

National analyses of nourishments;

*Coastal state indicators and driving forces for Domburg,
the Netherlands*

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Colophon

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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 (3) a single coastal laboratory is discussed. The Dutch 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 nourishment 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 continuously eroding, they still play a major role in the Dutch coastal protection system. Due to human interventions, like sand nourishments, the erosion of the coast is compensated. On average 12 million m³ 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 Domburg. It is situated in the southwestern part of the Netherlands at the former island Walcheren. The area is characterized by estuaries with large tidal influence and is strongly affected by coastal protection works (the ‘Delta works’).

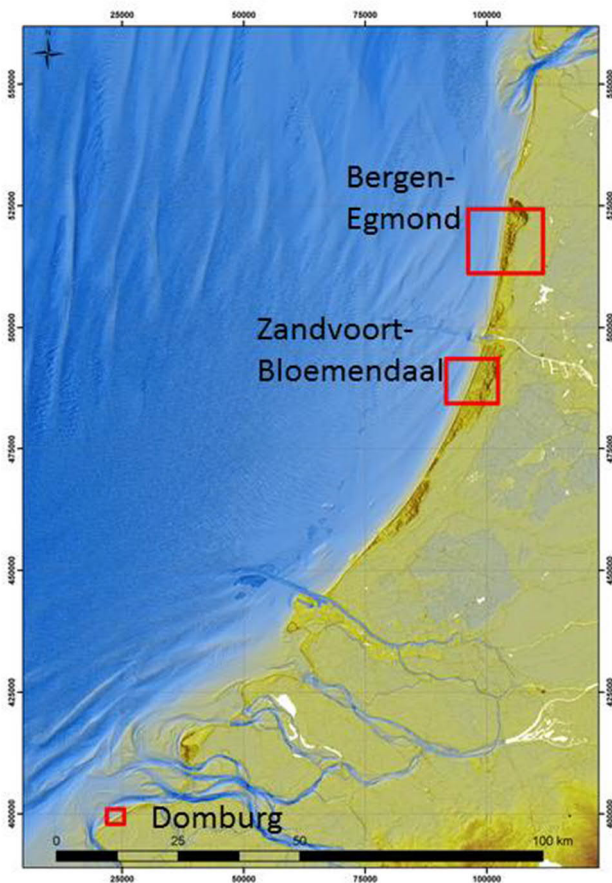


Figure 1: An overview map of the coast laboratories in the Netherlands

1.2 Objectives

In this study the performance of the beach nourishment of 2008 at Domburg is analysed. The main objective of this study is to obtain key information of the nourishment behaviour in a 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 of Domburg is located in the southwestern part of the Netherlands situated near the city Domburg (Figure 2). It is enclosed by the Eastern Scheldt estuary to the North and by the Western Scheldt to the South. The area is characterised by morphological features typical for such an environment, like ebb tidal deltas and tidal channels. The behaviour of these features strongly influences the management and maintenance of the coast. The area are strongly influenced by the waves, (tidal) currents, human interference and interactions between these processes.

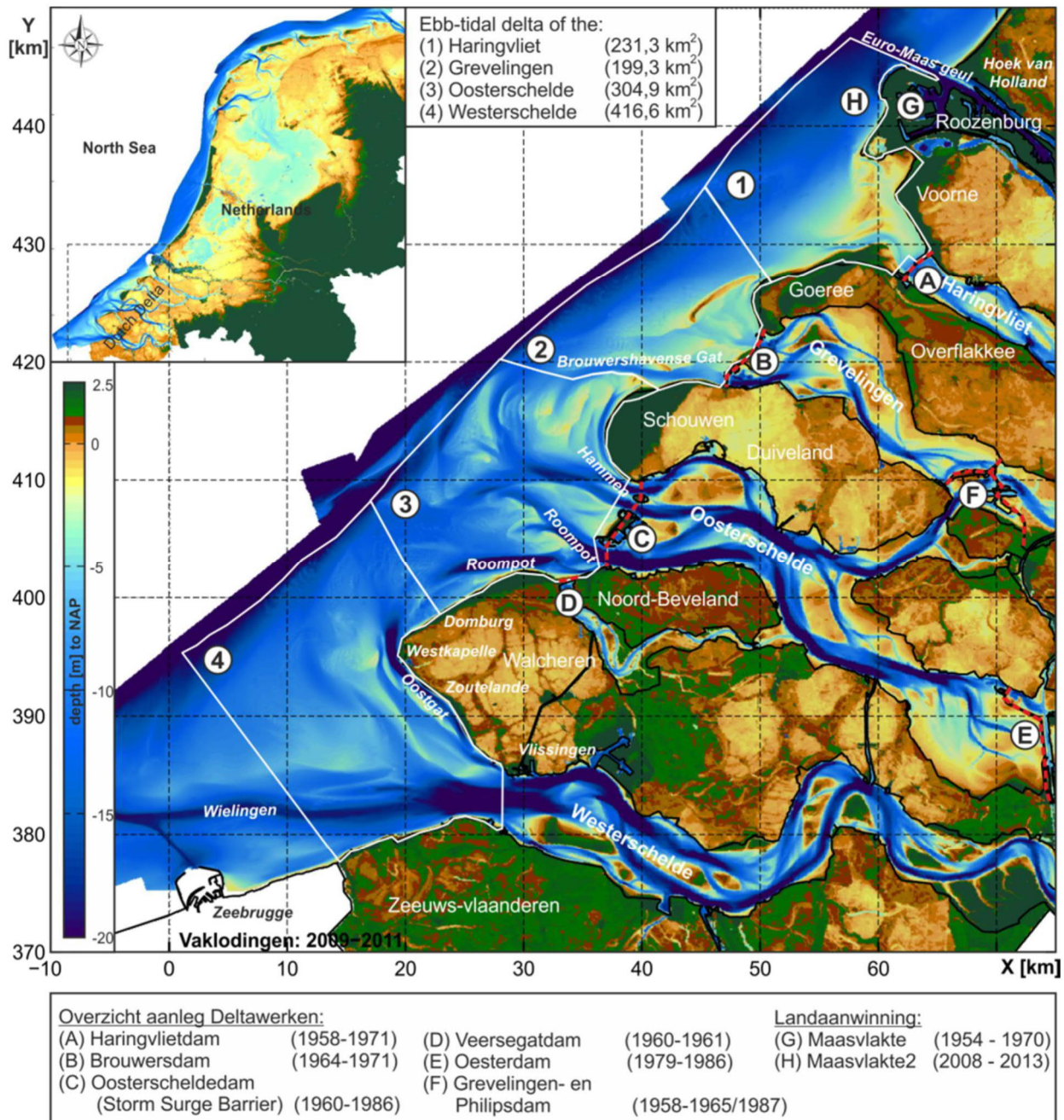


Figure 2: An overview of the coastal area near Domburg. The numbers and white lines indicate the ebb-tidal deltas. The dotted red lines and the letters indicate the major closer dams of the Delta Works. Reprint from (Elias , Spek, & Lazar , 2016)

To indicate the dynamics in the system the morphological changes are shown in Figure 3. The letters indicate several large morphological changes:

- A. Sedimentation North of the Rassen.
- B. The Oostgat is expending northward.
- C. The Roompot is expending westward.
- D. Sedimentation of the Roompot.
- E. Erosion in front of the Eastern Scheldt storm surge barrier.
- F. Deepening of the Oostgat.
- G. Narrowing of the Bankje van Zouteland
- H. Merging of de Geul van de Walvischstaart and Deurloo-West
- I. A sandbar arises between Rassen and Nolleplaat.
- J. Sedimentation of the sandbar at Oostgat/Sardijngeul
- K. Sedimentation eastward of the Nolleplaat
- L. Dumping ground for dredged sediment
- M. Deepening of the Wielingen due to dredging works.
- N. Sedimentation of the sandbar at the Veerse Gatdam and deepening of the Schaar van Onrust.

The figure suggests that the erosion of the beaches is limited and in several locations the dunes are growing. It should be taken into account that results from all the nourishment executed in this area are being displayed in the figure. Without these nourishments the coast would have been eroded significantly.

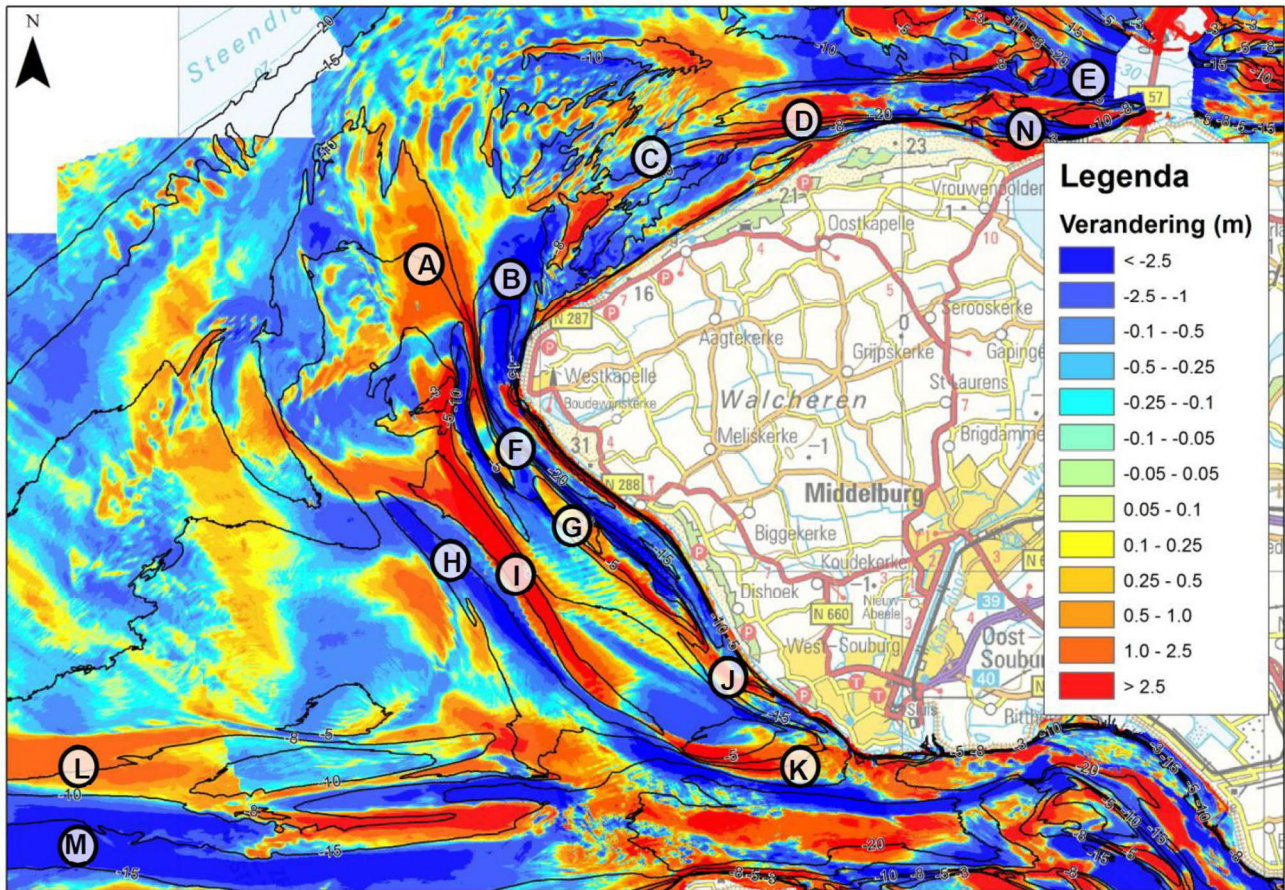


Figure 3: Map of the difference in bed level 1964 – 2010/2011 combined with the contours of 2010/2011. Several important morphological changes are indicated by the letter A till N. East of "L" an abrupt jump can be observed. This jump results from a difference in grid resolution between datasets and has no physical meaning. Reprint from (Vermaas & Bruens, 2012).

A considerable human intervention in the area is the construction of the Delta Works (1954-1997). After a catastrophic storm in February 1953 the Dutch ministry commissioned the construction of major floodgates and storm surge barriers in this the part of the Netherlands (see Figure 2). Several estuaries were closed off and only the Western Scheldt estuary stayed completely open. In the Eastern Scheldt, a storm surge barrier was built. Although the water can still flow in and out of this estuary, due to this barrier the tidal prism is reduced by 35%.

The construction of the Delta Works has a big impact on the system. Due to the (partly) closure of the estuaries the ebb-tidal deltas started to erode. Furthermore, the tidal current perpendicular to the coast strongly reduced. Also, erosion started in front of the Eastern Scheldt storm surge barrier (see Figure 3 location E). The dominant sediment transport direction remained the same, from South to North.

3 Nourishment description

3.1 Coastal infrastructure and earlier nourishments

At and in the vicinity of the nourishment location several coastal defence constructions are present. East of the location a former sea arm is closed off by a dam and the Eastern Scheldt storm surge barrier is located to the North. To the west, at the town Westkapelle, a sea dike is constructed. At the nourishment location itself wooden poles in rows perpendicular to the shore are present on the beach. An overview of the locations is given in Figure 4, images can be found in Figure 5.

Earlier nourishments at and around the nourishment location are shown in Table 1. At this location mainly beach nourishments were applied and in the 1980's also some dune reinforcements.

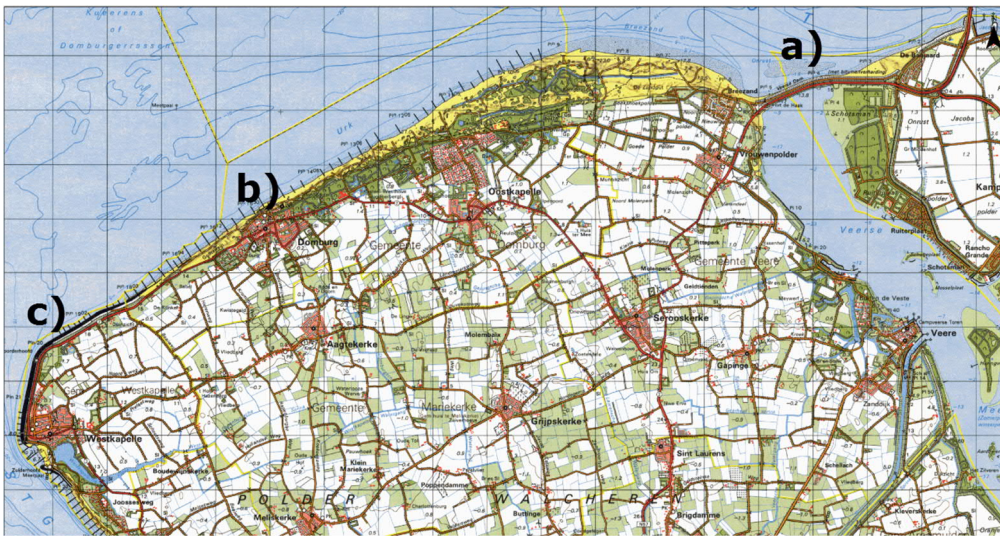


Figure 4: Overview map with coastal infrastructure: a) Veerse Gatdam with Eastern Scheldt storm surge barrier in the background, b) pole rows on the beach (black lines perpendicular to the coast), c) Westkapelse Seadijk.



Figure 5: Coastal infrastructure around the nourishment location: a) Veerse Gatdam with Eastern Scheldt storm surge barrier in the background, b) pole rows on the beach, c) Westkapelse Seadijk. Source: <http://beeldbank.rws.nl/>.

Table 1: Overview of nourishments around the nourishment location. *: studied nourishment

Start	End	Begin transect	End transect	Length (m)	Type	Volume (m3)
1/1986	12/1986	17.95	23	5050	dike	1,300,000
9/1986	9/1986	16.48	17.35	875	dune	25,000
9/1986	9/1986	16.48	17.35	875	dune	200,000
4/1989	5/1989	14.81	15.83	1020	dune	9,272
4/1989	5/1989	14.81	15.83	1020	beach	201,258
1/1990	12/1990	14.81	15.83	1020	beach-dune	245,517
1/1992	12/1992	12.8	17.42	4620	beach	637,000
1/1993	4/1993	14.3	15.85	1550	beach	318,000
1/1994	12/1994	14.33	16.05	1720	beach	453,000
1/1995	12/1995	16.86	18.89	2030	beach	550,000
1/2000	4/2000	14.06	18.83	4770	beach	886,127
4/2004	11/2004	14.65	18.85	4200	beach	777,565
5/2008	7/2008	14.06	16.33	2265	beach*	369,565
6/2008	11/2008	17.55	19.7	2150	shoreface	1,392,722
11/2008	12/2008	16.53	17.35	820	beach	110,435
11/2008	12/2008	17.55	19.7	2150	beach	1,022,609
2/2012	5/2012	14.89	16.32	1430	beach	250,399
11/2014	12/2014	14.8	16.32	1520	beach	350,000

1/2015	2/2015	17.55	19.48	1930	beach	600,000
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3.2 Studied nourishment

3.2.1 Beach profile

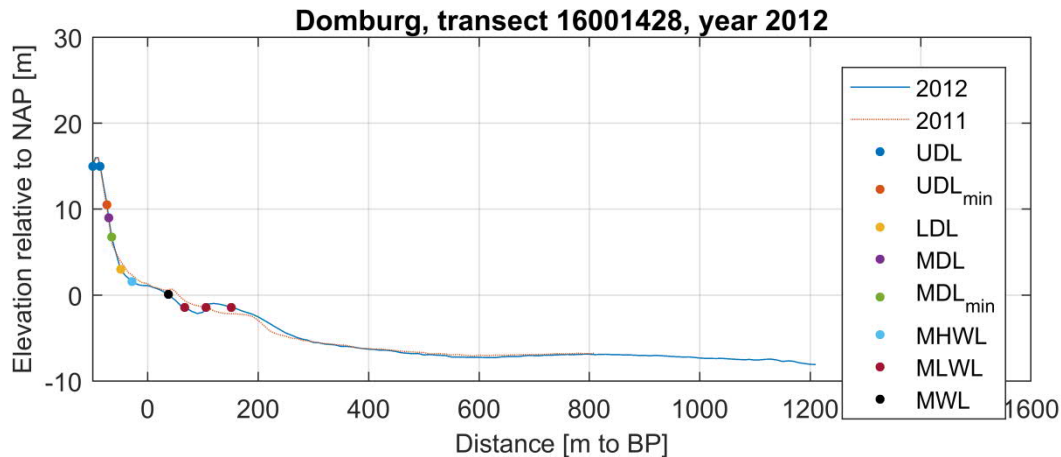


Figure 6: An example of coastal profile and the levels described as in 4.2.1. UDLmin means the Upper Dune Level minimum and the MDLmin the Mid Dune Level minimum.

A typical beach profile at Domburg is visualised in Figure 6, including the levels of the coastal state indicators (CSI's) for this lab (see paragraph 4.2.1). The values of the CSI's are given in Table 2. The profiles shows the first dune, a relatively small beach and a gently sloping shoreface without breaker bars.

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

Domburg	
Vertical location (with respect to NAP)	
Minimum Upper dune level (UDLmin)	10.48 m
Minimum Middle dune level (MDLmin)	6.74 m
Dune toe level (DF)	3.00 m
MHWL	1.61 m
MWL	0.09 m
MLWL	-1.44 m

3.2.2 Nourishment motivation

To prevent the Netherlands from flooding and keep up coastal functions the government is forced 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 Domburg, a sand nourishment is placed every 4-5 years. The nourishment investigated in this study is one of these regular nourishments.

Several stakeholders are involved in the nourishment procedure. First, the Dutch government represented by Rijkswaterstaat (executing agency of the Ministry of Infrastructure and Water Management), second, a dredging company to carry out nourishment. 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

The nourishment at Domburg consisted of a beach nourishment where sand was placed directly on the beach. This is typical for nourishments at Domburg. The nourishment is placed attached to the dunes and is designed at a height of NAP +4m. Like frequently done, a slope of 1/30 is applied resulting in landward position of the nourishment at a vertical position of NAP -1.9 m, see Figure 7. Other details of the nourishment are given in Table 3.

The period of interest is 5 years before and 5 years after the nourishment, in this case, from 2004 till 2012. The area of interest is focussed on 4 transects north and 4 years south of the nourished transects. It results in a scope from transect 13.26 till 17.14.

Table 3: The properties of the nourishment and the different time periods of interest.

Nourishment properties	
Transects	14.06 – 16.33
Type	Beach
Volume	369565 m ³
Length	2265 m
Volume	160 m ³ /m
Slope	1/30
Start nourishment vertical level	4.0 m
End nourishment vertical level	-1.9 m
Scope	Transect 13.26 – 17.14
Time periods of interest	
Year of nourishment	2008
Prior to nourishment	2003 till 2007
After nourishment	2008 till 2012
Begin construction (mm-yyyy)	05-2008
Finished construction (mm-yyyy)	07-2008

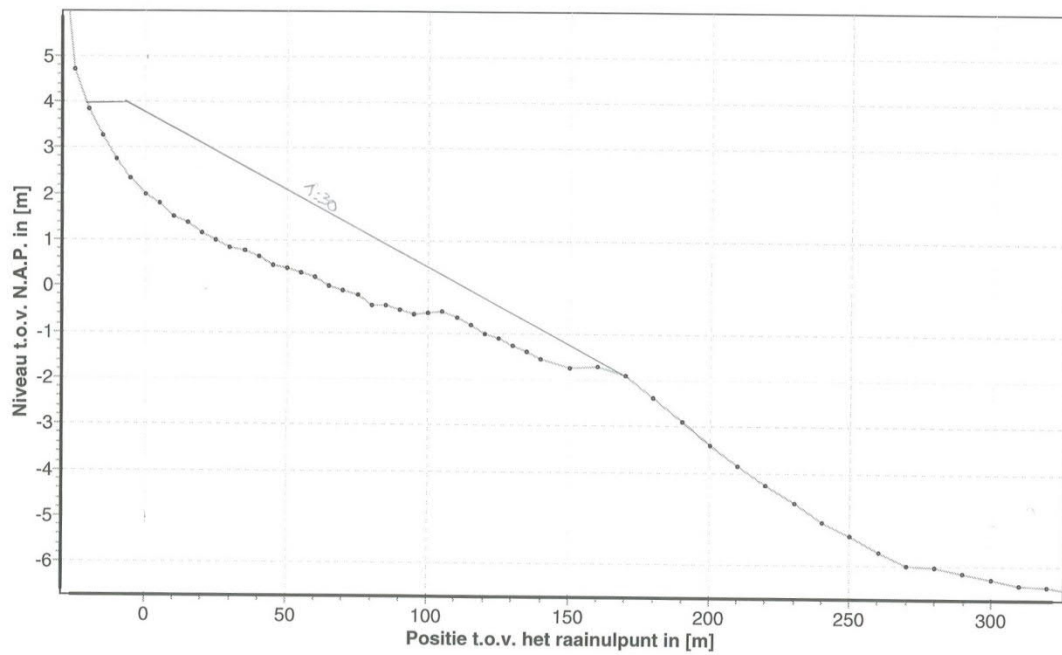


Figure 7: The design of the nourishment at Domburg for transects 15.30. The design was based on the bathymetry of 2006.

The actual placement of the nourishment is very close to its design, see Figure 8 and Figure 9. During the measurement of 2008 only the central part of the nourishment was placed, approximately between transect 1509 and 1571. The other parts are visible in the measurement of 2009, as can be seen in Figure 9 and Figure 10.



