National analysis of nourishments;

Coastal state indicators and driving forces for Zandvoort-Bloemendaal, the Netherlands

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1 Introduction

1.1 Background information

This report is one of three reports written as the Dutch contribution to the *"co-analyses of nourishments"*, within the Interreg Building with Nature project work package 3; coastal resilient laboratories. In each report a single coastal laboratory is discussed. The coastal laboratories in the Netherlands are: Domburg, Zandvoort-Bloemendaal and Bergen-Egmond, see Figure 1. For each coastal laboratory a specific time window, several years after nourishment, is investigated. Each laboratory is chosen such that the dominant physical processes and type of applied nourishment are different. This report focusses on the coastal laboratory Zandvoort-Bloemendaal.

The western coastline of the Netherlands mainly consists of sandy dunes combined with hydraulic structures like dams and storm surge barriers. Although the dunes are continuous eroding, they play a major part in the Dutch coastal protection system. Due to human interventions, like sand nourishments, the erosion of the coast is compensated. On average 12 million m^3 of sand is placed in the coastal area of the Netherlands to balance the erosion. It suggests that sand nourishments are almost business as usual.

The coastal laboratory Zandvoort-Bloemendaal is located in the middle of the Dutch western shoreline. It is located west of Amsterdam and south of the port of IJmuiden. The lab is situated at the straight coastline of Noord-Holland.

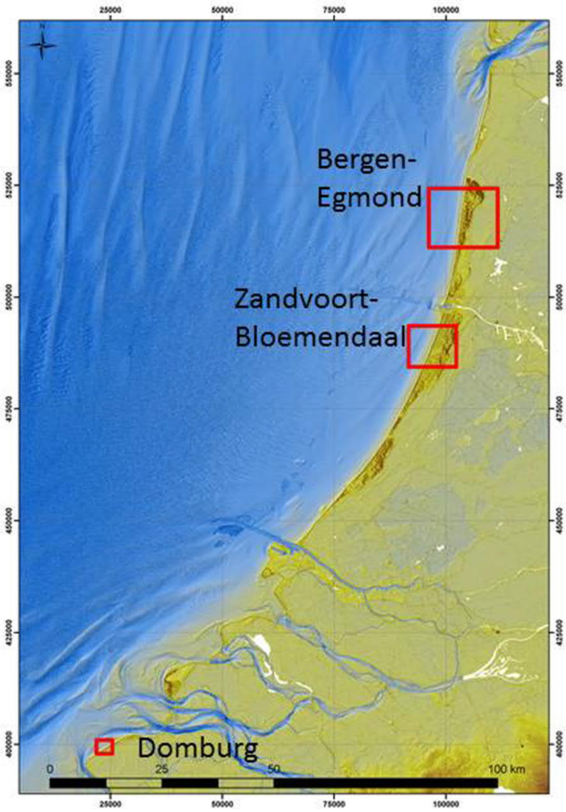


Figure 1: An overview map of the coastal laboratories in the Netherlands

1.2 Objectives

In this study the performance of the shoreface nourishment of 2004/2008 at Zandvoort-Bloemendaal is analysed. The main objective of this study is to obtain key information of the nourishment behaviour in an uniform way, to be able to compare the results with other coastal labs in the Building with Nature project.

1.3 Reading guide

This report consists of 9 chapters. In Chapter 2 the study site is further explained in more detail. The specific nourishment studied in this report is discussed in Chapter 3. The procedure to analyse the nourishment and the applied data is the topic of Chapter 4. Chapter 5 is dedicated to the hydraulic conditions like waves, currents and tides. The conceptual model of source-pathway-receptor for water and sediment is given in Chapter 6. The results of the analyses are given in Chapter 7 and combined into the synthesis of Chapter 8. Finally, the conclusions are given in Chapter 9.

2 Study site

The coastal laboratory Zandvoort-Bloemendaal contains several dune systems. These dunes formed around 5500 year ago in front of the former coast, see Figure 2. Later, the rate of sea level rise reduced and the dunes started to extend seaward. These dunes were dynamic, sometimes they grew but at other moments they were heavily eroded by storms. This dynamic behaviour continued until the 12th century when the conditions became milder and vegetation could settle on the dunes.

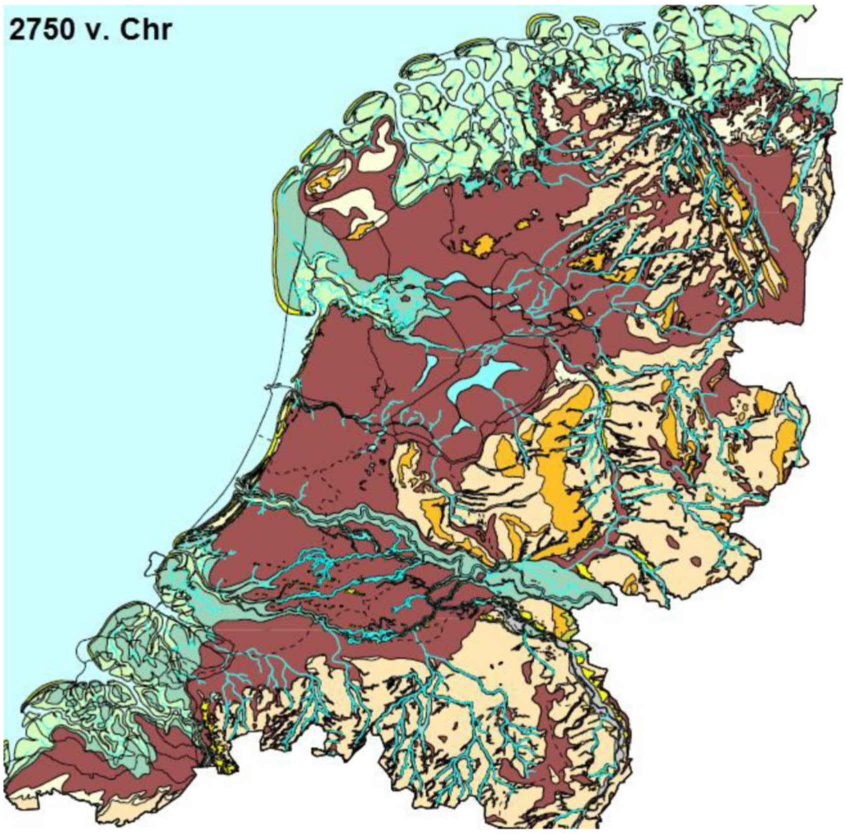


Figure 2: The different areas of the Netherland 2750 v. Chr. The yellow part indicate sand, the brown is peat and the green areas are partly submerged regions for example because of the tides. The thin black line indicate the current location of the Dutch coast.

The dune system we currently know is formed during the Middle Ages. The dunes were constantly moving and were unreliable as a sea defence. To make the dunes more reliable, vegetation (European beach grass) was planted. Furthermore, cattle were no longer allowed to graze on the dunes and the rabbit population was reduced. These measures were effective and stabilized the dunes.

Nowadays this area is more or less stable but is strongly influenced by human interventions. North of Zandvoort-Bloemendaal the IJmuiden sluice complex is located. In front of these sluices two large breakwaters were built (see also 3.1). The breakwaters interrupts the alongshore current and sediment transport. Consequently, sedimentation around the breakwaters takes place, see Figure 3. The sedimentation results in a seaward movement of the coastline with a maximum of 12 m/yr. The material mainly originates from the coastal area further away from the hydraulic structure. Here, the coastline is eroding with an averaged movement of 2.5 m/yr.

Figure 3: Yearly sand volume change (including nourishments) based on the JARKUS transect for -8 till +3m NAP and for -8 till -12 NAP. The black circle indicates the location of the Ijmuiden sluices and breakwaters. (Adjusted from Van Rijn, 2005)

At the shoreface a breaker bar system is present (Figure 4). The properties of these bars (height, size and migration speed) differ over the Dutch coast. In this area, there are 2 to 3 bars present. They migrate offshore with a velocity of 15-50 m/year and 5-25 m/year for the outer and inner bar, respectively. They have a height between 1-2 m and a width of 150-250 m. The natural periodic behaviour of the bars is 4 years.

As stated in the previous paragraph, the natural behaviour of the breaker bars is to migrate offshore. This offshore migration, however, is strongly influenced by sand nourishments. Nourishments in general are placed attached to the outer breaker bar. As a result, the bar system switches in migration direction and start to migrate onshore instead of offshore. The bar is then too large compared to its natural size and starts to erode. Finally, the nourishment is eroded away and the bar system returns to its natural behaviour to migrate offshore.

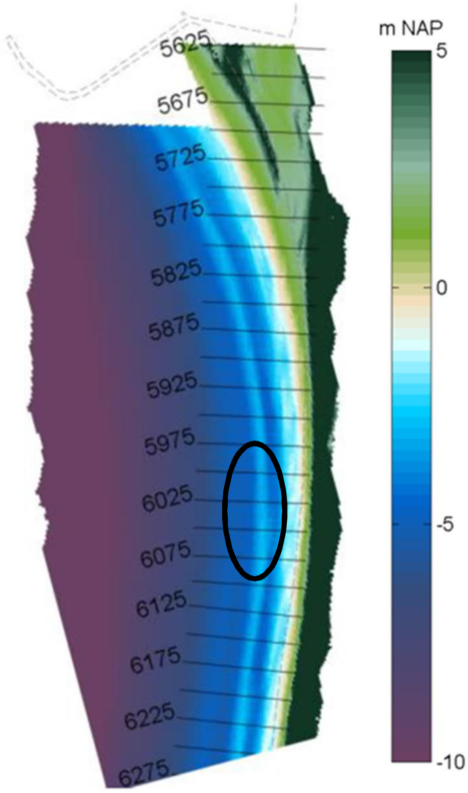


Figure 4: The bathymetry of the region south of the breakwater at Ijmuiden for the year 2000. The numbers indicate the Jarkus transects and the black circle indicates the breaker bars. Adjusted from (Kuijper, Nederhoff, & Vergouwen, 2015)

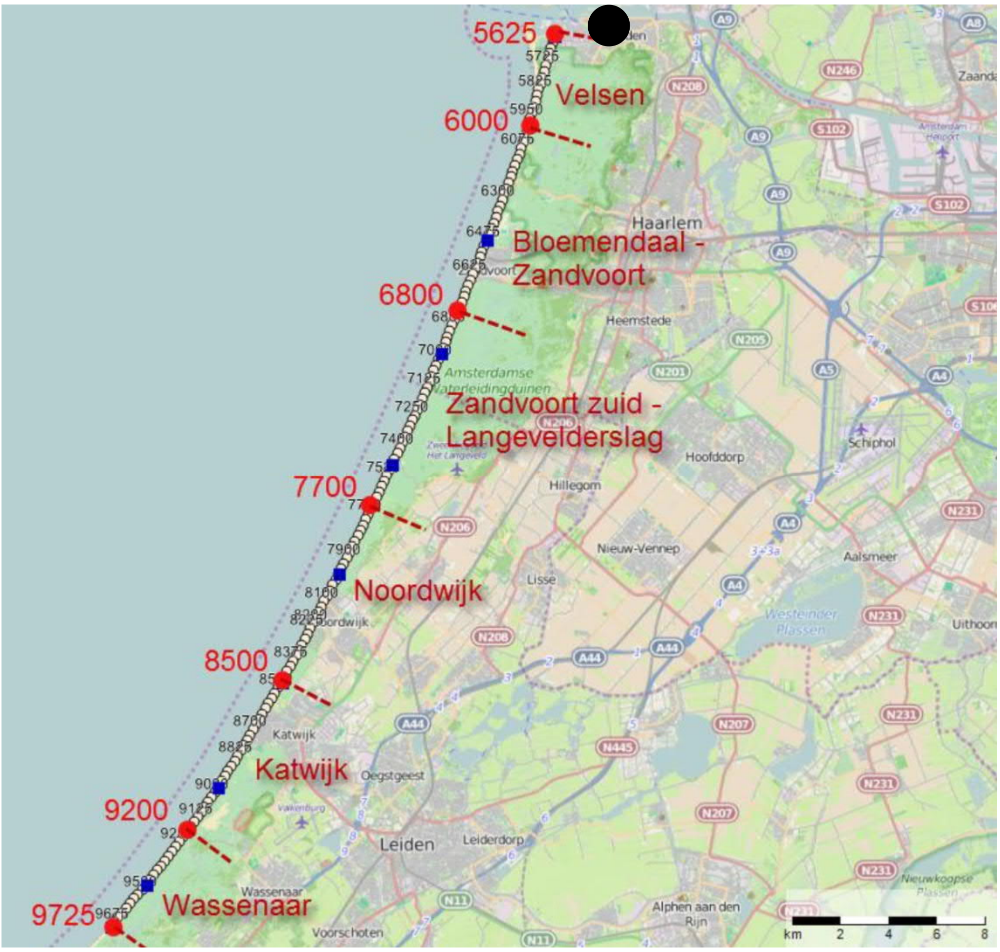


Figure 5: A map of the area around Zandvoort-Bloemendaal. The numbers indicate the different Jarkus transects. The black dot indicates IJmuiden were large breakwaters and sluices are located. Adjusted from (Kuijper, Nederhoff, & Vergouwen, 2015)

3 Nourishment description

3.1 Coastal infrastructure and earlier nourishments

For the coastal laboratory Zandvoort-Bloemendaal the major works in the vicinity are the extension of the Ijmuiden's breakwaters in 1962, see Figure 14. The breakwaters were extended to 2800 m offshore for the southern and 1850 for the northern breakwater. Due to the extension, the alongshore sediment transport is completely blocked. Consequently, in the areas just north of the northern breaker and south from the southern breakwater sedimentation started to occur.

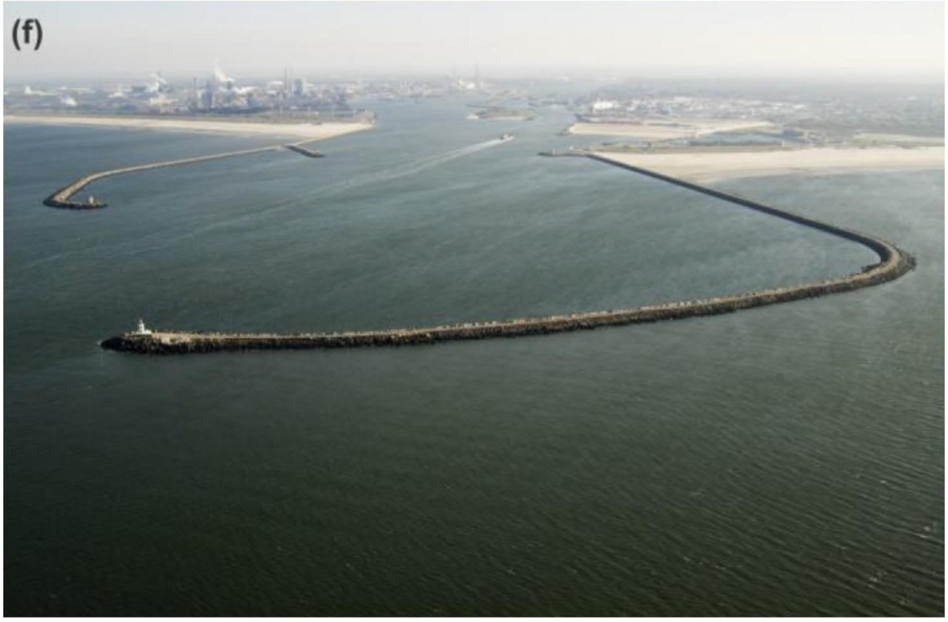


Figure 6: An aerial photograph of the port entrance at Ijmuiden, reprint from (Masterberg, Nederhoff, Valk, & Maarse, Beheerbibliotheek Noord-Holland, 2017)

In the coastal laboratory Zandvoort-Bloemendaal nourishments are performed frequently, see Table 1. The table reveals that the beach is nourished once every 3-4 years. Until 2004 only beach nourishments were applied, but since 2004 shoreface nourishments are applied as well. In this report, the focus lays on the nourishments of 2004 and 2008. The other nourishments are however also taken into account to fully understand the system.

Table 1: An overview of the nourishments in the coastal laboratory Zandvoort-Bloemendaal.

Begin Construction	**Finished Construction**	**Start Transect**	**End transect**	**Length**	**Volume per meter**	**Type**
01-08-1990	01-10-1990	62,00	63,25	1250		Beach
01-09-1993	01-05-1994	60,50	63,35	2850		Beach
01-05-1994	01-06-1994	65,00	67,30	2300		Beach
01-09-1998	01-10-1998	66,00	67,50	1500	170	Beach
01-09-1998	01-10-1998	61,50	63,50	2000	100	Beach
01-05-2001	01-06-2001	61,50	64,50	3000	200	Beach
01-05-2001	01-05-2001	66,25	67,50	1250	200	Beach
01-11-2004	01-02-2005	62,65	65.75	3000	400	Shoreface
01-10-2004	01-12-2004	65.75	67.75	2000	500	Shoreface
01-06-2008	01-09-2008	61.00	63.00	2000	500	Shoreface

01-06-2008	01-11-2008	67.75	70.25	2500	200	Shoreface
01-04-2016	01-10-2016	61,00	68,50	7500	320	Shoreface

3.2 Studied nourishment

3.2.1 Beach profile

The beach profile at Zandvoort-Bloemendaal can be described as a sandy dune system with breaker bars present at the shoreface. An example of a Jarkus transect located in the coastal laboratory Zandvoort-Bloemendaal is given in Figure 7. In this figure, the red arrow indicates the dunes and the yellow arrows point to the breaker bars. In this area typically 3 individual banks can be observed. The natural behaviour of these bars is that they move offshore. A nourishment can also be seen in the figure (green arrow). It shows that the nourishment is placed quite far from the shore. The bullets indicate different vertical levels (physical marks, see 4.2) in the beach profile. The different vertical levels are given in Table 2.

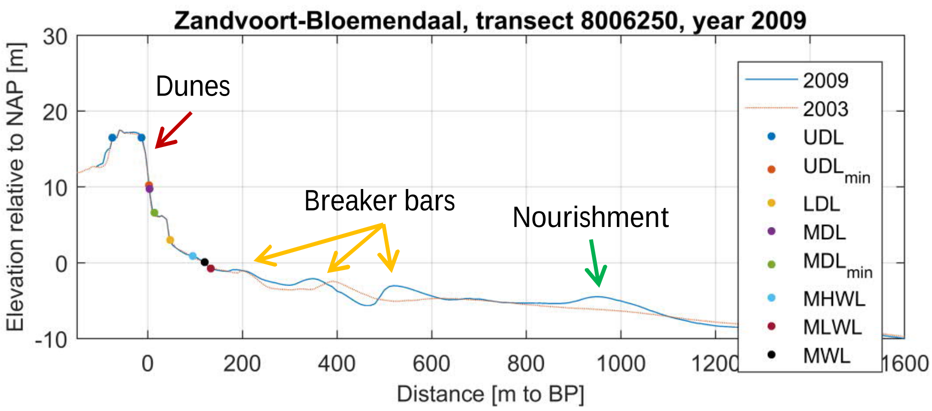


Figure 7: A example of a cross-shore profile at Zandvoort-Bloemendaal. The bullets indicate different reference level which will be explained in Section 4.2. The arrows indicate the dunes and the breaker bars.

Table 2: The vertical levels for each coastal laboratory which does not change over time or per transect.

Zandvoort-Bloemendaal	
Vertical location (with respect to NAP)	
Minimum Upper dune level (UDLmin)	9.98 m
Minimum Middle dune level (MDLmin)	6,49 m
Dune toe level (DF)	3.00 m
MHWL	0.93 m
MWL	0.09 m
MLWL	-0.74 m

3.2.2 Nourishment motivation

To prevent the Netherlands from flooding and to keep up coastal functions, the government is obligated by law to preserve the basic Dutch coastline. The basic coastline, with some small changes, is set as the coastline in 1990 of the Netherlands. Because the Dutch coast is continually eroding, sand nourishments are applied to preserve the coastline. The nourishments studied here are also part of these “regular” nourishments. In other words, the coast was eroded too much and therefore the shore was nourished with sand.

The beach-dune system at Zandvoort-Bloemendaal does not only protect against flooding but has several other functions as well. One of these functions is the purifications of drinking water. Fresh water, but not drinkable water, is pumped into the dune system. When the water flows into the ground it gets purified by the natural sand filters. When the water has reached a certain depth, it gets pumped up and it is pure enough to drink it.

The area is also used for recreational purposes. The beach at Zandvoort is one of the busiest beaches of the province of North-Holland. In 2005, 10.1 million foreigners visited this beach (Jonker & Janssen, 2007). Although the nourishments are a necessity for the beach and therefore of vital importance for the tourist industry, there is also a conflict of interest. During a nourishment, the beach cannot be used, especially in case of a beach nourishments.

3.2.3 Design of nourishment and placement

In this study four nourishments will be investigated. Two of the nourishments are placed at the end of 2004 and at the start of 2005. The other two are established in 2008, see Table 4. Limited information of the design of the nourishments is available. A typical shoreface nourishment is placed against the outer breaker bar at a depth -5 m NAP. An example of such design is given in Figure 8.

Table 3: The properties of nourishments 1 and 2. Each nourishment is subdivided in to two sub-nourishments based on their area.

Nourishment properties	Nourishment 1	Nourishment 2
Transects	62.75 – 65.75 65.75 – 67.75	61.00 – 63.00 67.75 – 70.25
Type	Shoreface	Shoreface
Volume	1202332 1001095	1002957 509913
Length	3000 2000	2000 2500
Volume	400 500	500 200
Grainsize	251-297	
Slope	unknown	unknown
Start nourishment vertical level	-5 (m NAP)	-5 (m NAP)
End nourishment vertical level	unknown	unknown
Scope	unknown	unknown
Begin construction	11-2004 10-2004	06-2008 06-2008
Finished construction	02-2005 12-2004	09-2008 11-2008
Time periods of interest	2000-2009	2004-2013
Year of reference	2003 and 2004	2008
Prior to nourishment	2000-2004	2004-2008
After nourishment	2005-2009	2009-2013
Transects of interest	60.00-71.25	60.00-71.25

For nourishment 1 both the years 2003 and 2004 are chosen as a reference year. The reason for this decision is the bathymetry measurement, see Figure 9 and Figure 10. In 2004 the lower shoreface, the area where a large part of the nourishment will be placed, was not measured. However, in 2004 the area where the physical marks are based on, is measured. Therefore, for the physical marks the reference year is 2004.

For the years prior to the nourishment 5 years are used and the year in which the nourishment is placed is defined as before the nourishment. This definition is used because the nourishment was placed later than the measurement was taken that year. Additional to a time period of interest, a spatial area of interest is prescribed. The area four transects north and four transects south of the nourishment are taken to participate on the movement of the sand.

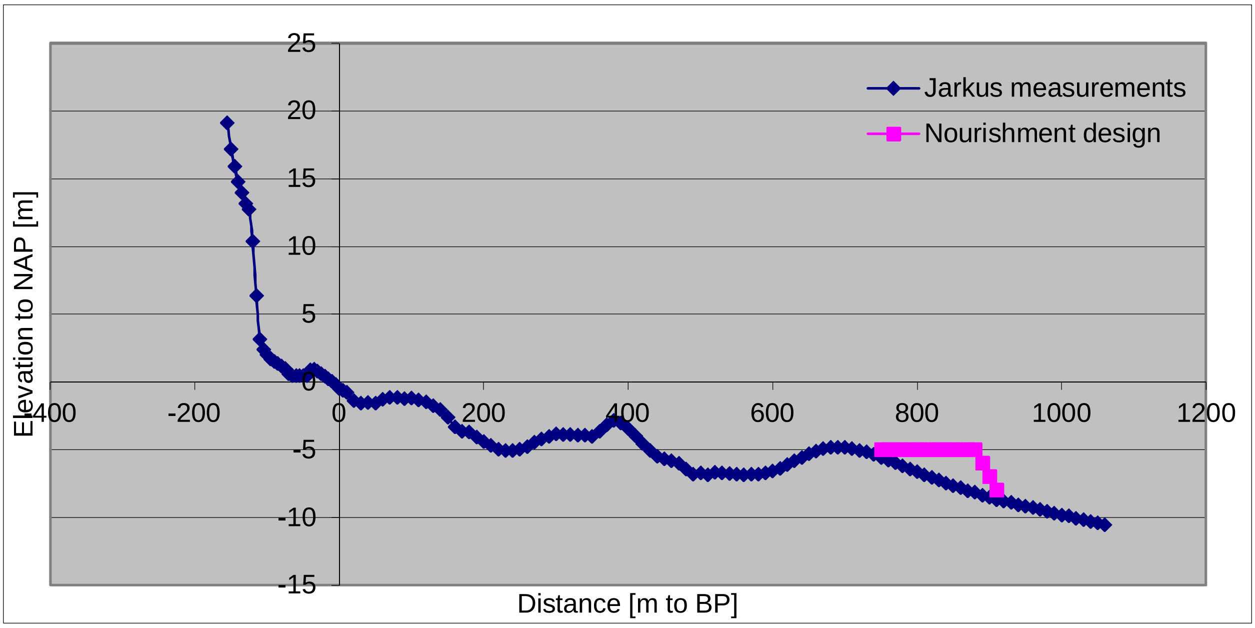


Figure 8: A, example of a shoreface nourishment. Here a nourishment at Bergen-Egmond (transect 3550 of 2008) is shown.

