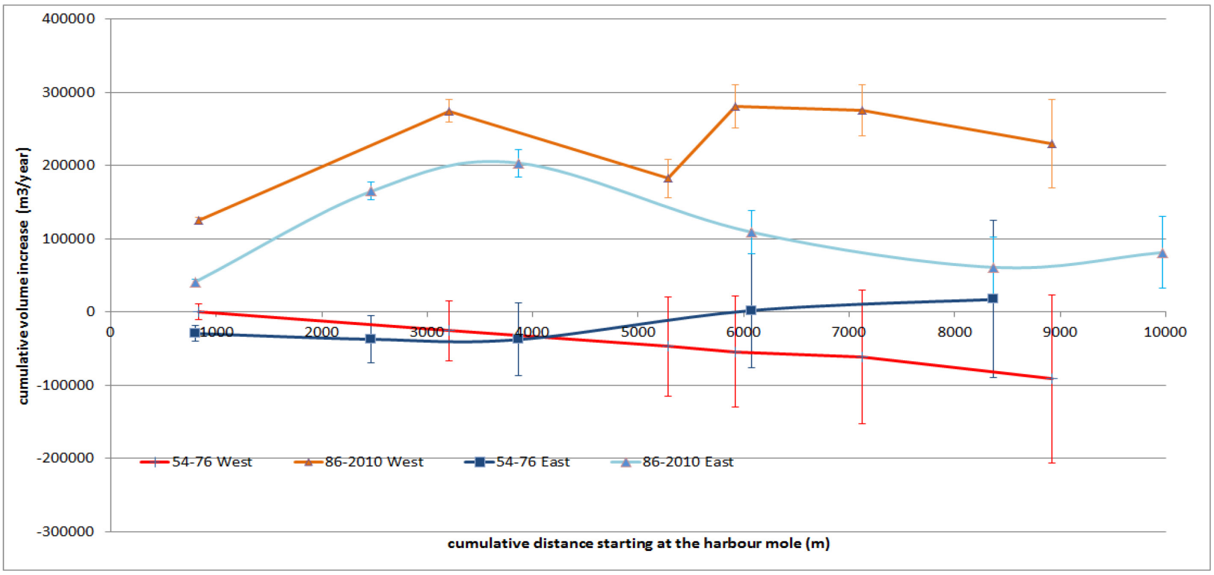


Figure 6-3 Cumulative yearly erosion (-) / sedimentation (+) east and west of Zeebrugge before and after the extension of the harbour of Zeebrugge

In Figure 6-4 the volume changes for all zones between Zeebrugge and the Zwin (presented in Houthuys (2012)) are integrated for the part of the profile above LW.

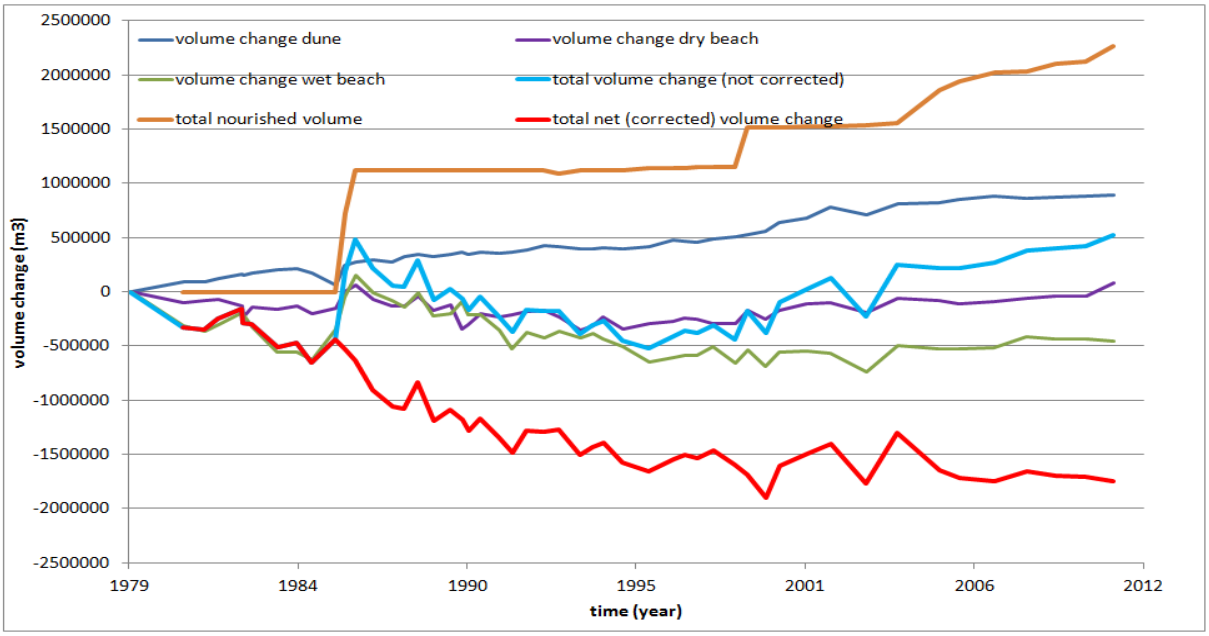


Figure 6-4 Volume changes for the zone between the harbour of Zeebrugge and the Zwin, volumes above LW

Already since 1979 the beaches of Knokke-Zoute and Lekkerbek erode. Since 1995/2000 this erosive trends seems to slow down. This can only partly be explained by the decrease in nourishments (after a nourishment, erosion increases).

It should be noted that between 1986 and 1997 big storms occurred. However, based on the wave height and direction measurements at Westhinder and using the sediment transport that was modeled near Blankenberge, using this wave information, it is estimated that the gross sediment transport was slightly higher in the period 1997 – 2010 compared to the period 1986-1997 (cf. §6.1.2.2).

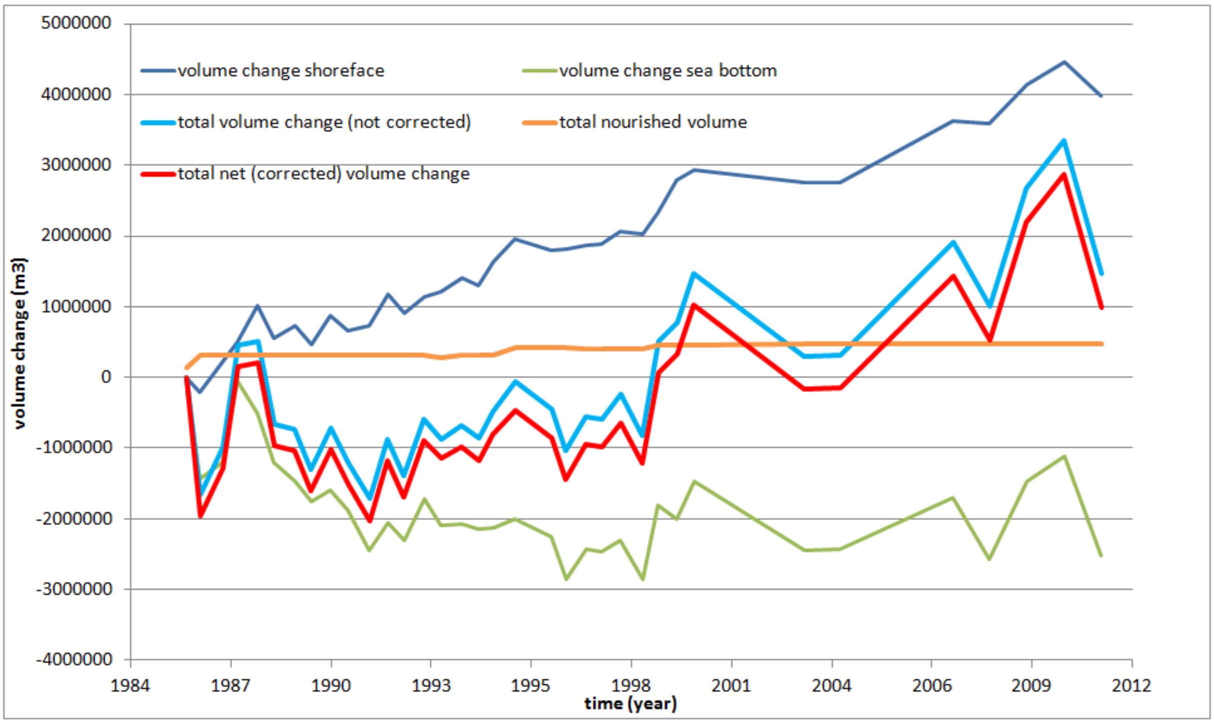


Figure 6-5 Volume changes for the zone between the harbour of Zeebrugge and the Zwin, volumes below LW

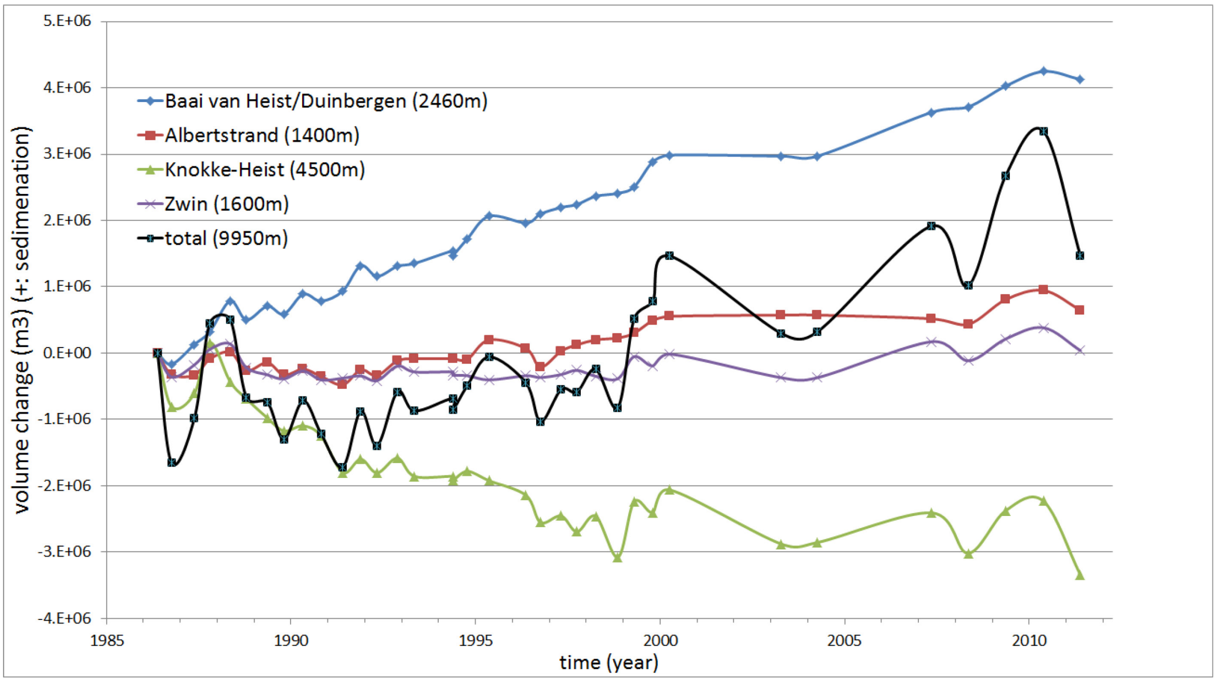


Figure 6-6 Volume changes for the zone between the harbour of Zeebrugge and the Zwin, volumes below LW - divided in 4 different areas

The morphological behavior below LW (Figure 6-5) is rather chaotic, with big jumps. An erosive behavior between 1986 (and probably before) to 1990 is visible, followed by a decade of stability, followed by a mild accretional behavior since 2000. As can be derived from Figure 6-5 the stabilizing of the volumes is mainly due to the stabilization of the sea bottom (below -4m TAW) (mainly in front of Knokke-Heist (the Appelzak) stabilization occurs (cf.Figure 6-6)) The sedimentation after 1986 and 1999 is due to offshore transport of nourishments at the beach to the area below LW).

Figure 6-7 shows the net (corrected) volume changes. The same conclusion as for the area below LW can be drawn.

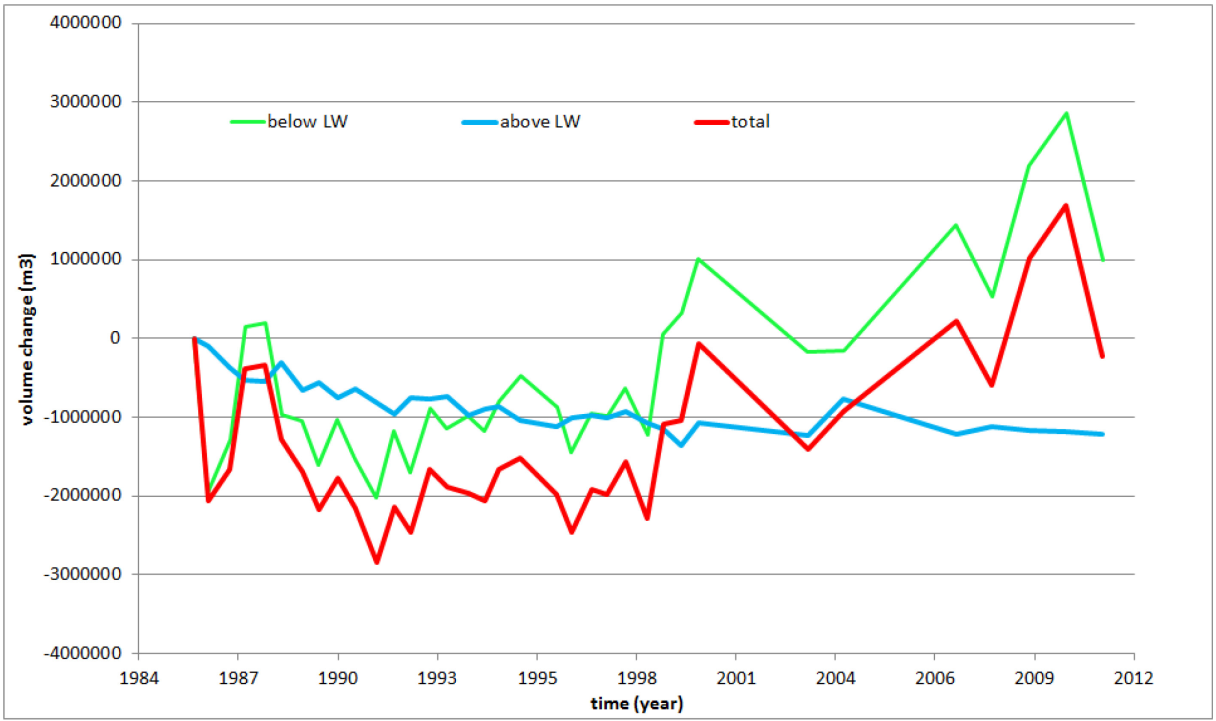


Figure 6-7 corrected volume changes for the zone between the harbour of Zeebrugge and the Zwin (below and above LW)

The rather stable overall behavior does not mean that locally no large erosion can occur, e.g. the shoreface of Knokke-Zoute is eroding strongly, especially after large nourishments (e.g. 1986 and 1999). This geographically differing behaviour is illustrated for 3 typical sections: in the sedimentation zone of Baai van Heist (Figure 6-8) – in the erosive zone of Knokke-Heist (Figure 6-9 and Figure 6-10) and for the Zwin (Figure 6-11). Because for Knokke-Heist, for the volumes below LW, 1997 was far below the trend line and 2010 was far above the trend line, the period 1997-2010 as in the above tables show (misleadingly large) accretion. This is avoided by looking at the trends as is done in Table 6-1.

Since the erosion is located / concentrated at the landward flank of the Appelzak-gully, this erosion is especially harmful for the beaches of Knokke-Zoute, where very frequent of maintenance is required.

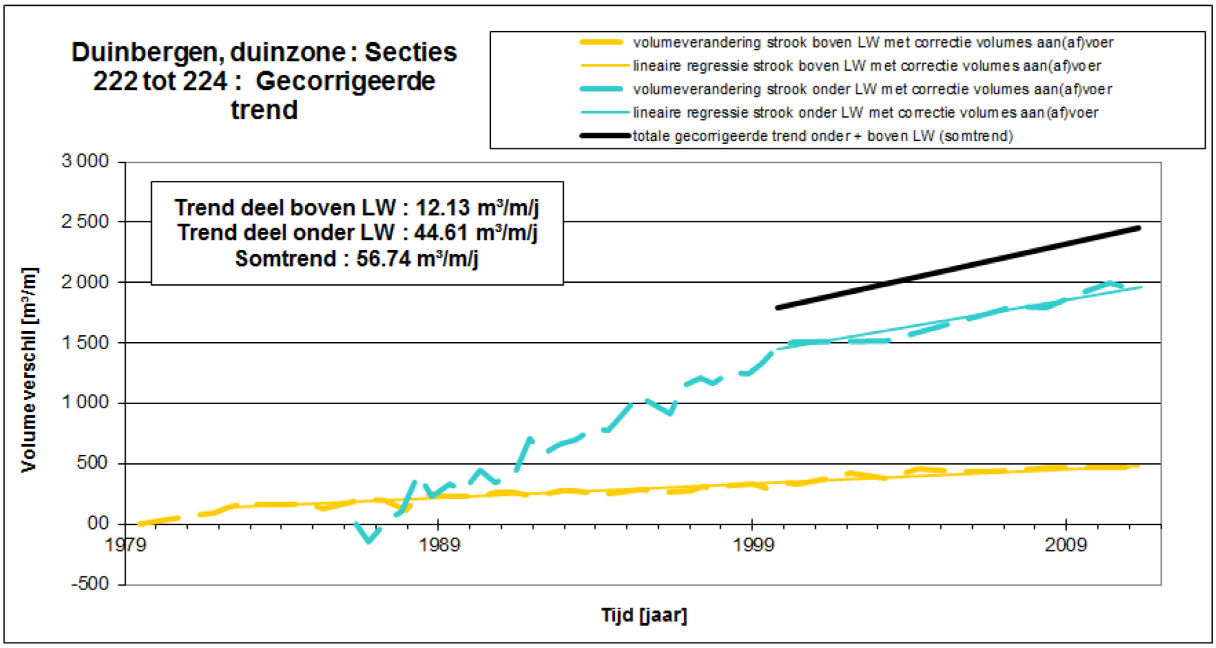


Figure 6-8 Morphological (corrected) trend for Duinbergen (part of Baai van Heist) (blue: shoreface ; orange: beach) (Houthuys, 2012)