Figure 8: Placement of nourishment in transect 1550

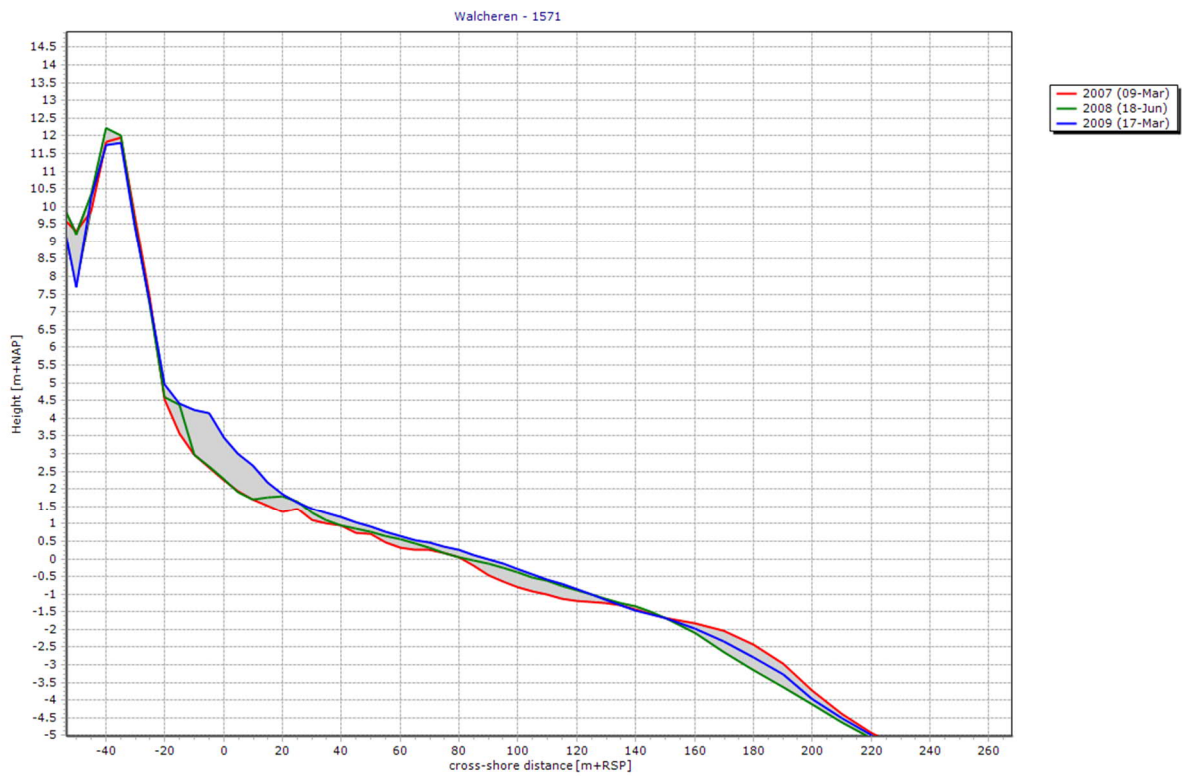


Figure 9: Placement of nourishment in transect 1571

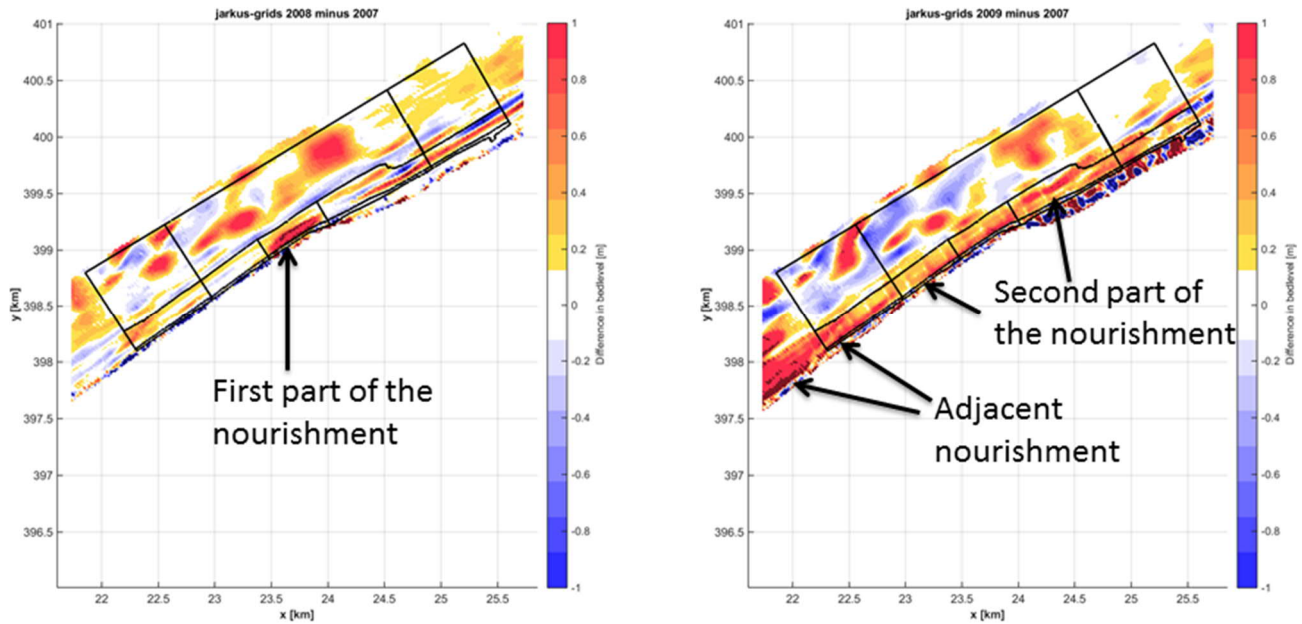


Figure 10: Placement of nourishment visible on difference maps 2008-2007 (left) and 2009-2007 (right)

In the central part the sediment volume increased between 2007 and 2008 with ca. 80.000 m³, in the entire nourished area with ca. 100.000 m³. In 2009 the entire nourished area gained ca. 180.000 m³ of sediment. This is much lower than the designed volume of ca. 370.000 m³, probably due to the long period between placement and, mainly, following measurement (2009) for the side parts, during which part of the nourished sediment already eroded.

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 hydrodynamic measurements. The different datasets are discussed in this chapter.

4.1.1 Transect data

Since 1965 the Dutch coast is yearly measured along cross-shore transects: the JARKUS transects, see Figure 11. These transects are located over the entire Dutch coast and are 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.



Figure 11: A top view of Walcheren. The blue lines indicate transect 540 till 1883. The black circle marks the transects which are considered in this report. Reprint from (Masterberg, Nederhoff, Valk, & Maarse, 2017)

4.1.2 Hydrodynamic data

In front of the Dutch coast a considerable number of measuring locations are available, see Figure 12. 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. For Domburg, several locations are combined to obtain sufficient data. The combination procedure is explained in Chapter 5.

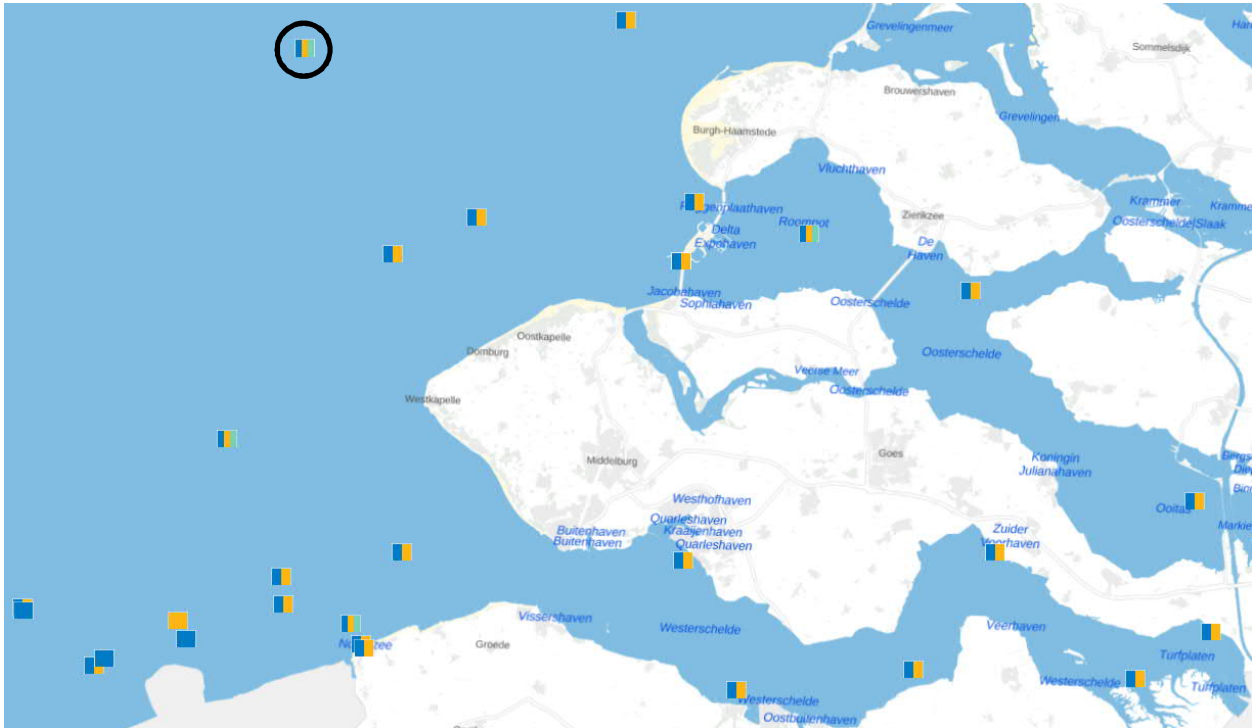


Figure 12: The measuring location for the wave height located in the area of Domburg. The vertical stripes of the symbols indicate which bulk wave condition is available at a station. The black circle marks the Europlatform; the station which is analysed in this report.

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 Building with Nature 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 13 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.

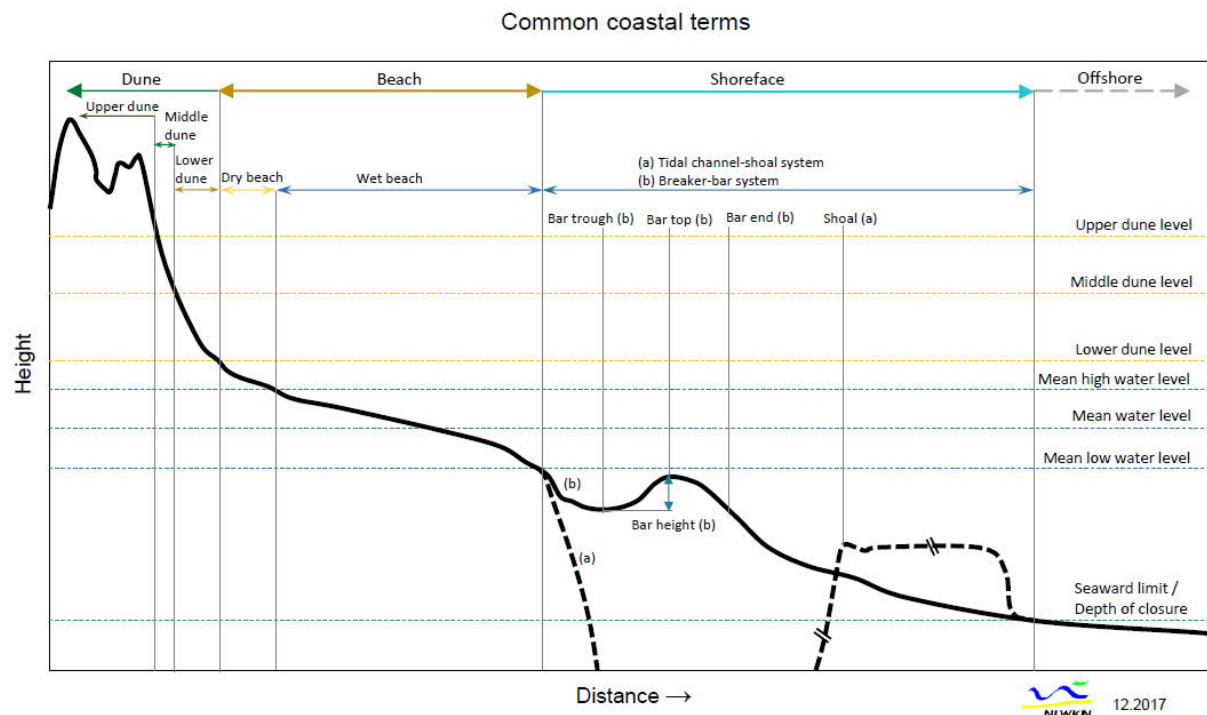


Figure 13: General definition/terminology coastal profile used. On the vertical axis various levels in the profile are shown. The horizontal axis shows different zones in the profile. Source: Simon Hillmann (NLWKN)

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.
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 (eg 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 14 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 over 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.

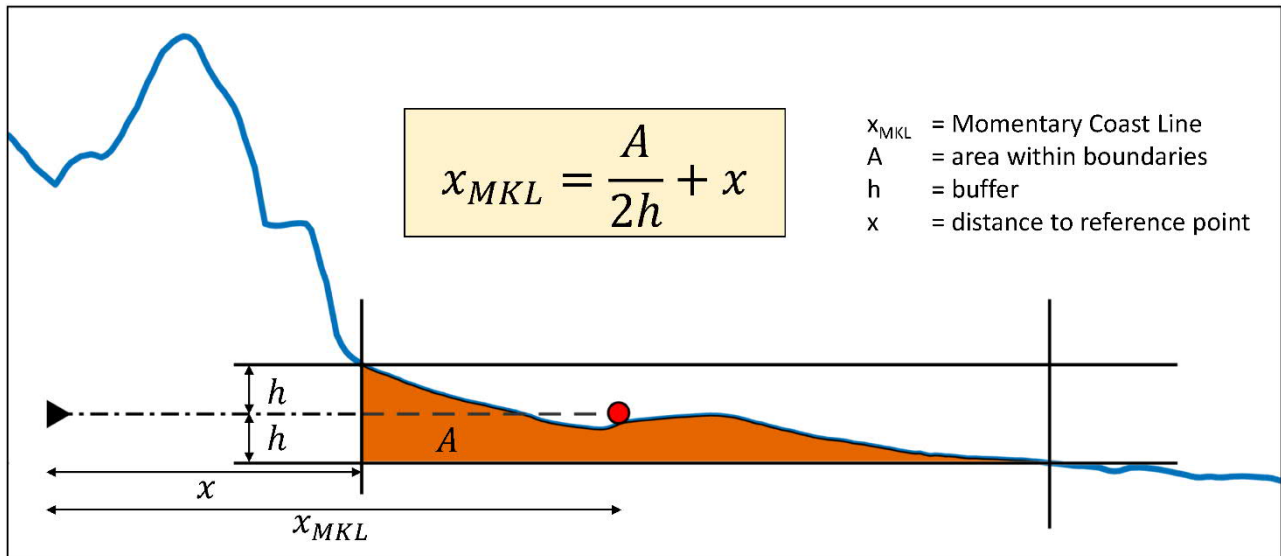


Figure 14: Example of the MKL-Model

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 Domburg nourishment the following levels were used: landward boundary based on data coverage; the upper level of the nourishment - NAP +4 m; the lower level of the nourishment (also low water level) – NAP -1 m 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.

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 volumes 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 sediments 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

For Domburg two logical measuring stations can be chosen: measuring location Europlatform and measuring location Schouwen Bank, see Figure 15. The measuring station Schouwen Bank is the station closest to the coastal laboratory. Therefore, the waves measured at this station should be most representative for the conditions at Domburg. On the other hand, only since 2004 measurements have been taken at the Schouwen Bank and the time series contains several intervals with no data, see Figure 16.



Figure 15: A google earth screenshot indicating the location of the Europlatform and the Schouwen Bank. The figure also contains the bathymetry based on the vaklodgingen.

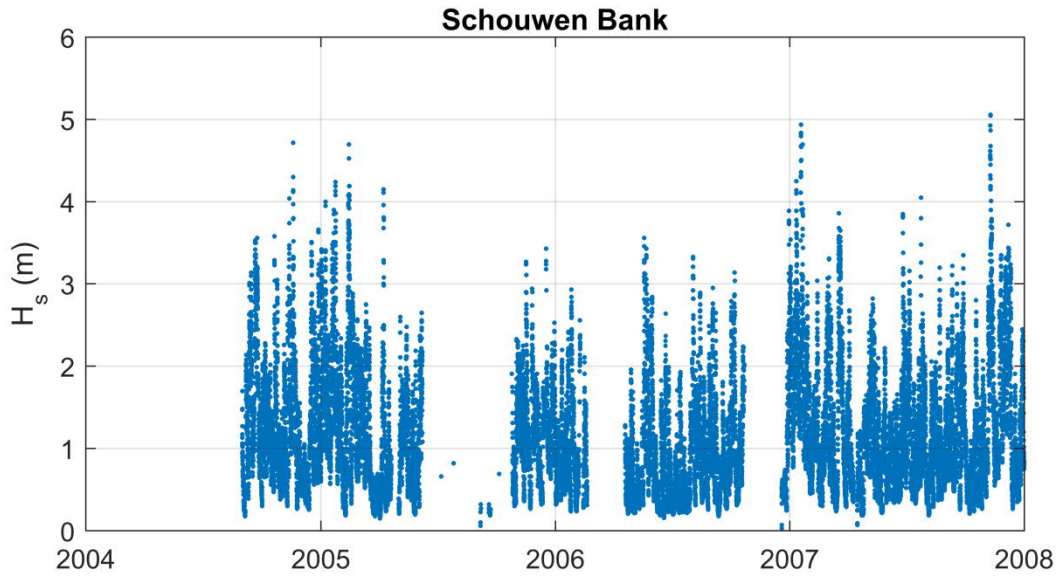


Figure 16: H_s measured at the Schouwen Bank before from 2004 till 2008.

At the Europlatform the wave height is measured since 1989. These measurements can be used in the analysis if they show the same pattern as the measurements at Schouwen Bank. Only the pattern requires to be the same because it is going to be used in a qualitative analysis. Figure 17, Figure 18 and Figure 19 show scatterplots of the measurements from 2004 till 2008 for which at both location measurements were available. The scatterplots reveal a good comparison between the hydraulic conditions. Therefore, the hydraulic conditions measured at the Europlatform are used as a measure for the hydraulic condition at Domburg.

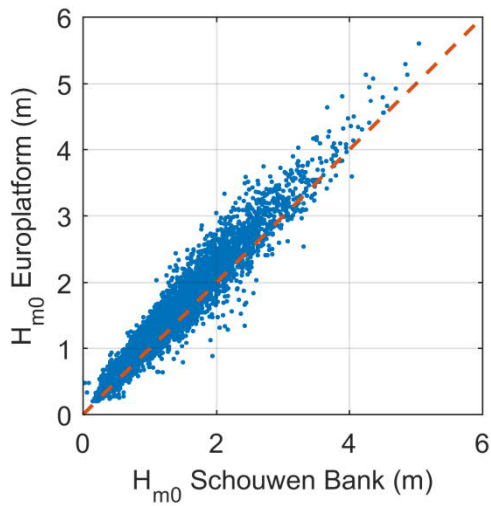


Figure 17: A scatterplot of the H_s measured at the Schouwen Bank and at the Europlatform from 2004 till 2008.

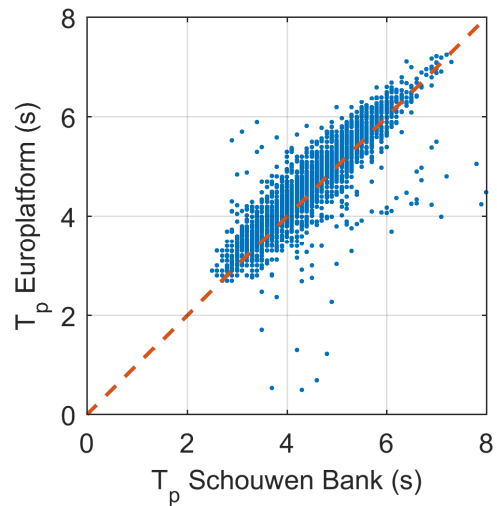


Figure 18: A scatterplot of the T_p measured at the Schouwen Bank and at the Europlatform from 2004 till 2008.

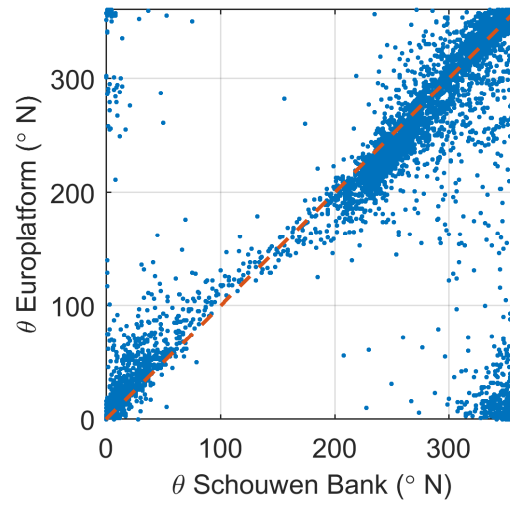


Figure 19: A scatterplot of the θ measured at the Schouwen Bank and at the Europlatform from 2004 till 2008.

The measured time series at the Europlatform are given in Figure 20, Figure 21, Figure 22. 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 5–6 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° till 50°.

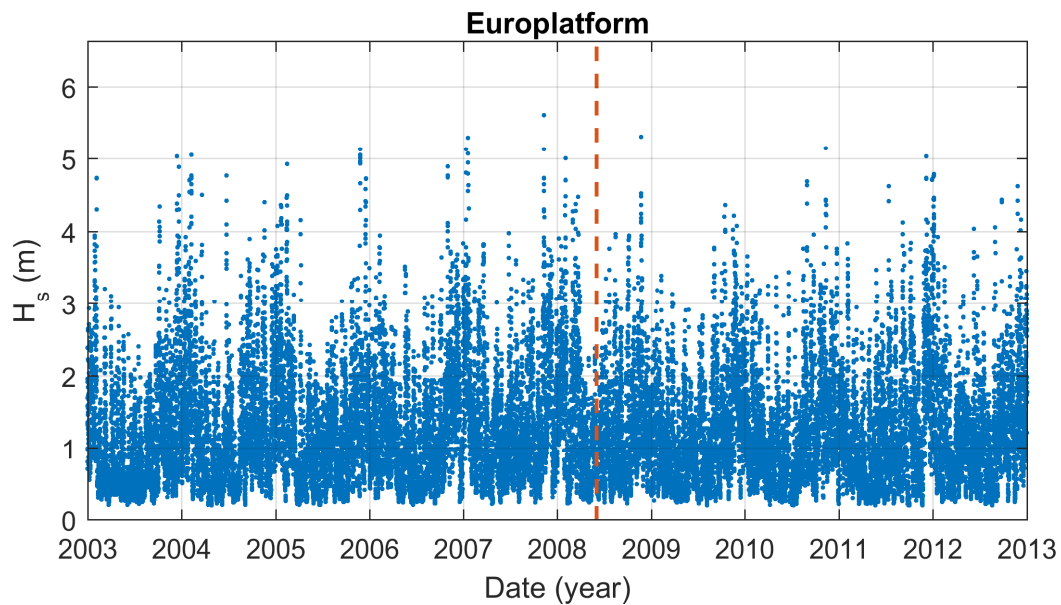


Figure 20: The measured value of H_s at the Europlatform. The red dotted line indicates the nourishment.

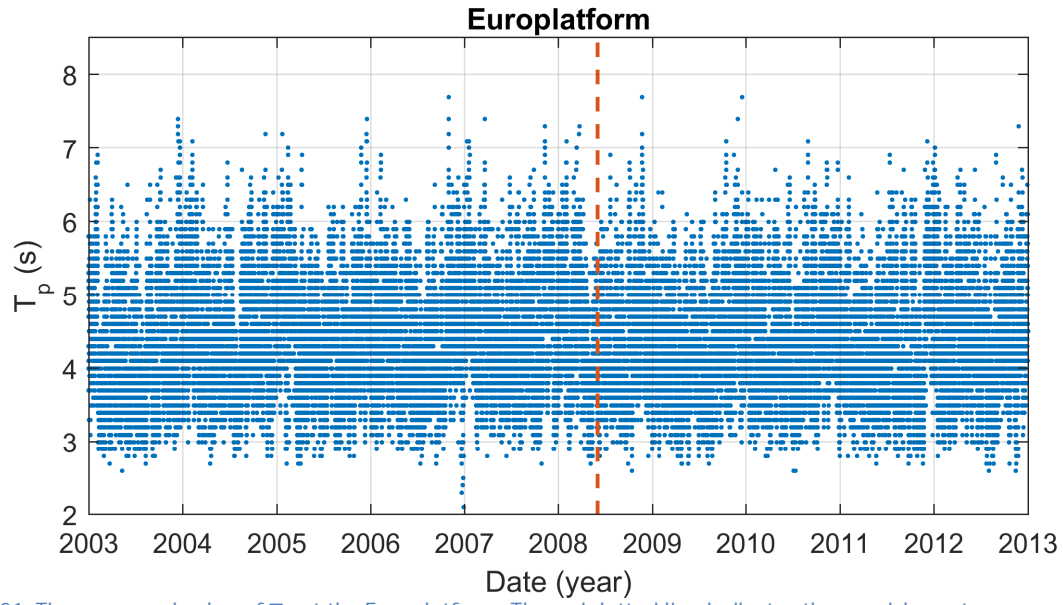


Figure 21: The measured value of T_p at the Europlatform. The red dotted line indicates the nourishment.