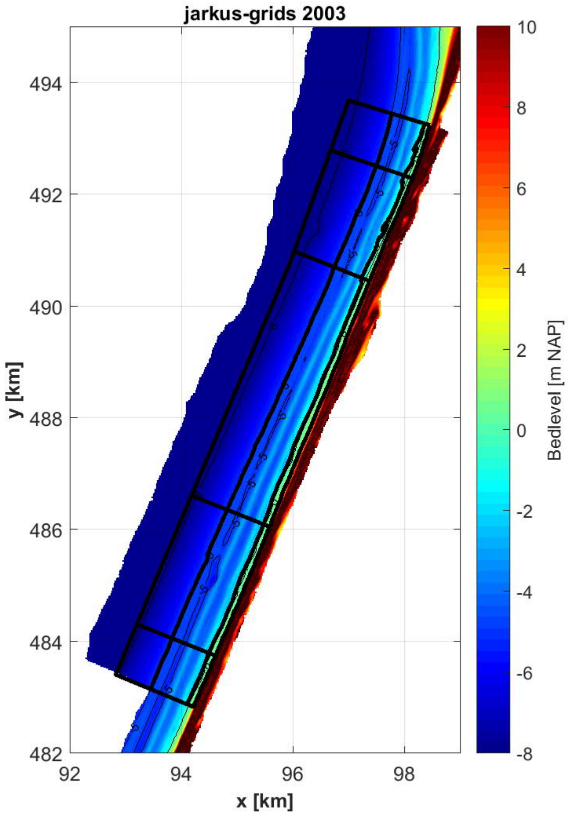


Figure 9: A top view of the bathymetry in 2003 based on Jarkus-grids. The black squares indicate different areas which will be used in Section 7.2.

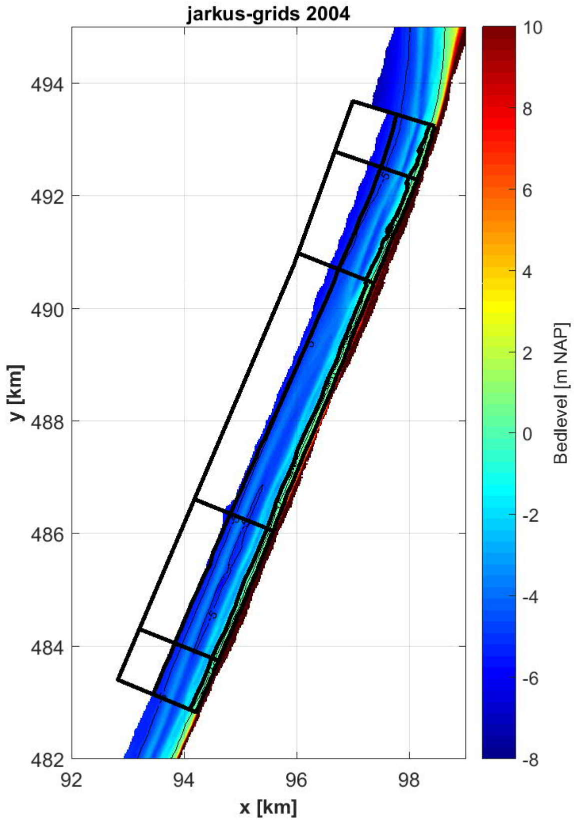


Figure 10: A top view of the bathymetry in 2004 based on Jarkus-grids. The black squares indicate different areas which will be used in Section 7.2.

A good spatial image of the different nourishments is revealed when the difference in bathymetry is plotted, see Figure 11 and Figure 12. In 2004 two nourishment-parts are in place. Figure 11 shows that they have fused together in 2005. The nourishment-parts in 2008 are visible in Figure 12. The northern nourishment is larger than southern nourishment per alongshore meter and therefore much more visible.

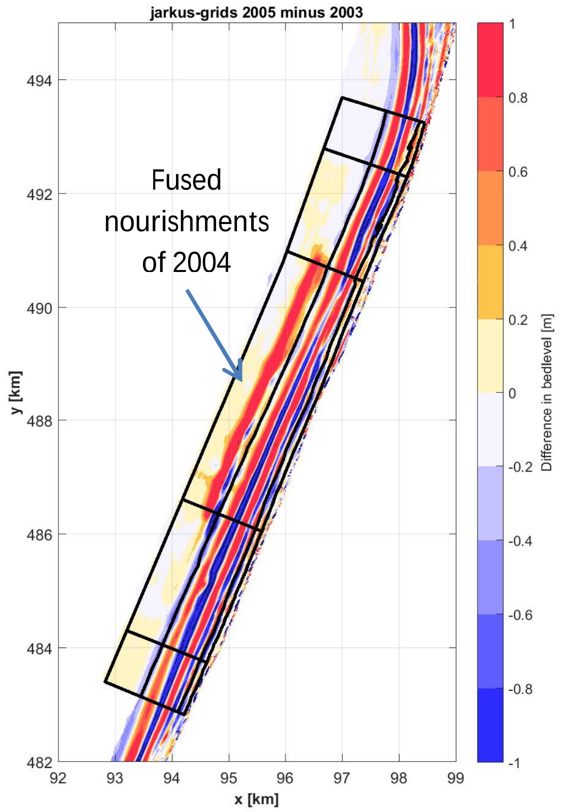


Figure 11: A top view of the difference in Jarkus grids 2005 minus 2003. The black squares indicate different areas which will be used in Section 7.2.

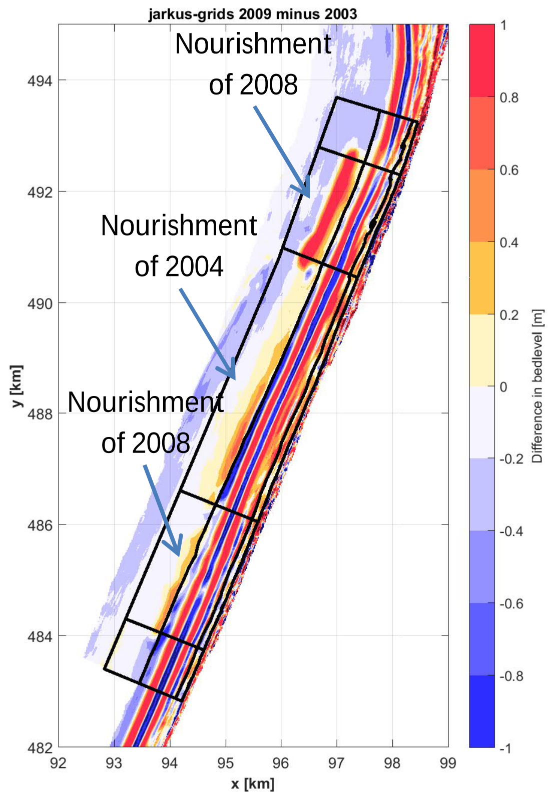


Figure 12: A top view of the difference in Jarkus grids 2009 minus 2003. The black squares indicate different areas which will be used in Section 6.2.

4 Method and data

4.1 Data, availability, accuracy and processing

Several data sources are available to analyse the bathymetry of the coastal laboratories: JARKUS transects, Vaklodingen and local measurements. The different dataset are discussed in this chapter.

4.1.1 Transect data

Since 1965 the Dutch coast is yearly measured along cross-shore transects: the JARKUS transect, see Figure 5. These transects are located over the entire Dutch coast and are between 130 to 210 m apart. For each transect part of the dunes, the beach and the shoreface is measured. The dry areas are measured using laser altimetry and the wet area by singlebeam echosounders. The data is combined to determine the vertical level along each transect. Because several sources are used, the cross-shore resolution changes from a 5 m resolution when altimetry data is used to a vertical level every 10 m for the echosounder data. Each year the position of the transects and the location of a vertical level along a transect are identical but extension of the measurement offshore differs.

4.1.2 Hydrodynamic data

In front of the Dutch coast a considerable number of measuring stations are available, see Figure 13. Their data is freely provided by Rijkswaterstaat (waterinfo.rws.nl). The physical quantities measured at each station can be different at each location. Also, the duration of the measurements varies from location to location. The Europlatform has the longest time series available of H_s, T_p and θ_p and therefore this station is used instead of station closer to the coastal laboratories. Also, the wave conditions before and after the nourishment are compared and therefore the exact value of wave conditions have little influence on our findings.

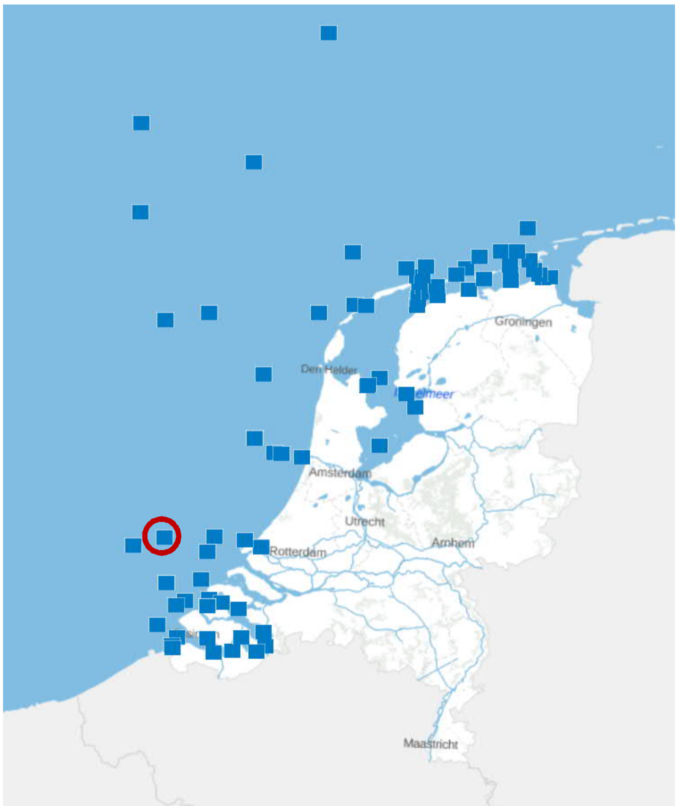


Figure 13: An overview of the different measuring station for H_s in the Netherlands. The red circle indicates the location of the Europlatform.

4.1.3 Nourishment data

For this nourishment no specific nourishment data, e.g. dredger information, is available.

4.2 Method

To analyse the nourishment several methods are applied. In this section the different procedures are discussed.

4.2.1 Terminology and coastal state indicators

The analysis of quantitative morphological development will be performed using coastal state indicators (CSI's), also indicated as 'physical marks'. Coastal state indicators are commonly agreed definitions of features that provide information on the state of a coast at a moment in time. The use of CSI's will align the national analyses carried out by each partner of the BwN project and allow to tie them into one joined co-analysis.

A coastal state indicator is a feature; morphological feature, morphological zone or height level which can be determined using cross-shore transects. When monitored over time a CSI shows the development of the morphological system and reveals changes in evolutionary trends. The monitored development depends on the type of CSI e.g. changes in sand volume in a zone, the width of a coastal zone, the cross-shore position of a morphological feature or height level. A description of the CSI's functions and criteria can be found in Lescinski (2010). Below the applied coastal terminology and the representative CSI's are presented.

The coastal zone terminology in figure 1 will be applied throughout the analysis. The CSI's corresponding to the coastal terminology are shown in Figure 14 and described in Table 4. The morphological development represented by the CSI will be analysed in order to reveal the morphodynamics and the effects of nourishments.

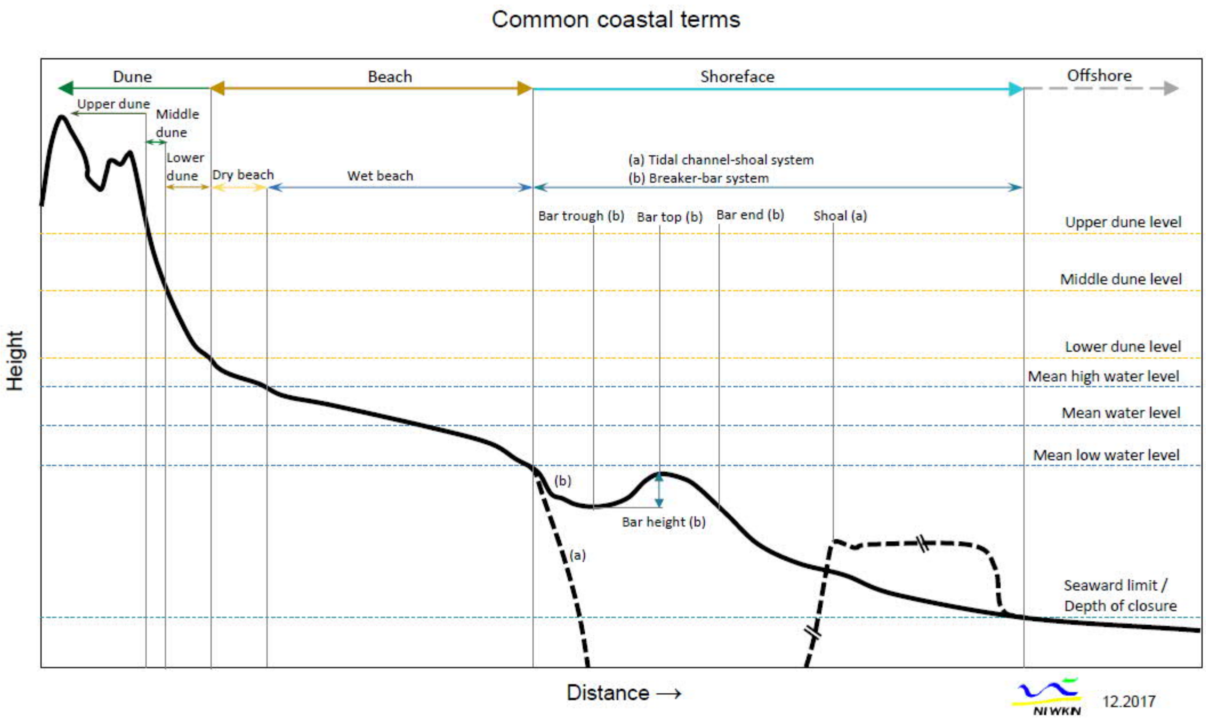


Figure 14: General definition/terminology coastal profile used. On the vertical axis various levels in the profile are shown. The horizontal axis shows different zones in the profile. Source: Simon Hillmann (NLWKN)

Table 4: Common definitions of Morphological zones (grey) and delimiting height levels – CSI (white). *The seaward and landward limit can be defined as a height level or as a distance.

Coastal-section	CSI	CSI type and definition
	Landward limit (LL)	Not a CSI -The landward limit is not monitored in itself, but sets the limits for calculating dune and system width and volume. The limit is set as a cross-shore position which is measured in all available profiles.
Dune	**Upper dune**	Coastal sub-section
	Upper dune level (UDL)	Fixed height level which is most responsive to dune erosion or human-made reinforcement. The minimum level of dune crests over time must be taken into account.
	Middle dune	Coastal sub- section
	Mid dune level (MDL)	Fixed height level where Aeolian sand transport and aggregation of sand should be of minor relevance. Changes at this level should be likely ascribed to acute dune erosion or man-made dune reinforcement. However, on longer time scales natural dune growth can be visible, as a response to a positive or negative sediment budget.
	Lower dune	Coastal sub- section
	Dune foot level (DF)	Fixed height level where the slope is distinctly changing. Dune growth on shorter time scales can be the result of human-built sand traps or of natural dune growth like Aeolian sand transport.
Bea ch	**Dry beach**	Coastal sub- section

	Mean high water level (MHWL)	Fixed height level: MWL + ½ Tidal Range. A best estimate and fixed height during the time of analysis is recommended for simplicity.
	Wet beach	Coastal sub- section
	Mean low water level (MLWL)	Fixed height level: MWL - ½ Tidal Range. A best estimate and fixed height during the time of analysis is recommended for simplicity.
Shoreface	**(a) Tidal channel-shoal system** **(b) Breaker-bar system**	(a) Morphological features. Channel: Deep section between MLWL and the front of the shoal. Shoal: a relatively large shallow area not connected to the beach which is shaped primarily due to tidal forces (e.g. ebb tidal delta's). (b) Morphological feature. Bar: sand accumulation created by the action of currents and waves. A bar has the following characteristics: Bar top: maxima in the shoreface profile where the slope changes sign. Bar trough: depression between two bar crests, or in between a bar top and a point landward from the bar, at the same depth. Bar height: difference in height between bar top and the deepest point of the bar trough. Bar landward limit: deepest point landwards of the bar top.
	Seaward limit (SL)	Not a CSI -The seaward limit is not monitored in itself, but sets the limits for calculating shoreface and system width and volume.

4.2.2 Physical marks

The physical marks (CSI's) are calculated from transect measurements using the MKL-Model (Momentary Coast Line) . The MKL-Model is described in the co-analysis method document. The model determines the surface area balance point of an area. Figure 15 shows an example of the MKL-calculation. In the calculation of the physical marks a buffer of 0.5 m is used for each height level. The analysis of physical marks is done for the following CSI's: UDL, MDL, MHWL and MLWL, for each transect (both in time and space).

The calculated distances to the physical marks are plotted in time-distance diagrams (change of one physical mark for one transect in time) and transect-distance diagrams (distance along the transects for one specific time, plotting multiple times with different colours). These graphs are used to analyse the development of the coastal area in time by visualizing trends of sedimentation or erosion, or periodic changes of both.

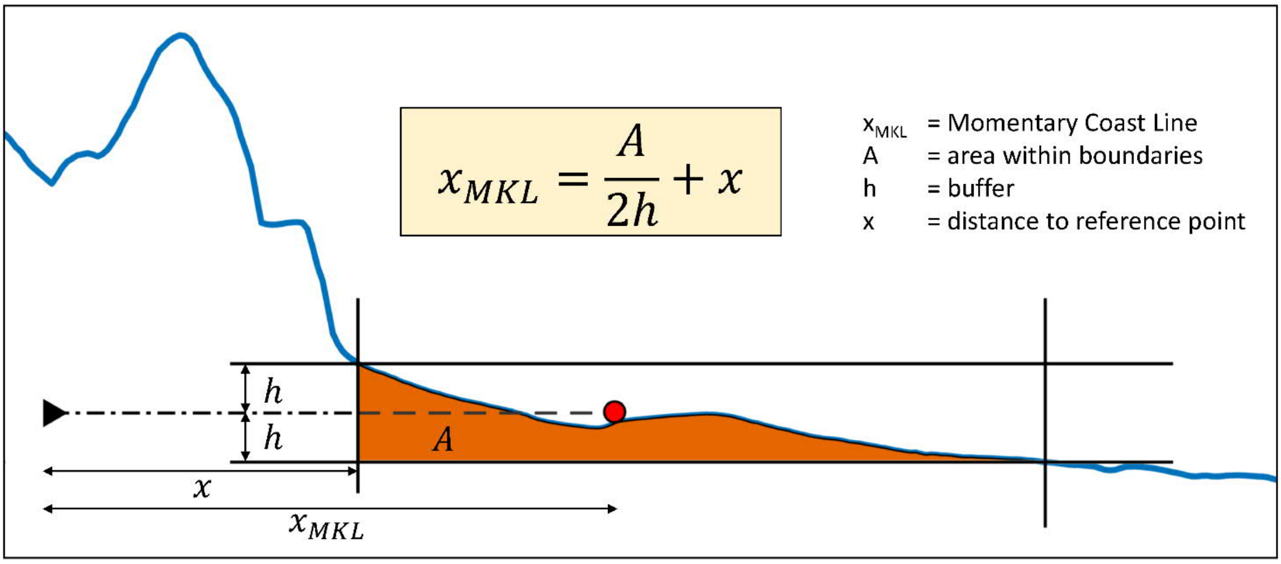


Figure 15: Example of the MKL-Model

4.2.3 Bar development

A well-developed bar system improves coastal resilience, since it dissipates wave energy through wave breaking. Therefore the impact of nourishments on the nearshore and its morphological characteristics, especially the dynamics of the breaker bars, are investigated, based on transect measurements. The magnitude and location of bars are examined both cross-shore and alongshore in order to show spatial and temporal evolution in the bar system. This is done by applying two sets of criteria: one to identify the bars present in each coastal transect and one to determine the longshore continuity of the bar.

The characteristics which define a bar are found in Table 4. In order to generically identify the bars within a coastal profile the following parameters are defined:

- Shape coefficient: bar width over bar height.
- Depth over bar: difference between MSL and the bar top.
- Bar position: distance between reference point (beach pole) and bar top position.

4.2.3.1 Cross shore bar identification

To distinguish relevant bars from other morphological features such as ripples, three morphological characteristics have to be fulfilled:

- Bars are found below 0 meter height relative to MSL
- Bar height $\geq$ 0.25 m
- Shape coefficient $\leq$ 1000
- Bar volume $\geq$ 10 m^3/m

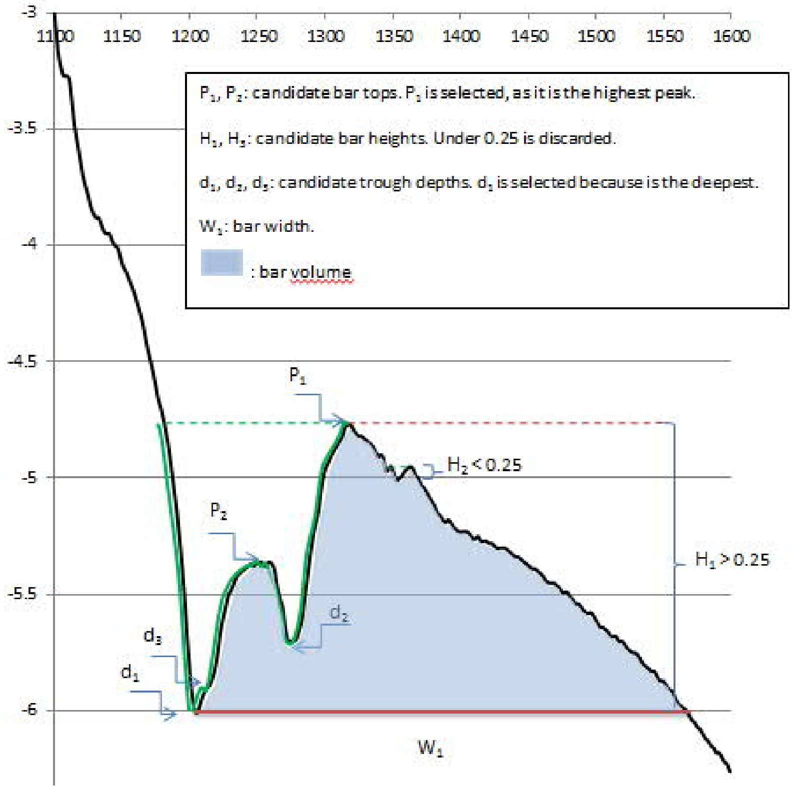


Figure 16: Definition of bar elements. The green line corresponds to the generalized case of through, while the red line shows the bar width.

The initial cross-shore criteria are based on mean wave height, the depth where bars are observed, their width and height. The initial longshore criteria are based on mean wave height, the longshore distance in between transects, and the variation in depth over bar. The initial criterion is then refined by iteration, e.g. by finding and posteriorly evaluating whether the results suit the actual beach morphology.

4.2.4 2D volume development: Volume boxes

In the 2D volume method first the boundaries of the boxes are defined. The coast parallel boundaries (based on vertical level) are chosen based on the physical marks and nourishment properties, while the coast perpendicular boundaries are based on patterns in erosion-sedimentation.

For the coast parallel boundaries, a selection of the physical marks levels and the top and bottom level of the nourishment is made based on expert judgement. For the studied nourishment at Zandvoort-Bloemendaal the following boundaries are used: dune foot (NAP +3 m), mean low water (NAP -1 m), just landward of the nourishment (NAP -5 m) and a seaward limit based on data coverage. The boundaries are defined on the last measurement with good coverage before start of the nourishment (2003) and are based on the depth contours retrieved with ArcGIS from the gridded bathymetry data.

The coast perpendicular boundaries are based on spatial erosion-sedimentation patterns: transects with similar change were combined. This automatically included boundaries at the beginning and end of the nourishment. The erosion-sedimentation patterns were retrieved by subtracting the last measurement before from the first measurement after the nourishment (using gridded bathymetry).

Within each of the defined areas the sediment volume are calculated relative to the last year before nourishment. This is done using raster data by creating difference maps between each measurement and the reference measurement. For each of these difference maps, the volume is calculated by taking the sum of the data within an area multiplied by the surface of one raster cell. In ArcGIS the 'Zonal Statistics as Table' function was used.

5 Environmental conditions/characteristics

The morphodynamic behaviour at the transects of interest is a response of the alongshore and cross shore sediment transport which depends on the hydrodynamic forcing. The hydrodynamics can be determined by waves, tides, storm surges and wind as the main forcing agents. Together with the available grain sizes and the additional sediment placed by nourishments it might be possible to describe a relation between the hydrodynamic forces and the morphological development of the coastal labs. The importance of the different loads may vary from one lab to the other. In order to generate specific parameters out of the different physical forces, the following parameters are derived to describe this forcing.

