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Report

Co-analysis of nourishments;

Towards a transnational understanding of nourishment behaviour

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Report

Colophon

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1 Table of content

1. Introduction

Building with Nature (BwN) is a phenomenon already known for several decades in which natural forces are used to build, construct or maintain a human intervention. Building with Nature is also known as Natural Flood Management (UK) or Natural and Nature-Based Solutions (USA). In this interregional North Sea project experiences with Building with Nature (BwN) in different countries are shared.

1.1. Interreg NSR VB Building with Nature project

The overall objective of the BwN project is to make coasts, estuaries and catchments of the North Sea Region (NSR) more adaptable and resilient to the effects of climate change. The main goal to achieve during the time frame of the BwN project is to create a well-documented evidence base, by transnational knowledge exchange, that allows for policymakers and asset owners to incorporate Building with Nature / Nature Based Solutions and principles in future decision-making processes.

1.2. Work Package 3 – Coastal resilient laboratories

Work package three (WP3) is one of the six work packages. It will demonstrate climate change solutions at seven target sites; coastal resilient laboratories. These sites comprise large-scale existing investment projects that will be leveraged and enriched with transnational best practice, performance monitoring, co-analysing and transnational practitioners' lessons learned on the effectiveness of these investments/interventions in different coastal management schemes (Wilmink, 2017).

WP3 focusses on beach and shoreface nourishments, sediment management and erosion control by means of ecosystem-based solutions (e.g. Eelgrass) as outlined in Wilmink et al. (2017). Learning by doing is a key element in this work package. By doing research to implemented BwN measures on a project's lifecycle through monitoring, it helps to identify knowledge gaps, provide lessons for other locations and enhances the understanding and applicability of BwN measures.

1.2.1 Research questions

Copied from Wilmink (2017): To come up with an evidence base of building with nature solutions with respect to climate resilience, several research questions are drawn. The main research question for this project is:

"In what way is resilience to climate change using Building with Nature principles best served in coastal management in the North Sea region?"

To answer the main question, several sub-questions are drafted:

- Given the current practices of all partners, which knowledge gaps can be identified to come up with a shared methodology of analysing all current practices (applied BwN solutions)?
- Can driving forces and/or coastal characteristics be identified which cause possible differences in coastal behaviour?

- What can be concluded from differences in coastal behaviour at each study site with respect to coastal management and climate resilience?
- What can be concluded from different approaches of building with nature solutions with respect to climate resilience?
- What can be concluded concerning the import and export of sediment towards the Wadden Sea back basin?
- Can a shared common best approach in coastal management be defined for all partners using Building with Nature principles?

1.2.2 Research approach

The first step in this research is the inventory and comparison of current practices of each partner and an inventory of behavioural differences of shoreface nourishment in the Netherlands by Bruins (2016). Besides the research of Bruins (2016), factsheets have been drafted for all partners on their current practice: 'From flood prevention strategy to the execution and evaluation of nourishments'. The merged factsheets can be found at: https://northsearegion.eu/media/3540/report-from-flood-prevention-strategy-to-current-practice-nourishments.pdf. In addition a data factsheet was drafted to share (meta)data and data availability of each partner (https://northsearegion.eu/media/3326/resilient-coastal-laboratories-data.pdf). Also, a common EU dataset out of all national data was built by Bregman (2017). This dataset helped to compare and identify key differences of the coastal labs, as presented in Naus (2018).

The next step was to comprise a shared transnational methodology (internal working document) to analyse all laboratories in a consistent way by means of the development of various coastal state indicators over time. The results can be found in the National analyses reports, per coastal laboratory available on the BwN project website (https://northsearegion.eu/building-with-nature/). In addition scientific research was conducted by principal component analysis into the behaviour of nearshore breaker bars and the impact of shoreface nourishments herein by Bartmentloo (2018).

The national analyses are being brought together (twinning programme) in a co-analysis of all laboratories. The co-analyses - this document - will focus on performance monitoring of beach and shoreface nourishments in the selected coastal laboratories by means of hypotheses testing. These results will also be published by means of an (conference) publication.

The individual analyses, data sharing, co-analyses, learning by doing, common lessons learned are now consolidated as an evidence base which is the input for the North Sea region nourishment practitioners' lessons learned document, the final product of this work package. The NSR practitioners' lessons learned on nourishments is drafted out of conclusions of the co-analysis and outlines technical guidance to help design, model, monitor and effectively implement BwN solutions along the North Sea region (see also Hillmann et al, 2019).

1.3. Reading guide

This report is the co-analysis document of the EU Interreg NSR VB Building with Nature project. Chapter 1 is a general project overview that included the research line of the coastal work package (WP3). Chapter 2 describes the coastal laboratories followed by the research methodology, the tested hypotheses and their results in chapter 3. Chapter 4 presents a syntheses with respect to the coastal management strategies and the conclusions.

2 Coastal laboratories

2.1 Short overview

In the Building with Nature project - work package 3 (WP3) - nourishments were analysed by the partners at 7 locations, called 'coastal laboratories'. The labs from north to south are; Skodbjerge (Denmark), Krogen (Denmark), Sylt (Germany, Schleswig-Holstein), Langeoog (Germany, Niedersachsen), Bergen-Egmond (the Netherlands), Zandvoort-Bloemendaal (the Netherlands) and Domburg (the Netherlands), see Figure 2.1. At each location, one or more nourishment(s) have been applied, studied and described in the National Analysis reports. Most labs are located in morphologically highly different areas, which results from the different genesis of the coastal areas. This has a strong influence on the analysis, results and conclusions, also regarding the specific nourishment design. For more detailed information about the labs, also see the National Analysis reports. In total two beach nourishments, four shoreface nourishments and one combined shoreface-beach nourishment were studied (Table 2.1). At Sylt the nourishment consisted of three separate parts, at Zandvoort-Bloemendaal the nourishments of 2004 and 2008 were designed together and therefore both analysed in the study. For further details of the nourishments we refer to the national reports (see https://northsearegion.eu/building-with-nature/output-library/ under 'National Analysis').

Table 2.1 Overview of the laboratories' main characteristics (source data: LKN, NLWKN, DCA, RWS)

Lab	Type Nourishment	Year	Tidal range [m]	Wave height (Hm0) [m]
Skodbjerge	Shore face	2011	0.7	1.32
Krogen	Shore face	2016	0.7	1.28
Sylt	Shore face	2006	2.0	1.45
Langeoog	Beach	2017/2018	2.6	1.15
Bergen-Egmond	Beach and shore face	2010/2011	1.6	1.22
Zandvoort-Bloemendaal	Shore face	2004/2008	1.7	1.19
Domburg	Beach	2008	3.1	1.08

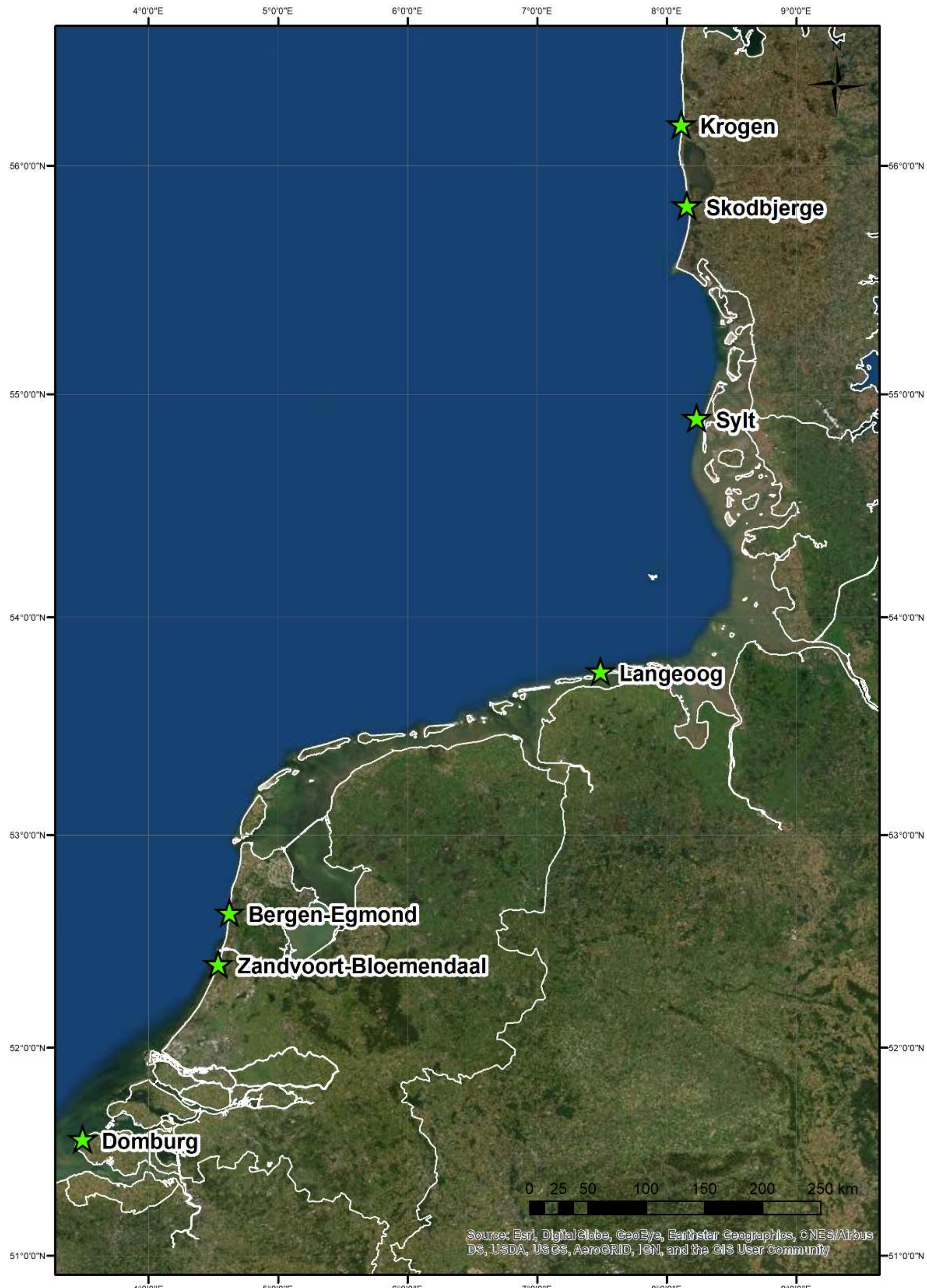


Figure 2.1 *Overview of coastal laboratories*

2.2 Coastal characteristics

2.2.1 Profiles

The coastal profiles of the labs are shown in Figure 2.2 (actual elevation) and Figure 2.3 (stacked). Only one profile for each lab is presented which gives an indication of the morphology. Due to the dynamics a profile can change in time and will also vary per location within each lab.

The first dune row of each lab has a similar steepness of the front but varies in height and width. The height ranges from around MSL +10m (Langeoog) to MSL +17 (Bergen), the width (from dune foot (here +3 m) to +5 m on landward side) is up to ~90 m at all labs except Zandvoort and Bergen where it is 200-300 m (not shown in the figures).

From the dune foot (+3 m) towards mean sea level (0) the profile at Sylt is remarkably different with a much steeper gradient. This might be related to the coarser grain size in this lab (see paragraph 2.2.5). The variation between the other labs are in the order of magnitude of local variations in morphology (due to e.g. rip channels).

The shorefaces of the labs are showing a variety in morphologies. Most profiles show breaker bars, except Langeoog and Domburg. These two labs have a relatively flat profile, with Langeoog being very shallow reaching MSL -5 m at 1500 m distance and Domburg MSL -10 m at that distance. The Langeoog lab is located on an island and in close vicinity of the ebb delta which supplies the lab with sediment.

The profiles which contain breaker bars also show differences in steepness, with Sylt being very steep (MSL -10 m at ~800 m distance), Bergen, Krogen and Skodbjerge are sloping a bit gentler and Zandvoort having a very gentle slope (MSL -10 m at 1500 m distance). The dimensions of the bars will change in time and can therefore not be compared entirely based on only one profile. Sylt generally has only one breaker bar in the system, while other labs may have two to three bars.

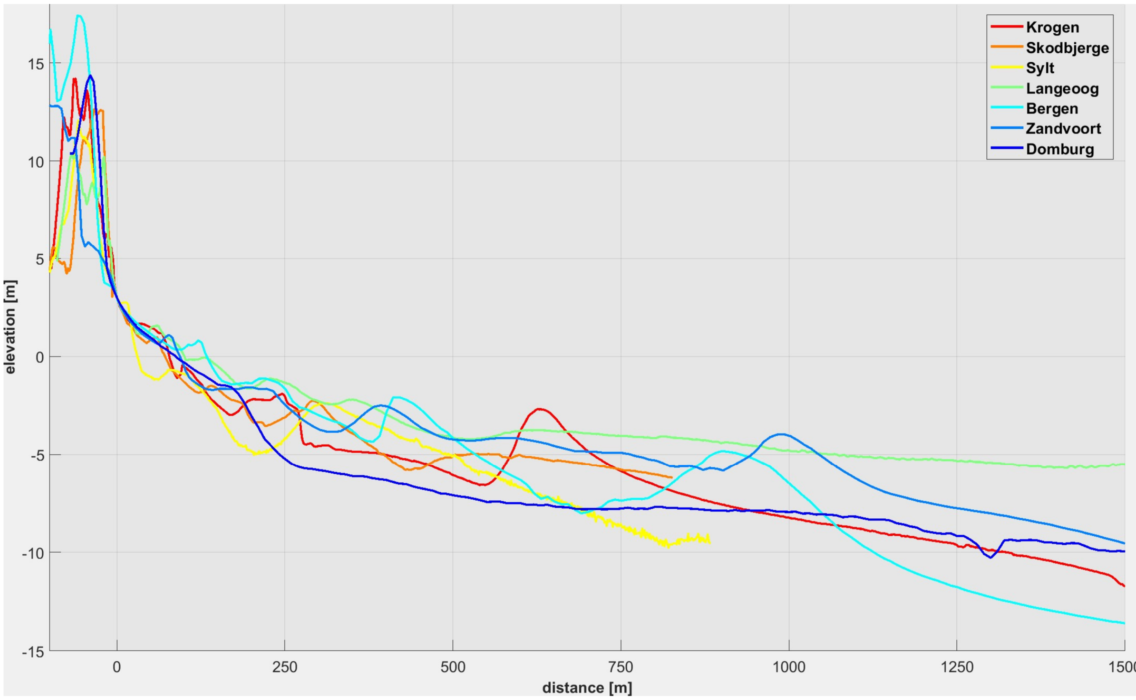


Figure 2.2 *Typical profile for each lab, distance at MSL +3 m is set at 0 for comparison*

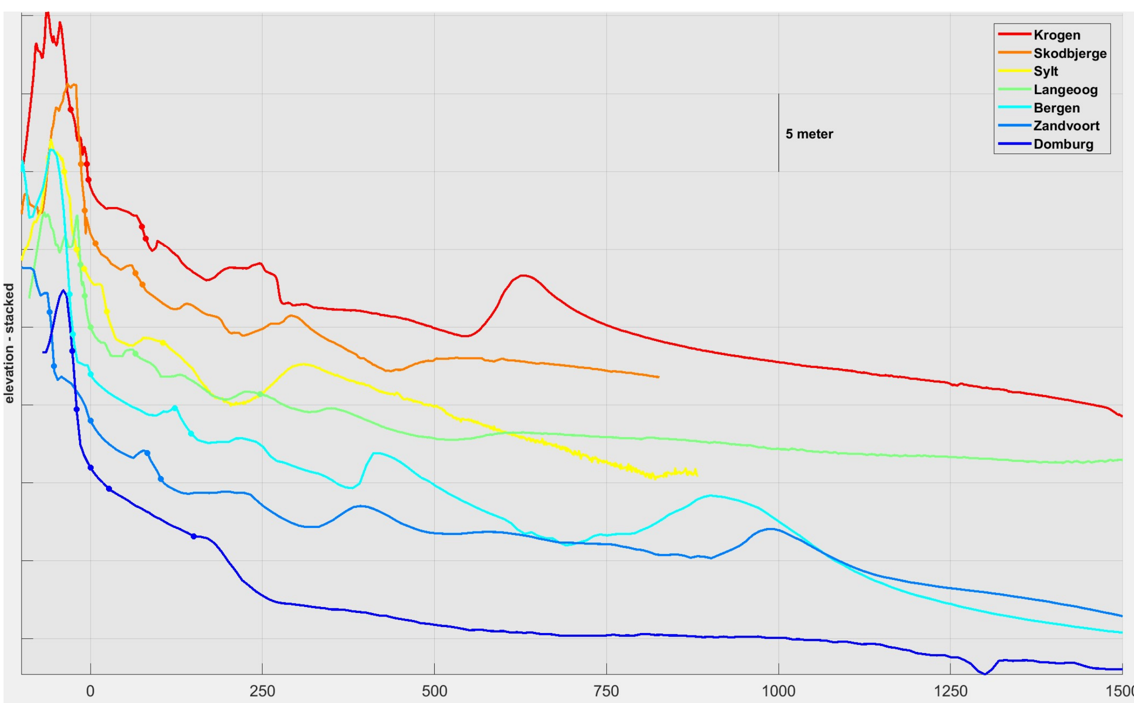


Figure 2.3 *Typical profile for each lab with an incremental offset in y (3 m between each profile), distance at MSL +3 m is set at 0 for comparison. Points indicate coastal state indicators (see next paragraph).*

There are some other characteristics (parameters) in the coastal laboratories that show the typical behaviour and the interaction between the various parameters. Although there are many kinds of interactions between all indicators, parameters, impacts and sediments; it can be shown that there are some distinct dependencies.

For each laboratory a set of different coastal state indicators is used (see Table 7.1 in Appendix A). Using the definitions of transects and coastal state indicators (CSI's), a set of additional parameters was calculated (for the transects were the nourishments are located). In addition to the coastal state indicators, a depth of -6.50 m MSL is taken for all labs as the seaward boundary for shoreface calculations. For the parameters as slopes, volumes and system volumes the calculations are done for the hypsometric layers as named in Table 2.2. The results for the system volumes are shown in this paragraph, the other parameters are shown in Appendix D.