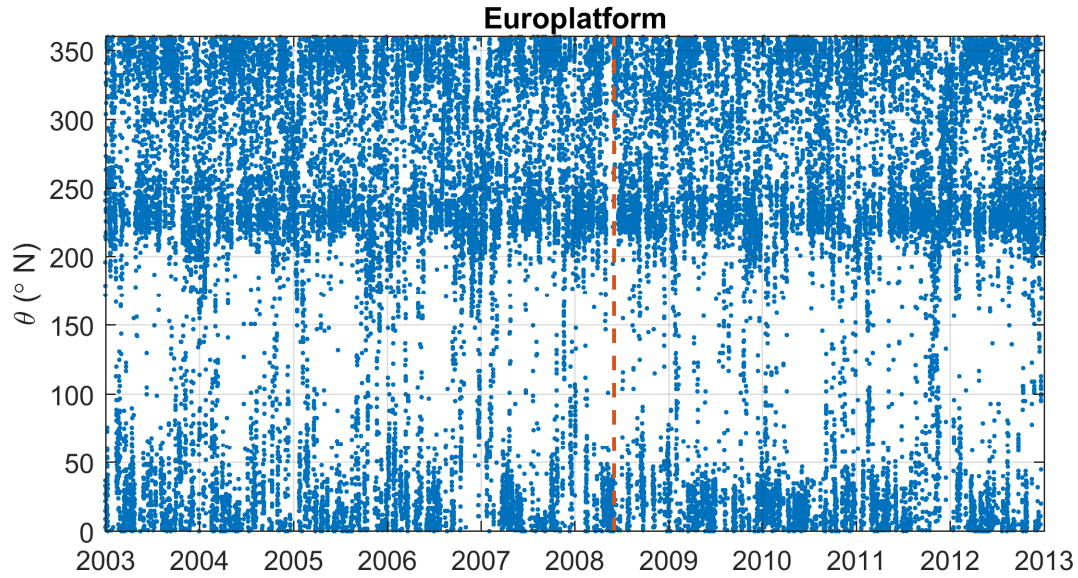


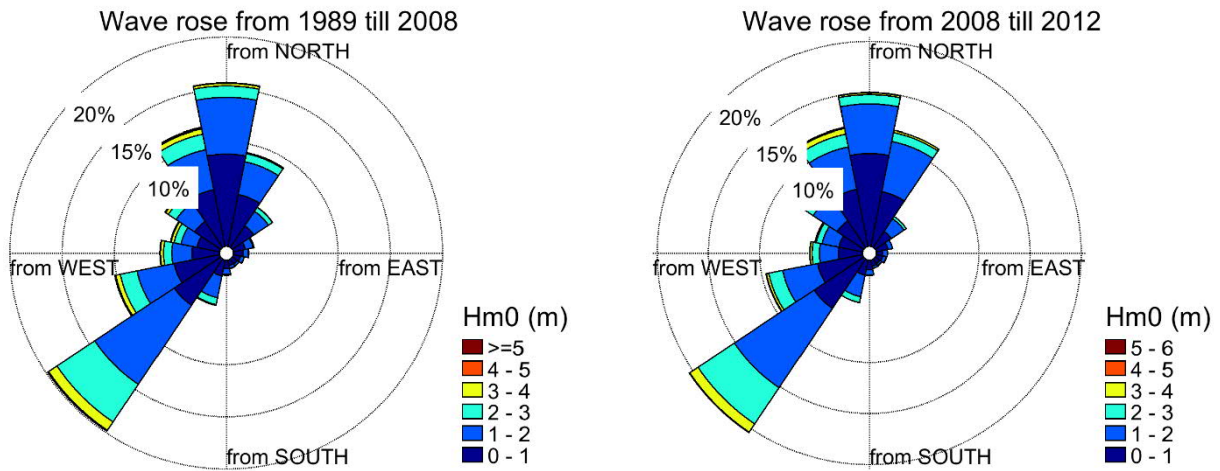
Figure 22: The measured value of θ at the Europlatform. The red dotted line indicates the nourishment.

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 nourishment are calculated from the start of the measurement in 1989 till 2008. 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 a different hydraulic condition.

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 (1989-2008)	Mean value after the nourishment (2008-2013)
\bar{H}_s (m)	1.26	1.22
\bar{T}_p (s)	4.4	4.3
\bar{E}_{par} (kg s ⁻²)	965	826
\bar{E}_{per} (kg s ⁻²)	947	853
$ \bar{E}_{par} $ (kg s ⁻²)	2002	1832
$ \bar{E}_{per} $ (kg s ⁻²)	1474	1357

To further analyse the direction, wave roses are plotted, see Figure 23. All the four roses show two dominant peaks, from the North West and South West direction. It is a so-called 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 the waves are mainly wind generated. 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.



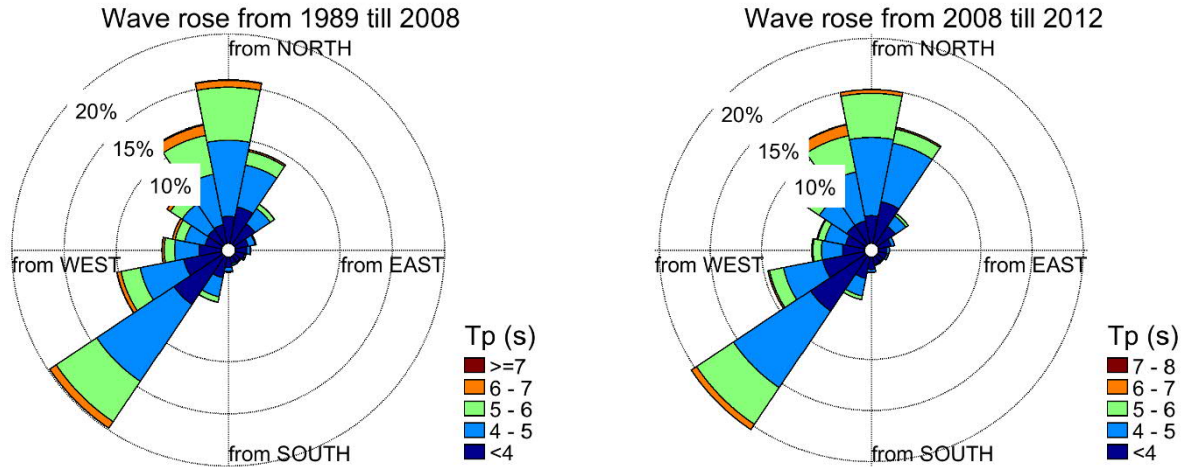


Figure 23: Wave roses based on the measurements at the Europlatform. The year 2003 till 2008 is before the nourishment and 2008 till 2012 is after the nourishment.

In Figure 24 and Figure 25 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 higher for the same value of H_s or T_p . It means that the hydraulic conditions before the nourishment were more harsh than after the conditions. Note, the percentage of exceedance is based on the number of measurements and not on the duration of a specific value.

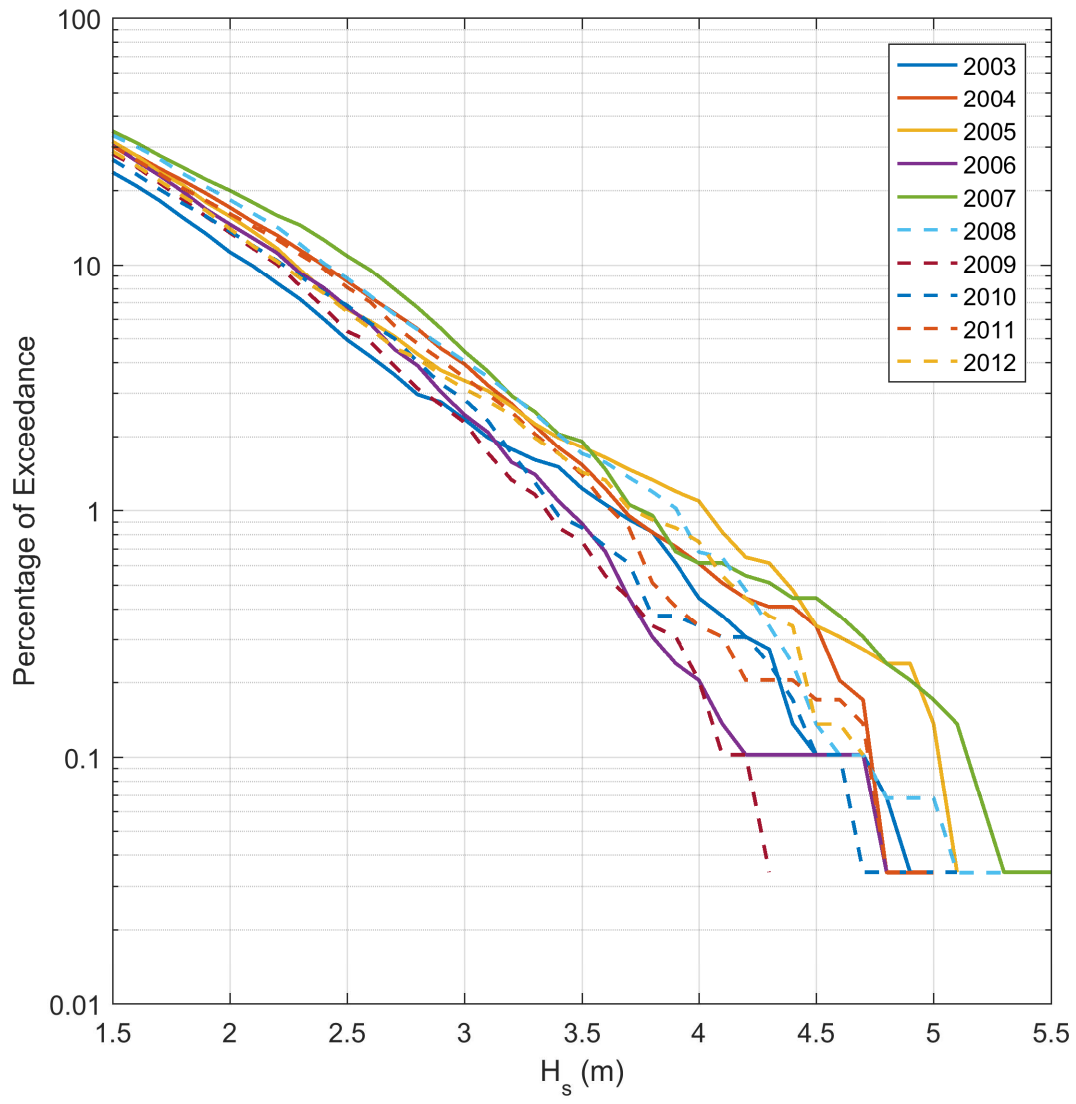


Figure 24: Percentage of exceedance of the measurements H_s at the Europlatform for each year.

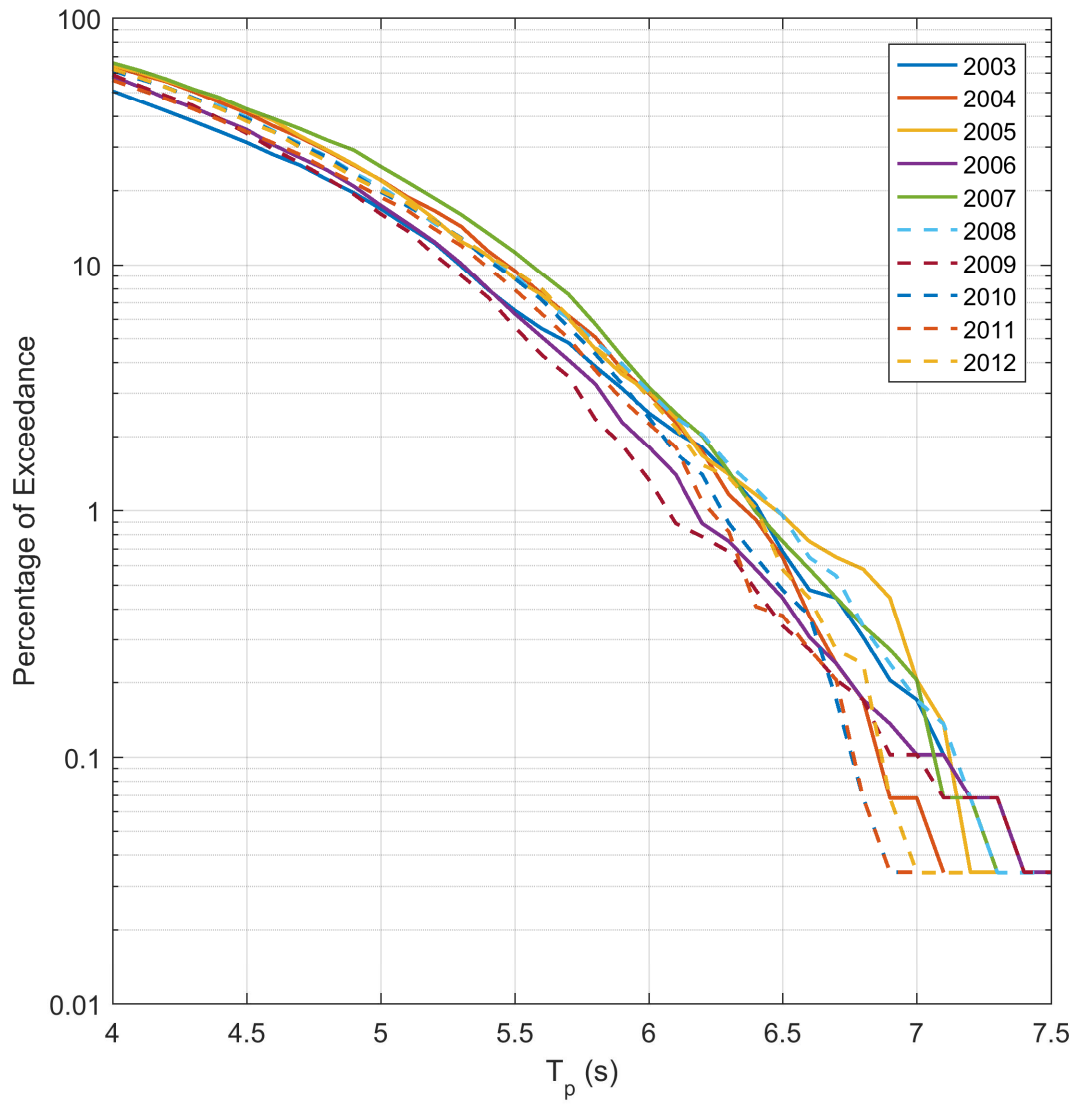
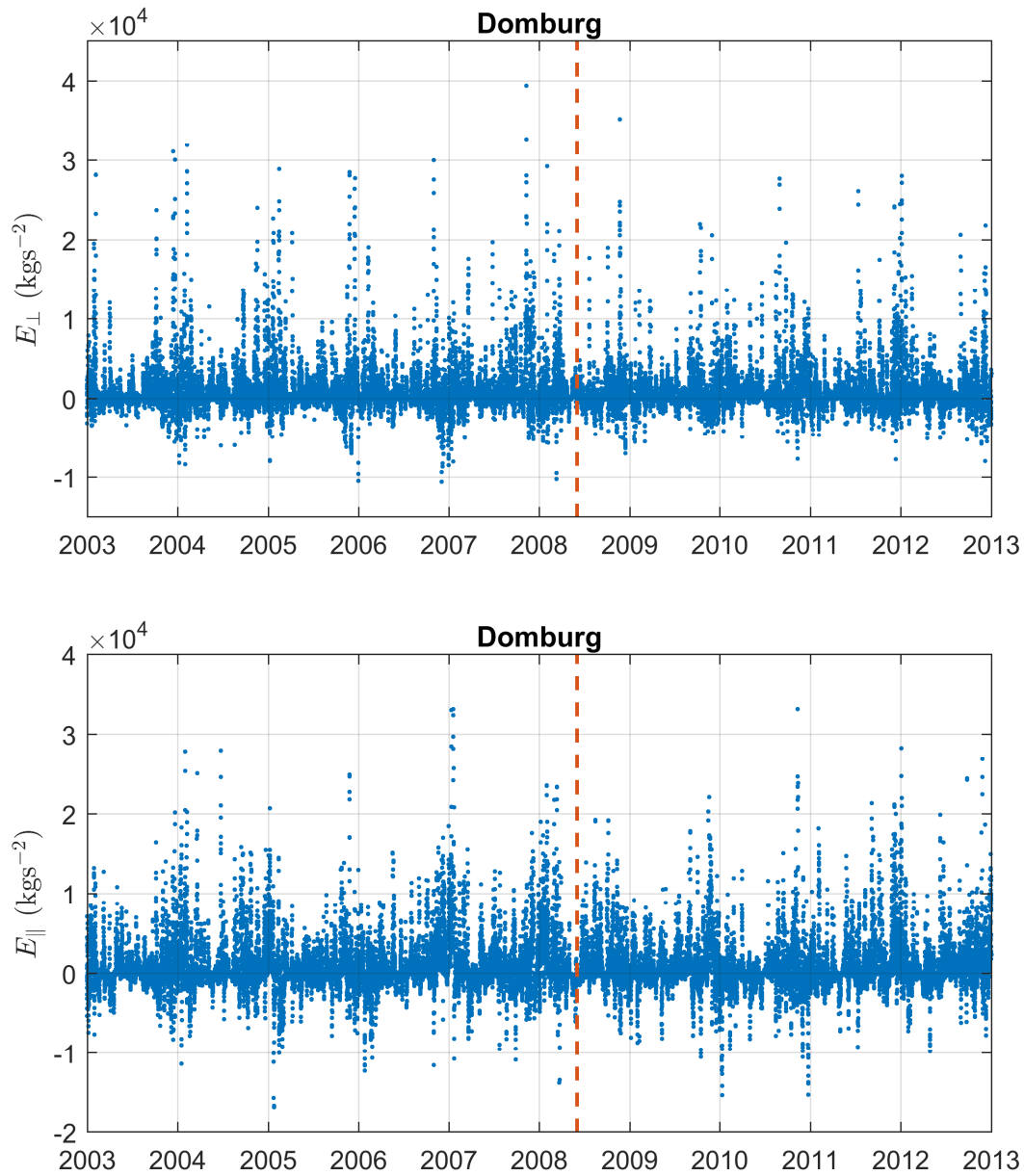


Figure 25: Percentage of exceedance of the measurements for T_p at the Europlatform for each year.



5.2 Tides

For tidal information the IHO station Schouwen Bank is used to provide the tidal elevation from 2000 till 2016. This data can easily be accessed by the Delft Dashboard (Nederhoff, Dongeren, & Ormondt, 2016). Part of the tidal signal is visualized in Figure 26. The signal reveals that the elevation is mainly semidiurnal (two low waters and two high waters each day) but also higher harmonics are visible. The three dominant tidal constituents are given in Table 6. The values for the constituents are in line with the tidal signal. The tidal signal shows two peaks each day due to the M2 and S2 tide. One peak is slightly higher than the other. The M4 tide is responsible for this difference. Also, the signal shows a long periodicity in the order of 14 days. This follows from the phase difference between M2 and S2.

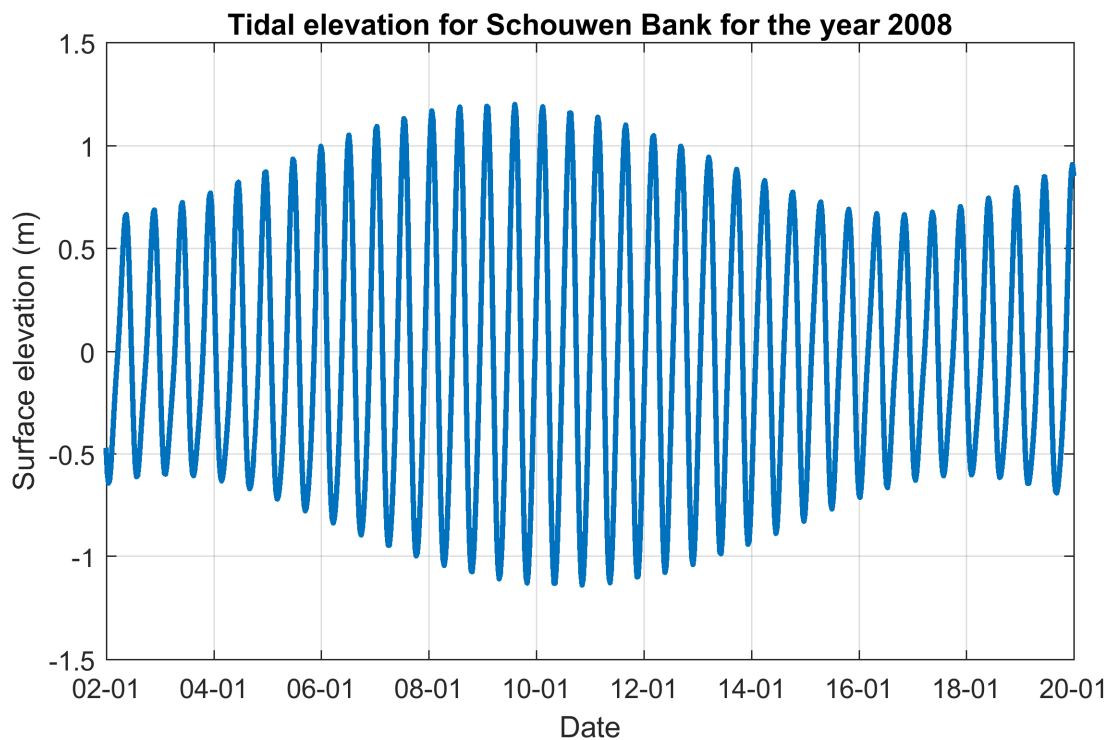


Figure 26: Part of the tidal signal from the IHO station Schouwen Bank.

Table 6: The three dominant tidal constituents.

Tidal Constituent	Period (hours)	Amplitude (m)	Phase (° UTC)
M2	12.4	0.895	30.02
S2	12.0	0.270	72.05
M4	6.2	0.142	134.04

Based on the tidal elevation from 2000 till 2016 different tidal levels are determined, see Table 7. The table shows that the difference between high and low water is of the order of two meter. The variation between the different high water level (MHHW, MHW, MLHW) is rather small. This is also expected because the amplitude of the M4 tide is small. When these levels are further interpreted, one should consider that these values are based on the IHO station Schouwen Bank and that this station is not located directly at the coast.

Table 7: The different tidal levels at the Schouwen Bank.

Tidal level	Abbreviation	Height (m)
Mean Higher High Water	MHHW	0.97 m
Mean High Water	MHW	0.95 m
Mean Lower High Water	MLHW	0.93 m
Mean Water Level	MWL	0.0 m
Mean Higher Low Water	MHLW	-0.86 m
Mean Low Water	MLW	-0.89 m
Mean Lower Low Water	MLLW	-0.90 m

5.3 Storm surges

The effect of a storm surge is analysed not by the investigating the storm surge itself but by considering the number of events when a value of H_s is exceeding a certain threshold. 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 is shown in Figure 27. 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 2008 (before the investigated nourishment) 0.6439% of the time the value of H_s was larger than 4 m. Furthermore, between 2008 and the end of 2012 the percentage was 0.4323%. In other words, slightly less extreme wave heights occurred after than before the nourishment.

