National analysis of nourishments;

Coastal state indicators and driving forces for Bergen-Egmond, 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 are: Domburg, Zandvoort-Bloemendaal and Bergen-Egmond, see Figure 1. Each laboratory is chosen such that the dominant physical processes and type of nourishments applied are different.

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 investigated in this report is Bergen-Egmond. Bergen-Egmond is at the Holland coast north of the IJmuiden harbour. It is situated at the straight coastline of Noord-Holland.

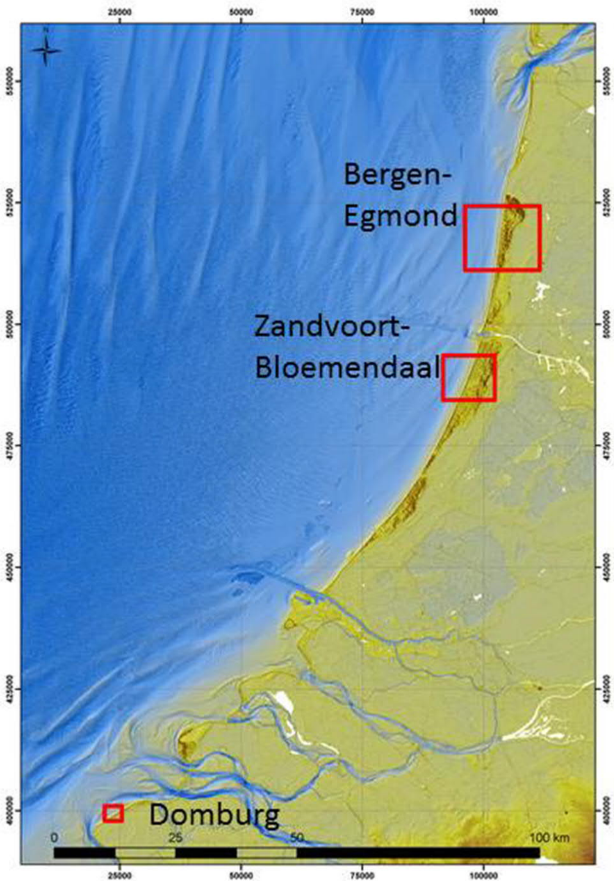

Figure 1: An overview map of the coast laboratories in the Netherlands

1.2 Objectives

In this study the performance of the combined beach-shoreface nourishment of 2010/2011 at Bergen-Egmond 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 8 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 lab Bergen-Egmond is located at the Holland coast in the coastal management area 'Noord-Holland' (Figure 2). Information about this part of the coast is described in Deltares (2017), this document is used for the description in this chapter.

The coast in this area has a closed, straight coastline and at the villages of Bergen and Egmond an extensive dune area. At this part of the Holland coast wave driven processes are dominant. The tide is flood dominant, which is northward directed. It is a relatively undisturbed part of the coast, while to the south the coast is influenced by the harbour jetties of IJmuiden and to the north the Hondsbosche and Pettemer seawall and tidal inlet of Texel are present.

The shoreface is characterized by a breaker bar system with offshore migrating bars. The bars decay offshore, after which a new bar forms at the coast and starts migrating offshore. At the parts of the coast which are nourished frequently, the bars became stable.

The natural erosion occurring at this part of the coast lies in the order of 1 million m^3 per year. Since 1990 this is compensated by approximately 2 million m^3 per year on average. This resulted in an increase of sediment at the coast of about 1 million m^3 per year. Especially the Bergen-Egmond stretch is nourished frequently, being an so called 'erosion-hotspot'. South of Egmond the coast is quite stable and only minor nourishments have been placed.

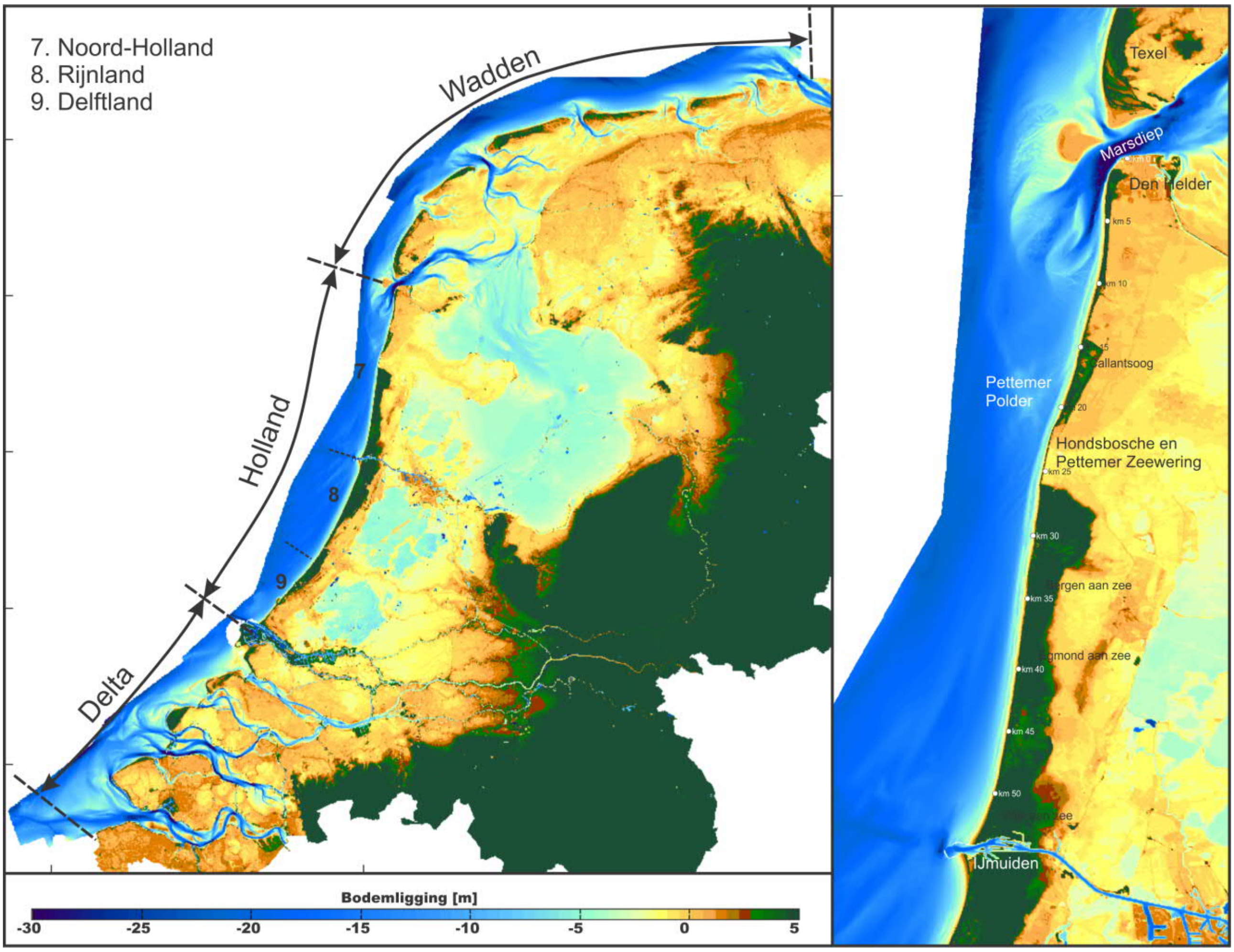

Figure 2: Overview of the coastal areas in the Netherlands (left) and details of the area of the coastal laboratory of Bergen-Egmond (right). Source: Deltares, 2017.

3 Nourishment description

3.1 Coastal infrastructure and earlier nourishments

In the coastal area Noord-Holland several hard constructions are built in the past, an overview is given in Figure 3 and Table 1. The seawall at Den Helder is not influencing the area of Bergen-Egmond directly, but relevant for the changes of the tidal inlet. The Hondsbosche and Pettemer seawall might still affect the north part of the study area. In the northern part of the study area groins are present. The harbour jetties of Ijmuiden influence the area south of the study area: directly north of the jetties sedimentation occurs for about 3 km, and north of this area erosion occurs for the next 5-6 km.

Table 1: Overview of coastal infrastructure in the coastal area Noord-Holland

Construction	Location (transect)	Period of construction	Remarks
Seawall Den Helder	0 – 1100	1721 1956	Construction Extension
Hondsbosche and Pettemer seawall	2000 – 2600	1500 / 1872/ 1954 1969 / 2015	Entirely nourished between 2014 and 2015 (35 million m^3)
Groins	400 – 3100	1880 - 1935	
Harbour jetties IJmuiden	5500 – 5600	1865-1879 1962-1967	Length 1.5 km Extended to 2.3 km (north) and 2.5 km (south)

Figure 3: Overview of coastal infrastructure for the Noord-Holland area: (a) construction periods of groins, from: Verhagen en van Rossum (1990), (b) seawall at Den Helder, (c) groins between seawalls of Den Helder and Hondsbosche-Pettemer, (d) Hondsbosche and Pettemer seawall in 1982, (e) south end of Hondsbosche and Pettemer seawall in 2011, and (f,g) harbour jetties of IJmuiden and sedimentation on the north side in 2011. Images from: https://beeldbank.rws.nl, Rijkswaterstaat. Source entire figure: Deltares, 2017

Table 2: Overview of nourishments in the proximity of the Bergen-Egmond coastal laboratory

Start	End	Begin transect	End transect	Length (m)	Type	Volume (m^3)
5/1990	6/1990	3225	3375	1500	beach	60,000
5/1990	5/1990	3700	3850	1500	beach	323,318
5/1990	6/1990	3225	3375	1500	beach	385,774
5/1992	11/1992	2620	3850	12300	beach	1,472,640
9/1992	11/1992	3765	3860	950	beach	69,225
6/1994	6/1994	3290	3350	600	beach	100,683
6/1994	6/1994	3785	3820	350	beach	106,343
5/1995	5/1995	3263	3363	1000	beach	306,000
5/1995	5/1995	3725	3875	1500	beach	306,000
5/1997	5/1997	3450	3575	1250	beach	158,000
5/1997	5/1997	3625	3880	2550	beach	314,000
6/1997	6/1997	3005	3105	1000	other	132,690
6/1997	6/1997	3105	3350	2450	beach	352,000
6/1997	7/1997	2600	3005	4050	beach	547,000
6/1998	7/1998	3750	3875	1250	beach	244,442
4/1999	5/1999	3250	3375	1250	beach	205,793
4/1999	4/1999	3725	3875	1500	beach	214,515
6/1999	9/1999	3690	3910	2200	shoreface	880,100
4/2000	8/2000	3225	3425	2000	shoreface	994,000
6/2000	7/2000	3800	3900	1000	beach	207,445
6/2000	6/2000	3275	3325	500	beach	225,000
6/2004	11/2004	3620	4020	4000	shoreface	1,800,699
4/2005	4/2005	3225	3375	1500	beach	300,436
4/2005	5/2005	3700	3925	2250	beach	486,023
8/2005	9/2005	3150	3620	4700	shoreface	1,306,114
8/2010	8/2011	3400	3900	5000	shoreface*	1,713,913
11/2010	8/2011	3150	3400	2500	beach*	500,000
11/2010	2/2011	3100	3400	3000	shoreface*	1,124,348
3/2011	4/2011	3700	3900	2000	beach*	400,000
8/2011	9/2011	3900	4000	1000	shoreface*	360,870
4/2015	4/2015	3700	3900	2000	beach	432,500
4/2015	4/2015	3125	3400	2750	beach	605,000
7/2015	9/2016	3100	4000	9000	shoreface	2,500,000

3.2 Studied nourishment

3.2.1 Beach profile

A typical profile for the study area is shown in Figure 4. The calculated coastal state indicators (see also paragraph 4.2) are shown in this profile and given in Table 3. The indicators are calculated for the nourishment area and 1 km north and 1 km south of the nourishment area for the year of nourishment.

The profile shows the first dune with a height at NAP +15 m and a steep slope towards the beach. The (wet) beach width is around 100 m. In the shoreface 1 to 2 breaker bars are present, in the example profile at 100 m and 400 m to reference (beach pole, BP).

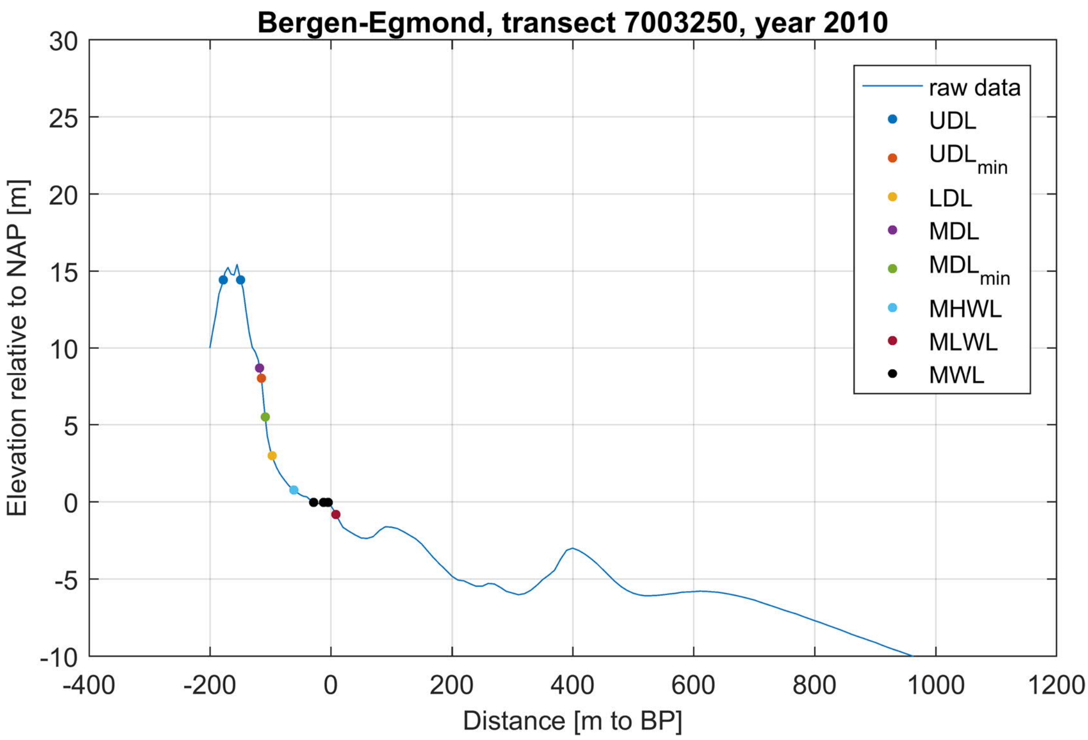

Figure 4: An example of the levels described in paragraph 4.2. UDLmin means the Upper Dune Level minimum and the MDLmin the Mid Dune Level minimum

Table 3: The vertical levels for the Bergen-Egmond coastal laboratory

Bergen-Egmond	
Vertical location (with respect to NAP)	
Minimum Upper dune level (UDLmin)	8.1
Minimum Middle dune level (MDLmin)	5.55
Dune toe level (DF)	3.0
MHWL	0.79
MWL	0
MLWL	-0.81

3.2.2 Nourishment motivation

To prevent the Netherlands from flooding and maintain coastal functions the government is obligated by law to preserve the 'basic Dutch coastline'. The basic coastline 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. At Bergen-Egmond, the basic coastline was exceeded in one transect at the beach entrance of Bergen (3275), while several other transects showed a negative trend and were expected to exceed the basic coastline in the following years (Rijkswaterstaat, 2009). This was the reason for the planning and placement of a shoreface and beach nourishment in 2010-2011 – the nourishments analysed in this study.

Several stakeholders were involved. First of all, the Dutch government represented by Rijkswaterstaat (executing agency of the Ministry of Infrastructure and Water Management). Second, a dredging company to carry out the nourishments. Finally, also local stakeholders were involved like communities and local residents and people who are using the beach.

3.2.3 Design of nourishment and placement

Both the beach and the shoreface nourishment consisted of multiple parts, which had different volumes and construction periods, see Table 4. The beach nourishment is placed between the dunefoot (NAP +3 m) and approximately low water (NAP -1 m). The shoreface nourishment is placed against the outer breaker bar with a top level at NAP -5 m. The sediment has a horizontal part of approximately 200 m and is then sloping to ca. NAP -8 m (see Figure 5, also for beach nourishment). The placement of the nourishment parts can also be seen in difference maps (Figure 6 and Figure 7).

Table 4: The properties of the nourishments and the different time periods of interest.

Nourishment properties	Nourishment 1	Nourishment 2
Transects	3100 – 3400 3400 – 3900 3900 – 4000	3150 – 3400 3700 – 3900
Type	Shoreface	Beach
Volume (m^3)	1,124,348 1,713,913 360,870	500,000 400,000
Length (m)	3000 5000 1000	2500 2000
Volume (m^3/m)	375 340 360	200 200
Start nourishment vertical level (m NAP)	-5	3
End nourishment vertical level (m NAP)	-8	-1
Year of reference	2010	2010
Begin construction (mm-yyyy)	11-2010 08-2010 08-2011	11-2010 03-2011
Finished construction (mm-yyyy)	02-2011 08-2011 09-2011	08-2011 04-2011

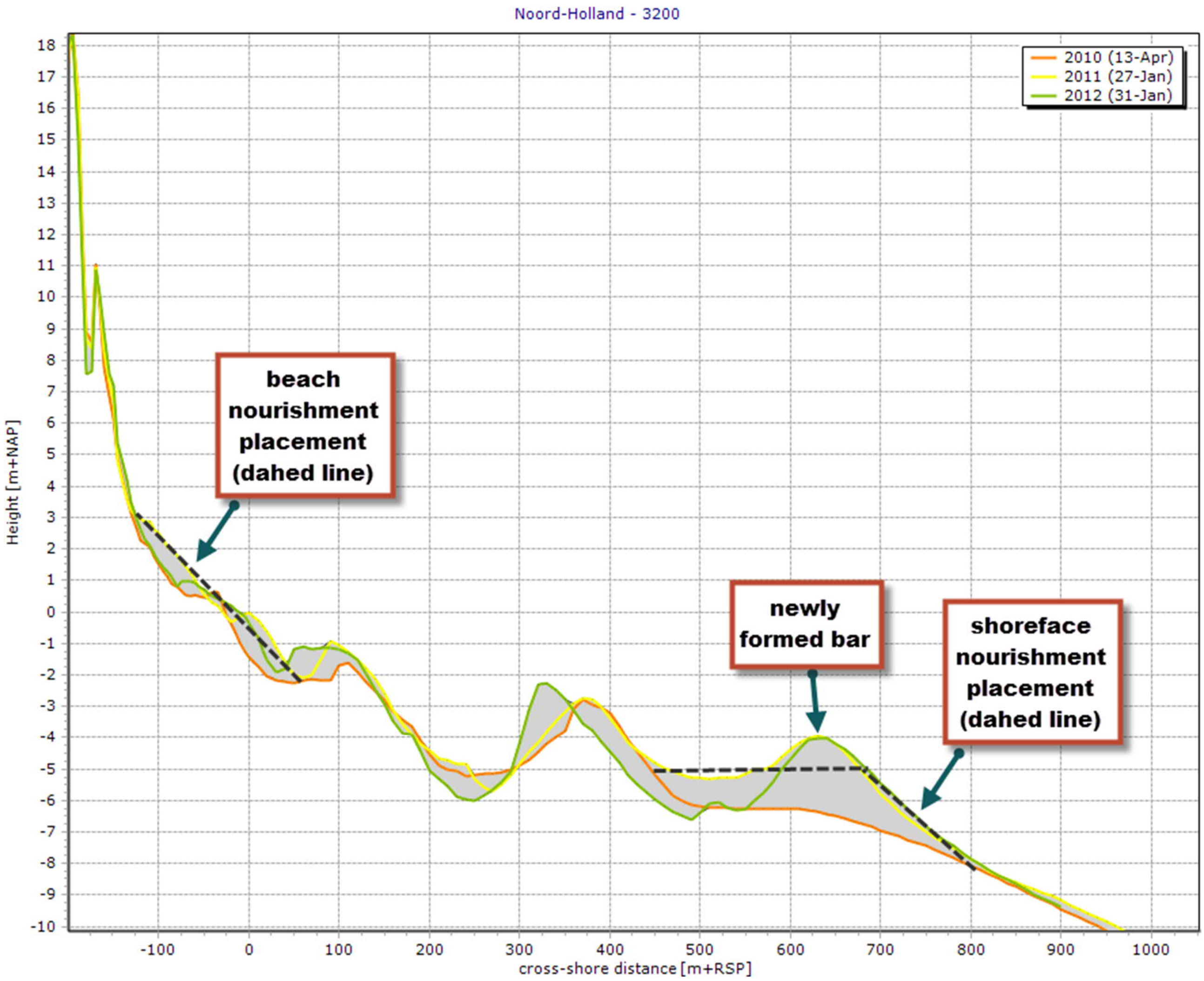

Figure 5: Transect 3200 showing the placement of the beach and shoreface nourishments. The actual placement of the beach nourishment is likely ending around NAP -1 m, not NAP -2 m as seen in this profile due to changes after construction.

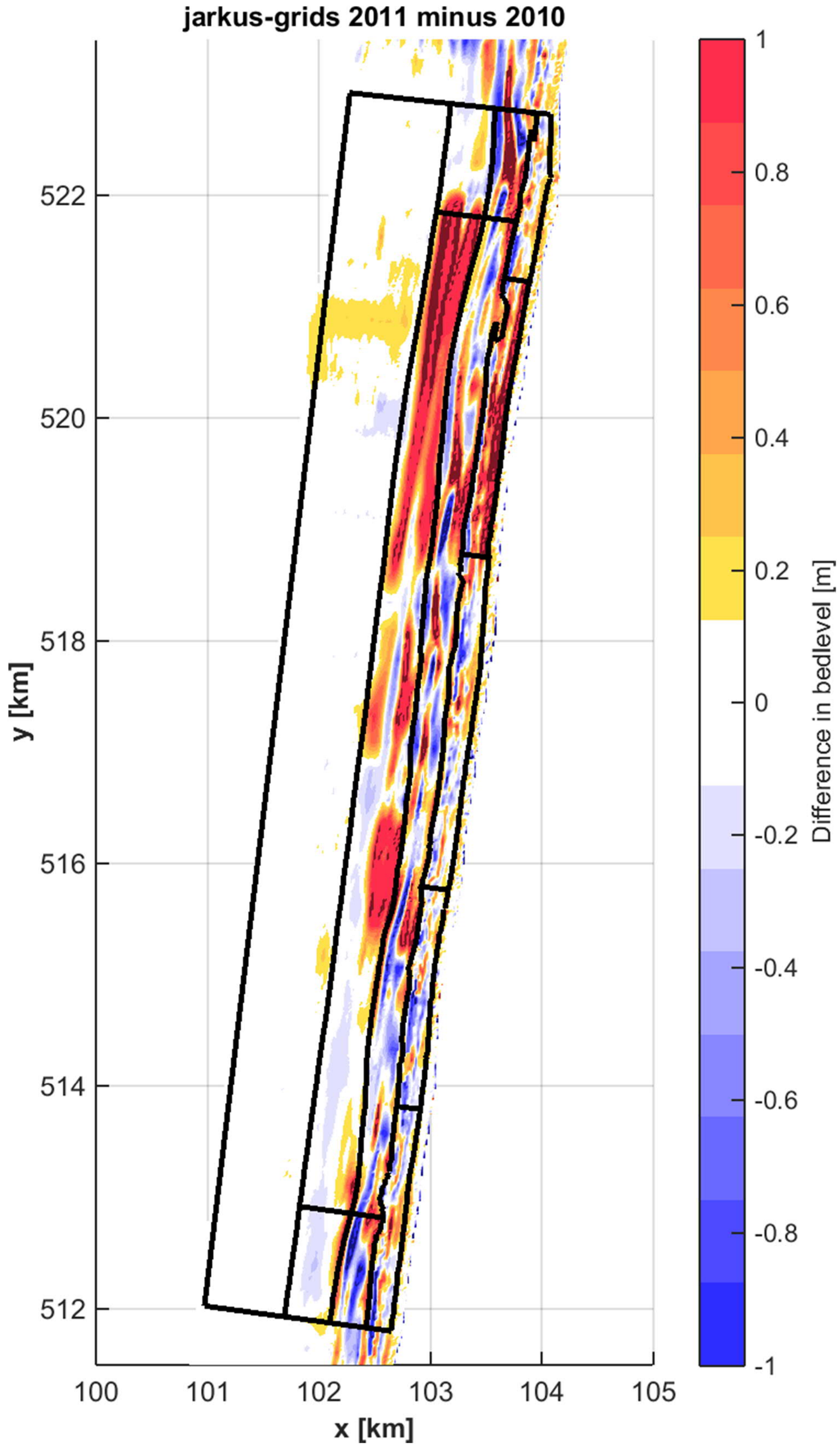

Figure 6: Difference map between 2010 and 2011 (positive = sedimentation, negative = erosion), showing placement of (part of) the shoreface nourishment and northern part of the beach nourishment

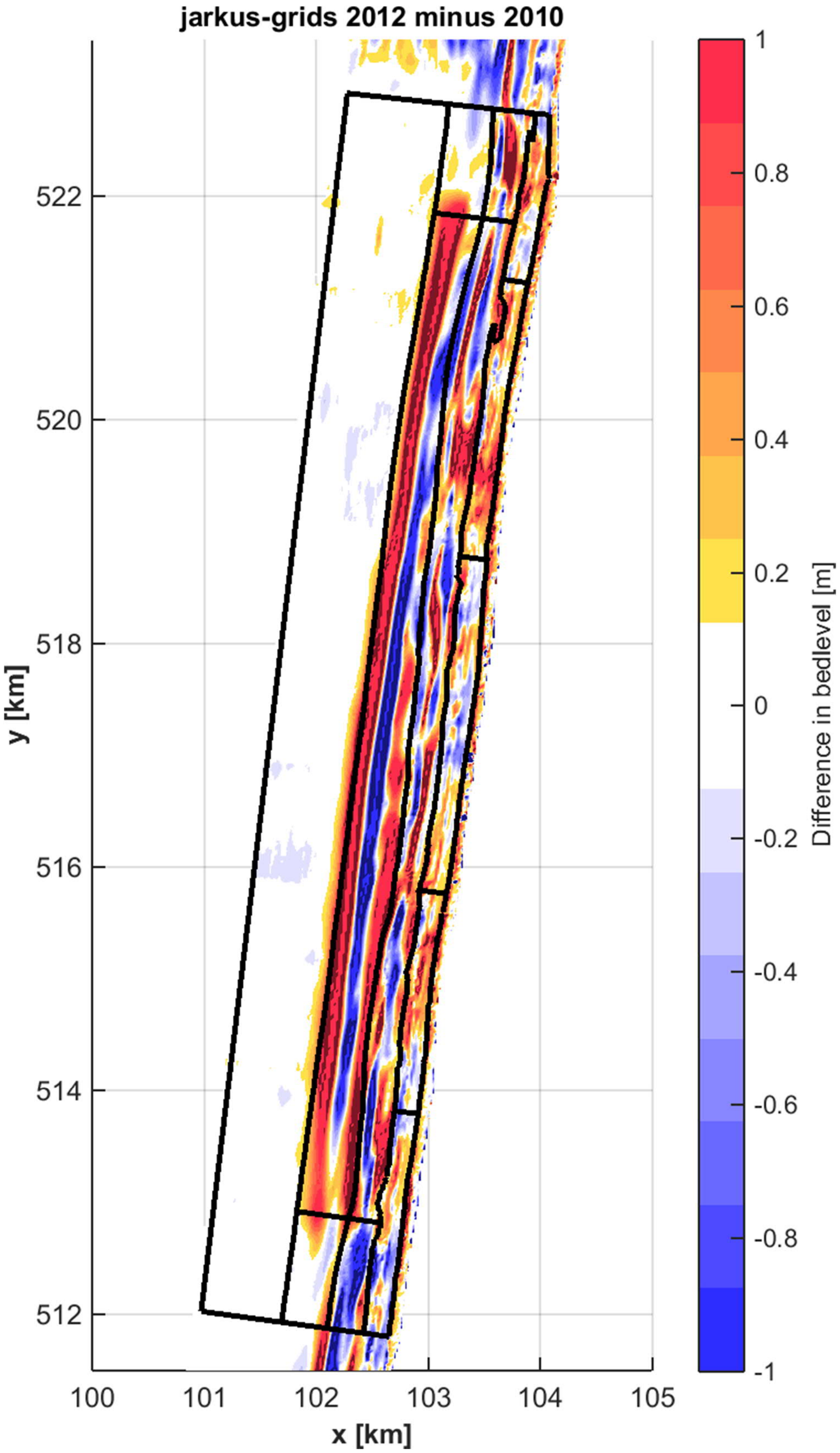

Figure 7: Difference map between 2010 and 2012 (positive = sedimentation, negative = erosion), showing placement of the shoreface nourishment and the beach nourishments

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. 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 single- or multibeam 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 echosounders 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 locations are available, see Figure 8. Their data is freely provided by Rijkswaterstaat (waterinfo.rws.nl). The physical quantities measured at each station can be different from 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.