Table 2.2 Hypsometric layers used for morphological calculations, see Table 7.1 for CSI levels for each lab.

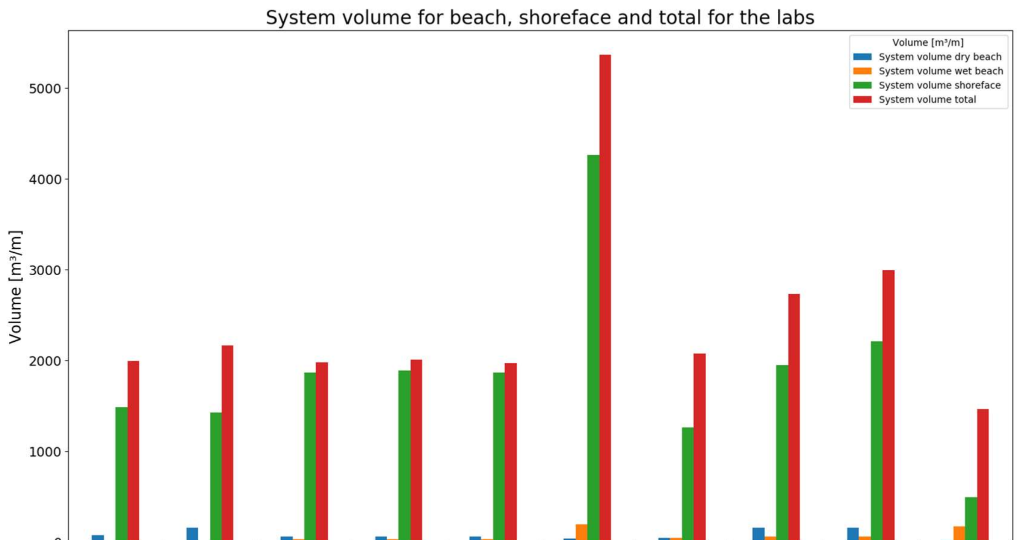
Hypsometric layer	From height (CSI)	To height (CSI)
Dry beach	LDL (DF)	MHW
Wet beach	MHW	MLW
Shore face	MLW	-6.5 m
Total	LDL (DF)	-6.5 m

In a first step the time-weighted averages between 1986 and 2018 for each parameter and lab is calculated.

In Figure 2.4 the mean system volumes of the different hypsometric layers are shown. The volumes differ from lab to lab and between the hypsometric layers. The main characteristics for the system volumes are as follows:

- Dry Beach: The system volume (available sand) of the dry beach is the least at Domburg (15 m^3/m), followed by Langeoog (37 m^3/m), Bergen (46 m^3/m) and the labs on Sylt (58 m^3/m), while the largest amount of sand is available at Zandvoort (154 m^3/m) and Krogen (161 m^3/m).
- Wet beach: The system volume of the wet beach is the least at Krogen (4 m^3/m), followed by the labs on Sylt (27 m^3/m), while the largest amount of sand on the wet beach is available at Langeoog (196 m^3/m) and Domburg (172 m^3/m).
- Shore face: The system volume of the shore face is the least at Domburg (491 m^3/m), while Langeoog has the largest amount of sand in the shore face (4258 m^3/m), followed by Zandvoort (2207 m^3/m to 1949 m^3/m).
- Total (beach and shore face down to -6.5 m): At the whole profile (beach and shore face) the least system volume is at Domburg (1464 m^3/m), while the largest amount of sand on the whole profile is available on Langeoog (5369 m^3/m), followed by Zandvoort (2996 m^3/m to 2730 m^3/m).

The labs Langeoog (most) and Domburg (least) show the extreme values in system volumes. Another difference of the labs can be recognized by the ratio of the shore face system volume and the total volume (including the beach system volume). At the labs on Sylt the main amount of available sand is coming from the volume in the shore face while in the other labs the beach has a larger contribution to the total system volume. Due to the measurements (beach and shoreface differ in time and space) it is not possible to add the single volumes (dry beach, wet beach and shore face) in order to get the total volume.



	Skodbjerge	Krogen	Rantum	PuanKlent	Sansibar	Langeoog	Bergen-Egm.	Zandvoort 2004	Zandvoort 2008	Domburg
System volume dry beach	78	161	59	58	58	37	46	154	155	15
System volume wet beach	4	4	27	28	28	196	43	60	57	172
System volume shoreface	1483	1427	1869	1888	1867	4258	1265	1949	2207	491
System volume total	1993	2168	1979	2010	1968	5369	2078	2730	2996	1464

Figure 2.4 System Volumes for different hypsometric layers (morphological zones) in the labs.

2.2.2 Coastal state indicators (CSI's)

At each lab the height level of morphological features, so called 'coastal state indicators' (CSI's), have been quantified. From top to bottom the following indicators were identified: upper dune level (UDL), middle dune level (MDL), dune foot (DF), mean high water (MHW) and mean low water (MLW), see Figure 7.1. The levels of the coastal labs are shown in a graph in Figure 2.5. A schematic profile with the CSI's, typical profiles of the labs with the CSI's and a table with the values per lab can be found in Appendix A.

The upper dune level lies between 7 m (Langeoog) and 10.5 m (Domburg). This level gives an indication of the height of the dunes in the areas but does not (necessarily) equal the highest dune height. Within each area the dune height will vary from profile to profile (alongshore) and in time.

The middle dune level shows a decrease from Domburg (6.74 m) in the south to Skodbjerge (4.5 m) in the north. This trend is the result of the used upper dune levels and dune foot levels, and not likely to represent an actual change occurring at other dunes along the North Sea coast.

The dune foot is chosen at 3 m for the Dutch labs and Langeoog, and slightly higher at Sylt (3.75 m) and Skodbjerge (3.5 m). It coincides roughly with the inflection point from the flatter beach to the steeper dune front.

From the MLW and MHW the tidal range can be observed (Figure 2.5), which is relatively large at Domburg (3 m) and Langeoog (2.6 m), intermediate at Bergen (1.6 m), Zandvoort (1.67 m) and Sylt (2 m) and smallest at Krogen and Skodbjerge (0.74 m).

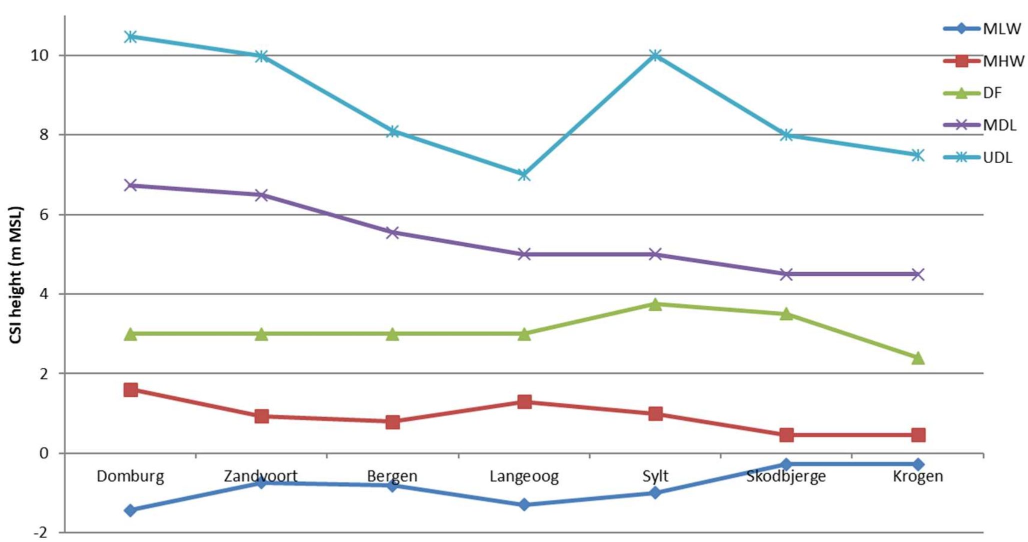


Figure 2.5 *Coastal state indicators used in each lab: upper dune level (UDL), middle dune level (MDL), dune foot (DF), mean high water (MHW) and mean low water (MLW)*

2.2.3 Sediment

To characterize the sediment for each lab, the d50 grainsize of the sand fraction have been reported. Although this gives relevant information for e.g. sediment transport, there are some remarks about this information.

The data available for the Dutch labs (Domburg, Zandvoort and Bergen) dates back to the 70's and 80's. At Sylt, the natural grainsize is strongly influenced by the grainsize of the nourishments, which is much coarser. At Danish locations coarse material is present, which is not reflected by the d50 of the sand fraction that only includes grainsizes smaller than 2 mm. With the coarser material included, the d50 at Krogen is 0.71 mm and at Skodbjerge 0.40 mm.

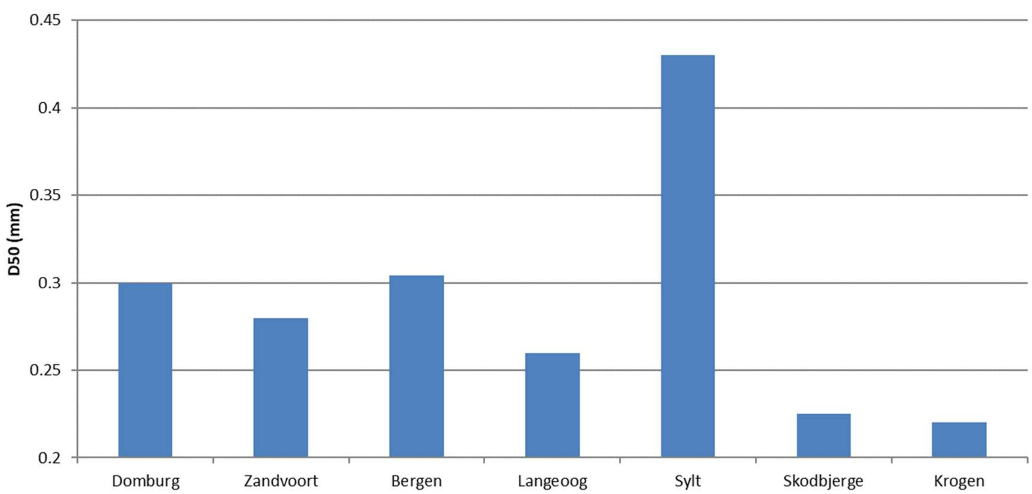


Figure 2.6 D50 grainsize of the sand fraction 63 to 2000 μm for the labs

2.2.4 Wave characteristics

For each lab wave characteristics have been calculated, based on local data and data from the CoastDat2 model database (see Appendix B for more detailed information on the CoastDat2 database). The data from CoastDat2 provides the most comparable values between the labs due to the availability at the same epoch and at a similar depth of the measurement locations in each lab. In this paragraph therefore only the CoastDat2 data is presented. Parameters have been calculated for the period 2000-2014.

Both the wave height and the wave period show in general an increasing trend from the southern to the northern labs (Figure 2.7). Although the wave period is overestimated by the CoastDat2 data, the comparison between the labs and therefore the trend are considered representative. The wave height (Hs) shows an increase from about 1 m at Domburg, the Netherlands, to almost 1.4 m at Skodbjerge, Denmark.

This increase in wave height and period is also reflected in the total wave energy (Figure 2.8). The slightly smaller wave height at Langeoog compared to Bergen causes a clear drop in wave energy, since this is related to the square of the wave height. Most labs have a large part of waves perpendicular to the coast, except Domburg and Langeoog. The ratio between left- and right-directed waves to the shore seems to show a decreasing trend in northward direction (see national analysis reports for details). This is assumed to be coincidence, since this is highly dependent on the local situation.

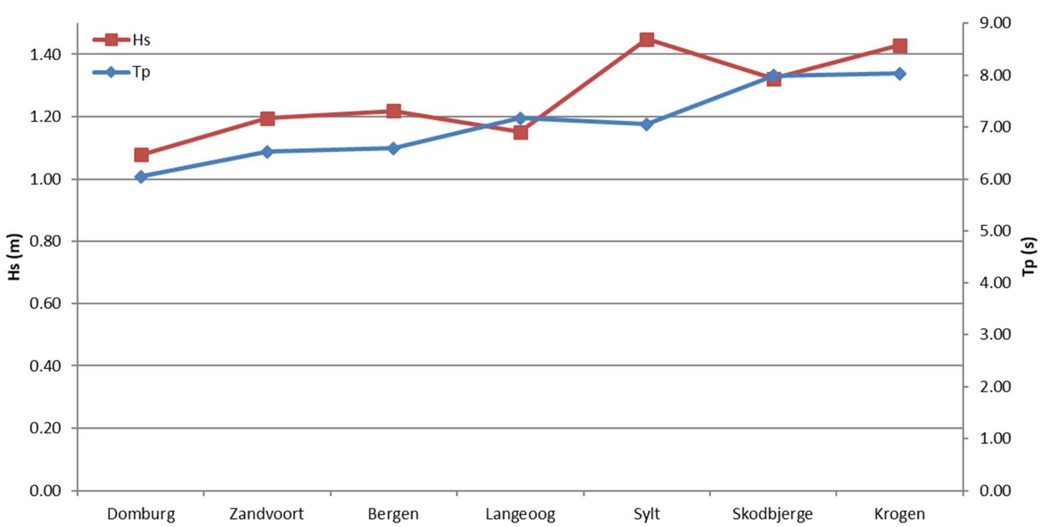


Figure 2.7 Wave characteristics from CoastDat2 database

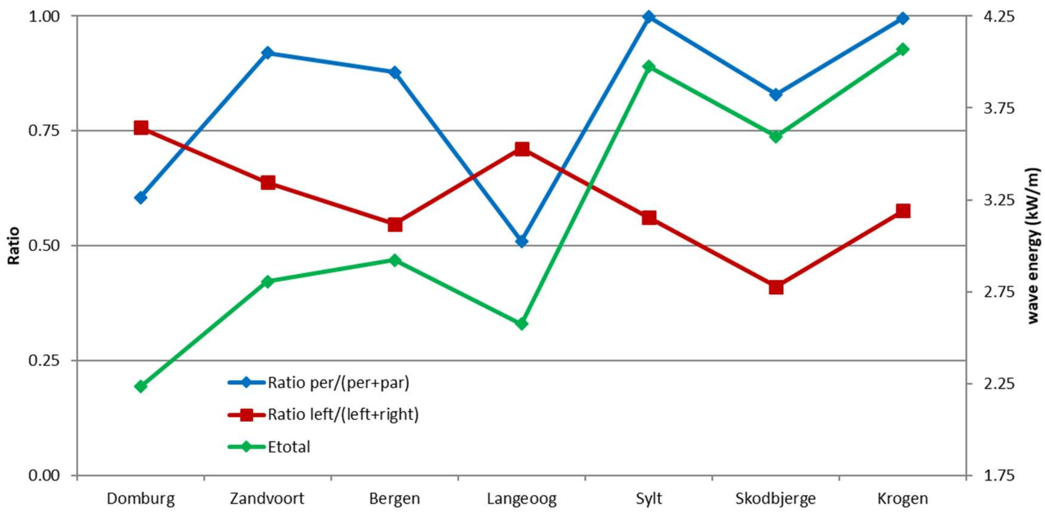


Figure 2.8 Wave energy based on CoastDat2 database. The total energy is expressed in KW/m (right y-axis)

3 Hypotheses

3.1 Introduction

As described in Chapter 2, in each coastal laboratory one or more nourishments have been studied. For each lab this provides valuable insights in the way the nourishment(s) at that specific location behaved. These insights give information on how nourishments in general (might) work. This general understanding of nourishments is described by several 'hypotheses', which are formulated based on the effects of nourishments.

3.2 Methods

Nourishment behaviour is complex to asses due to the complexity of the natural system in which many factors play a role (e.g. wind, waves, vegetation, sediment transport, morphological changes, etc.). Also, the co-analysis is not a full scientific study but rather an assessment on practitioners level. The number of labs is relatively small (for e.g. statistical tests), which makes it impossible in this study to prove scientifically how nourishments behave. Yet, for many aspects of the nourishments certain effects are observed and for these effects we formulated a 'proposed explanation for the phenomena'; a hypothesis. The hypotheses cover several aspects of the nourishments relevant for coastal management, both on the shoreface and beach.

The hypotheses are analysed by combining the results of each coastal lab. Besides a qualitative description, quantitative results are used if possible, e.g. in the form of graphs or (empirical) relations. This analysis is not a scientific study but is meant to gain practical insight in the behaviour of nourishments. If possible, they are supported by (scientific) literature.

Each hypothesis is described in two parts: 1 the observations in the labs relevant for the hypothesis and 2 the supposed mechanism(s) behind the hypothesis are described.

3.3 Results

3.3.1 Shoreface nourishments stabilize the beach

Explanation

On erosional coasts sustainable risk management includes counteraction of the erosion by adding sediment. The aim is often to stop the retreat of the dune- or coastal cliff face. This aim can be achieved by adding sand to the active pathway, i.e. from the outer bar to the landward side of the dunes.

A shoreface nourishment is placement at the outside of the outer bar. It is the cheapest way of adding sediment to the active pathway. In the labs this corresponds to a placement depth of about 5-6 m below mean sea level.

The effects of shoreface nourishments on the coast is (partly) related to their influence on the morphological behaviour of the breaker bars. Several effects have been described in literature and observed in the labs:

- interrupting or blocking of the offshore migration of bars;
- inducing bar switching (an inner bar connecting to an outer bar);
- stabilization of the outer bar;
- forming of an additional bar;
- extension of the bar in shore parallel direction;
- feeding sediment downstream;
- pushes sediment from the outer bar to the beach (or the nearshore);
- acts like a shore parallel breakwater;

The total effects on the retreat of the dune- or coastal cliff face are difficult to evaluate since it is influenced by several factors, e.g. knowledge of the coast's natural behaviour, the design of the nourishment and how the effect is documented. As an example: Vermaas (2017) described that shoreface nourishments have two effects that contribute to the restoring of the beach profile, a feeder effect and a lee effect (e.g., Van Duin et al., 2004; Grunnet and Ruessink, 2005). The feeder effect refers to the onshore sediment transport of the nourished sediment by wave asymmetry and slow onshore currents. The lee effect is the increase of wave dissipation due to the shallower coastal profile which leads to less energetic conditions at the water line and an increase in sedimentation from alongshore sediment transport.