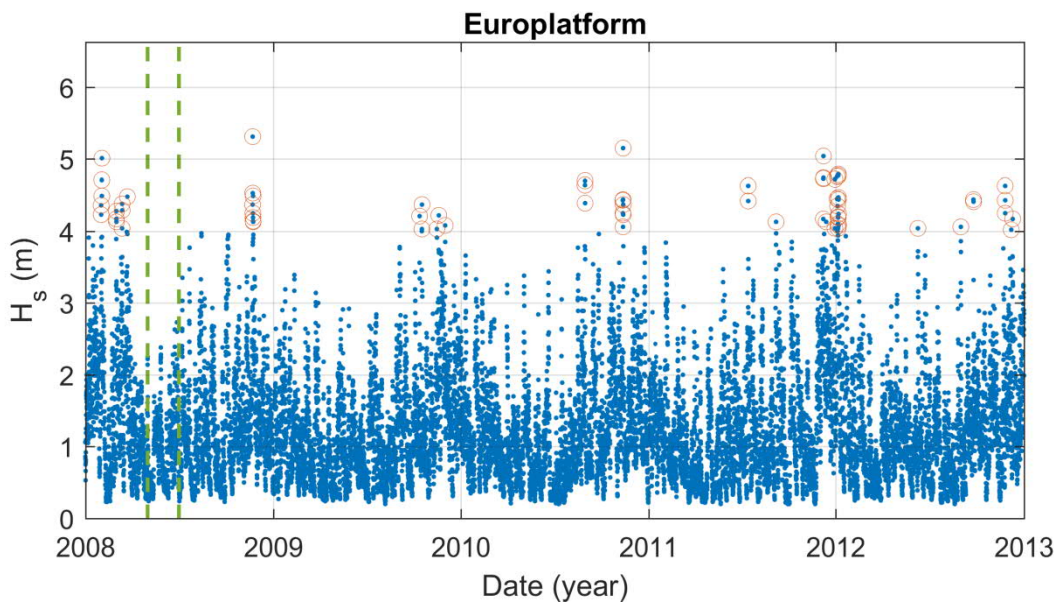


Figure 27: A time series of the wave height. The red circles indicate the events with $H_s > 4\text{m}$ and the green lines the start and end time the nourishment.

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 Vlissingen measurement station for the same periods as the wave data: 1989-2008 for the long term and 2008-2012 for the nourishment period. The data is presented in two wind roses, Figure 28 and Figure 29. The two periods show a similar wind climate, with dominant westerly and southwester winds. In the nourishment period the velocities from the west were slightly lower and occurrence of southwester wind slightly higher than in the long-term period.

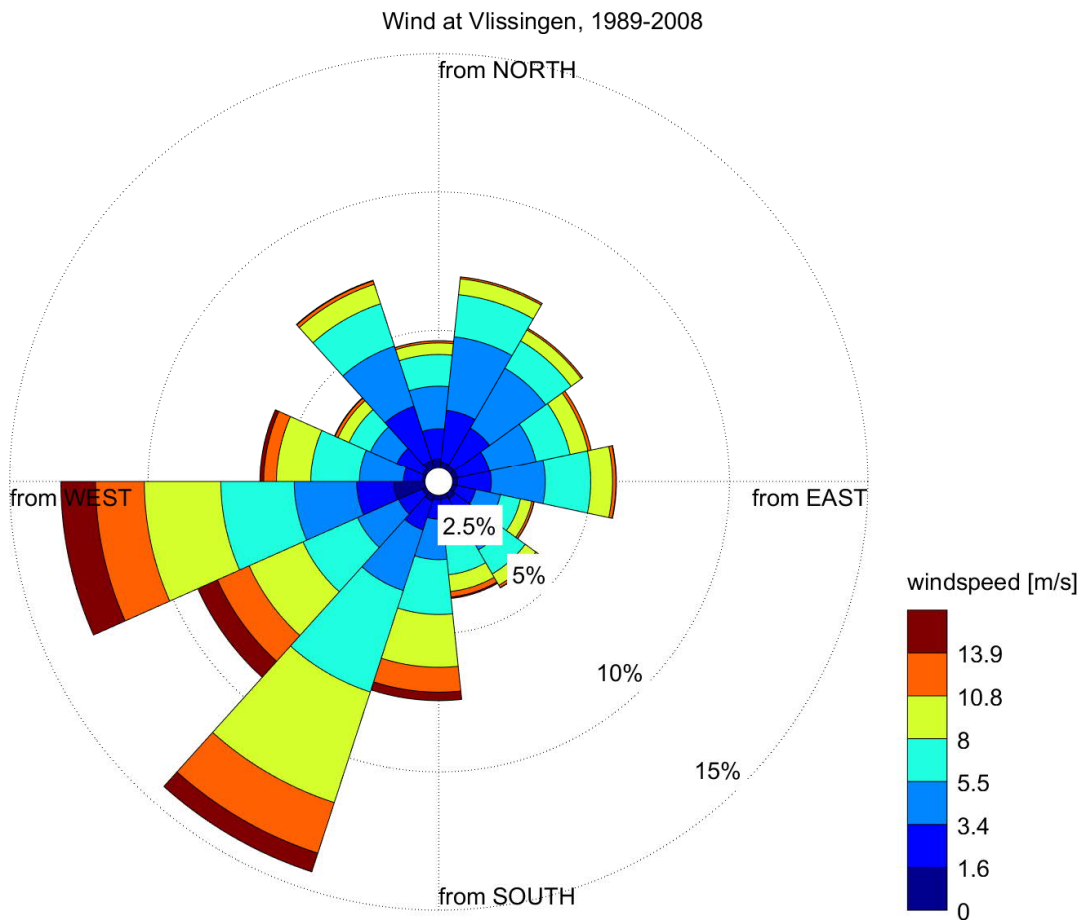


Figure 28: Wind conditions for the long term, pre nourishment period 1989-2008

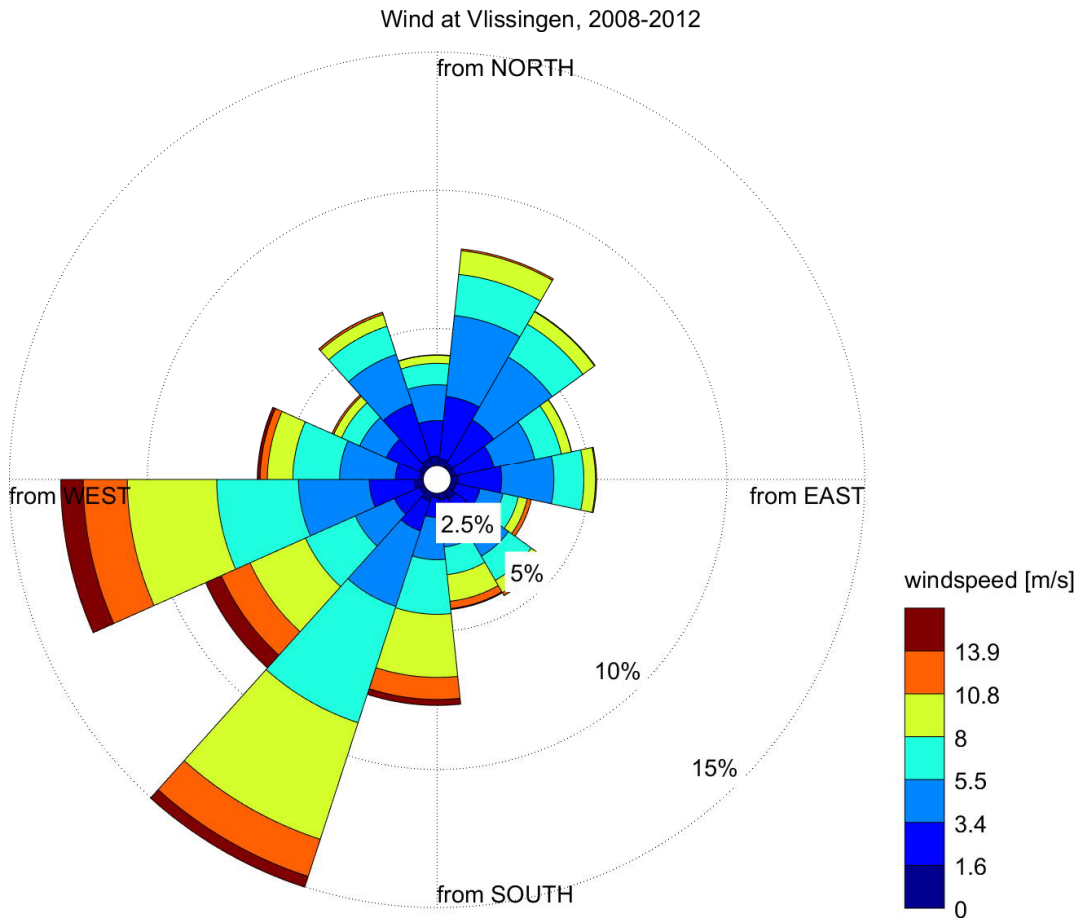


Figure 29: Wind conditions in the nourishment period

5.5 Grain size

There is very little information on the grainsize at the nourishment location. Only on grainsize information in the first dune is available, described by Kohsiek (1984). The average median grainsize for the dunes at the nourishment location is around 300 micron. The median grainsize shows an increasing trend towards the southwest Figure 30.

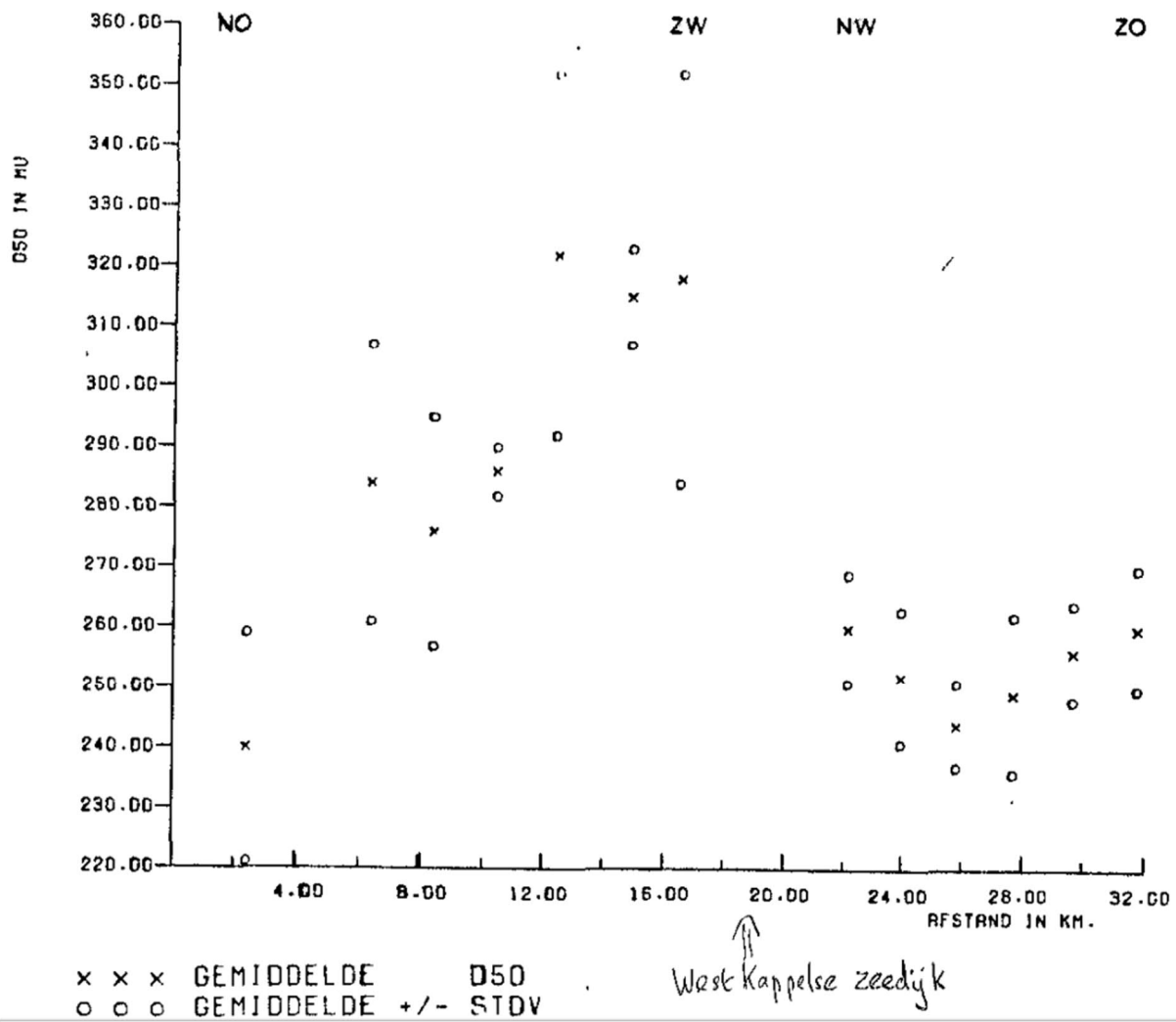


Figure 30: Average median grain size for the dunes of Walcheren, the studied nourishment is around 15.00 with a D50 around 300 micron. Source: Kohsiek (1984)

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 31 and Figure 32.

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.

The Domburg lab has a more tide dominated coast, with a tidal channel running close to the coast. Therefore, no wave induced breaker bars are present at the coast. In this lab the orientation of the coast is about northwest, resulting in an almost coast-parallel dominant wave direction from the southwest. The waves from the north approach the coast almost perpendicular, compared to the other labs. This results in a very dominant northeast directed wave transport.

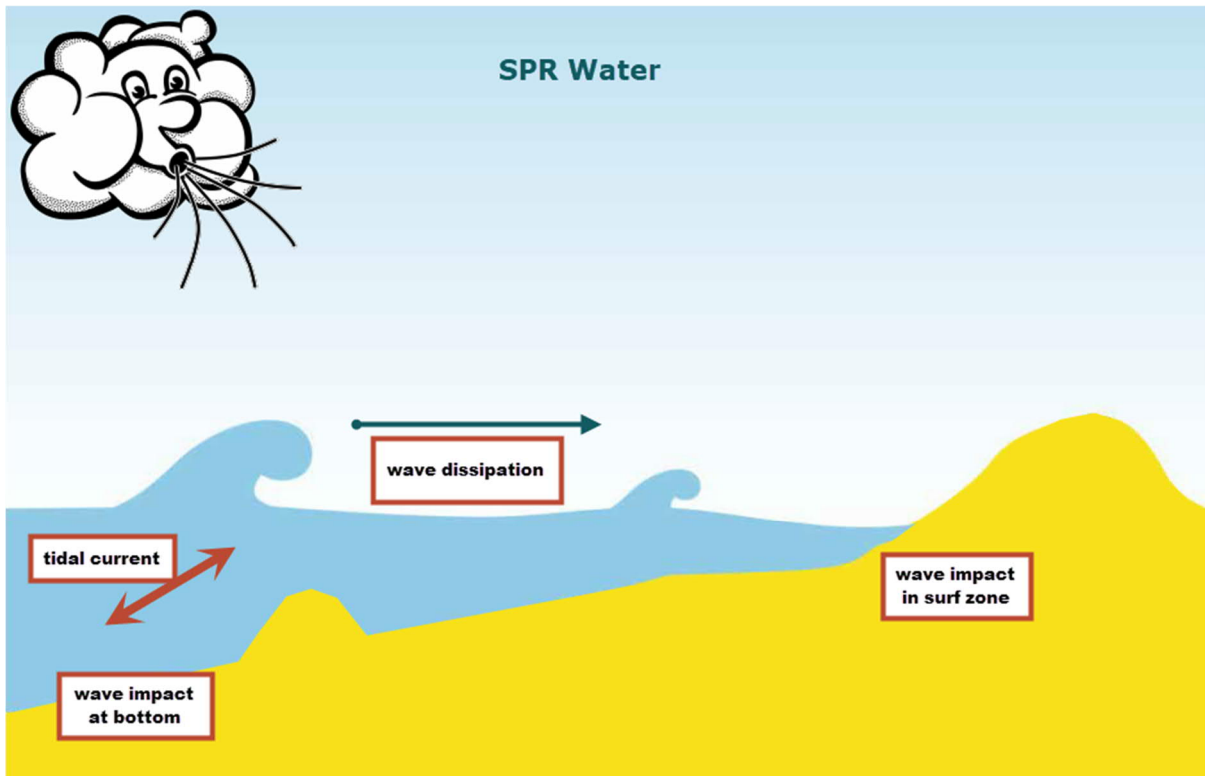


Figure 31: Schematic cross-section showing the main processes driving water

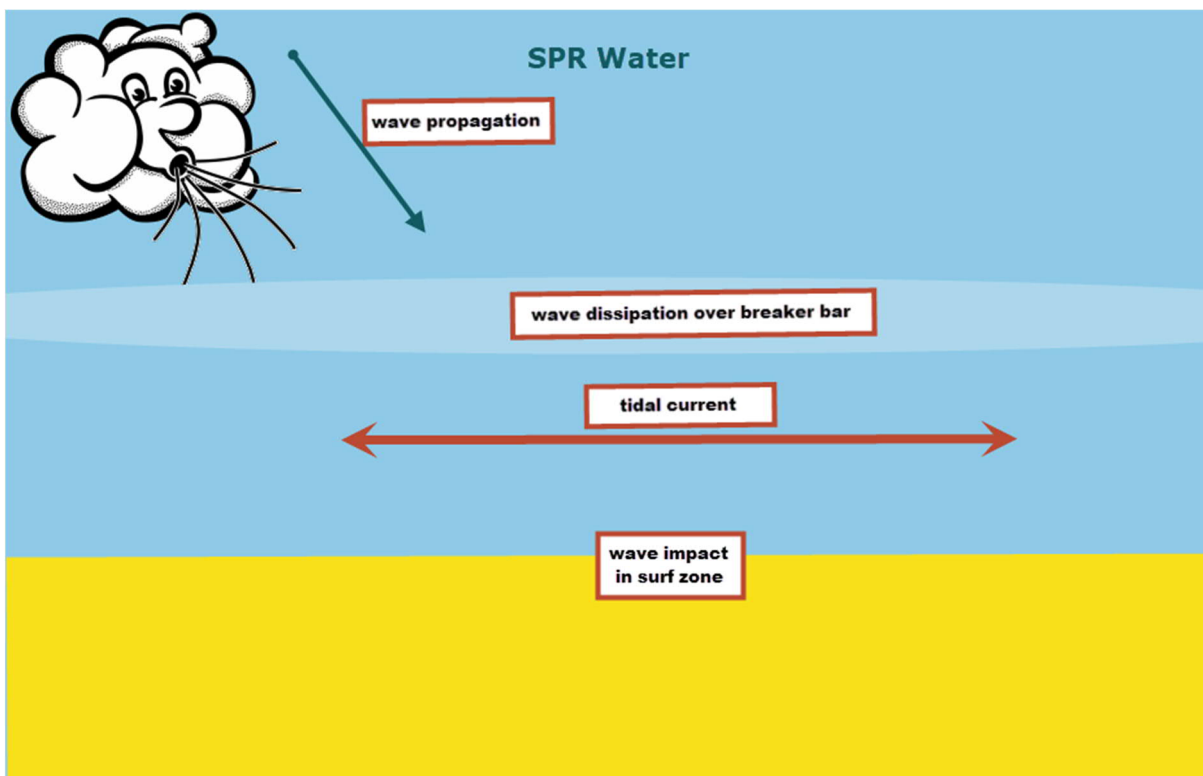


Figure 32: Schematic plan view showing the main processes driving water

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 33 and Figure 34). 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.

At the Domburg lab the beach nourishment is transported both offshore and towards the northeast by – mainly – the wave driven processes (Figure 35). Sediment transported offshore is directly taken up by the tidal current, hence resulting in net erosion with a receptor being the estuary and delta. The northeast directed transport has the neighboring beach as a receptor. Here also aeolian transport from the beach to the dunes is seen.

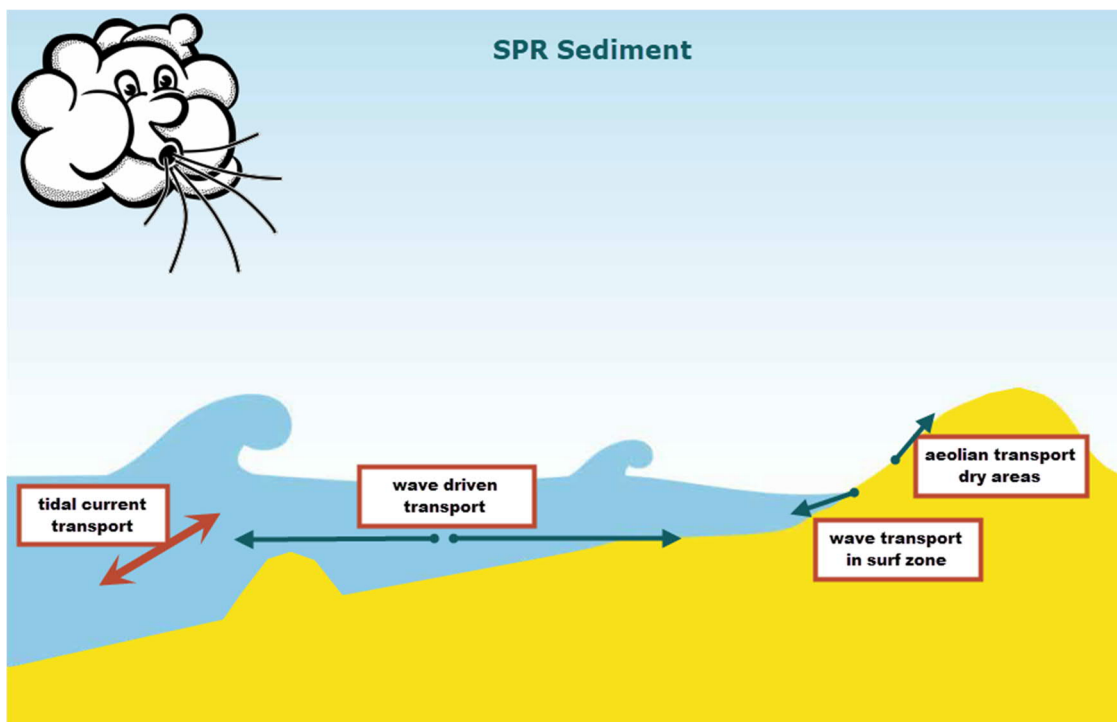


Figure 33: Schematic cross-section showing the main processes driving sediment transport

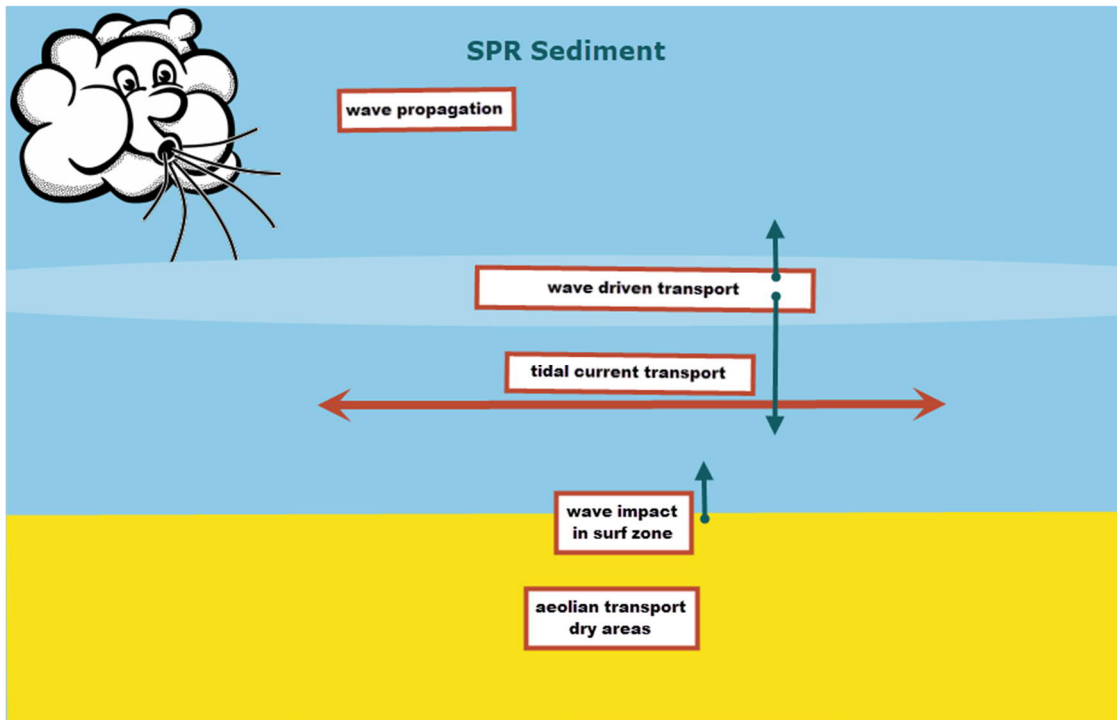


Figure 34: Schematic plan view showing the main processes driving sediment transport