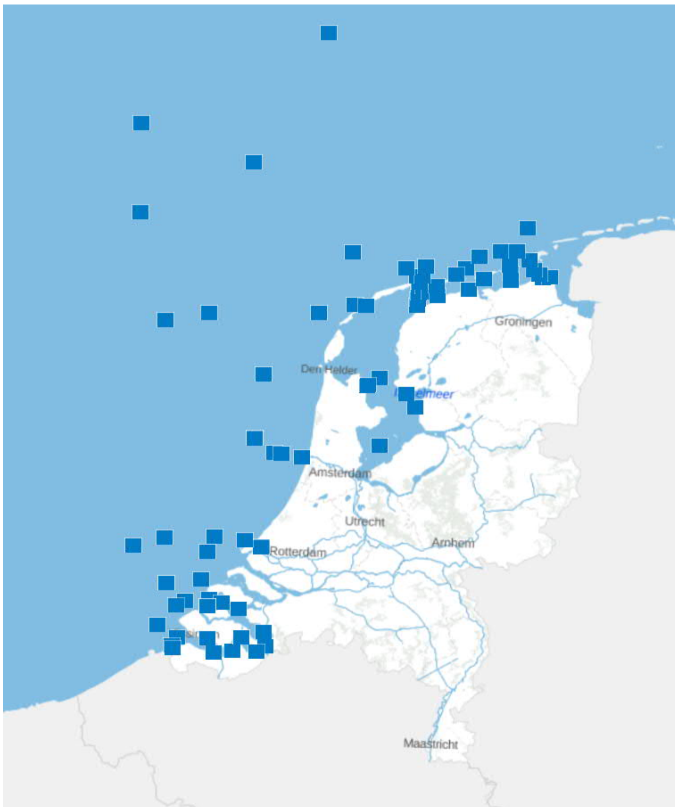

Figure 8: : An overview of the different measuring station for H_s in the Netherlands. The red circle indicates the location of the Europlatform.

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 9 and described in Table 5. The morphological development represented by the CSI will be analysed in order to reveal the morphodynamics and the effects of nourishments.

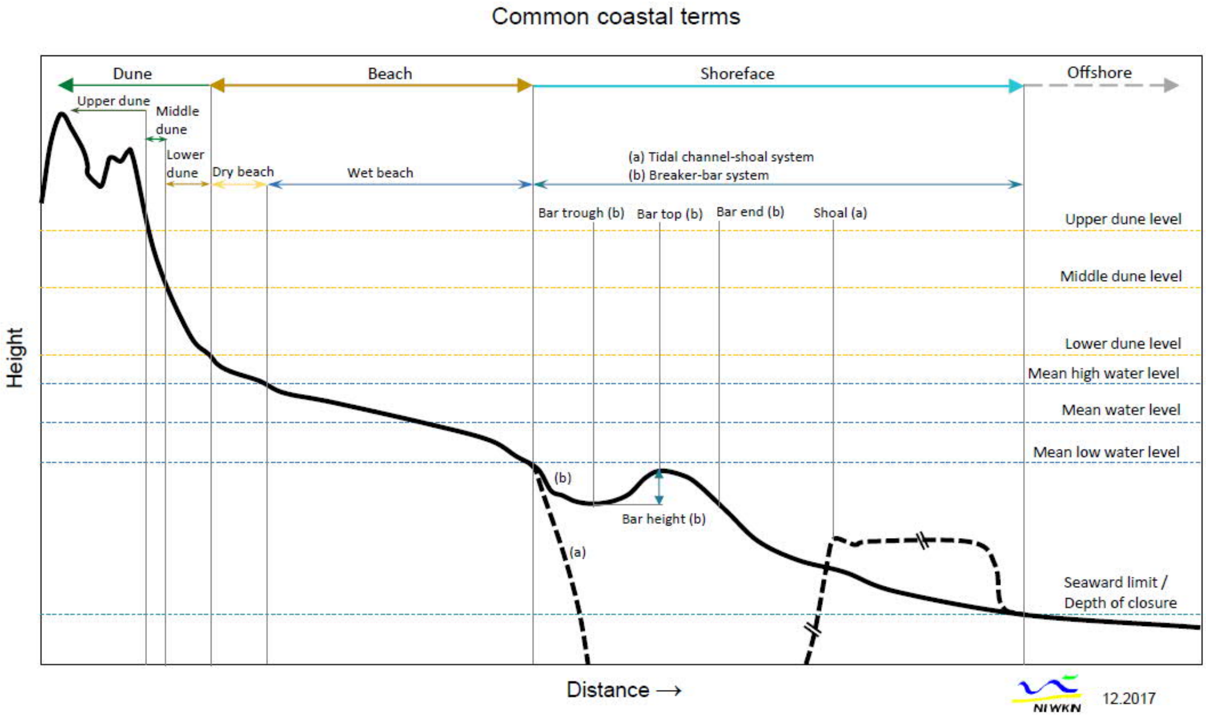

Figure 9: General definition/terminology coastal profile used. On the vertical axis various levels in the profile are shown. The horizontal axis shows different zones in the profile. Source: Simon Hillmann (NLWKN)

Table 5: 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.
Beach	**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 10 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.

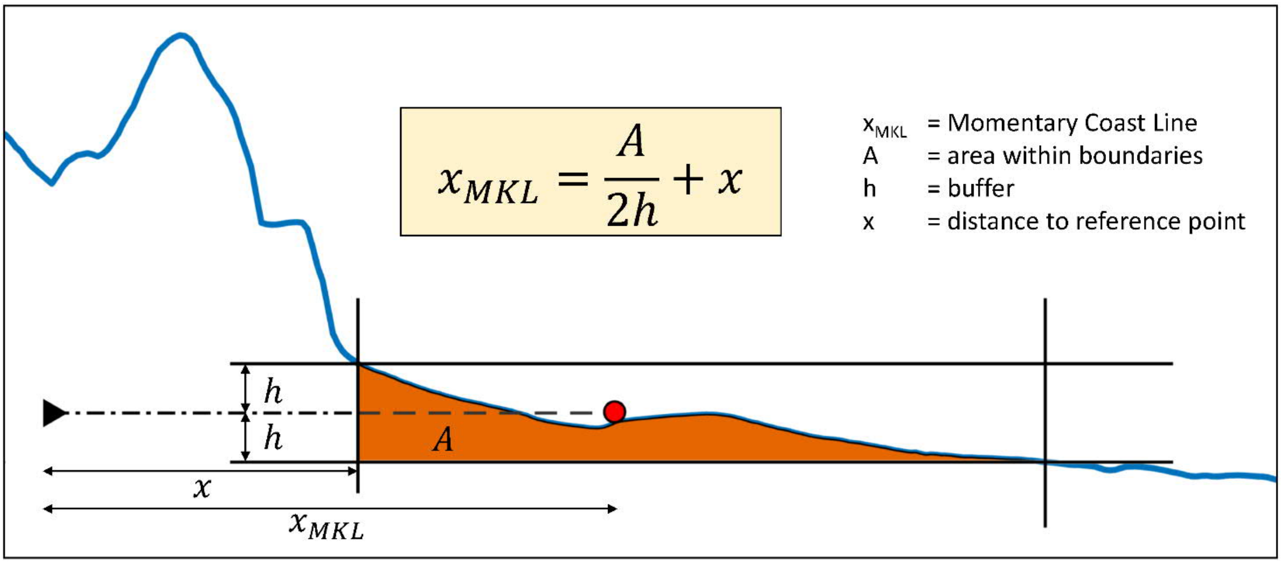

Figure 10: Example of the MKL-Model

4.2.3 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. At the Bergen-Egmond nourishments the following levels were used: landward boundary based on data coverage; the upper level of the beach nourishment - NAP +3 m; the lower level of the beach nourishment (also low water level) – NAP -1 m, the lower upper level of the shoreface nourishment – based on the difference map showing the nourishment and an offshore boundary based on data coverage. The boundaries are defined on the last measurement before start of the nourishment and are based on the depth contours retrieved with ArcGIS from the gridded bathymetry data. In total 12 areas are defined, see Figure 11.

The coast perpendicular boundaries are based on spatial erosion-sedimentation patterns: transects with similar changes 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.

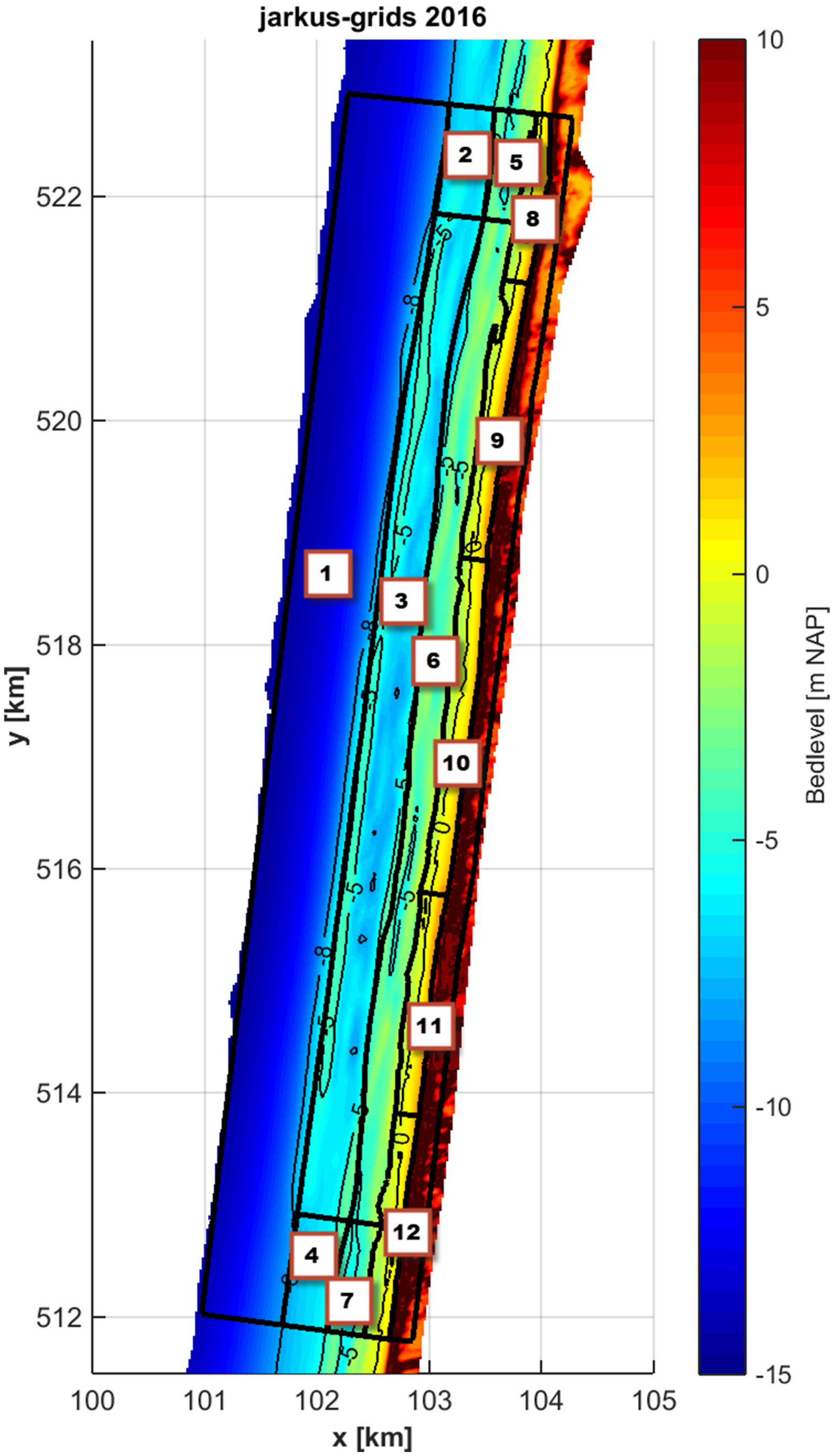

Figure 11: Overview of the resulting areas used for volume calculations

5 Environmental conditions/characteristics

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 12 to Figure 14. 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 storm. 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.

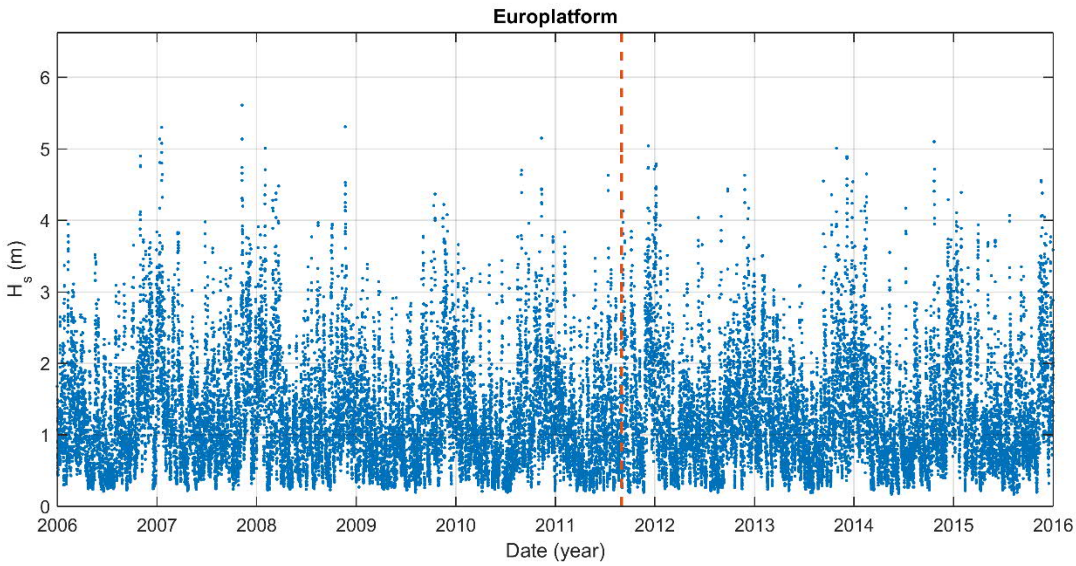

Figure 12: The measured value of H_s at the Europlatform. The red dotted lines indicate the nourishments

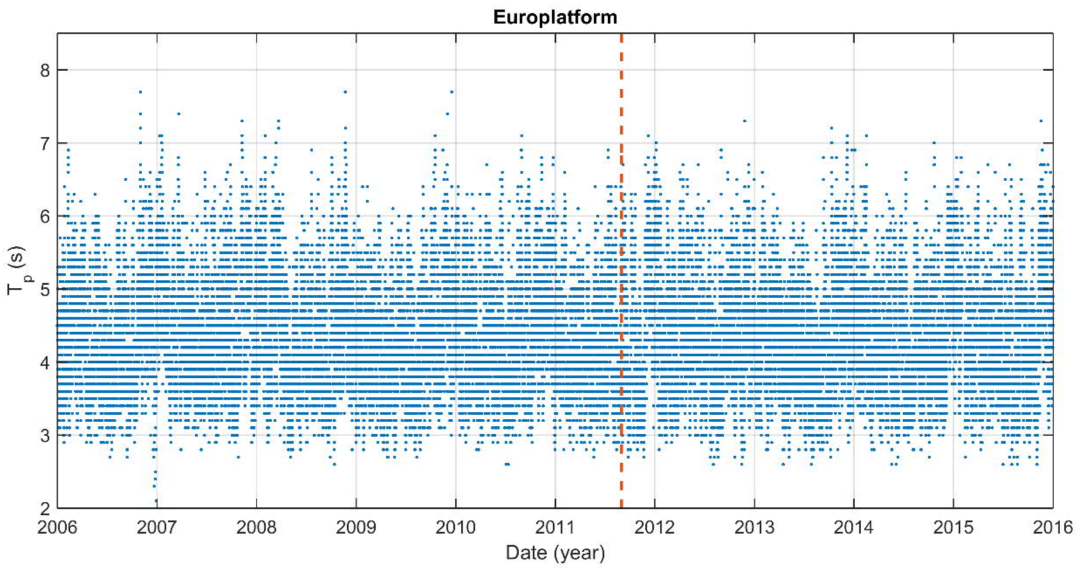

Figure 13: The measured value of T_p at the Europlatform. The red dotted lines indicate the nourishments

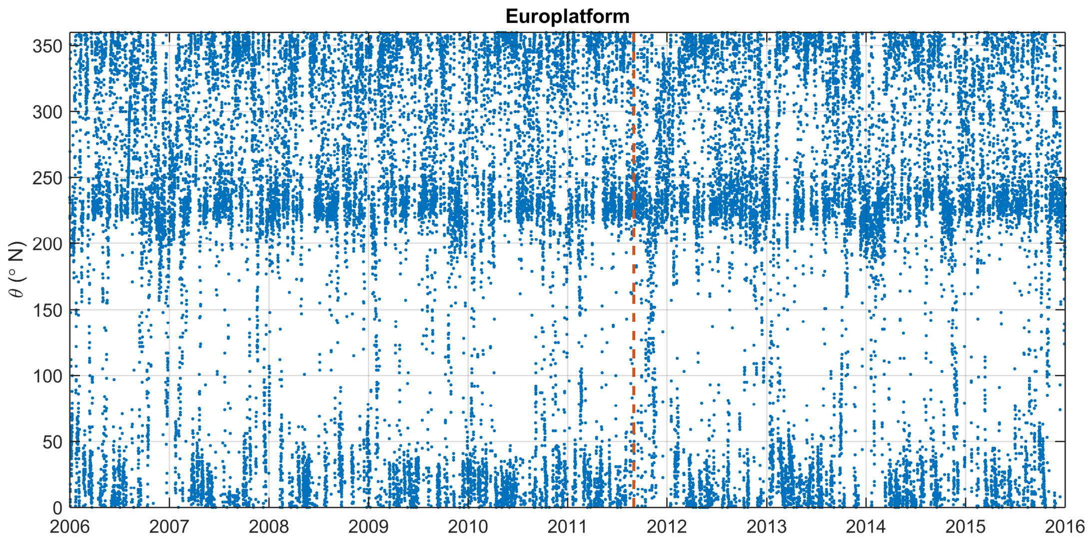

Figure 14: The measured value of **ϴ** at the Europlatform. The red dotted lines indicate the nourishments

The averaged values of the bulk wave parameters for a time period before and after the nourishment are calculated, see Table 6. The averaged values for H_s and T_p before the nourishement is calculated from the start of the measurment in 1989 till 2011. 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 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 condition. The distribution of energy over time can be seen in Figure 15 and Figure 16.

Table 6: The averaged bulk wave parameters before and after the nourishment.

Wave property	Mean value before the nourishment	Mean value after the nourishment
$\bar{H}_s$ (m)	1.25	1.26
$\bar{T}_p$ (s)	4.40	4.35
$\bar{E}_{tot}$ (kW m^{-1})	2.75	2.75
$\bar{E}_{par}$ North (kW m^{-1})	2.13	2.22
$\bar{E}_{par}$ South (kW m^{-1})	1.84	1.66
$\bar{E}_{per}$ (kW m^{-1})	1.64	1.70

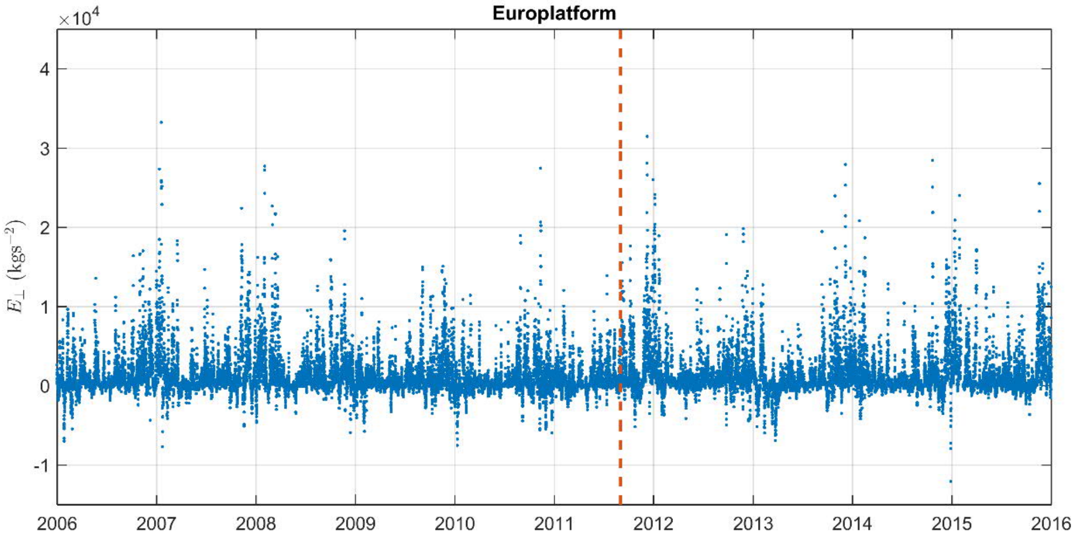

Figure 15:The wave energy perpendicular to the coast calculated using the wave measurements at the Europlatform

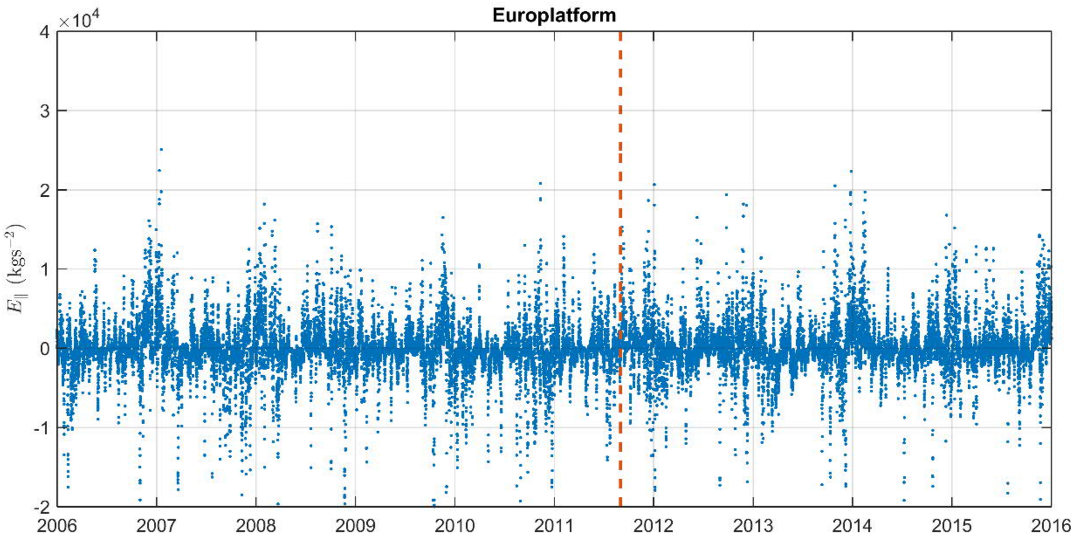

Figure 16:The wave energy parallel to the coast calculated using the wave measurements at the Europlatform

To further analyse the direction, wave roses are plotted, see Figure 17. 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 they are wind generated waves. When the wave rose is investigated in more detail, it shows that the highest waves are coming from the northwest, 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.

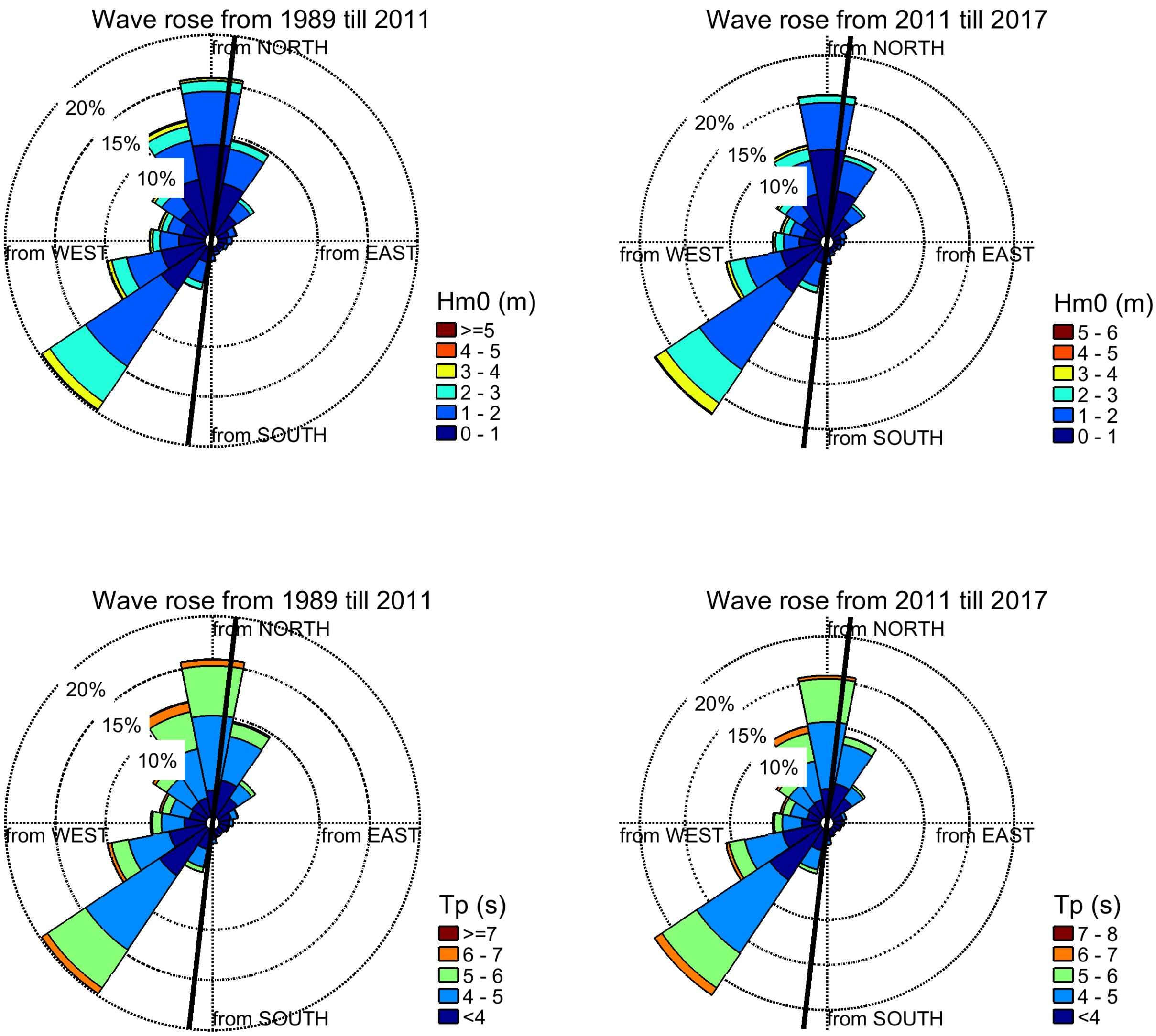

Figure 17: Wave roses based on the measurements at the Europlatform. The year 1989 till 2011 are before the nourishment and 2011 till 2017 is after the nourishment

In Figure 18 and Figure 19 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.