Due to these effects (including the first mentioned effect of adding sediment), a reduction in coastal retreat rate (coastline), with respect to a situation without a shoreface nourishment, is expected at the beach landward of a shoreface nourishment.

Results

In this hypothesis it is tested if shoreface nourishments stabilize the beach. The hypothesis is tested by using the results from the national reports off each laboratory.

Krogen
At Krogen five shoreface nourishments and four beach nourishments have been carried out in the period 2007-2018. The focus here is on the 2016 shoreface nourishment. The hypothesis will be tested by analysing the volume in three boxes (G, H and I) which includes the beach, see Figure 3.1. The shoreface nourishment was done in box A.

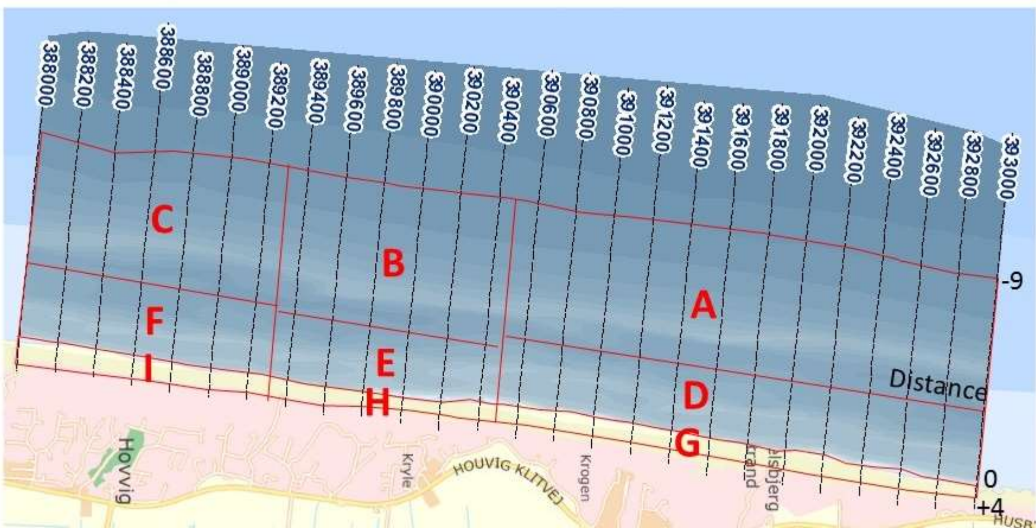


Figure 3.1 Position of boxes for volume calculations

In box G, directly behind the nourishment, the trend in volume is negative from 2012 to 2015 (Figure 3.2 The nourishment in 2015 increases the volume again. The nourishment in 2016 stabilized the volume in the 2-years after the nourishment. In box H, just downstream of the shoreface nourishment, the trend since 2012 is slowly erosional and the shoreface nourishment in 2015 causes an increase in volume. The shoreface nourishment in 2016 seems to stabilize the volume in the beach here, by increasing the alongshore sediment transport.

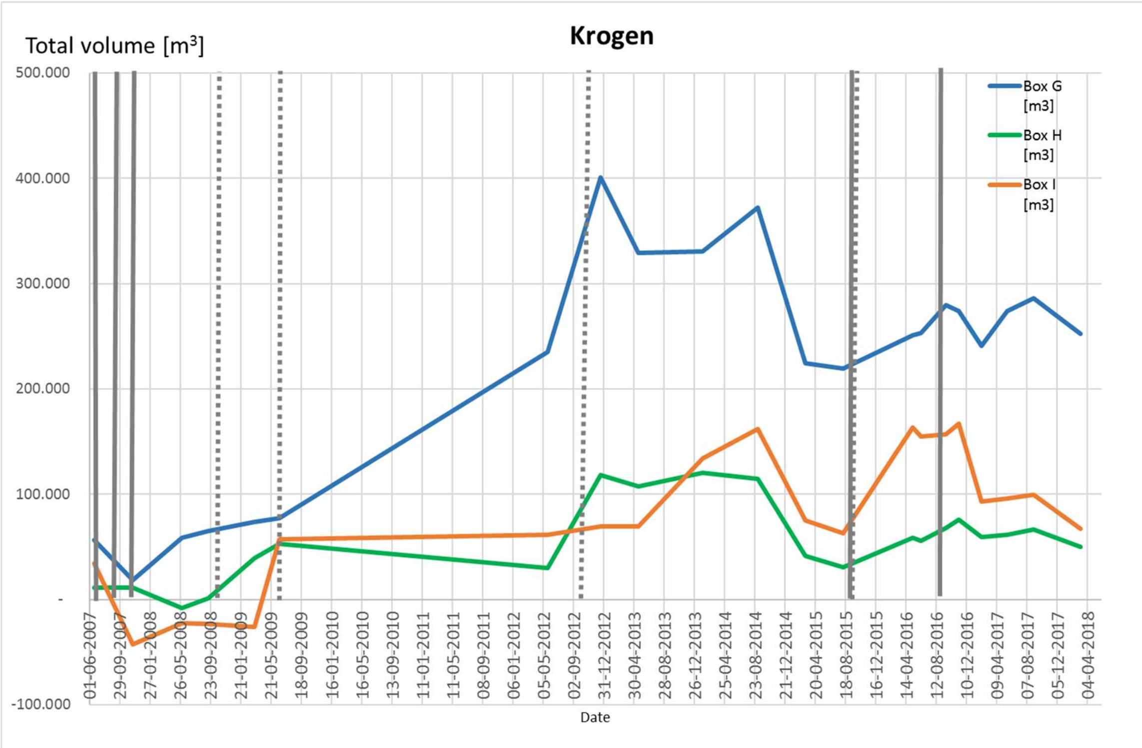


Figure 3.2 *Volume in beach boxes. G is directly behind the shoreface nourishment. Time of nourishments shown by grey lines. A solid line denotes a shoreface nourishment, a dashed line a beach nourishment. Box H and I are both downstream boxes.*

The trend in the most downstream box (I) from 2012 to 2015 shows a stable volume with large fluctuations. The nourishments in 2015 increased the volume at the beach. A positive downstream effect of the shoreface nourishment cannot be identified because erosion has taken place after the shoreface nourishment in 2016 in these boxes.

Conclusion: Shoreface nourishments stabilize the beach directly behind it for more than 2 years. A possible stabilizing downstream effect is not clearly observed.

Skodbjerge

At Skodbjerge the analysed shoreface nourishment was placed in 2011. Prior to the 2011 nourishment, in 2010 a shoreface nourishment was placed, which contained less volume per running meter.

At Skodbjerge the volume changes in the beach and dunes have been calculated in seven alongshore boxes. One directly landwards of the shoreface nourishment, called Nour in Figure 3.3. 4. Boxes downstream are denoted S1 (South), S2, S3 and S4. S1 is directly downstream of the Nour box. N1, and N2 are the upstream boxes.

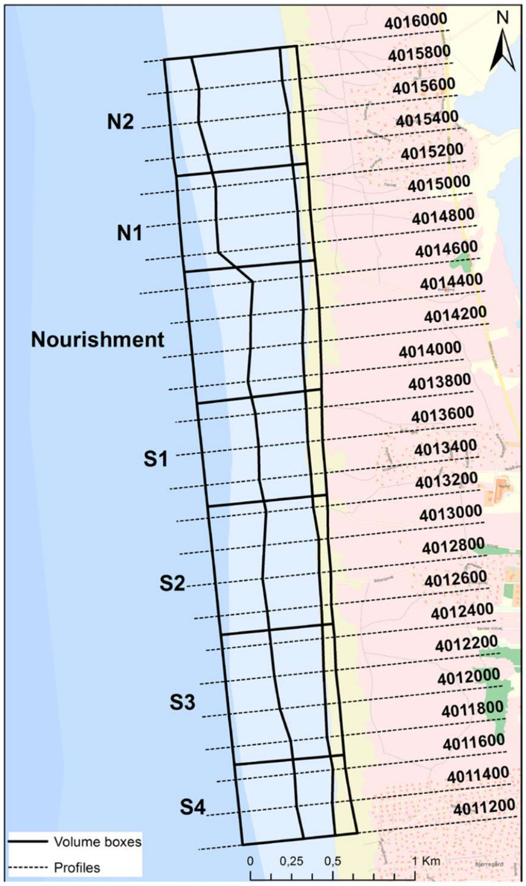


Figure 3.3 *Position of volume boxes and local survey lines*

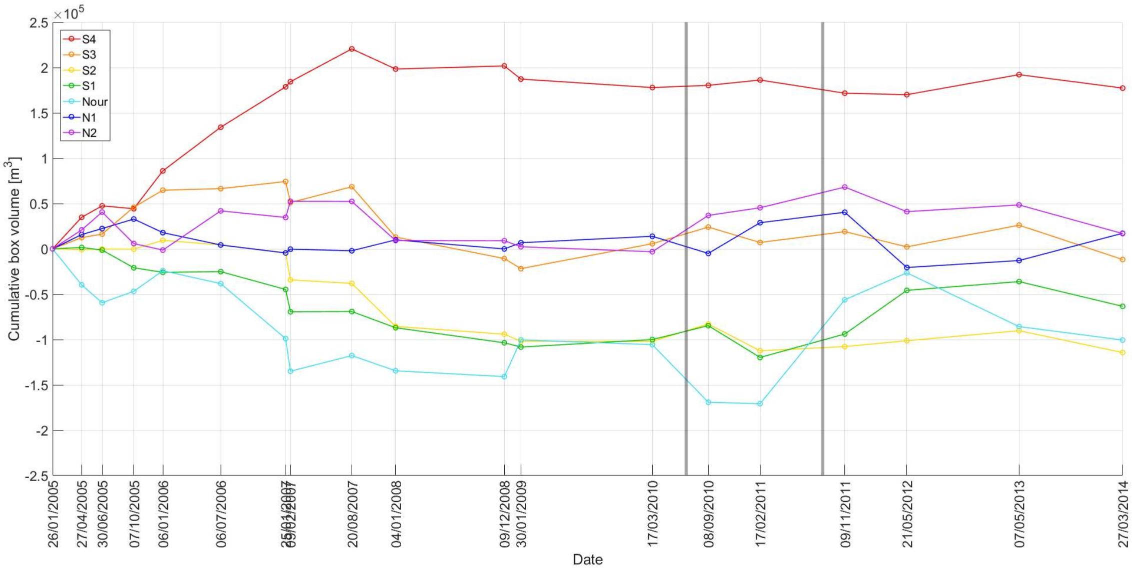


Figure 3.4 Cumulative volume evolution from 2005-2014 for the beach and dune.

The volume in the Nour box has a decreasing trend from 2006 to 2011 (Figure 3.4). The volume increases just after the nourishment took place. After 6 months the volume decreases again with the natural rate of that coastal stretch. The volume in the box just downstream S1 also has a decreasing trend before the nourishment. The volume increases after the nourishment and the volume is constant for at least 2 years. This indicates that there likely is an effect of the shoreface nourishment on the downstream beach. The volume in S2 has been relatively stable for long. Therefore it cannot be concluded that the shoreface nourishment has had an effect there.

The volume in the upstream box N1 is stable. The shoreface nourishment in 2010, which was also carried out in box N1, increased the volume slightly. The volume in N1 is decreasing quickly after the nourishment and returns to the volume prior to the nourishments. It is not evident that these changes are caused by the nourishment.

Conclusion: The shoreface nourishment stabilizes the beach just landwards for at least 2 years, and downstream of the nourishment.

Sylt - Rantum

The shoreface nourishment in Rantum was placed in 2006 with an aim to stabilize the beach and improve the longshore sediment transport into the Wadden Sea back basin.

Figure 3.5 shows the long term evolution of the volume of the beach, directly behind the shoreface nourishment of 2006. The beach nourishments placed in 1989, 2001 and 2004 are showing a different lifetime and immediate erosion can clearly be seen. The shoreface nourishment of 2006 seems to have a stabilizing effect on the beach since no significant loss is observed in a nine year period after the nourishments execution.

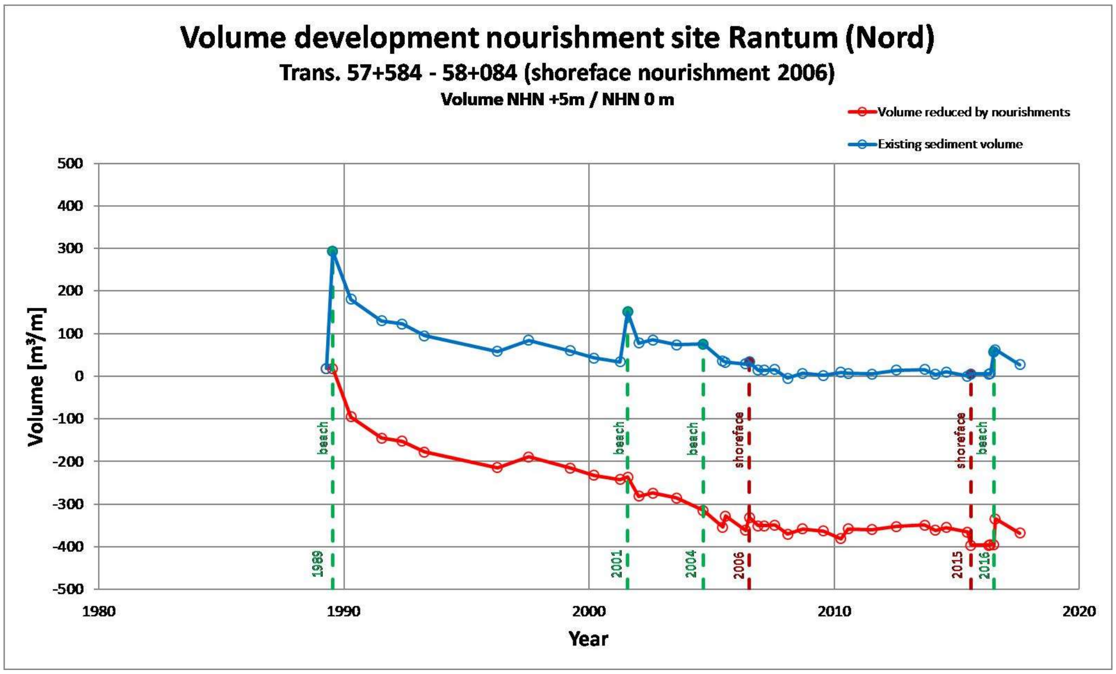


Figure 3.5 *Volume between mid-dune level and mean water level over time for the shoreface and beach nourishments in Rantum*

The volume changes at the beach landward of the shoreface nourishment in 2006 are shown in Figure 3.6. A small volume decrease is observed in a two-year period after the nourishment was placed. From the middle of 2008 onwards, the volume is stable in the beach box landward of the shoreface nourishment.

Figure 3.7 shows the volume development in the intermediate downstream box. A very small decrease of approximately 40,000 m^3 over a 12-year period is seen, which is not significantly different from the natural variations

Conclusion: The shoreface nourishment at Rantum stabilizes the beach for at least 10 years.

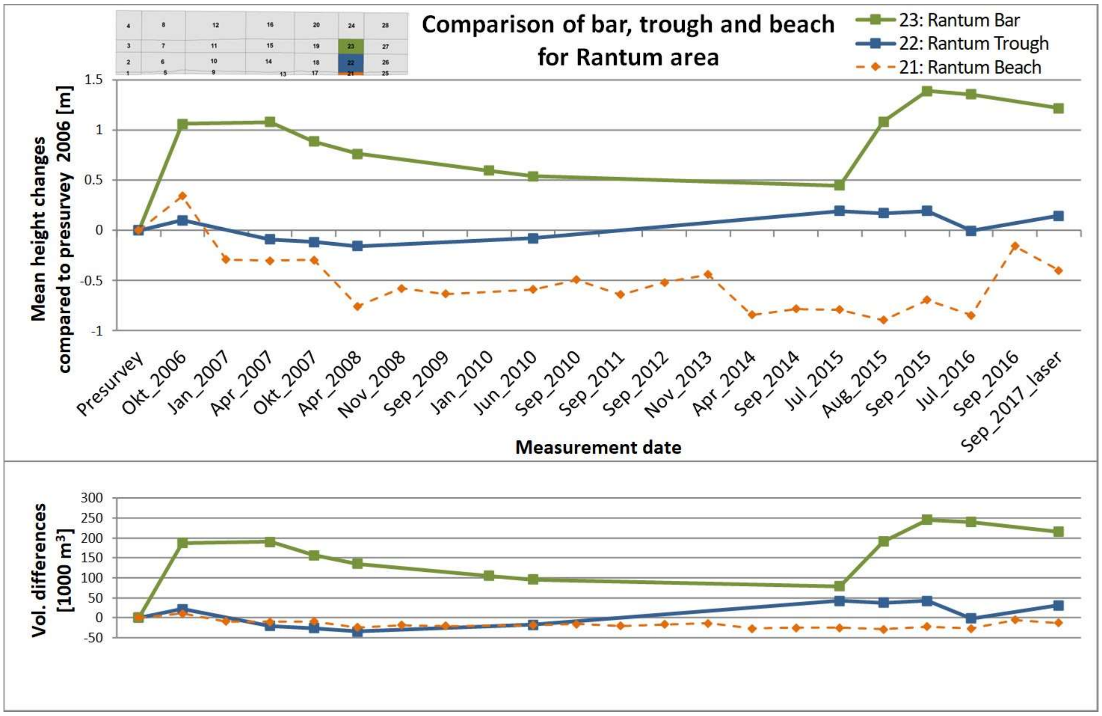


Figure 3.6 Comparison of bar, trough and beach volumes for Rantum area

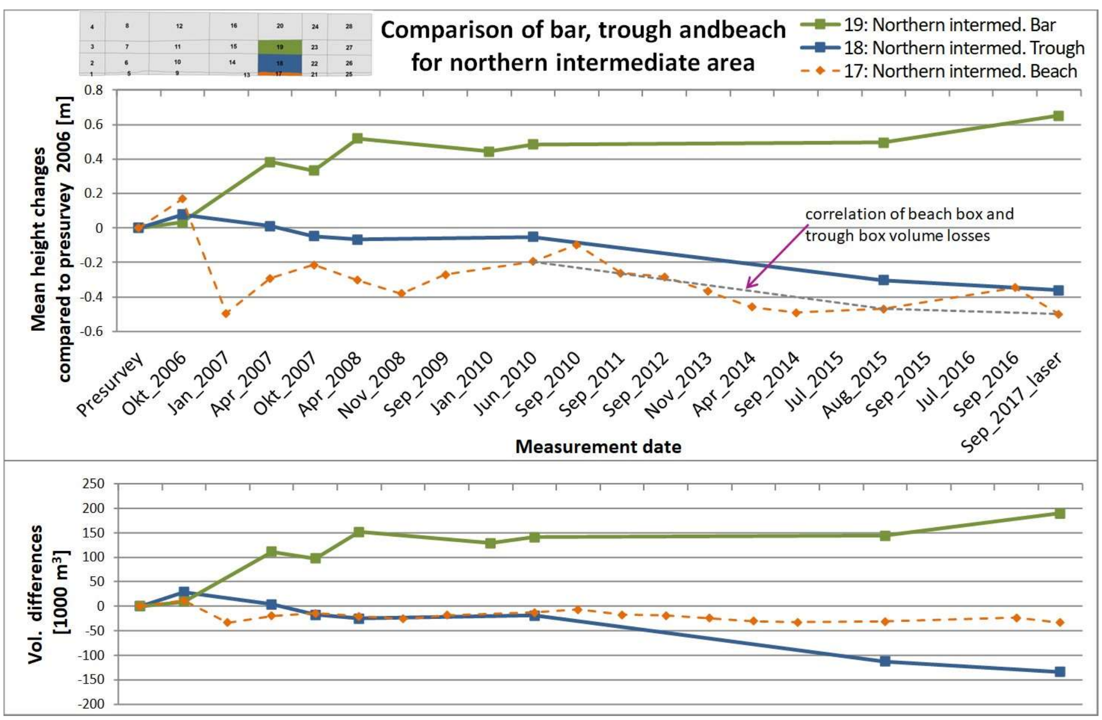


Figure 3.7 Comparison of bar, trough and beach volumes for the northern intermediate area

Sylt - Puanklent

The shoreface nourishment in Puanklent was in 2006 placed with an aim to stabilize the beach and improve the longshore sediment transport into the Wadden Sea. Puanklent is located downstream/southwards of Rantum.