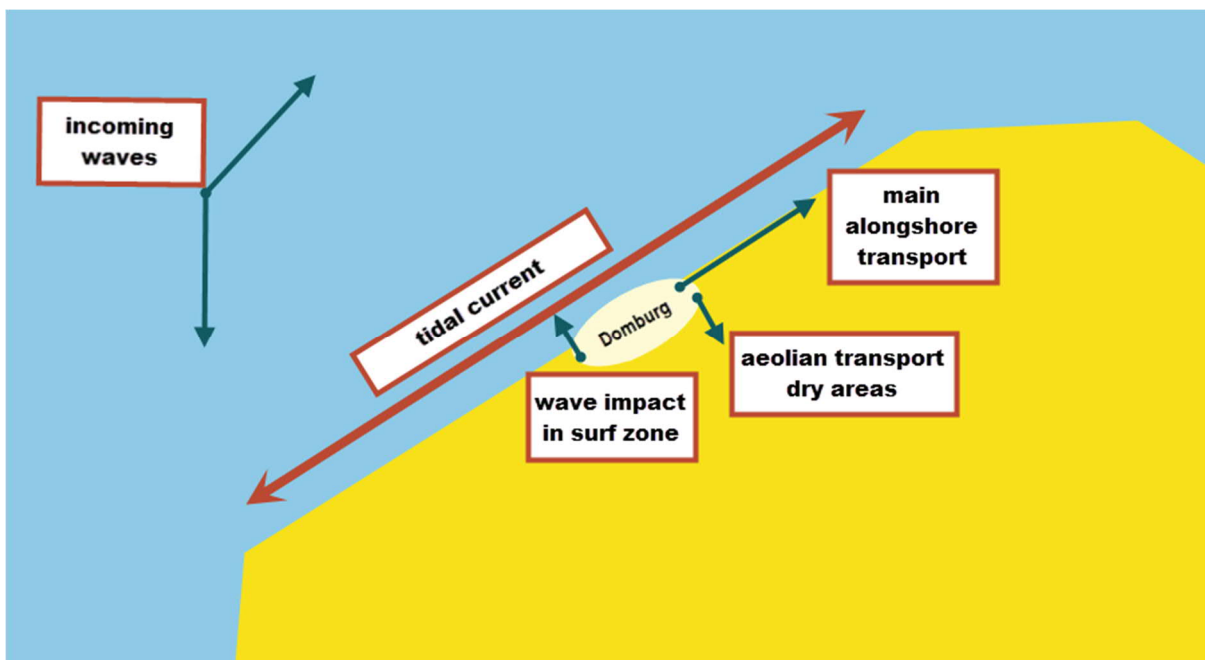


Figure 35: Schematic plan view showing the main processes driving sediment transport for the Domburg lab

7 Results

7.1 Qualitative Morphological development

7.1.1 Shoreface

The shoreface at the nourishment location deepens up to about NAP -8 m and remains at this depth for ca. 600 m, where the Roompot channel begins. The shoreface is relatively stable on the short term, see Figure 36 and Figure 37. Small undulations that are visible are caused by morphological bed forms similar to sand waves, which are visible in multibeam bathymetry, see Figure 38. No significant change in the shoreface is visible in the years after the beach nourishment.

On the long term more variation is visible: in transect 1386 significant sedimentation up to 4 m took place between 1967 and 2000 close to the shore, while further offshore about 1 m erosion is visible, see Figure 39. In the same period, transect 1550 showed about 1.5 m erosion, see Figure 40. The change from erosion to sedimentation lies around transect 1509; northeast of this transect sedimentation occurred, southwest of it erosion.

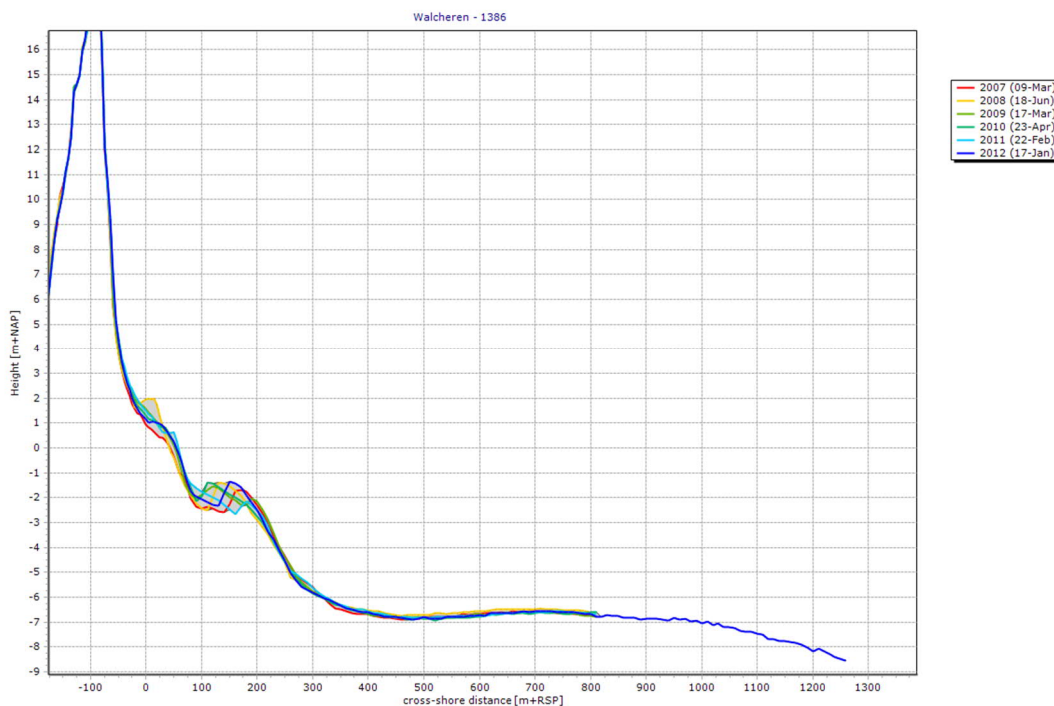


Figure 36: Development of shoreface in transect 1386 between 2007 and 2012

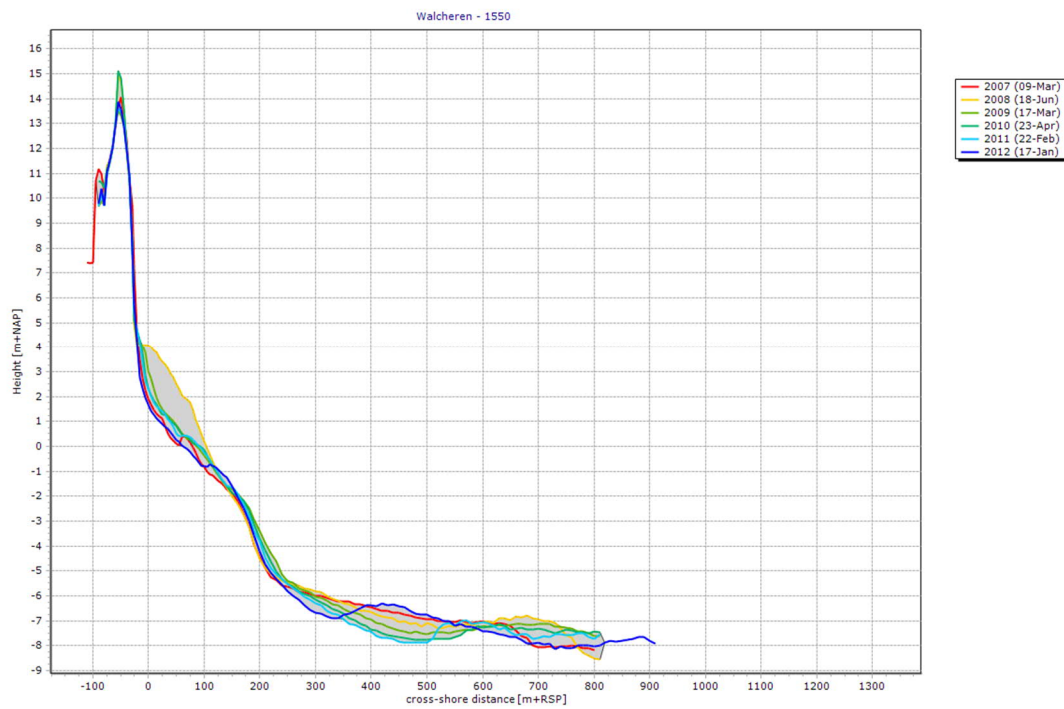


Figure 37: Development of shoreface in transect 1550 between 2007 and 2012

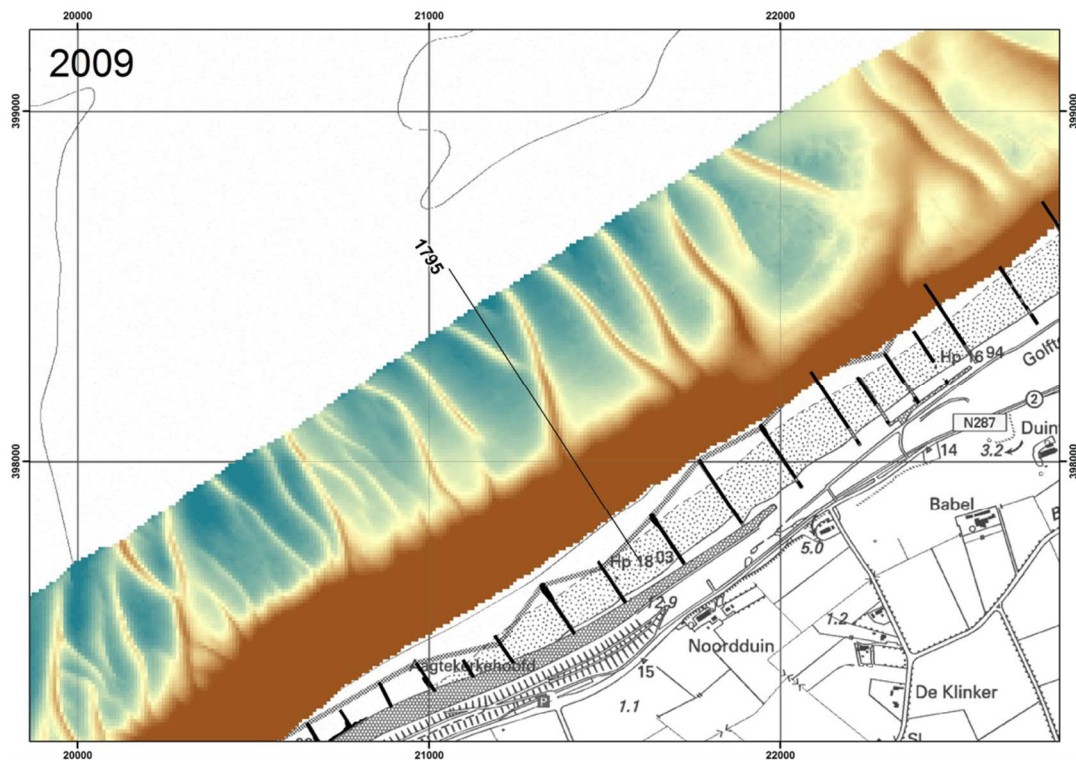


Figure 38: Multibeam bathymetry of shoreface close to Domburg (source: Mastbergen et al., 2017)

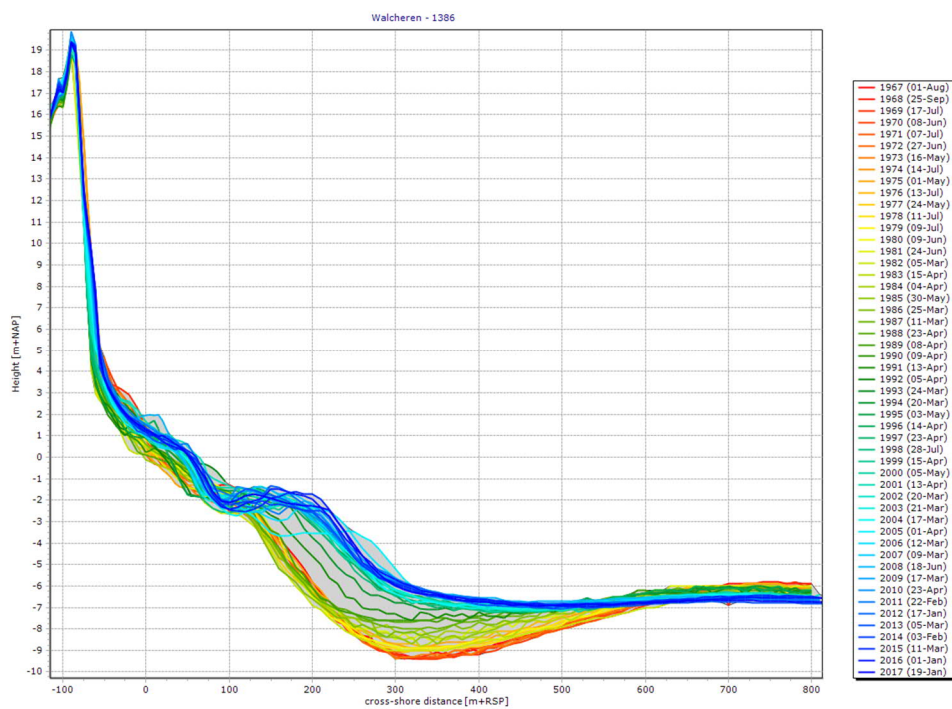


Figure 39: Development of shoreface in transect 1386 between 1967 and 2017

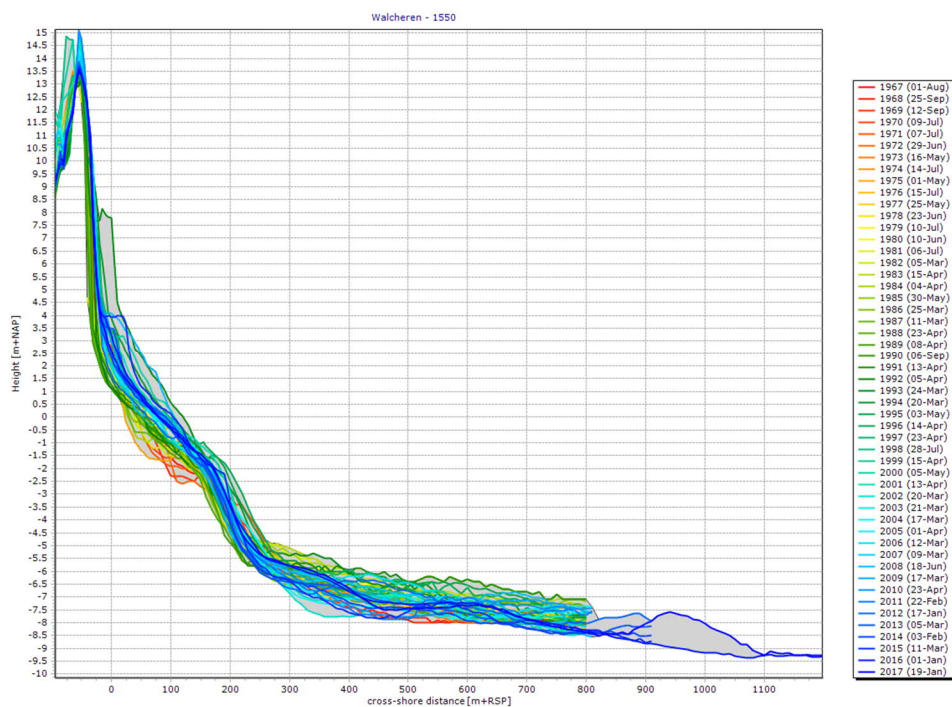


Figure 40: Development of shoreface in transect 1550 between 1967 and 2017

7.1.2 Beach and dune

The nourishment is only for the central part visible in the measurement of 2008, and in the other areas in the measurement of 2009. In transect 1489, see Figure 41, the measurement is visible in 2009, where the profile is increased with ca. 1 m. The largest increase is visible around NAP -1 m, while at the upper part the thickness decreases to become zero around NAP +4 m. Transect 1550 shows the nourishment much clearer, with an increase of ca. 2.5 m, see Figure 42. Its thickness decreases in seaward direction, to become zero around NAP -1 m.

On the long term a division in two periods can be made: before and after approximately 1990. In the period up to 1990 erosion occurred at the beach. Especially the upper part of the beach, above ca. NAP +0.5 m, shows constant erosion, see Figure 43, and Figure 44. After 1990 there is still erosion, however regular nourishments cause large jumps in the profile, with a small 'plateau' around NAP +4 m, see Figure 45 and Figure 46.

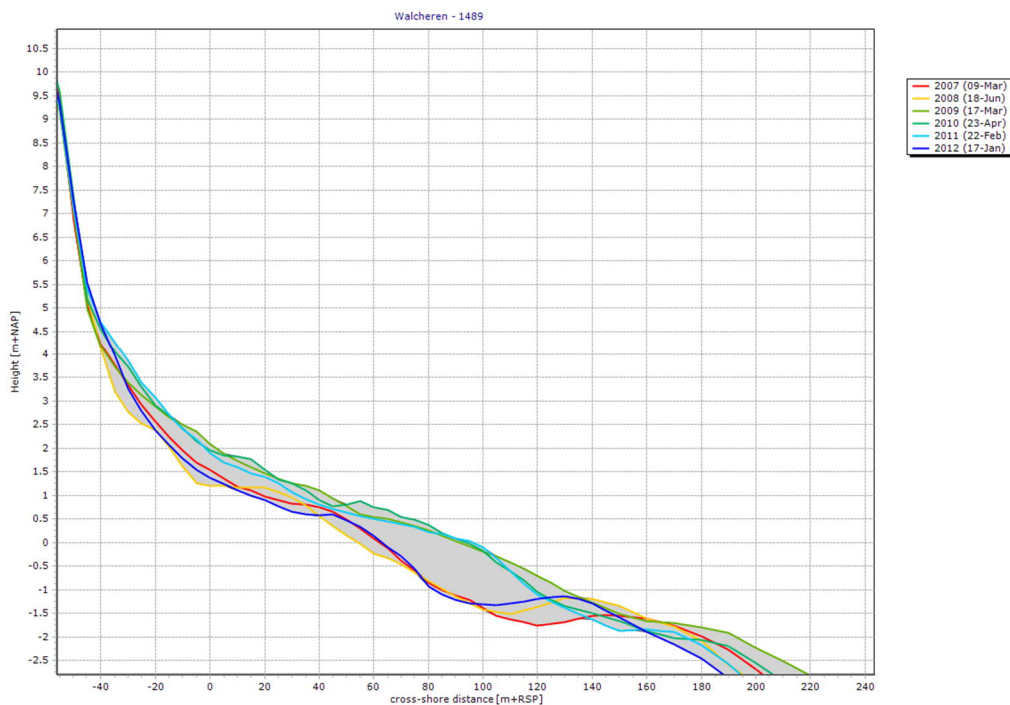


Figure 41: Development of beach and dune in transect 1489 between 2007 and 2012

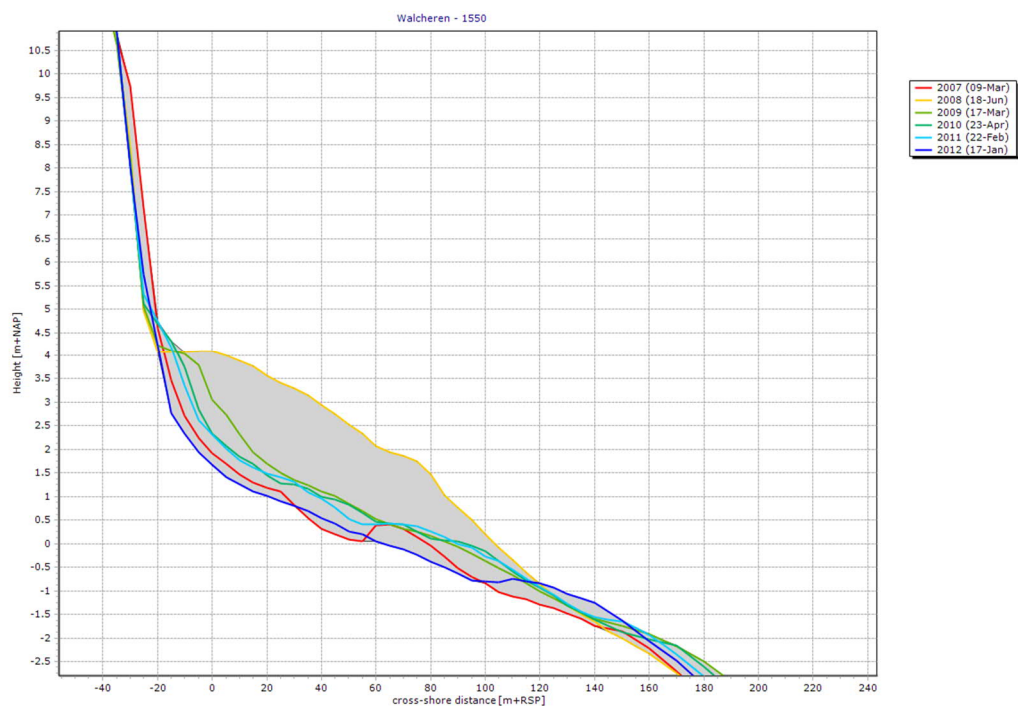


Figure 42: Development of beach and dune in transect 1550 between 2007 and 2012.

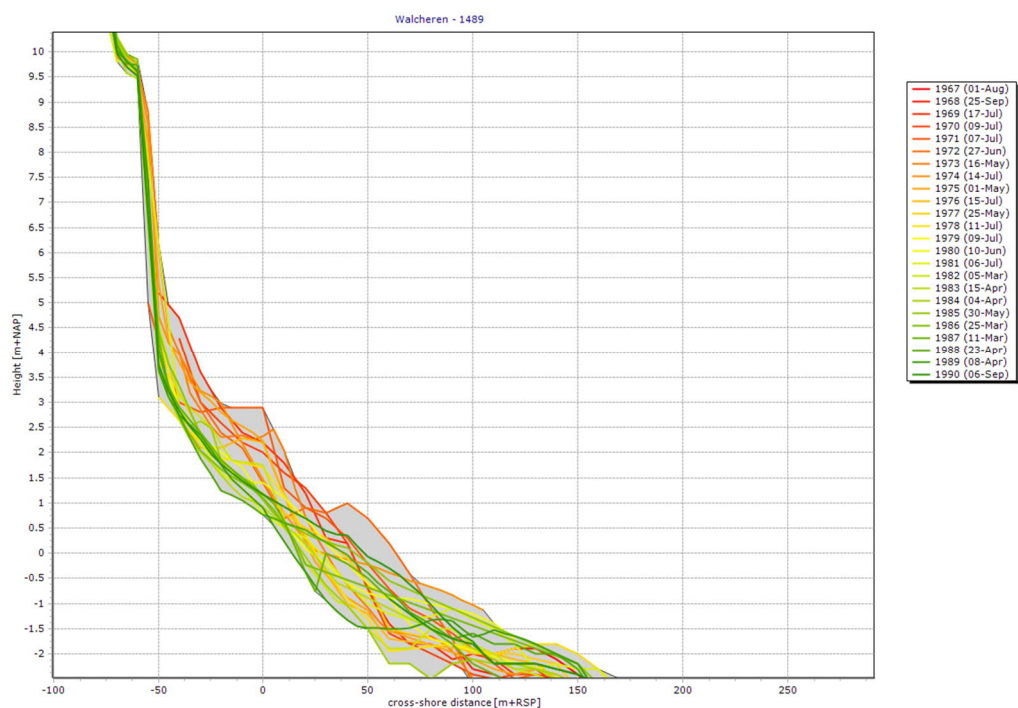


Figure 43: Development of beach and dune in transect 1489 between 1967 and 1990.