5.1 Waves

To indicate the wave conditions at the coastal laboratory, the hydraulic conditions at the Europlatform are analysed. The measured time series at the Europlatform are given in Figure 17. The time signal for H_s shows several local maxima due to storms. The maximum H_s during a storm is in the order of 4~6 m and each year contains multiple storms. The peak period is in the order of 7 s during these events. The 7 s period is typical for wind generated waves. The direction shows a dominant direction from the 200°N till 50°N.

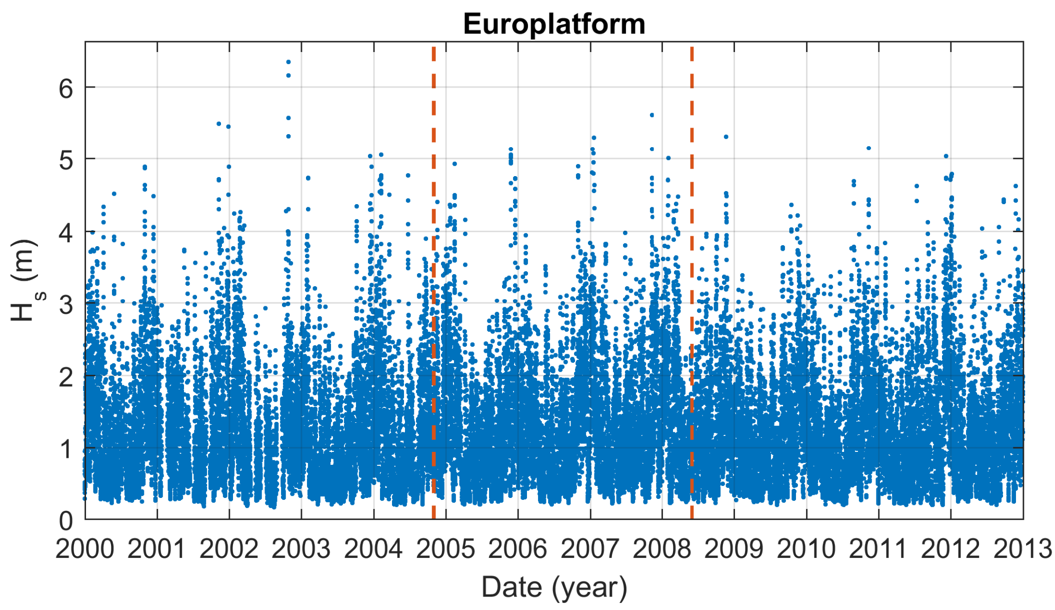


Figure 17: The measured value of Hs at the Europlatform. The red dotted lines indicate the nourishments.

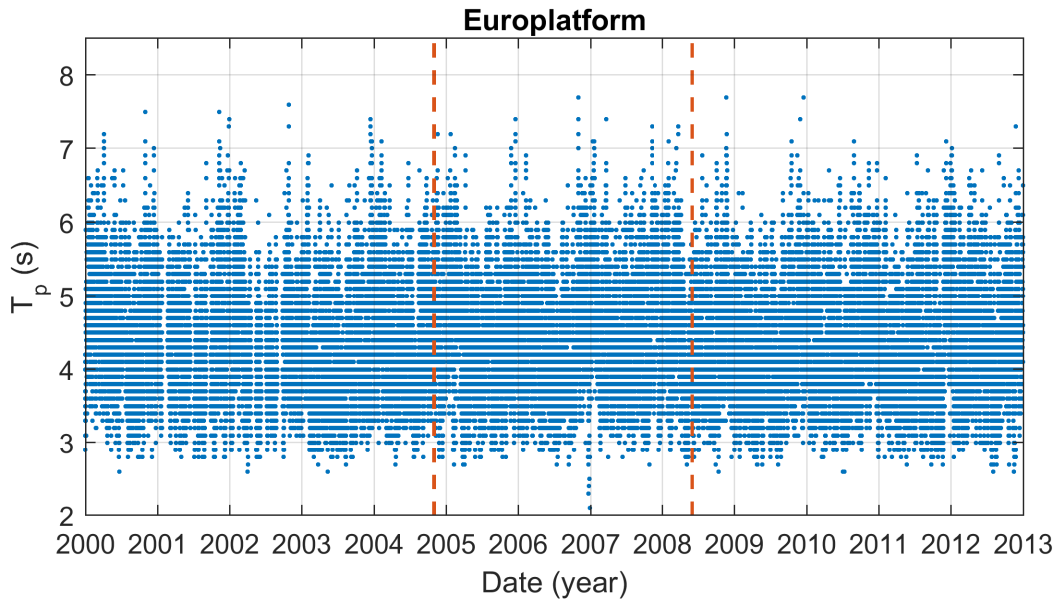


Figure 18: The measured value of T_p at the Europlatform. The red dotted lines indicate the nourishments.

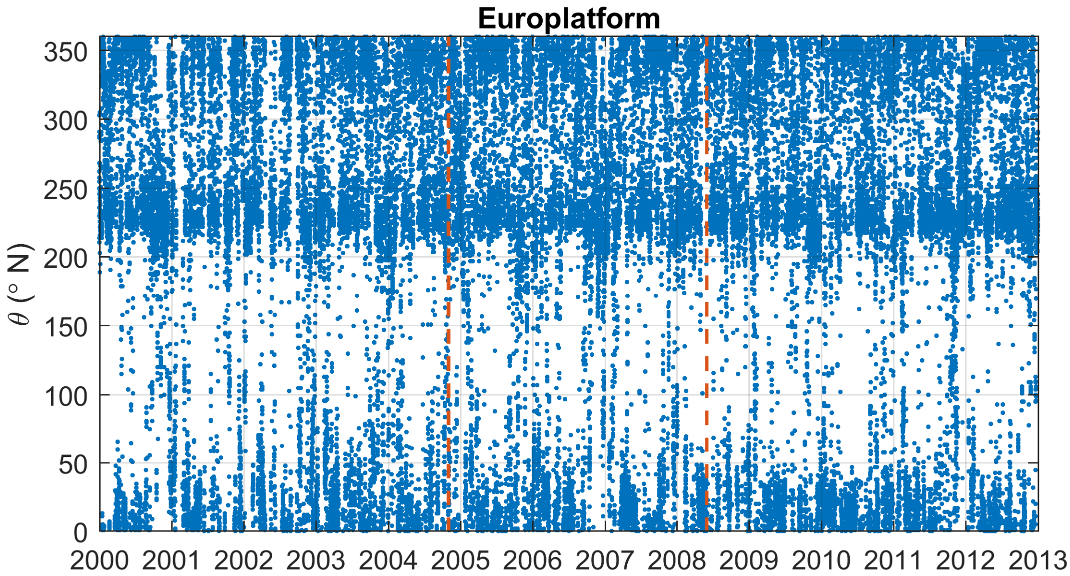


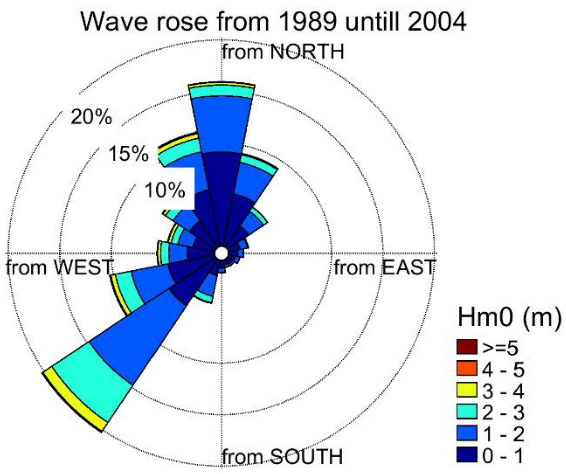
Figure 19: The measured value of ϴ at the Europlatform. The red dotted lines indicate the nourishments.

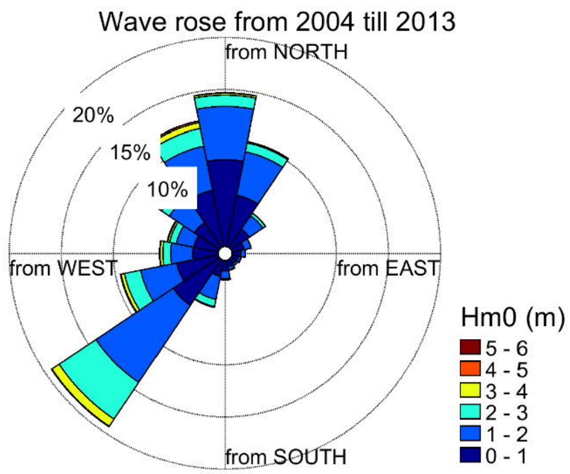
The averaged values of the bulk wave parameters for a time period before and after the nourishment are calculated, see Table 5. The averaged values for H_s and T_p before the nourishement is calculated from the start of the measurement in 1989 till 2004. This is done to determine the usual hydraulic conditions. The table also contains the wave energy parallel (E_{par}) and perpendicular (E_{per}) to the coast. The energy is explained in more detail at the end of the paragraph. The table shows that the averaged values for H_s, T_p, E_{per} and E_{par} before and after the nourishment are similar. It means that if the nourishment behaves differently than the previous nourishment it cannot be explained by the different hydraulic conditions.

Table 5: The averaged bulk wave parameters before and after the nourishment. For the energy both the mean and the mean of the absolute values are determined.

Wave property	Mean value before the nourishment (1989-2004)	Mean value after the nourishment (2004-2013)
$\bar{H}_s$ (m)	1.25	1.26
$\bar{T}_p$ (s)	4.41	4.37
$\bar{E}_{par}$ (kg s^{-2})	253	200
$\bar{E}_{per}$ (kg s^{-2})	1311	1295
$\lvert\bar{E}_{par}\rvert$ (kg s^{-2})	2068	2045
$\lvert\bar{E}_{per}\rvert$ (kg s^{-2})	1547	1506

To further analyse the direction, wave roses are plotted, see Figure 20. All the four roses show two dominant peaks, from the North West and South West direction. It is a so called a bidirectional system. The wave rose for T_p has a similar shape as for H_s indicating the correlation between T_p and H_s. It means it are wind generated waves. When the wave rose is investigated in more detail, it shows that the highest waves are coming from the North-West, the typical northwest storm. Most importantly, the wave roses show a similar pattern before and after the nourishment. In other words, similar hydrodynamic conditions took place before and after the nourishment.





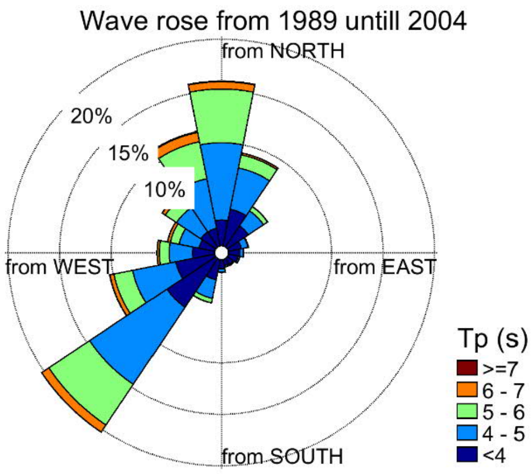


Figure 20: Wave roses based on the measurements at the Europlatform. The year 1989 till 2004 are before the nourishment and 2004 till 2013 is after the nourishment.

In Figure 21 and Figure 22 the percentages of exceedance of H_s and T_p are visualised to compare the severeness of the hydraulic conditions. The solid lines are the years before the nourishment and the dotted lines after the nourishment. Overall, the percentage of exceedance for the solid lines is comparable as for the dashed lines. In other words, similar hydraulic conditions occurred before and after the nourishment. Note, the percentage of exceedance is based on the number of measurements and not on the duration of a specific value.

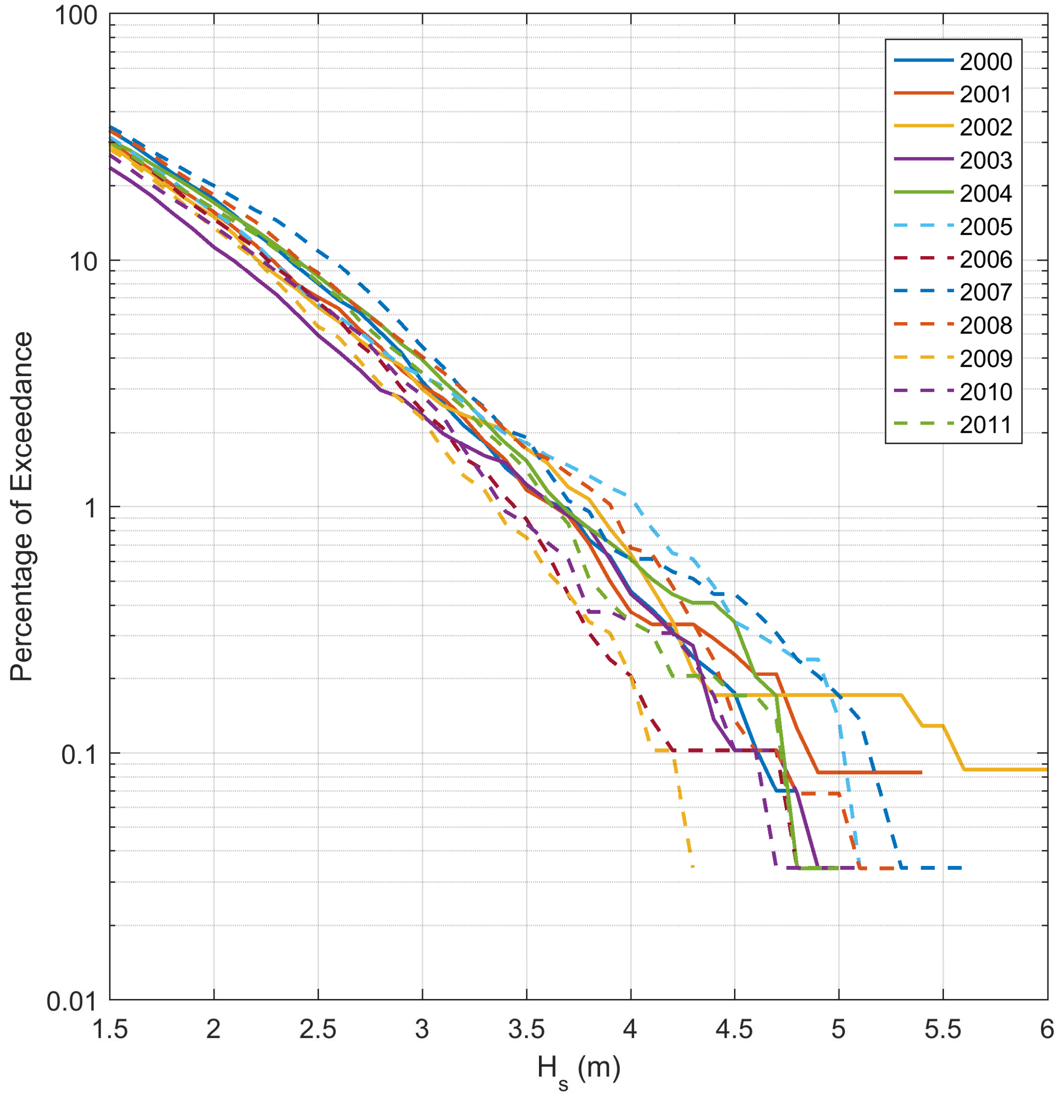


Figure 21: Percentage of exceedance of the measurements H_s at the Europlatform for several years.

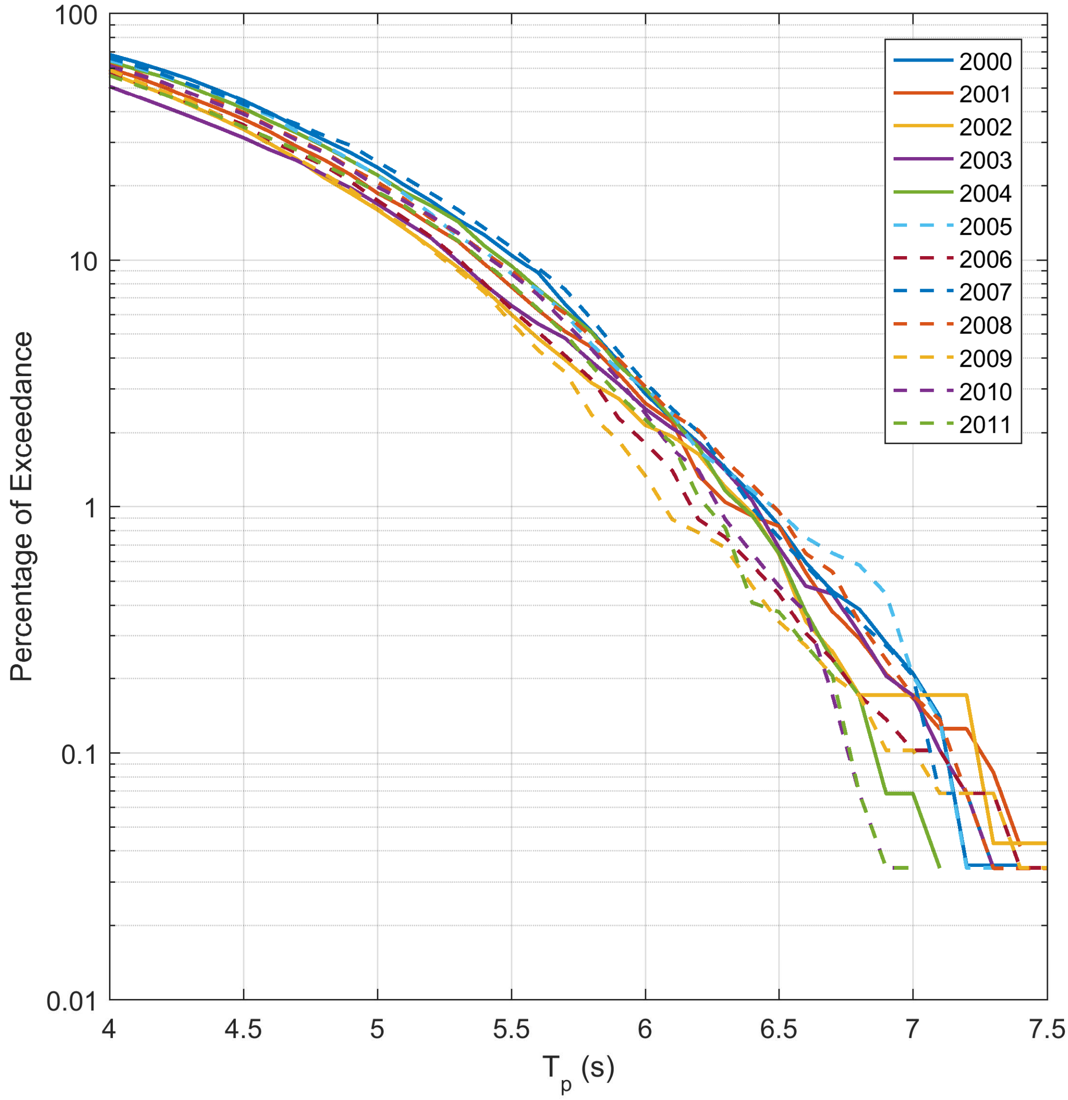


Figure 22: Percentage of exceedance of the measurements for T_p at the Europlatform for each year.

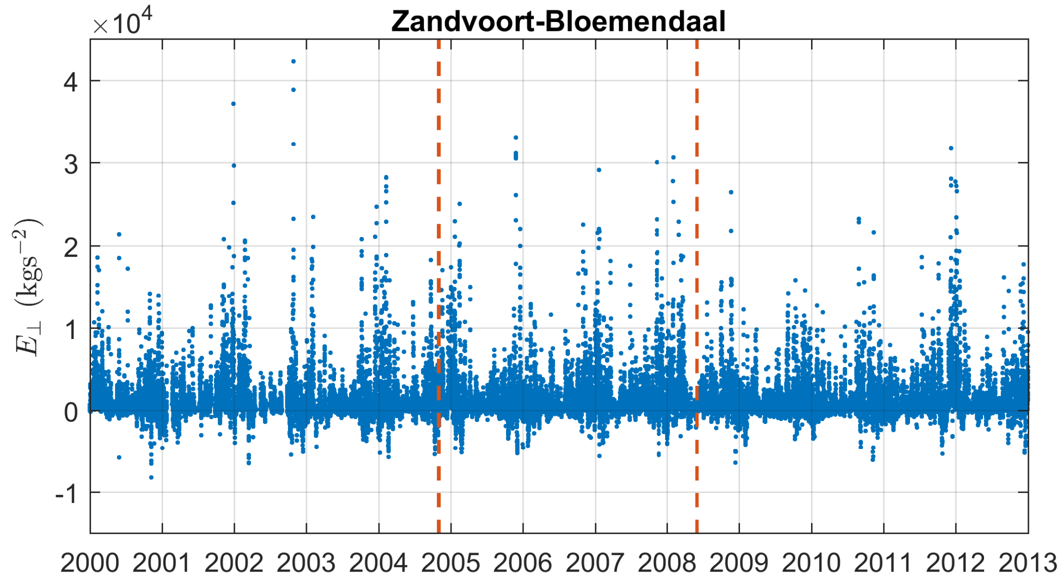


Figure 23: The wave energy perpendicular to the coast calculated using the wave measurements at the Europlatform.

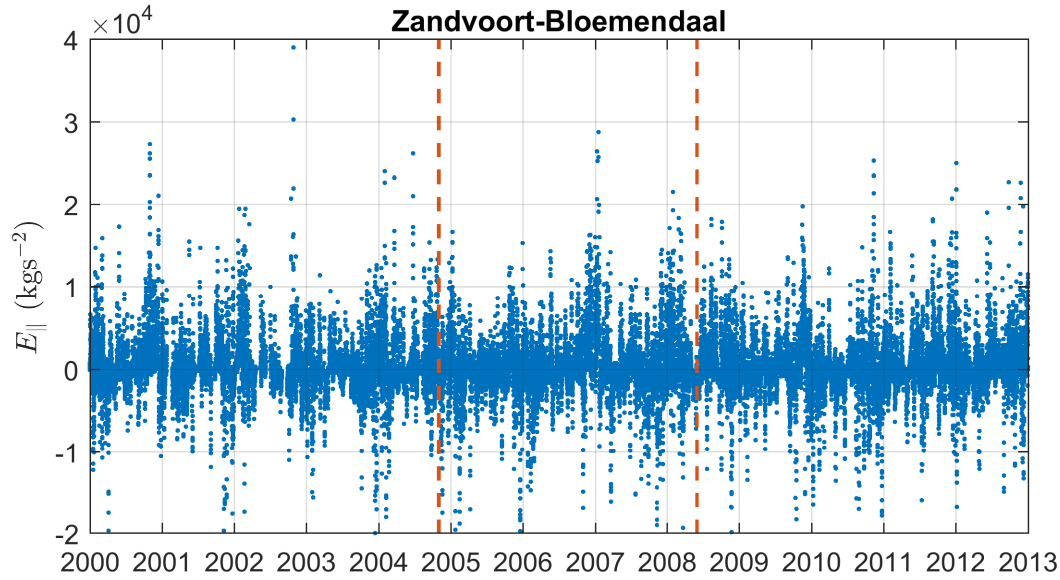


Figure 24: The wave energy parallel to the coast calculated using the wave measurements at the Europlatform.

5.2 Tides

For tidal information the IHO station Ijmuiden is used to provide the tidal elevation from 1998 till 2014. This data can easily being accessed by the Delft Dashboard (Nederhoff, Dongeren, & Ormondt, 2016). Part of the tidal signal is visualized in Figure 25. The signal reveals that the elevation is dominantly semidiurnal (two low waters and two high waters each day) but also higher harmonics are clearly visible. The visibility of the higher harmonics is endorsed by the table of the tidal constituents, see Table 6. The tidal elevation consists of an arsenal of different constituents.

The amplitudes of the different constituents explain the different levels in the tidal elevation. There is a large difference between the two daily high waters. Due to the M2 tide, two high waters arise each day.

The difference between two high waters follows from periods with half the period of the M2 tide. In other words, the M4 and the MS4 tide equality exist. In this case the amplitude of the M4 and MS4 tide is rather large compared to the amplitude of the M2 tide and therefore the difference between the two high waters is large.