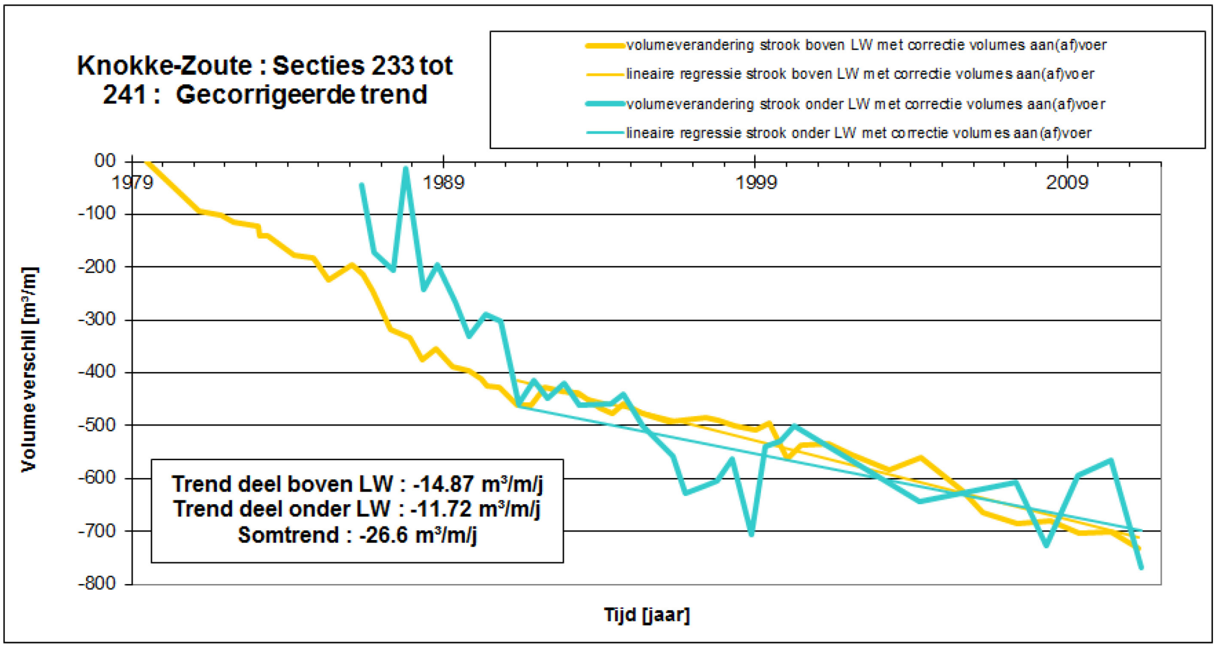


Figure 6-9 Morphological (corrected) trend for Knokke-Zoute (blue: shoreface ; orange: beach) (Houthuys, 2012)

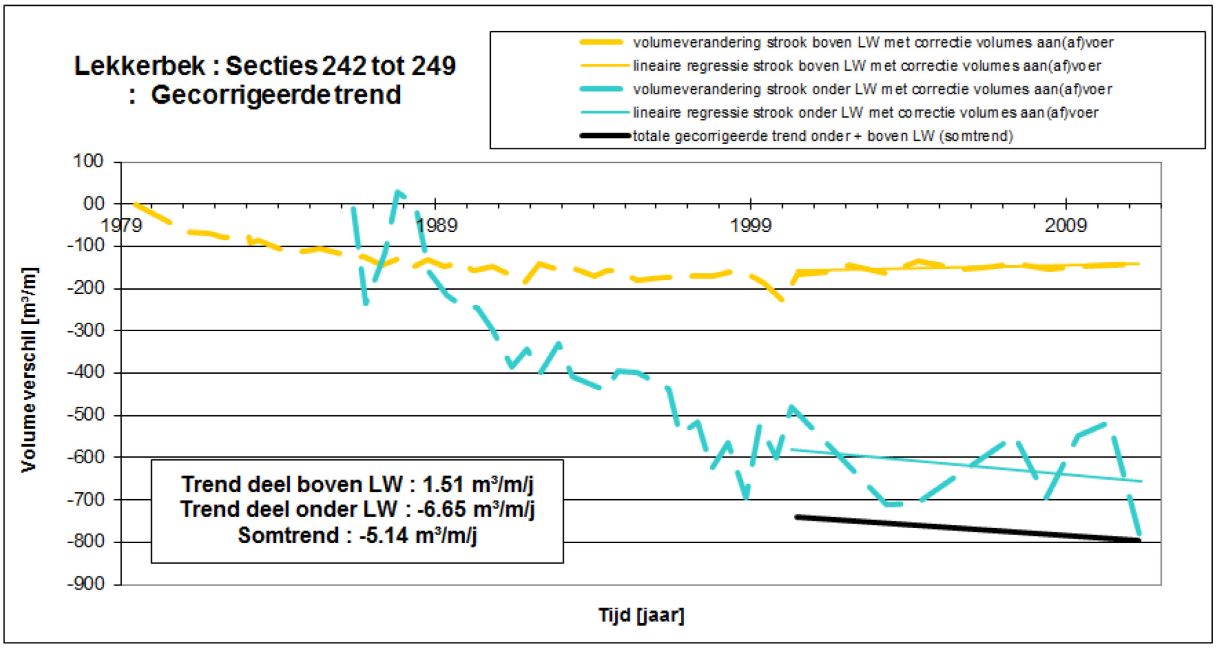


Figure 6-10 Morphological (corrected) trend for Lekkerbek
(blue: shoreface ; orange: beach) (Houthuys, 2012)

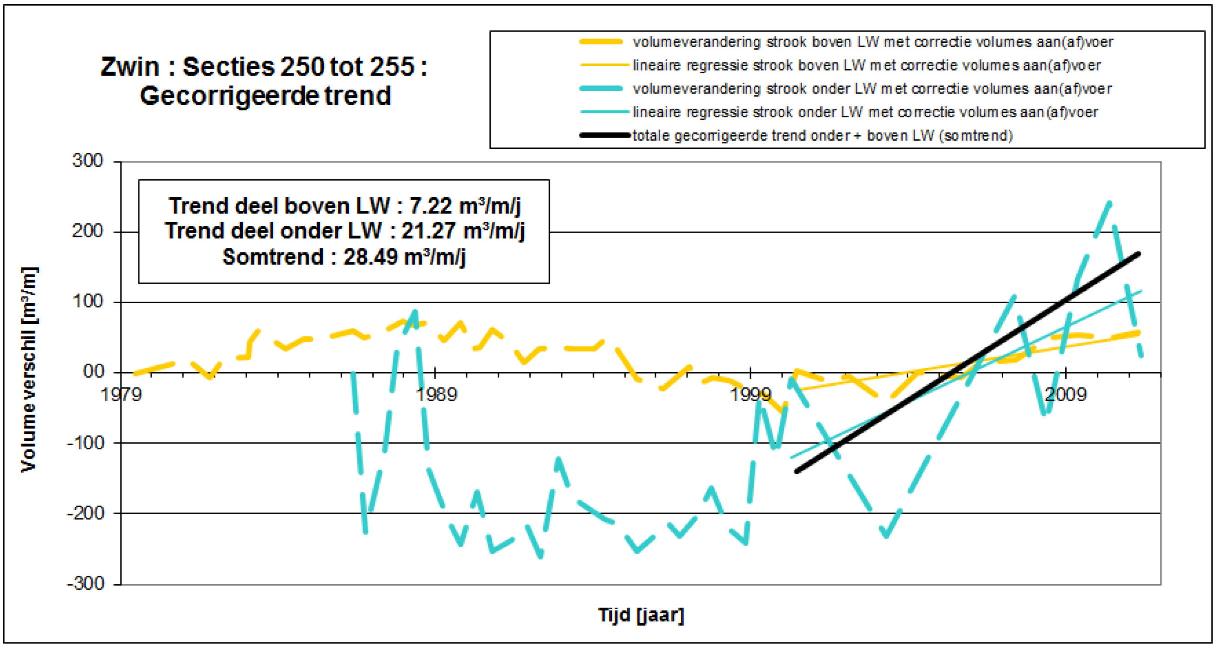


Figure 6-11 Morphological (corrected) trend for Zwin
(blue: shoreface ; orange: beach) (Houthuys, 2012)

Figure 6-13 shows a 2D presentation of the accretion and erosion between 1997 and 2011. The sedimentation at Baai van Heist (formation of a shoal) is visible, together with the erosion of the Appelzak. North of the Appelzak, also some sedimentation is visible.

Table 6-1 gives the results of a trend analysis for the different zones between Zeebrugge and Zwin, resp. above and below LW, for 2 different decades (within each decade a consistent trend is visible). Also the error on this trend is indicated (σ-value). Values are in 1000 m³/m/year (integration over the whole zone) The numbers are illustrated in Figure 6-18 and Figure 6-19).

Table 6-1 Trends of beach volume evolution and standard errors (in 1000 m³/m/year)

Baai van Heist			length	2460m		
	Above LW	σ	Below LW	σ	total	σ
1986-1997	-11	3,5	193	10	182	10,5
1997-2010	10	3	140	9	150	9,5
Albertstrand			length	1400m		
	Above LW	σ	Below LW	σ	total	σ
1986-1997	-3,5	2	26	10	22	10,5
1997-2010	4	1	41	8	45	8
Knokke-Zoute/Lekkerbek			length	4500m		
	Above LW	σ	Below LW	σ	total	σ
1986-1997	-51,5	6	-199	19	-251	20
1997-2010	-33,5	3,5	-26,5	20	-60	20,5
Zwin			length	1590m		
	Above LW	σ	Below LW	σ	total	σ
1986-1997	-10,5	2	-20,5	9	-30,5	9
1997-2010	8	1,5	34	10	42,5	10
Total			length	9950m		
	Above LW	σ	Below LW	σ	total	σ
1986-1997	-76,5	7,5	0	25	-77	26,5
1997-2010	-11,5	5	189	25,5	177	26

When looking at a single coastal unit, natural fluctuations are probably a more important source of possible misinterpretation of single numbers. This is illustrated for Wenduine (below LW) (Houthuys, 2012) (zone is part of the coastal unit Wenduine West). The 1997-point is the moment with the smallest volume of sand in the unit. This explains why for the period 1997-2010 Wenduine West shows some accretion, while the general trend remains erosion. For larger units, this effect is rather small, but it illustrates why it is also useful to look to the general trend (using all available measurements). The numbers in Table 6-1 are based on trends, the numbers in Annex 1 are absolute differences in volumes during the considered interval. Table 6-2 and Table 6-3 compare both values.

Table 6-2 Volume differences (m³/year) between end and beginning of considered period divided by the time length of the period

	Baai van Heist	Albert Strand	Knokke-Zoute	Zwin
1986-1997	164000	-1000	-283000	-34000
1997-2010	166000	72000	-24000	85000

Table 6-3 Morphological trend (m³/year) in the considered period

	Baai van Heist	Albert Strand	Knokke-Zoute	Zwin
1986-1997	182000	23000	-251000	-31000
1997-2010	150000	45000	-60000	43000

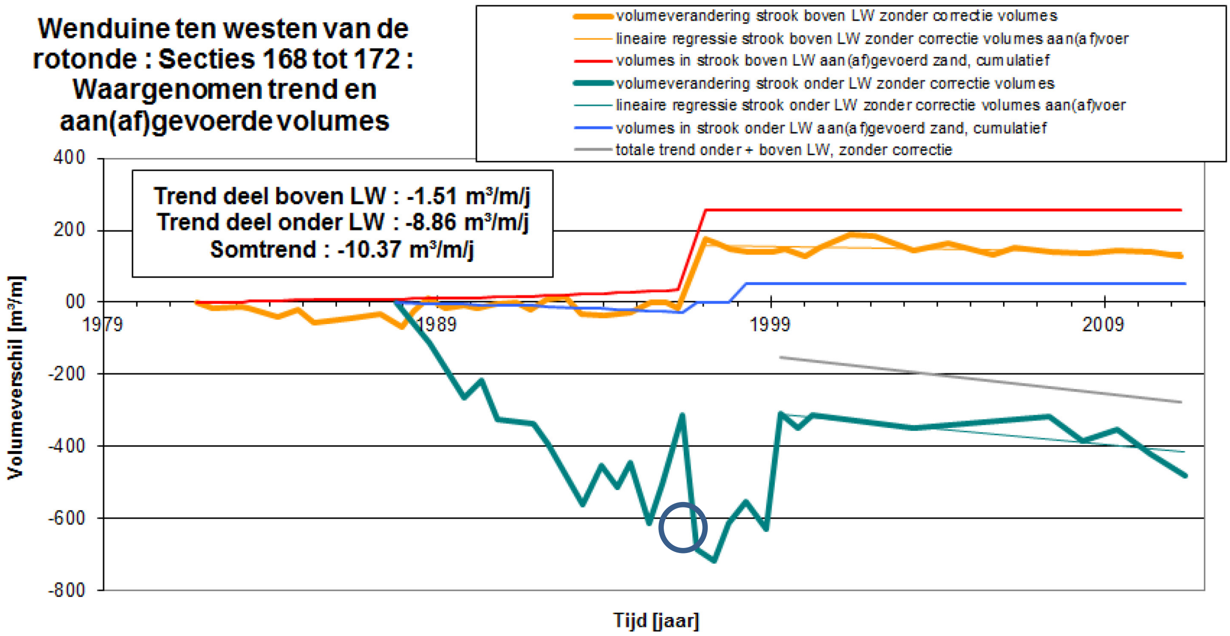


Figure 6-12 Morphological trend for Wenduine (Houthuys, 2012)

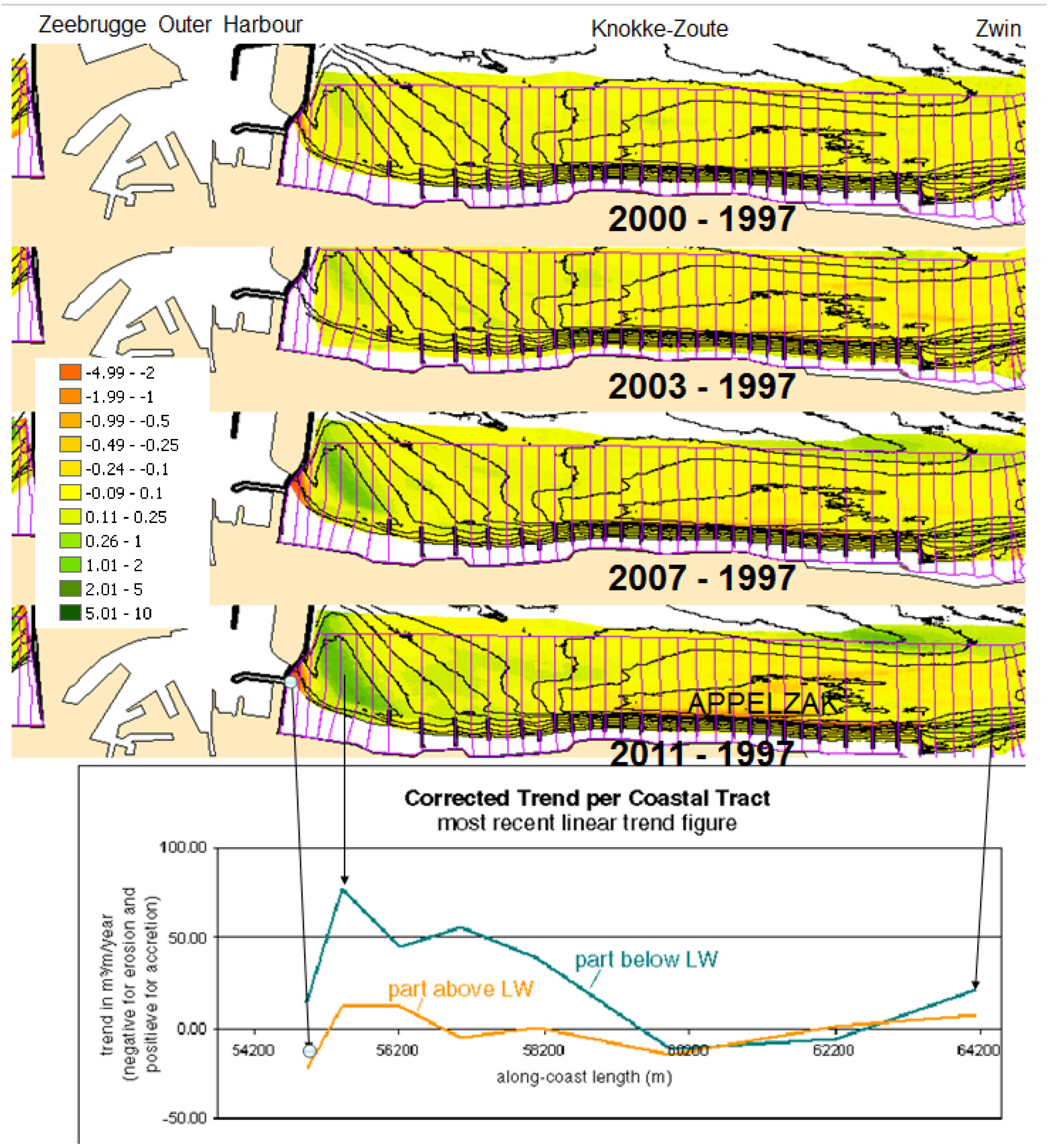


Figure 6-13 2D view of the erosion and sedimentation between 1997 and 2011 (maps above are not corrected for nourishments). (Houthuys, 2012)

Figure 6-14 shows the effect on the contourlines. The arrows indicate the shift in morphology, and are not necessarily an indication for net sediment transport direction.

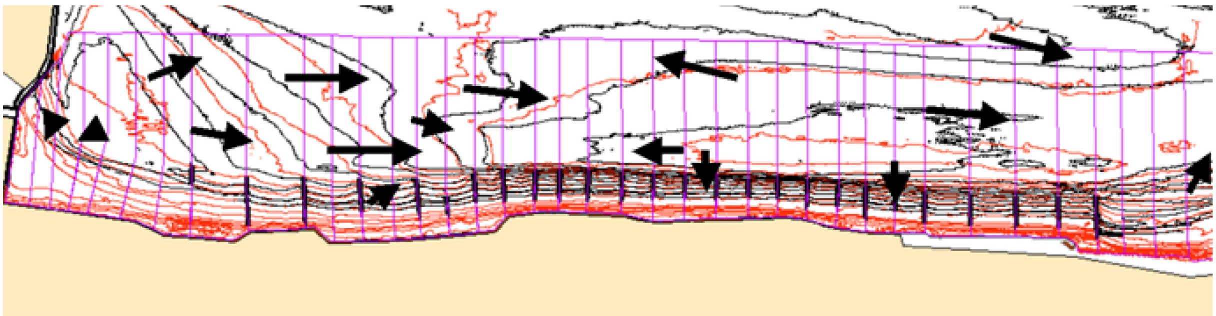


Figure 6-14 Contour line shift map between 1997 (red lines) and 2011 (black).
Contour line interval 1m. Black arrows indicate morphological changes, not necessarily net sediment directions (Houthuys, 2012).

Figure 6-15 and Figure 6-16 (Janssens et al., 2013) give the erosion/sedimentation trend between 1997 and 2010. The same features are visible, with again the sedimentation north of the Appelzak (=Paardenmarkt). Also the sedimentation at the shoreface of the Zwin is clearly visible.