Figure 3.8 shows the long term evolution of the volume at the beach directly landward of the Puanklent shoreface nourishment placed in 2006. Beach nourishments were executed in 1989 and 2003 and the immediate erosional trends at the beach can clearly be seen. The shoreface nourishment of 2006 seems to have a stabilizing effect on the beach since no significant loss is observed in a ten-year period after the nourishment.

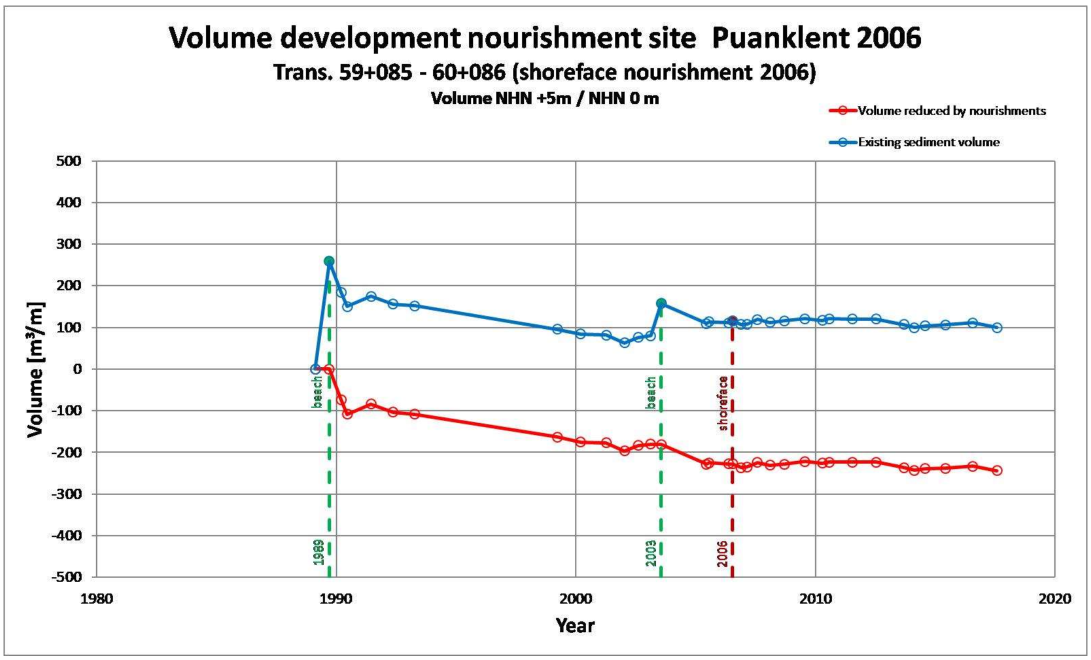


Figure 3.8 *Volume evolution over time between mid-dune level and mean water level for the shoreface nourishment Puanklent 2006*

The volume changes of the beach just landward of the shoreface nourishment is shown in Figure 3.9. The volume is stable in the beach box immediately landward of the shoreface nourishment for a period of ten years after the nourishment.

The volume differences in the box just downstream is shown in Figure 3.10. The volume in the beach is reducing since the nourishment took place. It cannot be evaluated if the erosion rate is less than before the shoreface nourishment was in place.

Conclusion: The shoreface nourishment at Puanklent stabilizes the beach directly landward of the shoreface nourishment for at least ten years.

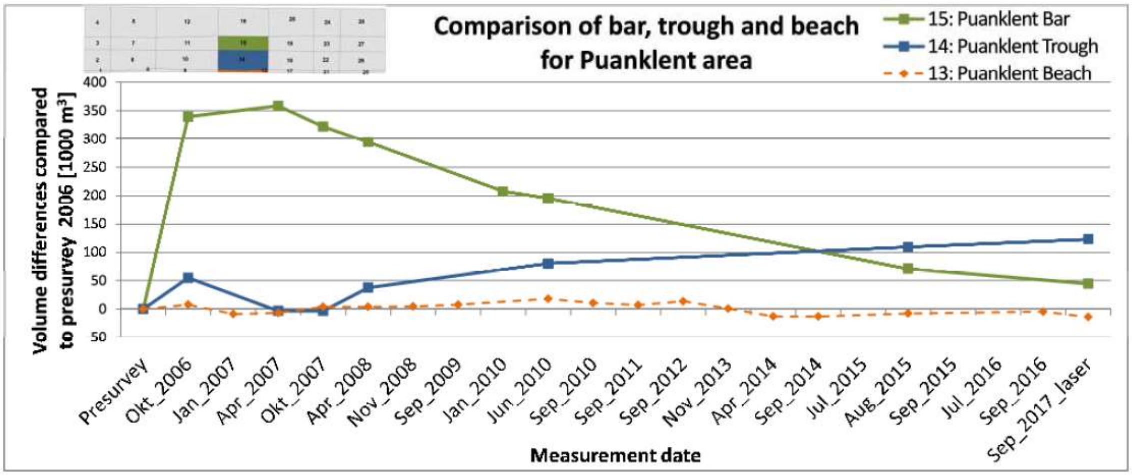


Figure 3.9 Trends of bar, trough and beach volumeboxes for Puanklent area

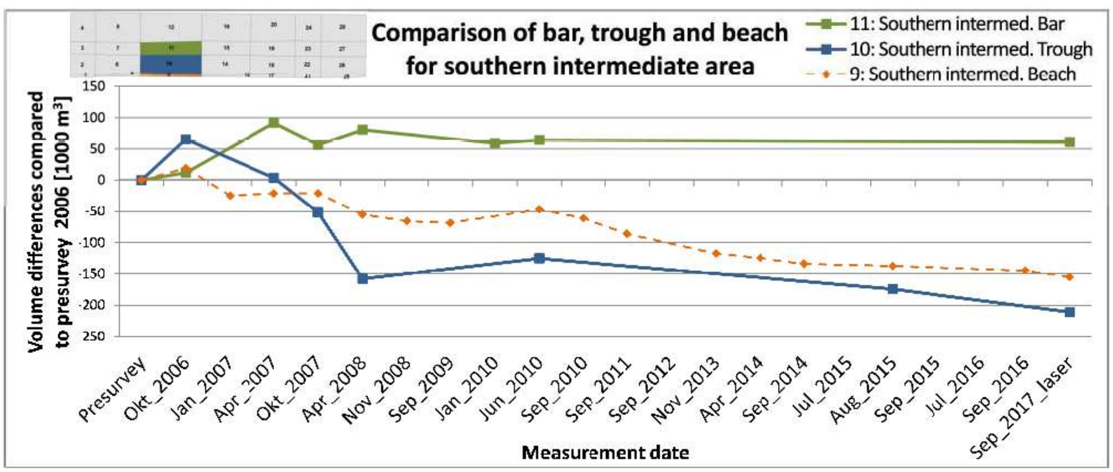


Figure 3.10 Trends of bar, trough and beach volume boxes for southern intermediate area

Sylt - Sansibar

The shoreface nourishment in Sansibar was placed in 2006 with an aim to stabilize the beach and improve the longshore sediment transport into the Wadden Sea back basin. Sansibar is located downstream/southwards of Rantum and Puanklent.

Figure 3.11 shows the long-term evolution of the volume at the beach landward of the shoreface nourishment. Beach nourishments were executed in 1989, 1993 and 2003, and immediate erosion of the beach afterwards can clearly be seen. The shoreface nourishment of 2006 seems to have a stabilizing effect on the beach since there is a slight increase of volume in a ten-year period after the nourishment took place.

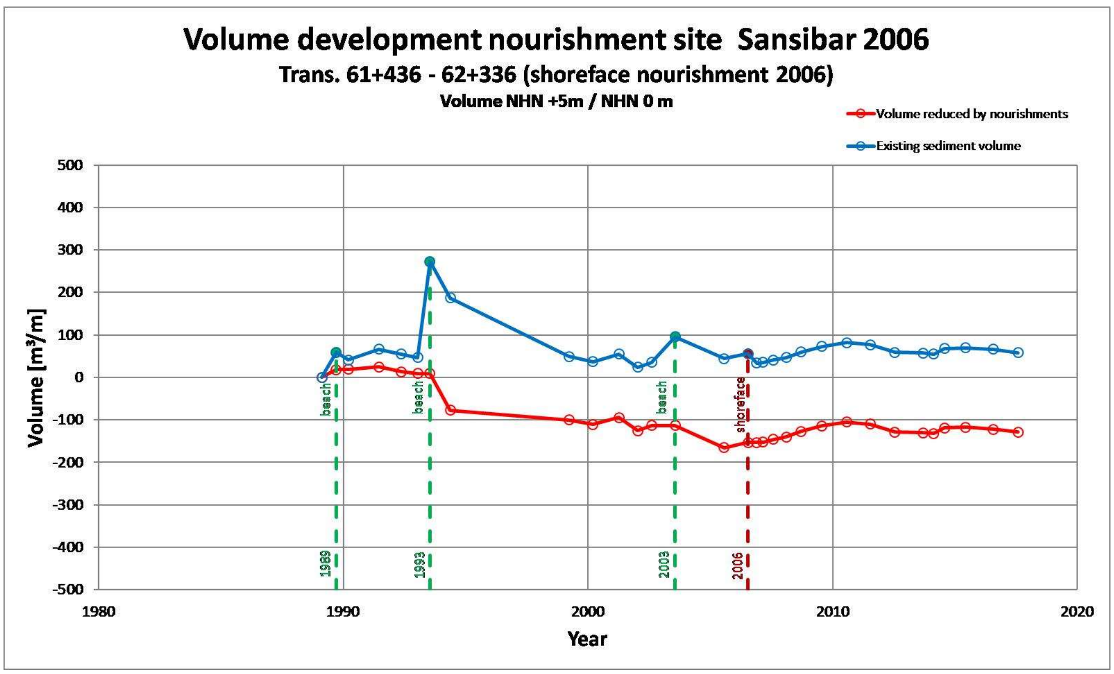


Figure 3.11 *Volume development over time between mid-dune level and mean water level for the shoreface and beach nourishments in Sansibar 2006*

The volume changes of the beach landward of the shoreface nourishment in 2006 is shown in Figure 3.12. The volume decreases a bit in the first half year after the nourishment. Thereafter the volume is stable in the beach box immediately landward of the shoreface nourishment for the next ten years.

Figure 3.13 shows the volume evolution of the downstream beach volume box. The volume in the beach is reducing since the nourishment took place. It cannot be evaluated if the erosion rate is less than before the shoreface nourishment was present.

Conclusion: The shoreface nourishment at Sansibar stabilizes the beach for at least ten years.

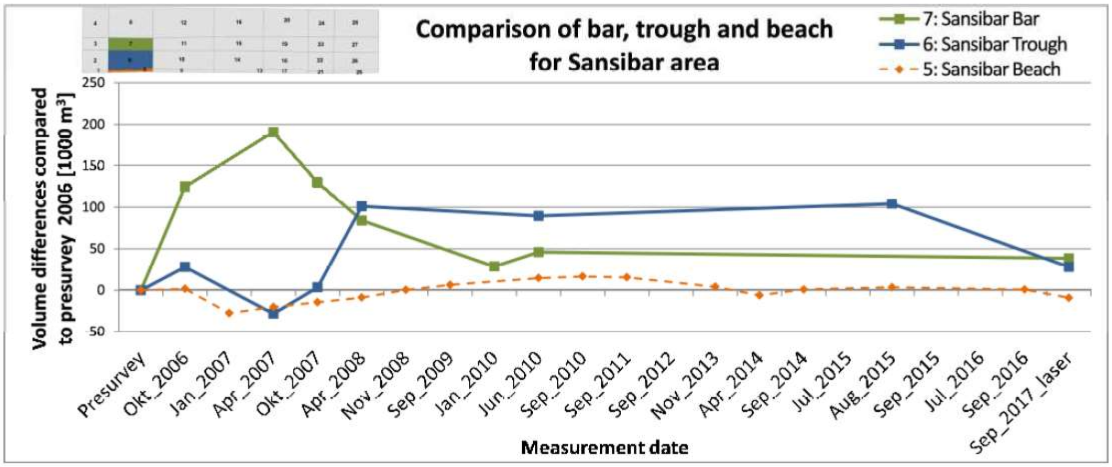


Figure 3.12 Trends of bar, trough and beach volume boxes for Sansibar

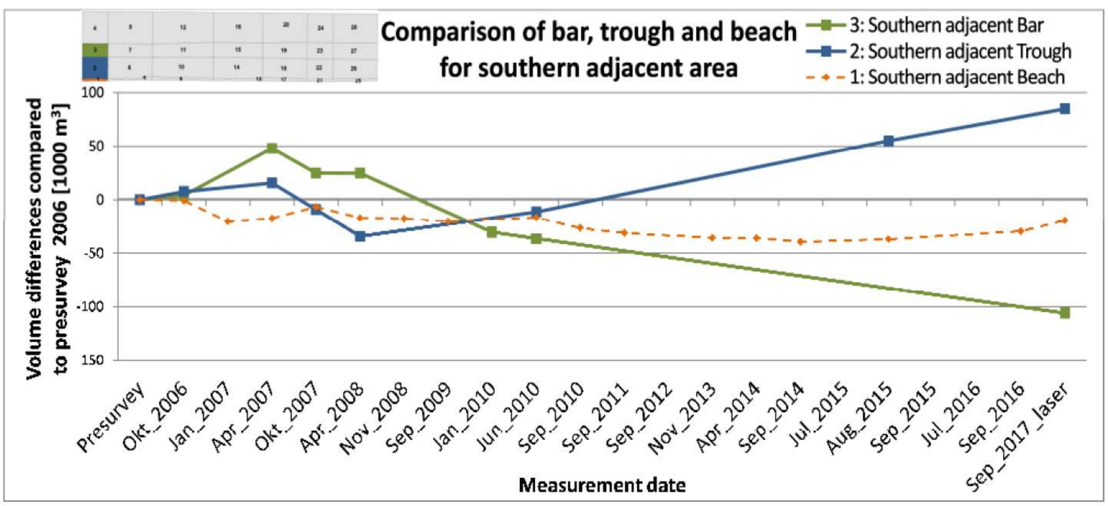


Figure 3.13 Trends of bar, trough and beach volume boxes for southern adjacent area

Zandvoort

In Zandvoort two shoreface nourishments are analysed, one in 2004 and one in 2008. The effects on the stability of the beach is evaluated by the volume changes in beach boxes 12-14, see Figure 3.14.