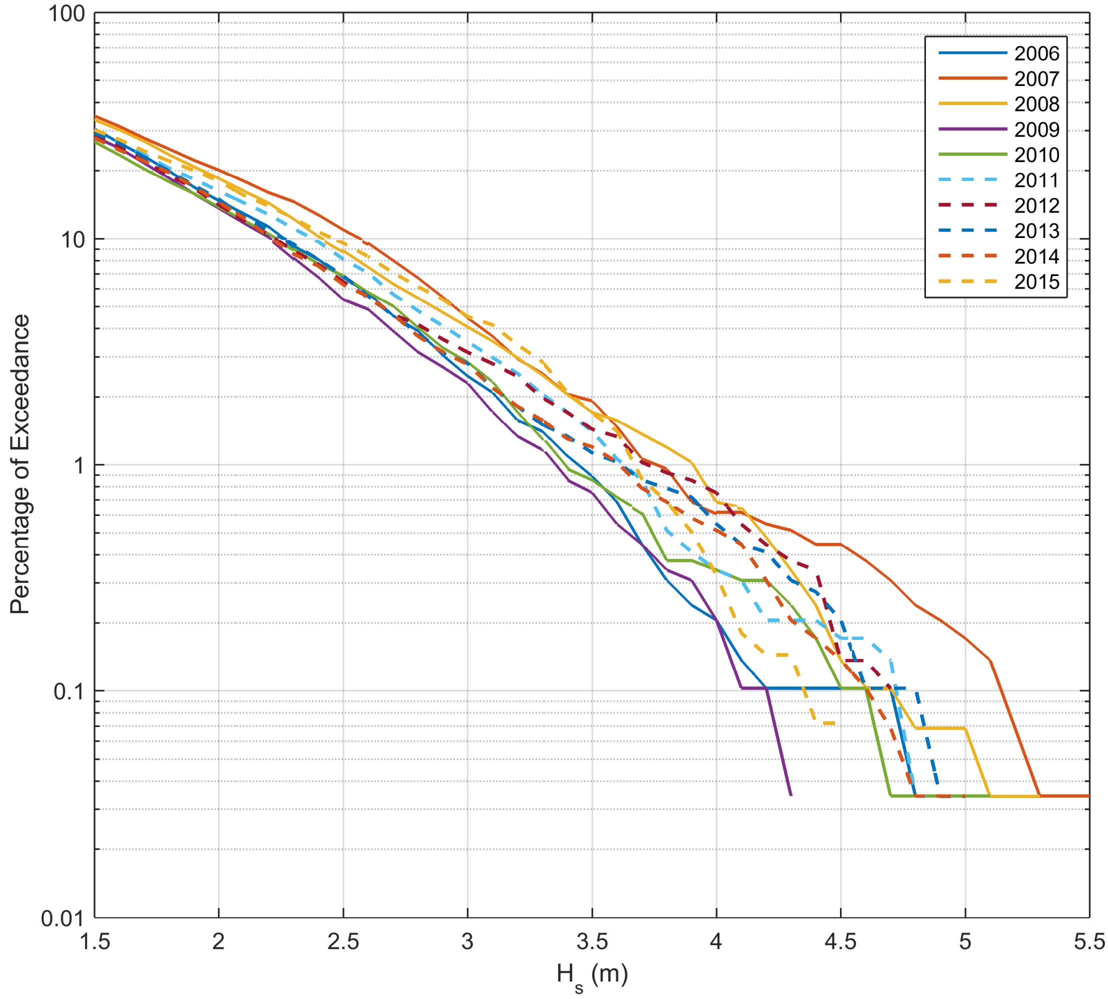

Figure 18:Percentage of exceedance of the measurements H_s at the Europlatform for several years

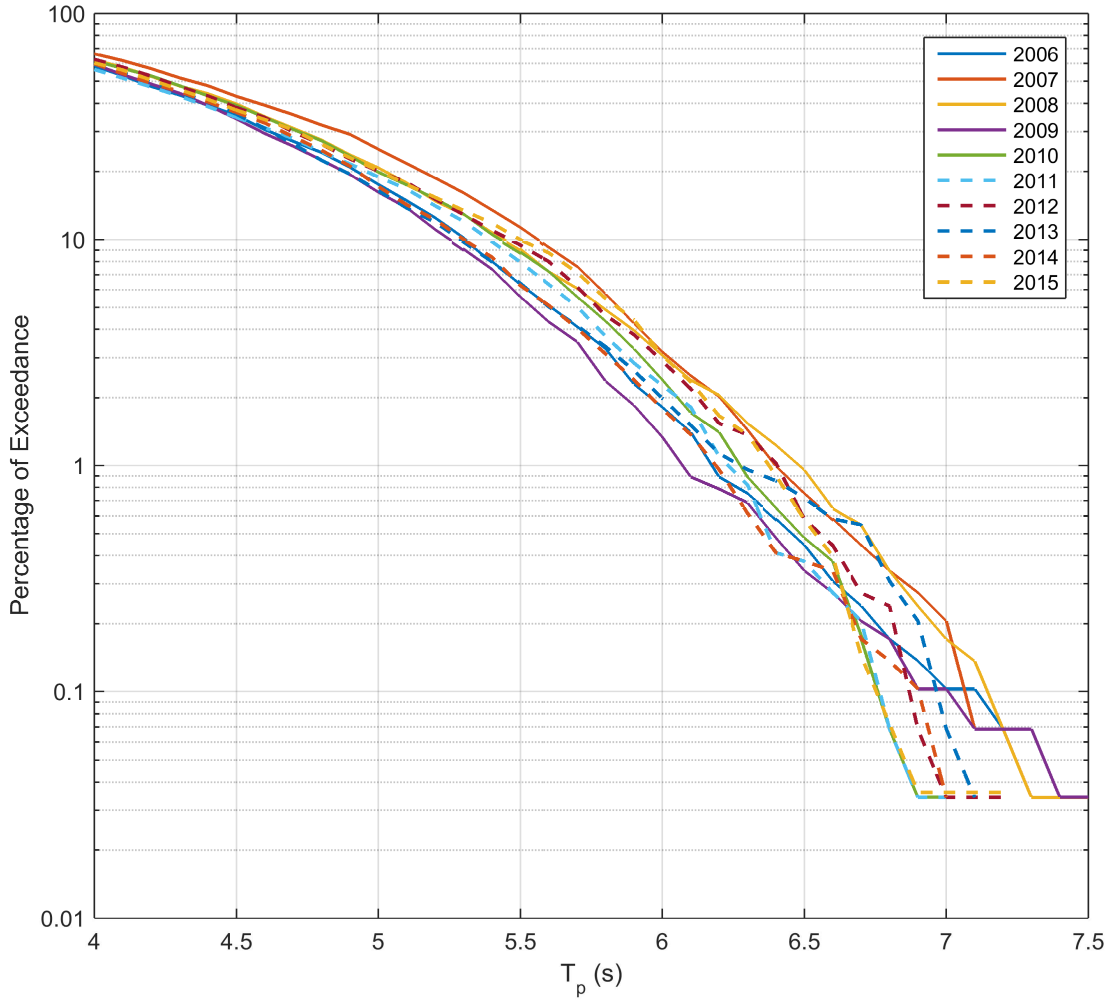

Figure 19:Percentage of exceedance of the measurements for T_p at the Europlatform for each year

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 20. 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 7. 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 the 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.

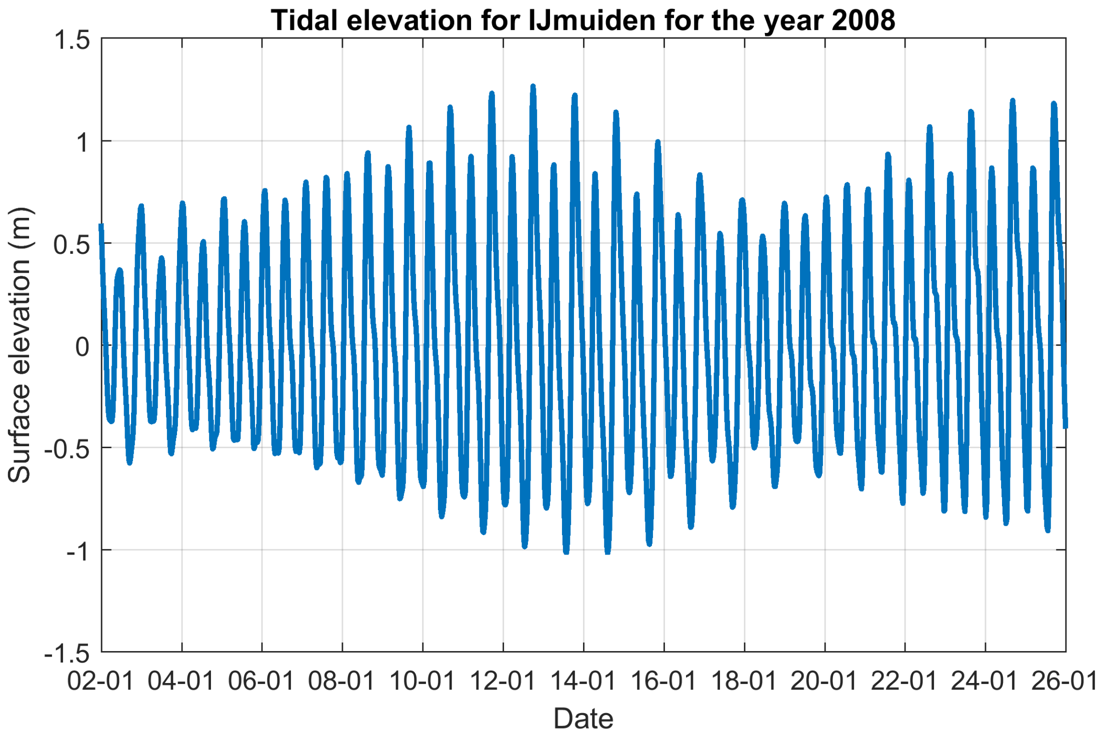

Figure 20: Part of the tidal signal from the IHO station Ijmuiden.

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 7: 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 water level elevation due to the tide, the different tidal levels are calculated, see Table 8. 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 20 is also represented in the different tidal level. Namely, there is a large inequality between the MHHW, MHW and MLHW level.

Table 8: 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 surge 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 105 storms are identified between 1989 and 2011, 39 between 2011 and 2018. 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 is shown in Figure 21. The figure shows 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 2011 (before the investigated nourishment) 0.5858% of the time the value of H_s was larger than 4 m. Furthermore, between 2011 and the end of 2017 the percentage was 0.5531%. In other words, slightly less extreme wave heights occurred after than before the nourishment.

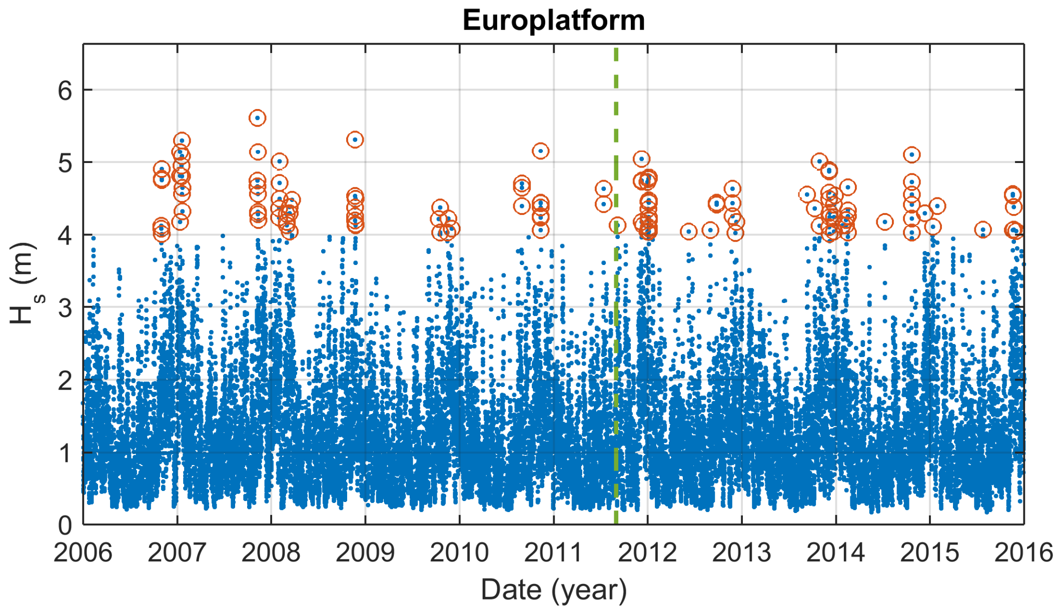

Figure 21: A time series of the wave height. The red circles indicate the events with $H_s > 4m$ and the green line the moment of the nourishment.

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 IJmuiden measurement station for the same periods as the wave data: 1989-2011 for the long term and 2011-2016 for the nourishment period. The data is presented in two wind roses, Figure 22 and Figure 23. The two periods show a very similar wind climate, with dominant direction from west and southwest.

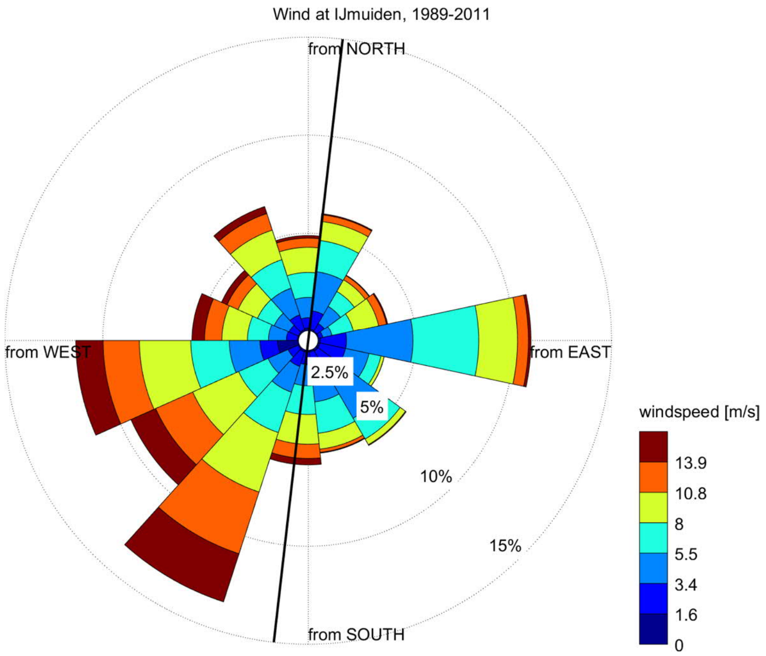

Figure 22: Wind conditions for the long term, pre nourishment period 1989-2011

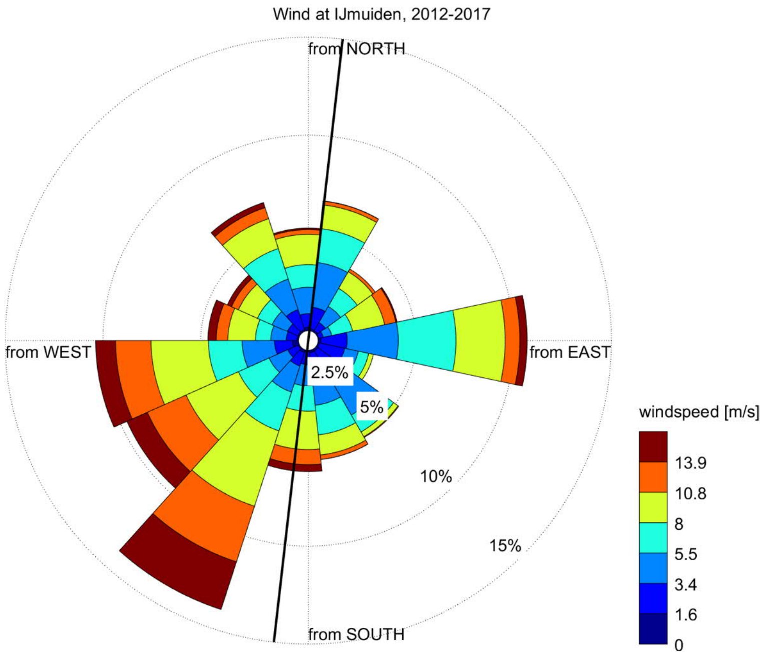

Figure 23: Wind conditions in the nourishment period

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 304 μm around mean sea level and 244 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 24 and Figure 25.

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 Bergen-Egmond 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.

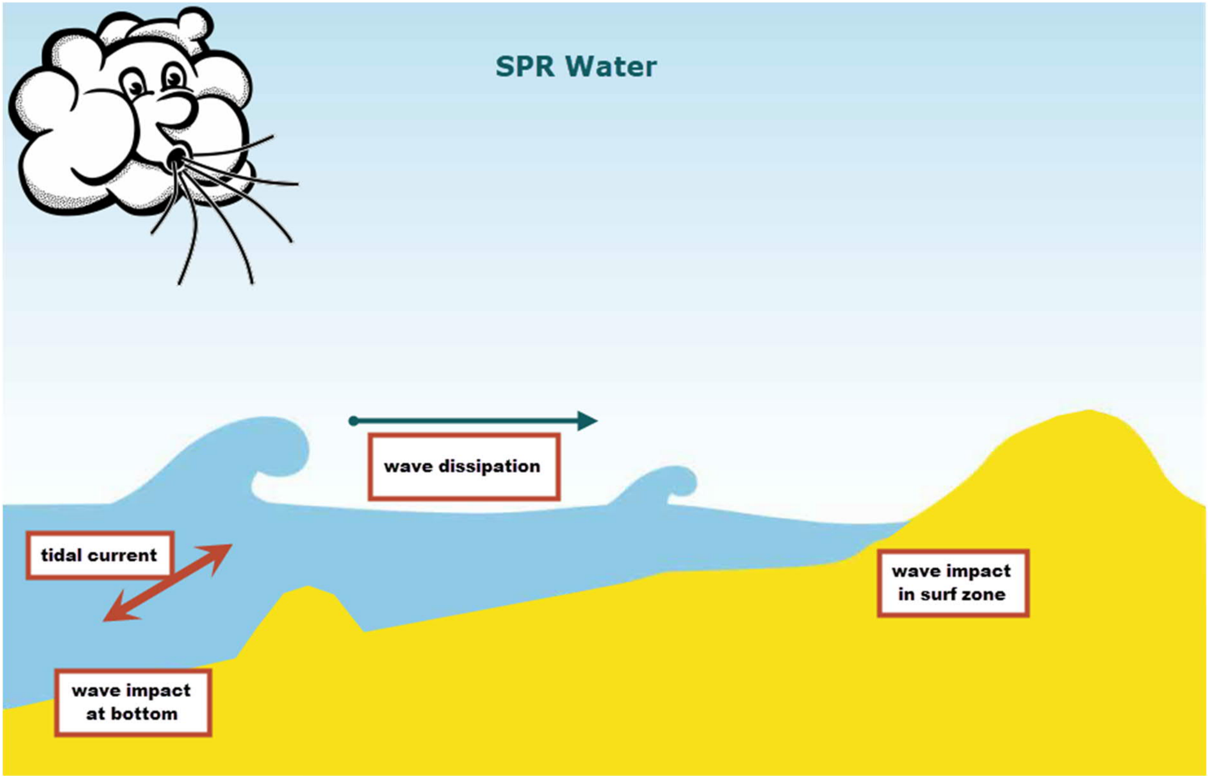

Figure 24: Schematic cross-section showing the main processes driving water

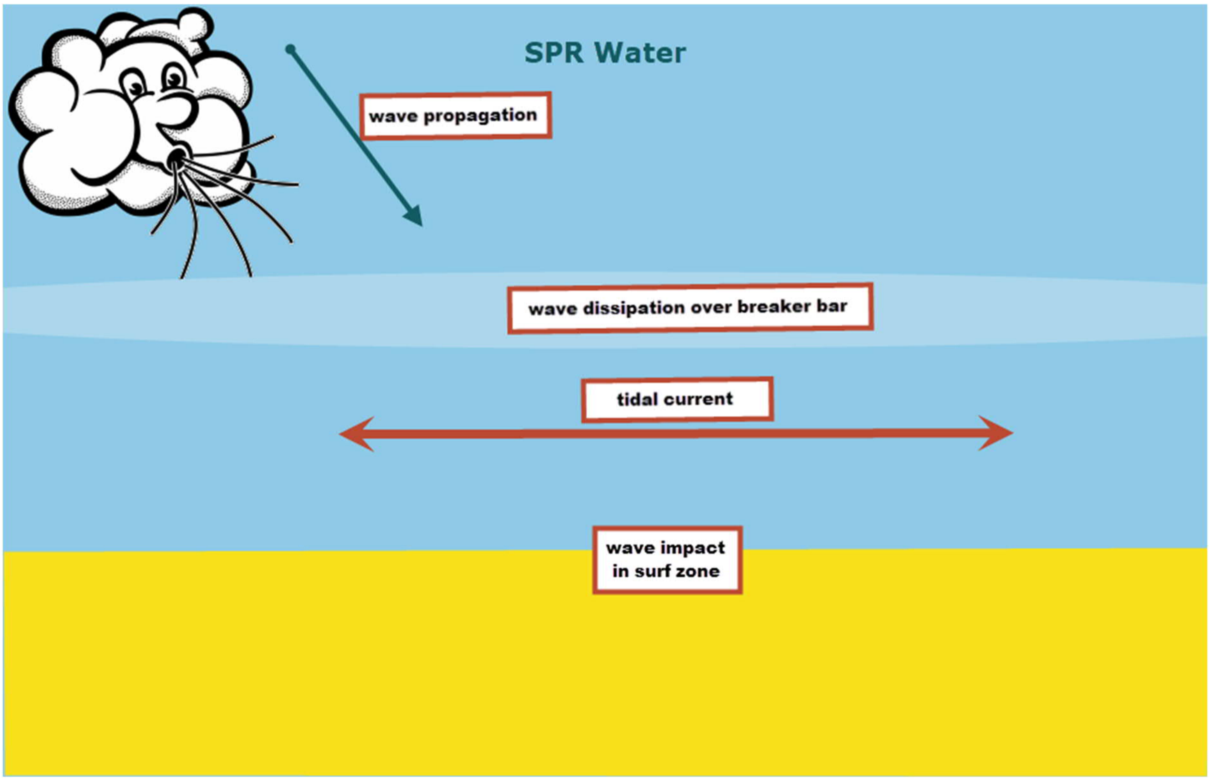

Figure 25: Schematic plan view showing the main processes driving water

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 26 and Figure 27). 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 Bergen-Egmond lab the shoreface nourishments have been seen to be the source for the breaker bar zone and possibly – indirectly – the beach (Figure 28). 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 also seen at Bergen-Egmond.

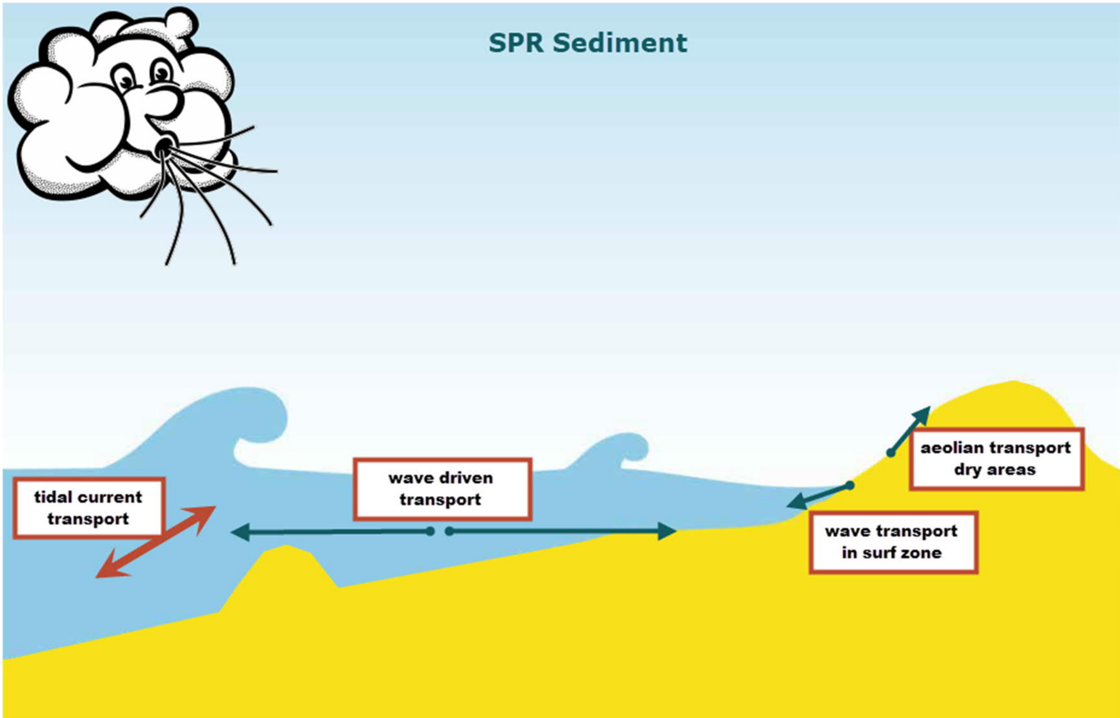

Figure 26: Schematic cross-section showing the main processes driving sediment transport

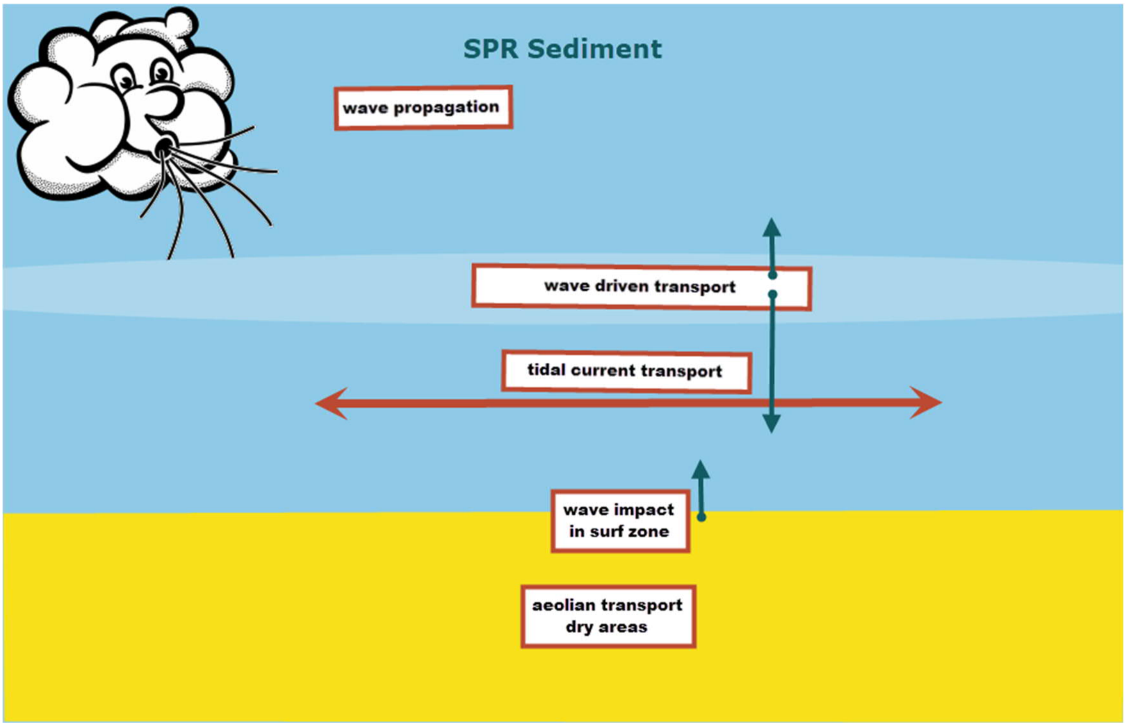

Figure 27: Schematic plan view showing the main processes driving sediment transport

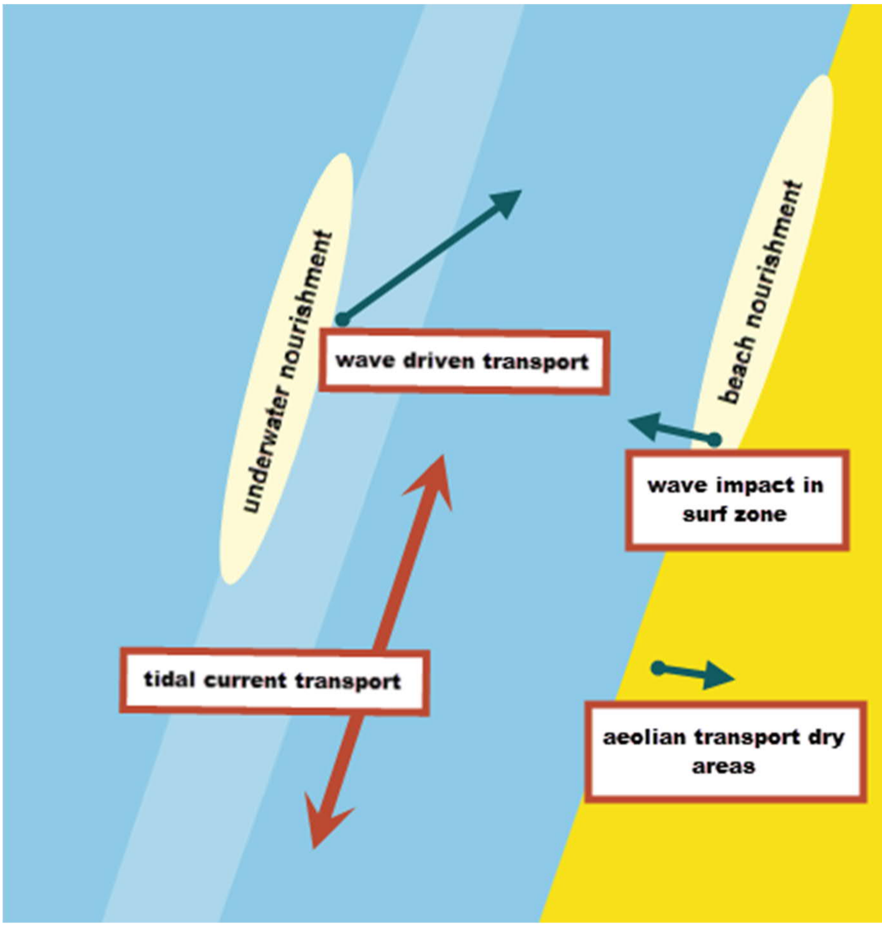

Figure 28: Schematic plan view showing the main processes driving sediment transport for the Bergen-Egmond lab

7 Results

7.1 Qualitative Morphological development

7.1.1 Shoreface

The shoreface nourishment has clearly an influence on the breaker bars present at the shoreface. Just north of the nourishment, in transect 3000 (Figure 29), a small outer bar is present before the start of the nourishment. After the nourishment the top of the bar becomes slightly deeper and the trough becomes a bit deeper. There is a small seaward migration of the bar. The position of the inner bar shows larger fluctuations but no clear direction in which its migrating.