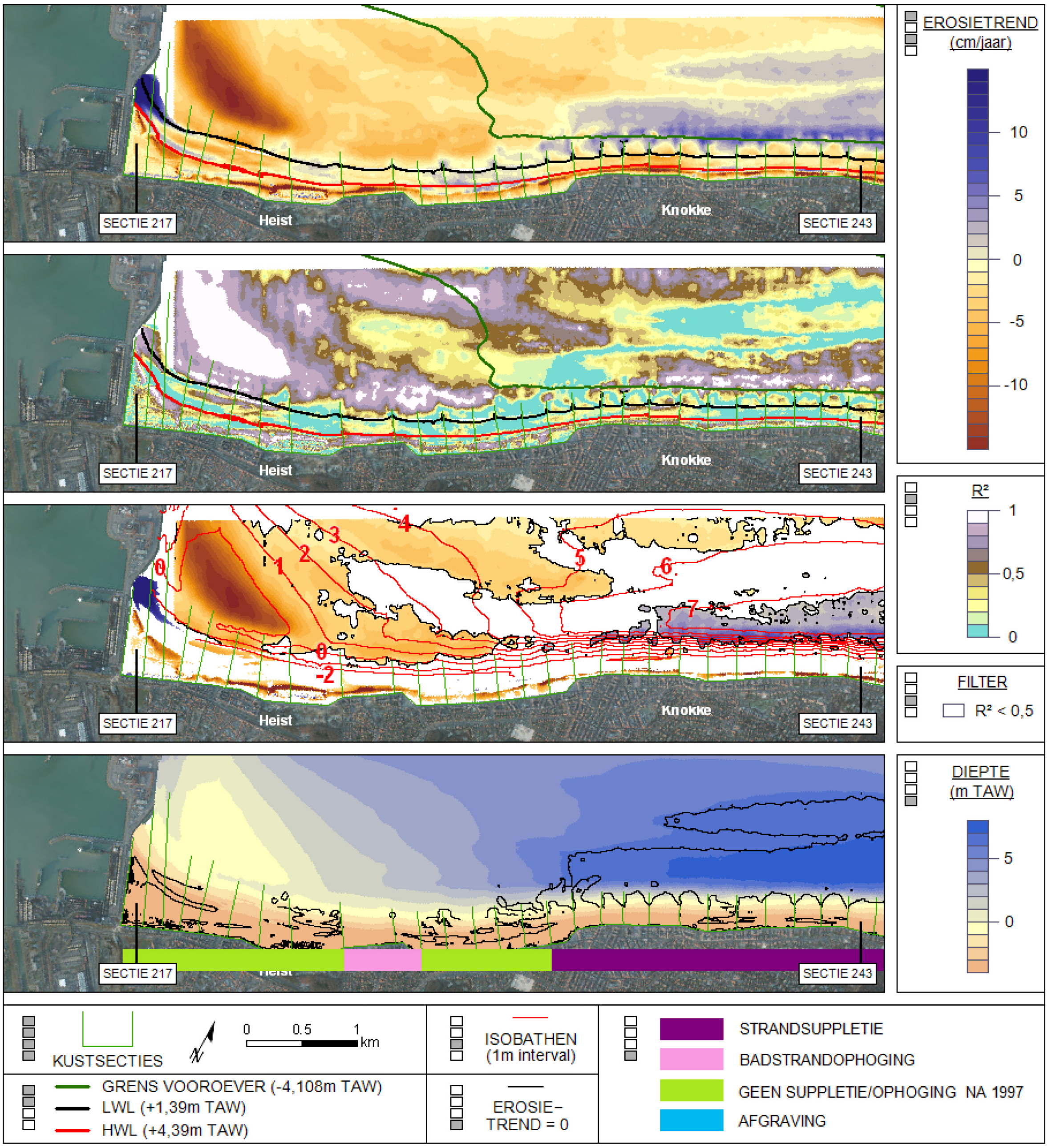


Figure 6-15 Erosion/sedimentation trend Zeebrugge – Knokke (Janssens et al, 2013)

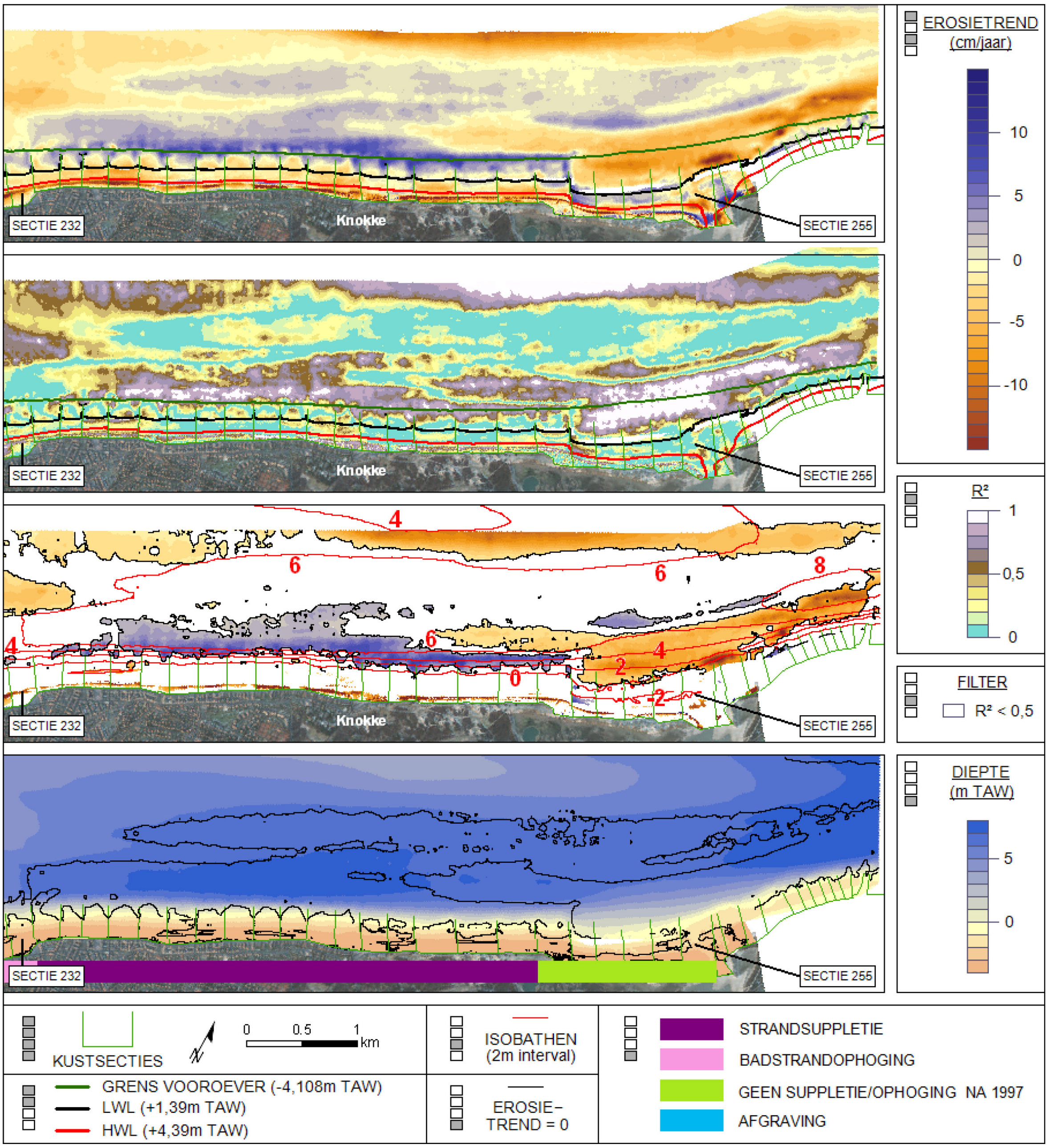


Figure 6-16 Erosion/sedimentation trend Knokke– Cadzand (Janssens et al, 2013)

Figure 6-17 shows the accretion/erosion trend around Zeebrugge. Offshore at of the harbor entrance an area of several km² is eroding (400.000m³/year). The currents are strongly flood dominated, so probably, this 400.000 m³/year is input for the coast between Zeebrugge and the Zwin (of which 150.000m³/year North of Baai van Heist, outside the coastal zone).

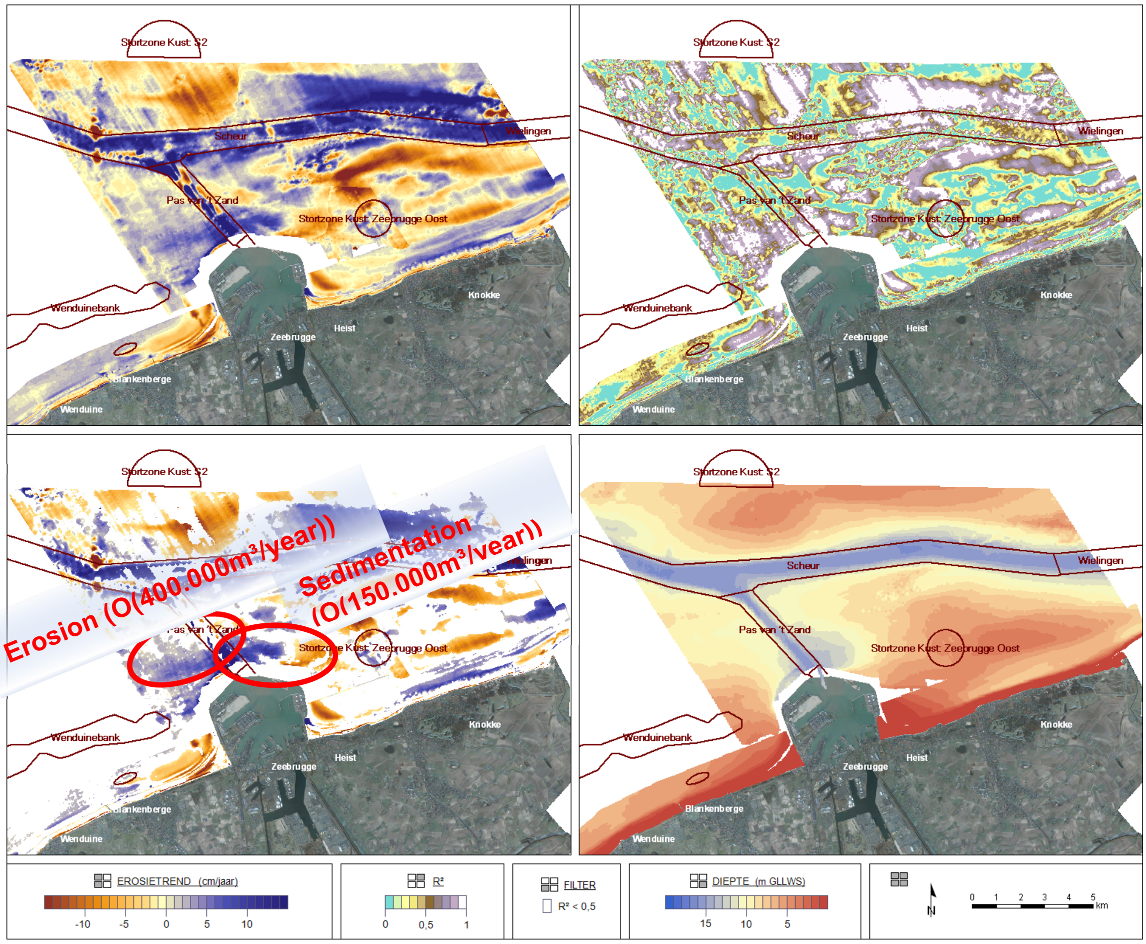


Figure 6-17 Accretion and erosion around Zeebrugge between 1997 and 2010 (Janssens et al, 2013).

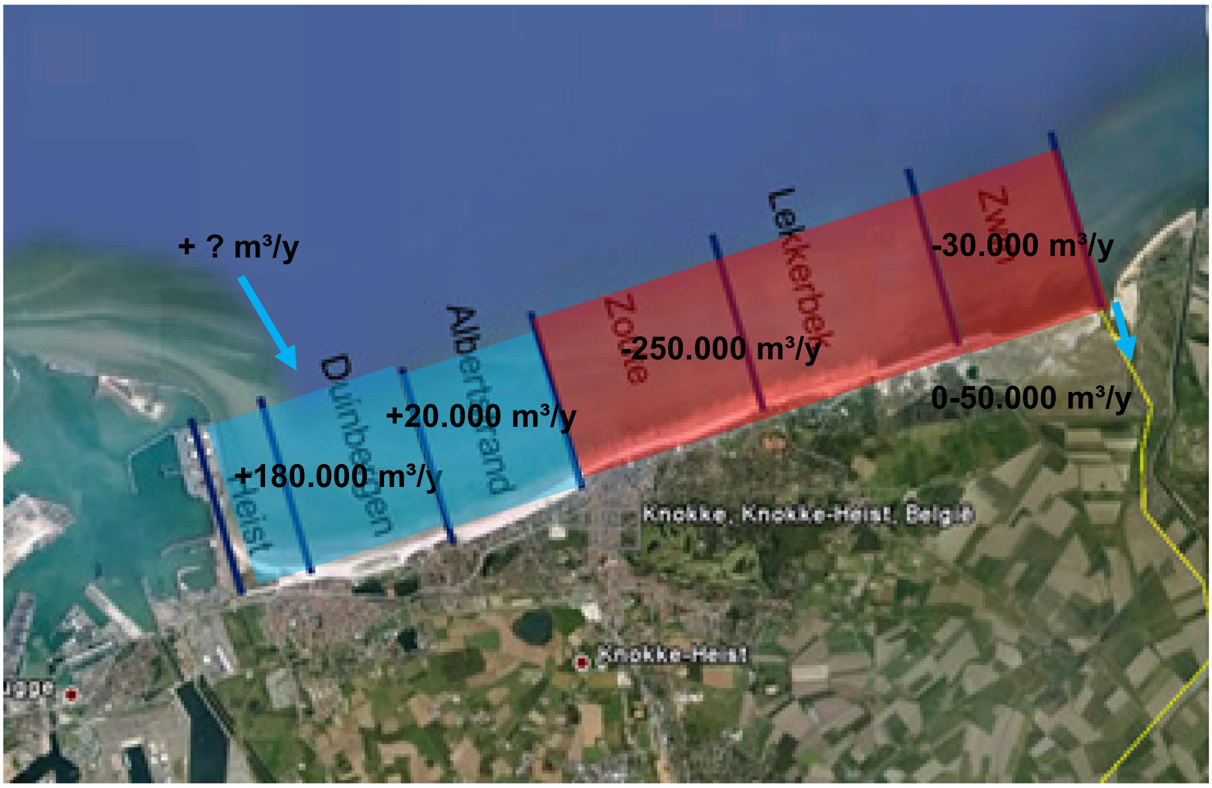


Figure 6-18 Sediment balance using the trends between 1986 and 1997 for the beaches and shoreface (up to 1500m offshore)

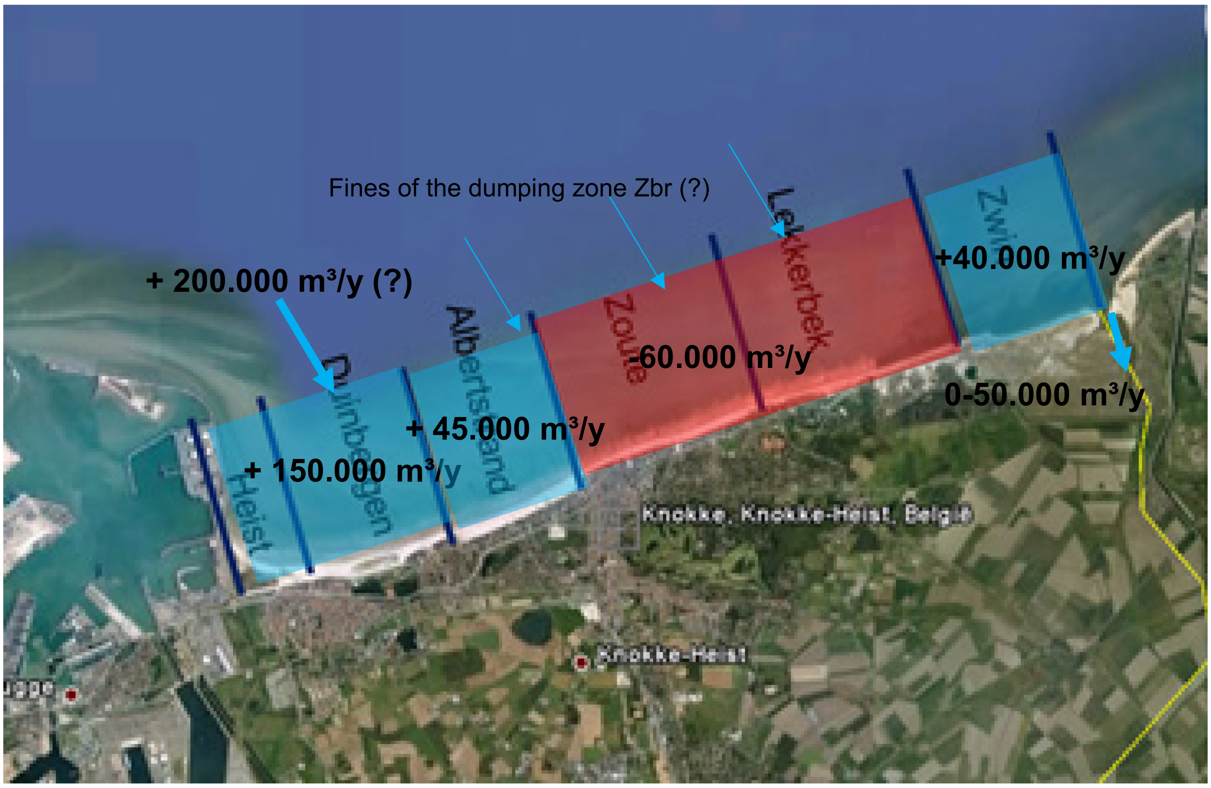


Figure 6-19 Sediment balance using the recent (last decade :1997-2010) trends for the beaches and shoreface (up to 1500m offshore)

Despite the possible ebb-dominance of the Appelzak-gully (cf. chapter 4), the net transport of sand in the coastal area seems to be eastward directed. This is also the situation in Blankenberge, where the net transport is about 300.000 m³/year in the West -> East direction. This is estimated based on numerical modelling and the sedimentation in the lee site of the harbour of Zeebrugge (Wang et al, 2012).

In Dutch studies the sediment transport is estimated in front of the Zeeuws-Flanders coast: Svasek(2012), based on CERC ; RWS: 300.000 m³/year eastward, 100.000 m³/year westward (these numbers are found in a publication of Bowman(1993), thus more applicable for the decade 1986-1997.

Also the coastline near the easternmost groin suggests net movement of sediment in eastern direction. Figure 6-20 and Figure 6-21 show that both in 1986 and 2005, the coastline migrated more landward at the eastern side of the last groin. And also the eastward movements of the Zwin gully indicate that in the past and recently, the net transport (at the beaches) is eastward. It cannot be excluded that more offshore, the direction is different.

It is unclear how much of the dumped material near the Paardenmarkt moves landward and contribute to the sediment balance of the coastal region. However, there are no indication of a considerable southward net transport.

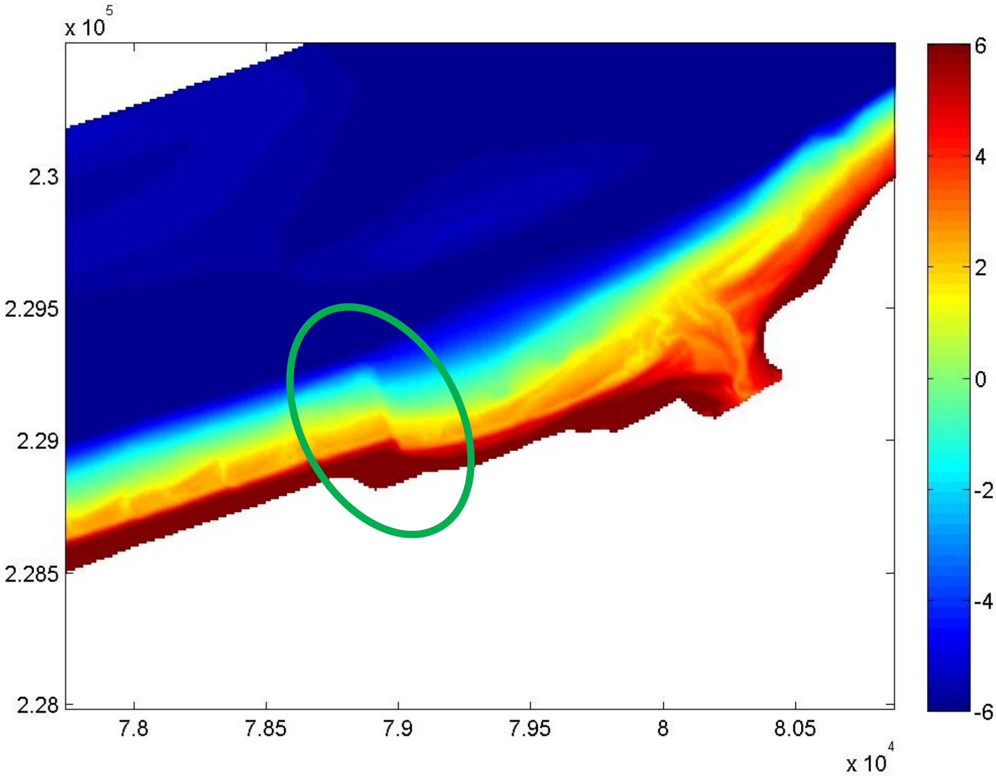


Figure 6-20 DTM of 1986 showing a steep gradient in the coastline near near the first groin West of the Zwin inlet (axis in m, UTM WGS84)

Figure 6-21 Google Earth image (2005) of the coast near the first groin West of the Zwin inlet

6.1.2 Further study of the change in trend between 1986 –> 1997 and 1998 -> 2010

In this chapter an attempt is made to study in more detail the trend change of the 2 last decades.