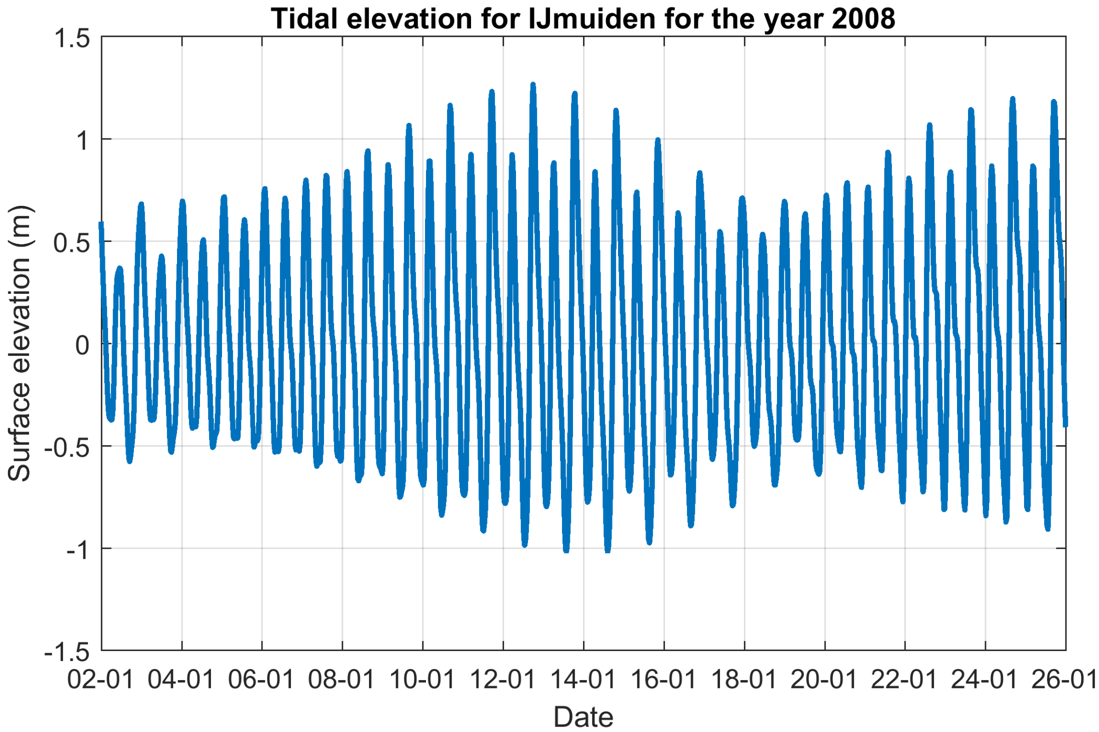


Figure 25: Part of the tidal signal from the IHO station Ijmuiden.

The time signal also presents a difference between the maxima around 13-01 with those at 19-01, further referred to as the long term maxima. The difference between these (long term) maxima is almost as large as the diversity between two daily maxima. The long term maxima follow from the phase difference between S2 and M2 tide. The amplitude of the S2 tide is relative small, especially compared to the amplitudes of the M4 and MS4 tide. As a result, the difference in long term maxima is small comparted to the equality between the two daily maxima.

Table 6: The tidal constituents of the IHO station Ijmuiden.

Tidal Constituents	Period (hours)	Amplitude (m)	Phase (° UTC)
M2	12.4	0.686	106
M4	6.2	0.196	138
S2	12.0	0.173	174
O1	25.8	0.116	180
MS4	6.1	0.104	196
N2	12.7	0.092	90
K1	23.9	0.079	346
MN4	6.3	0.058	108
K2	12.0	0.057	166
M6	4.1	0.054	215

L2	12.2	0.05	123
2MS6	4.1	0.05	274
M8	3.1	0.04	175
MM	661.3	0.039	129
Q1	26.9	0.033	146
P1	24.1	0.032	345
MF	327.9	0.032	323
LABDA2	12.2	0.028	116
MSF	354.4	0.024	360
2SM2	11.6	0.012	19
MO3	8.4	0.01	212
T2	12.0	0.007	183
MK3	8.2	0.006	277

Based on the time signal of the waterlevel elevation due to the tide, the different tidal levels are calculated, see Table 7. The difference between MWL and MHHW is larger than the difference between MWL and MLLW indicating that the tidal elevation is not symmetric. The difference in maxima visible in Figure 25 is also represented in the different tidal level. Namely, there is a large inequality between the MHHW, MHW and MLHW level.

Table 7: The different tidal levels at the IHO station IJmuiden.

Tidal level	Abbreviation	Height (m)
Mean Higher High Water	MHHW	0.94 m
Mean High Water	MHW	0.78 m
Mean Lower High Water	MLHW	0.63 m
Mean Water Level	MWL	0.0 m
Mean Higher Low Water	MHLW	-0.62 m
Mean Low Water	MLW	-0.67 m
Mean Lower Low Water	MLLW	-0.76 m

5.3 Storm surges

The effect of the storm surges is analysed not by the investigating the storm surge itself but by considering the number of events that the value of H_s is higher than a certain value. The threshold is set at 4 m. This level is comparable with the threshold level which would be used in a peak over threshold method to identify storms in the time series. Using this threshold 117 storms are identified between 1989 and 2013. The number of storms per year is, as expected, between the 4-5 storms per year. Note that there is a difference between events and storms. Namely, if two events lay within 48 hours of each other it is interpreted that they belong to the same storm.

Part of the events are shown in Figure 26. The figure reveals that the events are nicely grouped in storms. How many times the value of H_s is larger than 4 m indicates how long a high storm surge has occurred. From 1989 till 2004 (before the investigated nourishment) 0.6334% of the time the value of H_s was larger than 4 m. Furthermore, between 2004 and the end of 2012 the percentage was 0.5406%. In other words, slightly less extreme wave heights occurred after than before the nourishment.

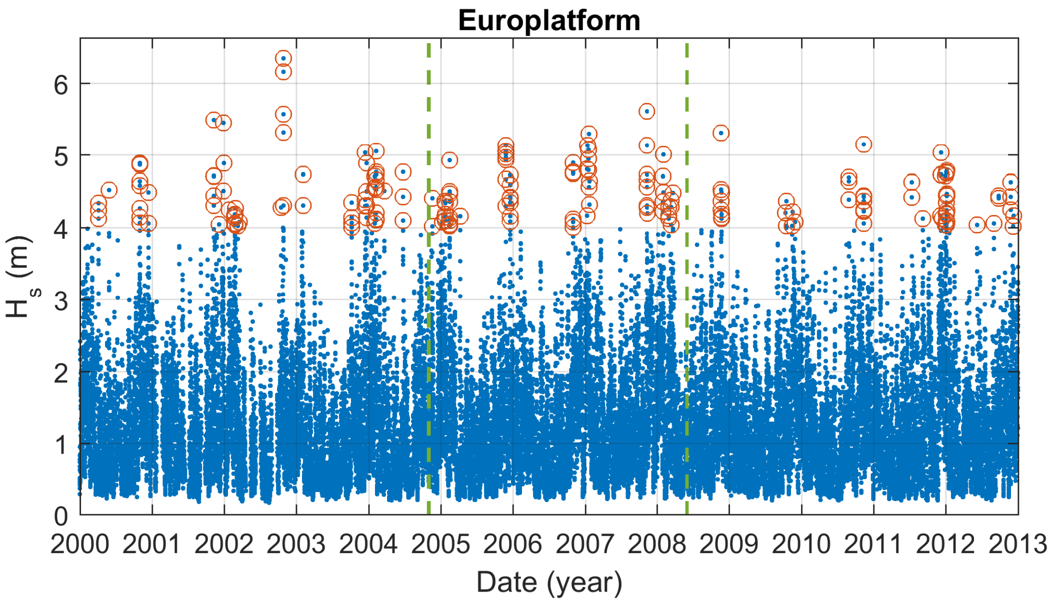


Figure 26: A time series of the wave height. The red circles indicate the events with $H_s > 4m$ and the green lines the moment of the two nourishments.

5.4 Wind

The wind characteristics were obtained from the Royal Dutch Meteorological Institute (KNMI, https://projects.knmi.nl/klimatologie/uurgegevens/selectie.cgi). Data were used from the Valkenburg measurement station for the same periods as the wave data: 1989-2004 for the long term and 2004-2013 for the nourishment period. The data is presented in two wind roses, Figure 27 and Figure 28. The two periods show a similar wind climate, with dominant westerly winds with both a northwest and southwest component. In the nourishment period the westerly winds were a bit less dominant and the northwester wind a bit more dominant than in the long term period.

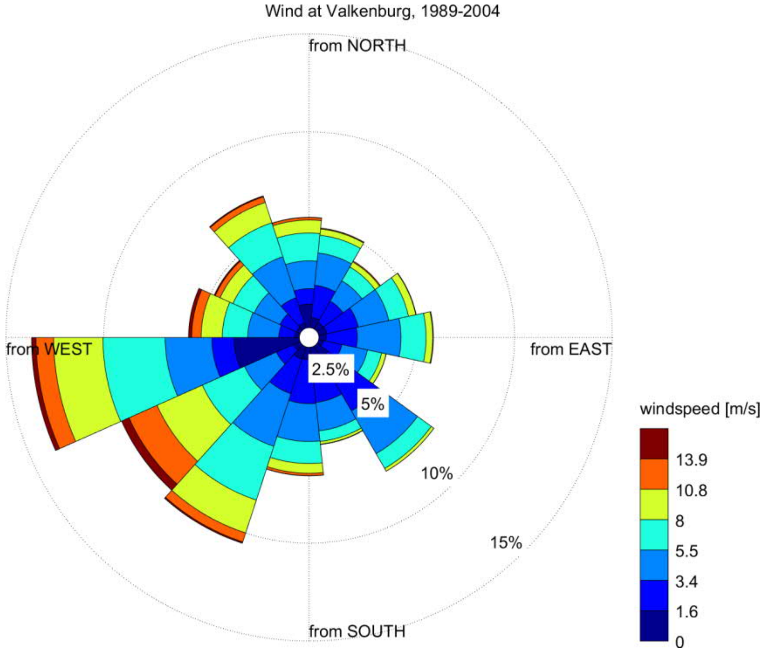


Figure 27: Wind conditions for the long term, pre nourishment period 1989-2004

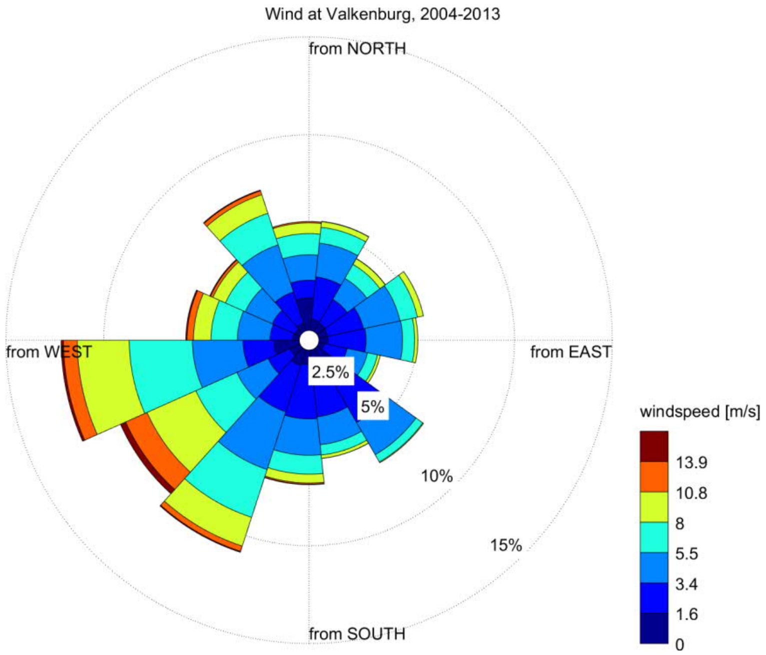


Figure 28: Wind conditions in the nourishment period

5.5 Grain size

For this area no recent grain size analysis are available. Based on measurements between 1976 and 1981 Glim (1985) reports an average median grain size of 282 μm around mean sea level and 221 μm in the dunes.

6 Source-Pathway-Receptor

The development of the coast and the nourishment placed at the shoreface or the beach is caused by several processes. To show these processes in a conceptual way they are described using the 'source-pathway-receptor' approach. In this approach the route is described from origin to endpoint for water and sediment. In the Building with Nature study by Hillman (2021) effects of storms and sea level rise on the receptors is studied, with varying pathways.

6.1 Water

There are two main processes that cause the water motion: waves and tide, the first caused by wind, the second by gravitation of the moon and sun (the 'source'), see Figure 29 and Figure 30.

The waves can originate further away (swell) or close to the coast (wind waves). The wind climate and orientation of the coast determine the local effects of the waves. The tide is affected by larger scale morphology, such as tidal inlets and estuaries. The seafloor morphology affects the water movement, with waves breaking and dissipating in shallower water depths (the 'pathway'). Shallower water, e.g. due to the presence of a breaker bar or shoreface nourishment, will increase the dissipation and result in smaller wave impact at the surf zone / beach.

For the waves two 'receptors' can be identified: the seafloor and the surf zone / beach. The first encounters the orbital flow velocities, from about 10 m water depth and less. The second zone is around the water level, and therefore affected by tide level and setup, e.g. due to a storm.

In the coastal lab Zandvoort-Bloemendaal the coast is wave dominated, with waves being the dominant process compared to tide. Wave induced breaker bars are present. The most dominant wave direction is from the southwest, with a second dominant direction from the north. With the coastline orientation around north-northwest, this results in dominant northward wave driven alongshore current. The eb-tide is directed south, the flood is north, with a dominant flood tide.

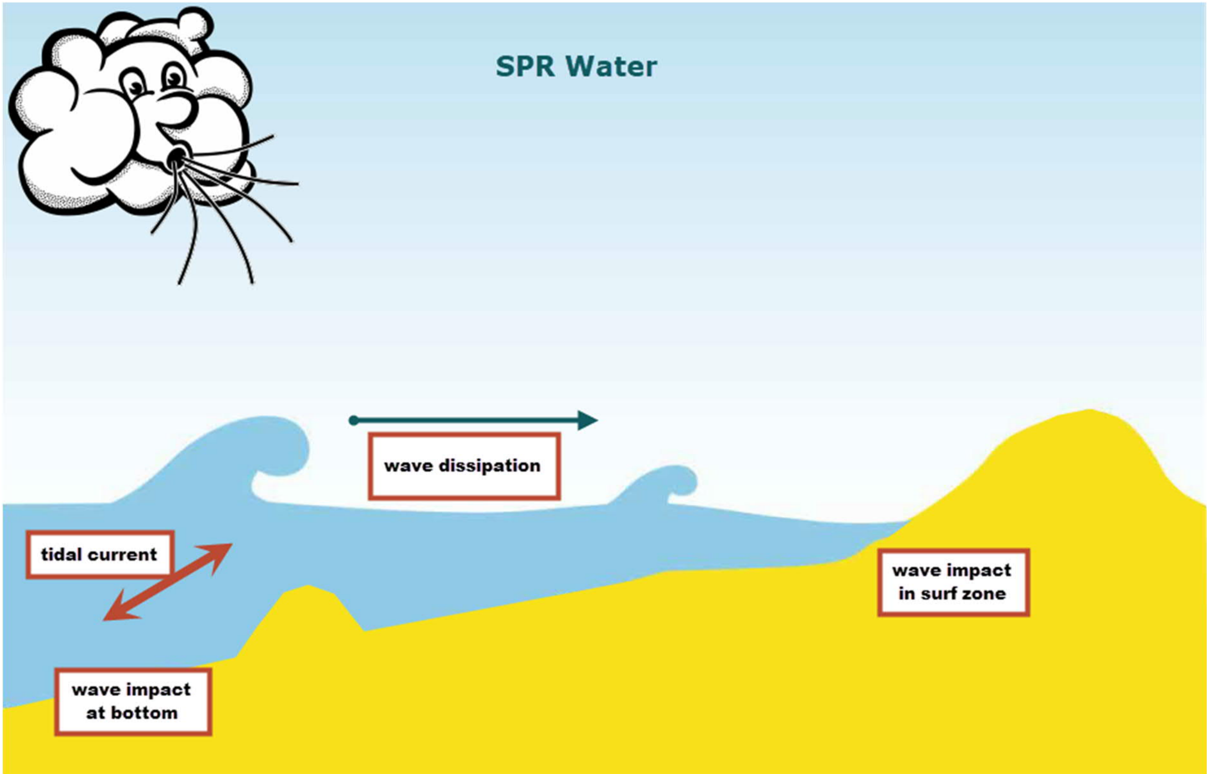


Figure 29: Schematic cross-section showing the main processes driving water

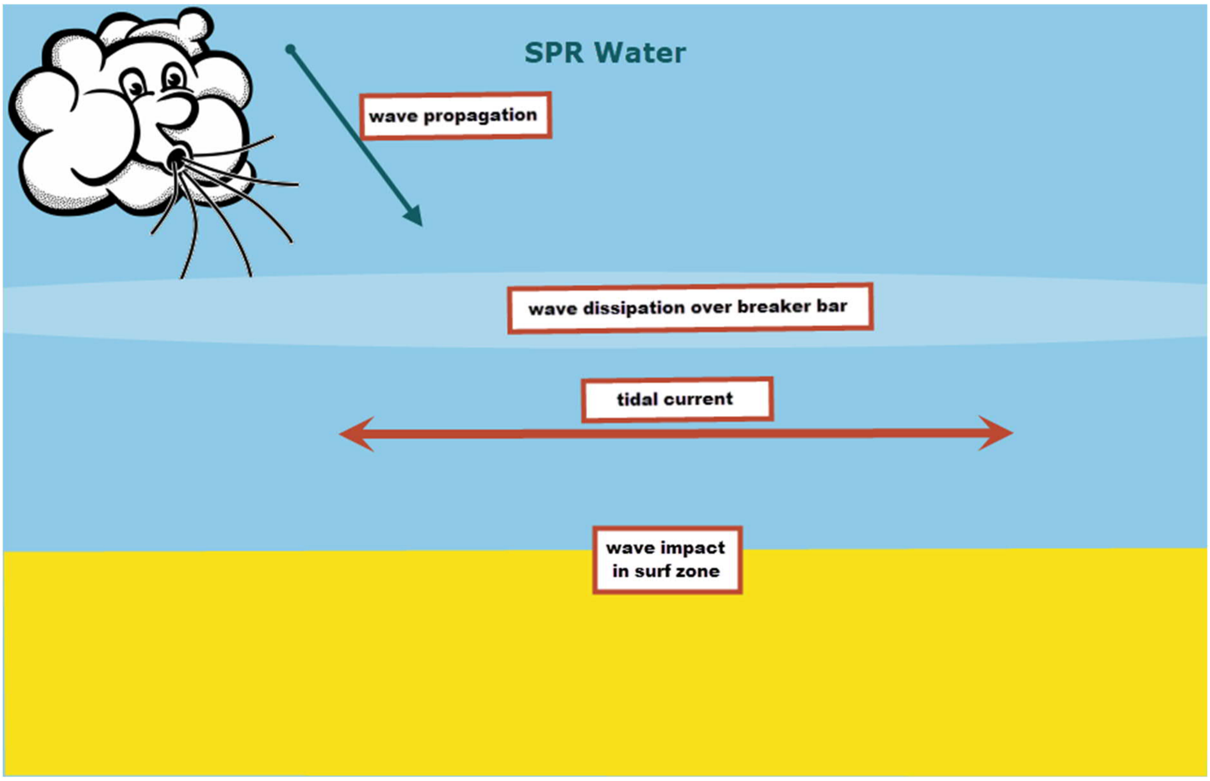


Figure 30: Schematic plan view showing the main processes driving water

6.2 Sediment

The sediment at the seafloor, beach and dunes is transported by the water movement (waves and tide) and - at the dry areas – the wind (Figure 31 and Figure 32). In theory any place will function as a source (sediment is transported away) and a receptor of sediment (sediment is deposited). Places where sediment is structurally disappearing can be seen as source, while areas where there is net deposition are receptors. The trajectory the sediment is transported along is the pathway.

For the Zandvoort-Bloemendaal lab the shoreface nourishments have been seen to be the source for the breaker bar zone and possibly – indirectly – the beach (Figure 33). Landward wave driven transport causes the effect to be mainly directly cross-shore, but due to the northward dominant wave driven transport and tide is also seen in northern direction. Aeolian transport from the beach to the dunes is not seen at Zandvoort-Bloemendaal due to the presence of a boulevard directly behind the beach.

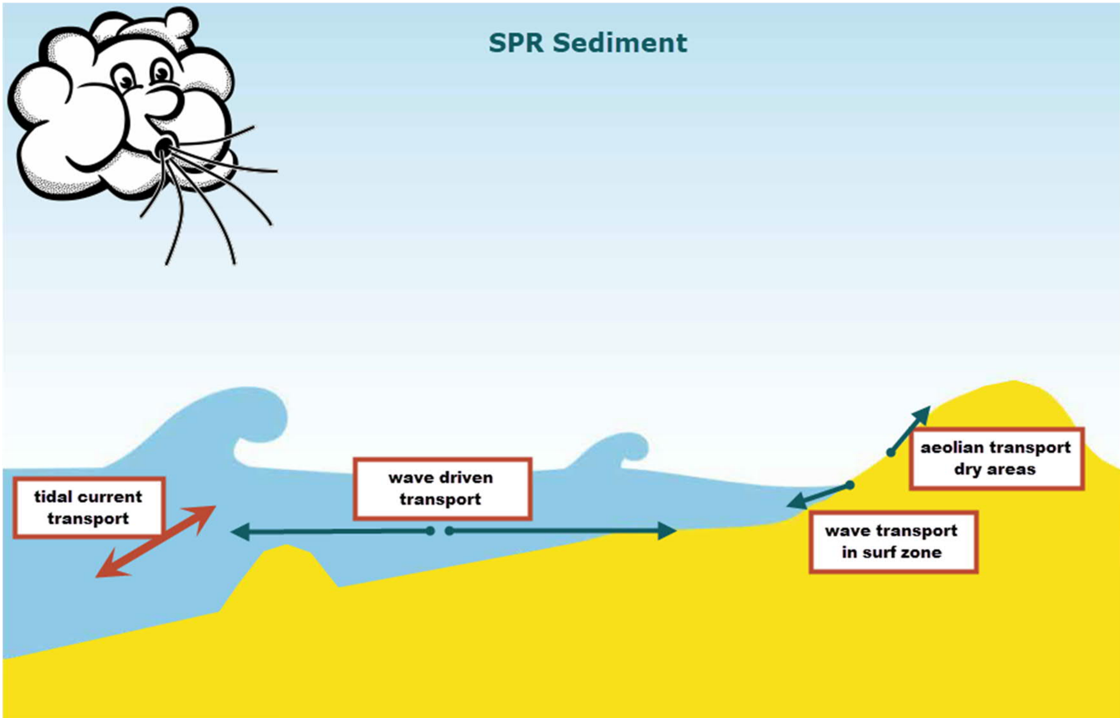


Figure 31: Schematic cross-section showing the main processes driving sediment transport

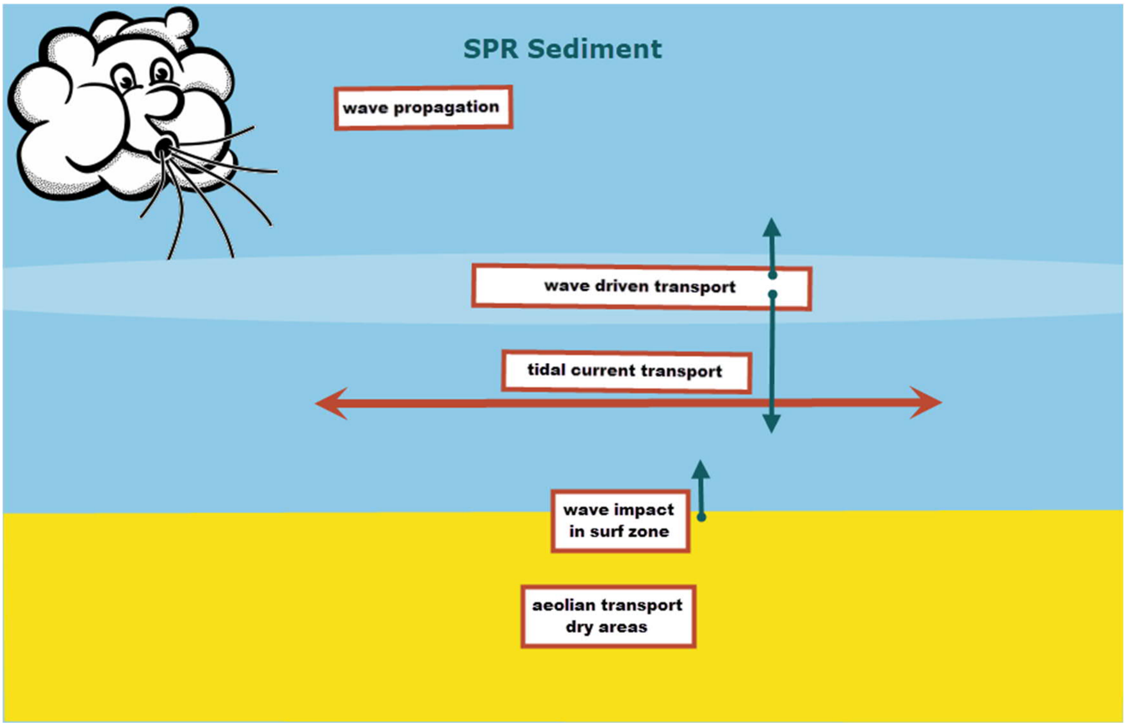


Figure 32: Schematic plan view showing the main processes driving sediment transport

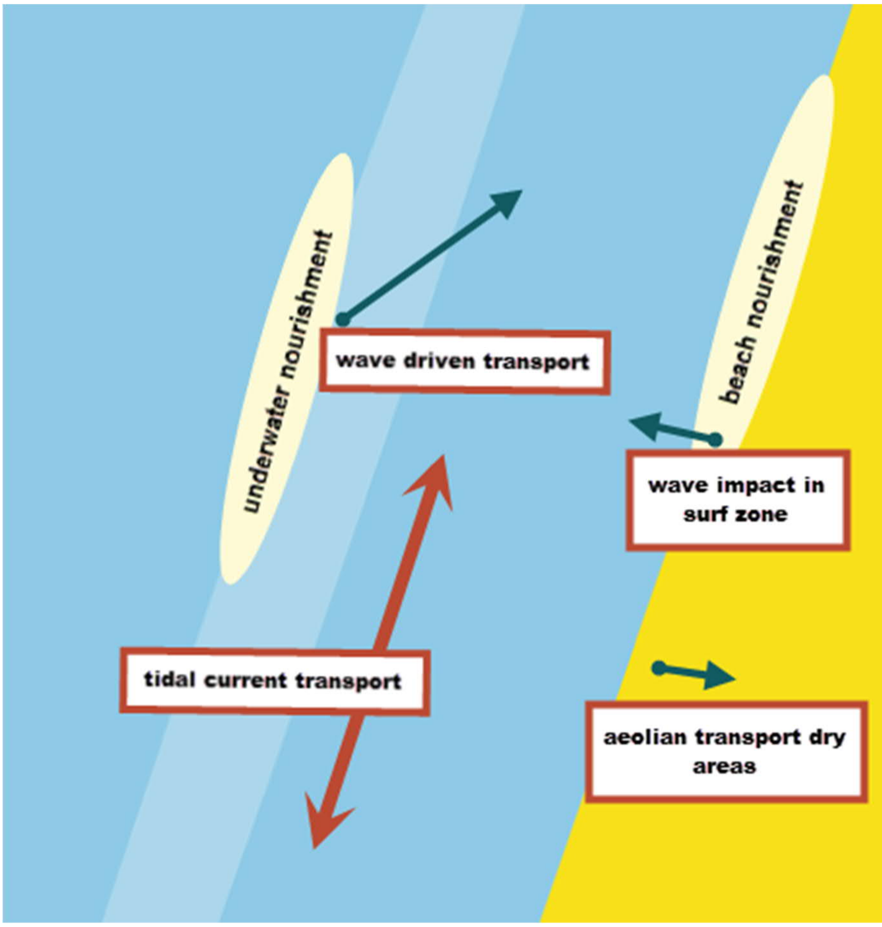


Figure 33: Schematic plan view showing the main processes driving sediment transport for the Zandvoort-Bloemendaal lab

7 Results

7.1 Qualitative Morphological development

7.1.1 Shoreface

On the lower shoreface the breaker bars are clearly visible, see Figure 7. When several years are plotted, the movement of the bars becomes clearly visible, see Figure 34. From 2001 till 2007 the bars migrate offshore, from 2008 till 2013 the bars start to migrate onshore for this transect. This change in direction coincides with the placement of the nourishment.