At transect 3200 (Figure 30) the north end of the nourishment is placed. Before nourishing, no outer bar was present in the profile. In the year after the nourishment a small outer bar is visible with a small trough. The trough deepens in the following years, while the top of the bar remains stable, both the horizontal position and the vertical level. After the nourishment, the inner bar migrates landward and its top becomes slightly shallower.

Further to the south, at transect 3600 (Figure 31), there is an outer bar present before the placement of the nourishment. After the nourishment the outer bar is larger and lying about 100 m further seaward, with an shallower top of the bar and deeper trough. The inner bar migrates slightly seaward but remains almost the same.

At the south end of the nourishment, at transect 4000 (Figure 32), there was a small outer bar present before the nourishment. The top of the bar got only slightly shallower after the nourishment, but eroded back to its original dimension in 2015. Before the nourishment, the inner bar moves seaward, after the nourishment it migrates landwards and gets a shallower top. Later on, the depth of the top decreases again and it migrates again offshore.

South of the nourishment, at transect 4100 (Figure 33), there is no outer bar present and no clear effects from the nourishments are visible. The inner bar shows small offshore migration after which it remains stable, both the horizontal position and the vertical level.

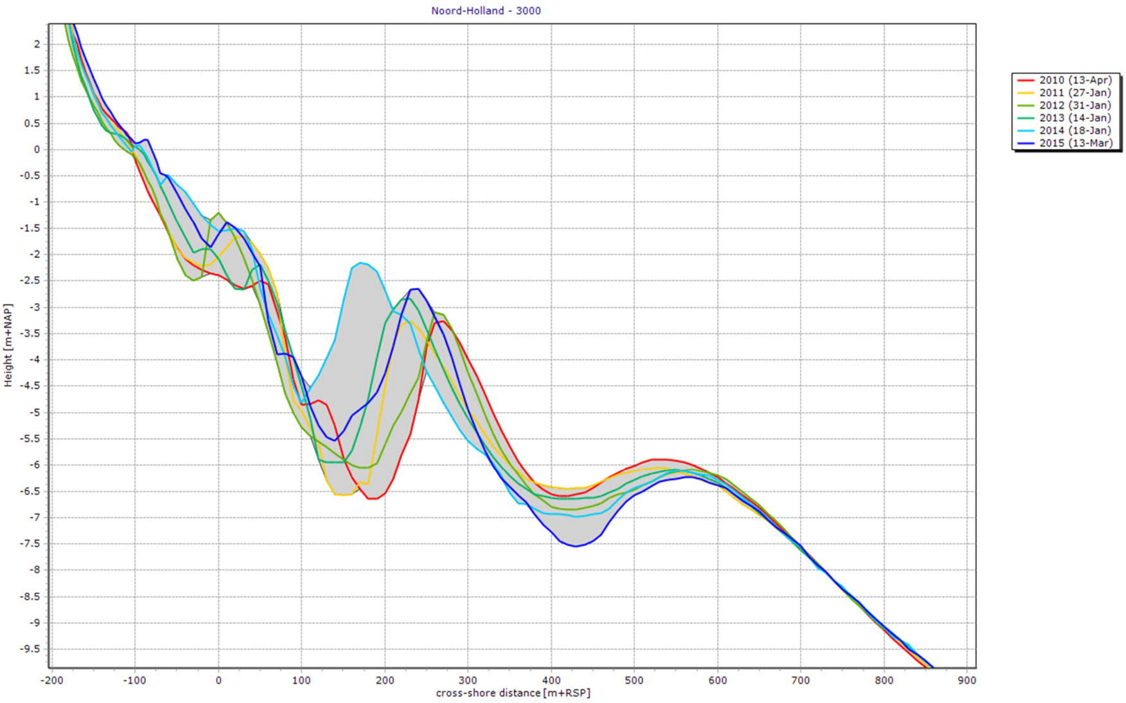

Figure 29: Profile 3000 showing the shoreface just north of the shoreface nourishment

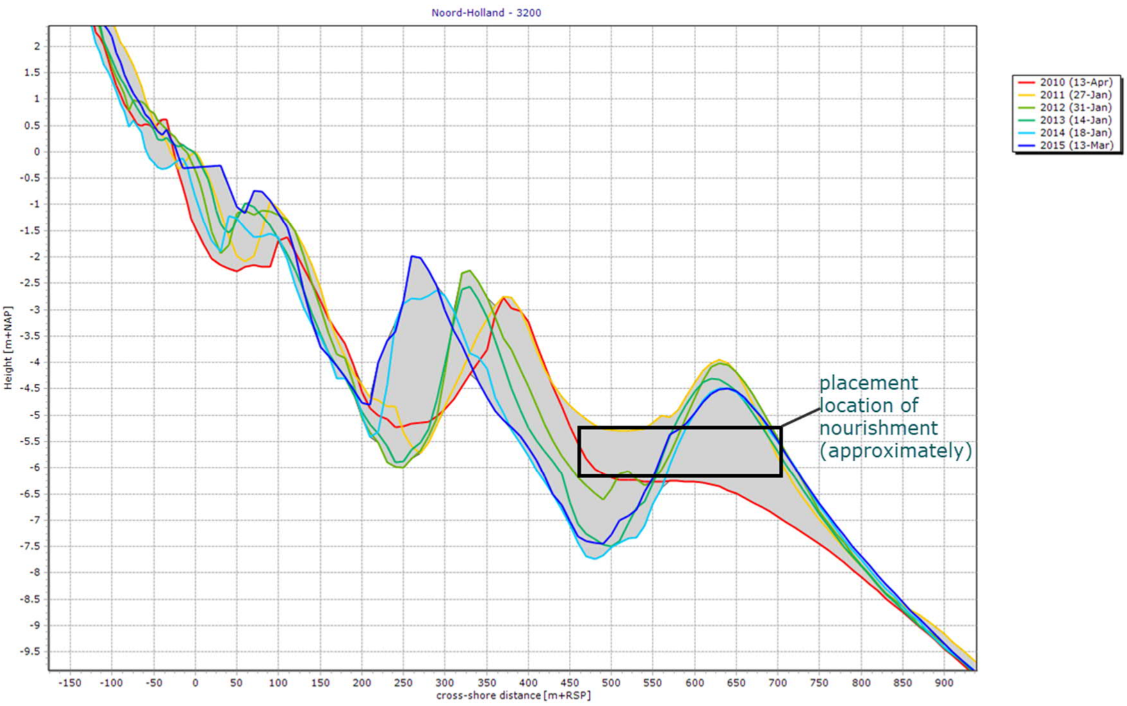

Figure 30: Profile 3200 showing the shoreface at the north side of the shoreface nourishment

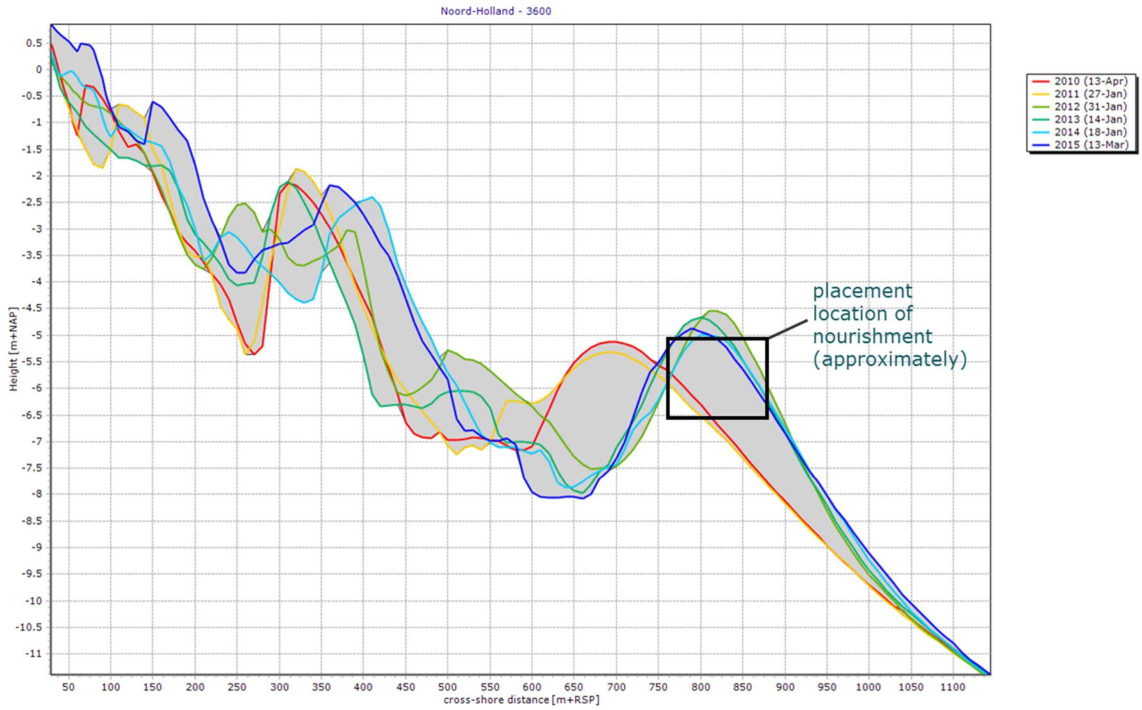

Figure 31: Profile 3600 showing the shoreface in the central part of the shoreface nourishment

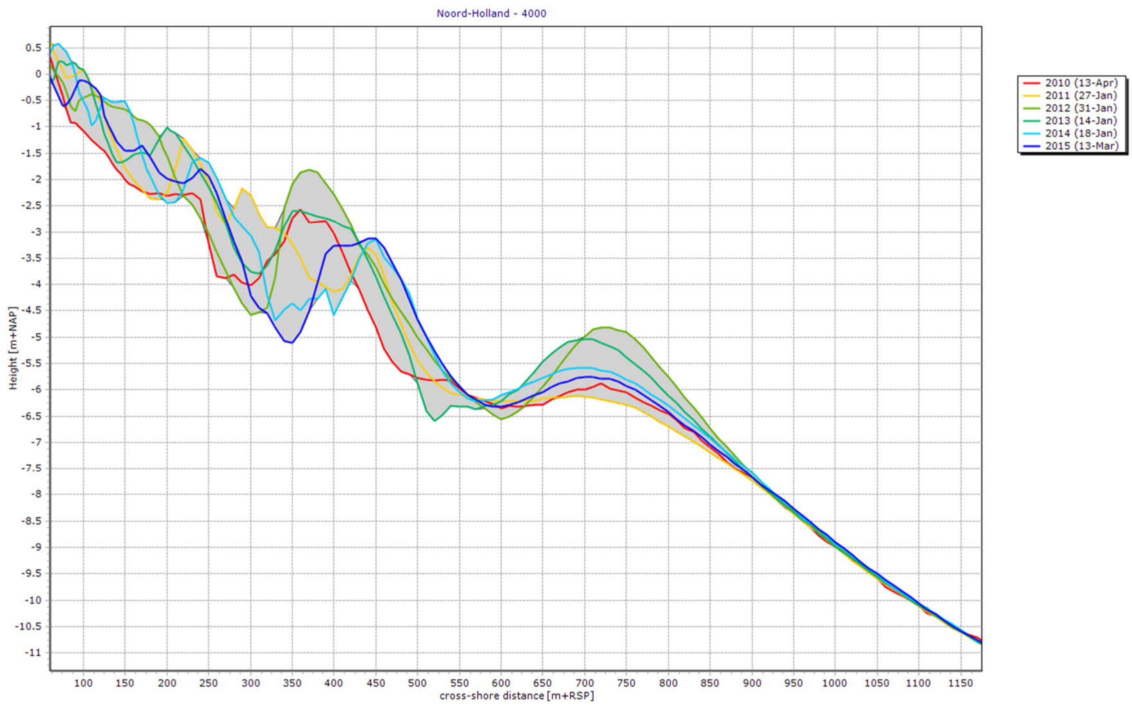

Figure 32: Profile 4000 showing the shoreface just south of the shoreface nourishment

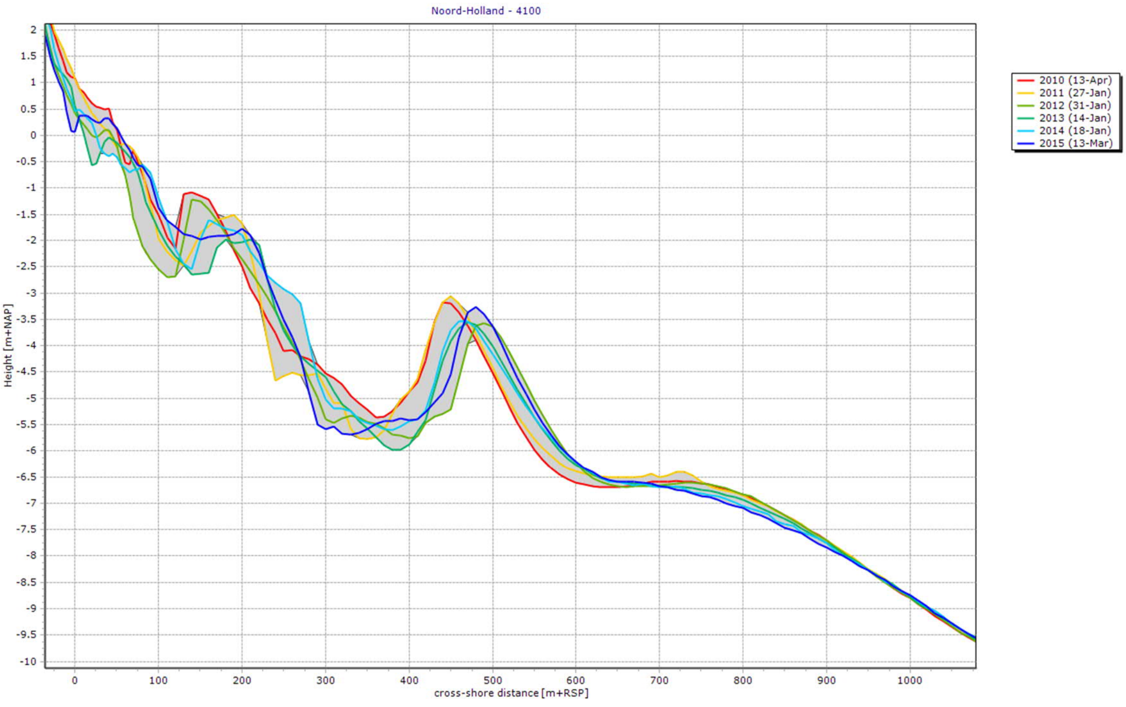

Figure 33: Profile 4100 showing the shoreface 1 km south of the shoreface nourishment

7.1.2 Beach

The nourishment is clearly visible in northern part (transect 3150 – 3400), but not so well in the southern part (transect 3700 – 3900).

In transect 3175 (Figure 34) the behaviour is twofold: above approximately NAP +0.5 m the sediment is almost entirely eroded by 2015, while below this level a significant amount is still present. A similar behaviour is visible in transect 3300 (Figure 35): part of the nourishment is eroded above NAP +0.5 m, while below there is net gain of sediment, although there are fluctuations.

Transect 3500 (Figure 36) lies between the northern and southern nourishment. Here sedimentation is visible above approximately NAP +1.2 m, while below small fluctuations of the profile occurred with a net gain of sediment in 2015. Further south transect 3600 (Figure 37) also lies between the nourishment parts and shows a similar pattern as 3500: some sedimentation above NAP +0.8 m, and below this level a significant net gain of sediment in 2015.

Both transect 3750 (Figure 38) and 3800 (Figure 39) are located at the southern nourishment. In these transects the nourishment is visible in the 2012 measurement. After that it eroded partly above NAP +0.2 m, while below this level a net gain of sediment in 2015 is visible.

At the south end of the southern nourishment, transect 3825 (Figure 40), the nourishment is hardly visible in the measurements. The profiles are fluctuating with no clear erosion or sedimentation trend.

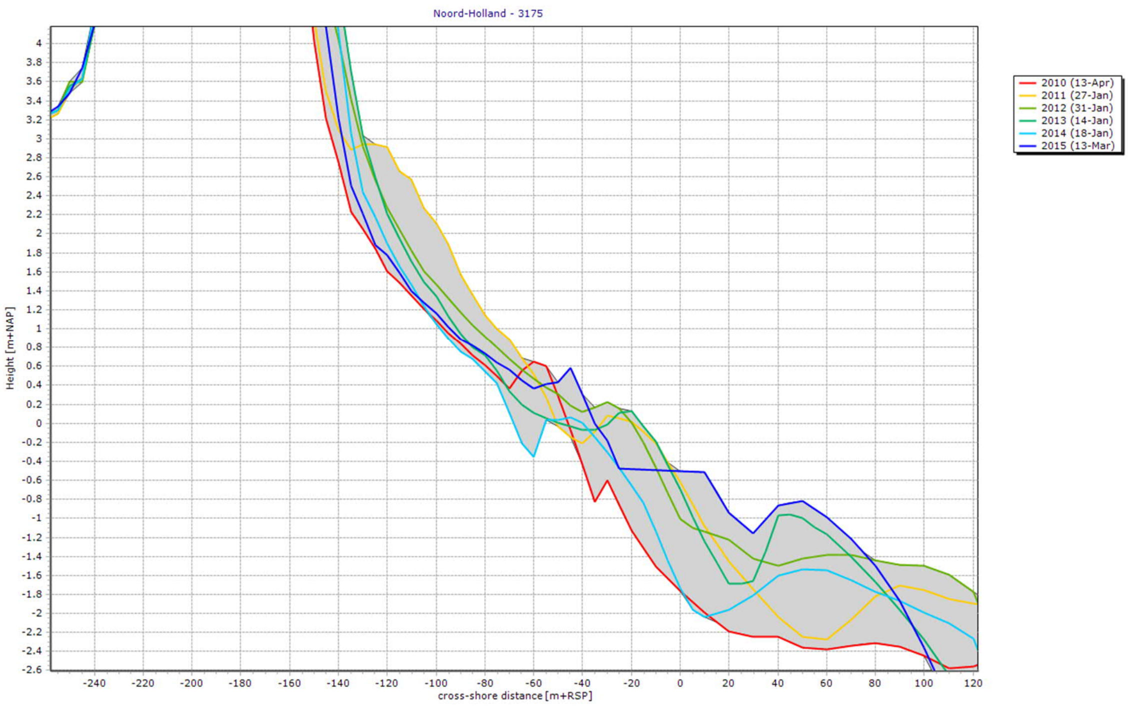

Figure 34: Profile 3175 showing the zone around the beach at the north end of the northern beach nourishment

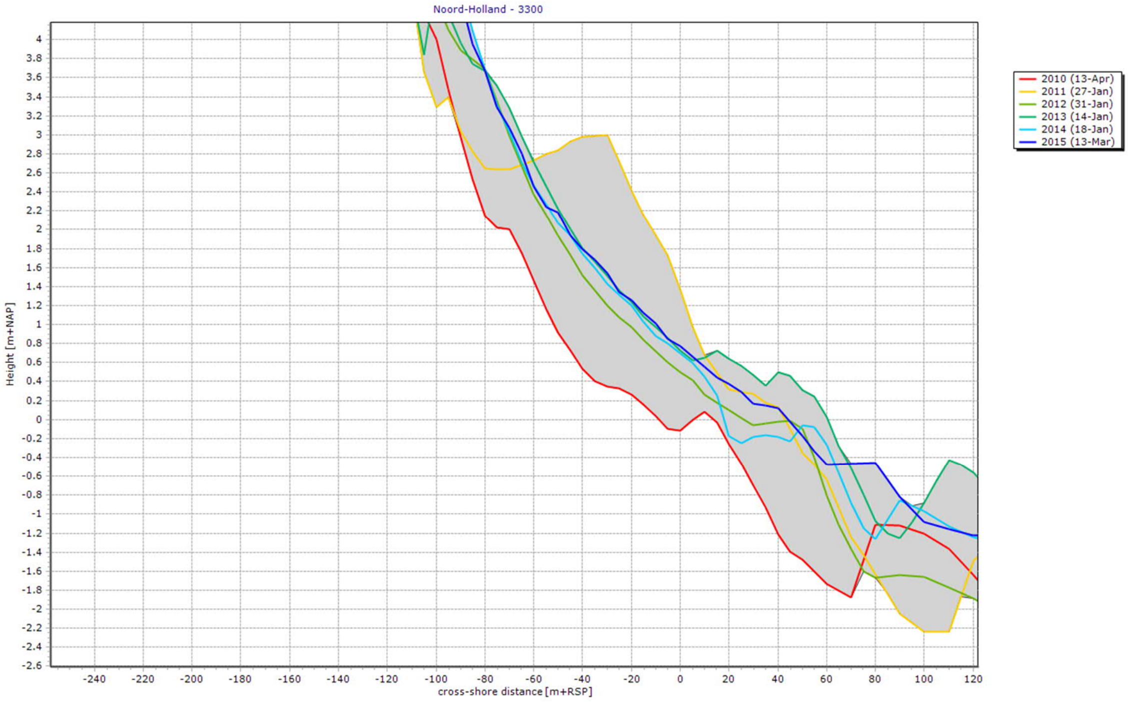

Figure 35: Profile 3300 showing the zone around the beach at the centre of the northern beach nourishment

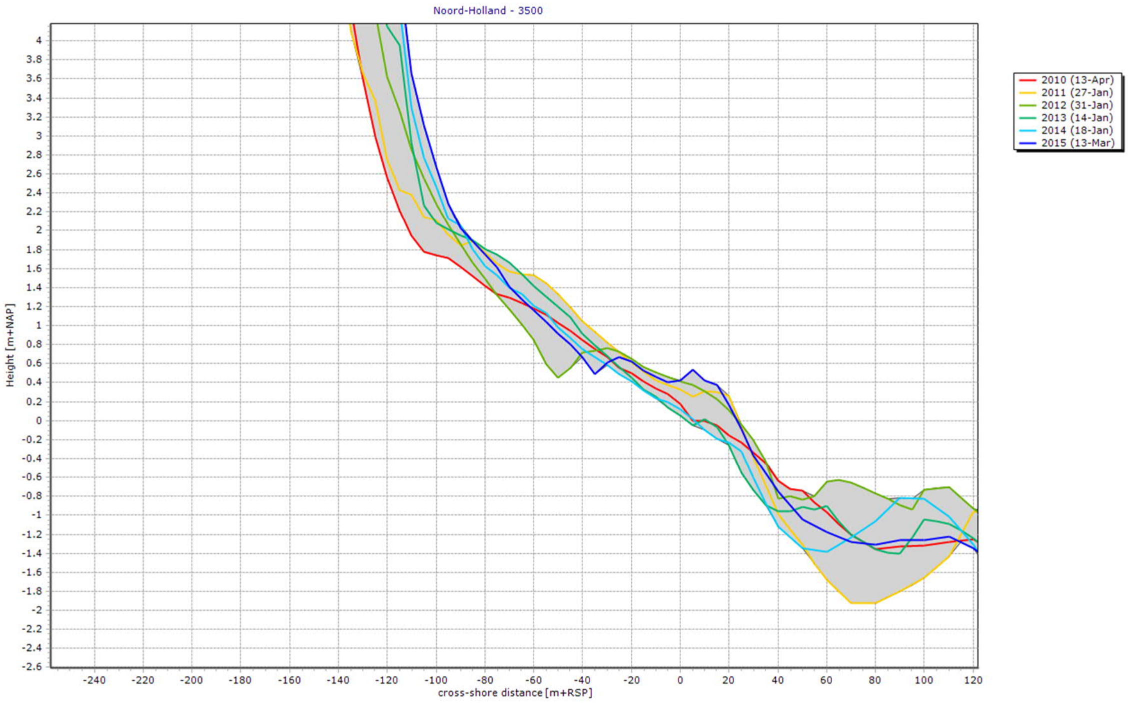

Figure 36: Profile 3500 showing the zone around the beach in between the northern and southern beach nourishments

Figure 37: Profile 3600 showing the zone around the beach in between the northern and southern beach nourishments

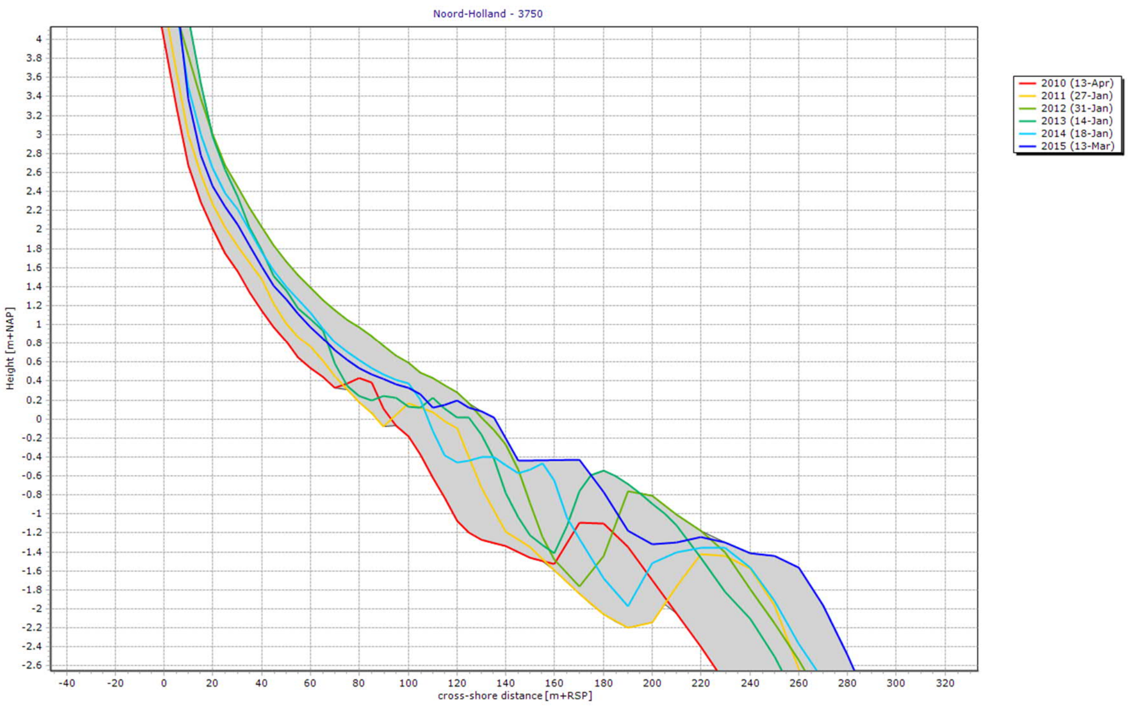

Figure 38: Profile 3750 showing the zone around the beach in at the north end of the southern beach nourishment