First the bathymetry is shown for 1986 – 1998 and 2009/2010 (each time first half year).The bathymetry for 1986 was obtained by digitalization of a chart, which explains the absence of groins.

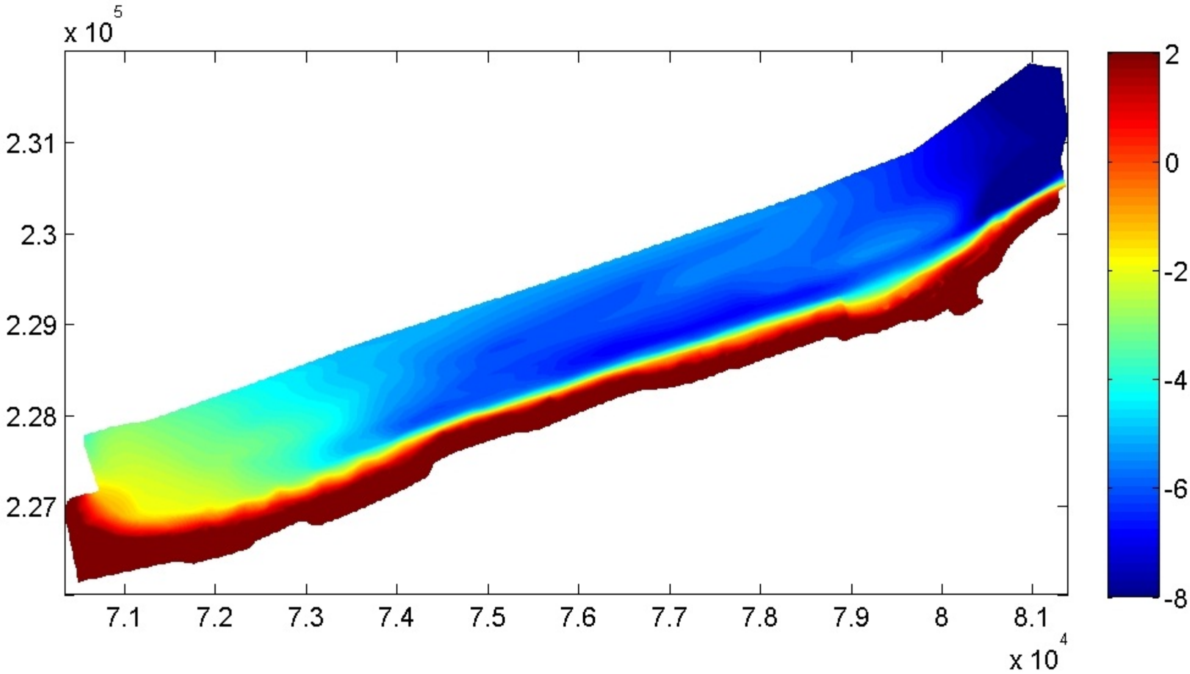


Figure 6-22 DTM of 1986 (in mTAW)
(axis in m, UTM WGS84)

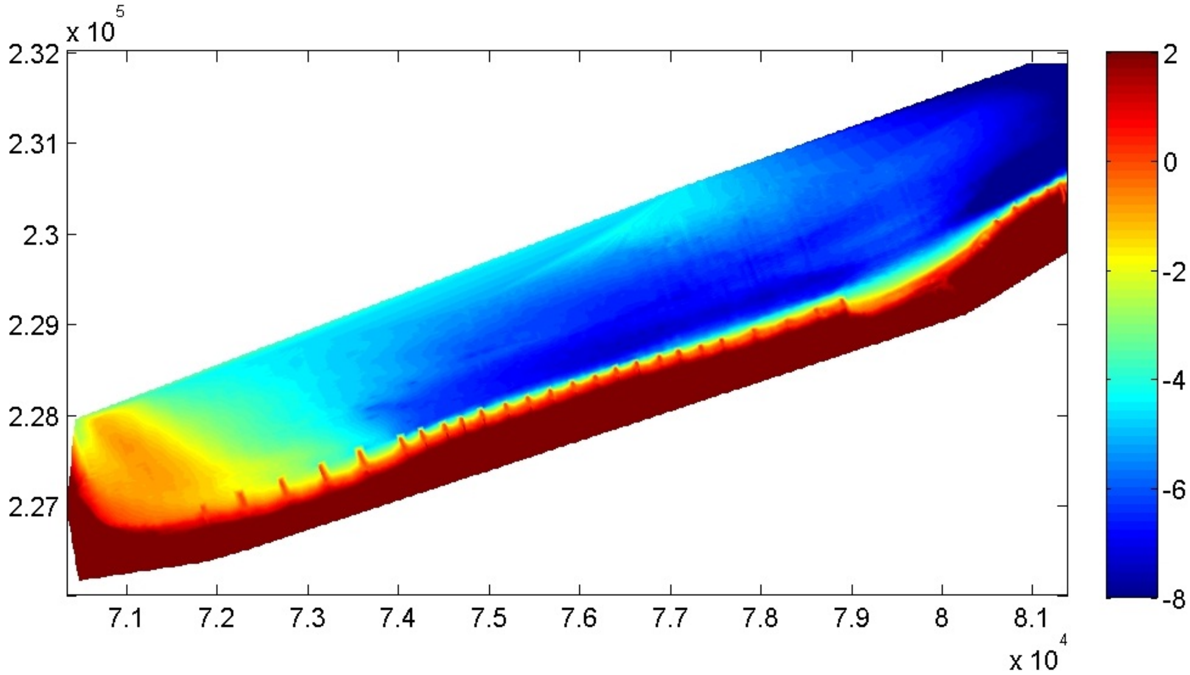


Figure 6-23 DTM of 1998 (in mTAW)
(axis in m, UTM WGS84)

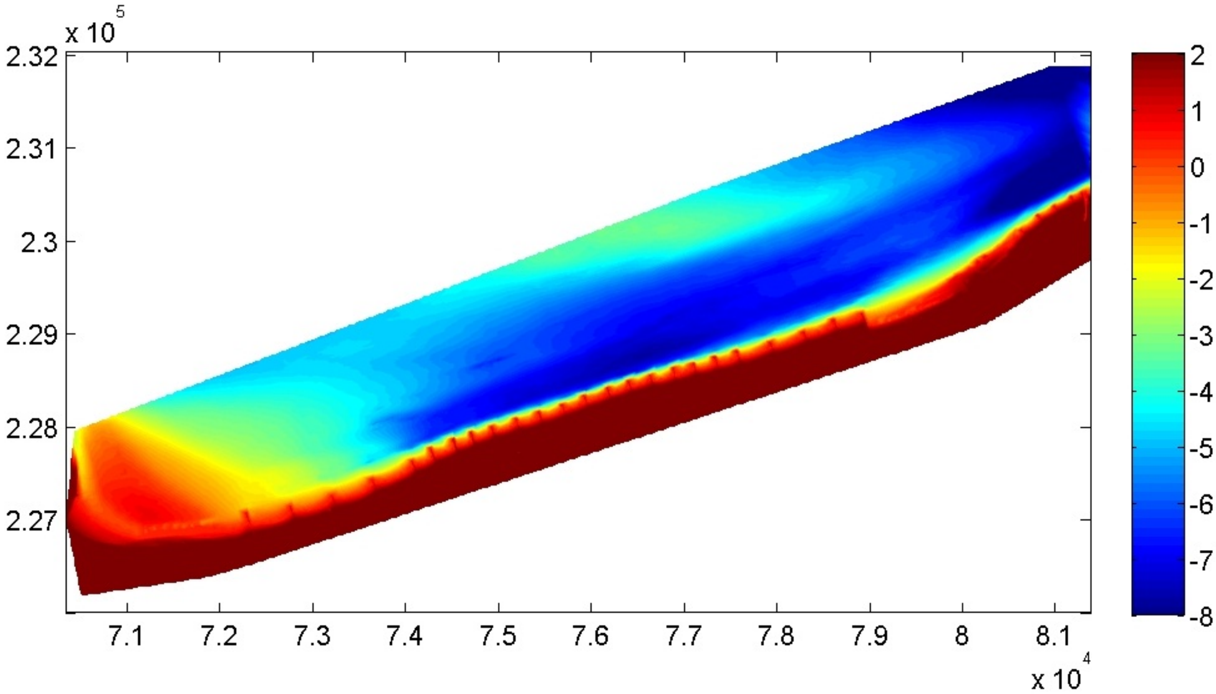


Figure 6-24 DTM of 2010 (in m TAW) (axis in m,
UTM WGS84)

From these DTM's it can be seen that in the North the sand bank is growing at this position (due to a general growth or migration of the bank, this can not be derived from these DTM's).

This is also visible on the sedimentation/erosion rate maps: (note: a growth of 0.05m/year, means a difference in height of 60cm over the considered time period of 12 years, significantly higher than the possible measuring error).

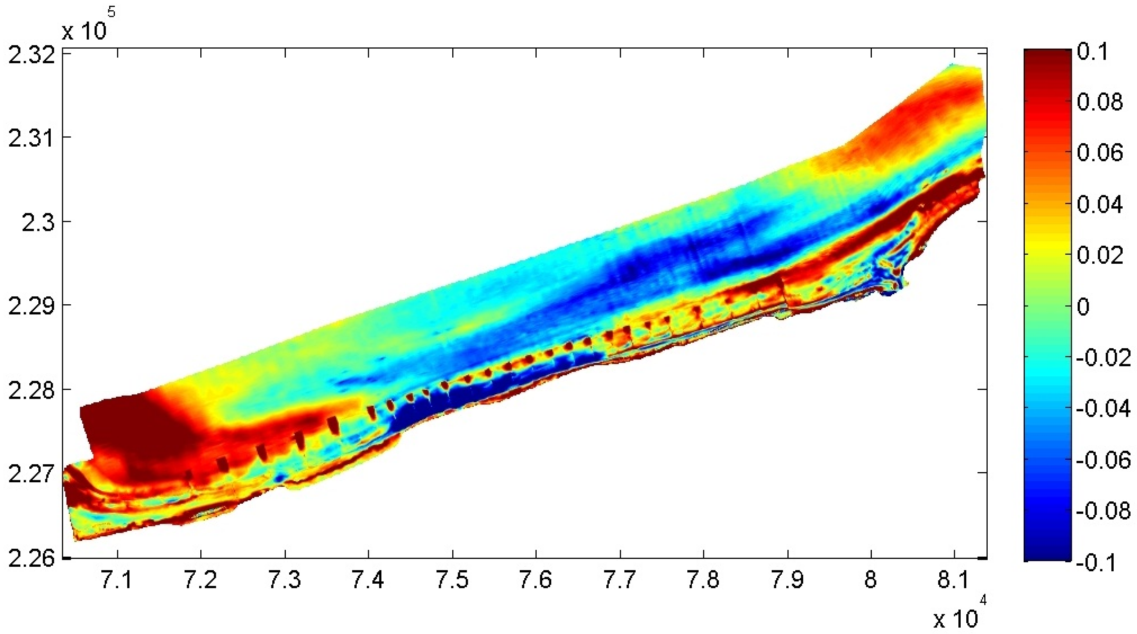


Figure 6-25 Erosion(-) – sedimentation (+) rate (m/year) between 1986 and 1998

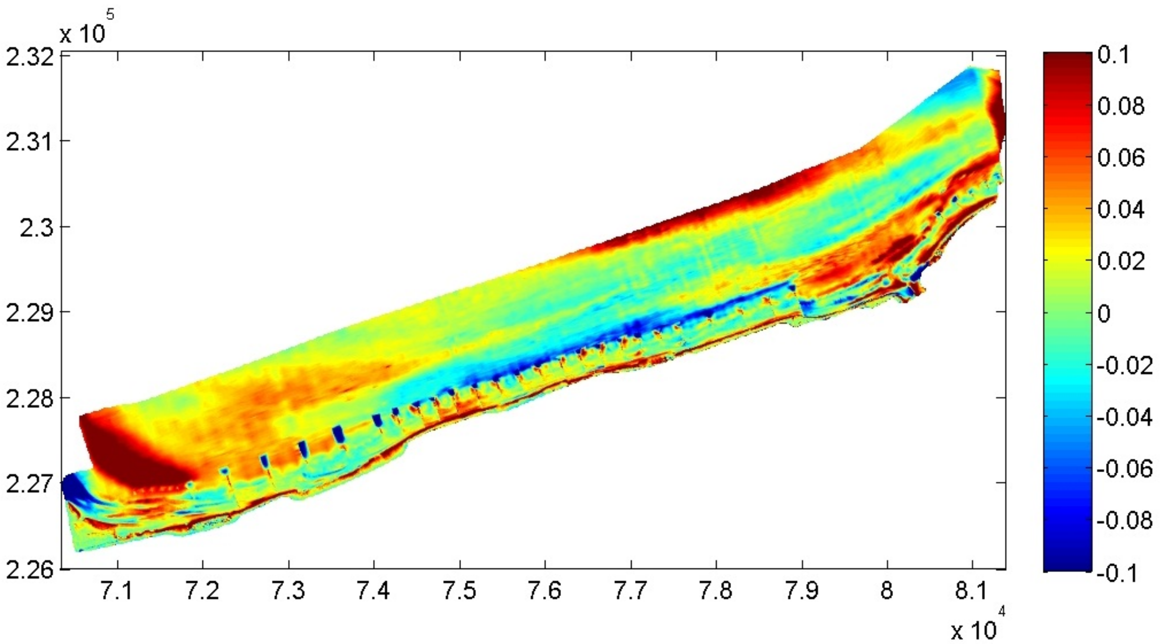


Figure 6-26 Erosion(-) – sedimentation (+) rate (m/year) between 1998 and 2010

The figures show again the growth of Baai van Heist, the erosion of the beaches at Knokke-Zoute and Lekkerbek and the stabilisation of the Appelzak area.

6.1.2.1 Effect of groins

Since the nourishment of 1986 the beach volume is decreasing (erosion is not completely compensated by nourishments). In this paragraph it is investigated what the effect of this decreasing beach volume could be on the relative height of the groins. For this purpose cross-sections and longshore sections are drawn up as indicated in Figure 6-27.

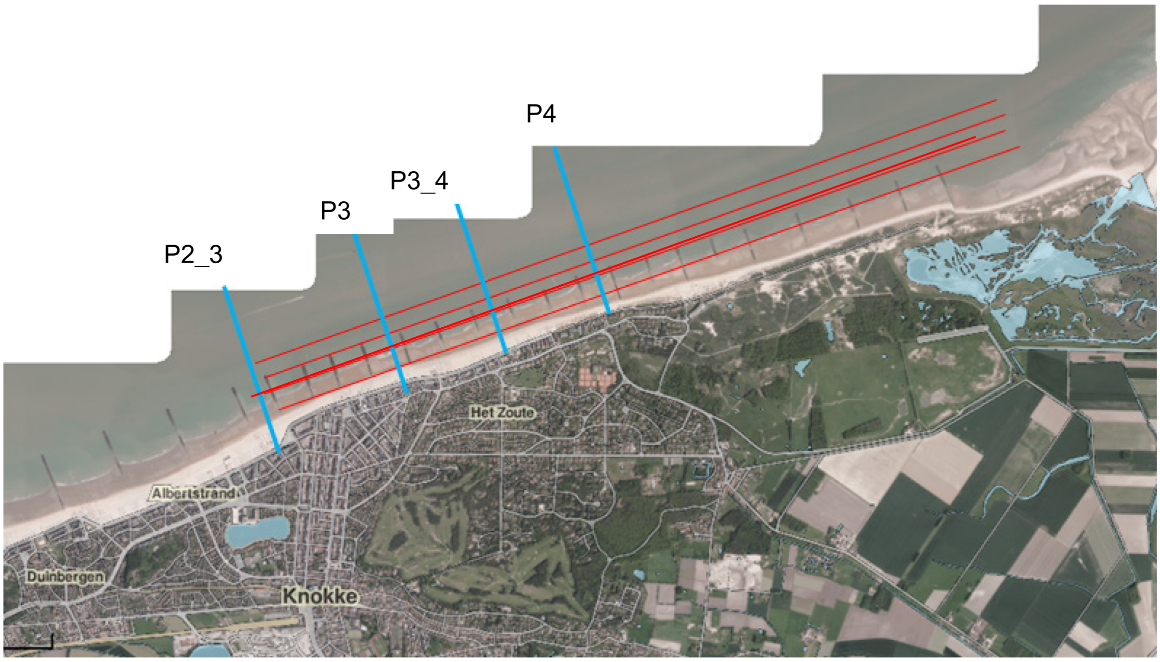


Figure 6-27 Location of longshore and cross-shore profiles

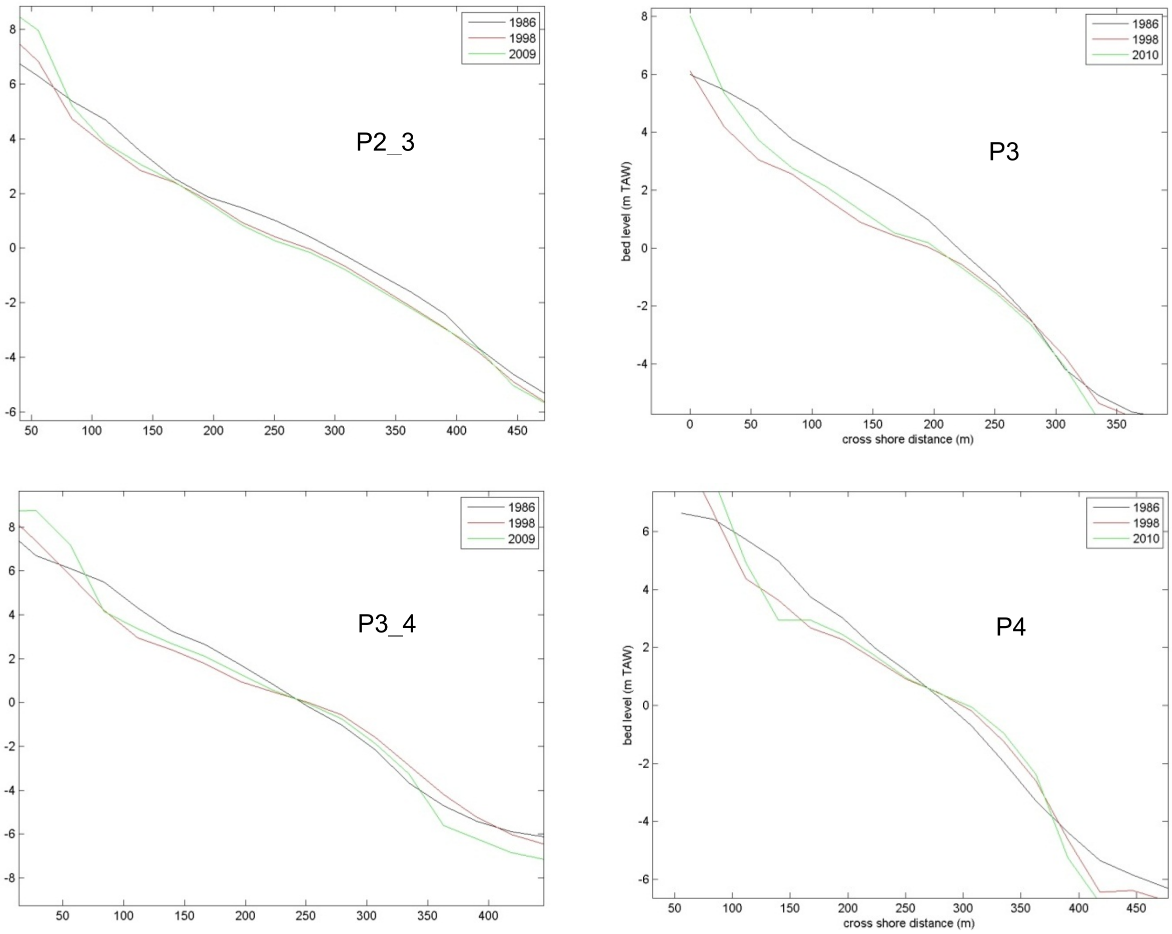


Figure 6-28 Cross shore profiles based on surveys of Coastal Division.