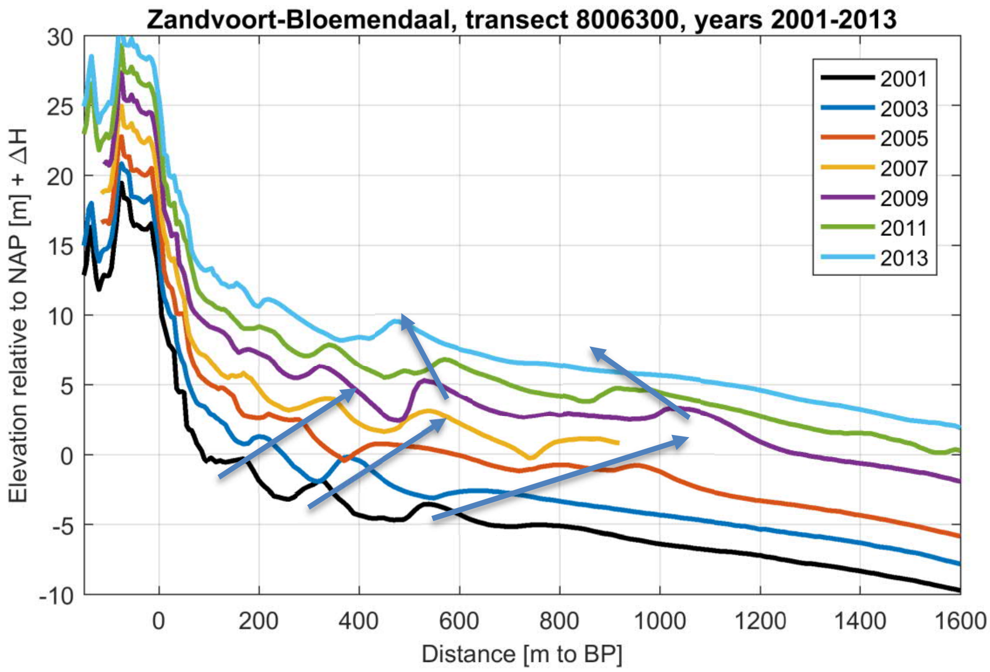


Figure 34: A plot of the bathymetry measurements for Jarkus transect 6300. The bathymetry is manually shifted up using a $\Delta \boldsymbol{H}$ = 2m for each line. The arrows indicate the movement of the bars.

7.1.2 Beach

The transects show a similar behaviour for the different sections. An example of such behaviour is given in Figure 35. The measurements started from 1965 and in the following years erosion of the beach can be observed. Around 1990 the beach started to accrete and this coincides when the Dutch government started with its nourishment policy.

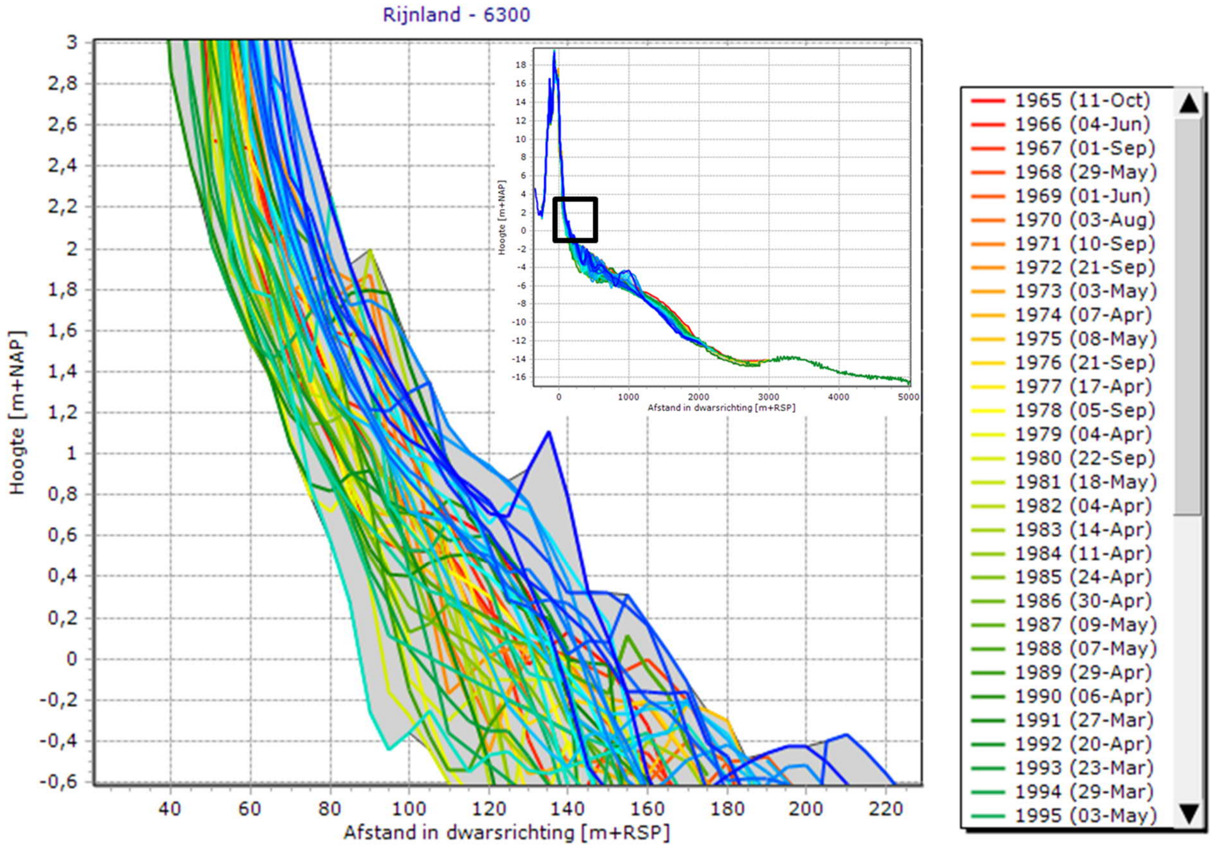


Figure 35: A cross section of the beach profile for Jarkus transect 6300. The black square indicates the location of the zoom area.

7.1.3 Dunes

The transects indicate that the trend of the dunes is different over the transects. First of all, several transects show a permanent seaward migration. These dunes are expanding constantly (Figure 36). Other transects have been eroding until 1990. When the nourishment started around 1990 the erosion stopped and the dunes started to accrete, see Figure 37. In some transects the dunes are still eroding, see Figure 38. Here the upper part of the dune is eroding but the lower area, below 5.5 m NAP accretion is occurring.

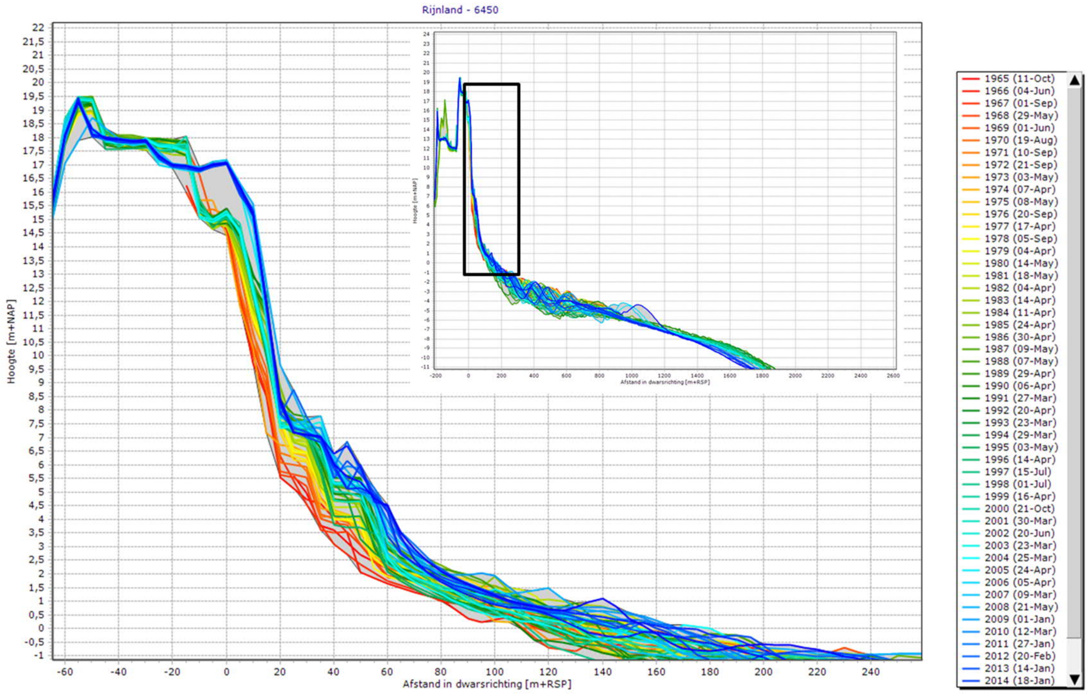


Figure 36: A cross section of the dune profile for Jarkus transect 6450. The black square indicates the location of the zoom area.

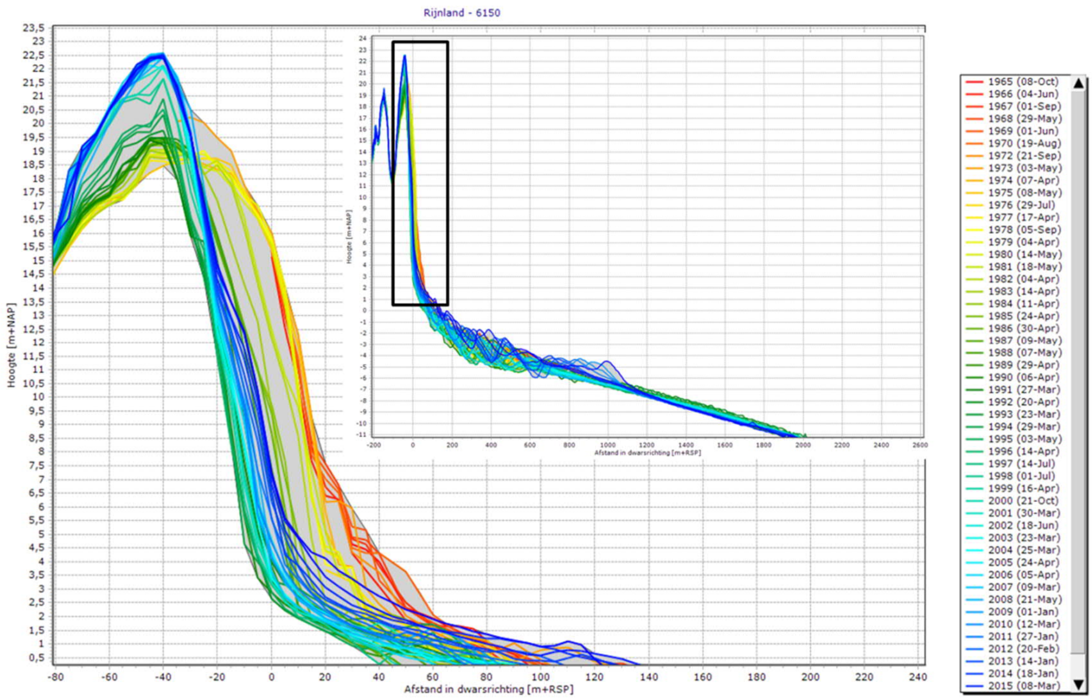


Figure 37: A cross section of the dune profile for Jarkus transect 6150. The black square indicates the location of the zoom area.

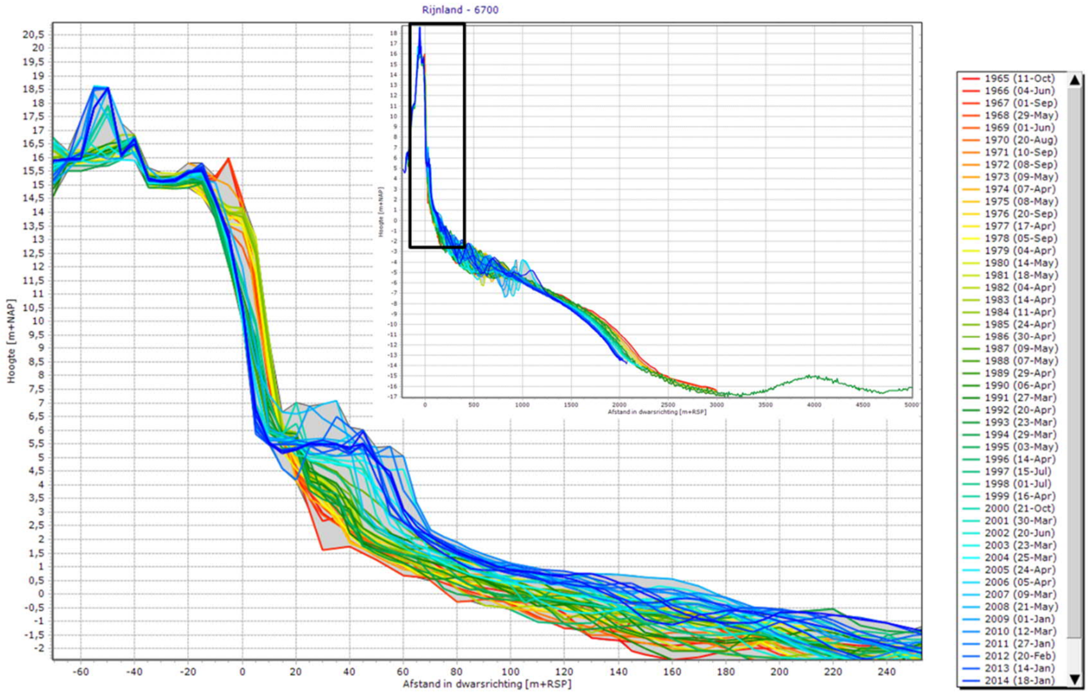


Figure 38: A cross section of dune profile for Jarkus transect 6700. The black square indicates the location of the zoom area.

7.2 Quantitative Morphological development

7.2.1 Physical marks

For the years 2004 (before the nourishment) and 2005 (after the nourishment) the horizontal position of the physical marks are presented in Figure 39 and Figure 40. The changes between these two years is larger for the indicators further seaward (MLWL, MWL and MHWL). The difference in UDL between 2004 and 2005 is much smaller than the difference in MLWL. Most likely this results from the fact that sand transport due to wind is much smaller than due to the hydraulic conditions.

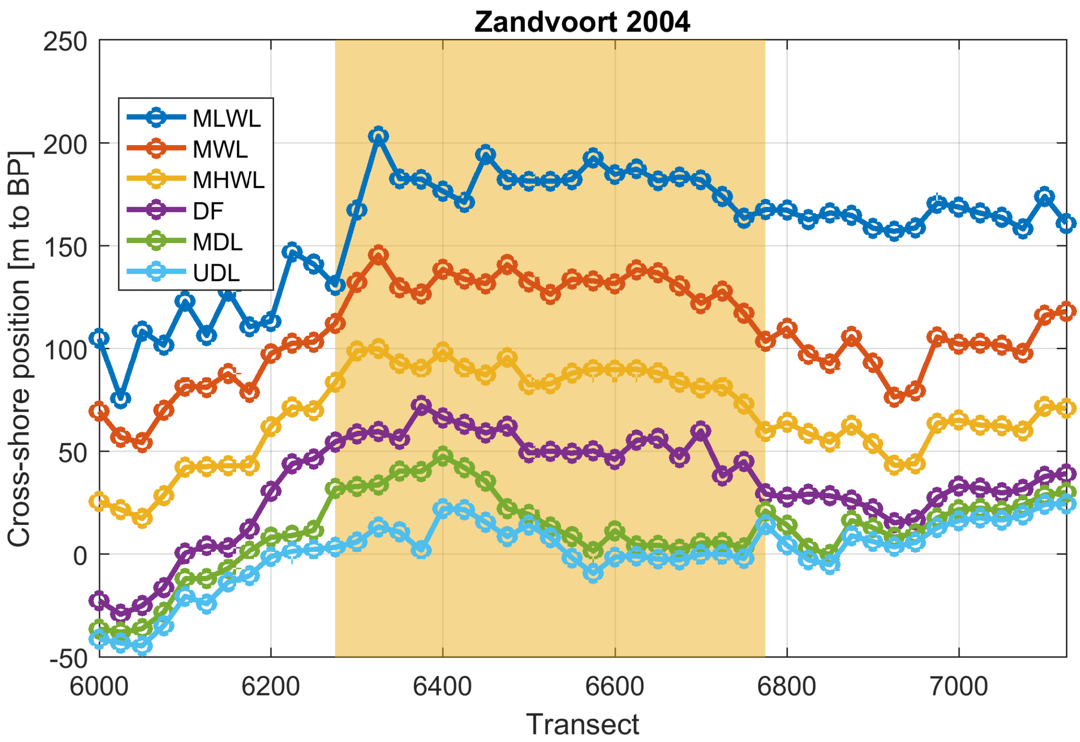


Figure 39: The position of the physical marks for the year 2004. The yellow area indicates the area of the nourishment in 2004. Just north and south of the yellow area nourishments are placed in 2008.

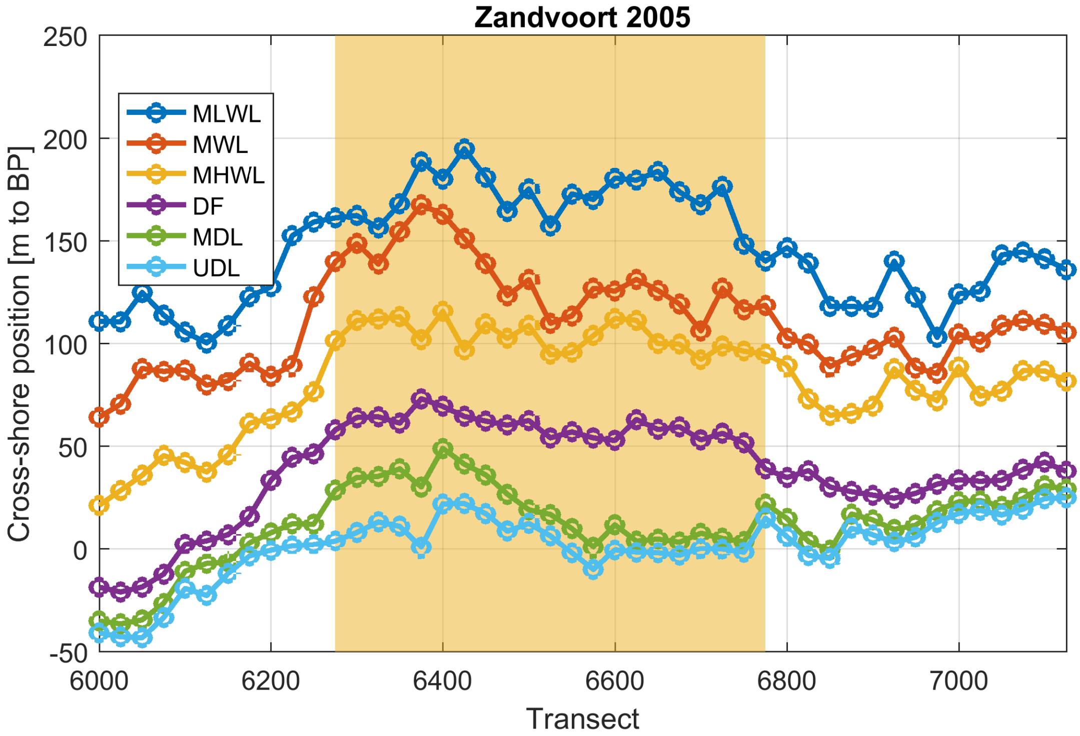


Figure 40: The position of the physical marks for the year 2005. The yellow area indicates the area of the nourishment in 2004. Just north and south of the yellow area nourishments are placed in 2008.

The different physical marks are plotted over time with respect to the year of reference (2004), see Figure Figure 41. The figure shows that the position of MHWL, from 2004 till 2008, moves seaward in the yellow area. After 2008 the level migrates landward again.

North and south of the yellow area the nourishment is placed in 2008. Here the behaviour of the MHWL level is much more chaotic and it hardly reveals a migration direction. Other physical marks do also not show a clear migration behaviour, for example the DF as shown in Figure 42. In other words, a clear migration pattern is only visible for MHWL position in the yellow area.

The long term timeseries of the coastal state indicators (Figure 43 and Figure 44) show that the fluctuations in the indicators become larger when at a lower level: the upper dune level is changing smoothly, while the mean low water level is showing fluctuations of up to ~30 m. In general the MLWL, MWL and MHWL indicators show a relative stable position until 1990 and an increase after 1990. The dunefoot shows a small positive trend for the entire period, while the middle and upper dune level are very stable.

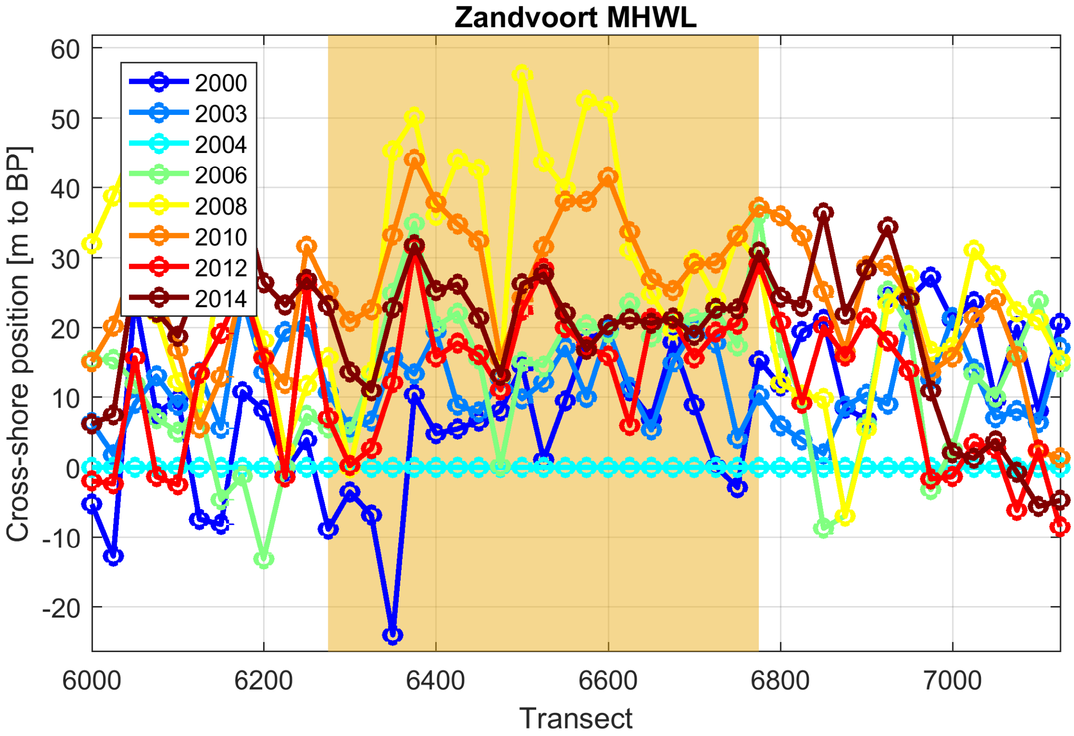


Figure 41: The position of the MHWL with respect to the year 2004 (before the nourishment). The yellow area indicates the area of the nourishment in 2004. Just north and south of the yellow area nourishments are placed in 2008.