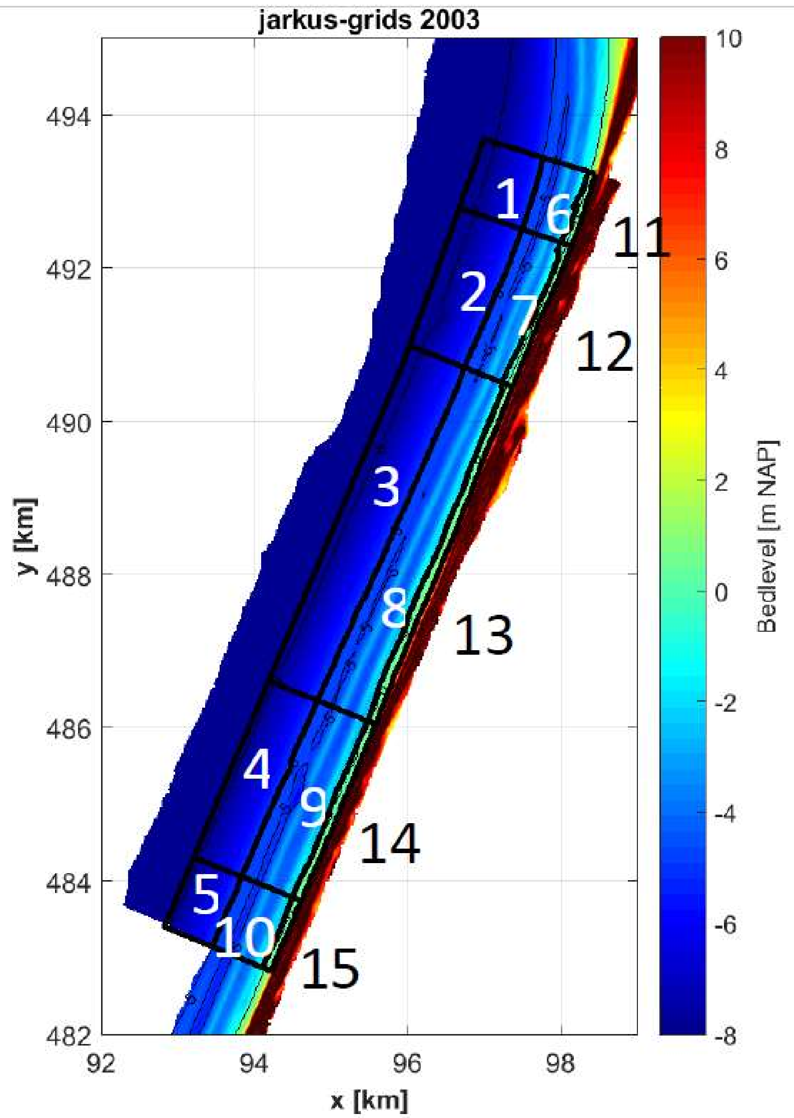


Figure 3.14 Volume boxes Zandvoort-Bloemendaal lab

Figure 3.15 shows a natural erosional trend from 1976 to 1990. The six beach nourishments are seen to cause an increase the volume of the beach. Just before the shoreface nourishment was placed in 2004 the volume has reduced to the same level as the relative stable period from 1968 to 1976.

The beach volume after the 2004 nourishment increased with an equal trend that has been observed from the start of the nourishments in Zandvoort in 1990. The shoreface nourishment in 2008 seems to increase the volume in the beach for nearly seven years, until 2015.

Conclusion: The shoreface nourishments in Zandvoort in 2004 and 2008 stabilized the beach. The shoreface nourishment in 2004 stabilizes the beach for at least four years. The shoreface nourishment in 2008 stabilizes the beach for at least seven years.

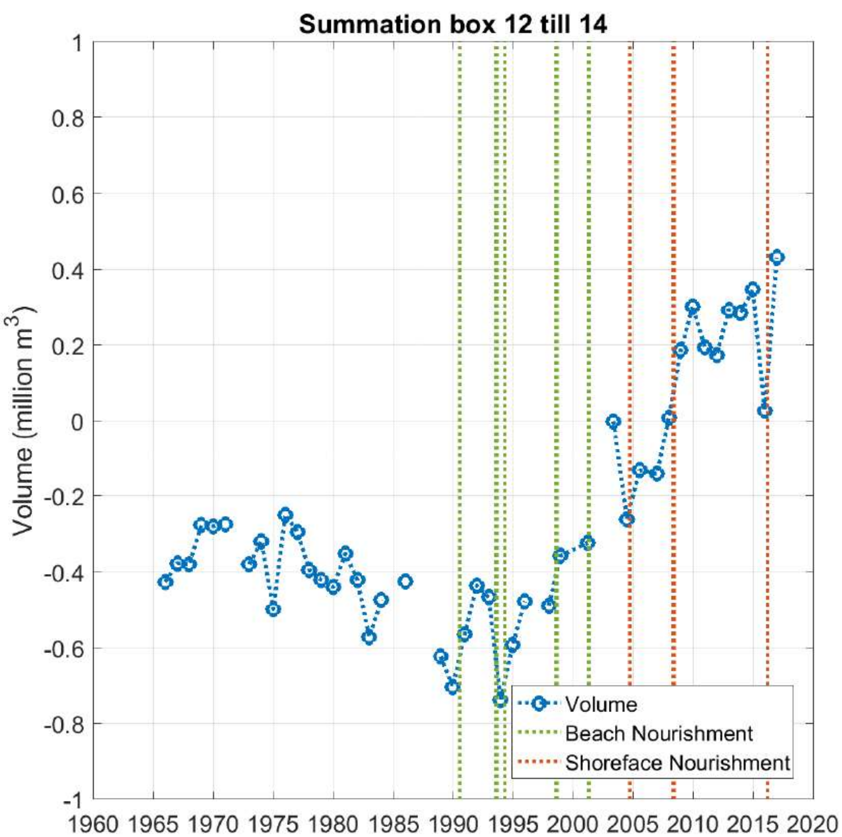


Figure 3.15 The summed volume of box 12 until 14. These are all beach boxes for the Zandvoort-Bloemendaal lab (the volume in 2004 has been set at 0).

Conclusions

The presented graphs in this chapter support the hypothesis that shoreface nourishments stabilize the beach. There are large variations in how long the stabilization lasts, from some years to more than ten years. Some shoreface nourishments seem to stabilize the beach downstream too.

3.3.2 A beach nourishment stabilizes a beach

Explanation

On erosional coasts sustainable risk management includes counteraction the erosion by adding sediment. The aim is often to stop the retreat of the dune- or coastal cliff face. This aim can be achieved by adding sand to the active pathway, i.e. from the outer bar to the landward side of the dunes.

A beach nourishment is placement directly at the beach from the duneface, extending seaward. Normally the sand is pumped to the beach via a pipeline, which results in a slope of the beach nourishments that corresponds to a relatively natural slope. This, in turn, results in less cross shore redistribution during the first storms, because the profile has a natural slope hence is in equilibrium with the forcing.

If sand dikes are used to control the outflow of sand on the beach during the execution of the nourishment, a more unnaturally slope of the beach nourishment can be achieved, thus leading into larger cross shore redistribution of sediment during the first storms (Dean, 2003).

The effect of beach nourishments on the coast is (partly) related to their influence on the morphological behaviour of the beach. Several effects have been described in literature and observed in the BwN coastal labs:

- widening of the dunes
- stabilization of the beach;
- feeding sediment to downstream areas

The total effects on the retreat of the dune- or coastal cliff face are difficult to evaluate since it is influenced by several factors, e.g. the knowledge of the coast’s natural behaviour, the design of the nourishment and how well the effect of the nourishment is documented.

Due to these effects, a reduction in coastal retreat rate (coastline), with respect to a situation without a beach nourishment, is expected at the beach where beach nourishments have been applied.

Results

In this hypothesis it is tested if beach nourishments stabilize the beach. The hypothesis is tested by using the results from the national reports off each laboratory.

Langeoog

The beach nourishment took place in 2017 and 2018. Figure 3.16 shows the boxes for volume calculations.

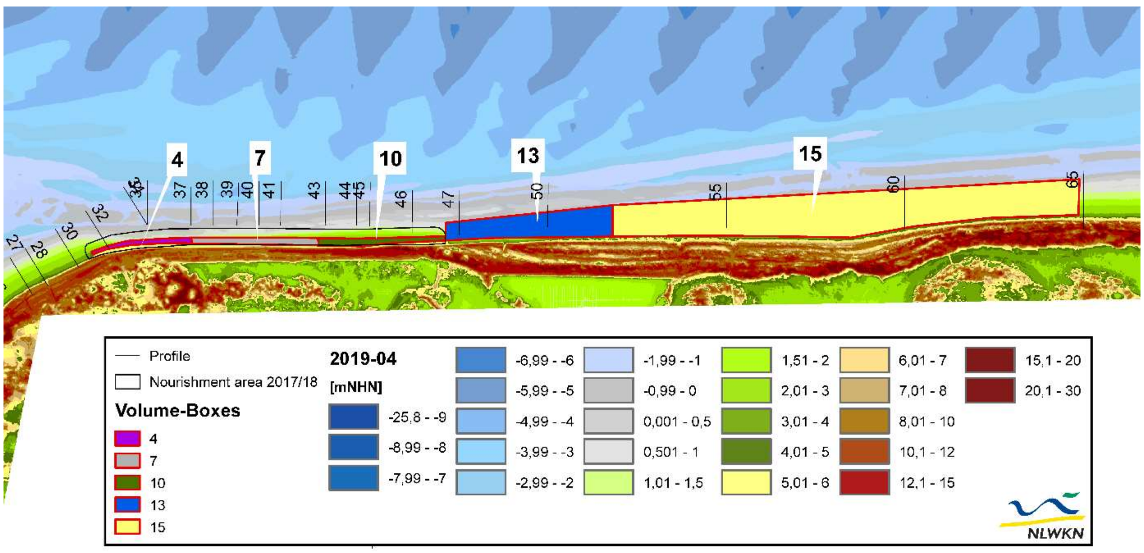


Figure 3.16 Location of the volume boxes at Langeoog, nourishment is in box 4, 7 and 10, indicated by the black line

The dune foot (Figure 3.17, red line 'Level 3 mNHN') shows an erosional trend from 2000 to the first nourishment in 2010. Between the nourishments from 2014- 2017 the dune foot is relatively stable from 2014-2017. The nourishment in 2017 and 2018 advances the dune foot shoreward to a position in 2019 that is approximately 25 m more seawards than before the nourishment in 2017.

The possible effect downstream cannot be assessed because the analysed box (4) contains part of the beach nourishment.

The volume development in boxes 4, 7, 10, 13 and 15 is shown in Figure 3.18.

Conclusion: The beach nourishment at Langeoog stabilizes the beach temporally. In the 3 nourishment boxes the diffusion time varies from one up to two years. There is a short period of stabilization in the downstream boxes for one to two years.

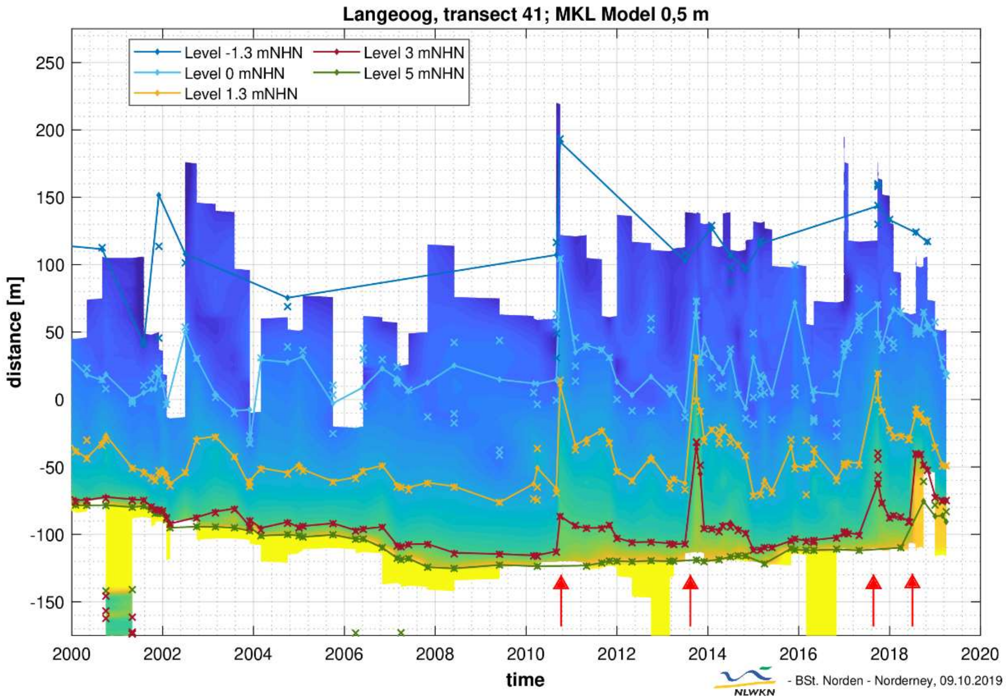


Figure 3.17 *Variation in the position of different levels from -1.3 to 5 mNHN in a representative transect. Red arrows indicate time of beach nourishments at Langeoog*

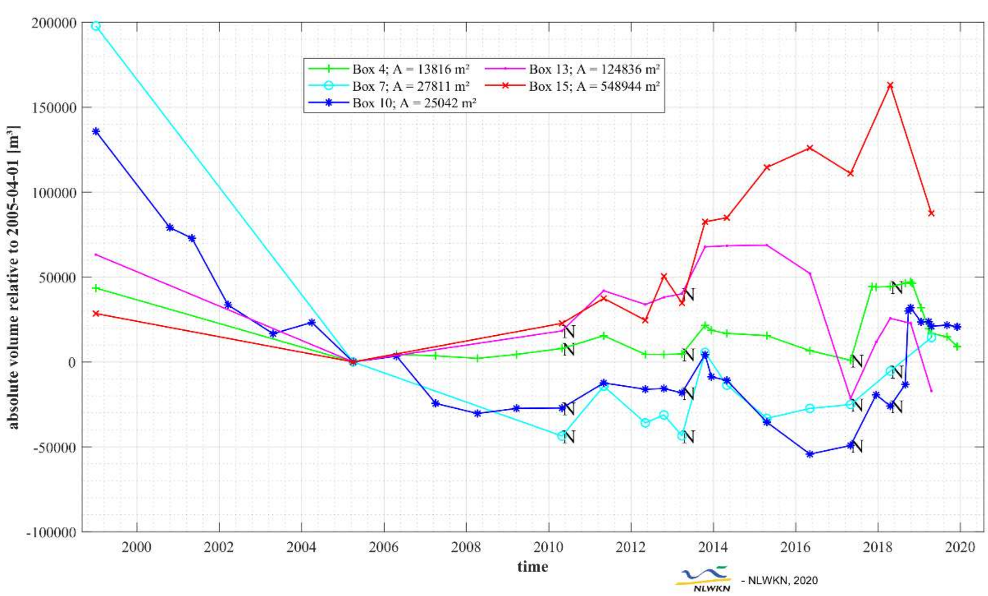


Figure 3.18 *Volume development in boxes 4,7,10,13 and 15*

Domburg

The analysis of the effect of the beach nourishment in Domburg in 2008 is based on the change in average bed level in boxes five to seven, see Figure 3.19.

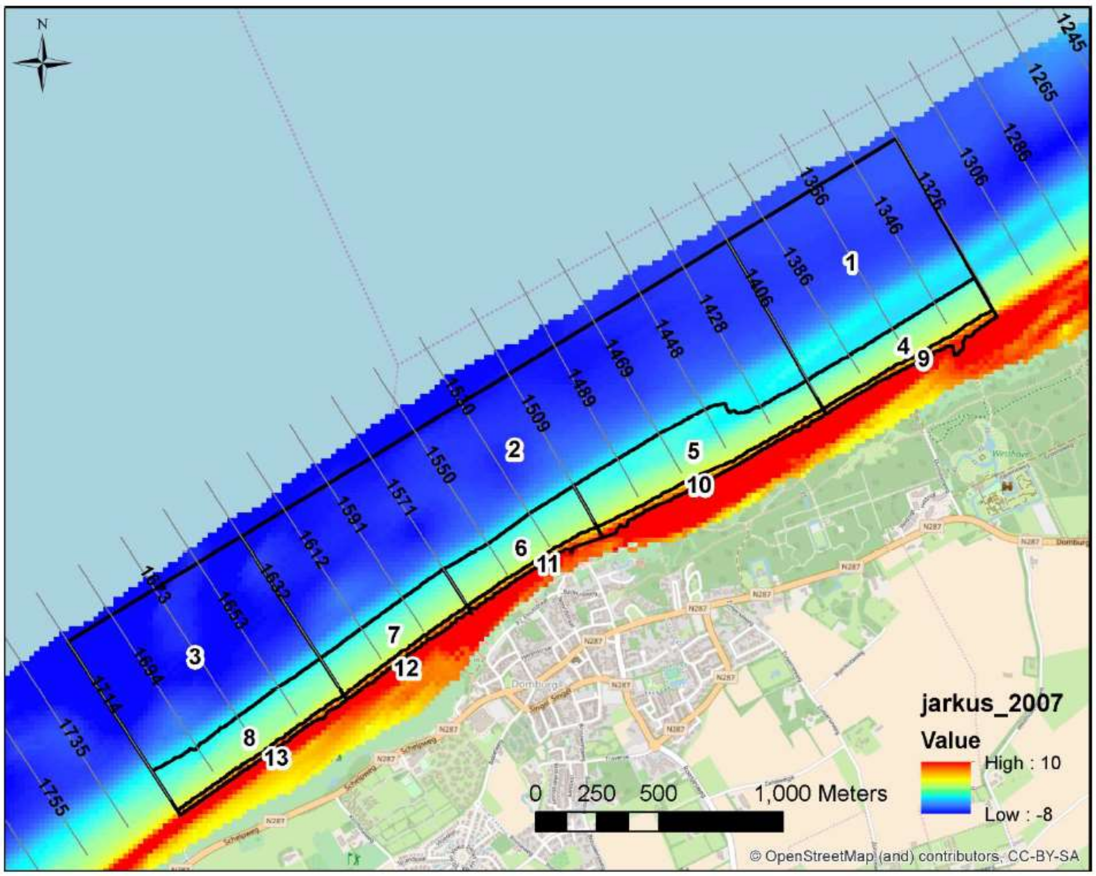


Figure 3.19 Boxes used for calculation of volumes, nourishment is placed in box 5-7

Figure 3.20 shows the variation in the bed level in each of boxes five to seven between 2007 and 2012. Figure 3.21 shows the volume variation of the beach boxes four to eight.