In the four cross shore profiles it is visible that at levels higher than 2m TAW (mean water level), erosion occurred (and in most of the profiles also between 0 and 2m TAW). In the eastern profiles(P3_4 and P4), part of the sand was deposited below LW.

Figures below show longshore profiles at different depths. It should be noted that the 1986 bathymetry is derived from digitisation of a map, without the groins.

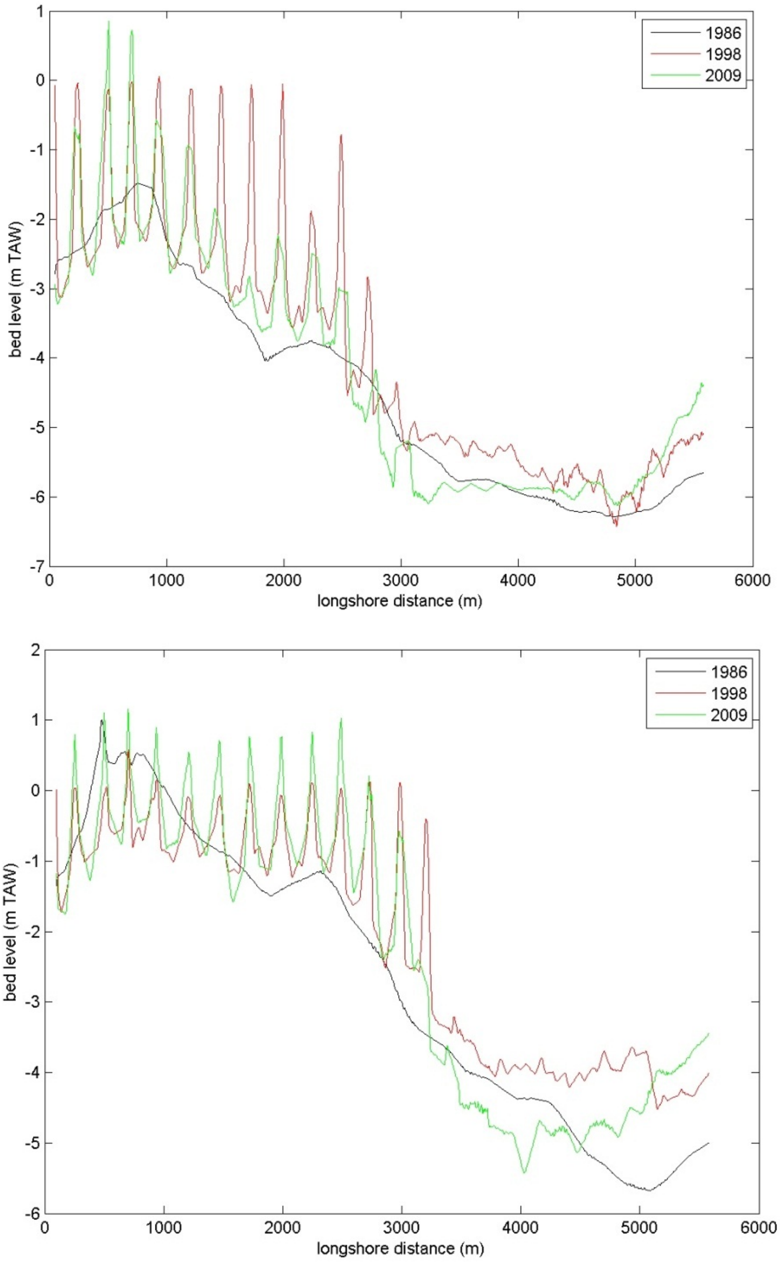


Figure 6-29 Longshore sections below LW

Figure 6-29 shows a longshore profile for which between x=0 and x=3000m the bottom depth is around -1 to +1m TAW (situated below LW). It shows that from x=0 to 1000m the beach was situated about 0.5m higher in 1986, making the groins slightly less effective in 1986, while between x=1500 and x=3000 the opposite occurs. More to the East, the bed is situated much deeper, so the groins are situated landwards of the profile.

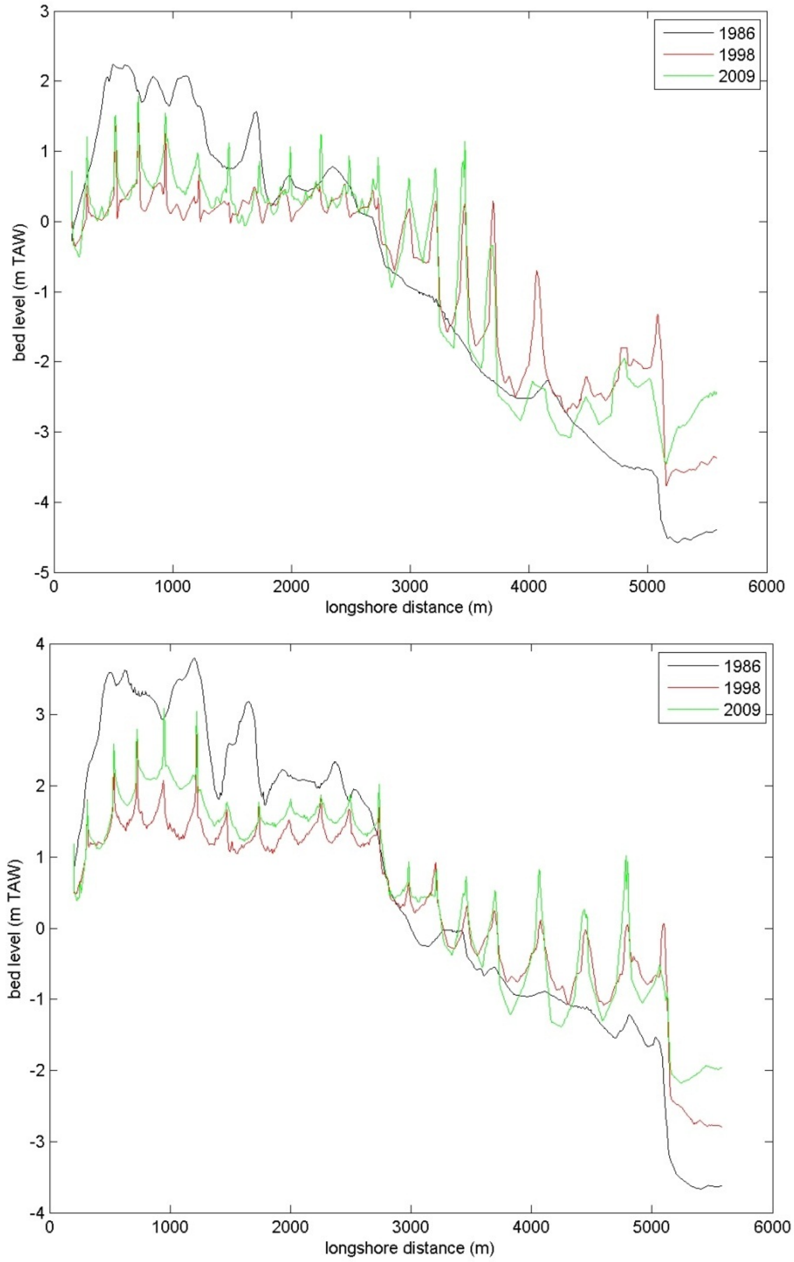


Figure 6-30 Longshore sections just above LW in the West and below LW in the East

Figure 6-30: between LW (0.5m TAW) and mean water level (2.5m TAW), it is clear that in 1986 the groins (between x=0 and 3000m) were covered by sand, while from 1998 on, the groins are again effective and partly block the longshore transport. In the eastern part (profiles just below LW) no significant differences are visible. This means that no real change in influence due to groins can be proved.

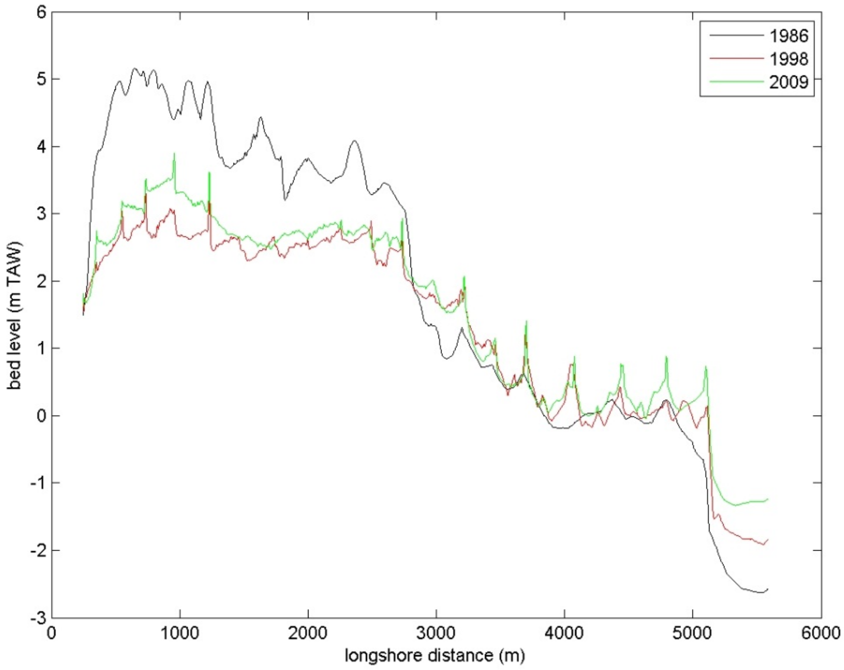


Figure 6-31 Longshore sections above MWL in the West and above LW in the East

Figure 6-31 shows that between x=0 and x=1000= the groins were covered in 1986, but became active due to the beach erosion. More to the East (x=1000 to x=3000m), the groins are still covered with sand. In the Eastern part, (x>3000m) the effect of the groins did not change over the last 25 years.

<u>Conclusion</u>: The groins at Knokke-Zoute (between x=0 and x=1000m) became more effective, mainly between LW and MW, but also to a certain extend below LW. The groins in this area stretch up to a bottom depth of -3m TAW! The further to the East, the smaller the change in activity of the groins.

So over a rather small distance, the change in effectiveness can have an influence on the morphological behaviour.

6.1.2.2 Effect of wave climate

The numerical “OKNO model” as described in Wang et al. (2012) has been used to calculate the longshore sediment transport in Blankenberge for each combination of wave height and wave direction in the wave climate table for offshore conditions (at Westhinder). In the original setting all conditions that occurred less than 1% of the time were not taken into account. In this exercise, where the effect of storms is examined, also these wave conditions are included. The corresponding sediment transport rate for these extra combinations is calculated by extrapolation of the modelled sediment transport rates for nearby wave conditions. Table 6-4 gives the yearly longshore sediment transport as a function of the wave height (left column, in cm) and the wave direction (+:from W->E;- from E->W). E.g. if during the whole year a wave height of 1.25m coming from NW would occur, the total sediment transport during that year would be 205.000m³/year. By multiplying the actual occurrence of all the combinations in the wave climate with the sediment transport, the total longshore transport can be obtained. For these calculations all waves are represented by the closest wave conditions in the table. E.g. a wave height between 1 and 1.5m is represented by the wave condition of 1.25m wave height.

This is done for all years between 1986 and 2011 both for real years and broken years from April to April, in order to correspond with the bathymetrical measurements (e.g. the year 1986 is from 1 April 1986 to 31 March 1987, so that the effect could be seen by looking to a difference map from spring 1987 and spring 1986). For years where the coverage of wave measurements is less than 80%, the results are judged to be unreliable and are omitted (most of the years have more than 95% availability). Two sources of wave measurements are used (two sources in order to have more complete information): the Wavec and Waverider at Westhinder from the measuring network Flemish Banks (Coastal Division).

Figure 6-32 shows the variation of the modelled yearly gross longshore sediment transport.

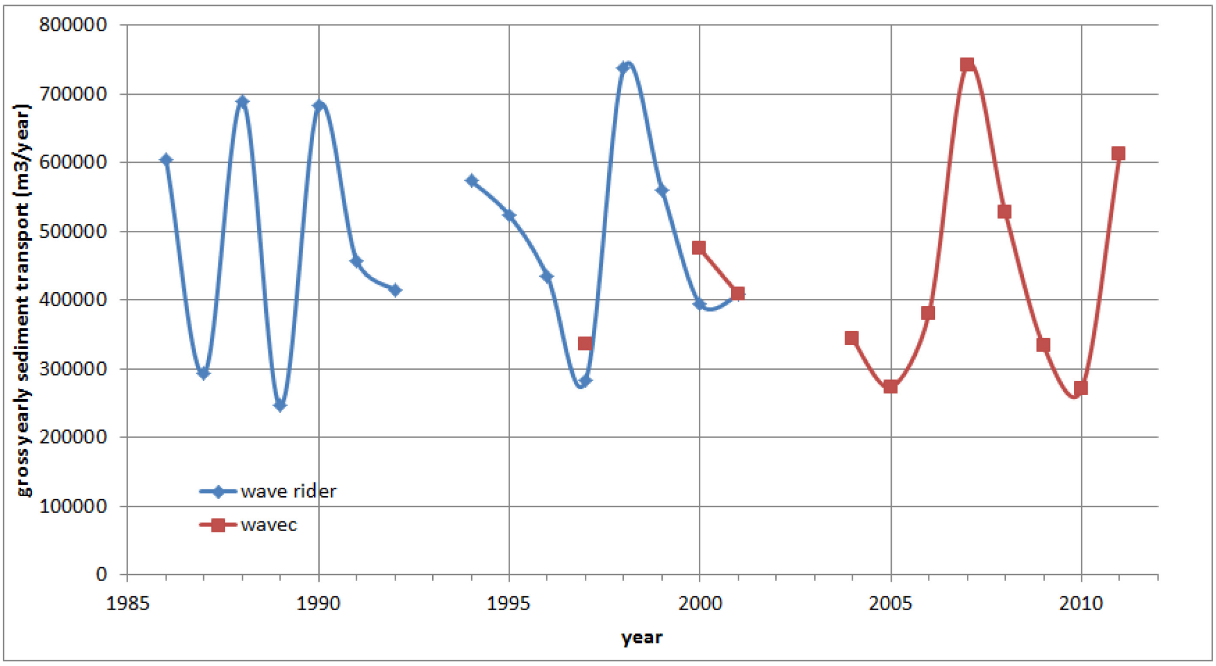


Figure 6-32 Modelled gross longshore sediment transport for real years (1 Jan -> 31 Dec) (+: West to East)

Table 6-4 gives the total yearly sediment transport for combinations of wave height and wave directions, assuming that this combination occurs during the full year. Multiplying these numbers with the percentage of occurrence (Table 6-5 and Table 6-7 for resp. 1986-1997 and 1998-2010) gives the actual contribution to the yearly transport (in resp. Table 6-6 and Table 6-8). Adding up all the contributions gives the total yearly transport.

Table 6-4 Modelled Longshore sediment transport (x1000m³/year) for different wave heights (in cm) and wave directions, positive means eastward transport.