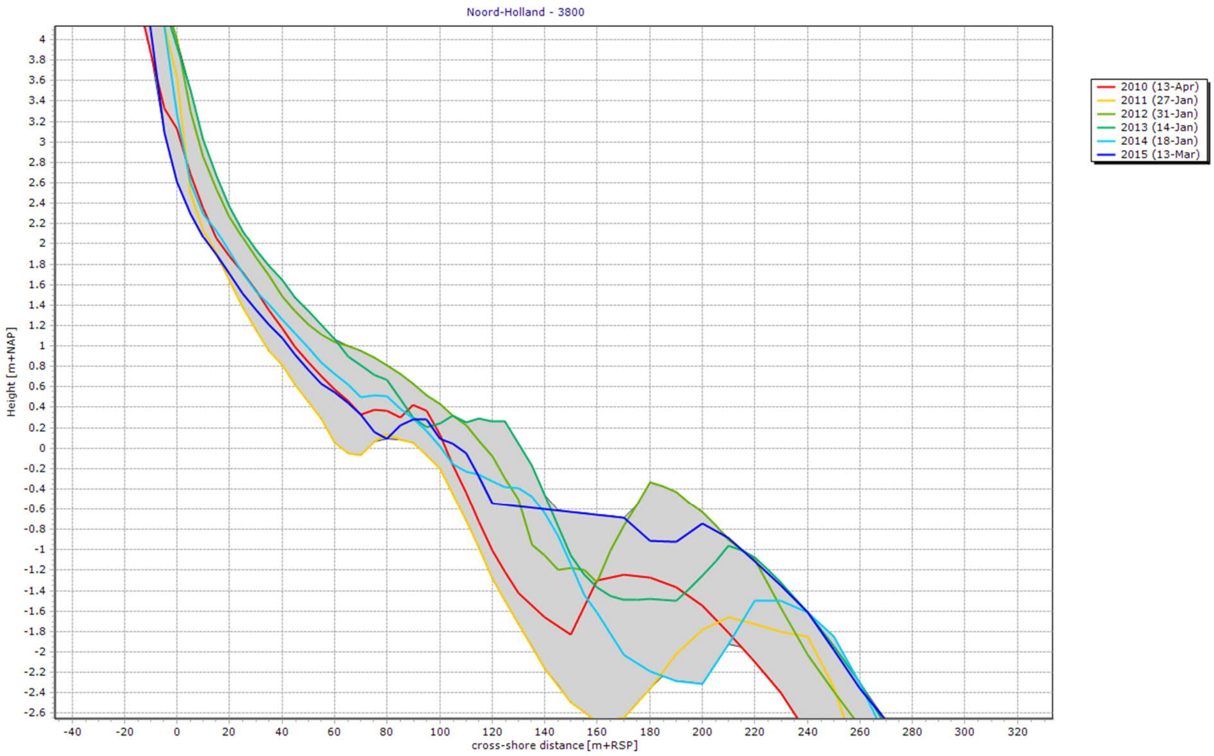

Figure 39: Profile 3800 showing the zone around the beach in at the centre of the southern beach nourishment

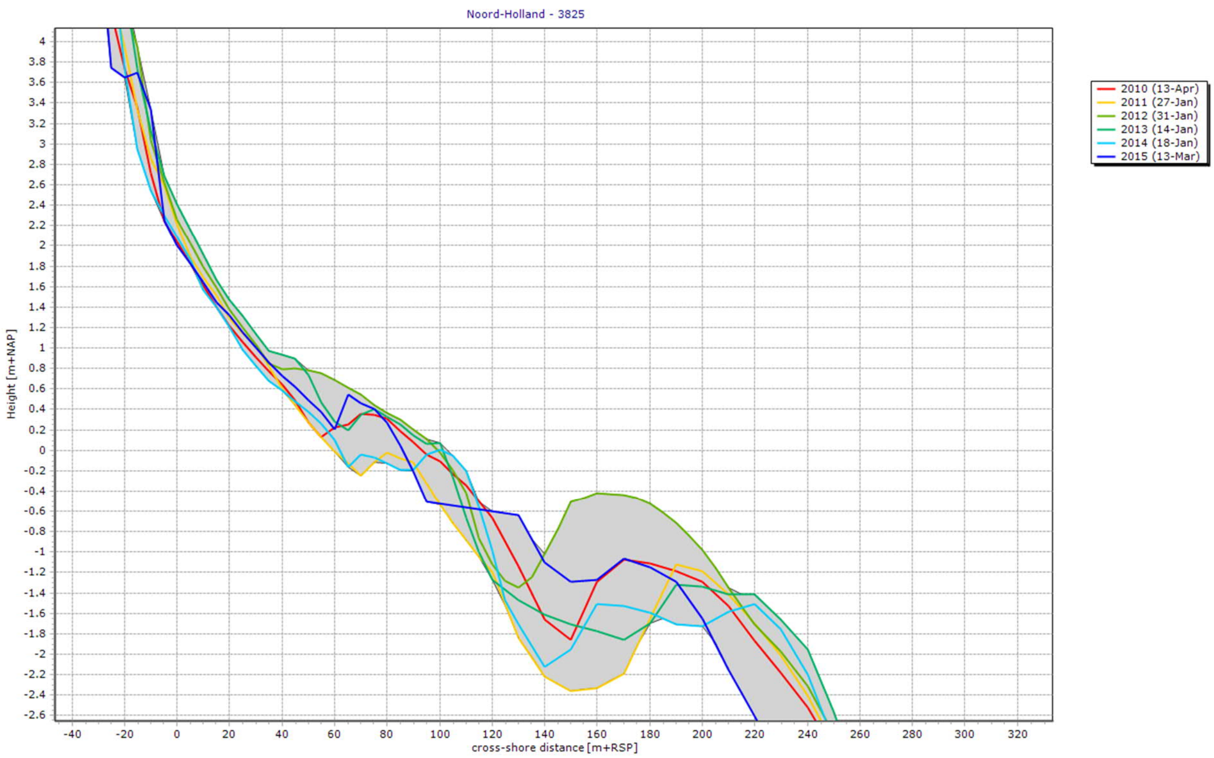

Figure 40: Profile 3825 showing the zone around the beach at the north end of the southern beach nourishment

7.1.3 Dunes

The general behaviour of the dunes in the study area is a significant sedimentation of the dune front. In many transects the entire front is building in seaward direction (Figure 41 to Figure 43), in some transects the sedimentation is different for different parts of the dune.

In transects 3300 (Figure 44) and 3500 (Figure 45) there is large sedimentation between NAP +3 m and NAP +7 m, while NAP +7 m the rate of sedimentation is much smaller.

Further south, transect 3800 (Figure 46) shows an opposite trend: there is erosion below NAP +4 m and sedimentation above this level up to the dune top.

A similar pattern is visible for 4050 (Figure 47): there is erosion below NAP+8 m and sedimentation above this level, becoming almost stable at the dune top.

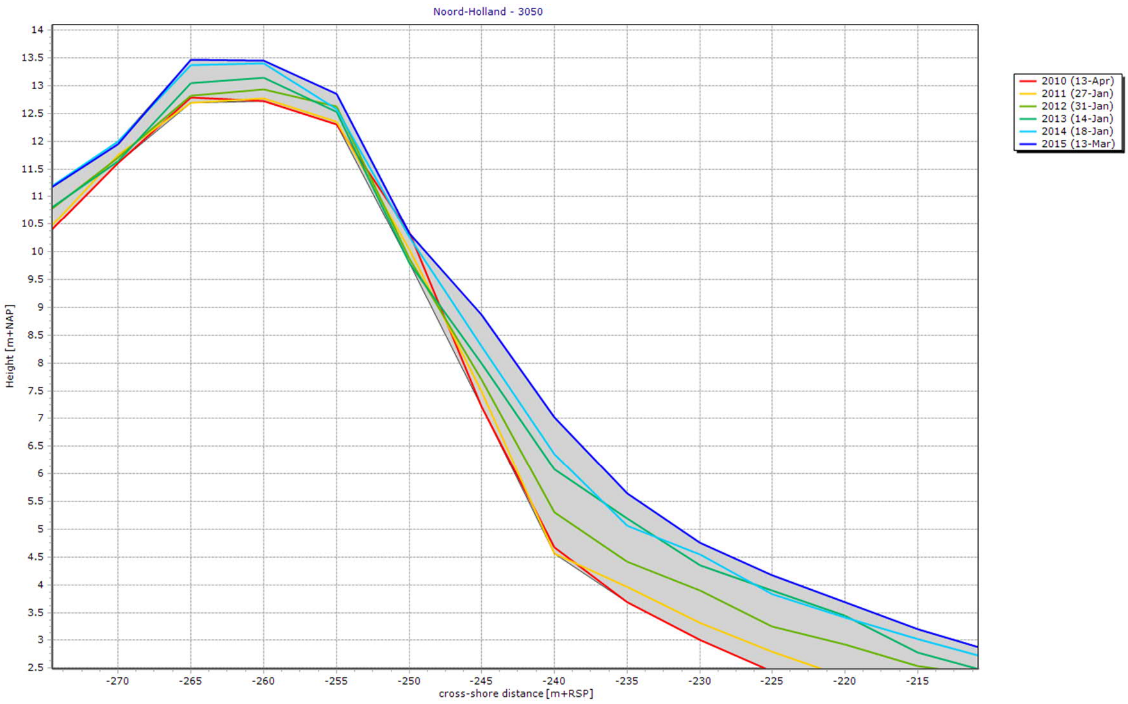

Figure 41: Profile 3050 showing the first dune 1 km north of the northern beach nourishment

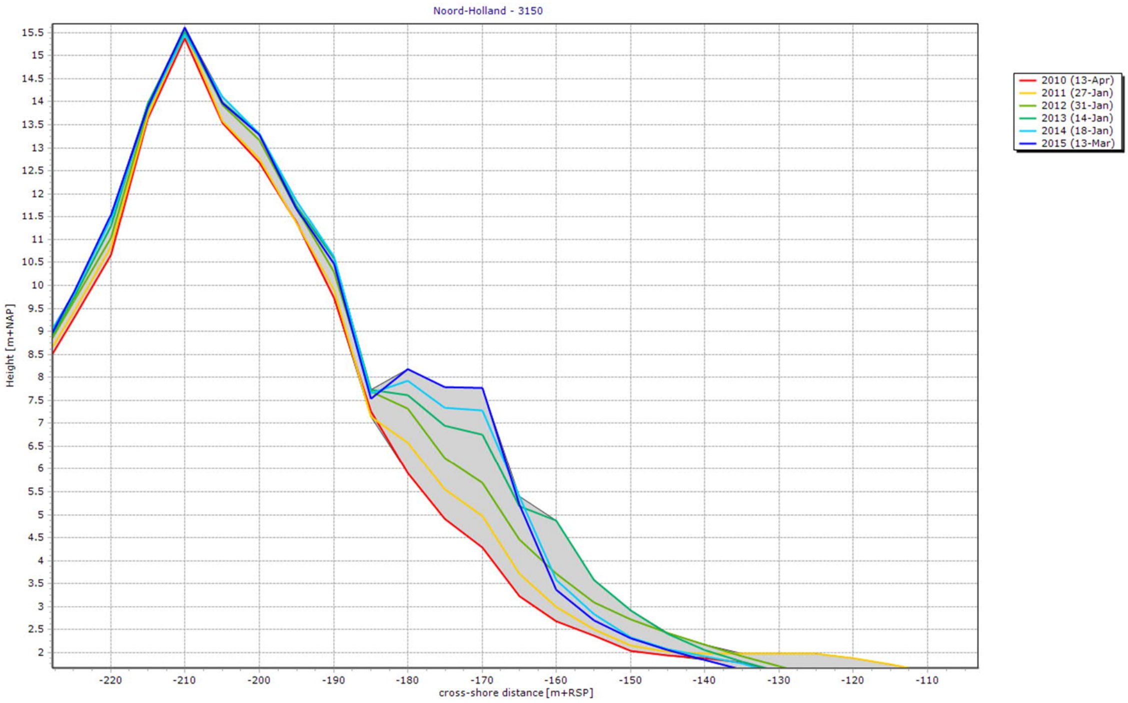

Figure 42: Profile 3150 showing the first dune at the north end of the northern beach nourishment

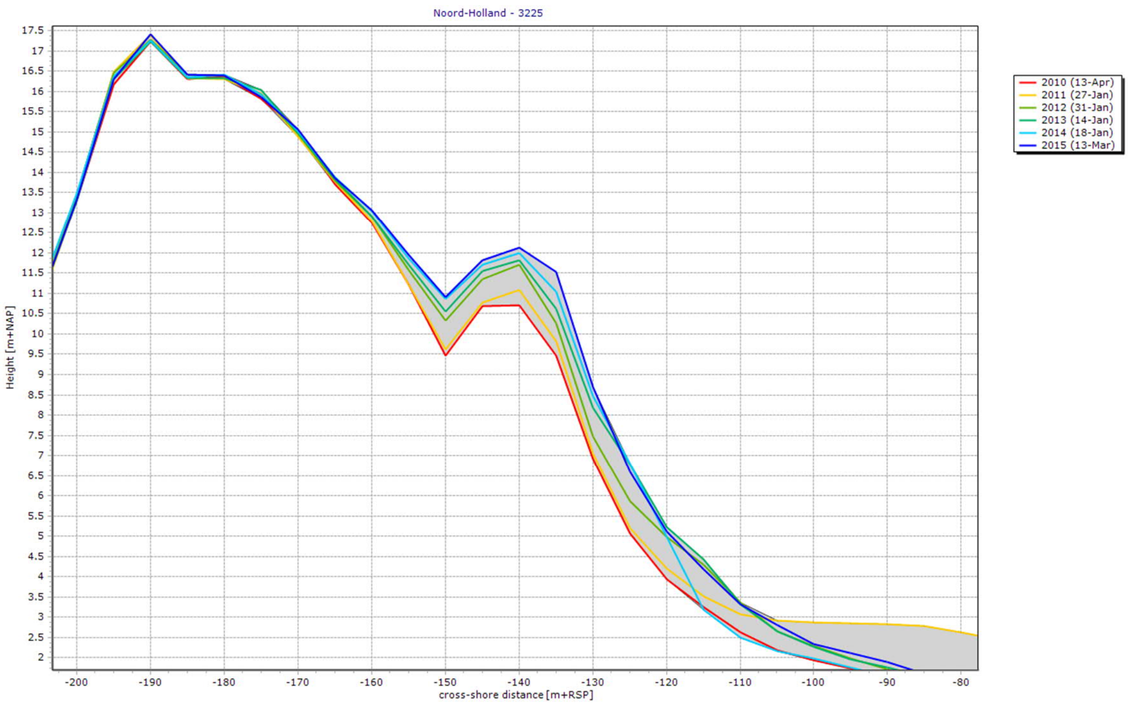

Figure 43: Profile 3225 showing the first dune at the centre of the northern beach nourishment

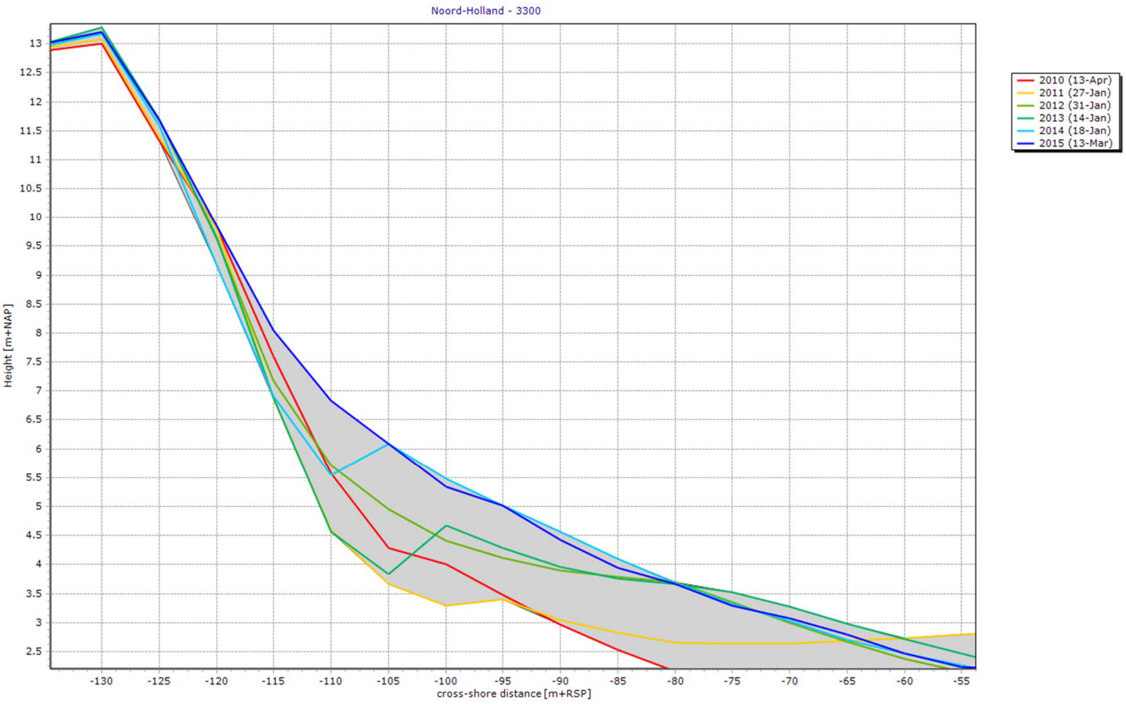

Figure 44: Profile 3300 showing the first dune at the northern beach nourishment

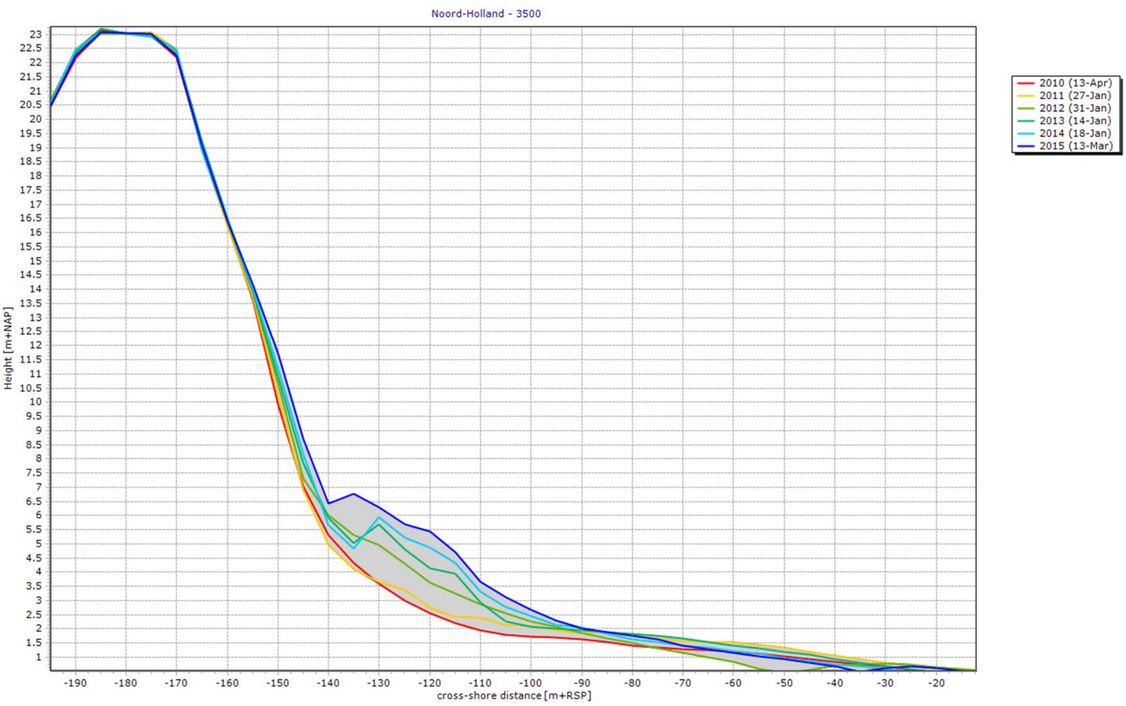

Figure 45: Profile 3500 showing the first dune just in between the northern and southern beach nourishment

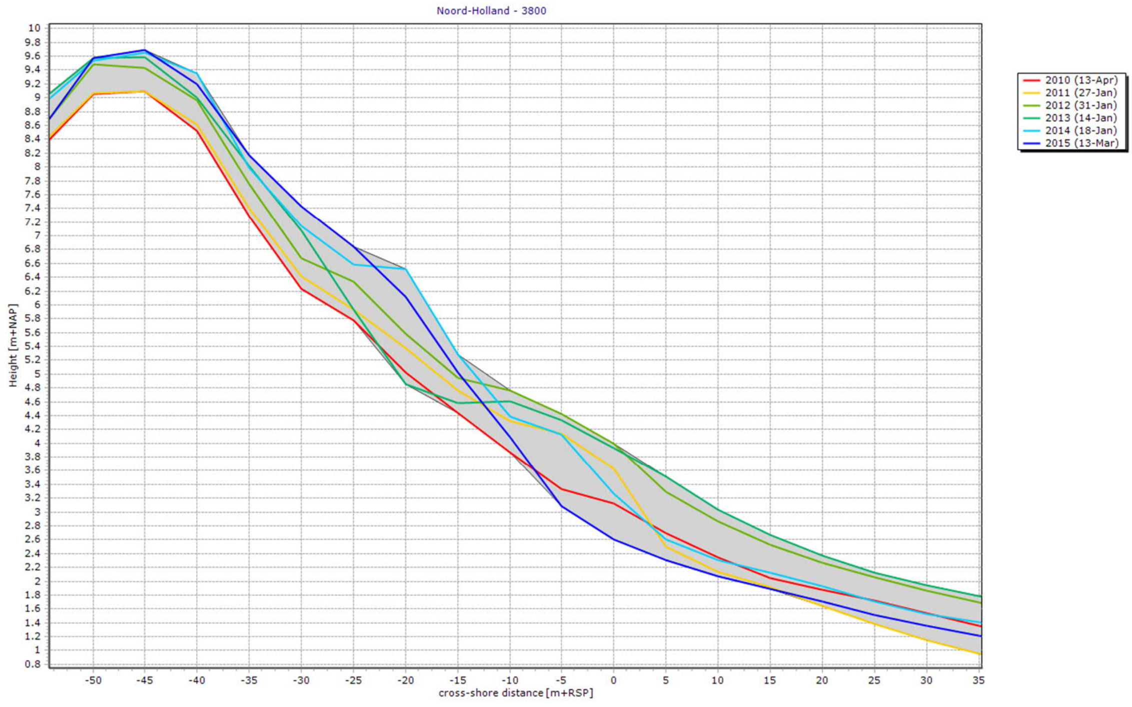

Figure 46: Profile 3800 showing the first dune at the southern beach nourishment

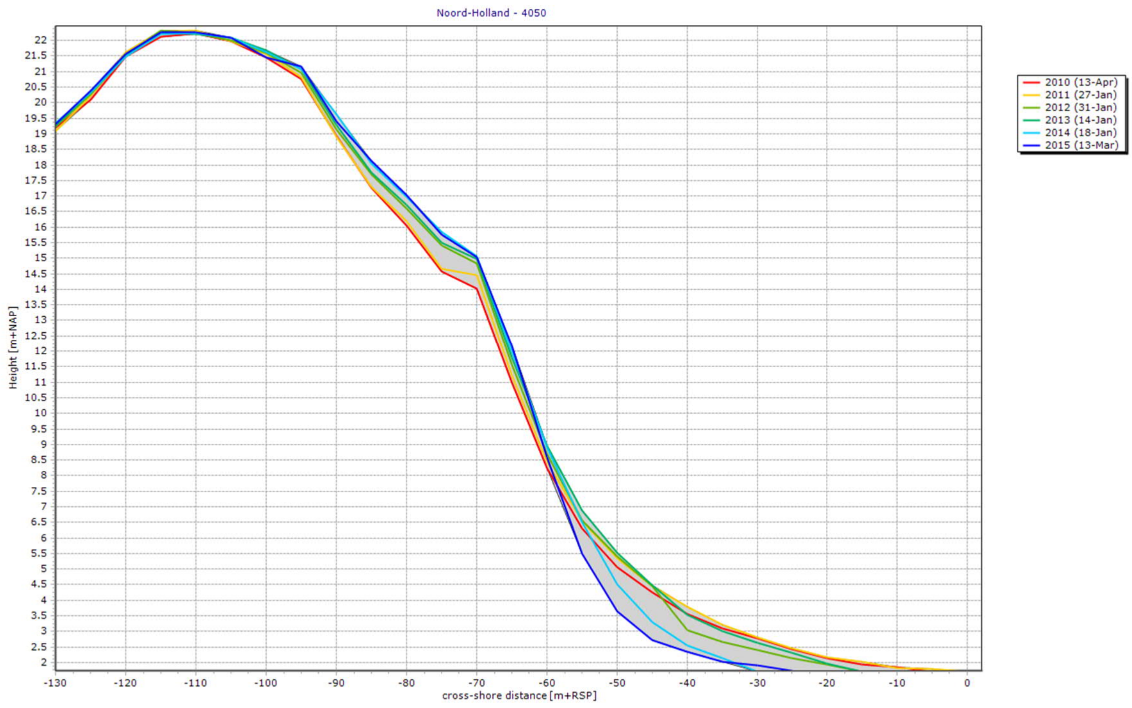

Figure 47: Profile 4050 showing the first dune just south of the southern beach nourishment

7.2 Quantitative Morphological development

7.2.1 Physical marks

In the period after the nourishments the following changes in the coastal state indicators can be observed.

All three dune indicators (dunefoot, mid dune level and upper dune level, Figure 48 to Figure 50) show a similar change. In general there is a seaward movement, indicating sedimentation of the first dune. In the dunefoot sudden large movement in seaward direction followed by a large landward direction is caused by the beach nourishments, which are constructed up to this level.

The low water level (Figure 51) shows large fluctuations, but also a net positive effect after nourishment of ca. 60 m. This is mainly seen at the nourishment locations, though also a large positive change can be seen in between the two nourishments. The mean high water level (Figure 52 and Figure 53) shows fluctuations in its position, but in this period a net seaward movement of ca. 60 m at the beach nourishment locations and much less in between the two nourishments.

The long term behaviour of the indicators is best visualized in the development of the indicators in time for one transect, examples are shown in Figure 54 to Figure 56.

The behaviour of the dune indicators shows that most transects have a landward displacement up to about 1990 and a seaward movement after this year. These trends are the strongest for the dunefoot – this position is also directly influenced by the beach nourishments. The mean high water level and mean low water level show (very) large yearly fluctuations of 20 m to over 50 m. The general trends seem to be that they are moving landward or are almost stable before 1990 and show a seaward movement after 1990.

Figure 48: Position of the dunefoot for the transects in the study area (3000 is in the north, 4100 in the south) from 2005 to 2017. Squares indicate nourishment positions: shoreface nourishment (yellow) and two parts of the beach nourishment (orange).