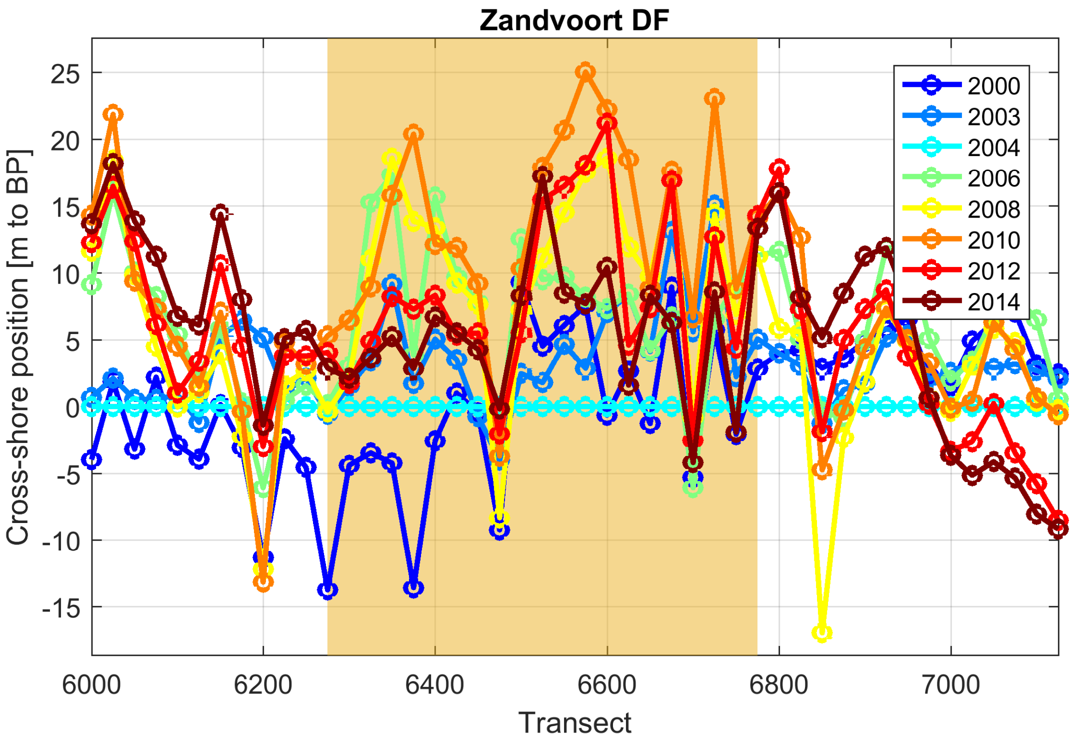


Figure 42: The horizontal position of the DF with respect to the year 2004 (before the nourishment). The yellow area indicates the area of the nourishment in 2004. Just north and south of the yellow area nourishments are placed in 2008.

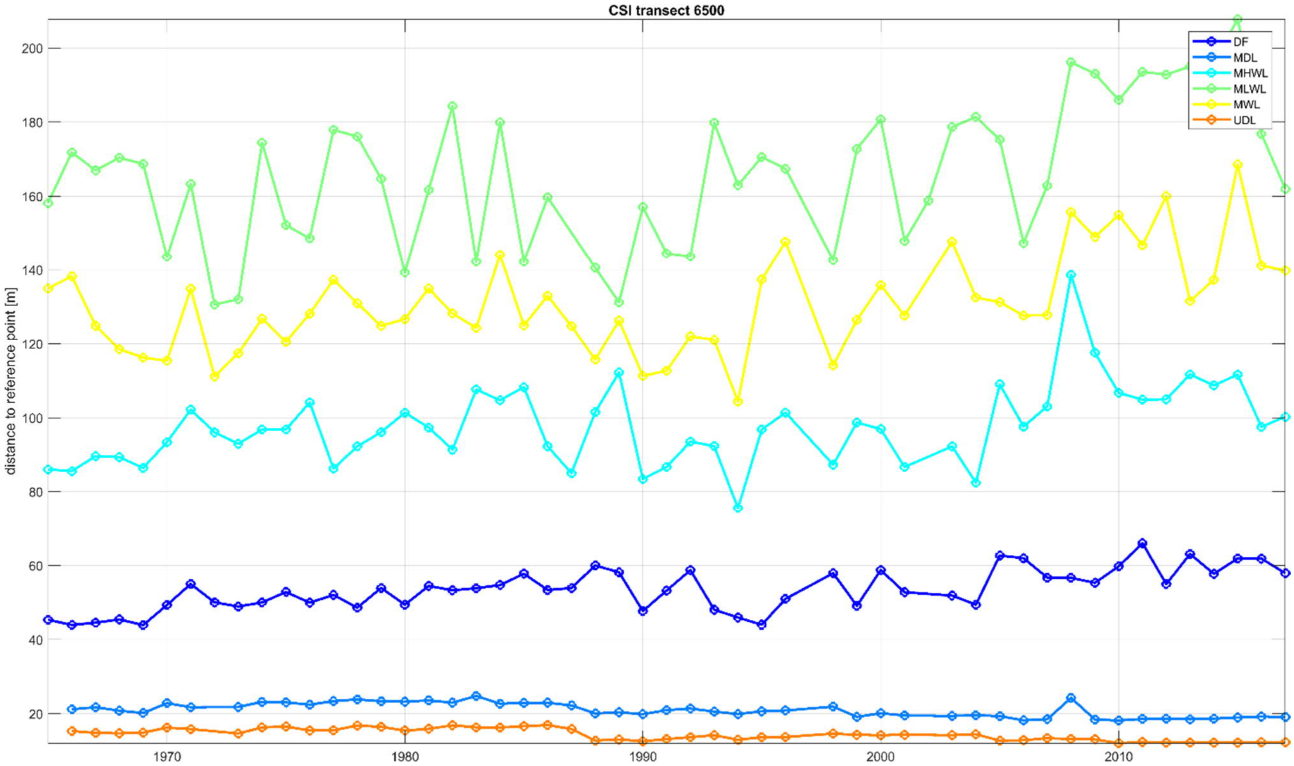


Figure 43: Timeseries of coastal state indicators for transect 6500

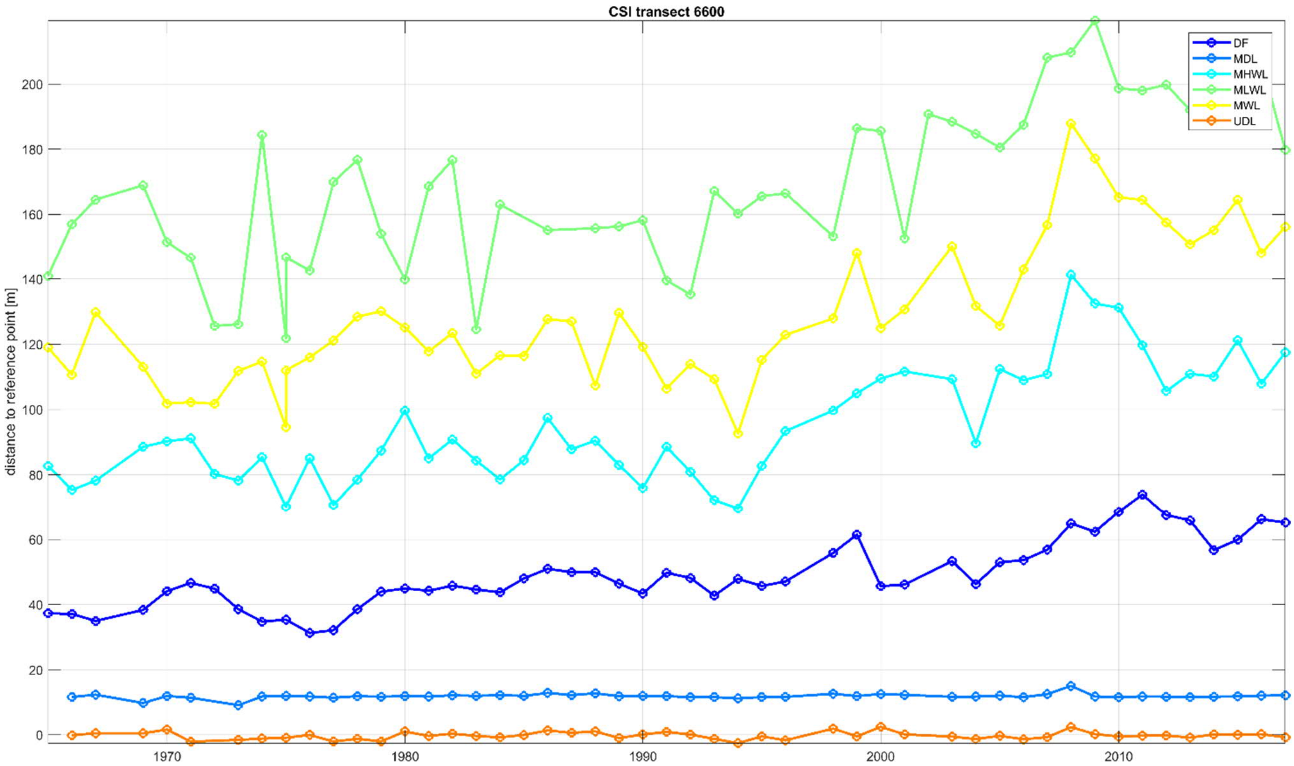


Figure 44: Timeseries of coastal state indicators for transect 6600

7.2.2 Bar development

The automated detection of breaker bars in general detects the bar crests at the correct location, see for example Figure 45 and Figure 46. In Figure 45 two clear, continuous bars can be seen and one discontinuous bar at the landward side.

Plotting the horizontal bar position for all available time steps, for one transect, gives good insight in the typical, natural bar behaviour (Figure 47). The bars migrate in offshore direction with a mostly (very) linear rate, up to a distance of 500 to 600 m to the reference, where they decay. A new bar appears just after or shortly before the decay of the outer bar. Most of the time there are two bars present, except for the period just before the decay of the outer bar, when there can be three bars.

The bars migrate offshore with a rate of 40 to 90 m per year. These rates are based on linear regression analysis for three randomly chosen bars (Figure 48). During the offshore migration the bar height first increases and then decreases, as can be seen by the colour and size of the circles in Figure 47 and the graph in Figure 49. The surface area of the bar shows a similar pattern (Figure 50). The depth of the bar decreases more or less linearly in time (Figure 51), therefore also clearly correlating with the horizontal bar position (Figure 52). In the latter figure also the depth and horizontal position of decay can be seen, which are around NAP -5.5 m and 750 m to reference. Over time the bar width increases, though the relation is not as linear as for the depth (Figure 53). The large bars visible around 1000 m distance are caused by the nourishment, see next paragraph.

After placement of the nourishment, an additional bar forms on the seaward side of nourishment. This bar is formed with the nourished sediment, has a larger surface area and lies much further offshore than the maximum offshore position of the natural bars (Figure 54 and Figure 55). This bar moves landward towards the natural position of decay and then also decays.

After placement of the nourishment, the horizontal position of the existing (natural) bars becomes stable or also moves landward for about 5 years. Thereafter the nourishment-bar disappeared and the natural bars start migrating offshore again, though at a lower speed.

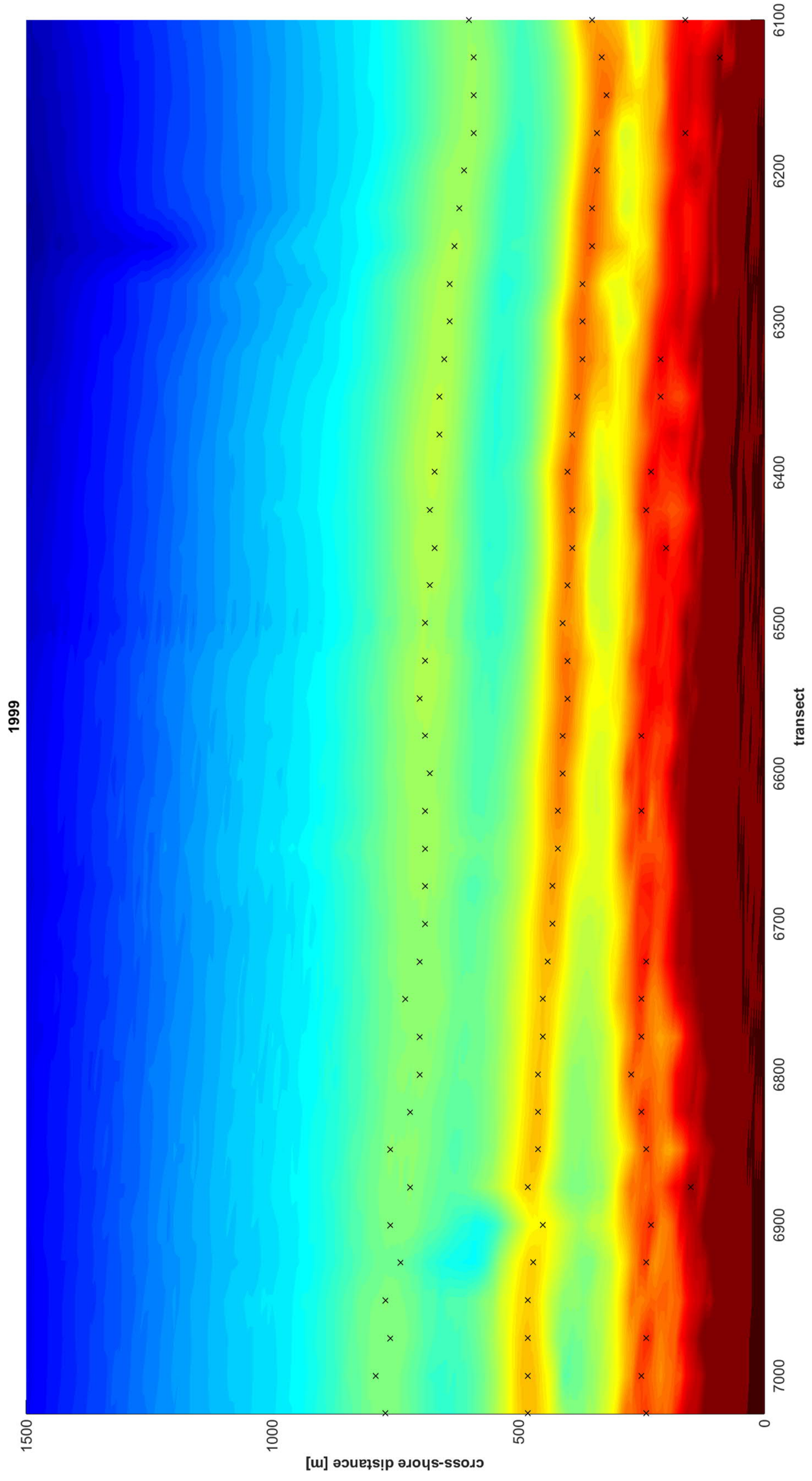


Figure 45: Bathymetry plot based on transect data (not gridded data) measured in 1999 with the detected bar crest position indicated with crosses

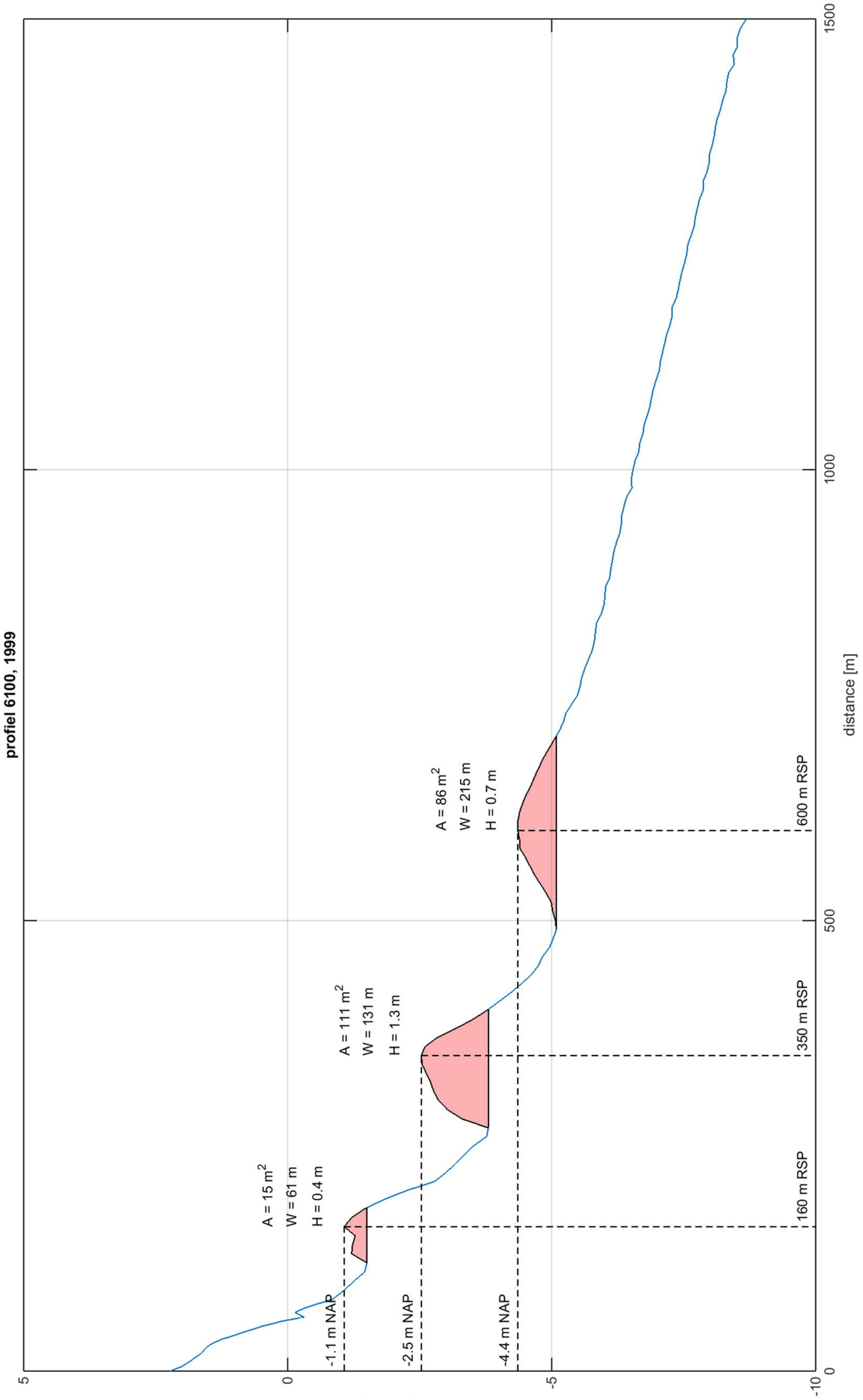


Figure 46: Profile 6100 measurement from 1999 showing detected bars with the horizontal and vertical crest position and bar characteristics: A=surface area (red area), W=bar width, H=bar height

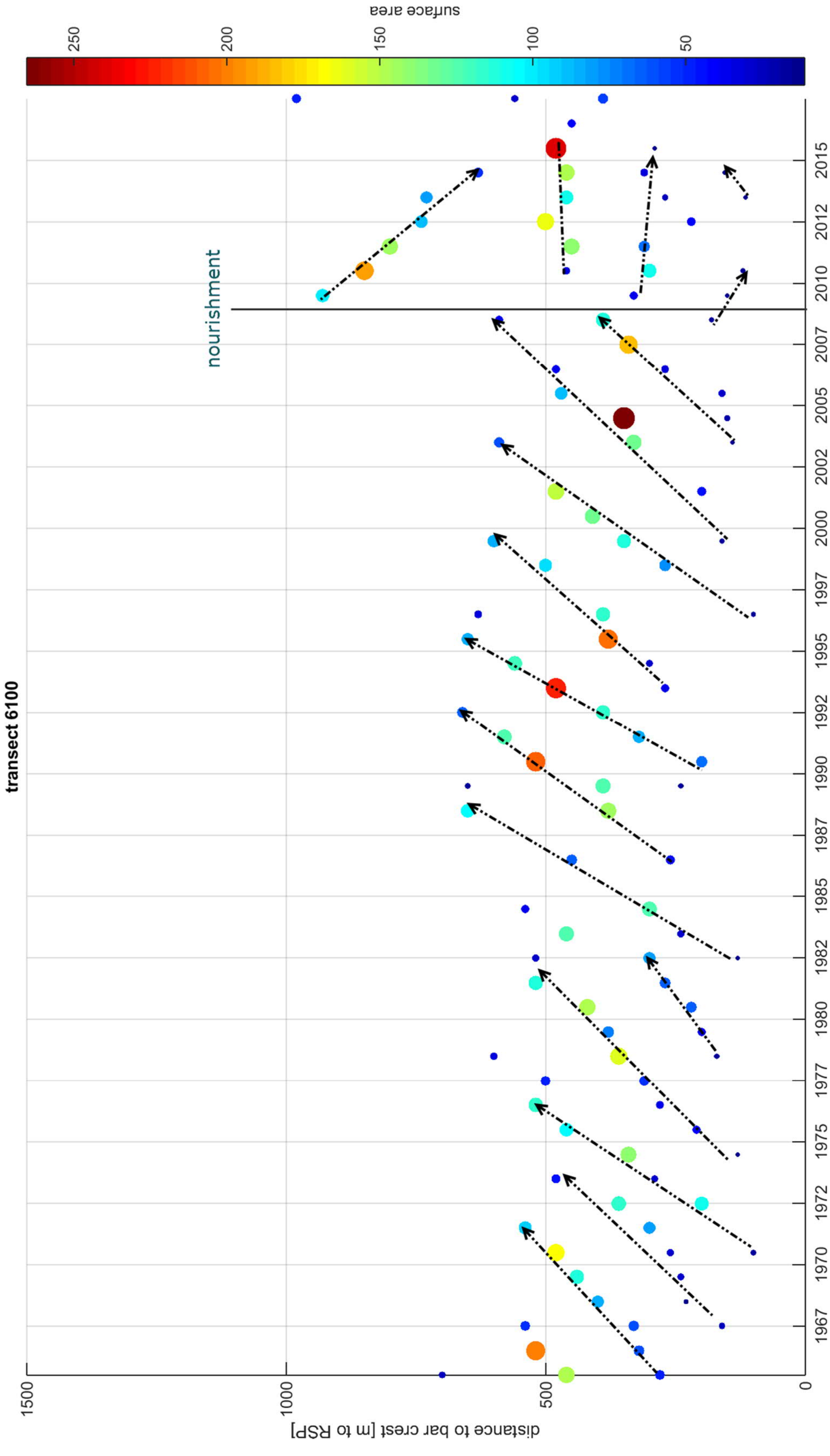


Figure 47: Development of bar crests position over time for transect 6100, colours and circle-size correspond with surface area of the bar (m^2), dashed arrows indicate movement of single bar in time

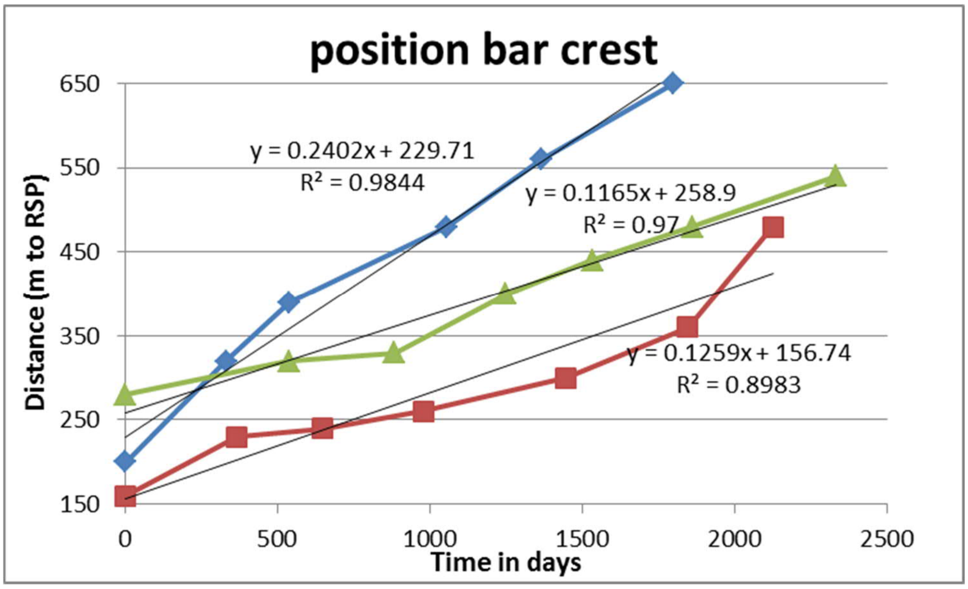


Figure 48: Linear regression analyses on change of bar crest position in time for three randomly chosen bar