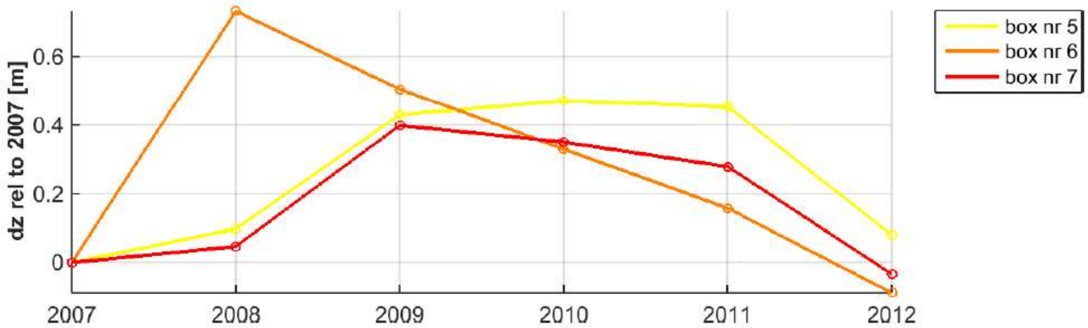


Figure 3.20 Change in average bed level for each polygon

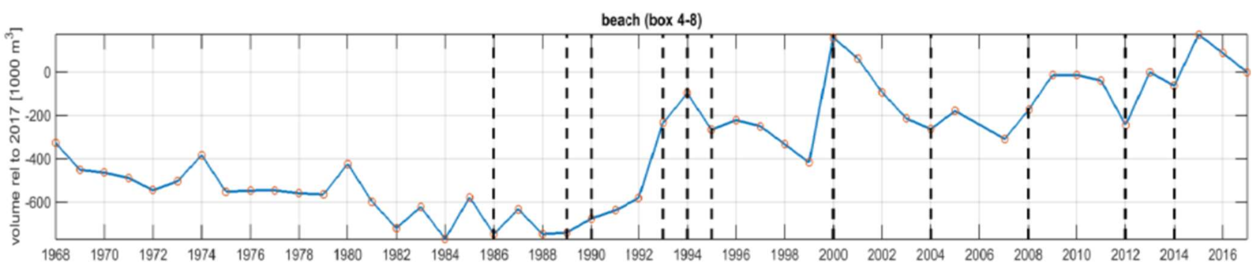


Figure 3.21 Long term volume development of the beach. Dashed lines indicate nourishments.

Beach nourishments were placed in box 6 at the time of the 2008 survey, but not yet in box 5 and 7. From Figure 3.21 a clear erosional trend of the beach is seen between the beach nourishments. The beach nourishment in 2008 is increasing the volume at the beach, in 2012 the volume in boxes 5-7 is back to the pre-nourishment volume, i.e. the lifetime is four years (a diffusion time of 2 years).

Conclusions: The beach nourishment at Domburg stabilizes the beach. It’s lifetime is around four years and stabilizes the neighbouring beaches too in this period.

<u>Conclusions</u>

The presented graphs from the national reports support the hypothesis that beach nourishments stabilize the beach. For how long is only supported by one laboratory where the effect lasted four years.

The potential feeder effect can only be analysed in one lab, where a feeding of sediment up and downstream of the nourishment has been observed.

3.3.3 When cross-shore processes are dominant, effects can be expected directly behind the nourishment. If the alongshore component becomes more important, effects will occur more oblique or parallel to the coast

Explanation

On morphologically dynamic sandy coasts, the sediment transport processes are very 3 dimensional. When the processes are analysed, they are often divided into alongshore and cross shore sediment transport processes. The longshore sediment transport is largest when the angle of the incident waves and the coastal feature, such as a bar, is approximately 40^0. The cross-shore sediment transport is largest when the waves are perpendicular to the feature observed.

When the energy flux of a particular part of the coast is nearly fully driven by cross-shore processes, a shoreface nourishment is expected to have an effect on the beach in cross-shore direction and less in alongshore direction. In BwN only numbers on wave characteristics are available, but tidal flow (asymmetry) and wind are relevant as well.

Results

Domburg

The studied beach nourishment was placed in 5-7 (Figure 3.22), in these areas the volumes go down after the nourishment (Figure 3.23). Both neighbouring areas on the beach, 4 and 8, show an increase in volume. The increase in area 8 is contributed to another beach nourishment, while area 4 most likely received sediment from area's 5-7 (the studied nourishment).

The offshore areas 1-3 show a deviating peak in area 2, which is most likely not real but an effect of the measurement method and interpolation. The rest of the graph remains more or less stable, with possibly a small increase in volume.

It is expected that the sediment is transported a) in northeaster direction along the beach and b) in offshore direction, and then transported away by the tidal current in the tidal channel. The first is alongshore transport, explained by the southwesterly wind and waves, while the second is cross-shore transport by waves from the northwest, in combination with the tidal coast-parallel flow. Conclusion: the effects of the nourishments are seen both alongshore and cross-shore.

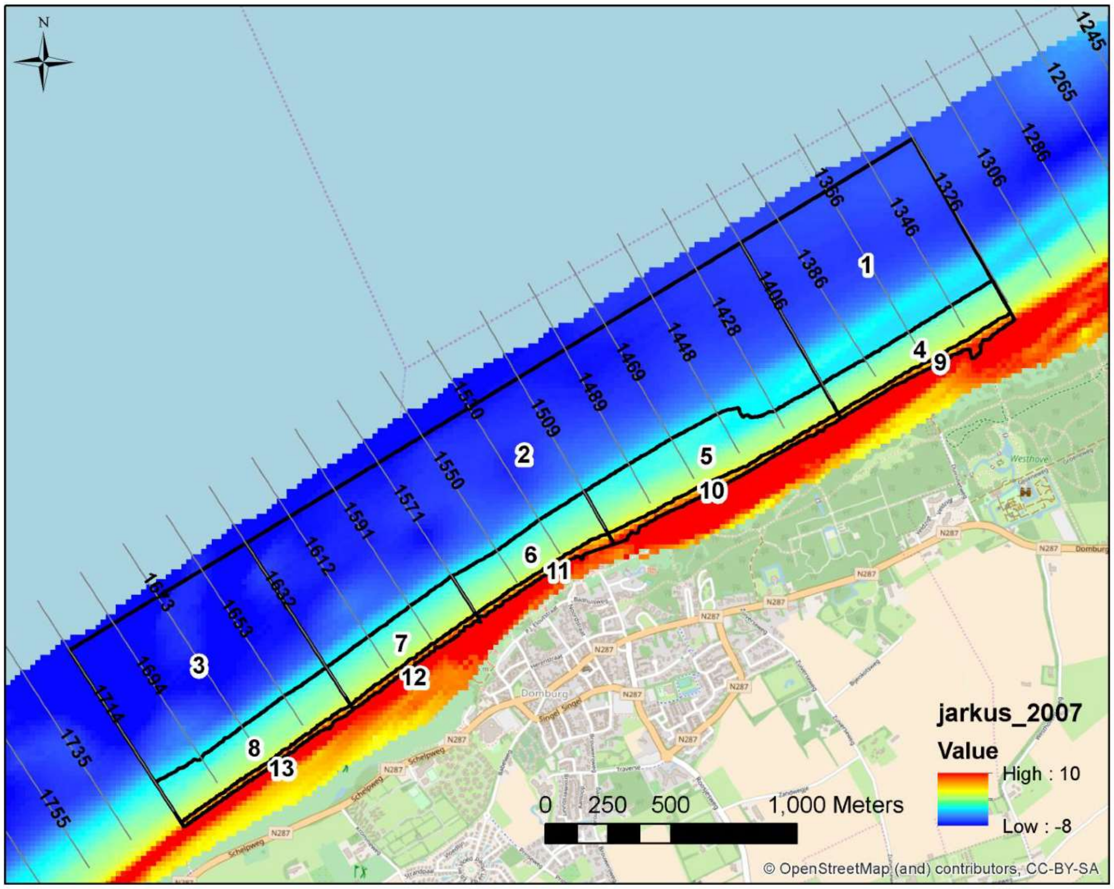


Figure 3.22 Volume areas for Domburg nourishment

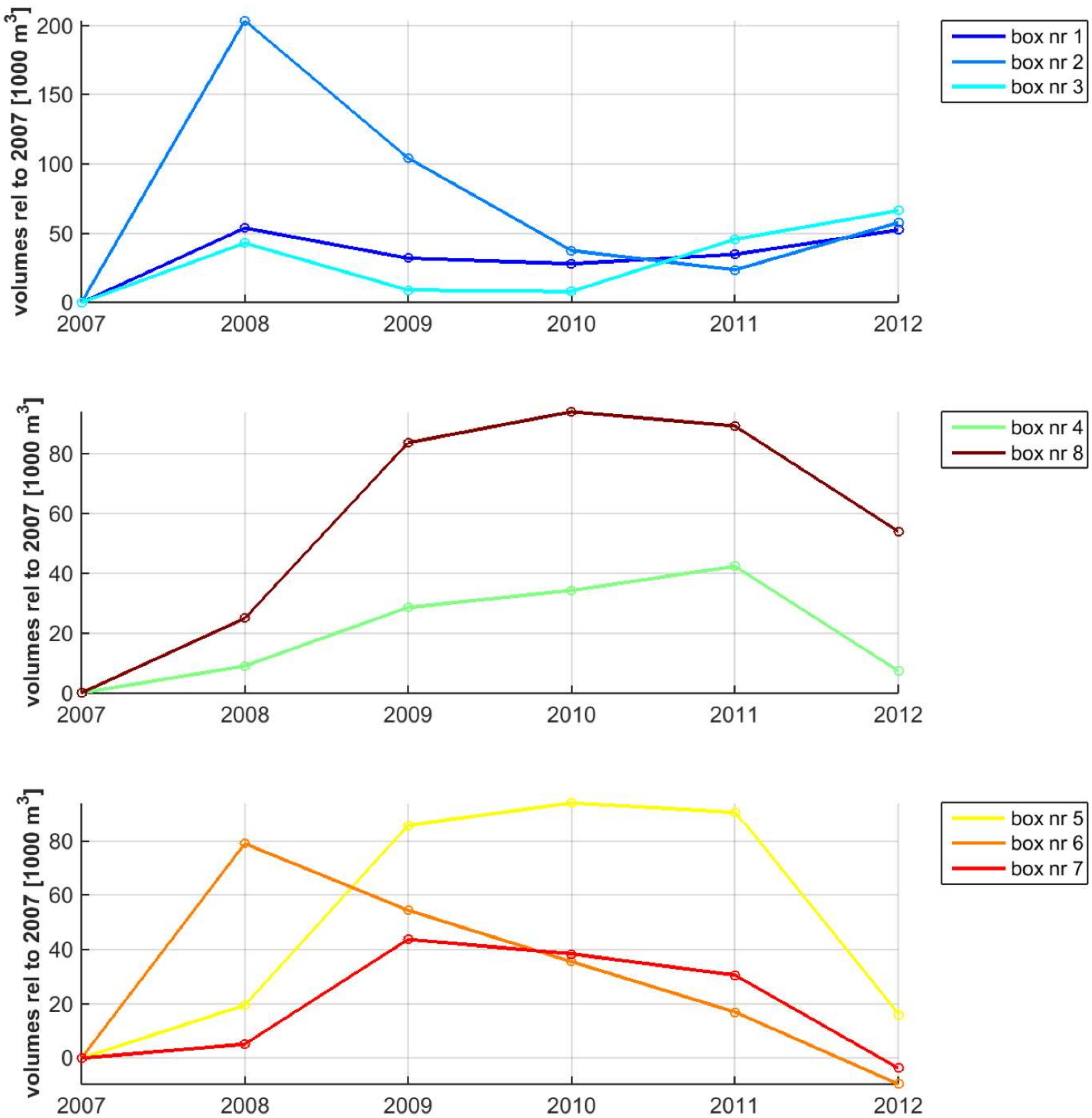


Figure 3.23 Volume development for Domburg nourishment

Zandvoort-Bloemendaal

At Zandvoort the shoreface nourishment of 2004/2008 was placed in area's 2-4, just offshore the breaker bar zone. The nourishment was mainly visible in area's 2 and 3 (Figure 3.24). The volume in these area's decreased after the placement (Figure 3.25), while an increase in volume was mainly seen in the area's directly shoreward in the breaker bar zone (area's 7-9). In the area's to the north and south of the nourishment (1 and 5) there is not a significant change of the volume. In the area's north and south in the breaker bar zone (6 and 10) a small increase in volume is visible, mainly in the area to the north (6).

Conclusion: the main effect is observed in cross-shore direction, which is in line with the large ratio perpendicular/parallel wave energy. The tidal flow is not a strong as in a tidal channel and has a small flood-dominance, which is towards the north.

Bergen-Egmond

At Bergen-Egmond a shoreface nourishment was placed at the location of the outer breaker bar (area 3, Figure 3.24). After the nourishment was placed in 2010-2011 the volume decreases in area 3 (Figure 3.25). In area 5 (cross-shore and alongshore to the north) and 6 (cross-shore) sedimentation takes place. The largest change in bed level occurs in area 5 but the largest change in volume in area 6, since the surface of area 6 is much larger than of area 5.

Conclusion: the effects of the nourishment are similar to Zandvoort-Bloemendaal, the main effect is observed in cross-shore direction, which is in line with the large ratio perpendicular/parallel wave energy. The conditions at Bergen-Egmond are also very similar to those at Zandvoort-Bloemendaal.

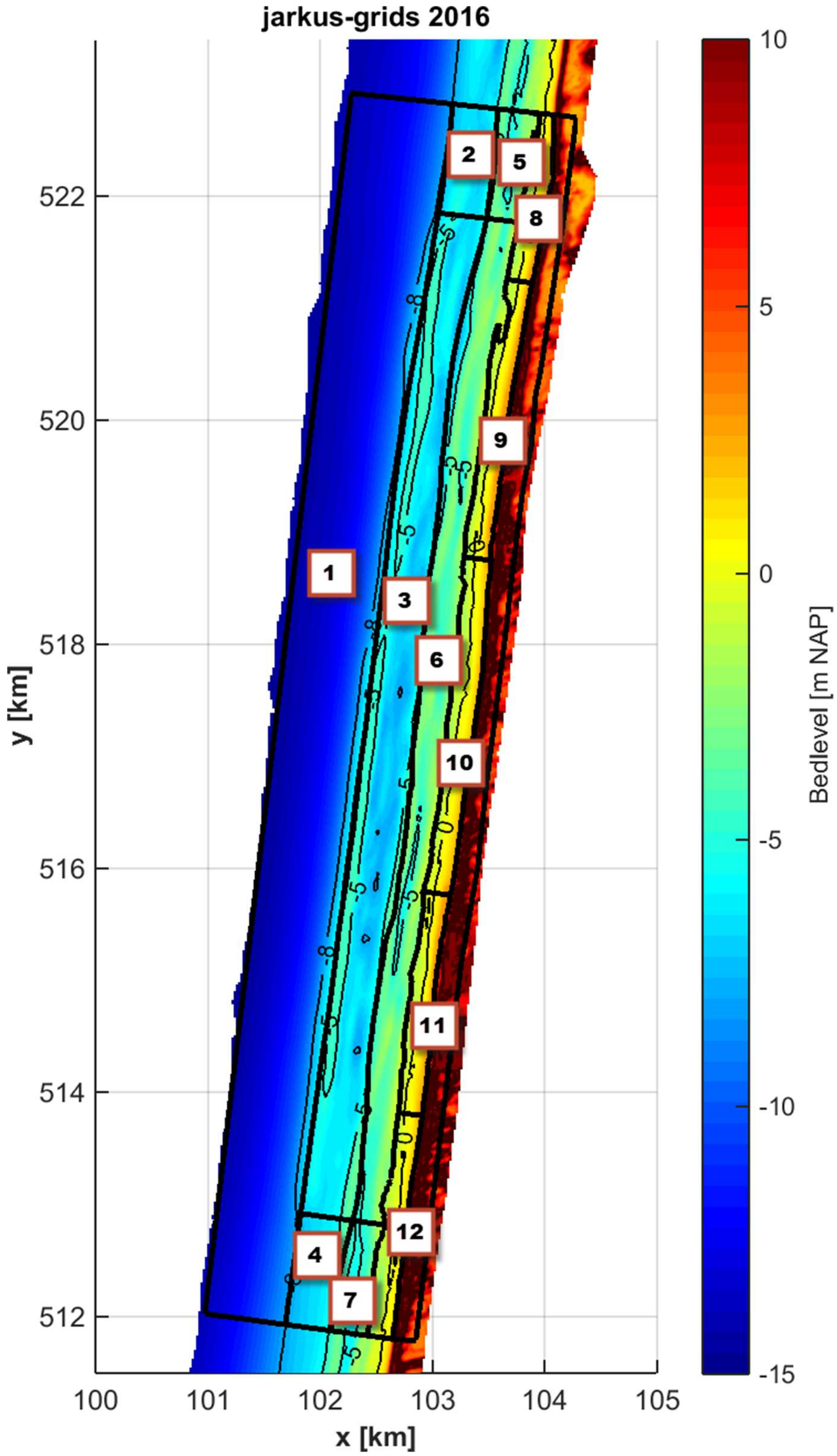


Figure 3.24 Volume areas for Zandvoort-Bloemendaal nourishment

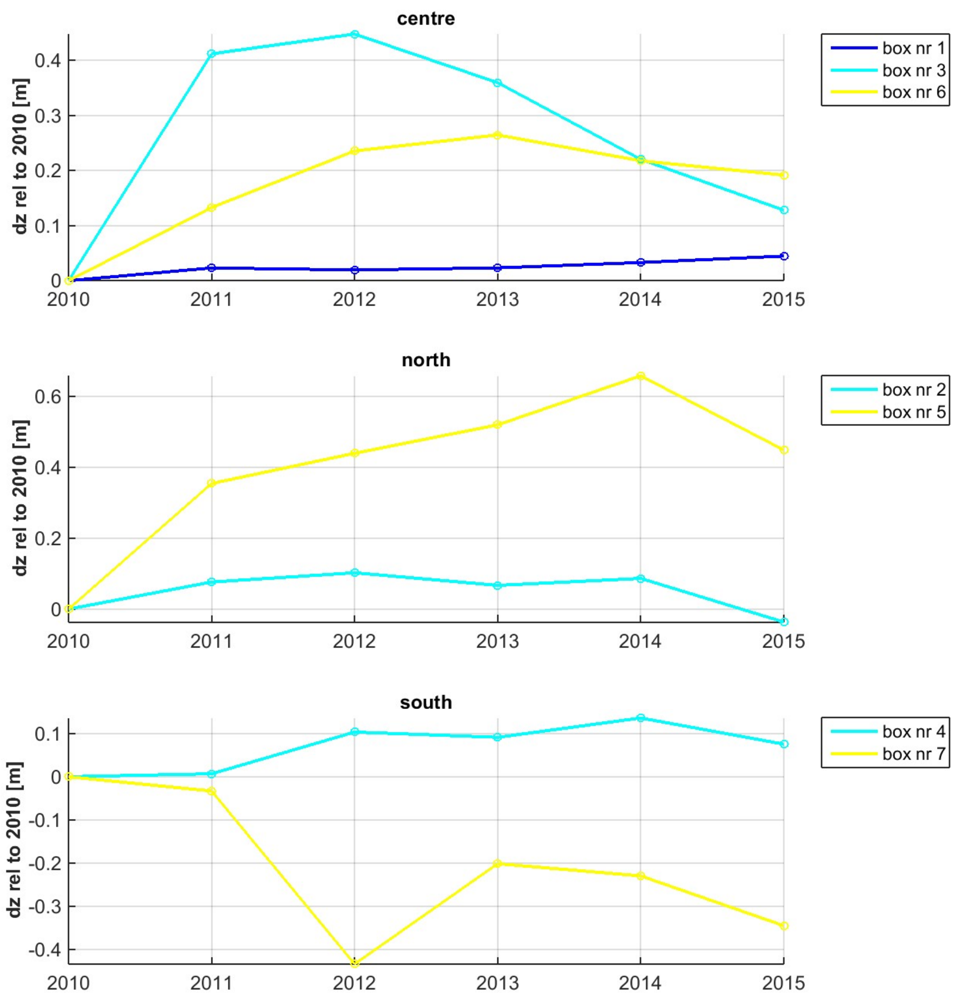


Figure 3.25 Change in average bed level for each polygon below low water for Zandvoort-Bloemendaal nourishment