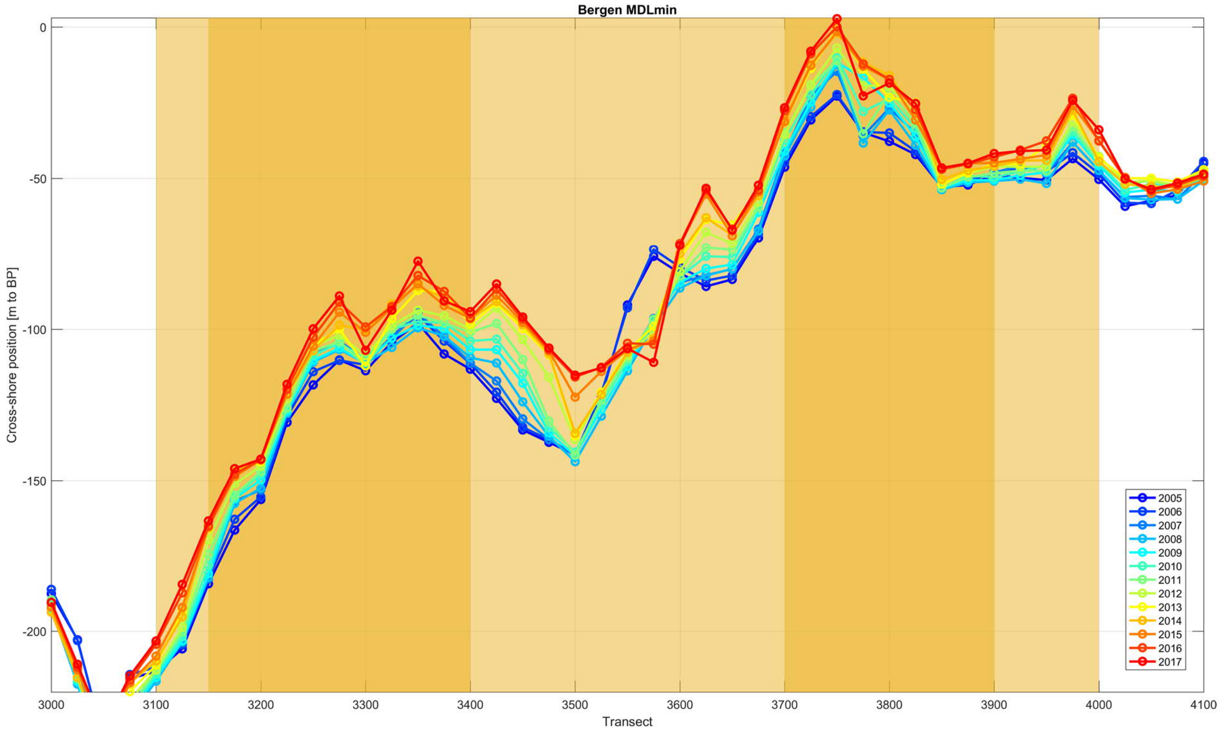

Figure 49: Position of the mid dune level for the transects in the study area (3000 is in the north, 4100 in the south) from 2005 to 2017. Squares indicate nourishment positions: shoreface nourishment (yellow) and two parts of the beach nourishment (orange).

Figure 50: Position of the upper dune level for the transects in the study area (3000 is in the north, 4100 in the south) from 2005 to 2017. Squares indicate nourishment positions: shoreface nourishment (yellow) and two parts of the beach nourishment (orange).

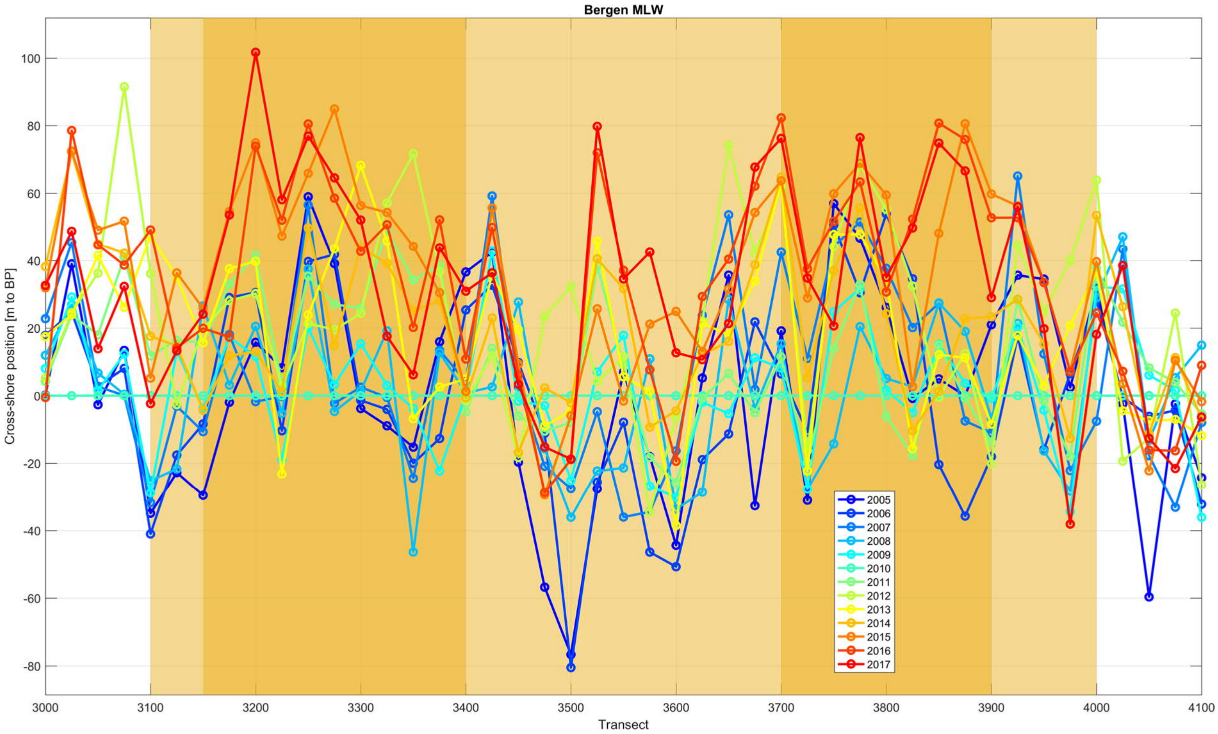

Figure 51: Position of the mean low water line relative to the position in 2010 for the transects in the study area (3000 is in the north, 4100 in the south) from 2005 to 2017. Squares indicate nourishment positions: shoreface nourishment (yellow) and two parts of the beach nourishment (orange).

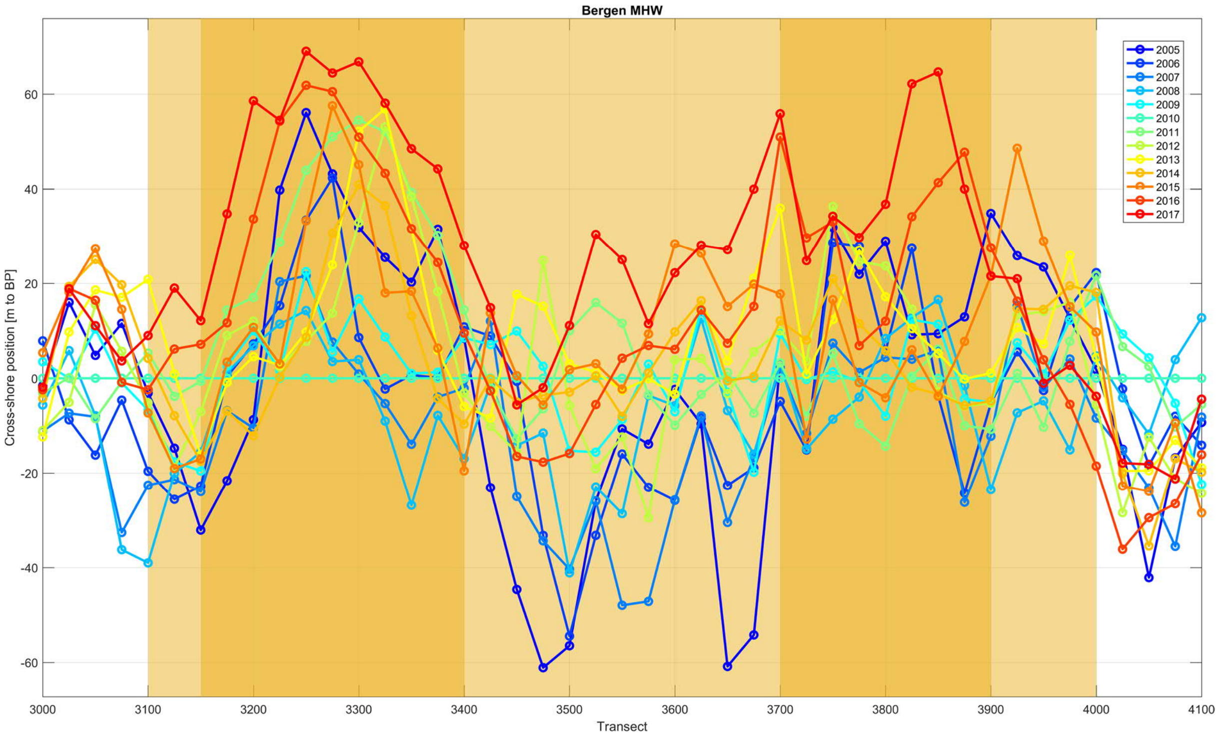

Figure 52: Position of the mean high water line relative to the position in 2010 for the transects in the study area (3000 is in the north, 4100 in the south) from 2005 to 2017. Squares indicate nourishment positions: shoreface nourishment (yellow) and two parts of the beach nourishment (orange).

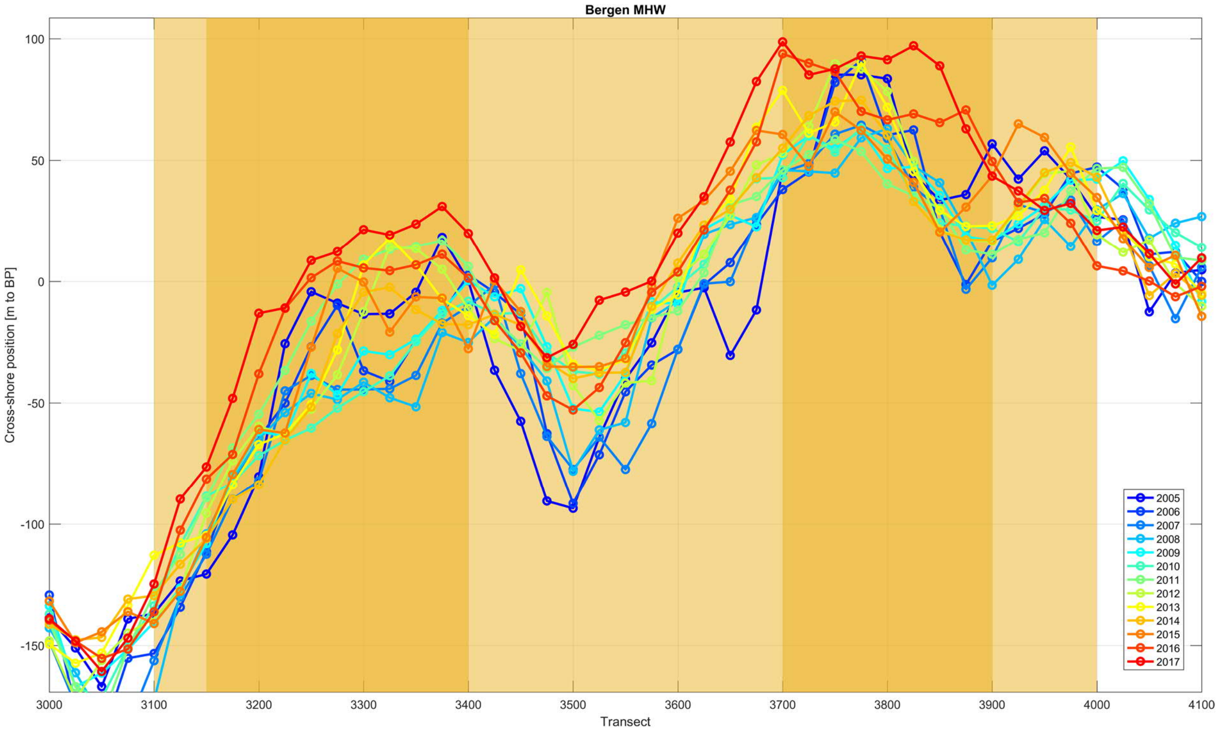

Figure 53: Position of the mean high water line for the transects in the study area (3000 is in the north, 4100 in the south) from 2005 to 2017. Squares indicate nourishment positions: shoreface nourishment (yellow) and two parts of the beach nourishment (orange).

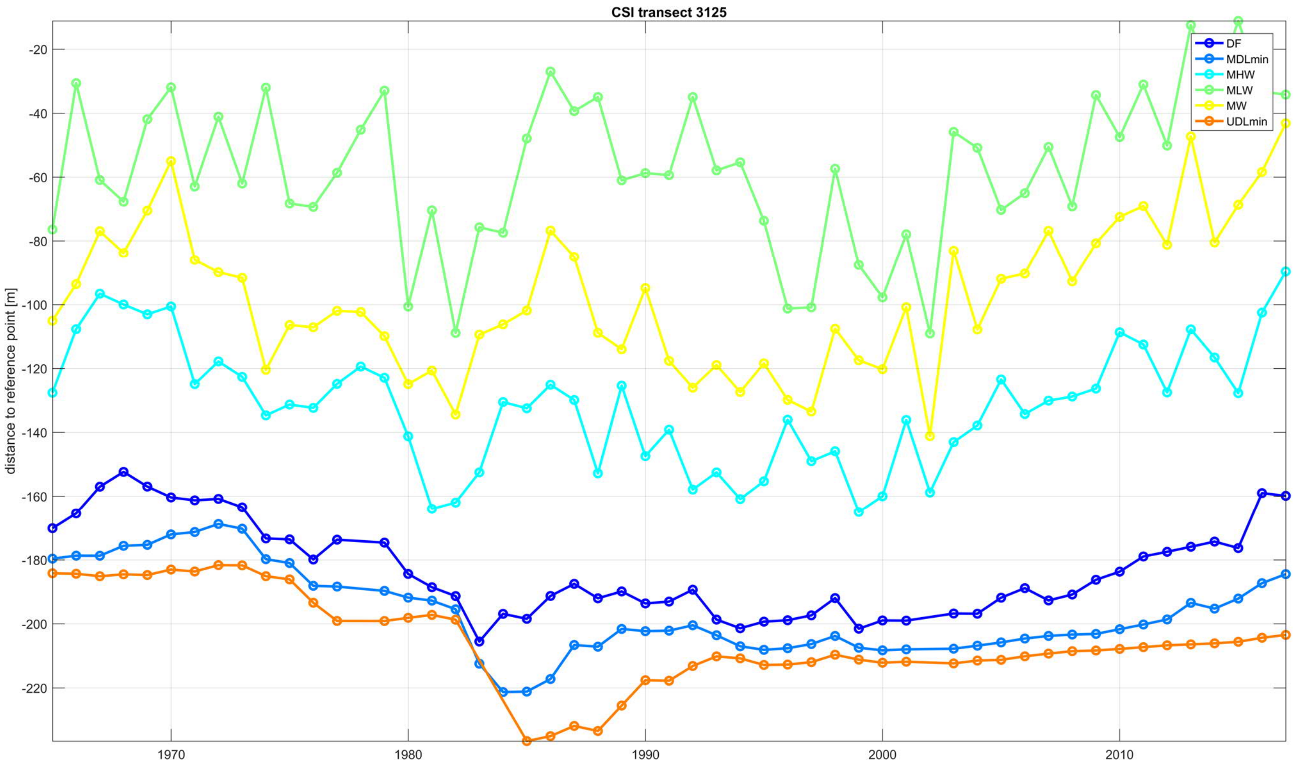

Figure 54: Development of all coastal state indicators in time for transect 3125

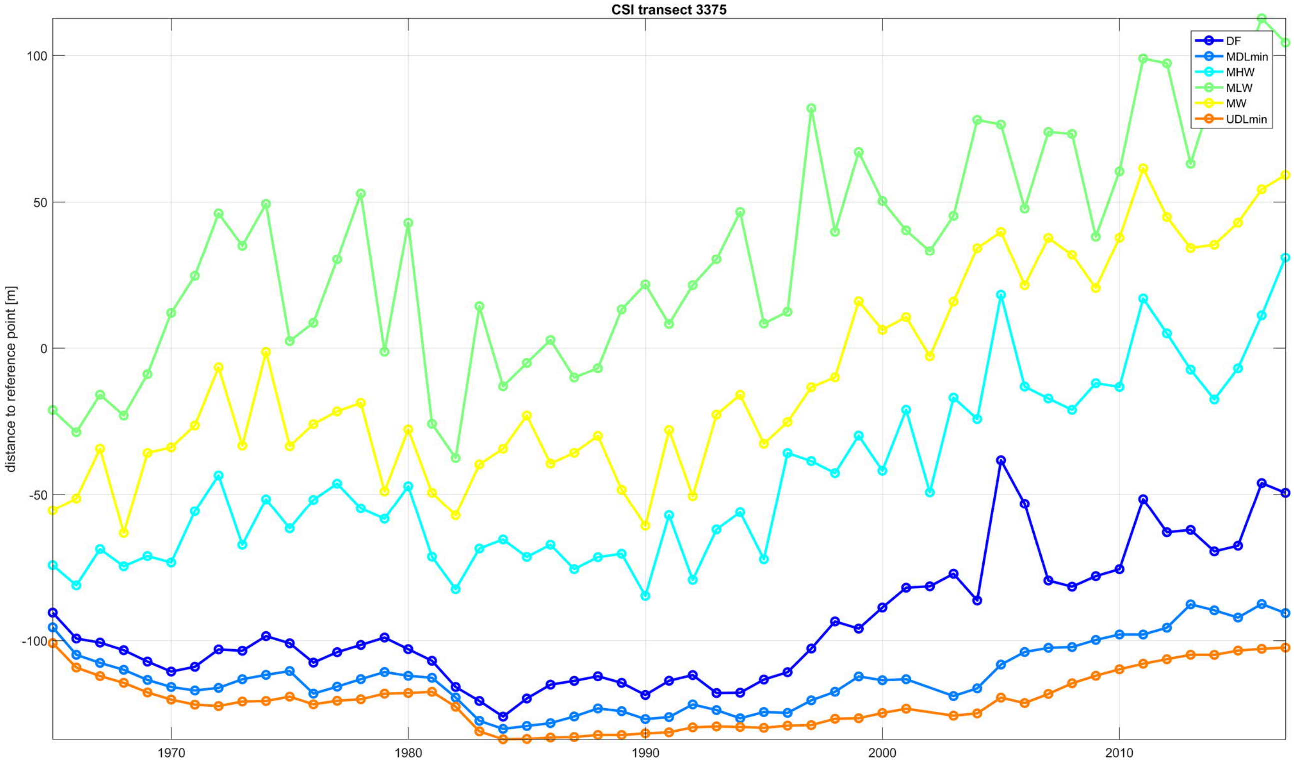

Figure 55: Development of all coastal state indicators in time for transect 3375

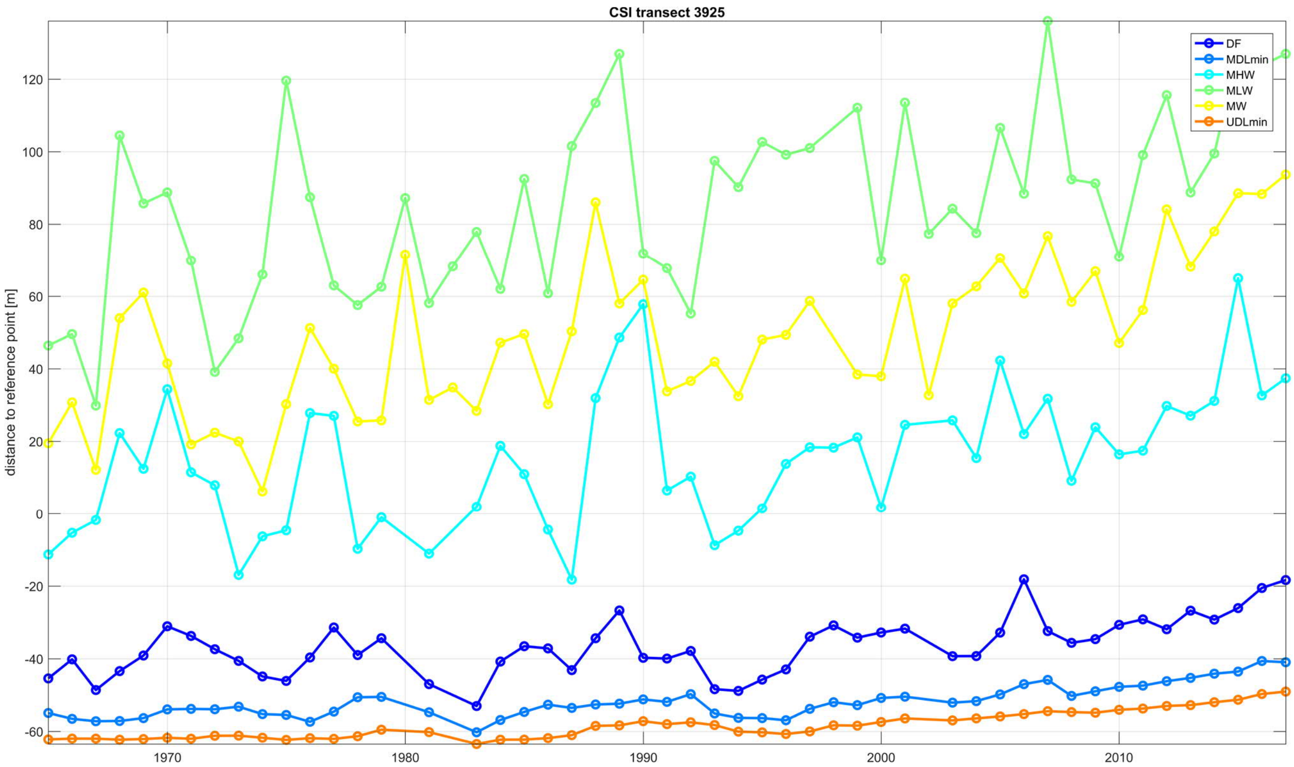

Figure 56: Development of all coastal state indicators in time for transect 3925

7.2.2 Bar development

In this area only one bar and at some moments two clear bars are present before the start of the first shoreface nourishments in 1999 (Figure 57). This bar migrates offshore where it decays, after which a new bar is formed and started migrating offshore. Migration rates are calculated for two bars in two profiles (Figure 58) and are between ca. 20 and 35 m/year. The bars migrate in 10 to 15 years to the zone of decay, where the crest is at ca. NAP -7 m. There is no clear behaviour of the bar height and bar area in time (Figure 59 and Figure 60). The crest depth shows a clear decreasing trend in time before start of the nourishments (Figure 61 to Figure 63).

The small nourishment from 1999/2000 did not have a significant effect on the bar behaviour, the large one of 2005/2006 did. The latter formed a new outer bar that remained stable at the same position until 2010 (Figure 64). The nourishment from 2010/2011 (studied in this report) shows the same behaviour as the 2005/2006 shoreface nourishment: remaining present as an outer bar at the same position (Figure 65). The nourishments also altered the decreasing trend of the bar crest in time.

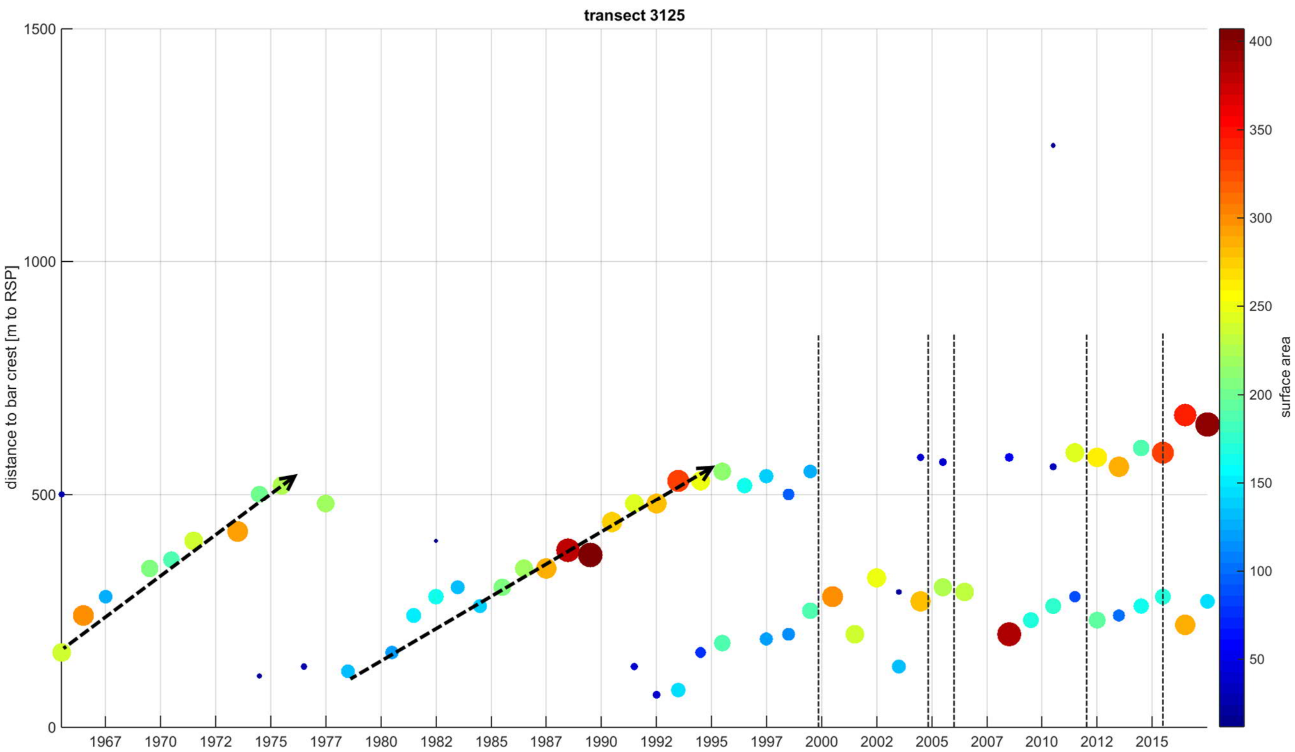

Figure 57: Development of bar crests position over time for transect 3125, colours and circle-size correspond with surface area of the bar (m^2), dashed arrows indicate movement of single bar in time, dashed vertical lines indicate shoreface nourishments.