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
<75	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
075	36	18	8	13	23	28	30	31	37	49	69	87	100	103	85	60
125	27	-17	-49	-32	-2	21	30	35	51	95	156	246	328	323	205	99
175	-44	-165	-292	-189	-70	3	27	39	80	195	380	879	1350	1290	634	174
225	-289	-614	-1030	-671	-270	-21	23	40	130	404	1050	2920	4680	4250	1880	322
275	-949	-1710	-2870	-1890	-792	-50	19	40	195	853	2610	7790	11900	10200	4170	460
325	-2040	-3740	-5341	-3527	-1492	-84	15	39	273	1690	5560	16400	22700	18300	7260	659
375	-3360	-6570	-8350	-5520	-2345	-123	10	37	363	2798	10500	25200	36369	25800	9980	817
425	-4710	-9550	-11846	-7835	-3335	-166	5	36	464	4139	16300	38100	52570	32677	12306	929
475	-6090	-12676	-15790	-10447	-4452	-212	0	34	575	5691	22891	54325	71089	38904	14209	988
525	-7499	-15945	-20157	-13339	-5689	-262	-6	31	696	7439	30223	73496	91771	44448	15644	977
575	-8937	-19353	-24925	-16496	-7039	-316	-11	29	827	9371	38256	95368	114496	49271	16547	898

Table 6-5 Occurrence of wave conditions between 1986 and 1997 (in %)

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	total
<75	0.4682	1.2755	1.6779	1.4141	1.3764	1.4390	1.5340	1.5431	1.6731	1.4019	1.2681	1.2670	0.9464	0.6333	0.5324	0.4008	18.851
075	1.1407	2.5835	2.3886	2.5378	2.1938	2.0797	1.7336	2.1551	3.2411	3.4715	3.4800	4.0013	2.2655	1.7235	1.2129	1.1747	37.383
125	0.8769	1.5781	1.4321	1.4236	1.1312	0.5436	0.4284	0.7702	1.7628	2.4778	2.7910	3.0660	1.4863	1.2665	1.0218	1.0584	23.115
175	0.3477	0.6943	0.6364	0.7208	0.3408	0.1093	0.0679	0.2102	0.5823	1.2400	1.6694	1.7108	0.9141	0.8174	0.5648	0.4719	11.098
225	0.2060	0.3753	0.3896	0.3514	0.1083	0.0366	0.0324	0.0600	0.2447	0.5499	1.0468	0.8992	0.3955	0.4767	0.2893	0.2399	5.701
275	0.0844	0.1417	0.1656	0.1157	0.0494	0.0143	0.0111	0.0318	0.0754	0.2065	0.4167	0.4305	0.1969	0.1937	0.1805	0.1269	2.441
325	0.0430	0.0780	0.0764	0.0324	0.0053	0.0074	0.0042	0.0048	0.0218	0.0616	0.1258	0.1295	0.0690	0.0955	0.1078	0.0695	0.932
375	0.0244	0.0260	0.0207	0.0159	0.0005	0.0011	0.0005	0.0005	0.0037	0.0292	0.0419	0.0409	0.0303	0.0271	0.0488	0.0127	0.324
425	0.0138	0.0085	0.0032	0.0032	0.0000	0.0000	0.0000	0.0005	0.0011	0.0127	0.0074	0.0138	0.0127	0.0127	0.0111	0.0074	0.108
475	0.0085	0.0027	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0021	0.0021	0.0021	0.0021	0.0037	0.0037	0.0005	0.0027	0.030
525	0.0016	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0005	0.0000	0.0016	0.0005	0.0042	0.0032	0.0005	0.0021	0.014
575	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0005	0.0000	0.0000	0.0000	0.001
total	3.215	6.764	6.791	6.615	5.206	4.231	3.812	4.776	7.609	9.453	10.851	11.562	6.325	5.253	3.970	3.567	100

Table 6-6 Total contribution to the gross longshore sediment transport of each wave condition (1986 and 1998 (in m³/year) (total = sum of the absolute values)

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	total
<75	148	403	530	447	435	455	485	488	529	443	401	400	299	200	168	127	5957
075	405	473	199	332	505	591	522	659	1196	1715	2415	3461	2261	1775	1036	700	18245
125	234	-273	-706	-457	-24	115	128	271	899	2354	4354	7542	4875	4091	2095	1051	29469
175	-154	-1146	-1858	-1362	-240	4	18	81	468	2418	6344	15038	12340	10545	3581	821	56417
225	-595	-2304	-4013	-2358	-292	-8	7	24	318	2222	10991	26256	18507	20258	5439	773	94366
275	-801	-2424	-4753	-2187	-391	-7	2	13	147	1761	10876	33535	23435	19762	7526	584	108203
325	-877	-2918	-4082	-1142	-79	-6	1	2	59	1041	6995	21241	15664	17485	7823	458	79874
375	-820	-1709	-1729	-879	-12	-1	0	0	13	817	4403	10300	11004	6984	4874	104	43650
425	-650	-811	-377	-250	0	0	0	0	5	527	1211	5258	6697	4163	1372	69	21 391
475	-517	-336	0	0	0	0	0	0	12	121	486	1153	2641	1446	75	26	6 815
525	-119	0	0	0	0	0	0	0	4	0	481	390	3897	1416	83	21	6 411
575	0	0	0	0	0	0	0	0	0	0	0	0	608	0	0	0	608
total	5322	12797	18248	9414	1978	1187	1163	1538	3650	13418	48956	124576	102228	88125	34071	4733	471 404

Table 6-7 Occurrence of wave conditions between 1998 and 2010 (in %)

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	total
<75	1.2339	1.4214	1.7955	1.3018	0.7945	0.4541	0.4020	0.4594	0.7086	0.9536	1.6395	2.7970	2.2876	1.4836	1.2528	1.0716	20.057
075	1.9588	2.4193	2.8813	2.5410	1.3313	0.6849	0.5874	0.9420	1.7064	2.2596	4.9760	5.4918	2.5926	2.2148	2.0146	1.5816	36.184
125	1.5215	1.5710	1.4230	1.1422	0.6912	0.2086	0.1739	0.4115	1.1148	1.5710	4.3022	2.9719	1.5895	1.5026	1.4093	1.1643	22.769
175	0.7792	0.5995	0.7191	0.5369	0.3266	0.0406	0.0379	0.1228	0.3999	0.8098	2.5352	1.7001	0.8076	0.7613	0.8156	0.8556	11.848
225	0.3741	0.2423	0.3619	0.2250	0.0811	0.0042	0.0011	0.0163	0.1196	0.2782	1.2528	0.8898	0.4246	0.3535	0.4141	0.5142	5.553
275	0.1723	0.1249	0.1365	0.0680	0.0126	0.0016	0.0021	0.0026	0.0227	0.0896	0.5432	0.3662	0.1538	0.1723	0.2418	0.2402	2.350
325	0.0875	0.0548	0.0574	0.0042	0.0005	0.0000	0.0011	0.0005	0.0037	0.0295	0.1886	0.1312	0.0400	0.0611	0.1127	0.1117	0.885
375	0.0242	0.0174	0.0174	0.0005	0.0000	0.0000	0.0000	0.0000	0.0016	0.0079	0.0432	0.0358	0.0153	0.0137	0.0321	0.0464	0.256
425	0.0142	0.0079	0.0021	0.0000	0.0000	0.0000	0.0000	0.0000	0.0005	0.0021	0.0179	0.0163	0.0037	0.0037	0.0037	0.0116	0.084
475	0.0016	0.0021	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0047	0.0032	0.0000	0.0000	0.0005	0.0005	0.013
525	0.0011	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0016	0.0000	0.0000	0.0000	0.0011	0.004
575	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.000
total	6.168	6.461	7.394	5.820	3.238	1.394	1.205	1.955	4.078	6.001	15.503	14.405	7.915	6.567	6.297	5.599	100

Table 6-8 Total contribution to the gross longshore sediment transport of each wave condition (1998 and 2010 (in m³/year) (total = sum of the absolute values)

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	total
<75	390	449	567	411	251	144	127	145	224	301	518	884	723	469	396	339	6338
075	695	443	240	333	306	195	177	288	630	1116	3453	4750	2587	2281	1721	943	20158
125	406	-272	-702	-367	-15	44	52	145	569	1492	6711	7311	5214	4853	2889	1156	32197
175	-346	-989	-2100	-1015	-230	1	10	47	321	1579	9634	14944	10903	9821	5171	1489	58599
225	-1081	-1488	-3728	-1509	-219	-1	0	7	155	1124	13155	25983	19873	15024	7785	1656	92788
275	-1635	-2135	-3916	-1284	-100	-1	0	1	44	764	14177	28524	18307	17572	10084	1105	99650
325	-1784	-2049	-3067	-149	-8	0	0	0	10	499	10487	21514	9089	11184	8185	736	68761
375	-814	-1142	-1452	-29	0	0	0	0	6	221	4536	9028	5557	3534	3207	379	29905
425	-670	-755	-250	0	0	0	0	0	2	87	2920	6223	1939	1205	454	108	14612
475	-96	-267	0	0	0	0	0	0	0	0	1085	1717	0	0	75	5	3246
525	-79	0	0	0	0	0	0	0	0	0	0	1162	0	0	0	10	1251
575	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
total	7997	9989	16021	5097	1128	385	367	633	1961	7184	66676	122040	74191	65943	39966	7925	427505

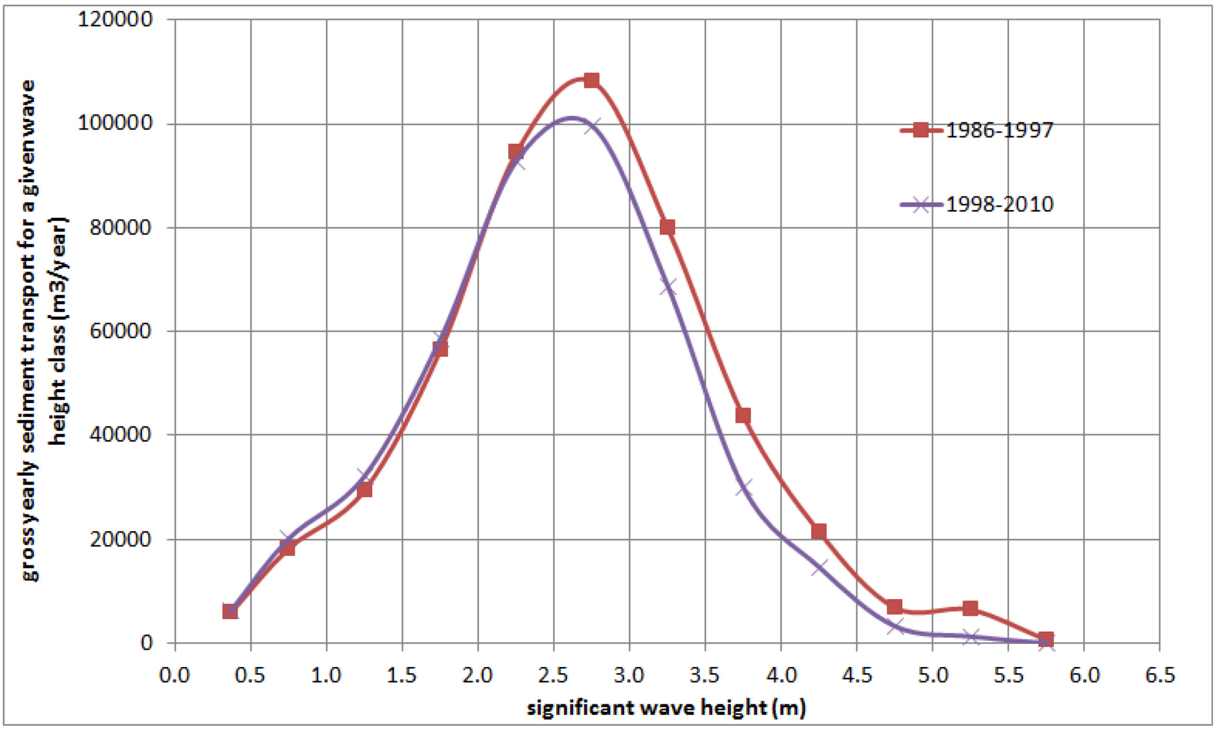


Figure 6-33 Gross yearly sediment transport for 2 decades as function of the wave height

Figure 6-33 gives the total contribution to the gross yearly sediment transport per wave height class (taking into account the occurrence of the wave class and the transport associated with this wave class). In this figure, it is visible that the difference between 1986-1997 and 1998-2010 is mainly due to a higher percentage of occurrence of wave heights larger than 2.5m in the first time period.

The average yearly gross longshore sediment transport is in the period 1986-1997 about 10% larger than in the period 1998-2010 (471.000m³/year vs 427.000 m³/year) (for these calculations all data are taken into account, so also the data of years with less than 80% data availability). This difference seems too small to explain the different morphodynamic behavior for these 2 time periods.

Although the difference is small, it should be noted that these high waves often occur together with high water levels and thus these waves cause much more visible damage to the beaches.

6.1.3 Conclusion

Both the difference in wave climate and the difference in relative crest height of the groins can partly explain the much higher morphological activity in the period 1986-1997, but this cannot be the only explanation. The general change in bathymetry might have an effect on the current and wave climate. This should be investigated further by numerical modelling. Also a general stabilisation after the extension of the harbour of Zeebrugge is expected. It should be noted that the biggest change in trend is at the sea bottom (below the -4m TAW contour) in Knokke-Heist (=Appelzak) (so nourishments probably have also limited influence).

6.2 Western Scheldt mouth

At a geological scale, the coastal zone between Zeebrugge and the Zwin is part of the mouth of the Western Scheldt estuary. The tidal currents in front of the coast are influenced by the water exchange with the estuary. Changes in sediment transport in the estuary probably have only an indirect effect due to changes in the bathymetry of the mouth (long term effects). For this reason the sediment exchange is only discussed briefly.

The sediment balance of the Western Scheldt mouth is examined in various studies, using bathymetrical difference maps, which are tried to be related to net sediment transport. Van der Slikke (1997 & 1998) describes the volume changes for the Dutch part. Between 1969 and 1993 about 115 ± 70 Mm³ disappeared from the mouth area. Possible causes are natural developments and human interference (dredging and dumping, construction of Zeebrugge, Eastern Scheldt-closure, …). It is also noted that the measuring inaccuracy is relatively high. The sediment is distributed to the Flemish coast, the North Sea, the Westernscheldt and the mouth of the Easternscheldt.

Haecon (2000) and Nederbragt & Liek (2004) concluded that the Scheldt exports about 7 Mm³/year (based on bathymetrical difference maps).

Bolle et al (2010) used a numerical model and found for 1970, 1983 and 2002 a net import of sand from the delta to the Scheldt.

Different literature sources give conflicting numbers and directions. It is also possible that the net direction of sediment transport is different for sand and mud.

From literature mentioned in this chapter, it can be concluded that the Scheldt changed from a sand importing to a sand exporting system. BMM (pers. communication) suggests that the exchange of sand with the Scheldt is also related to the 18.6 year – tidal cycle, but Nederbragt and Like (2004) did not find a correlation. At this moment, we might be at a minimum level of sand in the Western Scheldt mouth, suggesting that also in the area between Zeebrugge and Zwin the volume of sand will increase (or the decrease will slow down). However, e.g. Haecon (2006) estimates a general loss of sediment (no distinction between sand and mud) between 1972 and 2004, without a cyclic behavior).

It can, for this report, be concluded that it is not yet exactly known how the sand balance of the Western Scheldt works / evolves in time. Given the rather limited effect on the beaches between Zeebrugge and Zwin when looking to a relative short time interval, this is not worked out in detail. Readers are referred to the resp. references.

6.3 Paardenmarkt/Appelzak

6.3.1 Introduction

Until the beginning of the 20th century the Appelzak was flood dominated (cf. chapter 3), but now, it is known as an ebb-dominated gully. The landward slope below LW is steep (1/25) (due to the scouring of the Appelzak). Such steep slopes limit the possibility of beach recovering after storms during calm weather. During such a recovering, normally sand is moved from offshore to onshore on the beaches, but this is only possible if the slopes are not too steep. During storms, the sand is transported to the Appelzak and can be transported by the alongshore tidal current (in both directions). This explains the relatively high erosion rates for Knokke-Zoute and Lekkerbek.

6.3.2 Evolution of the Appelzak

Figure 6-34 shows the section averaged cross shore profiles for Knokke-Zoute, from which the evolution of the Appelzak in cross shore direction can be seen (based on data obtained in Eurosense(1998)) . The data are used to present some characteristics of this gully (next figures).

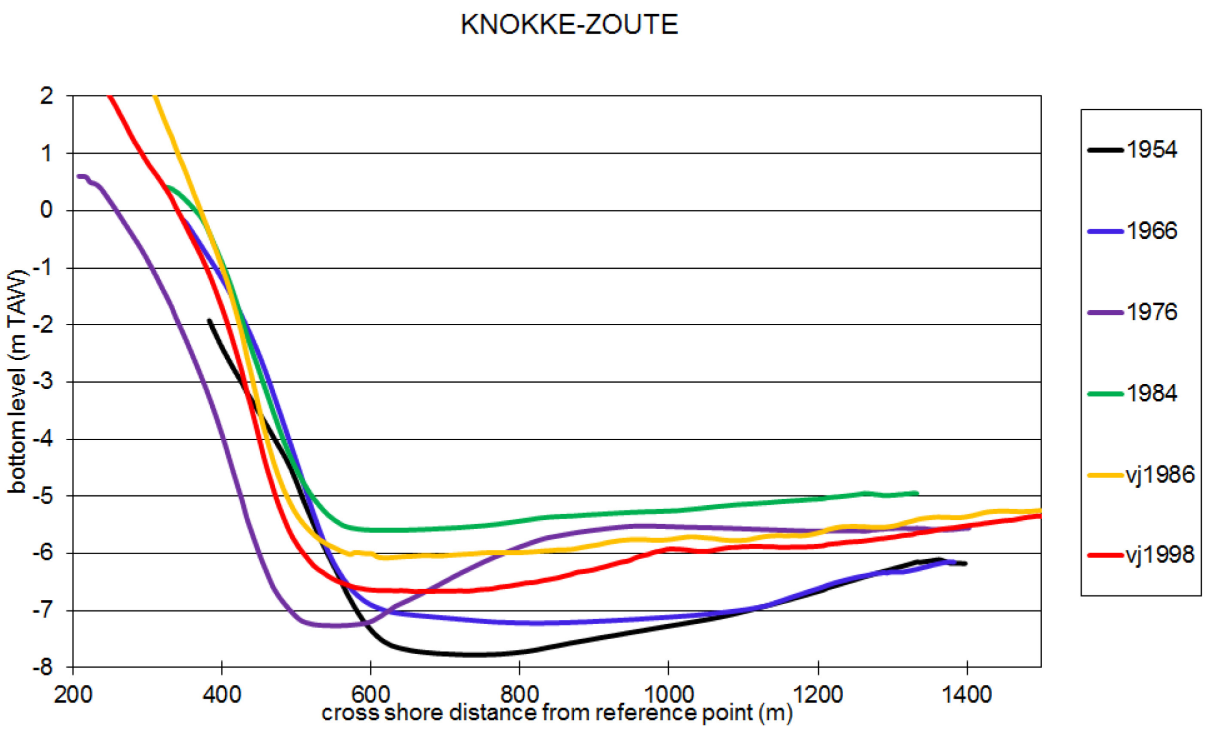


Figure 6-34 Selection of section-averaged cross shore profiles for Knokke-Zoute

In Figure 6-35 the position of the onshore contourlines of -1, -3 and -5m TAW are followed in time. Their movements represent the onshore/offshore movement of the Appelzak. In Figure 6-36 the maximum depth and the depth at x=1200m is shown. The depth at x=1200m is an indication of the behavior of the offshore slope of the gully, a deepening means an offshore movement of this slope.

As can be seen, the Appelzak moved slowly onshore between 1955 and 1972, together with a decrease in depth (note that between 1900 and 1930, the gully moved already 700m onshore (Van Cauwenberge, 1966)). In 1976, after a severe storm, the Appelzak moved about 50m more onshore than its position at the last available measurement before this storm (1974). Also to the North (Paardenmarkt), strong sedimentation is visible at that time (cf. right part in Figure 6-34). The nourishments of 1977-1979 artificially moved the gully about 100m offshore. The depth of the gully decreased between 1979 and 1984 (cf Figure 6-36), which might be explained by cross-shore transport of nourished (1979) sand, however, the decrease in depth occurred over a long cross shore distance up to 1984. Also between 1979 and 1984,the -5m contour is moving offshore, while the -1 and -3m TAW contour are already moving onshore. But since 1984 (after harbor construction and the large nourishment), the onshore movement continued at all depths at a rate of 2m/year for the slope at the onshore side of the gully while the slope at the offshore side of the gully did not move onshore, but seems to remain stable (more recent developments show also landward movement, cf. Figure 6-13). However, the maximum depth of the gully increases.