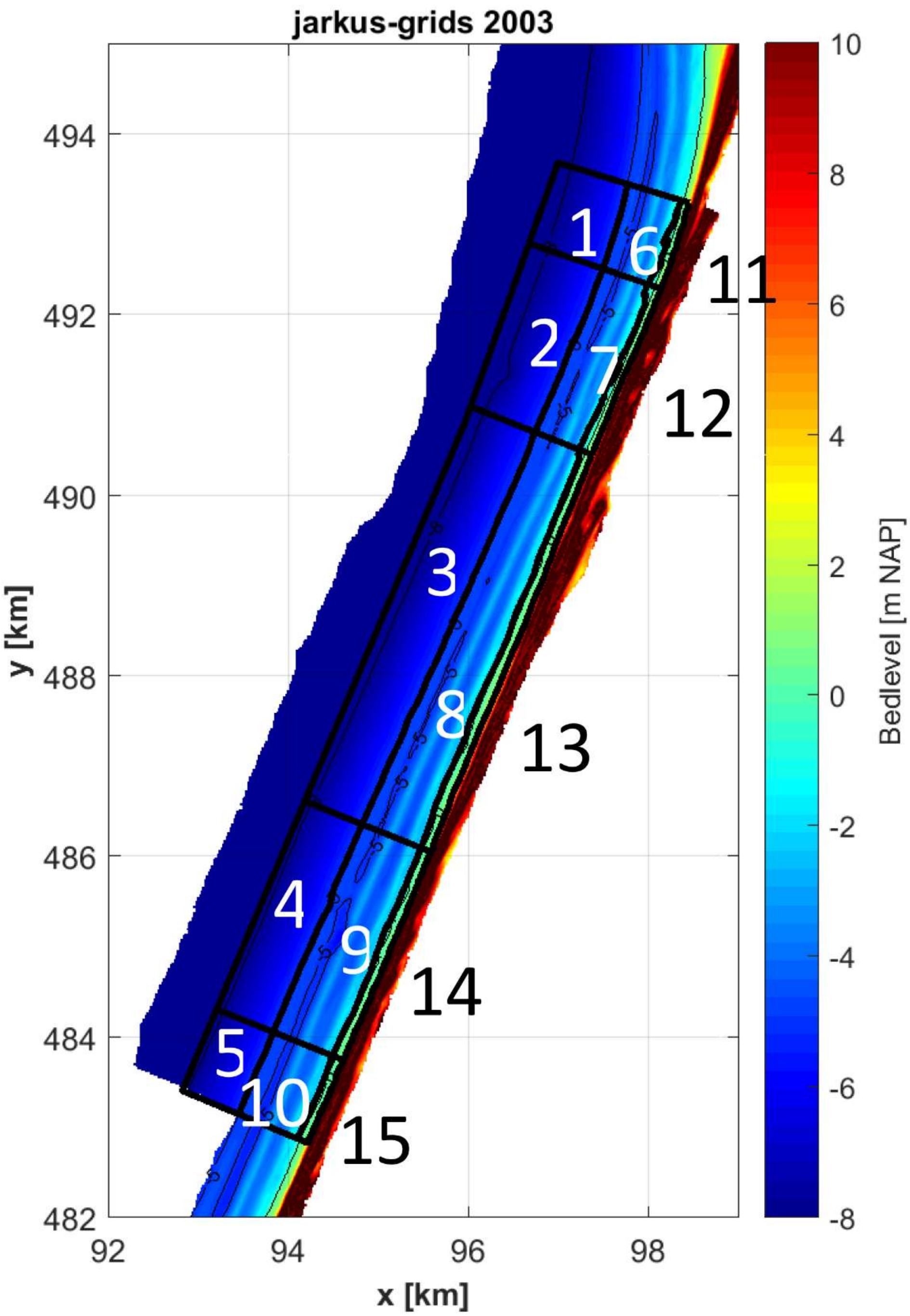


Figure 3.26 Volume areas for Bergen-Egmond nourishment

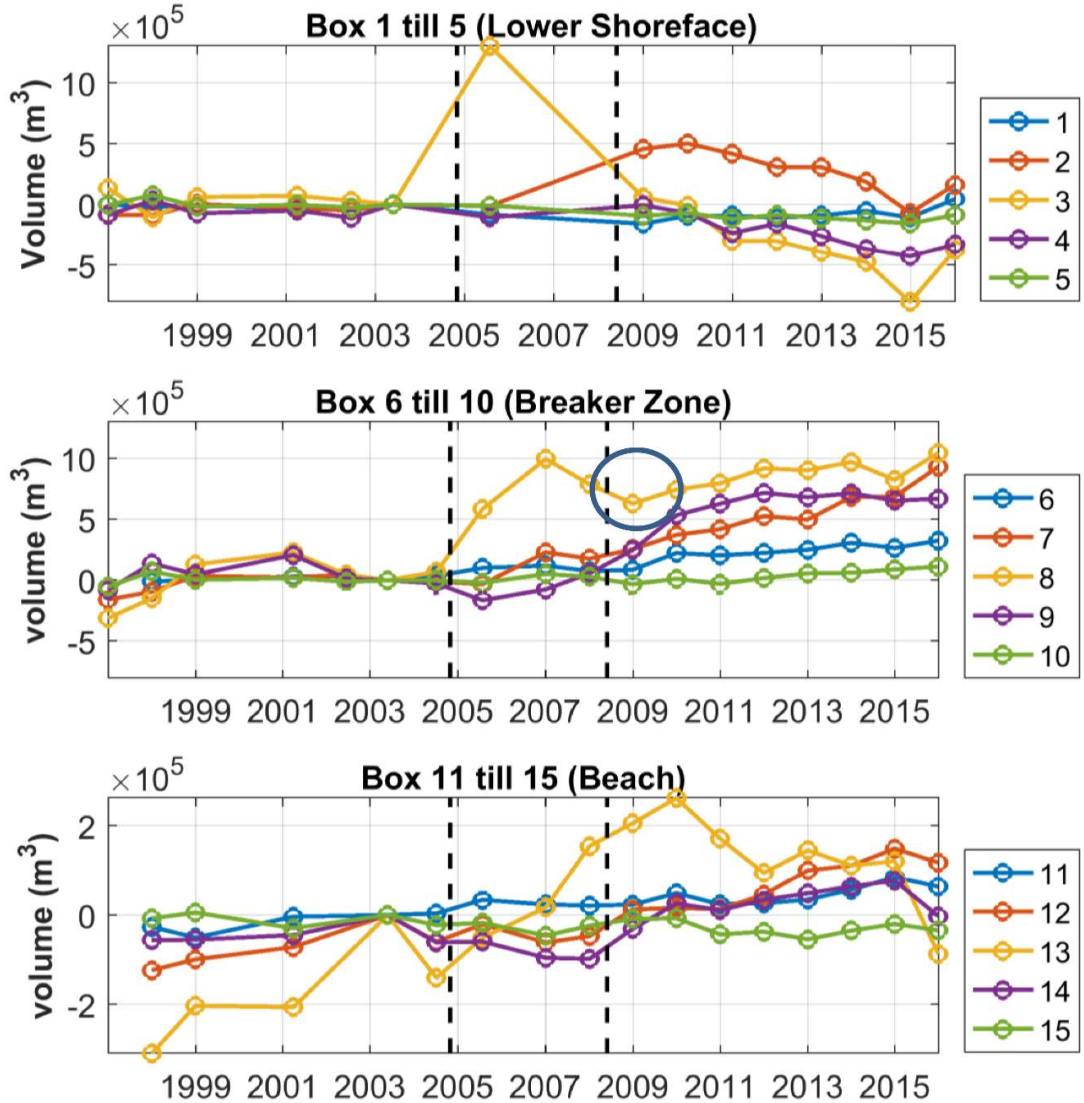


Figure 3.27 Volume development for Bergen-Egmond nourishment

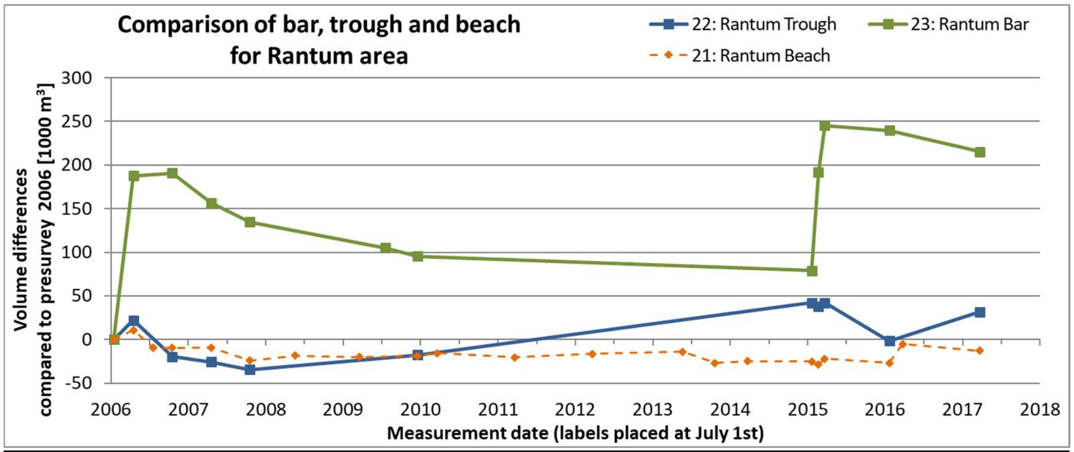
Sylt

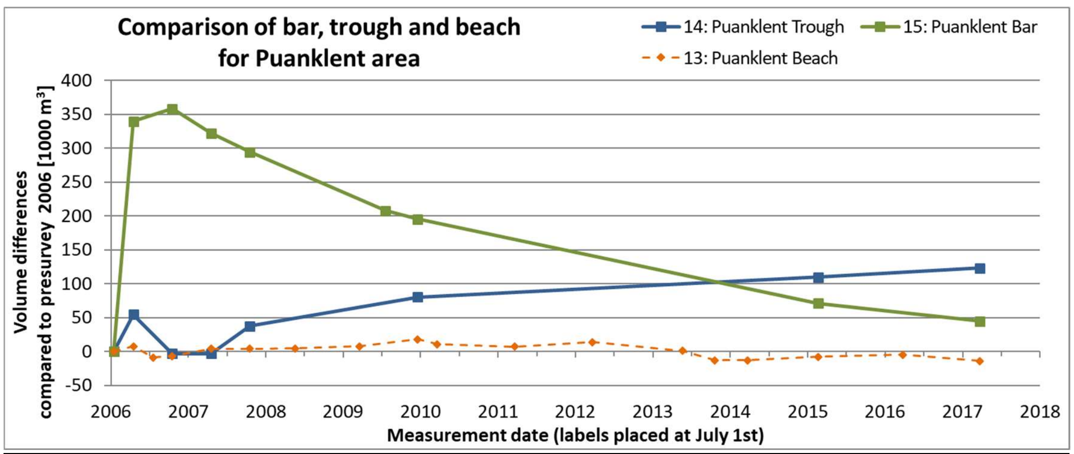
At Sylt the three shoreface nourishments are placed just offshore the outer breaker bar. At Sansibar the volume landward of the nourishment increased significantly in april 2008 the nourishment was placed, while at the other two locations the increase in volume followed much later and was much more gradual and smaller (after 2010, Figure 3.28).

In the morphological changes a difference can be seen between the areas cross-shore from the nourishments and the areas in between them (Figure 3.29). Directly cross-shore at the nourishments first a deepening of the bar trough can be seen, and landwards of this trough an increase in volume. This effect can be seen directly after the placement of the nourishment, at all three locations. Since the net volumes are relatively stable in this period, it cannot be concluded if the sedimentation (blue ellipses) is caused by sediment transport from the nourishments, of that they gain sediment from the deepened trough.

The areas besides the nourishments clearly gain sediment, which most likely came from the nourishments themselves. At this location the outer bar is located and became more continuous alongshore, just like the trough (dashed line). At Sansibar the breaker bar moved slightly landward in 2008, being the main reason for the net increase in volume.

Conclusions: in the morphology there is a clear effect directly cross-shore the nourishments, although this is not directly visibly in the net volume changes. In alongshore directions there is also a clear effect of the nourishments. At Sylt the wave energy is mainly perpendicular to the coast, explaining the strong cross-shore effect on the morphology. The alongshore changes are therefore most likely related to the tides, and morphological behaviours of the breaker bars.





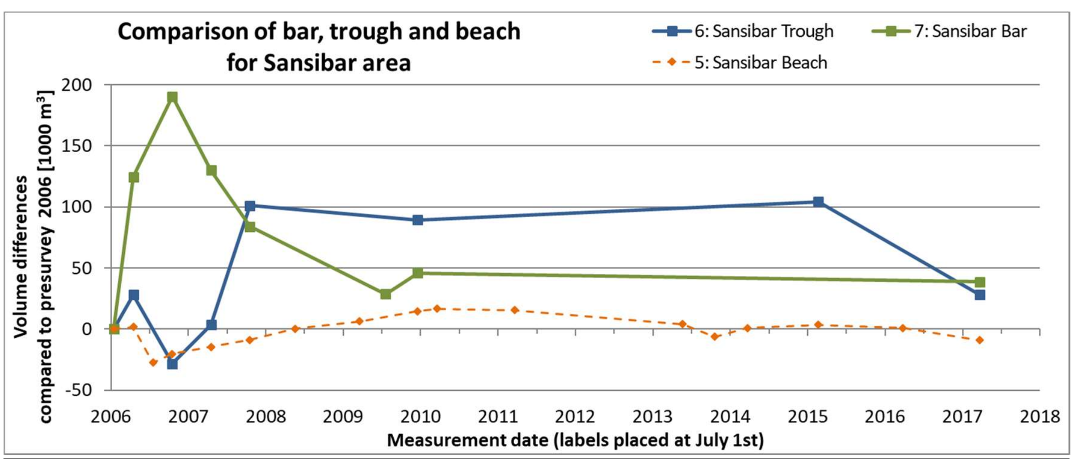


Figure 3.28 Volume development of Sylt nourishments and cross-shore areas (source: LKN.SH)

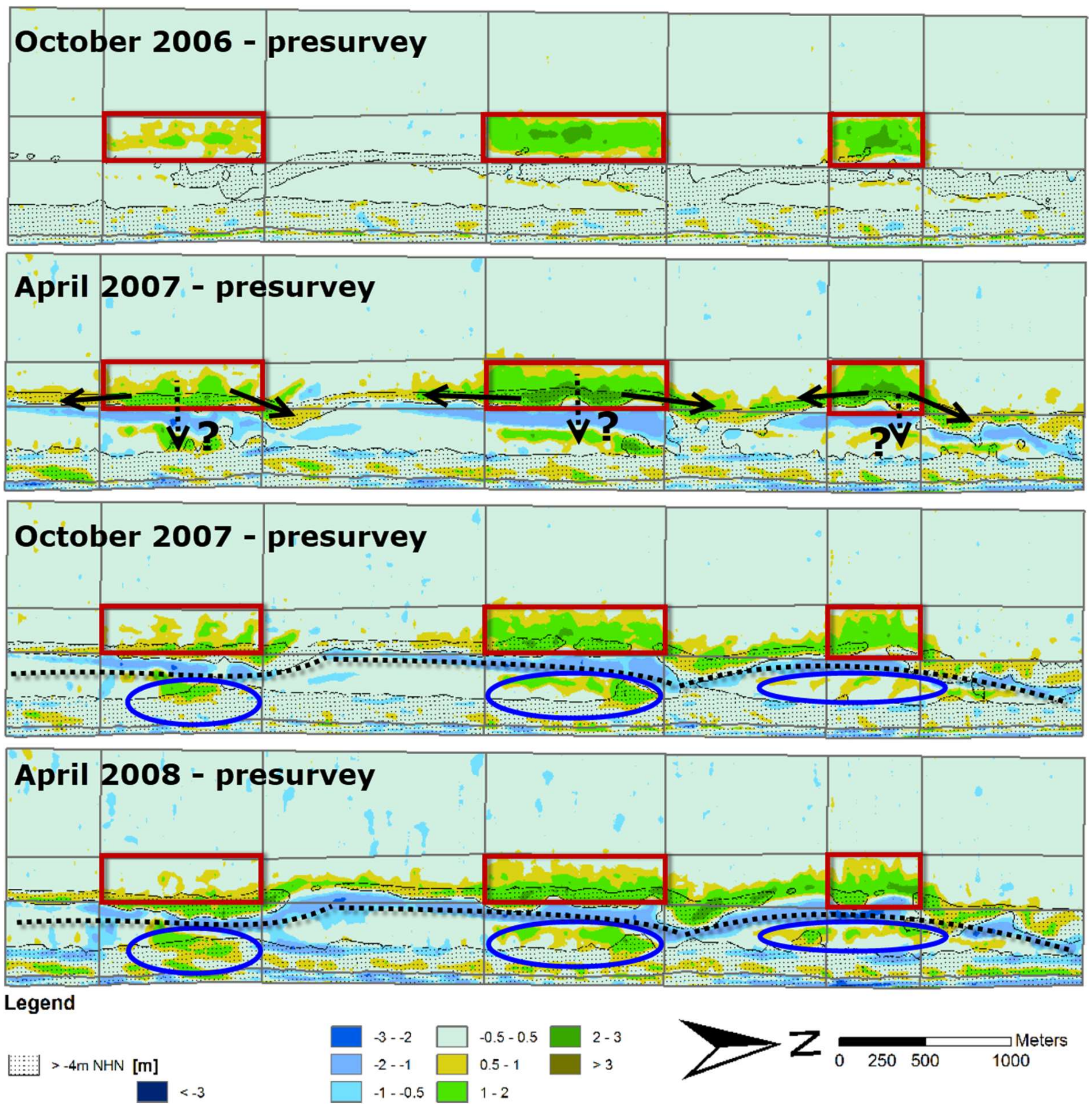


Figure 3.29 *Difference rasters for Sylt labs compared to pre-nourishment survey. Red squares indicate nourishment locations, arrows assumed (net) transport direction, dashed line trough position and blue ellipses locations with sediment accumulation (source: national analysis LKN.SH)*

Conclusions

Nourishments clearly can affect a different area - alongshore and/or cross-shore - , depending on the local processes. This is usually a complex combination of wind, waves and tide. Despite the fact that only the waves were quantified in this study, this hypothesis can be confirmed with local knowledge of the other processes.