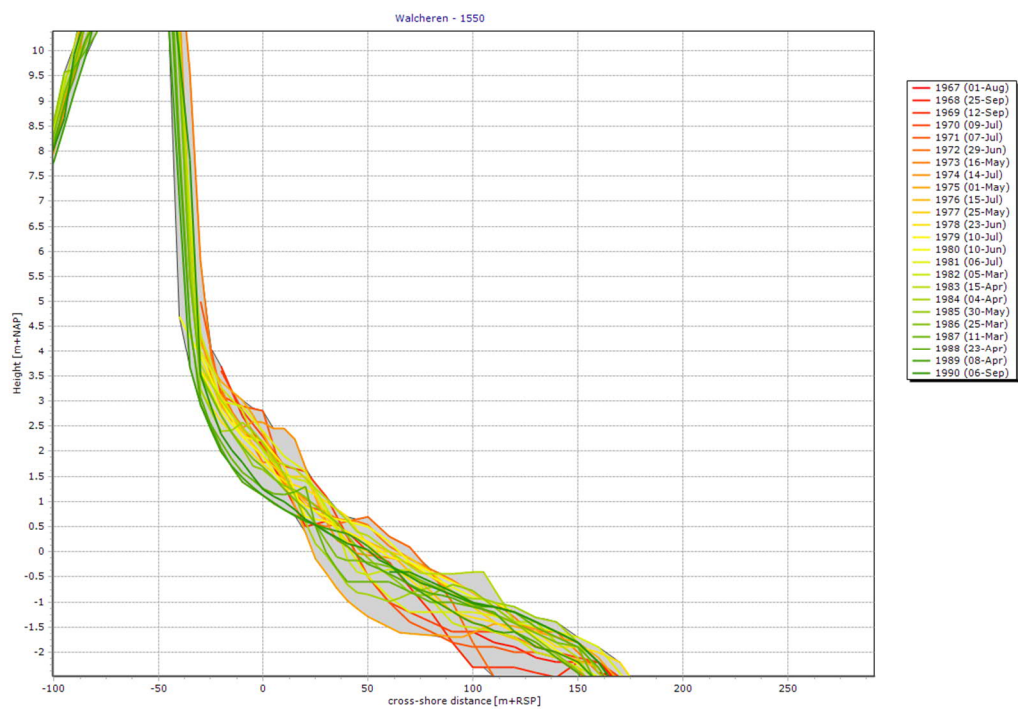


Figure 44: Development of beach and dune in transect 1550 between 1967 and 1990.

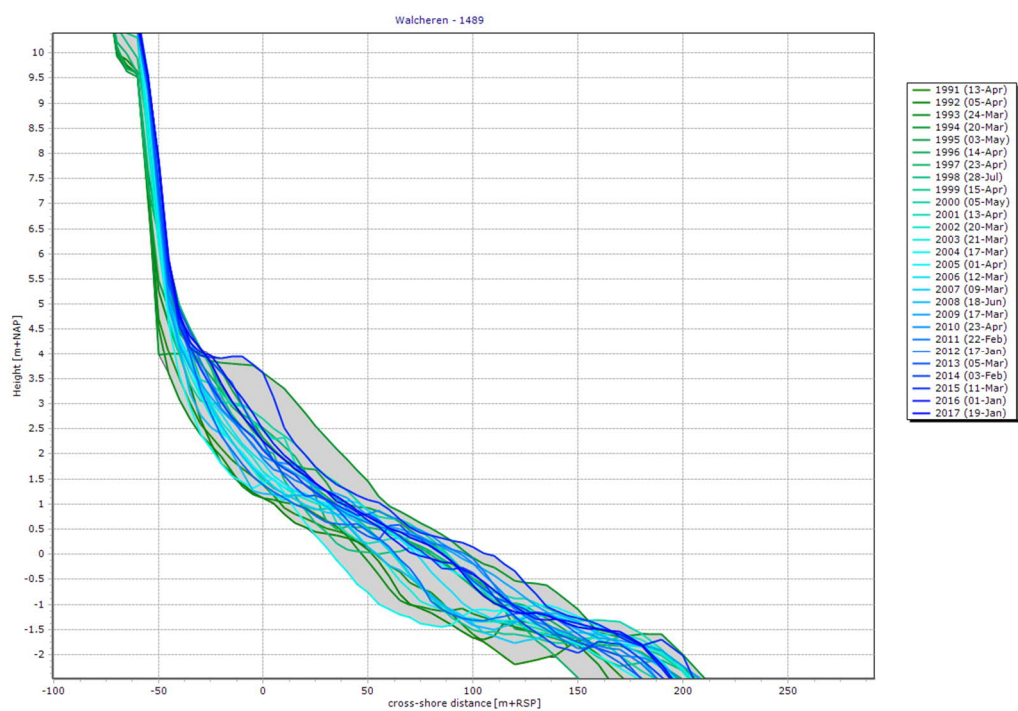


Figure 45: Development of beach and dune in transect 1489 between 1990 and 2017

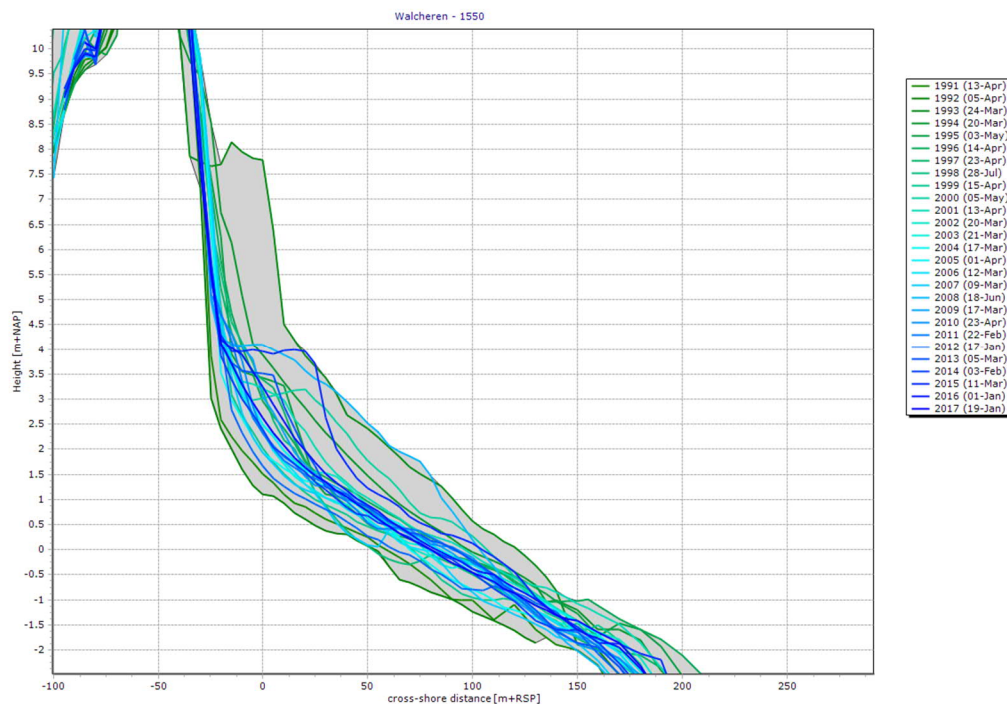


Figure 46: Development of beach and dune in transect 1550 between 1990 and 2017

7.2 Quantitative Morphological development

7.2.1 Physical marks

The physical marks for the year before and the year after the nourishment are shown in Figure 47. The difference between the two years in mid dune level and upper dune level is small. The dunefoot, mean high water level and mean water level display a jump in seaward direction, especially at transect 1550. Due to the nourishment these indicators moved offshore. The mean low water levels also moved offshore but less than the other levels. The mean high water level also shows a seaward movement on the west side of the nourishment area (indicated by black dashed lines) up to transect 1469. This is the result of a neighbouring beach nourishment. The studied nourishment was not completed yet during the measurement of 2008, therefore the effect on the physical marks is not visible in the entire nourishment area.

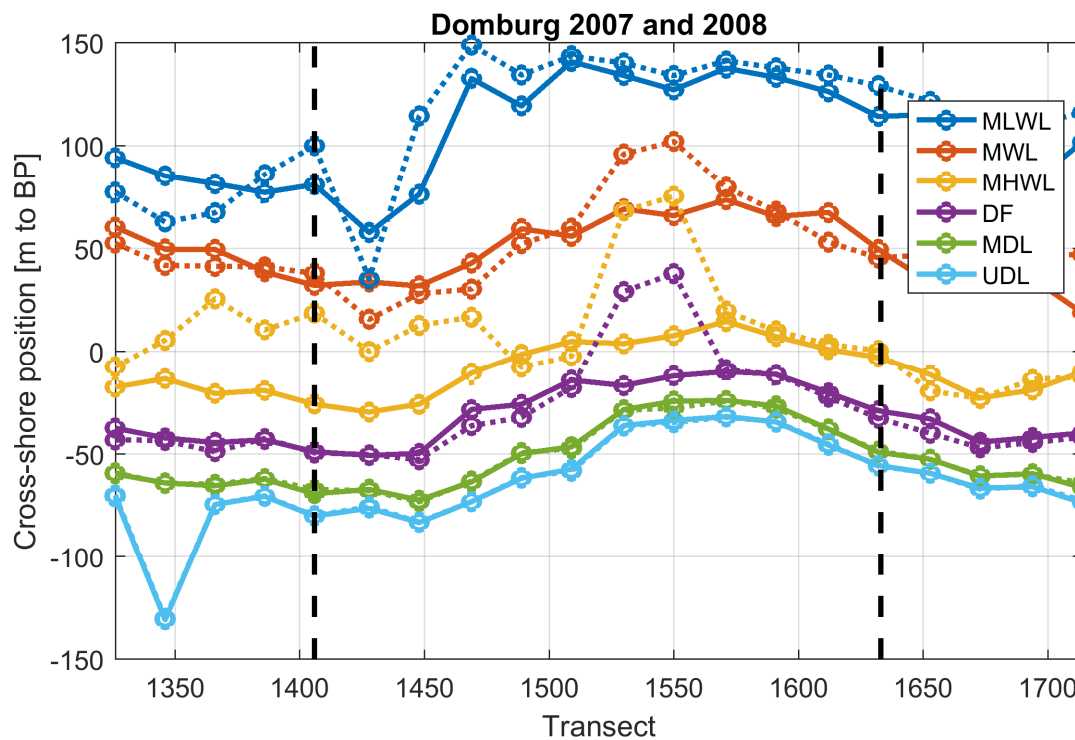


Figure 47: The physical marks of the transects at Domburg for the year 2007 (solid line) and the year 2008 (coloured dashed line). The colours indicate the defined level, see 4.2.1. The black dashed line indicates the prescribed boundary of the nourishment.

To analyse the long-term effects of the nourishment the difference in horizontal position is presented with respect to 2007, see Figure 48. From 2003 till 2007 the MHWL position is moving landward. The most inland position is in 2007. In 2008 the shore is nourished and the position lays further into the sea. Over the following years the shore keeps eroding. In 2012 the MHWL position lays within the natural variability at the same position as in 2007. The MWL and DF display a similar behaviour.

The long term position of MLW (Mean Low Water), MHW (Mean High Water) and the Dune Foot (DF) are presented as a function of time, see Figure 49. After the first nourishment in 1994, a typical saw shape pattern is visible. After each nourishment, the levels moved offshore. Due to the ongoing erosion the level slowly move inland until the next nourishment. This effect is visible in all physical marks except the mid dune and upper dune level (Figure 50). The net effect of the nourishments on the long term is still a seaward displacement of the indicators. Comparing the oldest, most recent and most seaward position (just before start of the nourishments) of the indicators (Figure 53 tot Figure 58) shows that at multiple transects the most recent position is already seaward from the oldest position.

The UDL level is also investigated, see Figure 48. The UDL location shows the opposite behaviour to the MHWL position. Namely, the UDL location is continuously moving seaward. To analyse this trend multiple years are investigated, see Figure 52. The figure displays the dune profile for transect 1428 for multiple years. The detailed subfigure shows seaward migration: the dune is growing over the years. The growth of the dunes might be related to the nourishments.

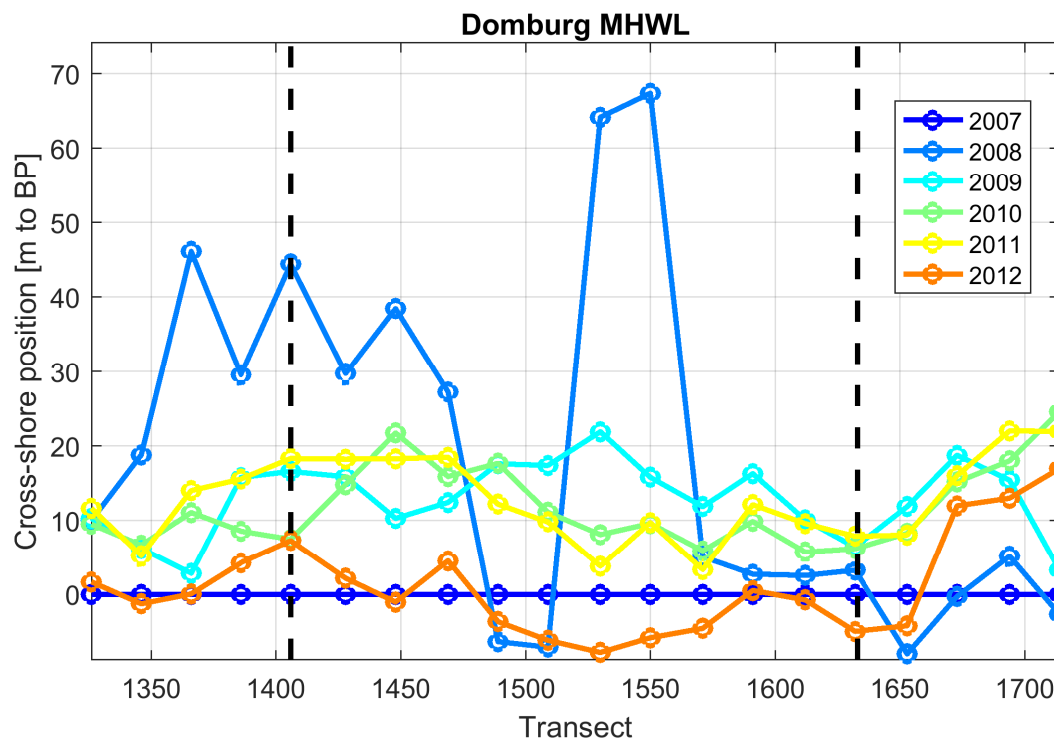


Figure 48: The difference in cross-shore position of MHWL with respect to 2007. When the value is positive the position lays more offshore than in 2007.

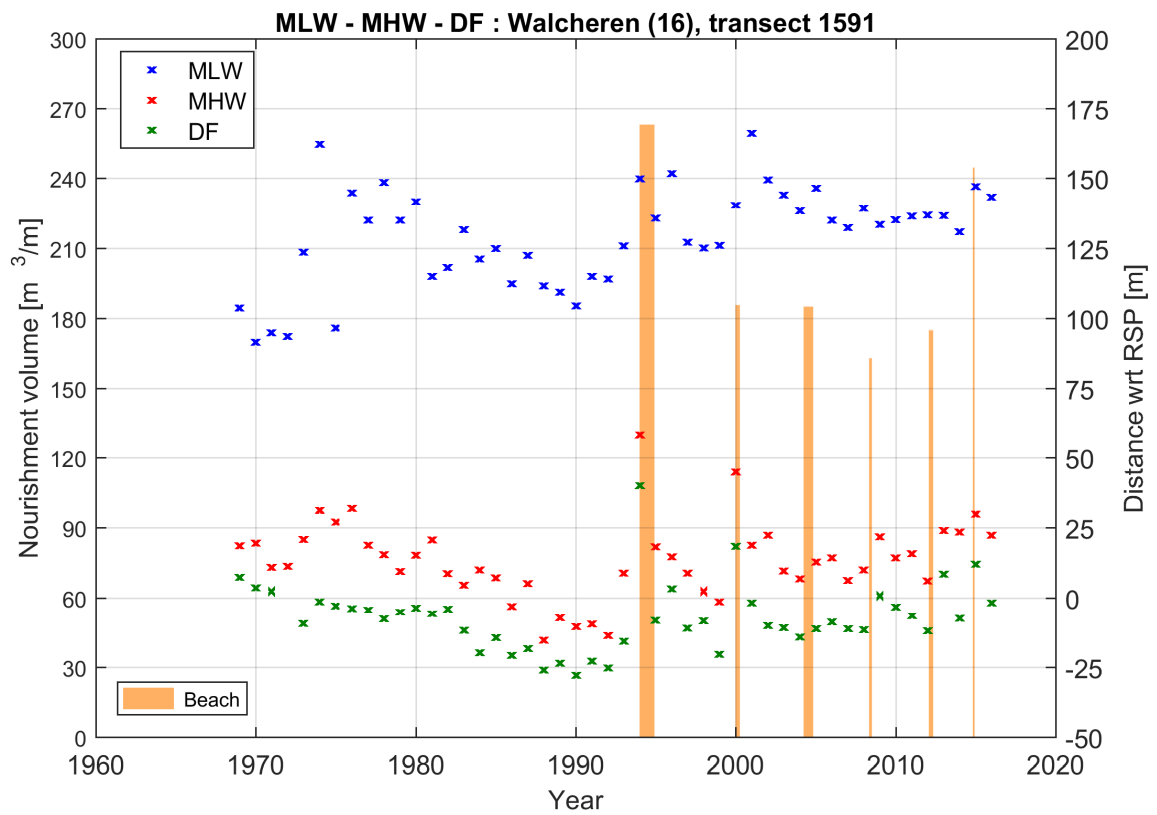


Figure 49: Long term location of the MLW (Mean Low Water), MHW (Mean High Water) and the Dune Foot (DF) as a function of time for transect 1591. The orange bars indicate the volume for a nourishment.

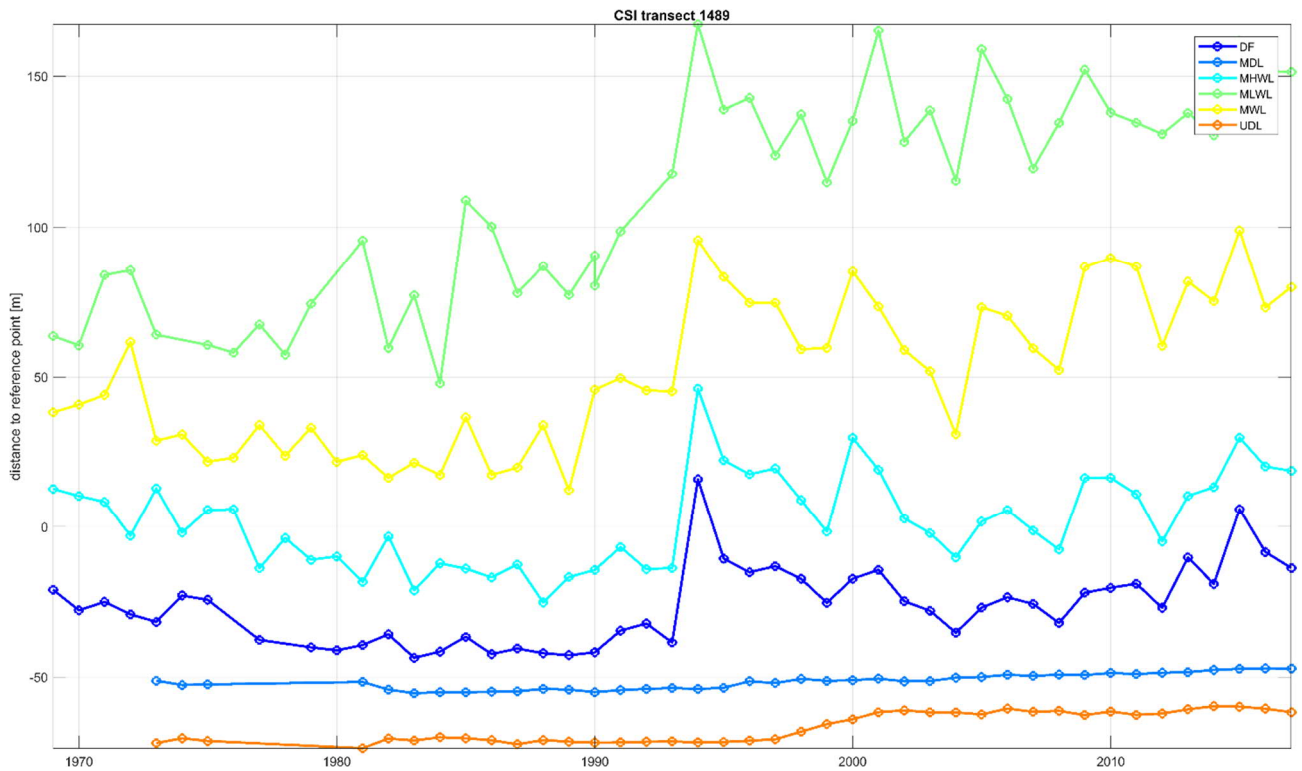


Figure 50: Timeseries of physical marks for transect 1489

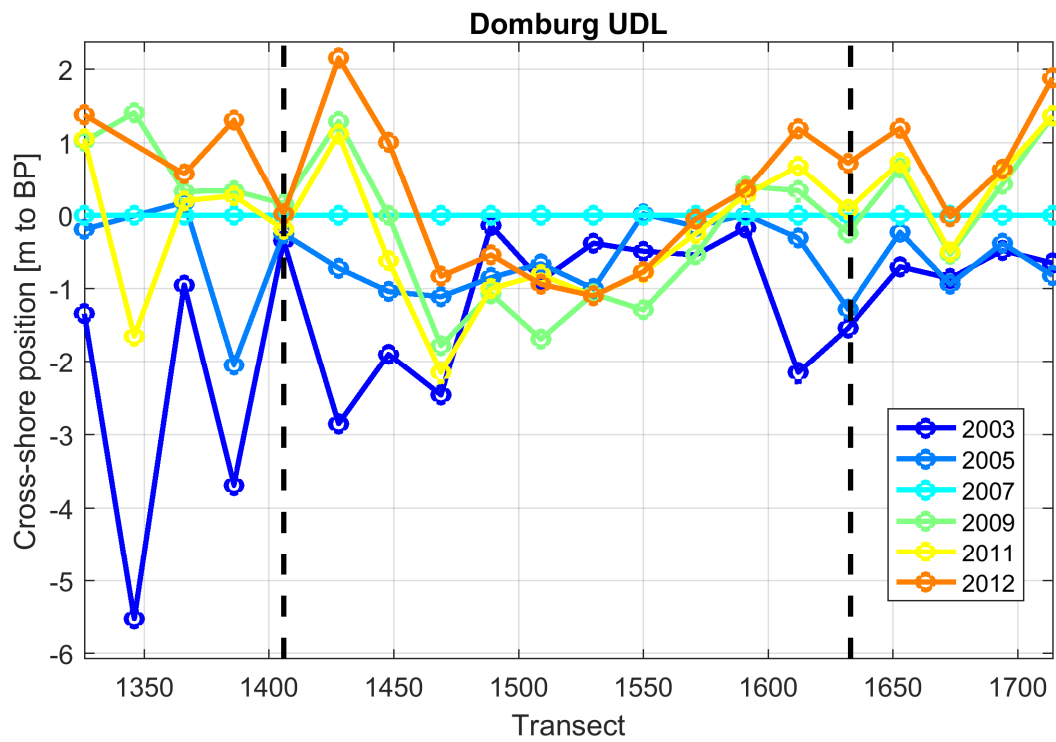


Figure 51: The difference in cross-shore position of MHWL with respect to 2007. When the value is positive the position lays more offshore than in 2007.