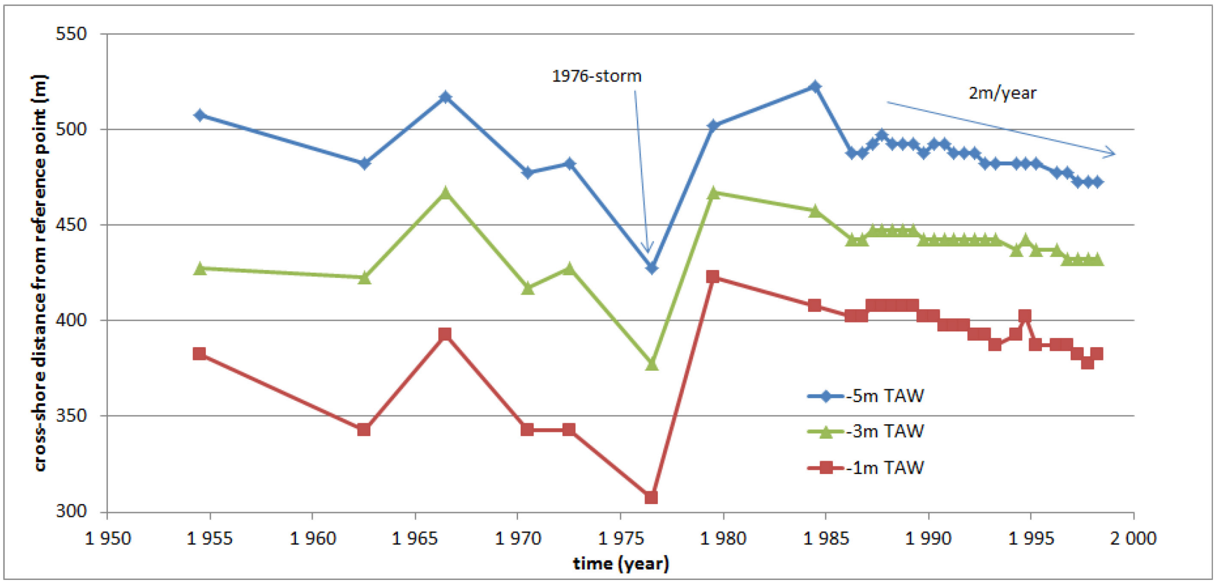


Figure 6-35 Movement of contourlines Appelzak

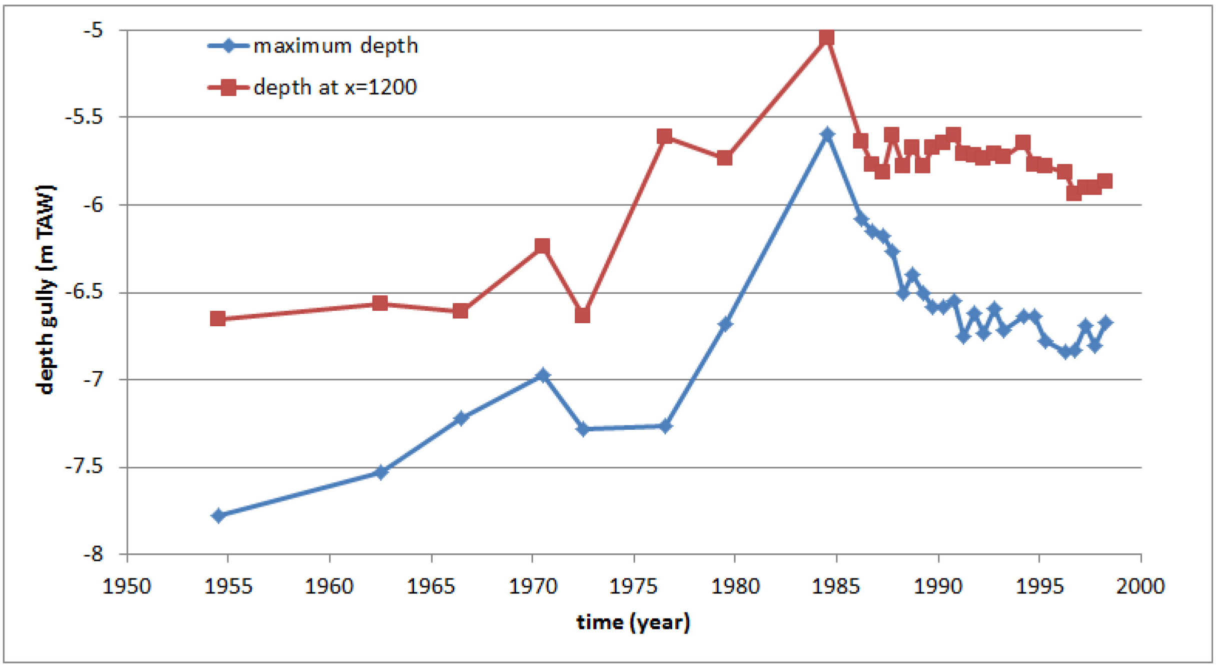


Figure 6-36 Maximum depth of the Appelzak

In Figure 6-37 the same evolution is visible, looking to the change in surface area below -6m TAW. The area decreased from 900m^2 to 0m^2 from 1954 to 1985. It looks like the further landward movement of the Appelzak is blocked by the (steep) beaches, while offshore a sediment flux causes sedimentation of the gully. But since that time, the deep area of the gully grows again, initially at a rate of 25m2/year, slowing down since 1992. This growth occurs over a wide (cross shore) distance (600m). The change in trend starts in 1984, suggesting that it is influenced by the extension of the harbour of Zeebrugge.

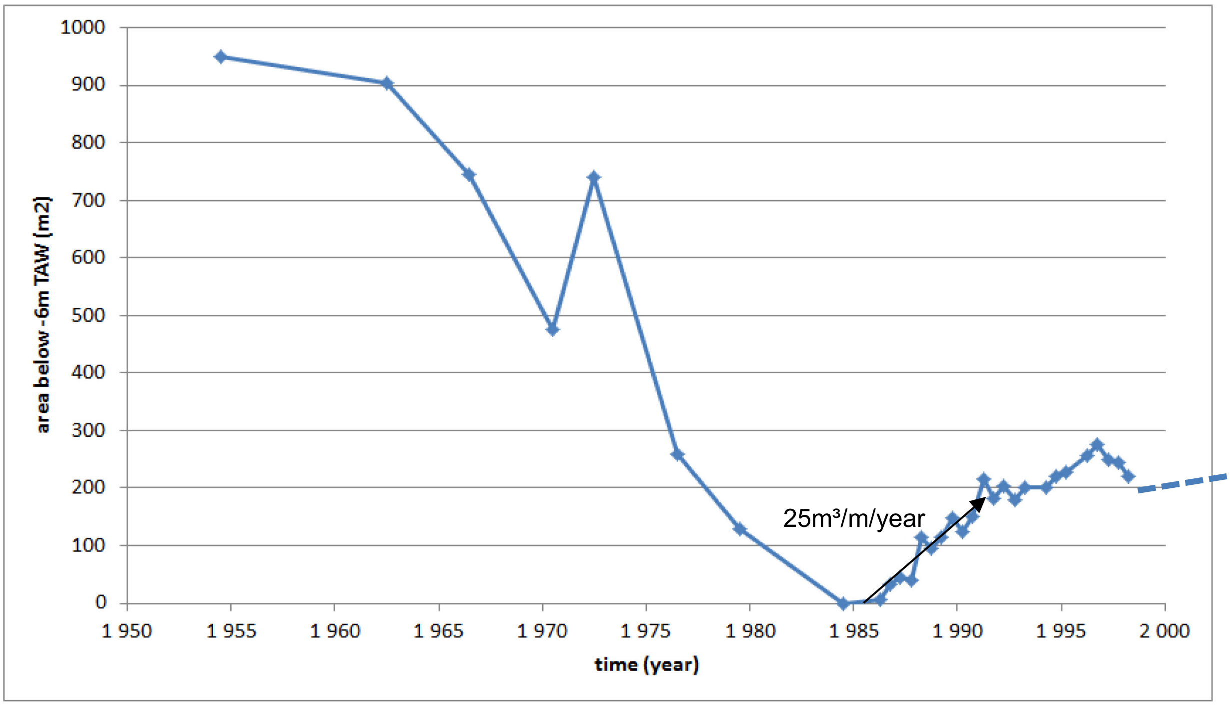


Figure 6-37 Area below the -6m TAW (dotted line based on the observation that recent data do not show much evolution anymore below -6m TAW, cf. e.g. Figure 6-40)

Unfortunately, the coastal unit averaged profiles are only available up to 1998. However, if the evolution of the shoreface (between -1 and -4 m TAW) and the sea bottom (from -4m TAW contour up to 1500m offshore) as reported by Houthuys (2012) are interpreted (for the section Knokke-Zoute), some indications can be found. The cross shore distance of the shoreface is about 100m and 1000m for the sea bottom (looking at Figure 6-34). Dividing the evolution of the volumes by these widths and the length of the coastal unit (2200m) gives an indication of the change in bottom level. Figure 6-38 suggests that since 1995-1998 a stabilization of the shoreface occurred (with important short term oscillations), while the sea bottom erosion slows down considerably. This corresponds (probably not accidentally) with the stabilization of the general sediment budget of the whole Zeebrugge-Zwin area.

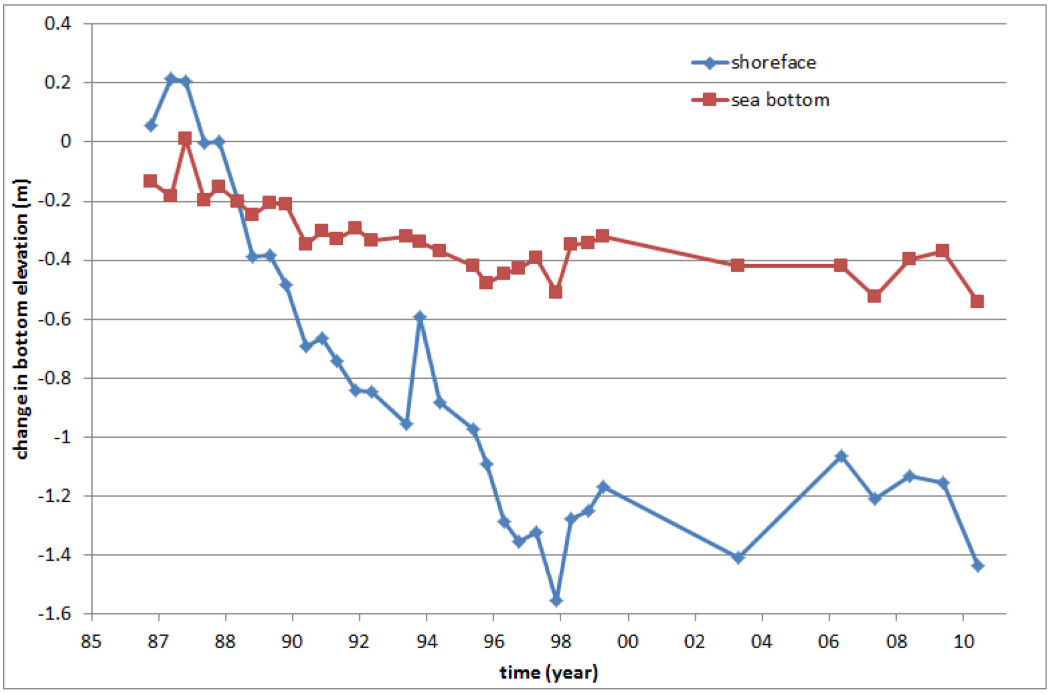


Figure 6-38 Change in bottom elevation for the coastal unit Knokke-Zoute

Verbanck (1999) describes the evolution of the Appelzak western boundary (assuming that the -6m contour is the boundary).(Figure 6-39). As can be seen on Figure 6-40 – profile 7, this boundary is stable since 1998.

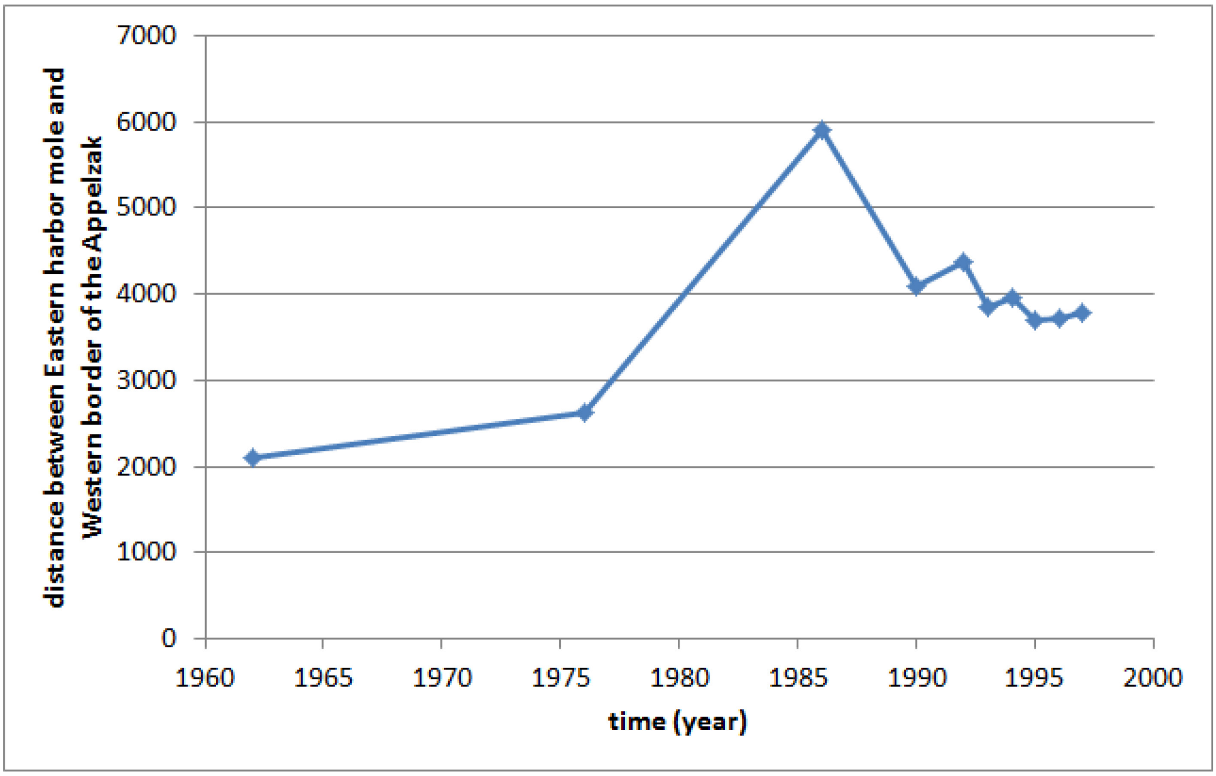
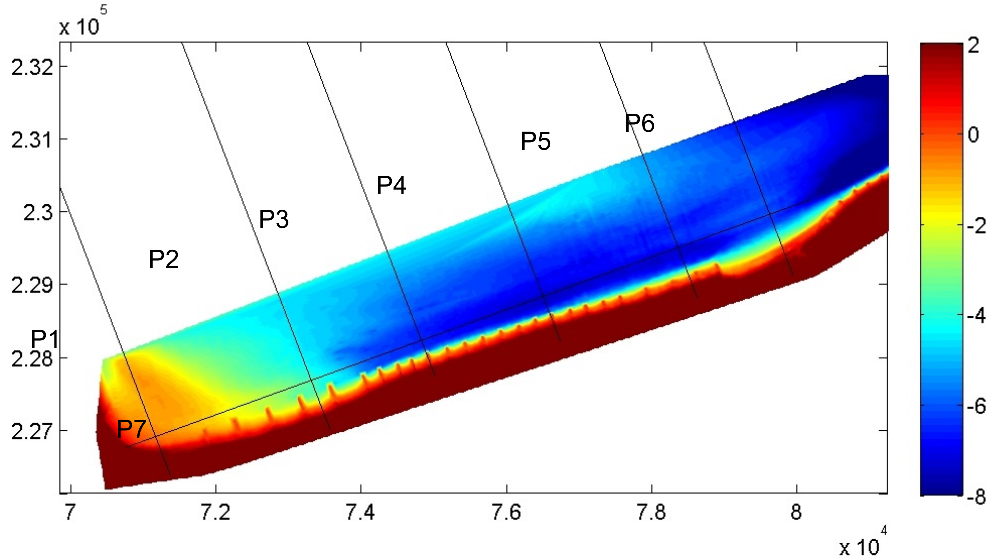


Figure 6-39 Position of the Western boundary of the Appelzak

Using the cross shore profiles P1 to P6 and a profile through the Appelzak (P7) the recent evolution of this gully can be seen:



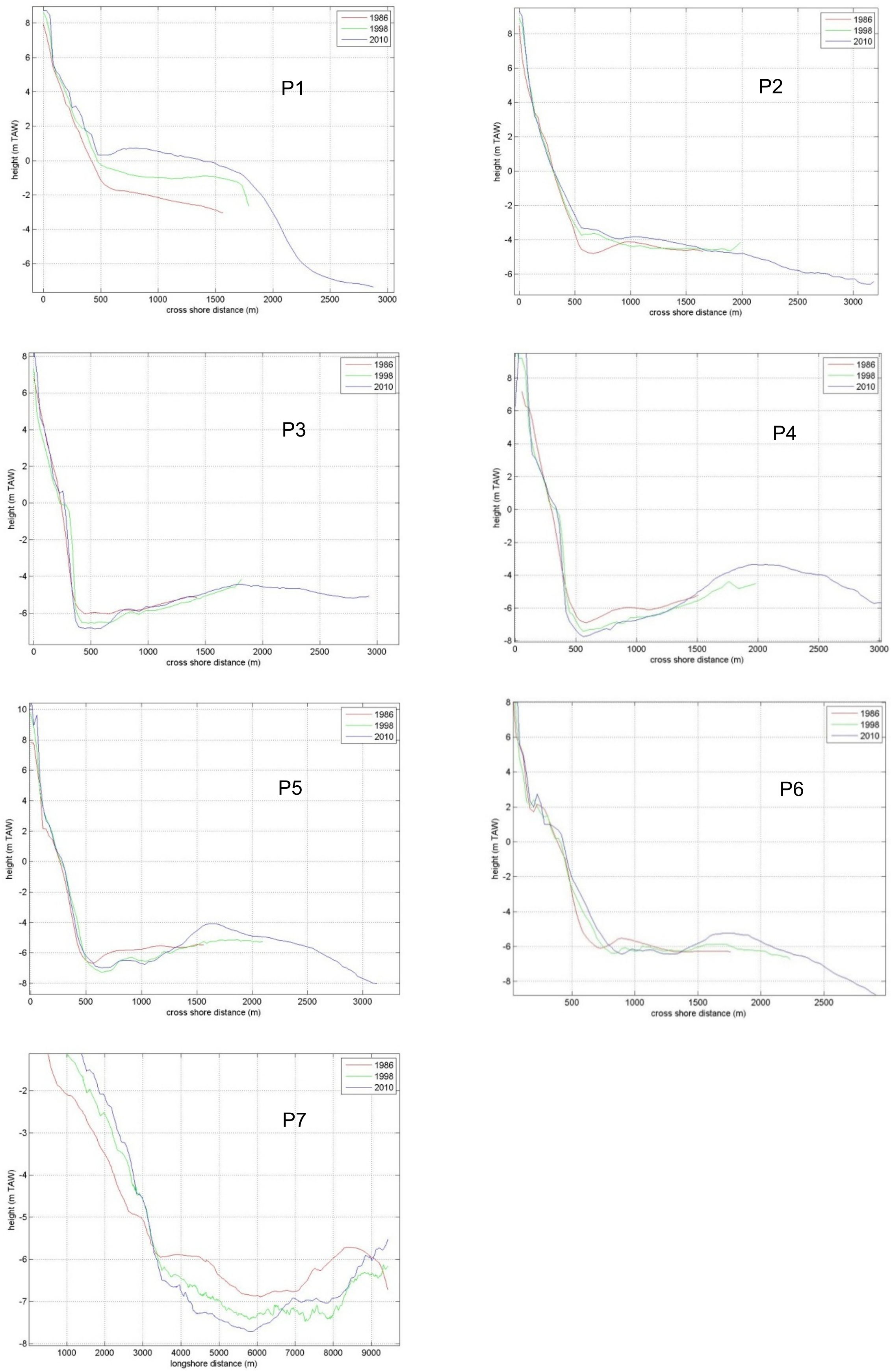


Figure 6-40 Evolution of cross shore profiles

From these figures it can be concluded that:

- The rate of deepening of the gully is decreasing significantly
- In the eastern part the change in rate is uniformly spread over the whole cross section
- In the Western part a big growth of the bank (offshore) can be seen, but also the gully is becoming somewhat less deep
- the Appelzak gully is shifting to the east

6.3.3 Transport in the Appelzak

The Appelzak has the shape of a ebb dominated gully (open to the Scheldt). However, only few data exist to judge whether the net sand transport in the gully is ebb or flood dominated. The tracer experiments (before the harbor extension) give different results (cf. chapter 3). Also the numerical modeling (cf. §4.1) give a mixed image. Probably, sand is transported in both directions and the net transport depends on the wave climate.