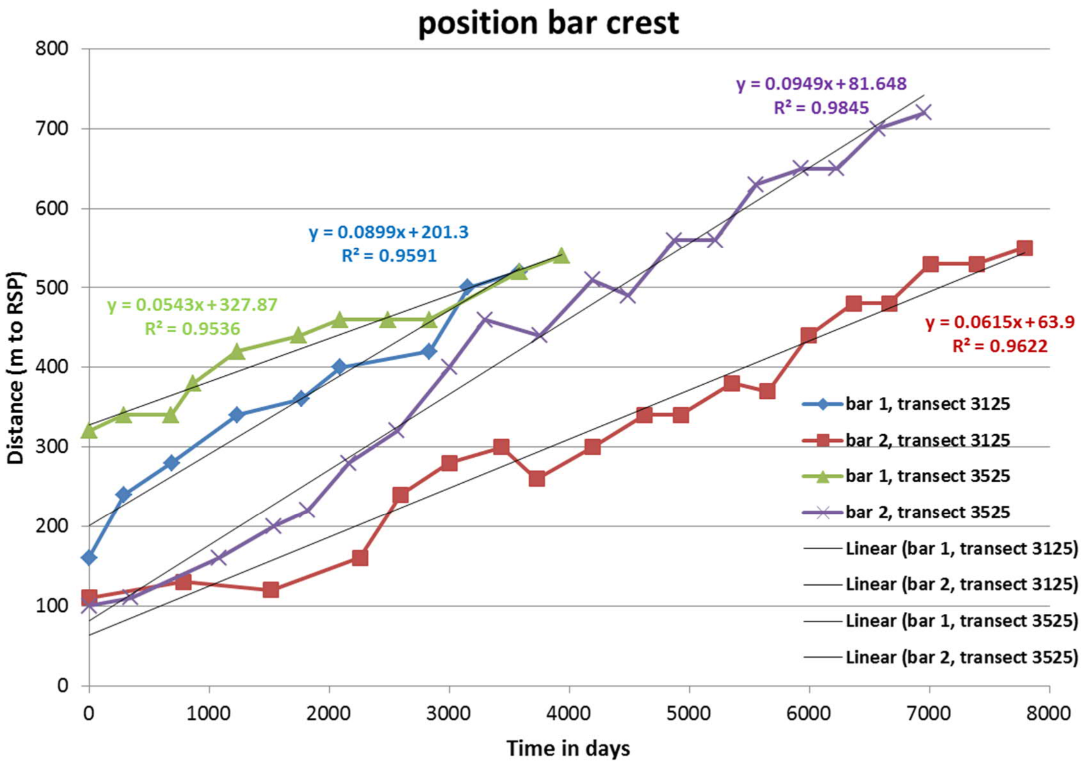

Figure 58: Linear regression analyses on change of bar crest position in time for four randomly chosen bars

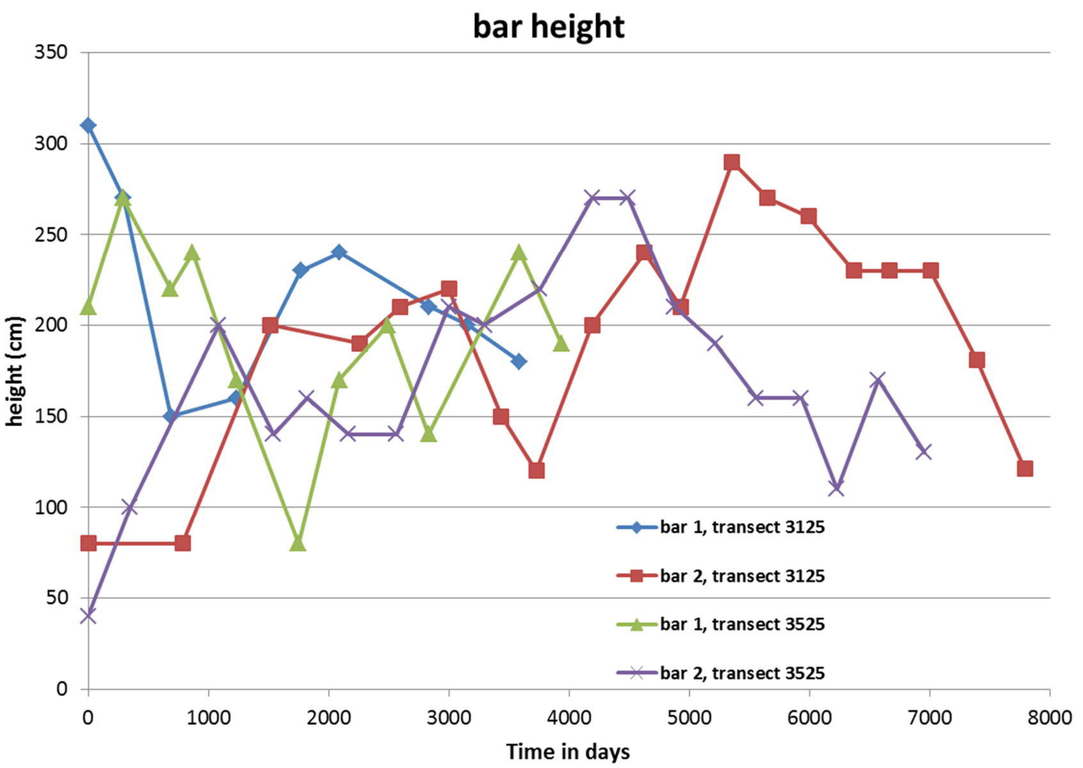

Figure 59: Change of bar height in time for randomly chosen bars

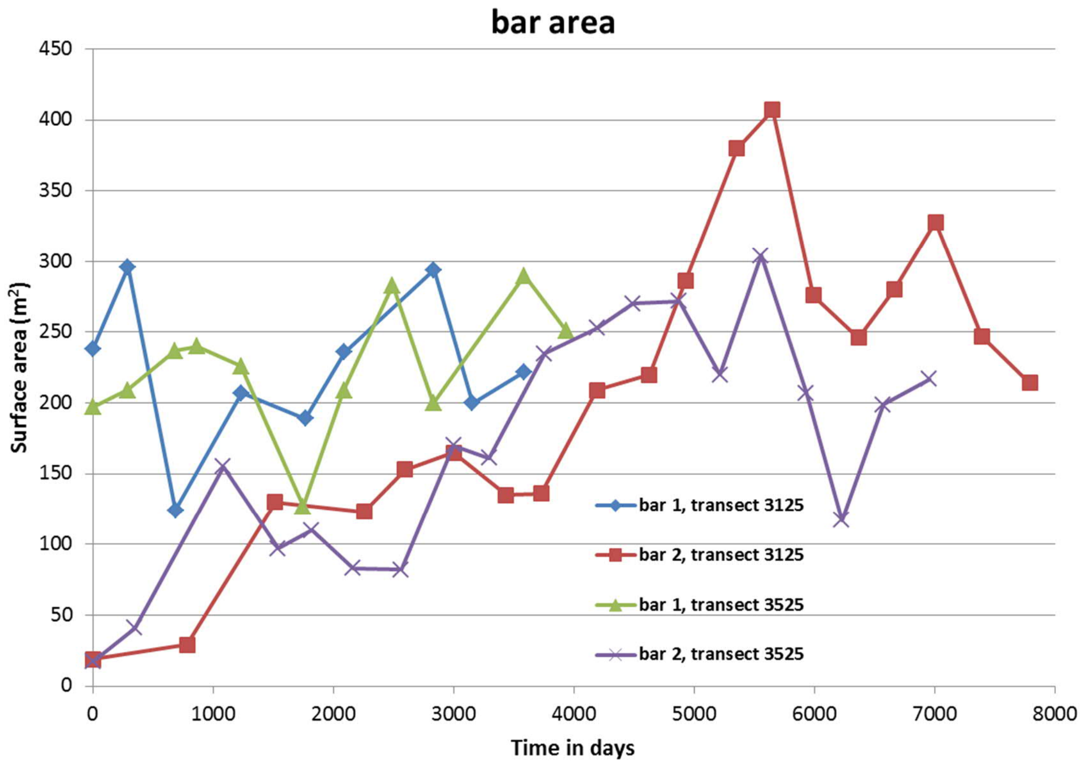

Figure 60: Change of surface area in time for a randomly chosen bars

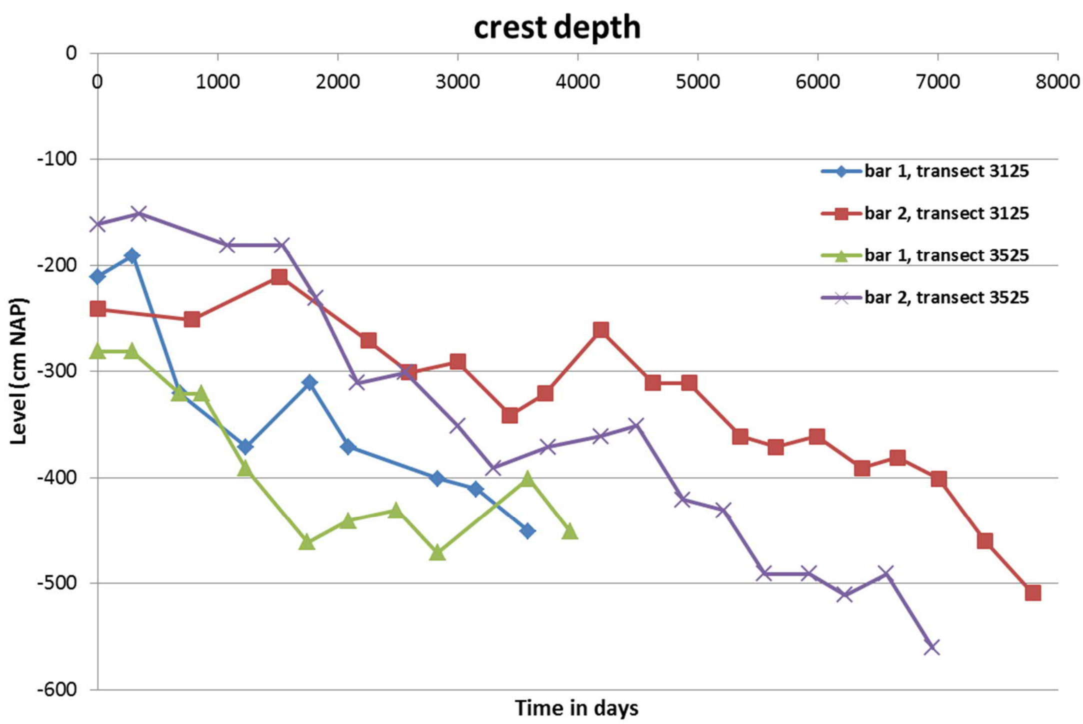

Figure 61: Change of crest depth in time for a randomly chosen bars

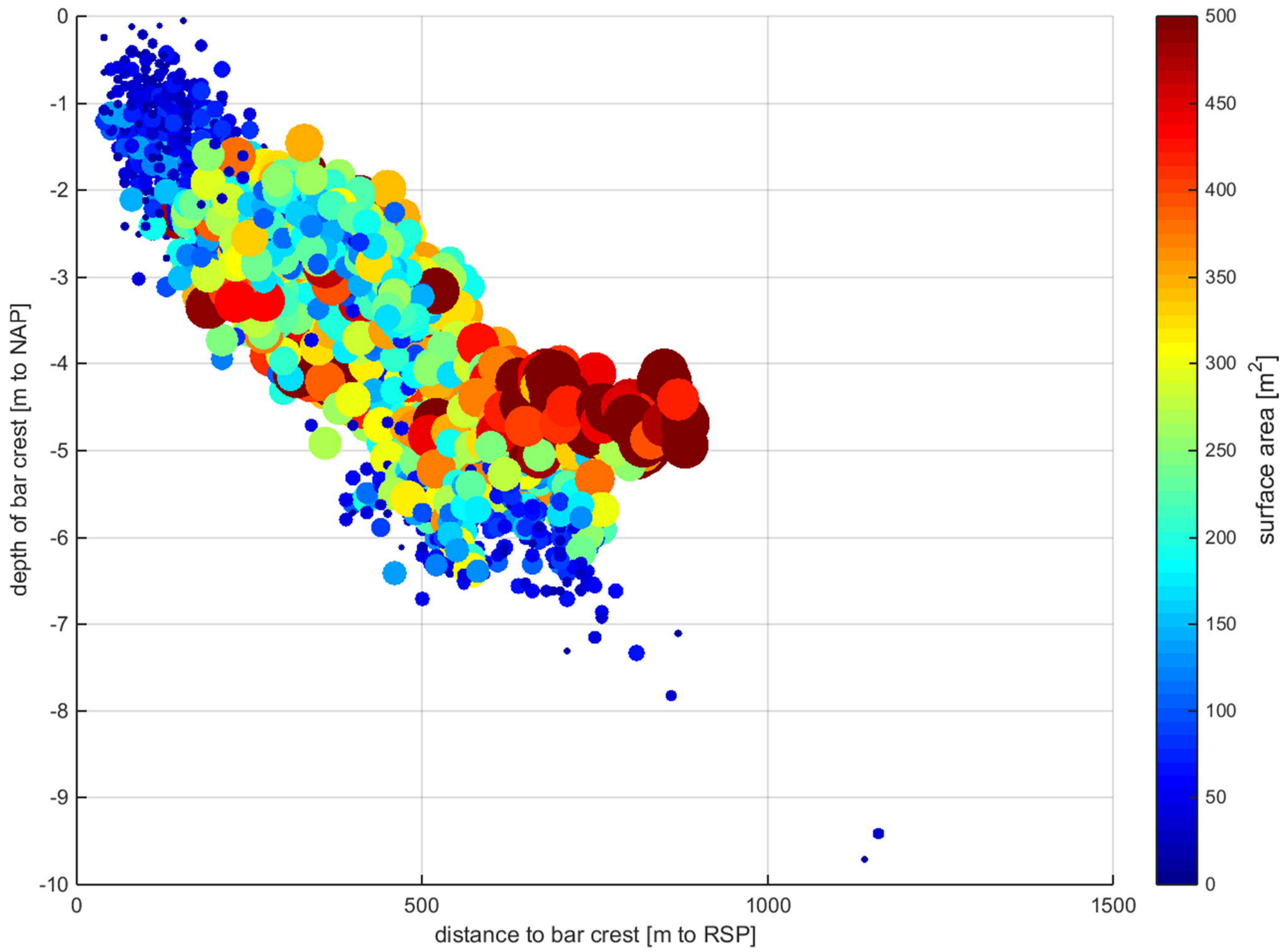

Figure 62: Relation between horizontal distance to bar crest and depth of the bar crest, for each bar in all measured years. Colours and circle-size correspond with surface area of the bar (m^2)

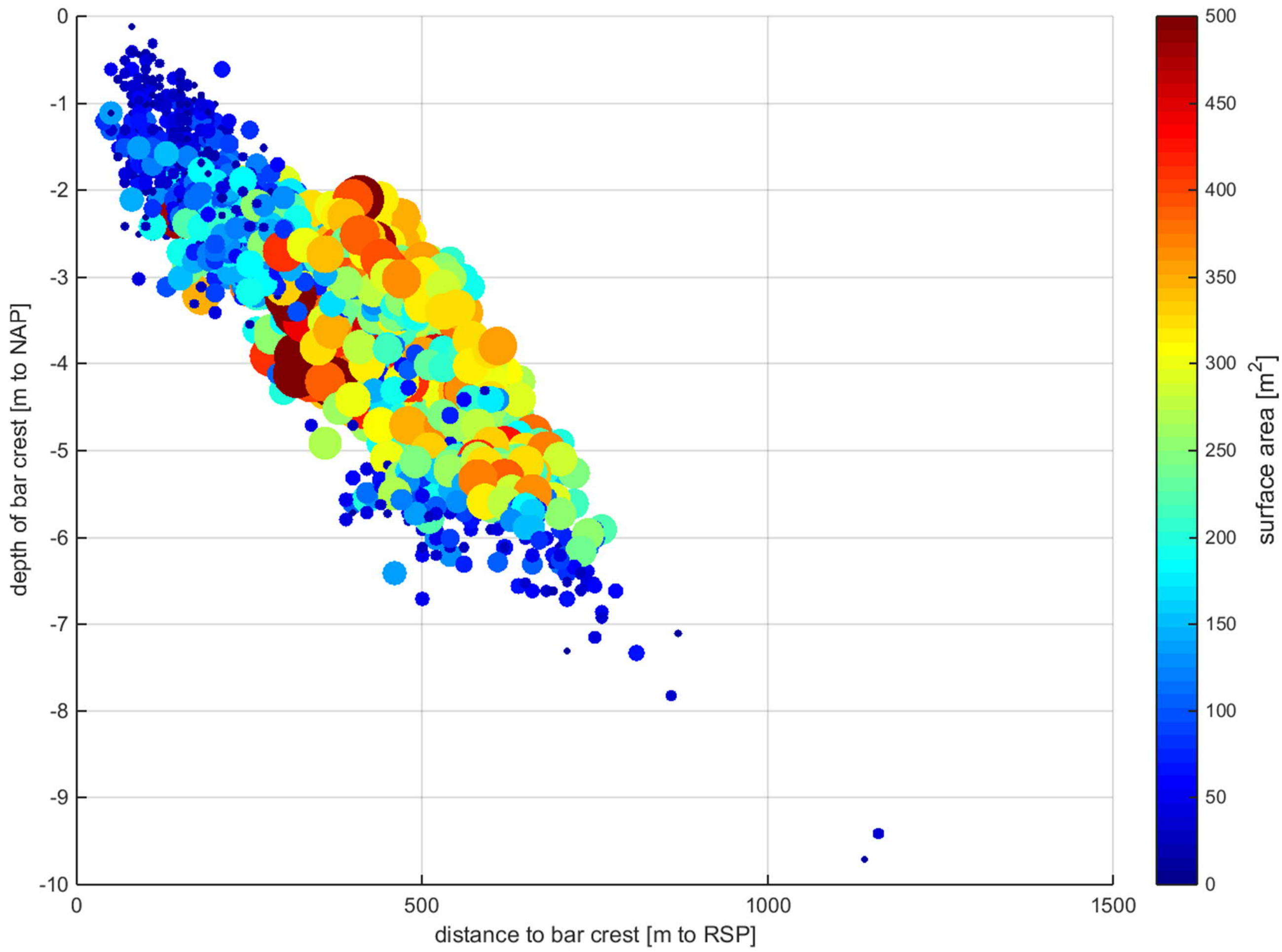

Figure 63: Relation between horizontal distance to bar crest and depth of the bar crest, for each bar in the years before the start of the shoreface nourishments (2000). Colours and circle-size correspond with surface area of the bar (m^2)

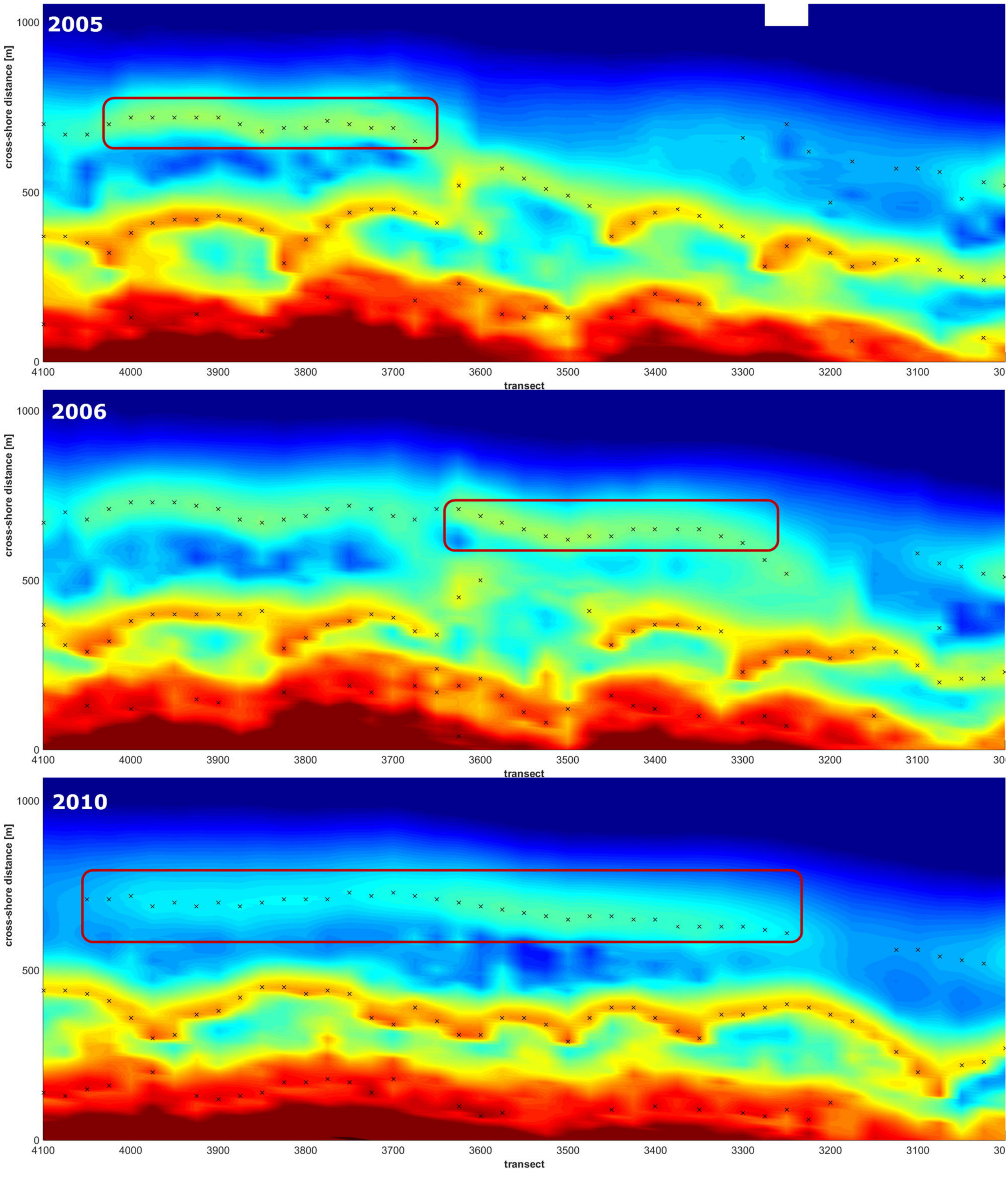

Figure 64: Bathymetry plot based on transect data (not gridded data) measured in 2005, 2006 and 2010 with the detected bar crest position indicated with crosses. The indicted areas show the shoreface nourishments of 2004 (top) and 2005 (middle), and their remaining sediment in 2010 (bottom)

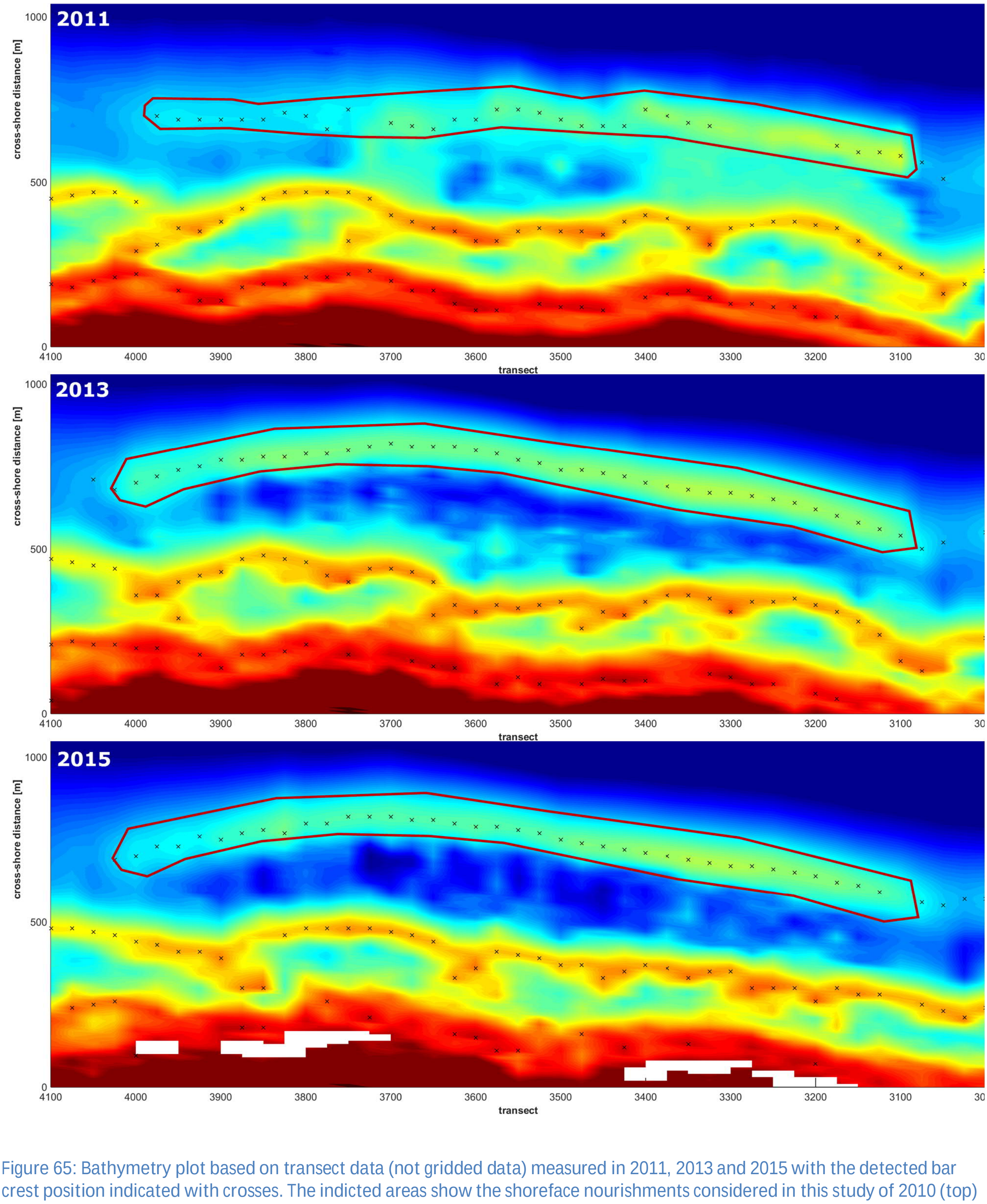

Figure 65: Bathymetry plot based on transect data (not gridded data) measured in 2011, 2013 and 2015 with the detected bar crest position indicated with crosses. The indicted areas show the shoreface nourishments considered in this study of 2010 (top) and 2011 (middle), and their remaining sediment in 2015 (bottom)

7.2.3 Volumes 2D

The calculated volumes are presented in two parts: the volume boxes below low water (1-7, Figure 66), and the volume boxes above low water (8-12, Figure 67), see Figure 11 for volume boxes. Summed volumes (absolute and relative) are shown for both the area below and above low water (Figure 68 and Figure 69). The average vertical change in bed level is also shown for the areas (Figure 70 and Figure 71). An overview of the boxes can be found in paragraph 4.2.3.

The volume of the shoreface nourishment is clearly visible in the increase of box 3. The majority of the volume was placed between 2010 and 2011, in the measurement of 2012 the last part is visible – although erosion likely took place in the period between finishing of the nourishment and the measurement. In the neighbouring boxes, box 1 (offshore) and box 6 (onshore) also part of the sediment ended up. After 2012 the volume in box 3 decreases very linearly, still having a volume of 0.5 million m^3 above the pre-nourishment volume (2010). The volume in the neighbouring boxes increased in this period, especially box 1 (offshore), box 6 (onshore) and box 5 (north-onshore). Box 2 (north) and 4 (south) slightly increased in volume, while box 7 (south-onshore) lost volume. Considering the different surface areas of the boxes, the changes in box 1, 2 and 4 are small (around 10 cm on average), while the other boxes showed more significant changes (up to 60 cm in box 5). The total volume increased with over 2.5 million m^3, about 85% of the design volume.

Of the two parts of the beach nourishments only the northern part (box 9) is visible in the volume changes. The volume of the southern part (box 11) increased between 2010 and 2015, but only with a fraction of the design-volume. The areas to the north (box 8) and in the centre (box 10) show a linear increase in volume between 2010 and 2015, while the area to the south (box 12) remained relatively stable with a small nett loss of sediment volume. The boxes at the beach have very similar surface areas, the average change in bed level therefore shows a similar graph to the volumes. Total volume reaches 0.5 million m^3 in 2011, about 55% of the design volume, and increases up to approximately 0.75 million m^3 in 2015, about 85% of the design volume.

The long term changes in the volumes are shown for three areas: shoreface (box 2-7), beach (box 8-12) and dune (box 13) for the years with high enough coverage of the measurements (Figure 72). For the shoreface the data coverage before 1985 was not high enough, therefore only the period with nourishments can be quantified. In this period the volume increases with 4 million m^3 net between 1985 and 2017. The shoreface nourishments are clearly visible by the rapid increase in volume around 2000, 2006 and 2010, after which the volume slowly decreases. The beach shows a decreasing trend between 1964 and 1990, losing approximately 1 million m^3. Between 1990 and 2017 the volume increased with approximately 3 million m^3. The dune area has good coverage from 1979, but has a large 'gap' in the measurements between 2000 and 2008. The general trend however is still clear, with a very stable volume until 1995 and a significant increase afterwards, gaining about 3.5 million m^3 by 2017.