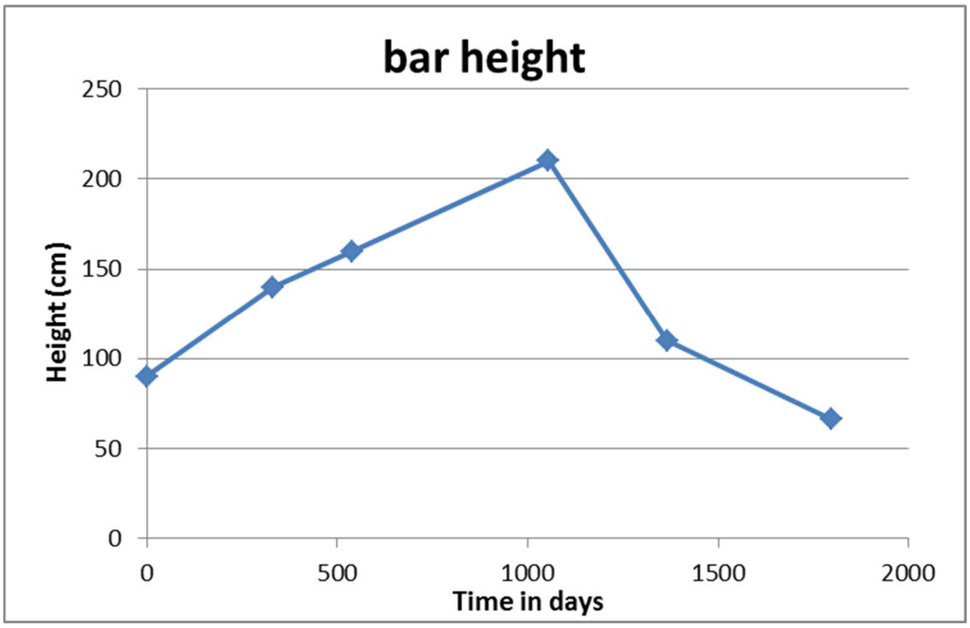


Figure 49: Change of bar height in time for randomly chosen bar

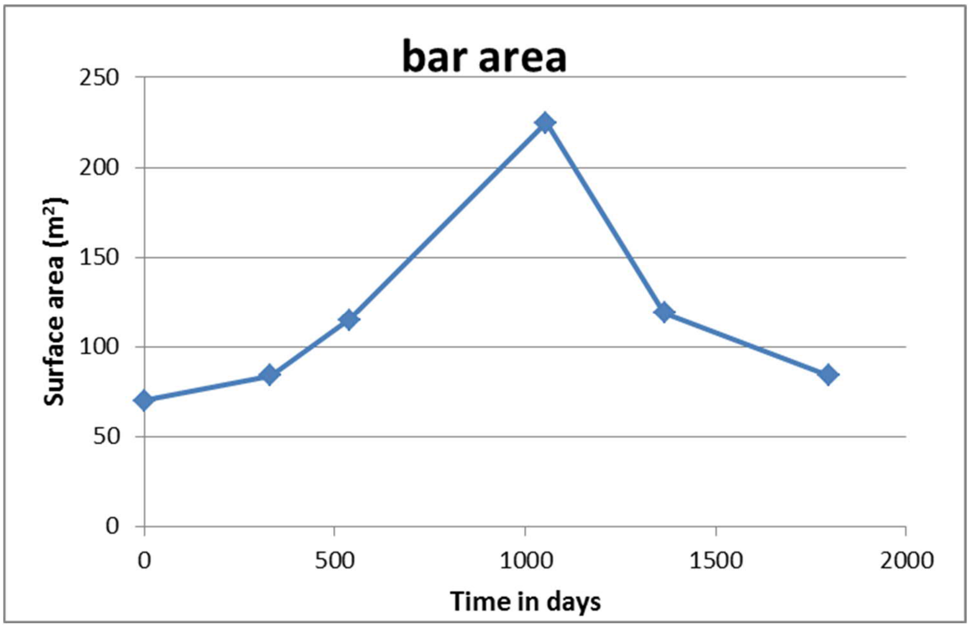


Figure 50: Change of surface area in time for a randomly chosen bar (same bar as in Figure 49)

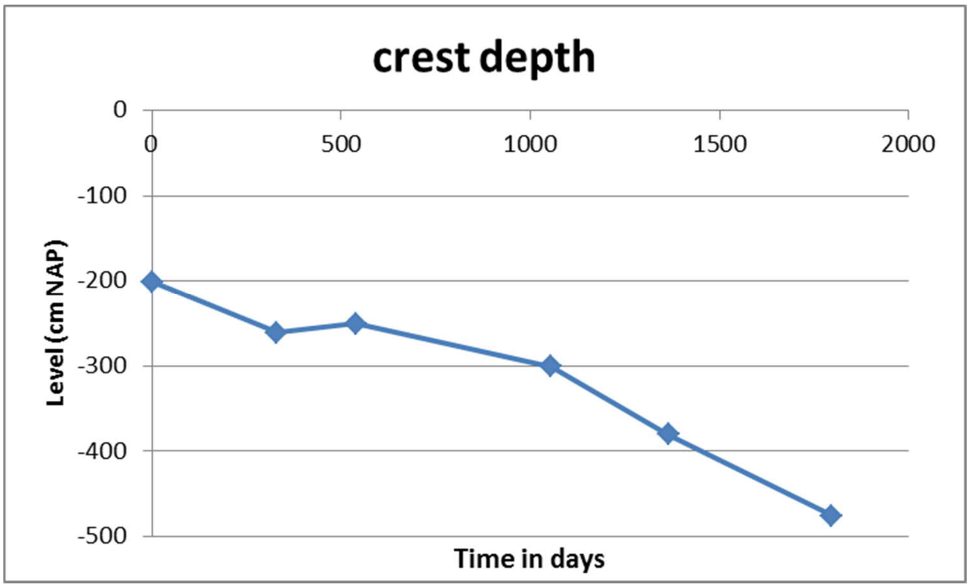


Figure 51: Change of crest depth in time for a randomly chosen bar (same bar as in Figure 49)

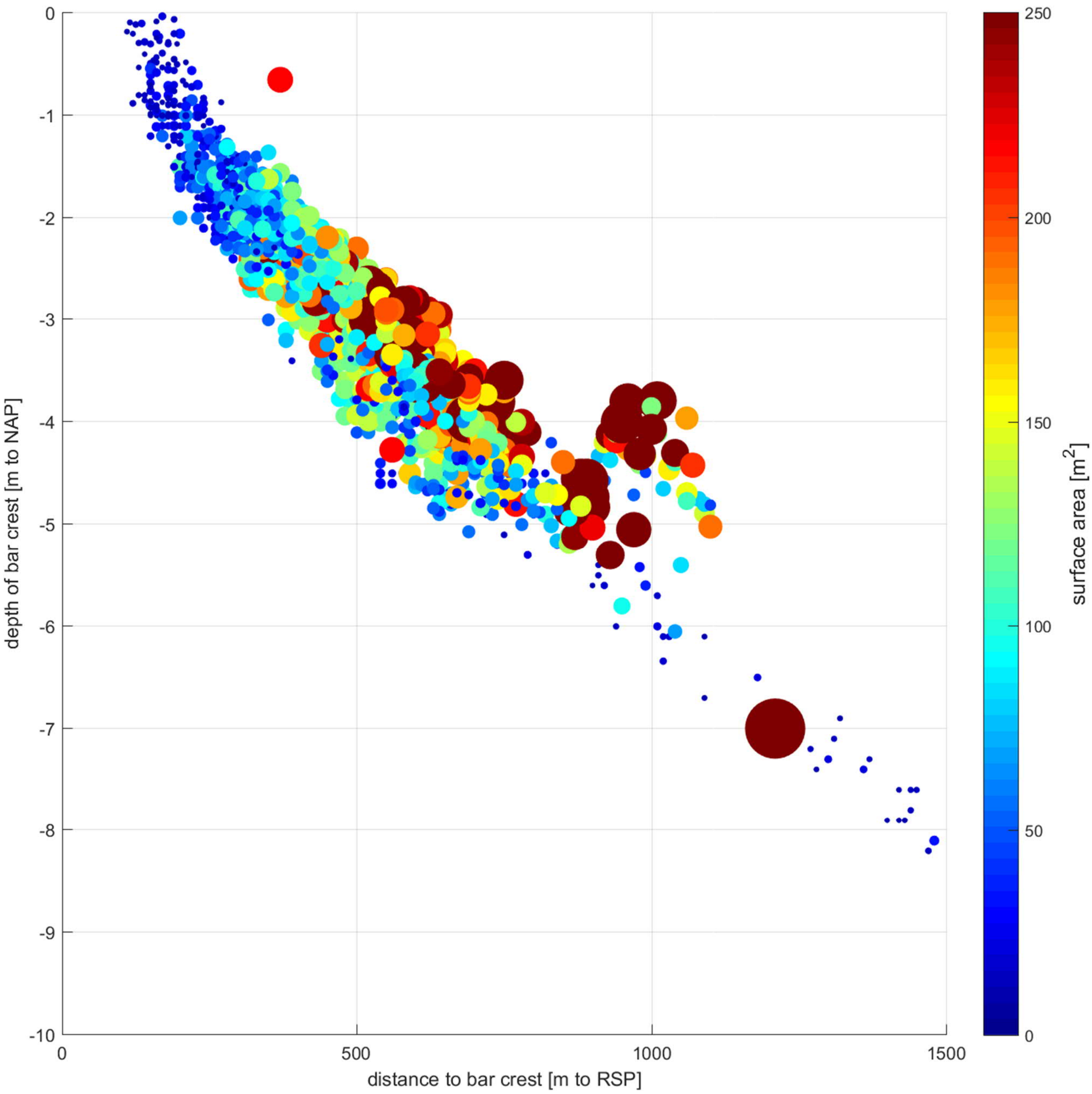


Figure 52: Relation between horizontal distance to bar crest and depth of the bar crest, for each bar in all measured years. Colours and circle-size correspond with surface area of the bar (m2)

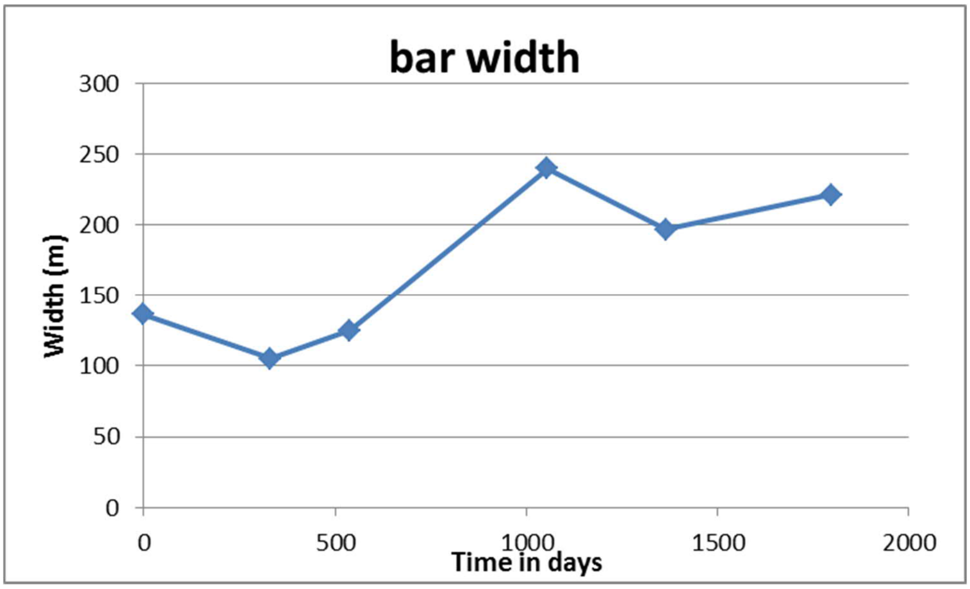


Figure 53: Change of bar width in time for a randomly chosen bar (same bar as in Figure 49)

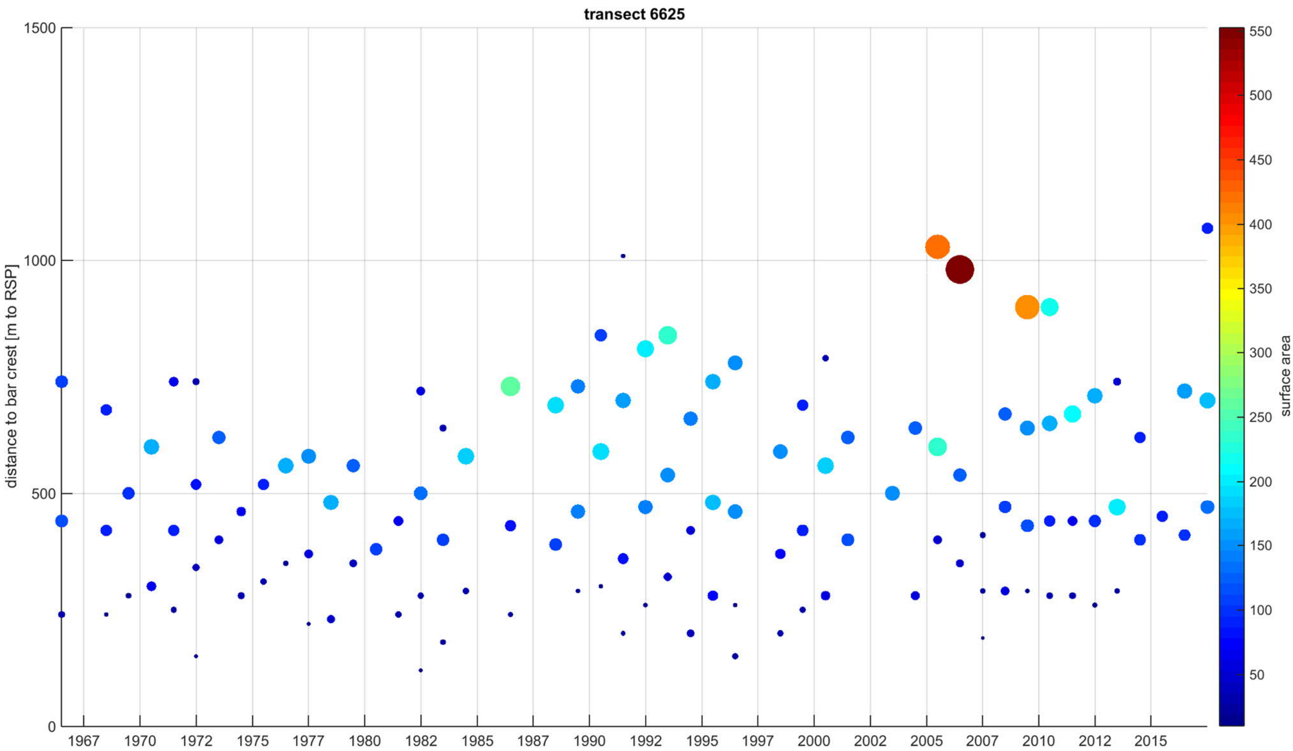


Figure 54: Development of bar crests position over time for transect 6625, colours and circle-size correspond with surface area of the bar (m²), dashed arrows indicate movement of single bar in time. The nourishment is clearly visible in 2005 by its larger surface area and far offshore position.

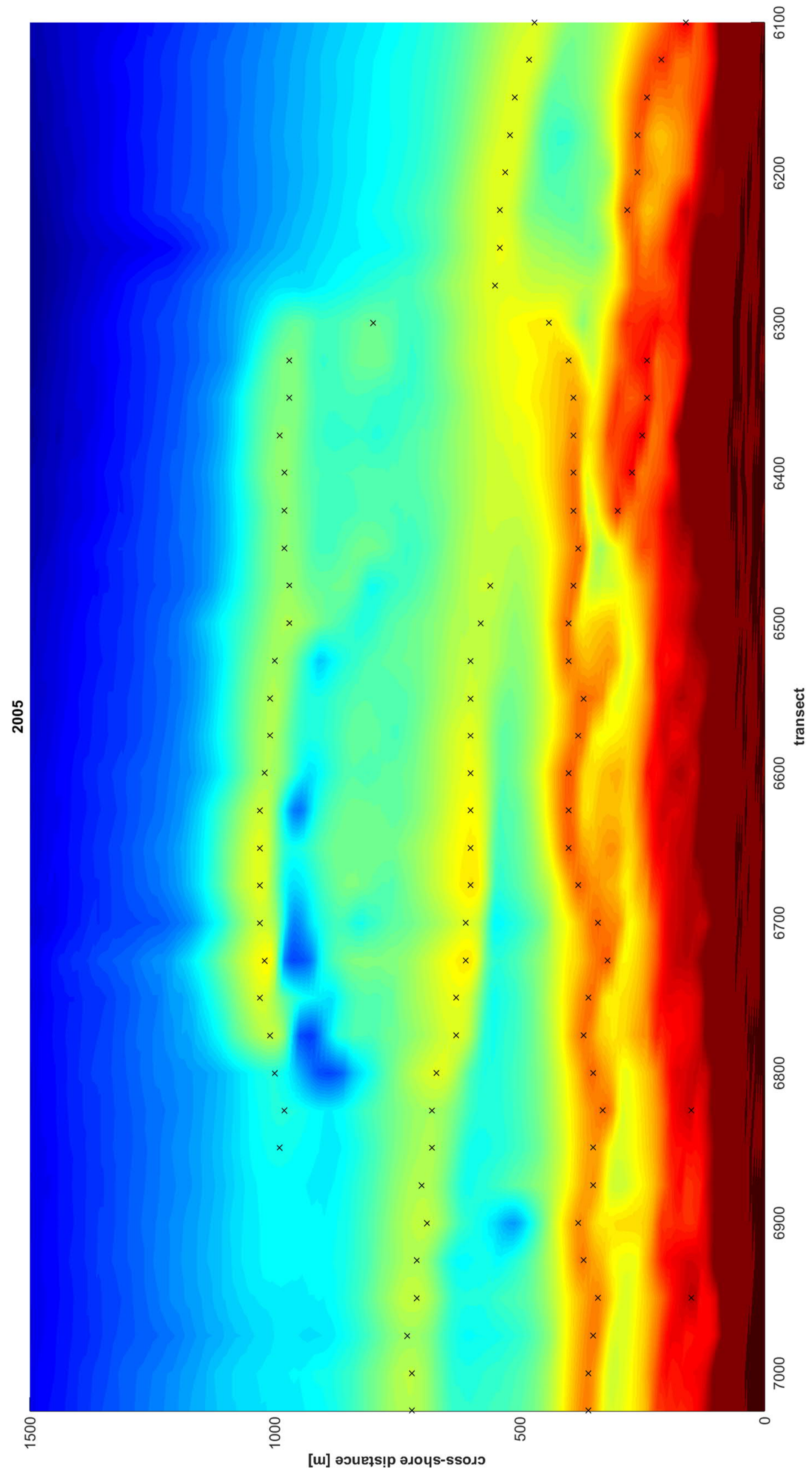


Figure 55: Bathymetry plot based on transect data (not gridded data) measured in 2005, first measurement including the nourishment, with the detected bar crest position indicated with crosses

7.2.3 Volumes 2D

The areas used for the volume calculations are shown in Figure 56. In area 3 the nourishment in 2004 is placed and in area 2 and 4 the nourishment is placed in 2008 (see also Figure 11 and Figure 12). Zone 7, 8 and 9 are the breaker zones related to each nourishment zone. Zones 12 – 14 are the beach zones related to each nourishment. The area just north and south of the coastal laboratory are also considered to better understand where the sand is moving towards.

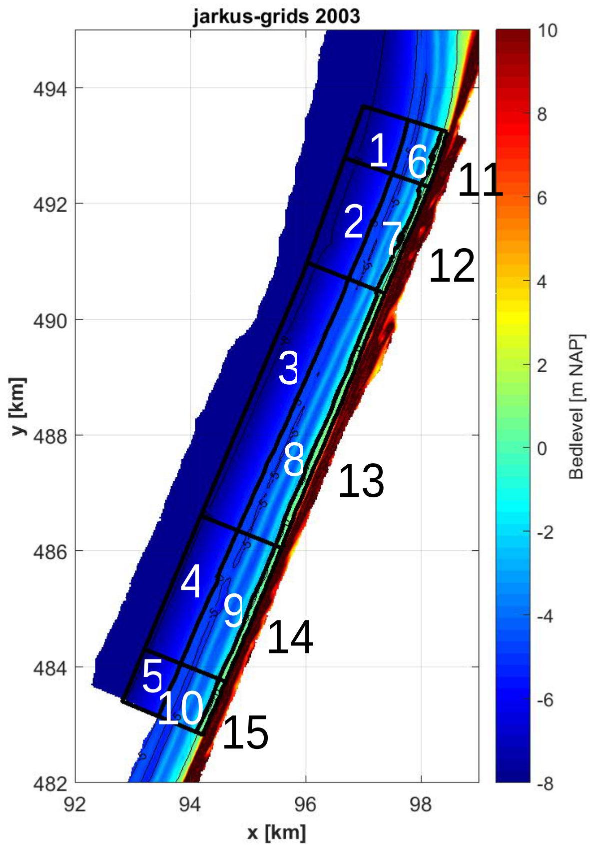


Figure 56: A top view of the Jarkus grids 2005 in 2003. The black squares indicate different areas and the numbers are used to name each region.

For each area the volume change is determined for every year, see Table 8. The coverage of the areas by the measurements is changing over the years. Especially the areas 1 till 5 are only measured in the recent years. Only for areas with high enough coverage (at least 98% of the area) the volumes are calculated, n/a is indicating too low data coverage.