In the last decade, the beaches of Knokke-Zoute and Lekkerbek (over 4500m) lost about 50.000m³/year. Probably, a significant part moved into the Appelzak. Since the Appelzak was stable/slightly erosive, this volume has to be transported out of the Appelzak.

6.3.4 Short Description of the Paardenmarkt

Missiaen and Henriet (2002) studied the Paardenmarkt and concluded:

- The bottom sediments are a mixture of sand and mud, probably because of the dumping zone Br&W Zb Oost.
- Between 1954 and 1976 erosion occurred (which could explain why munition was found by divers in 1972)
- Since the harbor extension the sediment volume increased considerably (up to 4m in the SW-corner, decreasing towards the north). Northwest of the dumping zone, erosion occurs. This erosive area seems to move to the east.

The dump site is located in a turbidity maximum area hydraulically trapping the muddy deposits Missiaen and Henriet (2002). Calculated residual transport directions based on bottom sediment variations confirm the flood dominance in the area and indicate a coastward transport near the munition dump site (but just south of the area, the net transport is directed northward). Towards the East of the dump site, the ebb tidal current seems to induce an important net ebb-directed bedload transport Missiaen and Henriet (2002).

Charlet (2001) (thesis RCMG of Ghent University) states that “Generally bedforms are rare which is mainly due to the prominence of very fine to fine sands, largely enriched with mud. Small to medium dunes do occur north of the sandy shoal and along the eastern extremity of the Paardenmarkt munition dumpsite with a strike more or less perpendicular to the coastline. Interestingly a field of large to very large dunes (with dune heights of up to 2 m) occurs north of the Paardenmarkt shoal in the Wielingen area. On the basis of the characteristics of the small to medium dunes, transport directions can be deduced more or less parallel to the coastline, but as well flood- as ebb-dominated. Given the shallowness of the area (-2 to -10 m MLLWS) it seems likely that these bedforms are too sensitive to be used for residual transport directions. The large to very large dunes have also a strike more or less perpendicular to the coastline. Interestingly, the western dunes have a flood dominated asymmetry whilst some dunes at the eastern part are ebb-dominated. A zone of symmetrical dunes exists between both. Together with the sediment trend analysis results and numerical modelling, it can be deduced that the field of larger dunes represents a zone of bedload convergence, which can slightly shift in space according to the ruling hydro-meteorological conditions”.

6.4 The Zwin

The Zwin is a tidal inlet which is not stable. The tidal prism is about 250.000 m³ (modeled) – 400.000m³ (based on DTM) at spring tide (IMDC, 2007), while the longshore sand transport is order of magnitude 100 to 500.000m³/year, giving a Bruun parameter (ratio of tidal volume over longshore transport) between 1 and 4, while 20 is required for a stable situation. In the coming years, the Zwin area will increase with about 120ha and the tidal prism will increase up to 1 million m³, increasing the Bruun parameter with a factor of 4. It should be noted that the gully in the inlet part is restricted to above the +2m TAW contour (cf. Figure 6-20), so only part of the longshore sediment transport is passing over the gully mouth. This might make the Bruun rule less applicable in this situation.

Due to the permanent vegetation in the Zwin, the precision needed to detect the changes related to sedimentation at the year-timescale is lacking. Nevertheless, some indications can be obtained from earlier calculations of the tidal prism.

E.g. Kerckaert (1989) reports that the tidal prism did hardly change between 1973 and 1986. He reports a tidal prism, based on a DTM of 103.000m³, taking into account an averaged tide, while IMDC (2006) reports, with data of 2000 a tidal prism of 126.000m³ in the same circumstances. Assuming a sedimentation rate of 2 cm/year (reported by DHV (only at some specific areas in the Zwin) based on numerical modeling) in the whole Zwin seems conservative, even in the periods without the presence of a sand trap pit in the entrance. Given the surface of the area (about 100ha), a sedimentation rate of 2 cm/year would require an input of 20.000 m³/year.

Houthuys et al (2013) estimates the sediment input at 3.000m³/year, assuming that all the sedimentation of sand in the sand pits is only caused by the sedimentation of sand due to the presence of the pit, sand that otherwise would flow back to the sea. If this sand would otherwise not flow back to the sea, but would sedimentate at another location, the sand input would be 41.000m³/year.

Also the bathymetry of the gullies is not measured regularly. For some years, a sand trap pit was dug and monitored. Houthuys (2013) reports that between 1990 and 2003 about 550.000m³ was removed for the sand pit and 200.000m³ for the relocation of the channel. This is about 55.000m³/year. In Figure 6-41 (Eurosense, 1996) the evolution of the volume is estimated. E.g. in 1992 90.000m³ was removed and in the year after (with a lot of storms) about 40.000 m³ was sedimentated. The report also mentions that before the digging of the sand pit (period 1987-1989 the Southern part (main channel, former lakes M1 and M2) of the Zwin sedimentated at a rate of 15.000m³/year. After the digging and maintenance, no more sedimentation was observed at this location. In the Western part, the only available observation was that the bottom was stable after the digging-works.

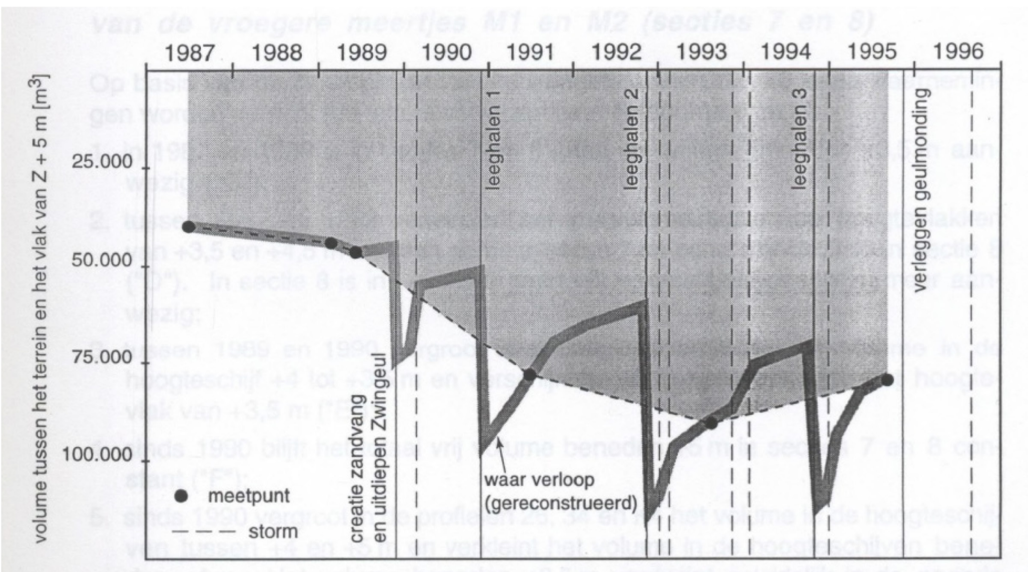


Figure 6-41 Evolution of the sand pit (Eurosense, 1996)

This is not necessarily the sand input in the Zwin because a) the sand pit also catches sediments that otherwise would flow out of the Zwin and b) it cannot be excluded that the sand pit was already filled after a shorter period.

It can be concluded that the input of sand is between 3.000 and 40.000 m³/year, but probably maximally 20.000m³/year. It should be noted that in the inlet coarse/medium sand is found in the offshore part and medium/fine sediment in the onshore part of the entrance (Bowman, 1993).

This input is mainly caused by the tidal asymmetry. The longshore sediment transport also pushes the entrance channel to the east. Between 1980 and 1989 (before human interference started), this rate was on average 23m/year (while Econnection, 2004 report 50 to 75m/year). It would be interesting to examine the rate in the last years, when the Zeebrugge-Zwin area was much more stable and human interference in the Zwin was nihil.

7 Conclusions

The coastline between Zeebrugge and the Westerscheldt is rather straight. However, the area is very complex due to the presence of the harbour of Zeebrugge and the Westerscheldt. At Baai van Heist about 200.000m³/year of sediments are being deposited since the extension of the harbour in 1979-1985. The sediment is probably coming from around the harbour of Zeebrugge, which compensated in some extent the blocked longshore transport due to the presence of the harbour, but probably the material is much finer compared with the lost input of longshore transport. At the deposition area at Baai van Heist sand is found (about 100 to 120 µm), but the material in suspension consist mostly of fine (<63µm) sediments and also the material at the erosion areas around the harbour consists of very fine sediments (but based on a limited number of measuring points).

In front of Knokke-Heist the beaches are eroding due to the presence of the Appelzak-gully. The Appelzak shows a long term landward movement. However the movement and development of the gully seems to slow down during the last 10 years. Some figures indicate that during the last decade some equilibrium is reached. Looking to the long term behaviour of the Appelzak, it seems that the last decade was the most stable period of the last century. Although confirmation is needed (both based on further trend analysis and numerical modelling), this might suggest that big scale measures to reduce erosion, might be less necessary. It seems reasonable to monitor at least for some years the next planned large nourishment of the coastal safety plan, before starting important infrastructure works. Possible reasons for the less erosive behaviour during the last decade are the calmer weather and the more pronounced groins (due to the erosion they become relatively more exposed). This report however shows that this can only be part of the explanation. Other possibilities are the more equilibrium state of the system after the extension of the harbour of Zeebrugge..

Consequently, also the erosion in front of Knokke-Heist is clearly slowing down during the last decade. The Appelzak is known as an ebb-dominated gully. However, the net transport pattern in the Appelzak is not clear from available measurements and numerical model output.

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Appendix: Historical evolution sand volumes beach and shoreface

Table 0-1 Evolution shoreface (LW - > -4m TAW) (x 1000m³)

	Wenduine West (168-176)	Wenduine Oost (177 -181)	Blankenberge westelijk deel (182-184)	Blankenberge (185-194)	Zeebrugge – pier (195-210)	Zeebrugge Strand (211-216)	Heist (217-221)	Duinbergen (222-226)	Albertstrand (227-232)	Zoute (233-241)	Lekkerbek (242-249)	Zwin (250-255)
length	1800	1200	640	2075	2372	837	800	1670	1400	2200	2300	1600
1954-1966	311	462	166	270	33	251	240	835	700	440	575	-
1966-1976	-364	-230	-192	-540	-318	-117	-400	-752	-700	-990	-575	-320
1976-1986	256	24	0	332	263	1143	3880	2422	560	880	1035	80
1986-1997	-146	-23	-32	238	970	1000	700	1400	11	-290	-22	65
1997-2010	70	31	-6	319	2040	500	2954	2734	2449	720	1310	390

Table 0-2 Evolution sea bottom (-4m TAW - > 1500m offshore) (x 1000m³)

	Wenduine West (168-176)	Wenduine Oost (177 -181)	Blankenberge westelijk deel (182-184)	Blankenberge (185-194)	Zeebrugge – pier (195-210)	Zeebrugge Strand (211-216)	Heist (217-221)	Duinbergen (222-226)	Albertstrand (227-232)	Zoute (233-241)	Lekkerbek (242-249)	Zwin (250-255)
length	1800	1200	640	2075	2372	837	800	1670	1400	2200	2300	1600
1954-1966	297	145	128	125	111	62	320	835	420	550	690	0
1966-1976	-900	-540	-259	-332	-403	-178	-200	-919	-280	1100	-115	480
1976-1986	-277	-204	-179	-166	778	201	720	2171	1540	880	690	0
1986-1997	-967	-306	-150	-50	-30	69	38	50	20	-1000	-1100	-390
1997-2010	294	148	120	229	190	2	0	7	520	172	85	481

Table 0-3 Nourishment volumes (+) or extraction volumes (-) (-4m TAW - > 1500m offshore) (x 1000m³)

	Wenduine West (168-176)	Wenduine Oost (177 - 181)	Blankenberge westelijk deel (182-184)	Blankenberge (185-194)	Zeebrugge - pier (195-210)	Zeebrugge Strand (211-216)	Heist (217-221)	Duinbergen (222-226)	Albertstrand (227-232)	Zoute (233-241)	Lekkerbek (242-249)	Zwin (250-255)
lengte	1800	1200	640	2075	2372	837	800	1670	1400	2200	2300	1600
1954-1966							83	174	146	230	240	167
1966-1976							522	0	0	0	0	0
1976-1986	not reported, probably small						part of the 8.5 million m³ nourishment					
1986-1997	-16	0	-1400	1436	0	0	287	-4	0	-6	-3	0
1997-2010	56	-28	-1000	805	-13	0	0	-36	0	90	20	0

(*) in this decade also the harbor moles of Zeebrugge were constructed, making this period anyway difficult for morphological analysis

The 1.2 milj. M³ nourishment after the 1953 storm (1955-1957) is assumed to be distributed uniformely over the area. In 1973-1976 dumped material was dumped in the Appelzak to counter the erosion of the Appelzak gully. This volume is not incorporated.

Table 0-4 net (corrected) effect below LW (x 1000m³)

	Wenduine West (168-176)	Wenduine Oost (177 - 181)	Blankenberge westelijk deel (182-184)	Blankenberge (185-194)	Zeebrugge - pier (195-210)	Zeebrugge Strand (211-216)	Heist (217-221)	Duinbergen (222-226)	Albertstrand (227-232)	Zoute (233-241)	Lekkerbek (242-249)	Zwin (250-255)
length	1800	1200	640	2075	2372	837	800	1670	1400	2200	2300	1600
1954-1966	608	607	294	394	145	313	560	1670	1120	990	1265	-
1966-1976	-1264	-770	-451	-872	-721	-295	-600	-1670	-980	110	-690	160
1976-1986	-22	-180	-179	166	1041	1343	volume increase of 15 million m³, partly due to the nourishment					
1986-1997	-1097	-329	1218	-1248	940	1069	451	1454	31	-1284	-1120	-325
1997-2010	308	207	1114	-257	2243	502	720	1353	910	111	0	831

Table 0-5 net (corrected) effect below LW in m³/m/year

	Wenduine West (168-176)	Wenduine Oost (177 - 181)	Blankenberge westelijk deel (182-184)	Blankenberge (185-194)	Zeebrugge - pier (195-210)	Zeebrugge Strand (211-216)		Heist (217-221)	Duinbergen (222-226)	Albertstrand (227-232)	Zoute (233-241)	Lekkerbek (242-249)	Zwin (250-255)
length	1800	1200	640	2075	2372	837		800	1670	1400	2200	2300	1600
1954-1966	28	42	38	16	5	31		58	83	67	38	46	-
1966-1976	-70	-64	-71	-42	-30	-35		-75	-100	-70	5	-30	10
1976-1986	-1	-15	-28	8	44	161		volume increase of 150m³/m/year, partly due to nourishment					
1986-1997	-55	-25	173	-55	36	116		51	79	2	-53	-44	-18
1997-2010	13	13	134	-10	73	46		69	62	50	4	0	40

Table 0-6 Beach evolution (above LW) (x1000m³)

	Wenduine West (168-176)	Wenduine Oost (177 - 181)	Blankenberge westelijk deel (182-184)	Blankenberge (185-194)	Zeebrugge - pier (195-210)	Zeebrugge Strand (211-216)		Heist (217-221)	Duinbergen (222-226)	Albertstrand (227-232)	Zoute (233-241)	Lekkerbek (242-249)	Zwin (250-255)
length	1800	1200	640	2075	2372	837		800	1670	1400	2200	2300	1600
1986-1997	231	-35	20	270	75	420		226	73	-42	-605	-100	-104
1997-2010	79	150	90	132	740	330		-12	245	66	192	186	100

Table 0-7 Beach nourishments (above LW) (x1000m³)

	Wenduine West (168-176)	Wenduine Oost (177 - 181)	Blankenberge westelijk deel (182-184)	Blankenberge (185-194)	Zeebrugge - pier (195-210)	Zeebrugge Strand (211-216)		Heist (217-221)	Duinbergen (222-226)	Albertstrand (227-232)	Zoute (233-241)	Lekkerbek (242-249)	Zwin (250-255)
length	1800	1200	640	2075	2372	837		800	1670	1400	2200	2300	1600
1986-1997	59	0	0	476	10	0		399	0	0	0	3	14
1997-2010	541	128	80	634	390	-670		0	153	40	674	121	0

Table 0-8 Net(corrected) Beach evolution (above LW) (x1000m³)

	Wenduine West (168-176)	Wenduine Oost (177 - 181)	Blankenberge westelijk deel (182-184)	Blankenberge (185-194)	Zeebrugge - pier (195-210)	Zeebrugge Strand (211-216)		Heist (217-221)	Duinbergen (222-226)	Albertstrand (227-232)	Zoute (233-241)	Lekkerbek (242-249)	Zwin (250-255)
length	1800	1200	640	2075	2372	837		800	1670	1400	2200	2300	1600
1986-1997	172	-35	20	-206	65	420		-173	73	-42	-605	-103	-118
1997-2010	-462	22	10	-502	350	1000		-12	92	26	-482	65	100

Table 0-9 Net (corrected)Beach evolution (above LW) (in m³/m/year)

	Wenduine West (168-176)	Wenduine Oost (177 - 181)	Blankenberge westelijk deel (182-184)	Blankenberge (185-194)	Zeebrugge - pier (195-210)	Zeebrugge Strand (211-216)		Heist (217-221)	Duinbergen (222-226)	Albertstrand (227-232)	Zoute (233-241)	Lekkerbek (242-249)	Zwin (250-255)
length	1800	1200	640	2075	2372	837		800	1670	1400	2200	2300	1600
1986-1997	9	-3	3	-9	2	46		-20	4	-3	-25	-4	-7
1997-2010	-20	1	1	-19	11	92		-1	4	1	-17	2	5

Table 0-10 Total net (corrected) beach evolution (beach, shoreface and sea bottom) (in 1000m³)

	Wenduine West (168-176)	Wenduine Oost (177 - 181)	Blankenberge westelijk deel (182-184)	Blankenberge (185-194)	Zeebrugge - pier (195-210)	Zeebrugge Strand (211-216)		Heist (217-221)	Duinbergen (222-226)	Albertstrand (227-232)	Zoute (233-241)	Lekkerbek (242-249)	Zwin (250-255)
length	1800	1200	640	2075	2372	837		800	1670	1400	2200	2300	1600
1986-1997	-925	-364	1238	-1454	1005	1489		278	1527	-11	-1889	-1222	-443
1997-2010	-154	229	1124	-759	2593	1502		708	1445	936	-371	65	931

Table 0-11 Total (corrected) beach evolution (beach, shoreface and sea bottom) (in m³/m/year

	Wenduine West (168-176)	Wenduine Oost (177 - 181)	Blankenberge westelijk deel (182-184)	Blankenberge (185-194)	Zeebrugge - pier (195-210)	Zeebrugge Strand (211-216)		Heist (217-221)	Duinbergen (222-226)	Albertstrand (227-232)	Zoute (233-241)	Lekkerbek (242-249)	Zwin (250-255)
length	1800	1200	640	2075	2372	837		800	1670	1400	2200	2300	1600
1986-1997	-47	-28	176	-64	39	162		32	83	-1	-78	-48	-25
1997-2010	-7	15	135	-28	84	138		68	67	51	-13	2	45

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