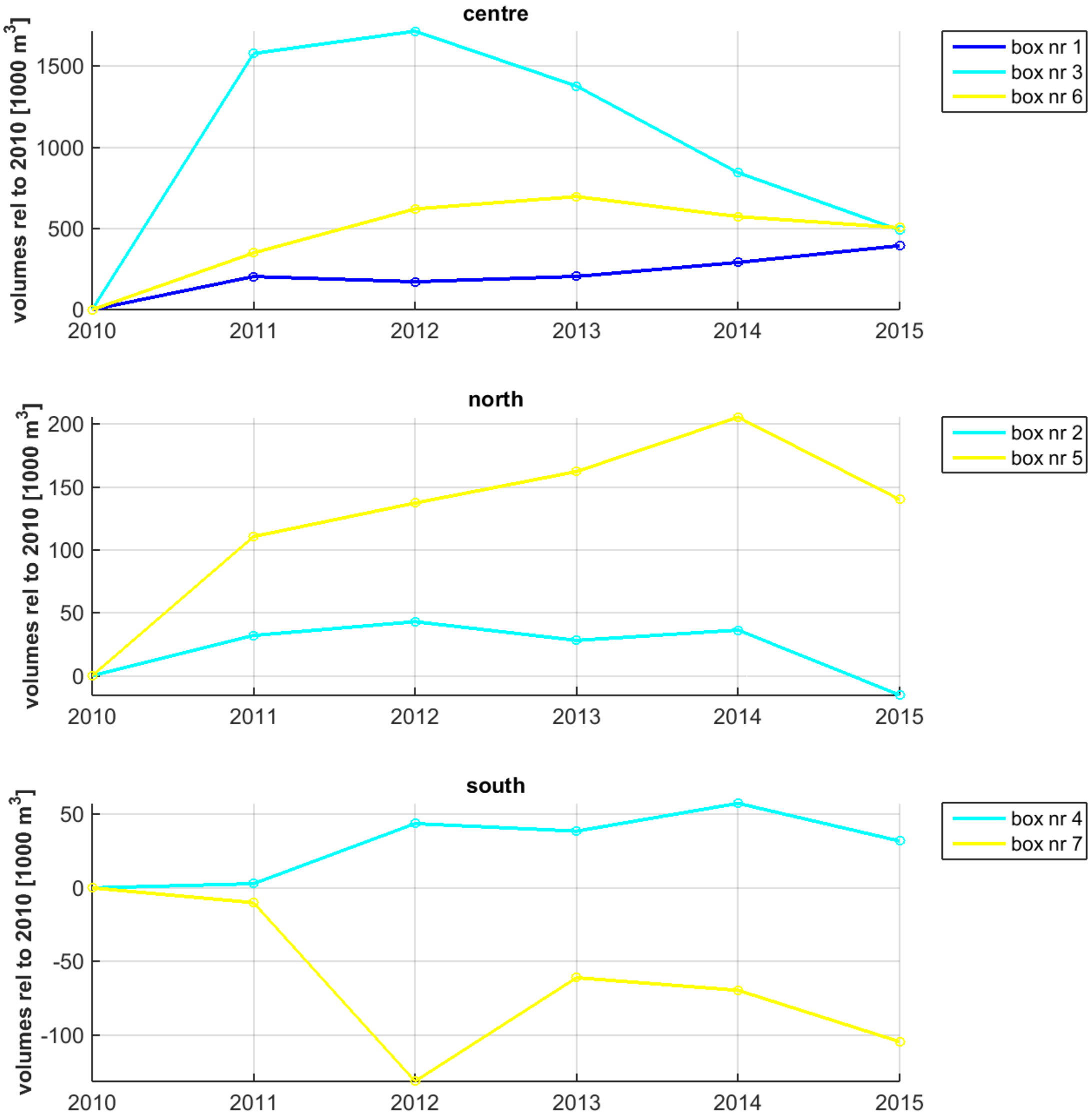

Figure 66: Volume development from one year before the nourishment until the last year before the next nourishment for the boxes below low water

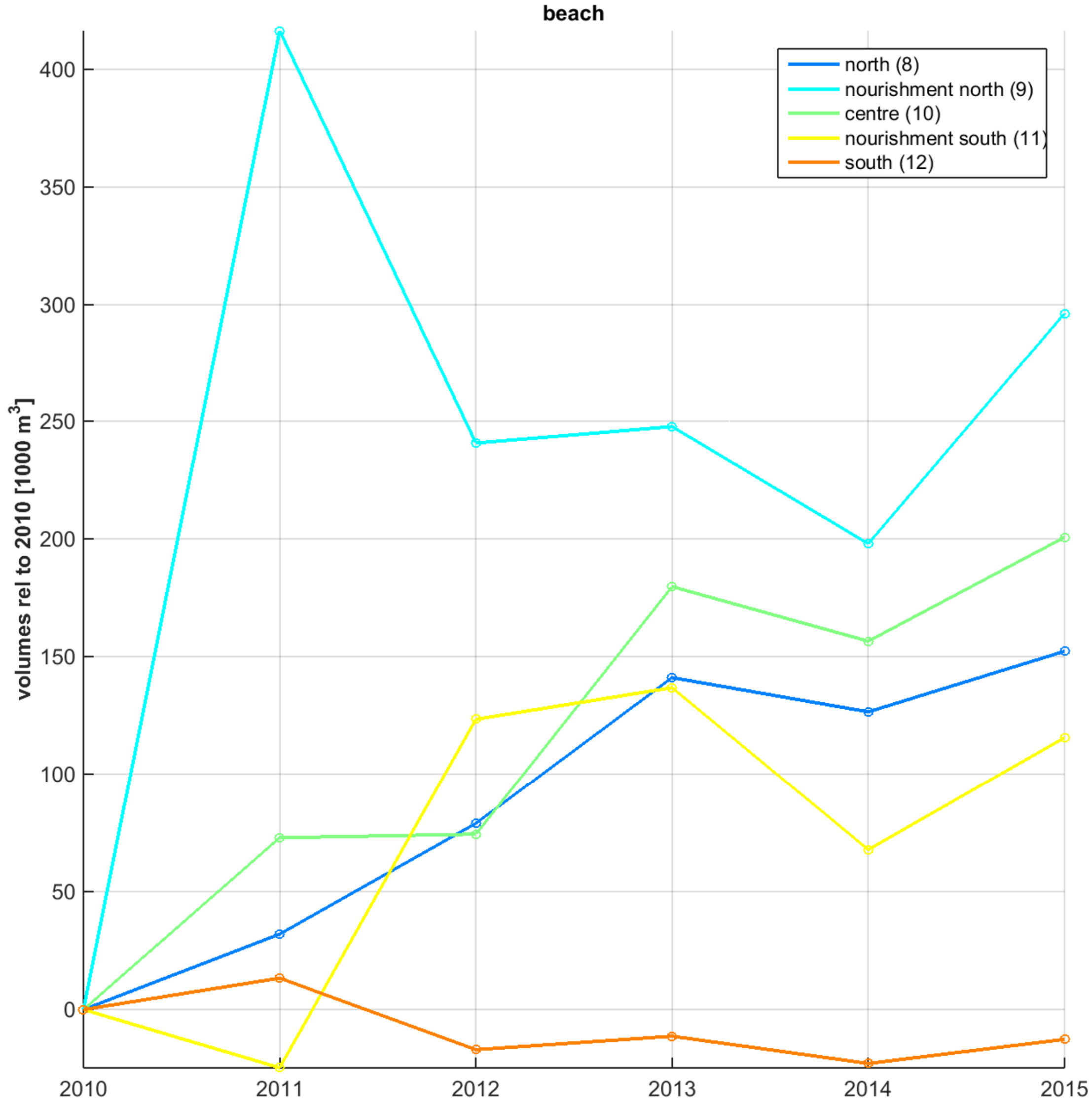

Figure 67: Volume development from one year before the nourishment until the last year before the next nourishment for the boxes above low water

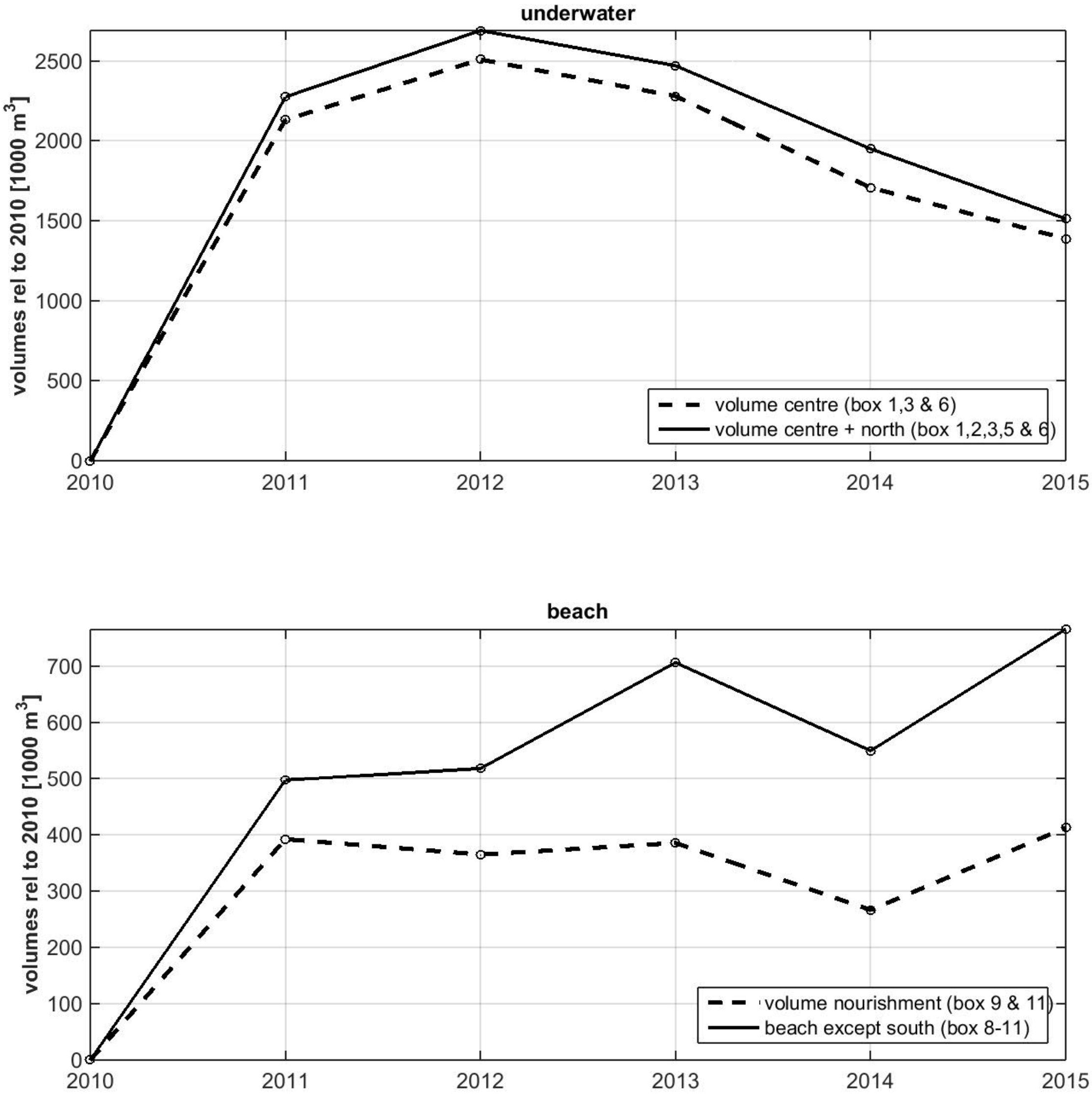

Figure 68: Volume development nourishment boxes and larger area for shoreface (upper) and beach (lower)

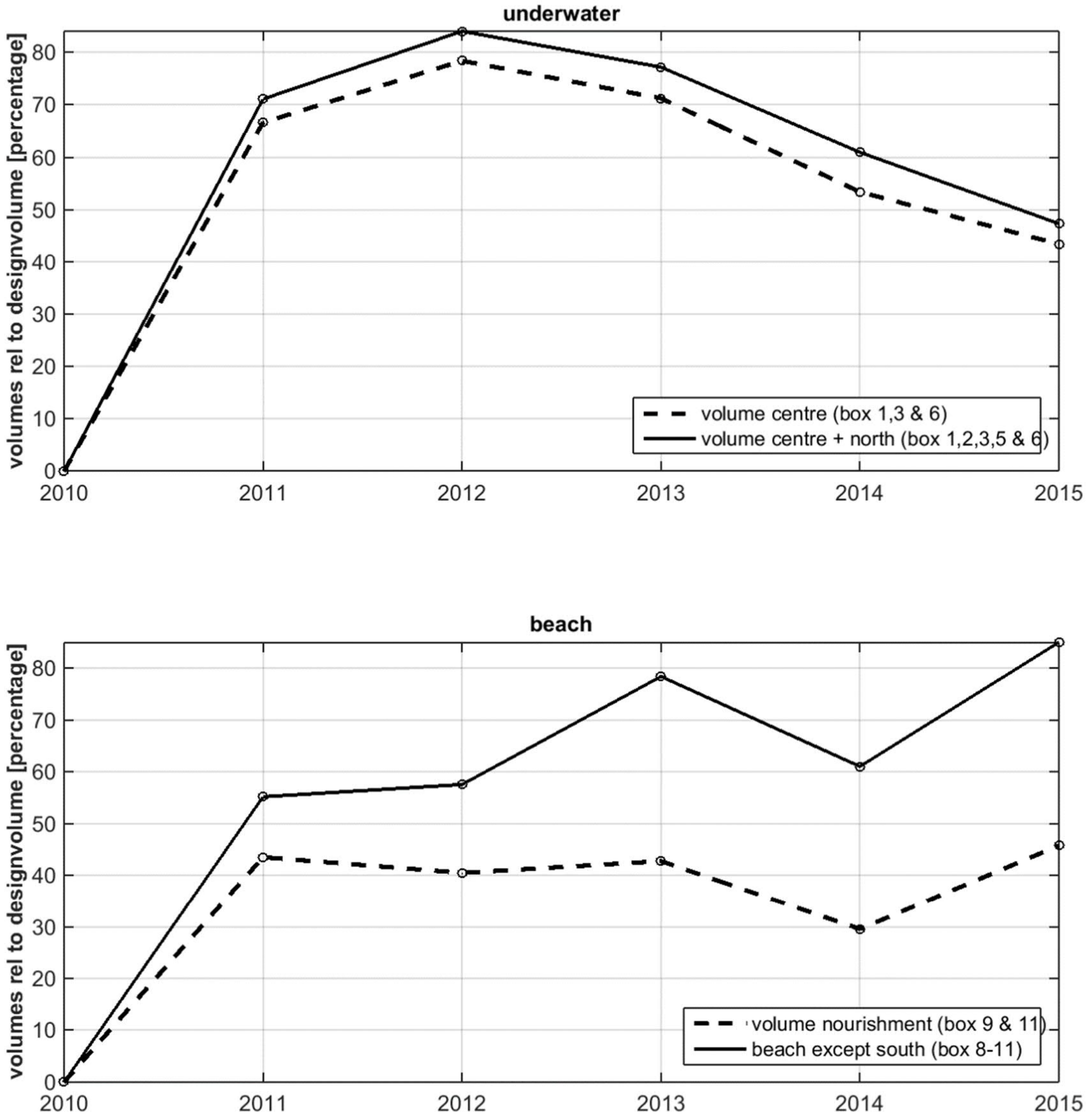

Figure 69: Volume development in percentages for sum of selected boxes relative to the design volume

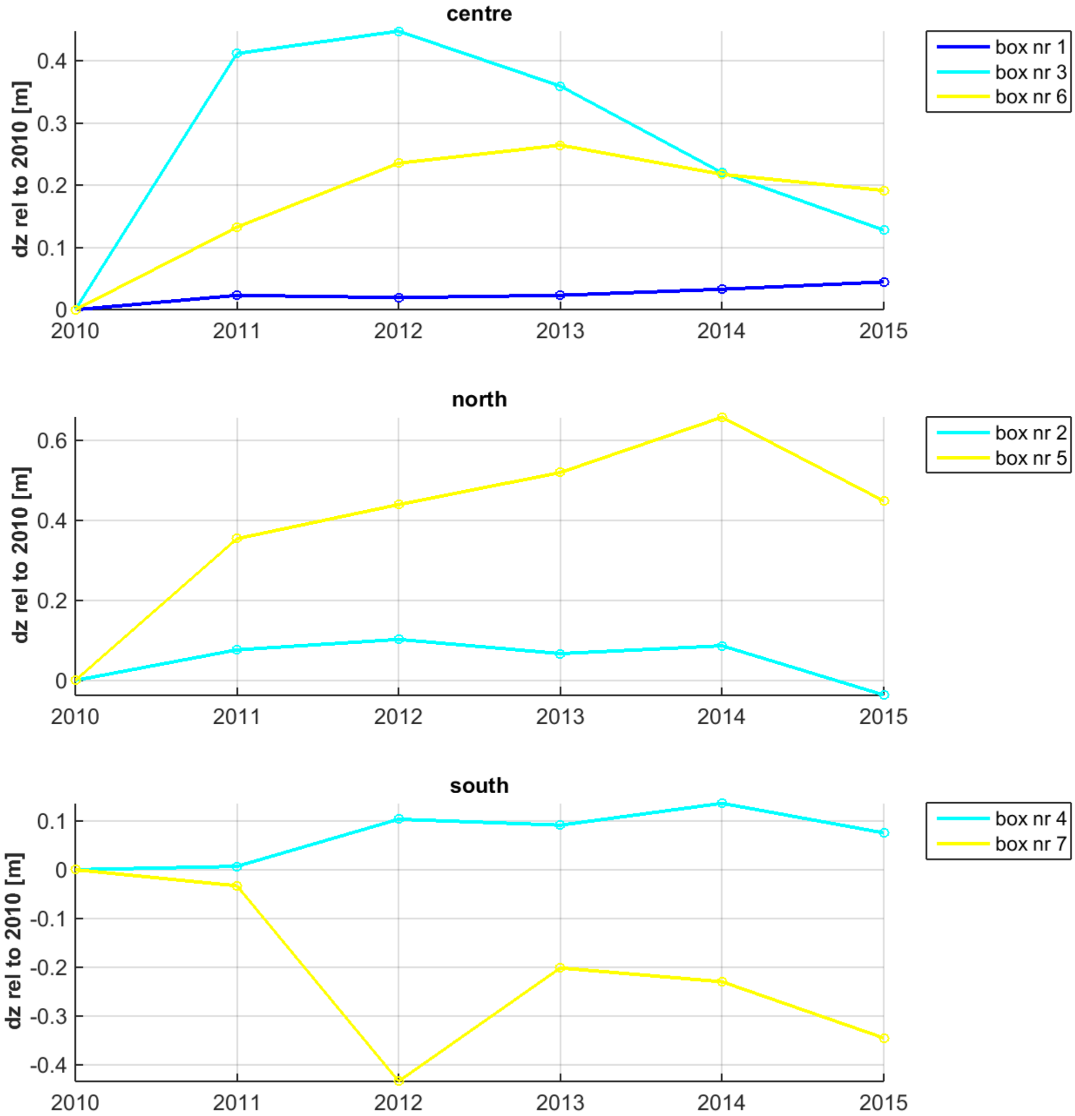

Figure 70: Change in average bed level for each polygon below low water

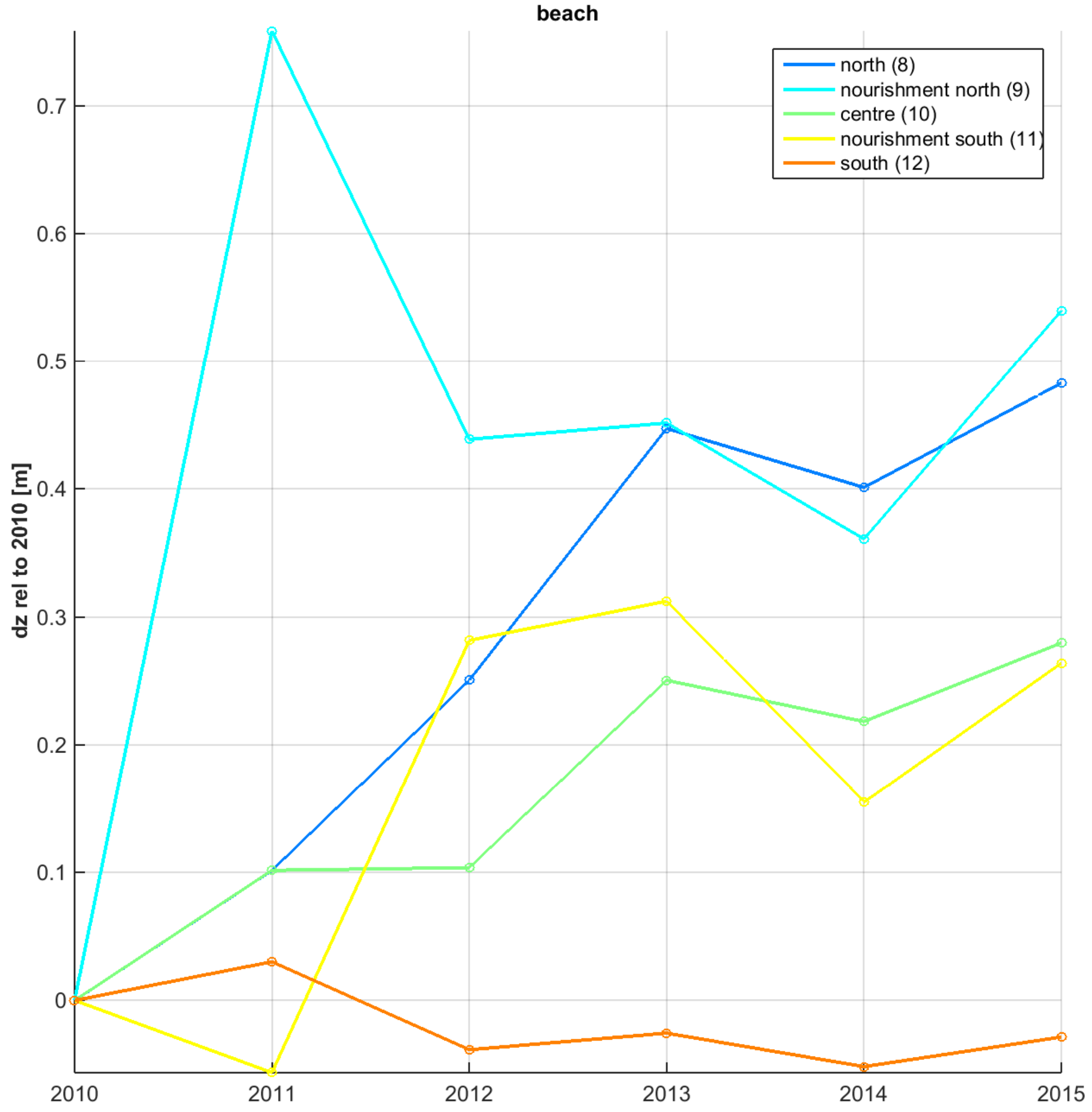

Figure 71: Change in average bed level for each polygon above low water

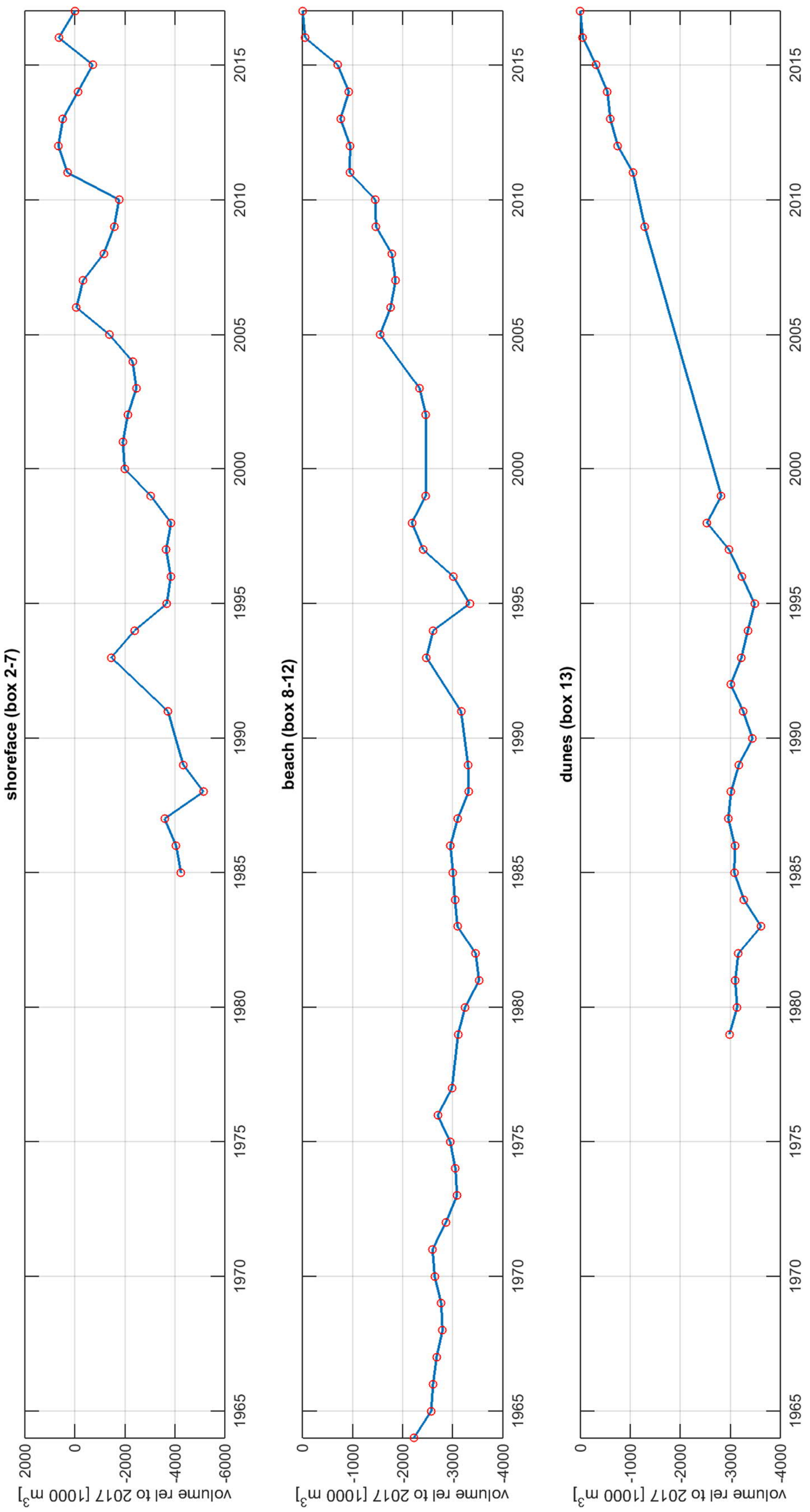

Figure 72: Long term volume development shoreface, beach and dune

8 Synthesis

8.1 Nourishments performance

The effect of the nourishments on the physical marks is mainly correlated to the beach nourishments, which are placed between mean low water line and the dune foot, so at the location of the indicators. The shoreface nourishments don't directly influence the indicators, but have a strong influence on the breaker bar morphology and the sediment volume in the breaker bar zone.

The beach nourishments seem to have an effect on the indicators dune foot, high water and low water, and not so clear on the mid dune and upper dune. On the long term changes in the indicators, however, the effect of the beach nourishments is clearest in the dune indicators (dune foot, mid dune level and upper dune level). In the mean high and mean low water also long term effects can be seen, but the natural fluctuations in these indicators are relatively large. We expect that the effect of the beach nourishments on the dune indicators might be small, but steady, and therefore shows a clearer pattern in the long term. The indicators around mean water, on the opposite, have a large and abrupt effect of the nourishments – since they are placed in this zone. The natural changes are also larger, since these indicators are in a very dynamic environment. Hence it takes longer before the effect of the nourishments on the long term becomes larger than the natural fluctuations.

The breaker bars in the study area show a natural offshore migration which is relatively slow, therefore only two undisturbed cycles can be observed in the measurements. Still, it is clear that the shoreface nourishments disturb the offshore migration. The smaller shoreface nourishments performed in 1999/2000 interrupts the offshore migration, but the effect on the morphology is of short duration. The larger shoreface nourishments that followed later, formed a new outer bar that remained at the same location for a long period. The surface area of these 'artificial' outer bar is large compared to the surface area of natural bars at the same position. The larger surface area is caused by a shallower position of the crest and a deeper trough. We think that the newly available sediment that was nourished makes it possible for a larger bar to form.

The changes in sediment volume suggest that the general transport direction is northward: adjacent areas north of the nourishments in the north gained sediment, while in the south there was erosion. Sediment from the shoreface nourishment is thought to feed the entire breaker bar zone by cross-shore transport. There is however no clear effect of the shoreface nourishment visible on the beach volume – or indicators – this would imply limited cross-shore transport from the breaker bar zone to the beach. However, it is likely that the shoreface nourishment has a positive effect on the beach, by 'shielding' effect and blocking the offshore migration of the inner bar, hence having a positive effect on the lifetime of the beach nourishments.

8.2 Strategic goals

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

9 Conclusions

From this study the following conclusions can be made:

- The effect of nourishment was most clear for the long term change in dune coastal state indicators (CSI). The mean high water, mean water and mean low water show larger natural fluctuations and therefore the trend is less clear;
- Sediment from the nourishments is transported northward, visible by the increasing volume on the adjacent area;
- The volume of the first dune was stable and is growing since start of nourishments: the nourishments contribute to more landward sediment transport;
- On long term, the repeated nourishments increased the volume, although directly after a nourishment the (local) erosion rate is increased;
- Lifetime of the shoreface nourishment is about four years, for the beach nourishment this could not be determined since the volume increased;
- At the location of the shoreface nourishment 71% of the sediment volume is lost after three years, while in the larger area around the nourishment only 44% is lost;
- The sediment from the shoreface nourishment is transported to its direct surroundings;

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