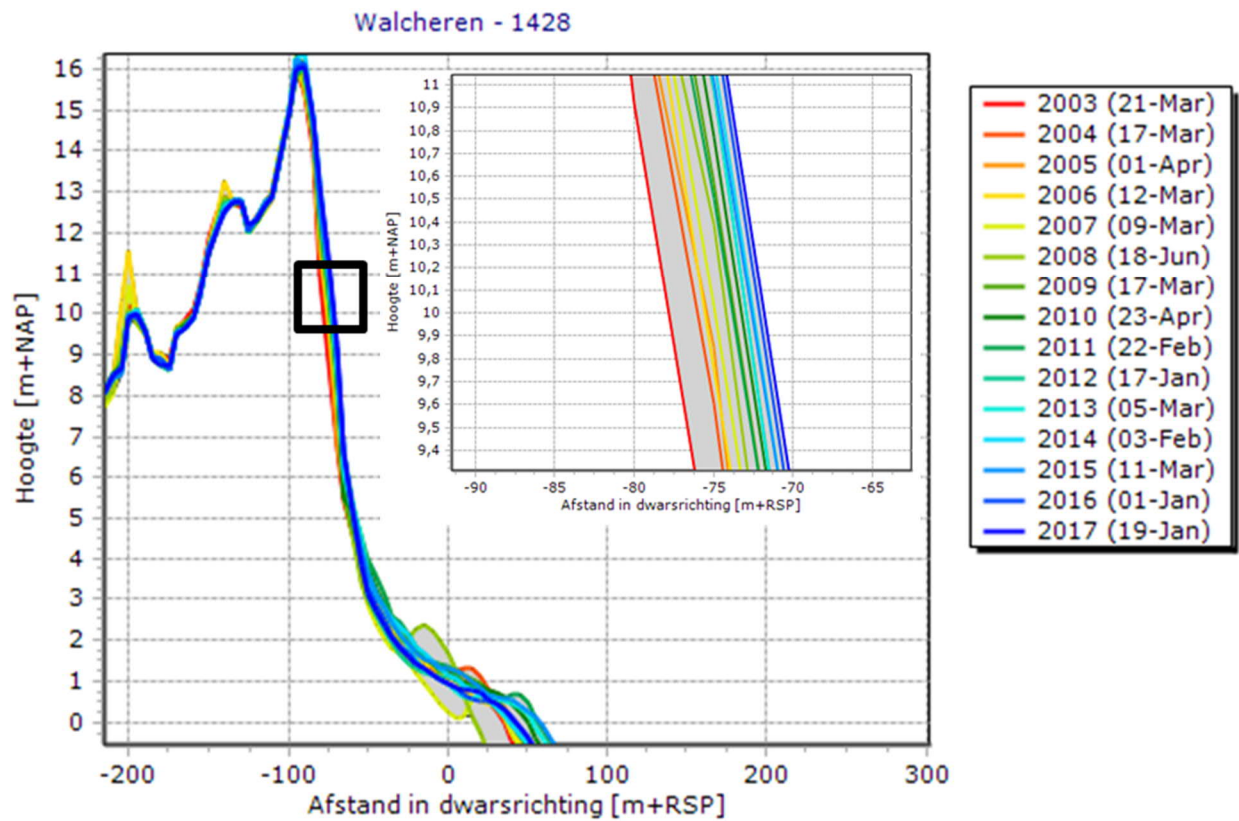


Figure 52: The dune profile for transect 1428 for the years 2003 till 2017. The colours represent various years. The figure also contains a zoom in of the profile. The black square indicates the location off the zoom in.

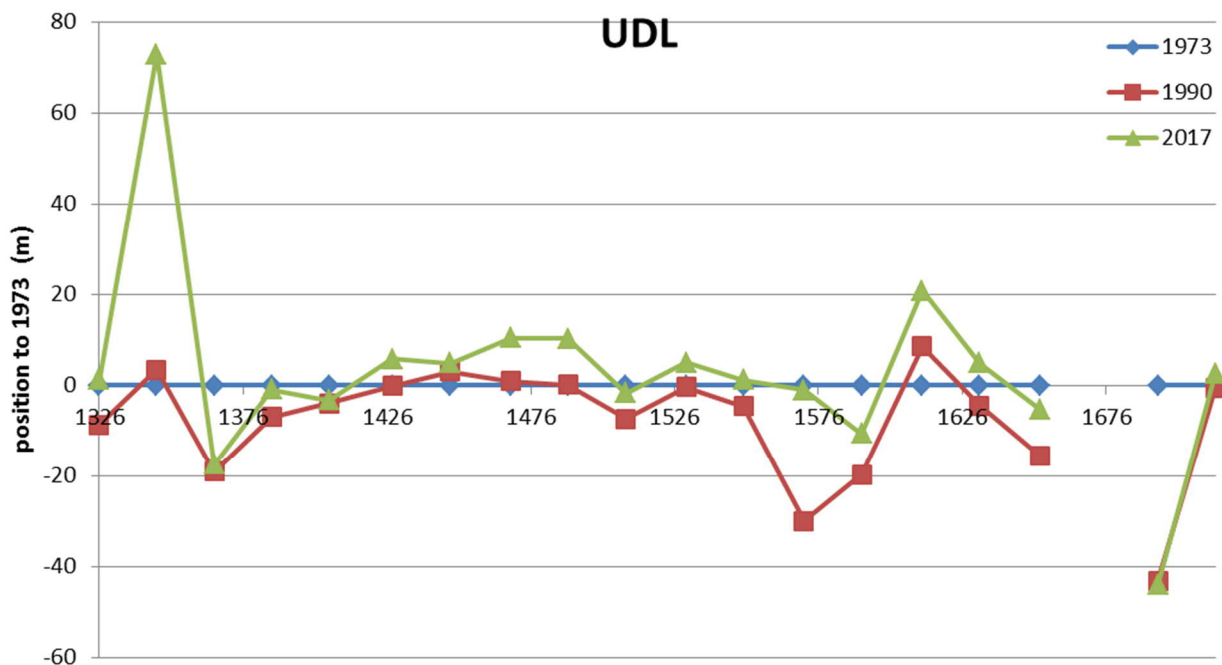


Figure 53: Position of the upper dune level for studied transects in 1973, 1990 and 2017

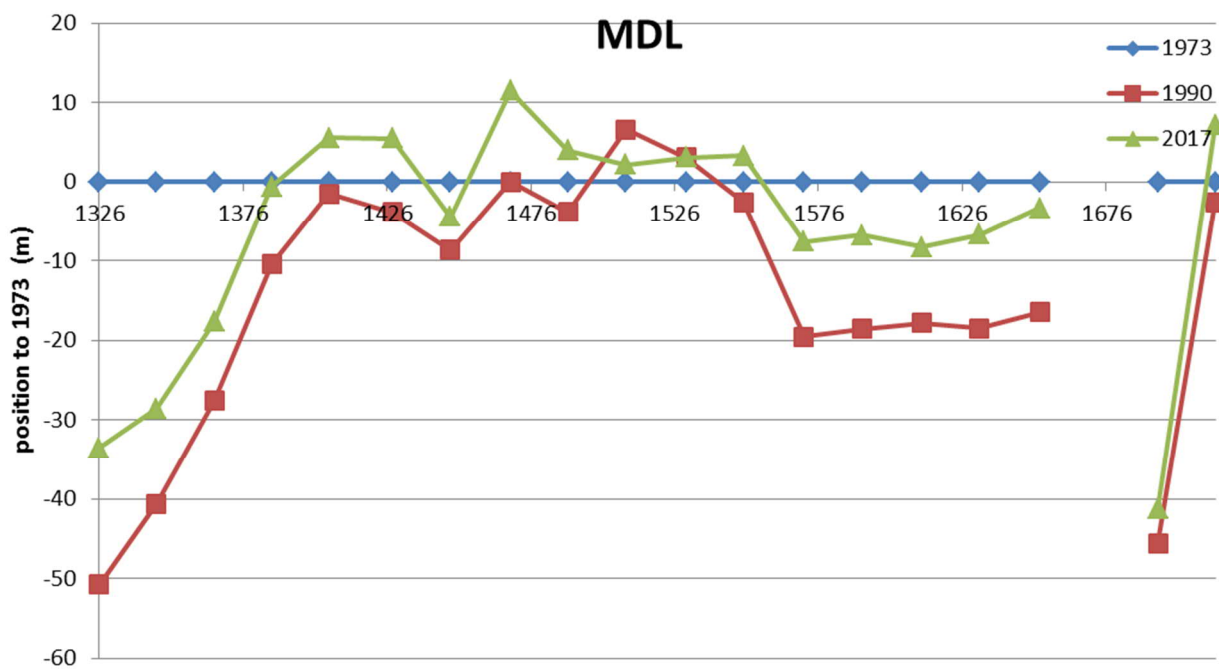


Figure 54: Position of the middle dune level for studied transects in 1973, 1990 and 2017

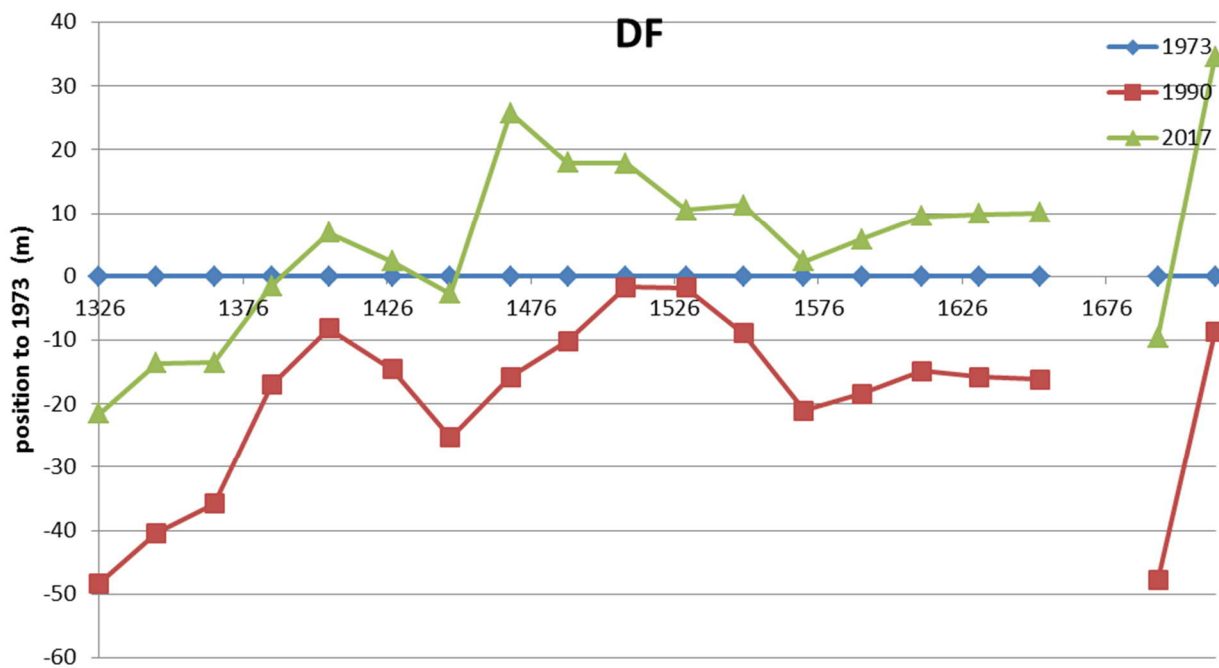


Figure 55: Position of the dune foot for studied transects in 1973, 1990 and 2017

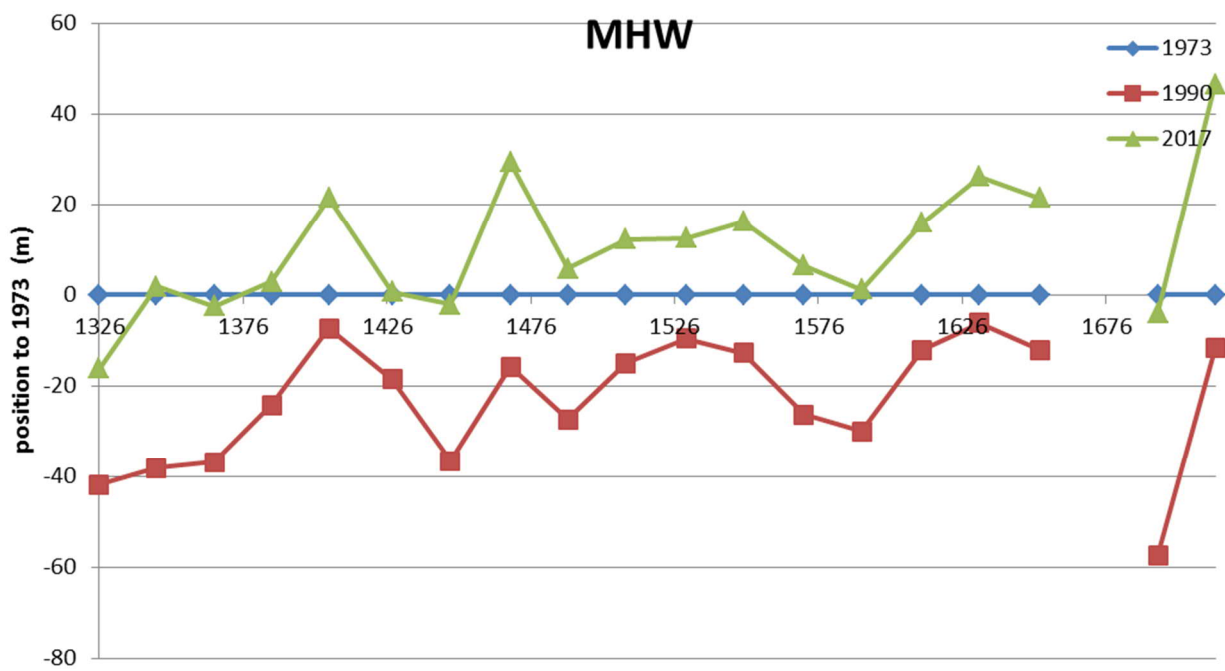


Figure 56: Position of the mean high water level for studied transects in 1973, 1990 and 2017

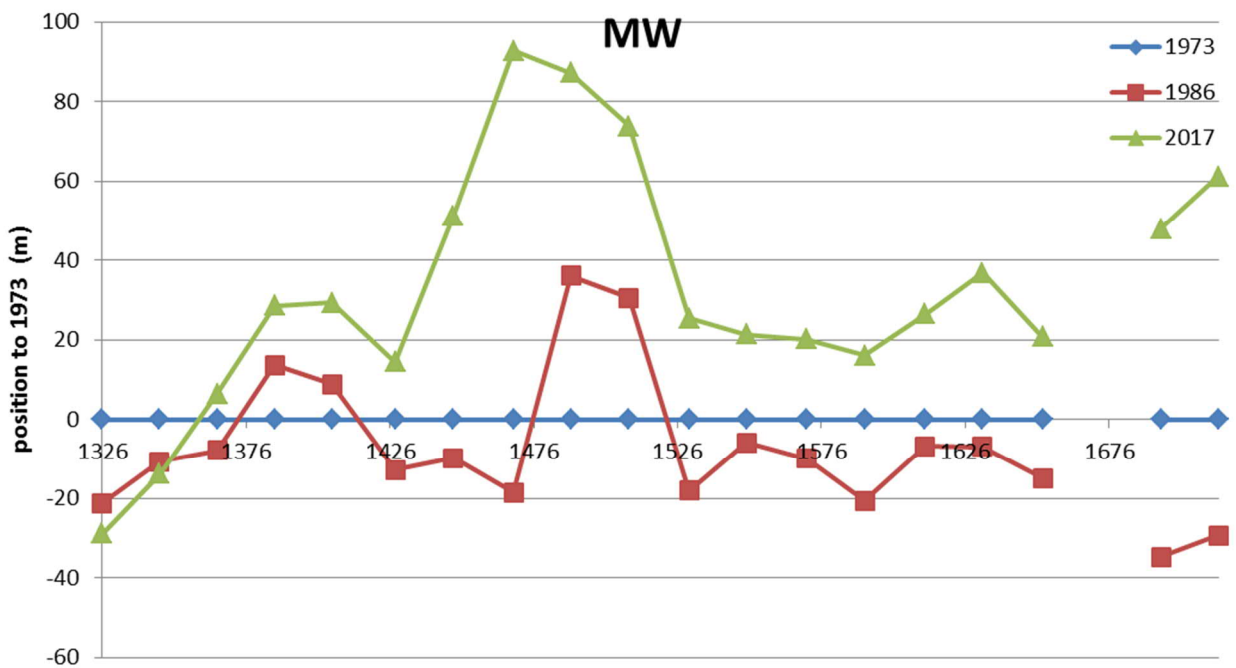


Figure 57: Position of the mean water level for studied transects in 1973, 1986 and 2017

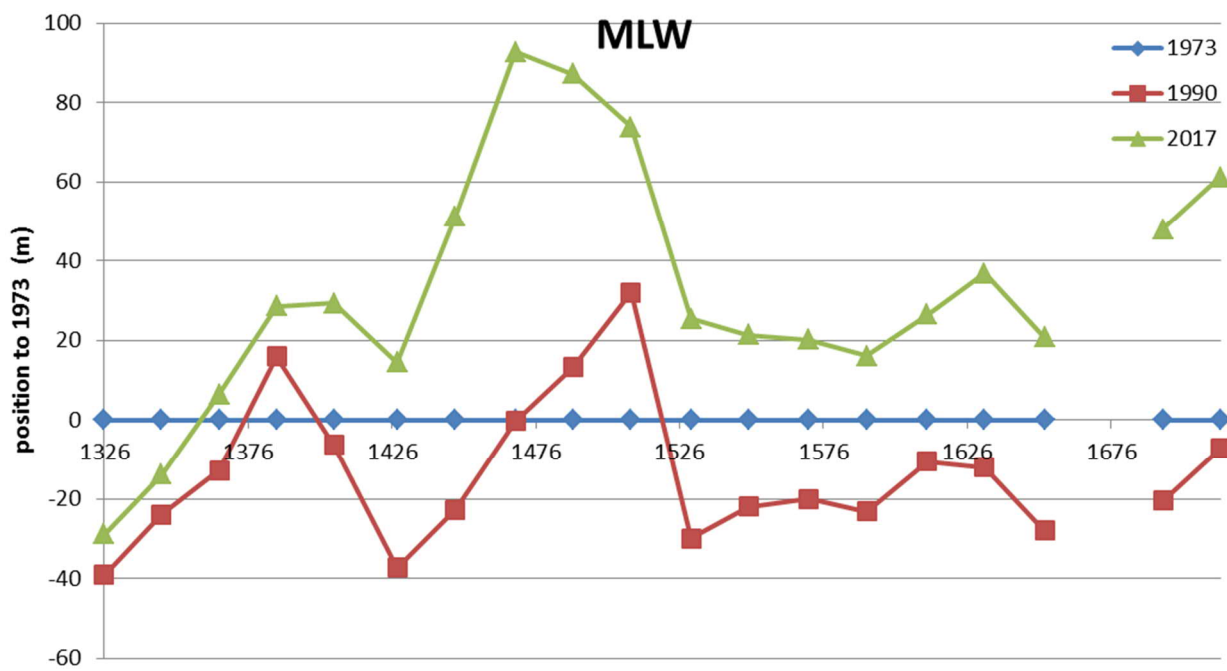


Figure 58: Position of the mean low water level for studied transects in 1973, 1990 and 2017

7.2.2 Volumes 2D

In total 13 areas were used to study the development of sediment volumes (Figure 59). The areas in the dunes, 9-13, were only used for the long-term behaviour.

The nourishment area consists of the areas 5-7, where area 6 encompasses the central part in which the nourishment was already present in the 2008 measurement. This is clearly visible in the increase of ca. 80.000 m³ in 2008 (Figure 60). The other nourished areas show only a small increase in volume in 2008 and increase further in 2009. The volume in area 6 shows a linear decrease in volume after 2008 and is below its 2007-volume in 2012. Area 5 and 7 show a relatively stable volume up to 2011 and a much larger decrease between 2011 and 2012. In 2012 the volume is around the 2007-volume.

The other areas on the beach, 4 and 8, show an increase in volume up to 2011 and a sudden decrease between 2011 and 2012. Between 2007 and 2012 the shoreface, area 1-3, shows a quite stable volume with a small increase in 2012 compared to 2007. The high volume of area 2 in 2008 is most likely an outlier.

The erosion of the nourished area (5-7) between 2008 and 2012 is 25.000 m³/year. This is relatively low, caused by the incomplete volume in the measurement of 2008. When in 2008 the design volume of 370.000 m³ would have been reached, the erosion rate is 93.000 m³/year, similar to the erosion rate after the 2000 nourishment (100.000 m³/year erosion in area 4-8 between 2000 and 2004). For the total area (1-8) the erosion was 49.000 m³/year, when correcting for the outlier of area 2 in 2008 and the incomplete nourished volume this is 79.000 m³/year.

The entire nourished area gained ca. 180.000 m³ in 2009, the entire area (1-8) increased with a bit more than 400.000 m³ (Figure 61). The relative change in volume (Figure 62) shows that in 2011 still 80% of the maximum amount of sediment was present in the nourished areas, while one year later this decreased to 0. When compared to the designed volume, already in 2009 the volume was reduced to about 50% and further decreased to slightly less than 40% in 2011 and 0% in 2012. The volume in the total area decreased slightly slower, reaching about 60% in 2012.

The average vertical changes (Figure 63) show similar change in time as the volumes (Figure 60). The most significant difference is the much lower vertical change in the shoreface areas (1-3), caused by the much larger surface area.

The changes in volume on the long term are presented in Figure 64. The shoreface shows large fluctuations from year to year. Up to about 1986 the volume is fluctuating around approximately 1 million m³ below the 2017 volume. Between 1986 and around 1995 the volume increased up to a level around the 2017 volume.

The beach and dunes show in general the same changes: decrease in volume up to about 1990, an increase until present. The beach volume in 1968 was approximately 300.000 m³ lower than in 2017, further decreases to ca. 700.000 m³ lower than 2017 in 1990 – -23.500 m³/year. The increase up to 2017 occurs with 'jumps' in volume after a nourishment, after which a rapid decrease in volume follows (clearly visible after e.g. 2000) - +25.000 m³/year.

The dunes are first measured in 1973, when the volume was only a little bit less than in 2017. In 1990 the

volume was decreased with more than 200.000 m³ – -12.300 m³/year. The increase up to 2017 is very linear – +8.500 m³/year.