Table 8: The volume changes in million m³ for the different areas of Figure 56 with respect to 2003. When the table contains an n/a, less than 98% of the area was measured.

year	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8	Area 9	Area 10	Area 11	Area 12	Area 13	Area 14	Area 15
1964	n/a	n/a	n/a	n/a	n/a	0,12	0,43	1,16	n/a	n/a	n/a	n/a	-0,28	-0,13	n/a
1965	n/a	n/a	n/a	n/a	n/a	0,01	0,28	0,33	n/a	n/a	n/a	n/a	-0,36	-0,20	-0,08
1966	n/a	n/a	n/a	n/a	n/a	0,10	0,38	0,63	0,24	n/a	0,16	0,17	-0,37	-0,22	-0,11
1967	n/a	n/a	n/a	n/a	n/a	0,05	0,51	0,86	n/a	n/a	0,15	0,18	-0,38	-0,18	-0,06
1968	n/a	n/a	n/a	n/a	n/a	0,10	0,40	0,69	n/a	n/a	0,15	0,20	-0,35	-0,22	-0,06

1969	n/a	n/a	n/a	n/a	n/a	0,02	0,40	0,30	n/a	n/a	0,15	0,22	-0,32	-0,17	-0,05
1970	n/a	n/a	n/a	n/a	n/a	0,01	0,29	0,84	n/a	n/a	0,14	0,21	-0,34	-0,15	-0,05
1971	n/a	n/a	n/a	n/a	n/a	0,06	0,21	0,47	n/a	n/a	0,12	0,19	-0,29	-0,18	-0,04
1972	n/a	n/a	n/a	n/a	n/a	0,01	0,25	0,48	n/a	n/a	0,00	0,00	-0,35	-0,18	-0,06
1973	n/a	n/a	n/a	n/a	n/a	0,01	0,23	0,44	n/a	n/a	0,10	0,18	-0,39	-0,17	-0,06
1974	n/a	n/a	n/a	n/a	n/a	-0,01	0,26	0,10	n/a	n/a	0,05	0,08	-0,25	-0,14	-0,04
1975	n/a	n/a	n/a	n/a	n/a	0,04	0,22	0,60	n/a	n/a	0,02	0,05	-0,36	-0,19	-0,07
1976	n/a	n/a	n/a	n/a	n/a	0,03	0,26	0,53	n/a	n/a	0,04	0,07	-0,22	-0,10	-0,03
1977	n/a	n/a	n/a	n/a	n/a	-0,06	0,18	0,54	n/a	n/a	0,01	0,06	-0,25	-0,10	-0,03
1978	n/a	n/a	n/a	n/a	n/a	-0,21	-0,20	0,22	n/a	n/a	0,00	0,03	-0,28	-0,14	-0,03
1979	n/a	n/a	n/a	n/a	n/a	-0,08	0,00	0,46	n/a	n/a	0,00	0,03	-0,28	-0,17	-0,05
1980	n/a	n/a	n/a	n/a	n/a	-0,12	-0,09	0,12	n/a	n/a	0,00	0,00	-0,28	-0,16	-0,05
1981	n/a	n/a	n/a	n/a	n/a	-0,09	0,04	0,48	n/a	n/a	-0,01	-0,01	-0,21	-0,13	-0,04
1982	n/a	n/a	n/a	n/a	n/a	-0,06	-0,07	0,27	n/a	n/a	-0,03	-0,05	-0,21	-0,16	-0,04
1983	n/a	n/a	n/a	n/a	n/a	-0,07	0,03	0,70	n/a	n/a	-0,03	-0,05	-0,34	-0,18	-0,05
1984	n/a	n/a	n/a	n/a	n/a	-0,03	-0,06	0,31	n/a	n/a	-0,04	-0,05	-0,27	-0,15	-0,02
1985	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1986	-0,04	0,33	1,19	0,33	n/a	0,11	0,28	0,77	0,53	0,27	-0,01	-0,10	-0,21	-0,11	-0,01
1987	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1988	0,00	-0,05	-0,21	n/a	n/a	-0,01	-0,26	-0,71	0,00	n/a	-0,03	-0,12	-0,32	n/a	n/a
1989	-0,10	-0,08	-0,08	-0,33	n/a	0,01	-0,12	-0,51	-0,10	-0,08	-0,01	-0,08	-0,34	-0,21	-0,05
1990	-0,15	-0,14	-0,20	-0,29	-0,10	-0,12	-0,15	-0,76	-0,09	0,01	-0,06	-0,13	-0,42	-0,15	-0,07
1991	-0,01	-0,17	0,19	0,02	n/a	-0,02	-0,26	-0,23	0,28	0,07	-0,04	-0,08	-0,37	-0,11	-0,05
1992	0,11	0,63	1,36	0,49	0,06	0,05	0,23	0,18	1,02	0,19	-0,02	-0,08	-0,32	-0,04	0,00
1993	0,19	0,35	0,60	0,34	0,14	0,25	0,00	-0,30	0,68	0,24	0,02	-0,14	-0,25	-0,08	0,02
1994	0,11	0,47	0,85	0,46	0,18	0,12	0,25	0,61	0,93	0,27	-0,03	-0,08	-0,47	-0,18	-0,04
1995	-0,03	-0,14	-0,15	-0,05	-0,01	0,00	-0,11	-0,10	-0,01	-0,05	-0,02	-0,11	-0,38	-0,10	-0,01
1996	0,00	-0,11	0,00	-0,19	0,01	-0,02	-0,24	-0,39	-0,19	-0,10	-0,01	-0,09	-0,28	-0,10	-0,01
1997	0,00	-0,08	0,13	-0,09	0,00	n/a	-0,16	-0,31	-0,08	-0,05	n/a	n/a	n/a	n/a	n/a
1998	-0,02	-0,09	-0,10	0,03	0,08	-0,01	-0,09	-0,15	0,14	0,07	-0,03	-0,12	-0,31	-0,06	-0,01
1999	0,00	0,00	0,06	-0,07	-0,02	0,00	0,04	0,13	0,05	0,00	-0,05	-0,10	-0,20	-0,06	0,01
2001	-0,04	-0,03	0,07	-0,05	0,00	0,03	0,02	0,23	0,21	0,02	0,00	-0,07	-0,21	-0,04	-0,03
2002	-0,03	-0,05	0,03	-0,11	-0,03	0,04	0,05	0,05	0,01	-0,01	0,00	0,00	0,00	0,00	0,00
2003	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2004	n/a	n/a	n/a	n/a	n/a	0,04	-0,01	0,07	-0,03	0,00	0,00	-0,06	-0,14	-0,06	-0,02
2005	-0,08	-0,01	1,30	-0,11	-0,01	0,10	-0,03	0,58	-0,16	-0,02	0,03	-0,02	-0,05	-0,06	-0,02
2007	n/a	n/a	n/a	n/a	n/a	0,12	0,23	1,00	-0,08	0,05	0,02	-0,06	0,02	-0,10	-0,05
2008	n/a	n/a	n/a	n/a	n/a	0,08	0,18	0,79	0,06	0,03	0,02	-0,05	0,15	-0,10	-0,02
2009	-0,16	0,46	0,06	-0,01	-0,09	0,09	0,26	0,63	0,25	-0,03	0,02	0,01	0,21	-0,03	-0,01
2010	-0,09	0,50	-0,01	-0,07	-0,07	0,22	0,37	0,75	0,53	0,01	0,05	0,02	0,26	0,03	-0,01
2011	-0,09	0,42	-0,30	-0,24	-0,12	0,20	0,42	0,80	0,63	-0,03	0,02	0,01	0,17	0,01	-0,04
2012	-0,11	0,31	-0,30	-0,16	-0,08	0,22	0,53	0,92	0,72	0,02	0,03	0,05	0,09	0,03	-0,04
2013	-0,09	0,31	-0,39	-0,26	-0,11	0,25	0,50	0,90	0,68	0,06	0,03	0,10	0,15	0,05	-0,05
2014	-0,05	0,19	-0,48	-0,37	-0,13	0,31	0,68	0,97	0,71	0,06	0,06	0,11	0,11	0,06	-0,03
2015	-0,11	-0,07	-0,80	-0,43	-0,16	0,27	0,69	0,82	0,65	0,09	0,08	0,15	0,12	0,08	-0,02
2016	0,04	0,16	-0,38	-0,33	-0,09	0,33	0,93	1,05	0,67	0,11	0,06	0,12	-0,09	0,00	-0,03
2017	0,03	0,38	0,23	-0,26	-0,10	0,33	0,92	1,09	0,68	0,10	0,11	0,23	0,13	0,08	-0,02

The volumes for each area are plotted for several years, see Figure 57. The yellow line in the top figure clearly shows a steep increase. This increase is directly the result of the nourishment in section 3. In Section 8 a similar but smaller increase is observed. It is likely that this increase is due to the indirect effect of the nourishment. Maybe part of the nourishment is directly placed in sector 8 but this is not shown in Figure 11. In 2007 the increase in sector 8 is almost similar as previous year. The small decrease can be explained considering the volume of the nourishment has reduced. Sector 7 and Sector 8 also show an increase and likely this is also due to the nourishment. Sector 6 and sector 10 do not show an increase for the year 2007 most likely because they are located too far away from the nourishment.

Figure 57 shows a change from erosion to sedimentation in the year 2009 for zone 8, indicated by the blue circle. This is likely caused by the influence of the 2008 nourishment, after initial erosion of the sediment this area gained from the 2004 nourishment.

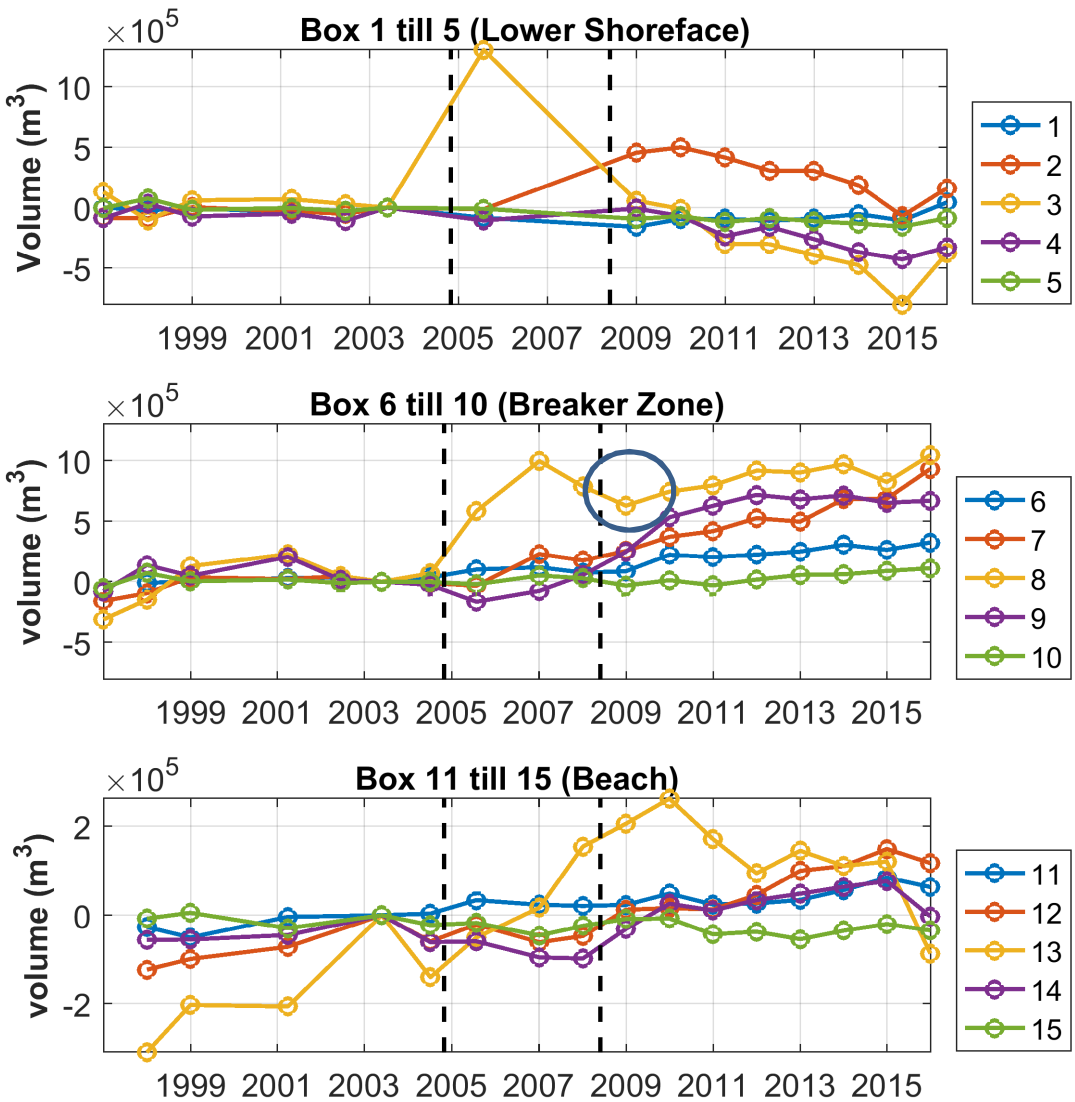


Figure 57: The volumes as a function of time for area 1 till 15. The black lines indicate the moment of the nourishments. The blue circle is further explained in the text.

The beach areas, visualised in the bottom panel of Figure 57, show an increase for several areas. In box 12 a slow, but continuous increase in volume can be seen. The volume of sand in box 13 has a steep increase from 1998 till 2010, after which the volume is decreasing. Box 14 shows several smaller fluctuations and a net sedimentation in this period. The volume of box 15 is fluctuating but shows no significant increase or decrease.

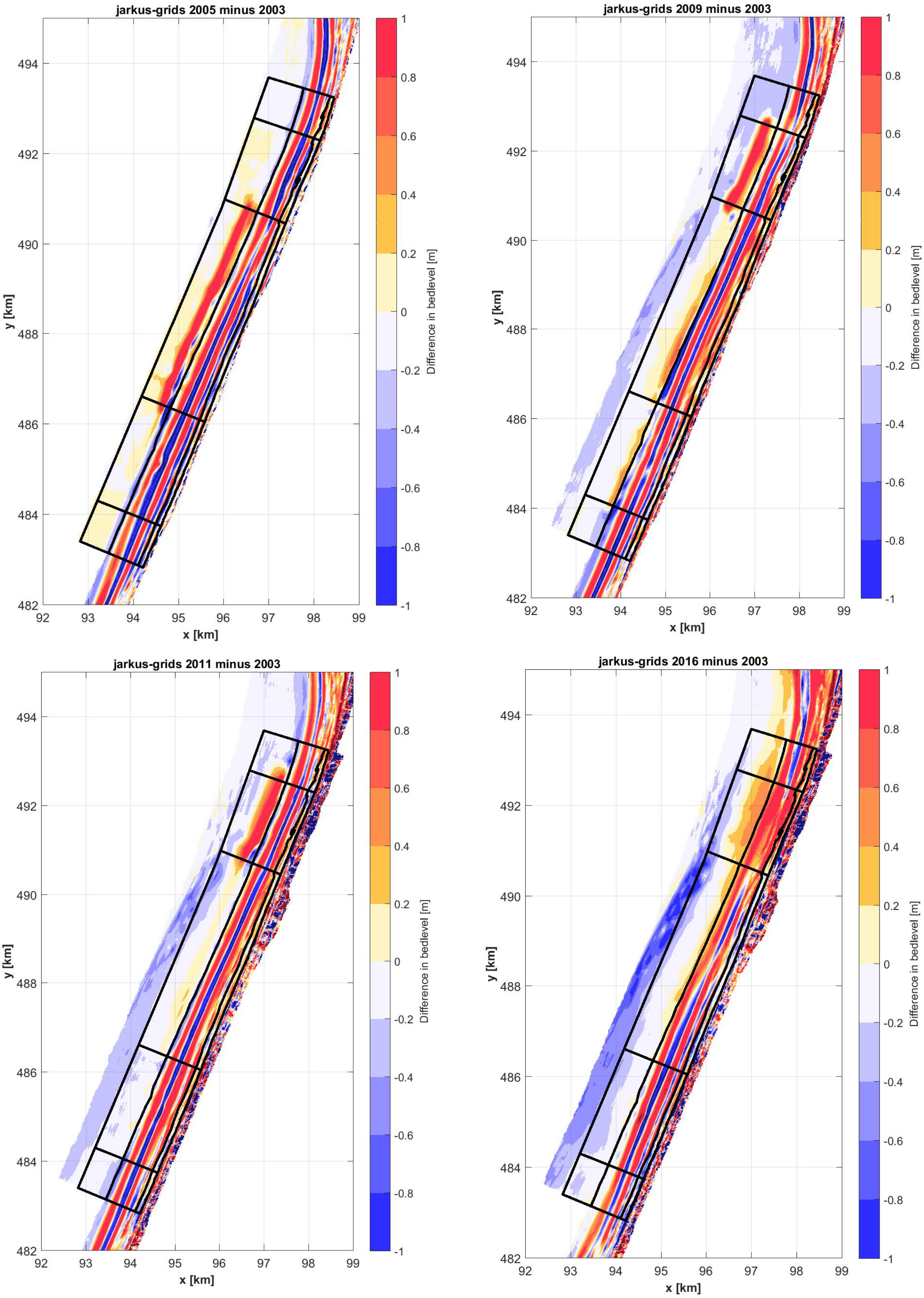


Figure 58: The difference in height between different Jarkus grid. The difference are calculated compared to the year of reference 2003.

To quantify the effectiveness of the nourishments, the placed sand volumes are compared with the change in volume based on the Jarkus grids. These volumes are given in Table 9. The theoretical volume is based on the design of the nourishment. This is a prescribed volume. The volume in the lower shoreface is the change in volume in the box where the nourishment is placed. For the nourishment in 2004 and the northern nourishment in 2008 part of the nourishment can be found in the alongshore boxes just north and south of the nourishment, see Figure 58. These volumes are estimated. Part of the sand will already been transported towards the shore. Therefore the increase in sand volume in the cross-shore box is also considered. The total volume change in these boxes gives an estimate on how much sand can be found back in the system. For the nourishment in 2004 87.5% of the nourishment can be retrieved and for the nourishment parts in 2008, 57.1% and 64.0%.

Table 9: The volumes based on the design of the nourishment and based on the Jarkus grids.

Nourishment location	Middle (m^3) Box 3 (nourishment in 2004)	South (m^3) Box 4 (nourishment in 2008)	North (m^3) Box 2 (nourishment in 2008)
Theoretical volume	2.20E+06	5.10E+05	1.00E+06
Volume in Lower Shoreface	1.30E+06	9.94E+04	4.56E+05
Volume in alongshore boxes (estimate)	1.10E+05	0	1.00E+05
Volume in cross shore boxes	5.16E+05	1.92E+05	8.55E+04
Total	1.93E+06	2.91E+05	6.41E+05
Percentage of theoretical volume	87.5%	57.1 %	64.0%

The long term development of the different volumes are investigated for the beach and breaker bar zone. The overall pattern for the breaker zone and the beach is presented in Figure 59 and Figure 60. For the lower shoreface a similar figure cannot be plotted due to lack of data. Both figures show a decrease in sand volume from 1965 till 1990. Since 1990 nourishments are placed at the beach and since 2004 also on the shoreface. It coincides with the moment that the volumes started to increase instead of decrease. The volumes continue to increase with a similar rate in the period with shoreface nourishments as the period with beach nourishments.

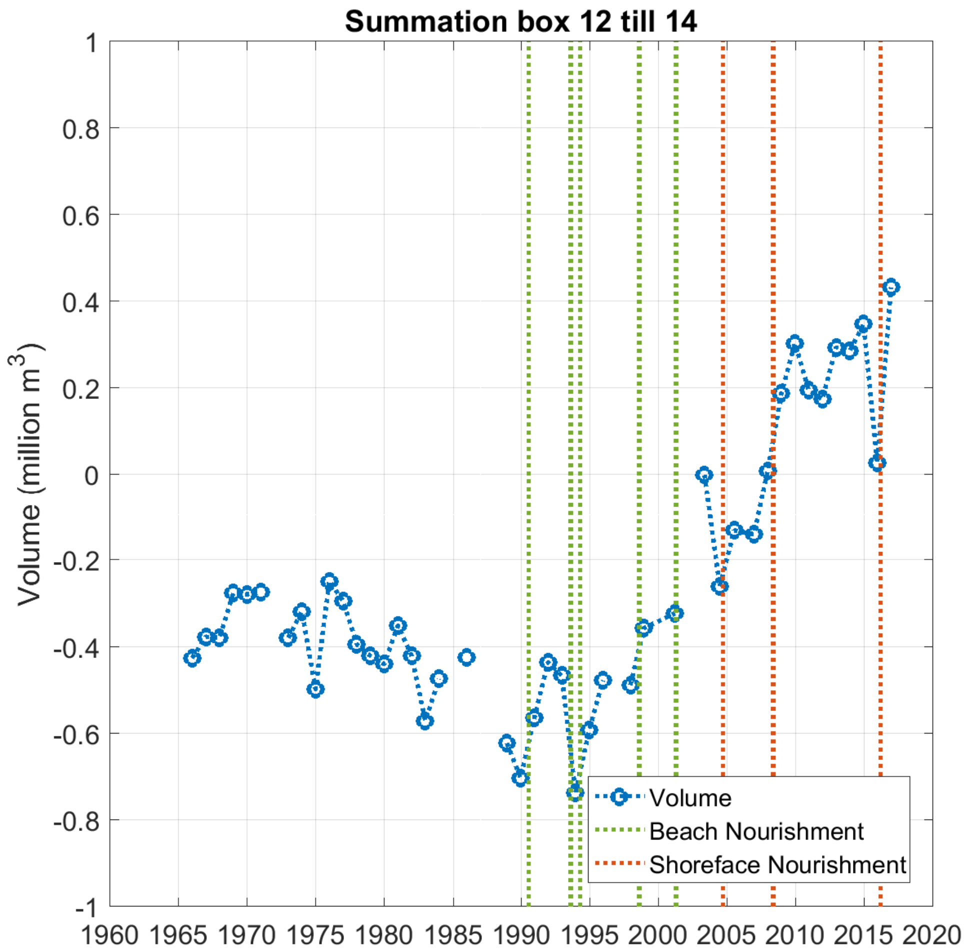


Figure 59: The summed volume for box 12 until 14. These are all beach boxes.

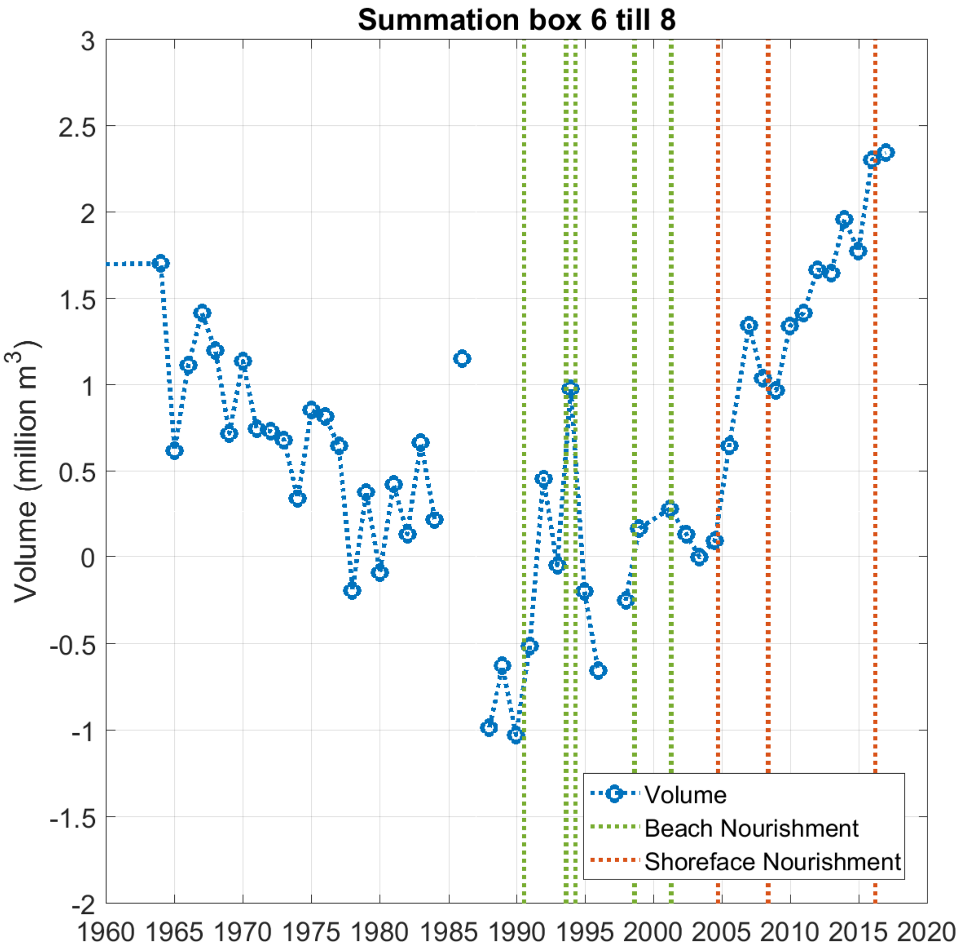


Figure 60: The summed sand volume of box 6 until 8. These boxes are all located in the breaker zone.

7.3 Relation between nourishment development and hydrodynamic characteristics

The nourishment is placed adjacent to the outer sandbar and consequently the sandbar is larger than its natural volume. Due to hydraulic conditions, especially the wave conditions, the artificial bar is eroded. This sand is moved through the system and results in an increase in sand volume in the different areas. During this spreading, a certain percentage is not transported towards the shore but is transported offshore. This sand can be considered as lost for the Zandvoort-Bloemendaal beach. In other words, due to the hydraulic conditions sand gets moved towards the shore but due to the same hydraulic conditions sand is transported out of the system and it reduces the effect of the nourishment.

The hydraulic conditions in the 5 years after the nourishment is similar as for the previous years before the nourishment, see Figure 20. Therefore, the nourishment is influenced by regularly occurring storm conditions but rare extreme events have not occurred.

8 Synthesis

8.1 Nourishment performance

The nourishments perform as an artificial, large outer bar. The bar erodes and the sand is transported to surrounding areas and outside the study area. The nourishment in 2004 can still be observed in the Jarkus transects of 2011. The second nourishment in 2008 behaves similar to the nourishment in 2004. The unnatural large outer bar is eroded and part of the sand is transported landward. The effect of the northern nourishment part in 2008 is larger than of the southern part. This is most likely due to the different size of the disturbance: the northern part contains twice as much sand as the southern part.

The artificial bar formed by the nourishments interrupts the natural offshore migration of the breaker bars. After placement, the bar migrates in landward direction. This is most likely because the bar is located further seaward from the natural point of decay, and is moving towards this position.

Both nourishments have a clear, direct effect on the sediment volume in the breaker zone, which increases after the nourishment. The volume in the beach zone also shows a positive trend, but this trend can already be observed before the placement of the nourishment. Therefore the increase of beach volume cannot be linked directly to the shoreface nourishments. It is however likely that the beach volume is gaining sediment on the long term due to the shoreface nourishments.

The changes in volumes from 1965 until 2017 show clear switch from an eroding coast to a coast which is extending. This switch coincides with the moment that the first nourishments were placed in this area. Therefore, it is likely that this switch is caused by the nourishments. The frequency and volume of the nourishments is such that the natural erosion of the beach is not only compensated but resulted in an increase of volume.

The first nourishments placed at Zandvoort-Bloemendaal from 1990 were beach nourishments and show a direct increase of volume at the beach. Since 2004 only shoreface nourishments are applied in this area. The change of the nourishment type did not alter the increasing trend of the beach volume. There might be two possible reasons: 1) the shoreface nourishments have the same effect on the beach volume as the beach nourishments, and 2) the switch to sedimentation of the beach is (partly) driven by a natural change, coinciding the start of the beach nourishments.

8.2 Strategic goals

The long-term trends show that the shoreface nourishments at the Zandvoort-Bloemendaal area contribute to the strategic goals to prevent chronical erosion so coastal functions can remain at the coast.

9 Conclusion

From this study the following conclusions can be made:

- Effect of the nourishment on the physical marks is not very clear, and does not exceed natural variability in their positions;
- The shoreface nourishments form an artificial outer bar, which interrupts the natural offshore migration of the breaker bars;
- The volume of the breaker bar zone (landward of the nourishment) increases after and due to the nourishments;
- Both beach and shoreface nourishments show a positive effect on the beach volume. However, for the latter the effect cannot be linked directly;
- The lifetime of the nourishment is about six years, part of this sediment remains in the direct surroundings. For the larger area the effect of the nourishment will be about 10 years;
- Average daily conditions are the driving force that caused the observed changes.

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