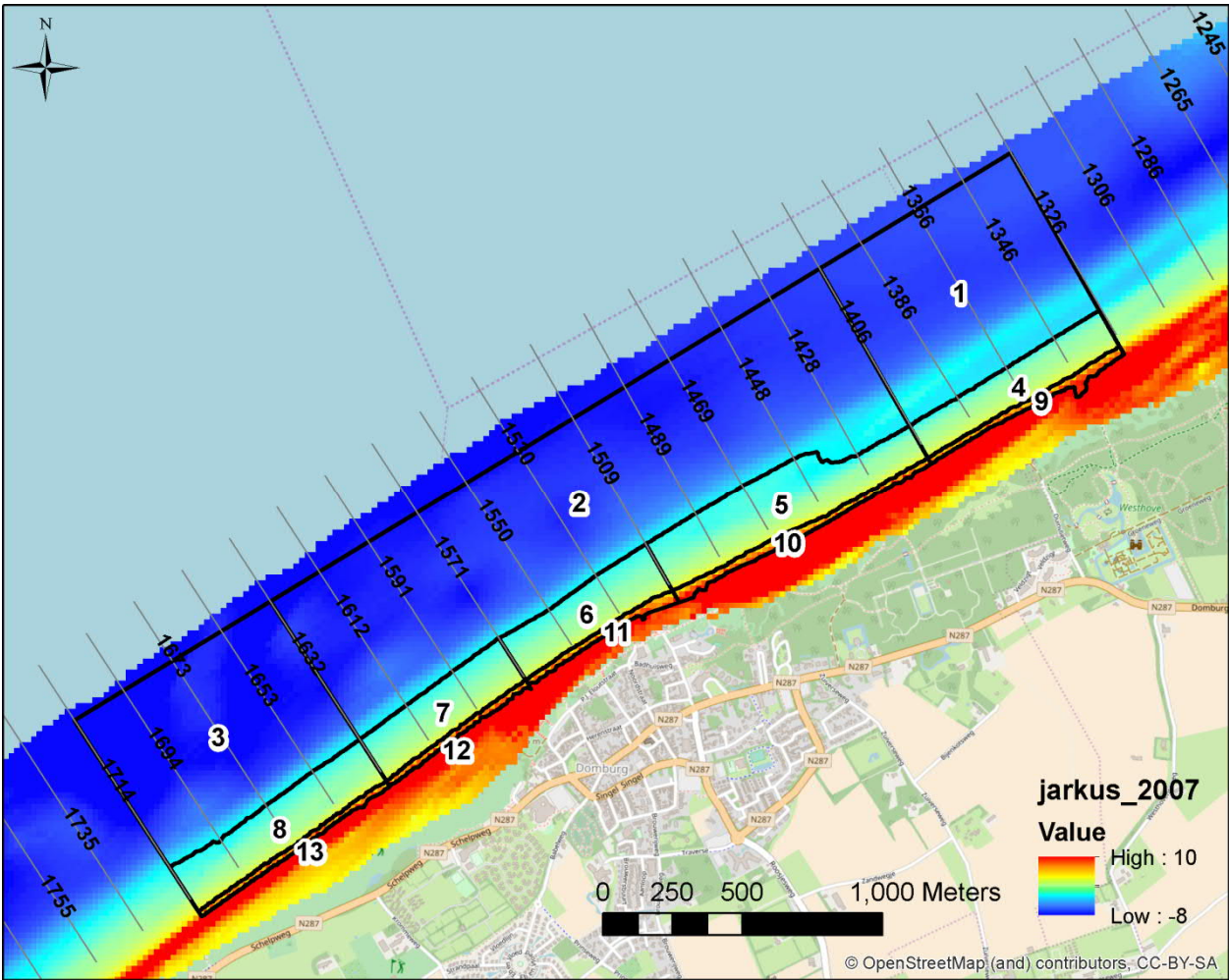


Figure 59 Areas used for calculation of volumes

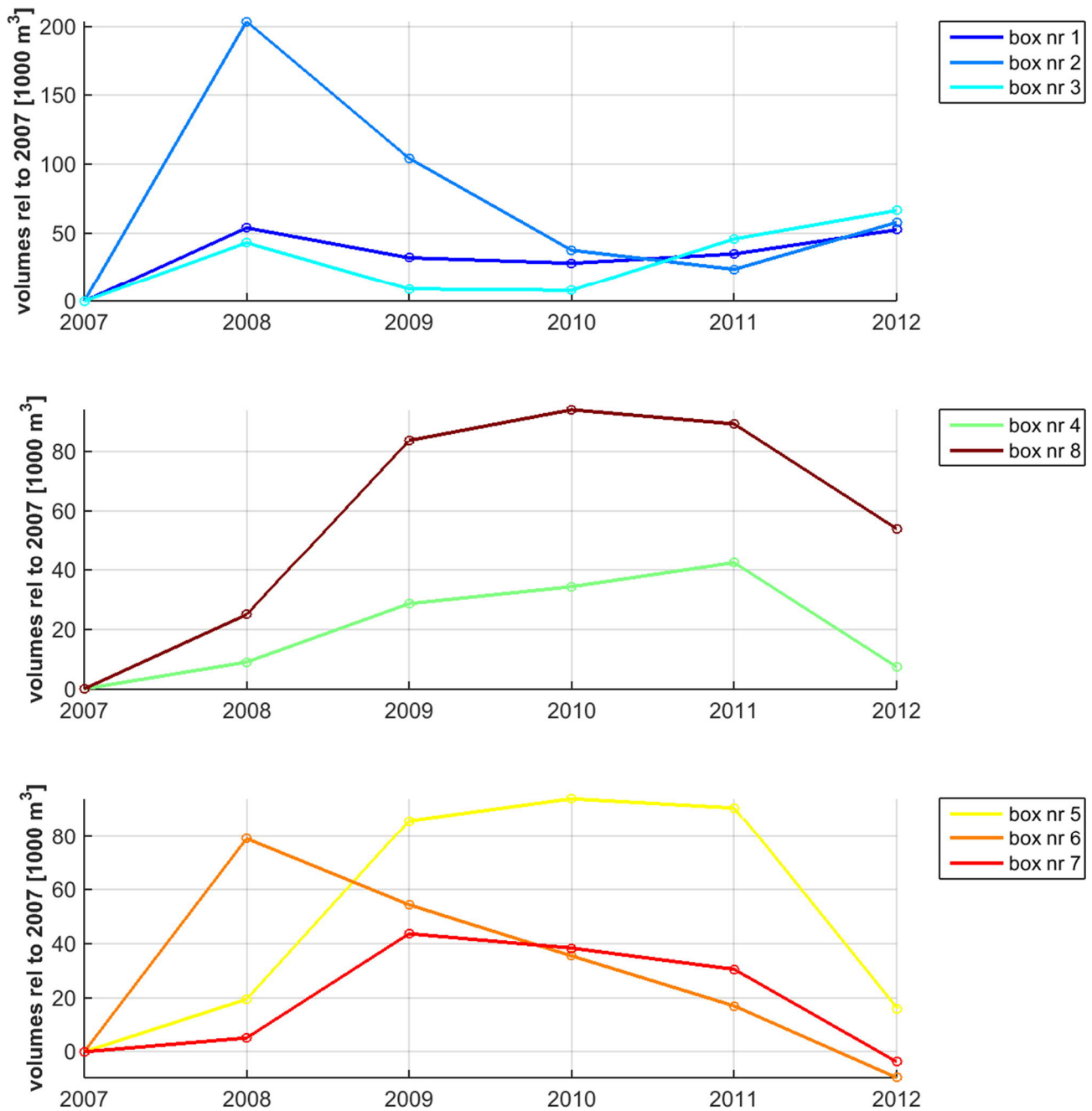


Figure 60 Volume development from one year before the nourishment until the last year before the next nourishment

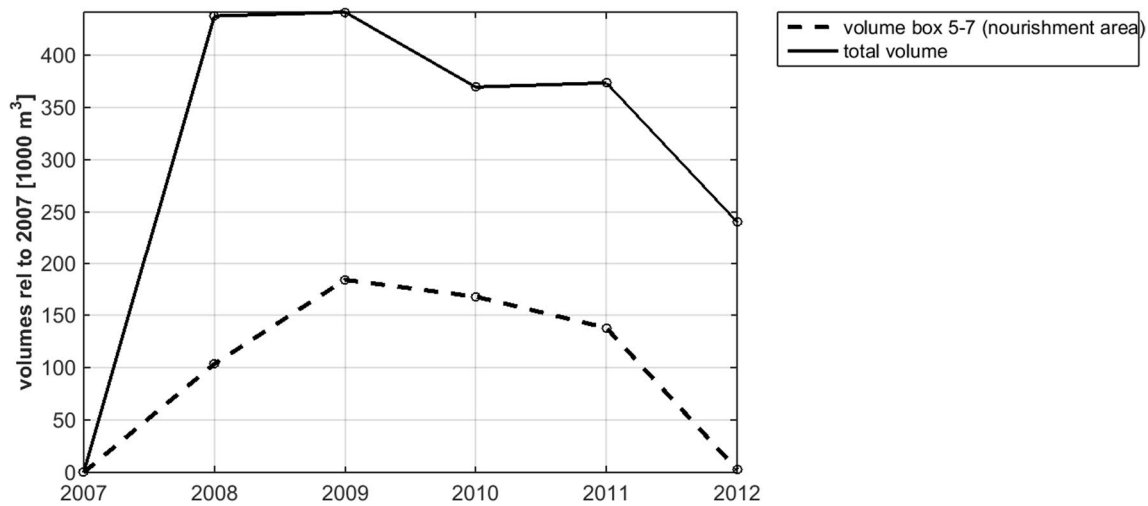


Figure 61 Volume development nourishment polygons (5-7) and polygons 1-8 (total volume)

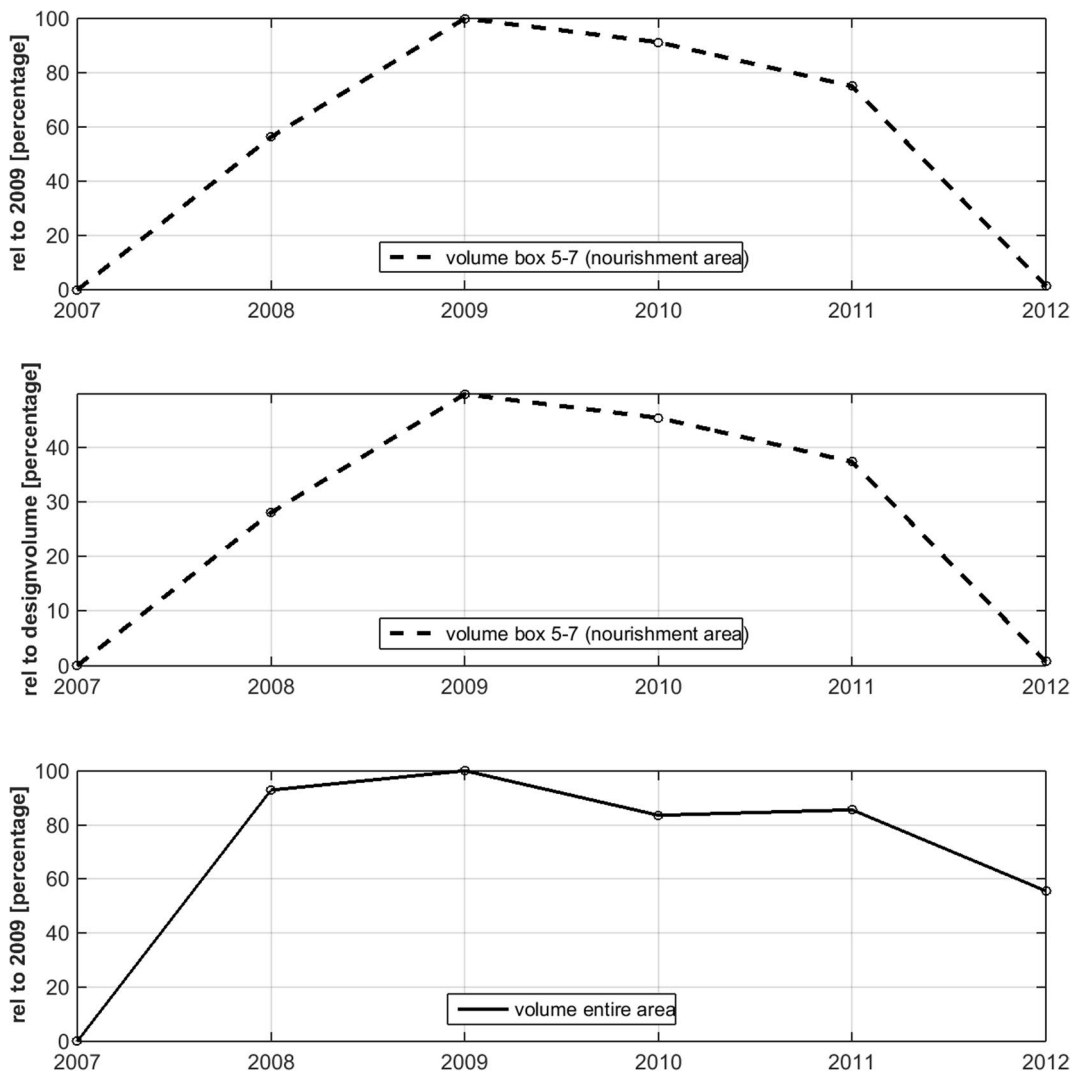


Figure 62 Volume development in percentages for nourishment area relative to maximum volume in 2009 (top), relative to design volume of 370.000 m³ (middle) and for entire area (area 1-8) relative to maximum volume (bottom)

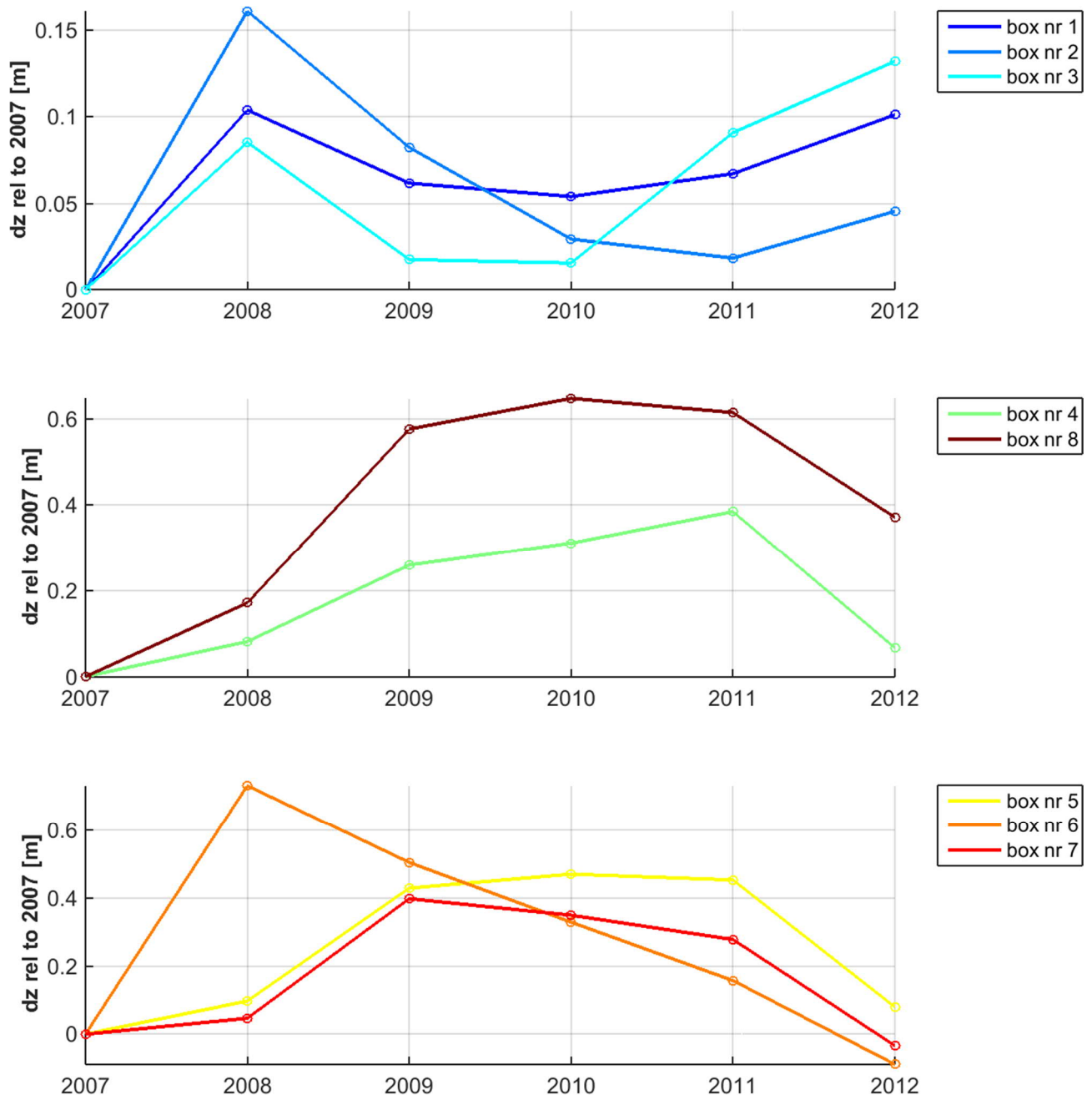


Figure 63 Change in average bed level for each polygon

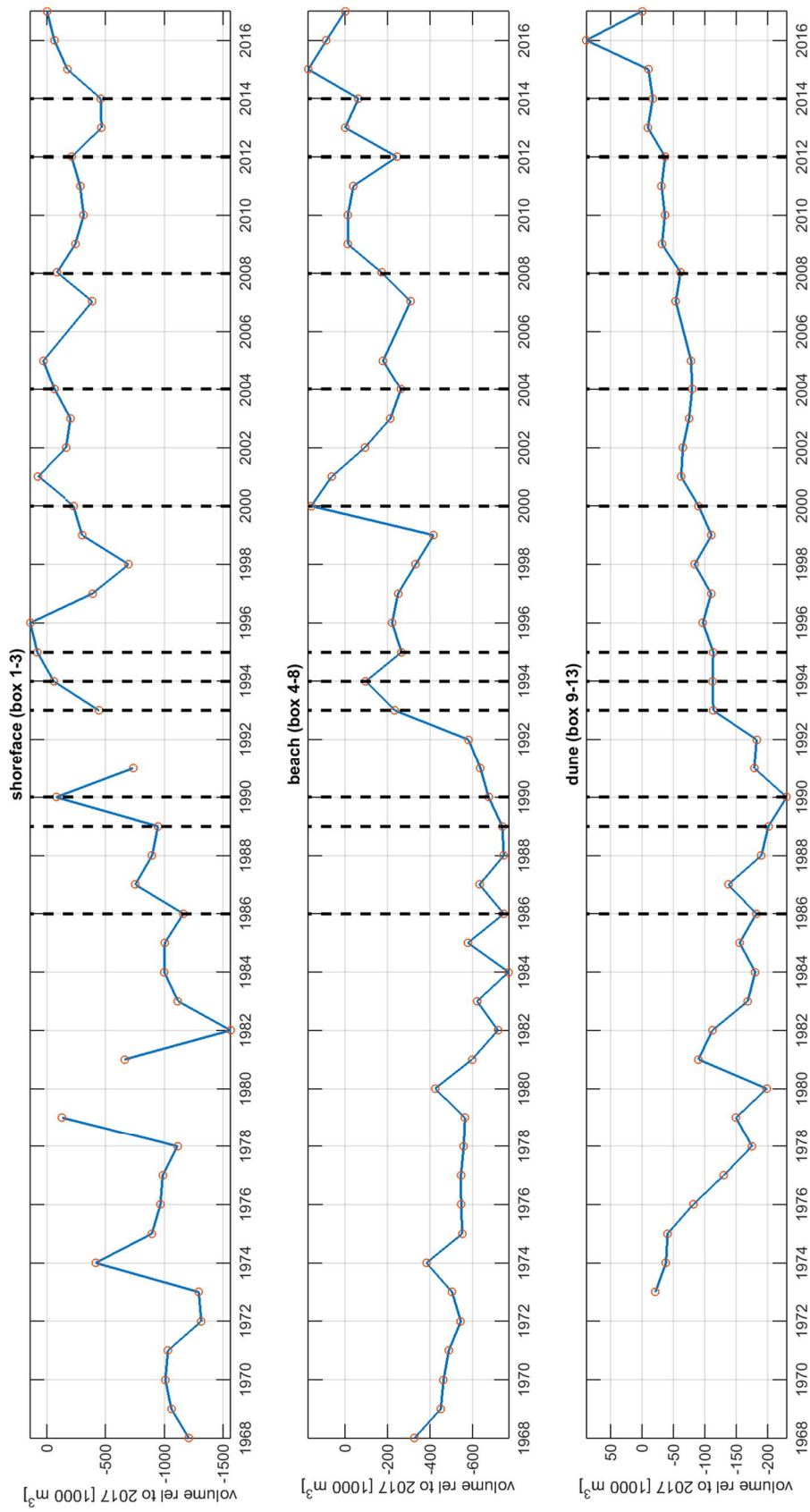


Figure 64 Long term volume development shoreface, beach and dune, dashed lines indicate nourishments

8 Synthesis

8.1 Nourishment performance

The studied nourishment at Domburg was clearly visible in the position of the physical marks and volumes. Also, another nourishment on the west side of the studied nourishment influenced the volume analysis.

Despite these influences the nourishment increased the sediment volume of the beach and caused a seaward displacement of the dune foot, mean high water line and mean low water line. In the lower shoreface no clear effect of the nourishment was found. The fluctuations in the volume of this area are most likely caused by a combination of data acquiring and local morphology. The morphology consists of shore-perpendicular oriented sand wave-like bed forms, no breaker bars are present.

After the nourishment the sediment volume of the beach to the east and west increased significantly. The area in the west was largely influenced by the new nourishment placed one year after the studied nourishment. Therefore, it is not clear if sediment transport to the west contributed or that the increase was (mainly) due to the new nourishment. However, considering the dominant westerly wind, it is likely that the major part of the transport is in easterly direction.

The fast disappearance of the nourished sediment volume from the beach is in line with the autonomous behaviour. Despite the short lifespan of the nourishment of about four years, on the long term this type of nourishment clearly have an effect on the volumes and positions of the physical marks. At several locations the most recent state (volume, physical marks) is better than the most seaward position before start of the nourishments.

It is likely that the eroded sediment is moved offshore and there transported by the tidal current towards the ebb tidal delta and the Eastern Scheldt estuary. The long-term changes show that also the dunes move seaward and increase in volume, implying increased sediment transport landward due to the nourishments.

8.2 Relation between nourishment development and hydrodynamic characteristics

The development of the nourishment occurred quite normally compared to other nourishments. Only the faster decrease in volume between 2011 and 2012 was remarkable. The hydrodynamic characteristics in this year however do not deviate from the other years (Figure 65). Also compared to the long-term hydrodynamic characteristics the period after the nourishment does not deviate (see also chapter 5).

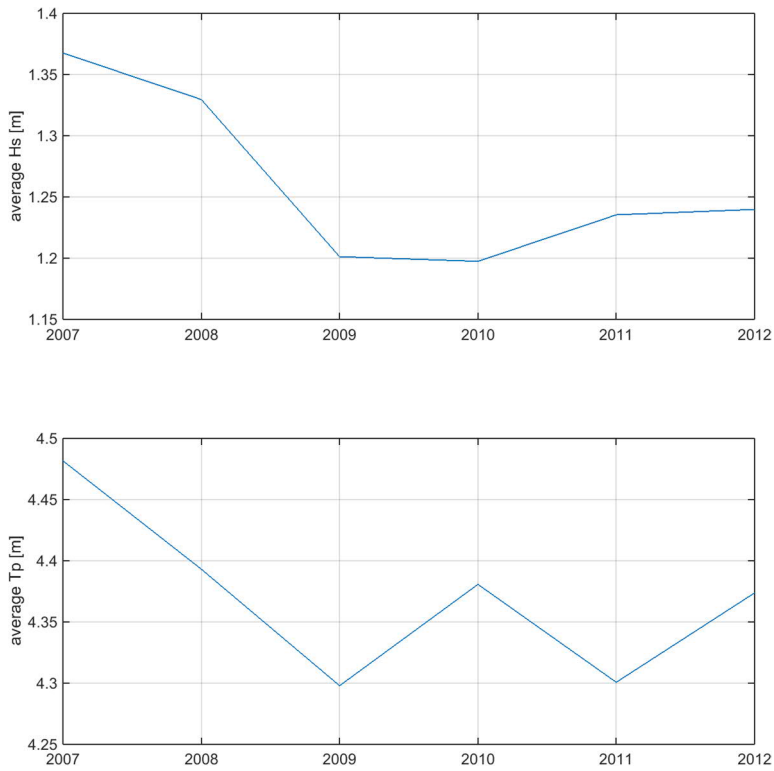


Figure 65 Yearly averaged significant wave height (top) and period (bottom)

8.3 Strategic goals

The long-term trends show that the high frequency of beach nourishment at the Domburg area contribute to the strategic goals to prevent chronic erosion so coastal functions can remain at the coast.

9 Conclusion

From this study the following conclusions can be made:

- The nourishment had the largest effect on the physical marks (coastal state indicators) around the beach: dune foot, mean high water and mean water;
- Sediment from the nourishment is transported eastward, increasing volume on adjacent the beach;
- The dunes are slightly growing since start of nourishments: the frequent beach nourishments contribute to more landward sediment transport;
- Sediment transported seaward is taken further away by tidal current
- On long term, the repeated nourishments increased the volume, although directly after a nourishment the (local) erosion rate is increased;
- Lifetime of the nourishment is about four years; the half time is about one year;
- In the beach and shoreface (areas 1-7) 35% of the sediment volume is present after four years (after corrections);
- Average daily conditions are the driving force that caused the observed changes.

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