3.3.4 The lifetime of a nourishment is influenced by the difference in beach slope prior and post execution of the nourishment

a. The diffusion time of a nourishment is longer when a nourished beach slope (is less steep than) < unnourished slope;

b. The diffusion time of a nourishment is shorter when a nourished beach slope (is steeper than) > unnourished slope

<u>Explanation</u>

The wave impact on a nourishment is less abrupt when the slope of the nourishment is smaller than the natural beach slope. In that situation the wave energy is dissipating gentler from offshore towards the dune foot. This explanation can also be seen vice versa for hypotheses 3.3.4b.

The diffusion time of a nourishment describes the lifetime, although it considers that the sand migrates from the nourishment area to neighbouring parts of the coast were still supports coastal protection. The used /chosen diffusion time D(50%) is reached when 50 % of the nourished volume is diffused from the nourishment area itself. It is chosen to get a comparable indicator which can be calculated easily. Figure 3.30 shows the estimation of this hypothesis with examples.

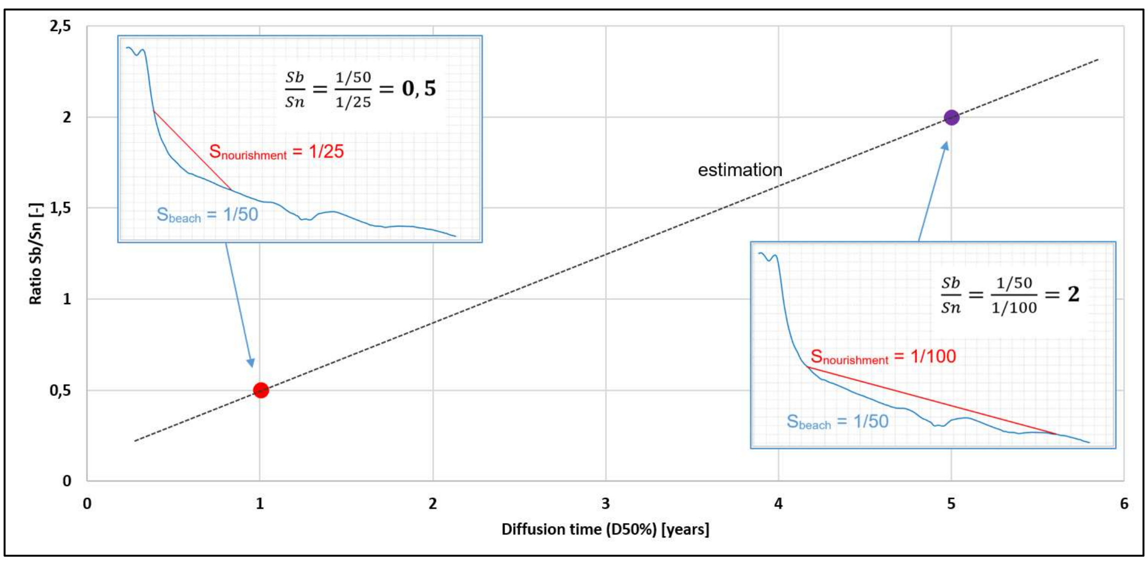


Figure 3.30 Example of the hypothesis and the calculation method

Method

The slope is calculated between lower dune level (dune foot) and mean low water level. For this hypothesis the slopes of all transects in the respective area are calculated. A mean slope is developed by calculating a weighted mean, taking into account the distance between the transects. The ratio Sb/Sn is the result of the slopes measured prior to nourishment execution and as soon as possible after the nourishment has been finished (depending on available surveys, the time lag can be over one year in some cases). The diffusion time is determined by volume calculation in transects or by use of the volume boxes. The diffusion time can vary within the nourishment area, a best estimate is then selected by the experts of that lab.

Results and discussion

Figure 3.31 shows the results of this hypothesis.

1. All (in-depth-)analysed nourishments of the labs (Table 2.1) have a diffusion time of one to two years. However, in some cases, a diffusion of 50% nourishment volume did not take place during the analysed period (Langeoog 2017/18 and Bergen-Egmond 2011). Possible reasons are natural sand supply or sand supply of other nourishments in the area. The additional blue and dark orange data points of Sylt – beach and shoreface – nourishments show a larger variety.
2. On Langeoog different nourishments at the same location are showing different behaviour than expected in the hypothesis. However, diffusion times are quite close to each other, possible reasons are:
    a. High variability of natural sand supply from the ebb-tidal delta affects the system.
    b. Larger volumes can be placed if the slope is steep, which leads to a longer absolute diffusion time.
3. All slopes are calculated in the beach area (dune foot to low water level). The nourishment-slope is calculated directly after the shoreface nourishment is placed, however, shoreface nourishments might not directly affect the beach area. Shoreface nourishments aim to affect the beach on a longer time scale.
4. The slope of a nourishment does not fully represent a nourishment design. The height of the nourishment is also relevant for the diffusion time. If sand is placed high on a beach, it can stay longer on the (dry) beach or feed the dunes, because the water simply does not reach up to the nourishment. However, due to a developing cliff, wave energy is not dissipated gently as stated in the hypothesis. A method to include a relative slope (slope/nourishment height relative to tidal parameters) could be topic of further research.

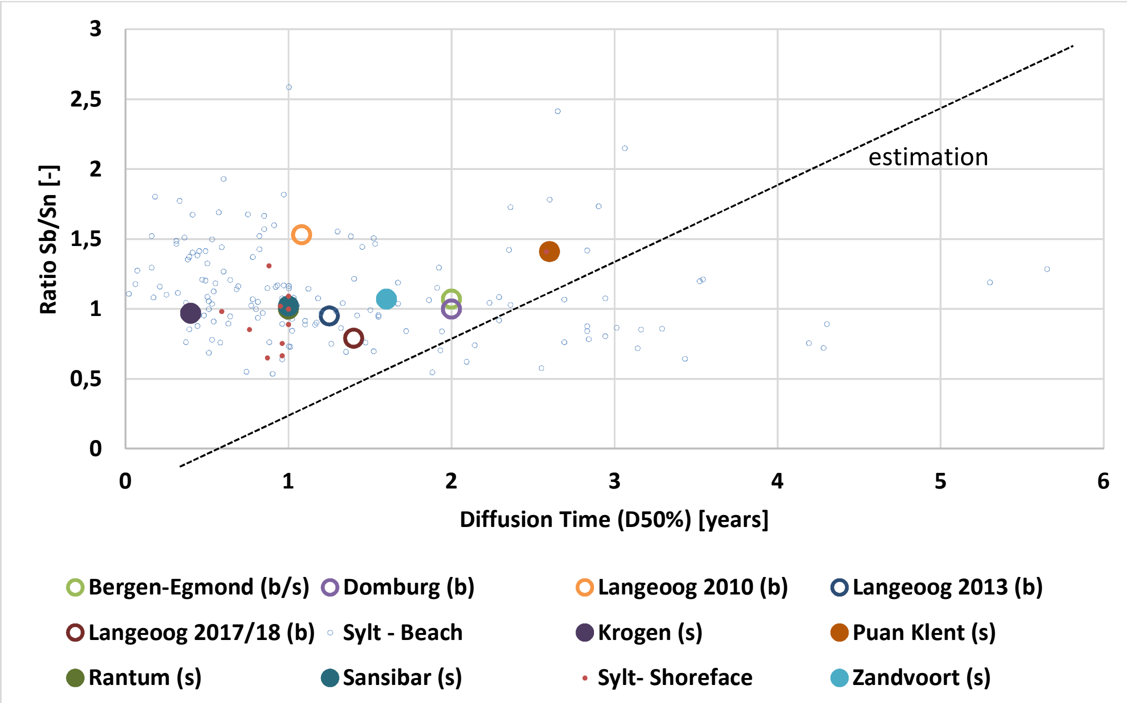


Figure 3.31 *Results of the Hypothesis of various coastal labs. (b) = beach nourishment; (s) and filled circle = shoreface nourishment*

<u>Conclusion</u>

At the moment the hypothesis cannot be supported by the information from the studied labs. No clear correlation between the diffusion time and the post/prior beach slope is found. Different factors like natural sand supply, nourishment design (including placement in the shoreface or on the beach) and nourishment objectives (regarding the diffusion time), can be reasons for the lack of a clear correlation. However especially for beach nourishments it is known that relatively steep beach nourishment slopes can result in beach scarps (Van Bemmelen, 2018). For coastal management it might therefore be important use gentle beach slopes when avoiding beach scarps is important.

Although the hypothesis is not giving a clear signal for the assessed nourishments, the method could be useful for comparing other nourishments, which have similar designs or are located in comparable morphological systems.

3.3.5 A beach nourishment's diffusion time is positively correlated with the sediment volume in the active zone

Explanation

The general idea is that a larger sediment volume in the active zone will result in more dissipation of the wave energy before it is reaching the beach. The part of the coastal profile where the largest morphological changes occur is considered as the 'active zone'. The lower amount of energy will then likely cause smaller gradients in sediment transport resulting in less erosion and a longer diffusion time of the beach nourishment.

Results

The diffusion time for the beach nourishments of the coastal labs is plotted against the average system volume (Figure 3.32). The system volume is calculated as an average in time and over the transects of the lab, between the mean low water level and MSL-6.5 m (see section 2.2.1).

In total three beach nourishments were studied in this project, however the beach nourishment at Bergen-Egmond shows an increase in volume. Hence, the diffusion time would theoretically be infinite, and is therefore not plotted in the graph. For Langeoog the large system volume is the result of the local morphology: the lab is located at the head of an island, where periodically sand bars migrate and attach to the coast. At periods, the system volume will be large, while at other periods – when nourishments are needed and placed – the system volume is small. The average volume therefore is higher than in the situation of the nourishment for which the diffusion time is calculated.

With only two datapoints it is not possible to analyse a relation between the plotted variables.

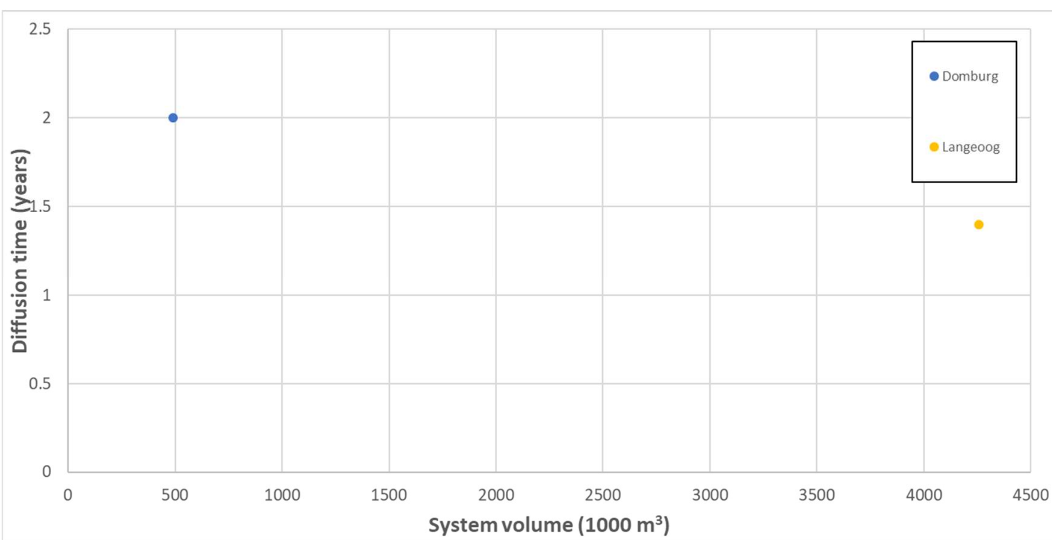


Figure 3.32 System volume of the shoreface (mean low water to MSL -6.5 m) plotted against diffusion time (time to 50% of nourishment volume) for the labs where beach nourishments have been applied.

Conclusion

This hypothesis cannot be supported directly by the information from the studied labs, although it is a relevant principle for nourishment design. The basic principle that waves have higher dissipation when the water depth is smaller – so with a higher sediment volume in the active zone, resulting in small water depths – is still supporting this hypothesis.

3.3.6 Larger nourishments will have larger initial losses

Explanation

Larger nourishments bring the coast more out of equilibrium and will have larger initial losses. These losses become smaller when they erode and the coast comes closer to its equilibrium state.

Results

The initial losses are not calculated in this project but can be seen in the volume development of the studied nourishments. Figure 3.33 to Figure 3.40 show the change in volume (1D or 2D) over time of the nourishments.

For the nourishments at Sylt (Sansibar, Puanklent and Rantum) and Langeoog the graphs show a steep first part of the curve (larger erosions rates, initial loss) and a decrease in steepness thereafter (smaller erosion rates, even stable volume). The initial losses are clearly larger than the losses later in time(indicated by the red, orange and green dashed lines in the figures). The volumes at Sylt show an increase *after* the nourishment was finished, caused by the morphological changes of the breaker bar which transported some sediment from the landward box towards the nourishment box. After this, the bar moves landward, resulting in an even steeper decrease of the volume. To account for this effect focus has been on the volume directly after the nourishment was placed. It is likely that nourishments at these locations with a smaller volume will induce erosion rates closer to the flatter part of the curve.

For the other labs the change in steepness is not observed. The nourishment at Skodbjerge is not clearly visible in the volume development, the nourished sediment is eroded very fast and therefore the erosion rates are not visible in the measurements. For the labs of Domburg, Zandvoort-Bloemendaal and Bergen-Egmond the volumes change almost perfectly linear. It is expected that when the change in volume would be undisturbed for a longer period of time (the analysed period is until the next nourishment), the curve will be become flatter. A possible explanation is that these area's are still far out of equilibrium, so only the steep part of the curve is visible.

Conclusions

The changes in volume of the nourishments in several coastal labs indicate that the erosion rates become smaller when there is less volume left, this supports the hypothesis.

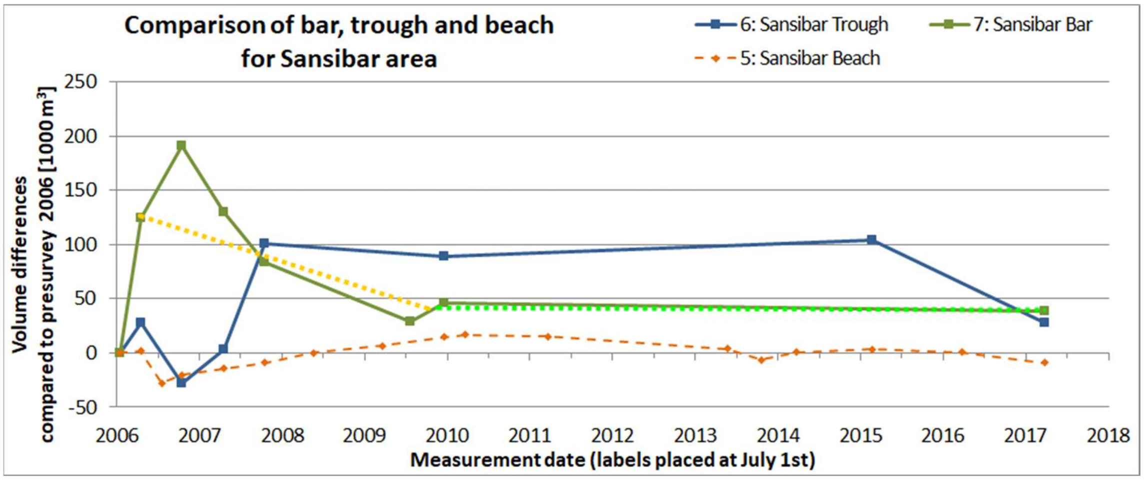


Figure 3.33 *Volume development of shoreface nourishment (Sansibar Bar box) at Sansibar, Sylt (LKN.SH national analysis). Dashed lines indicate rate of change (red=high, orange=intermediate, green=(almost) stable).*

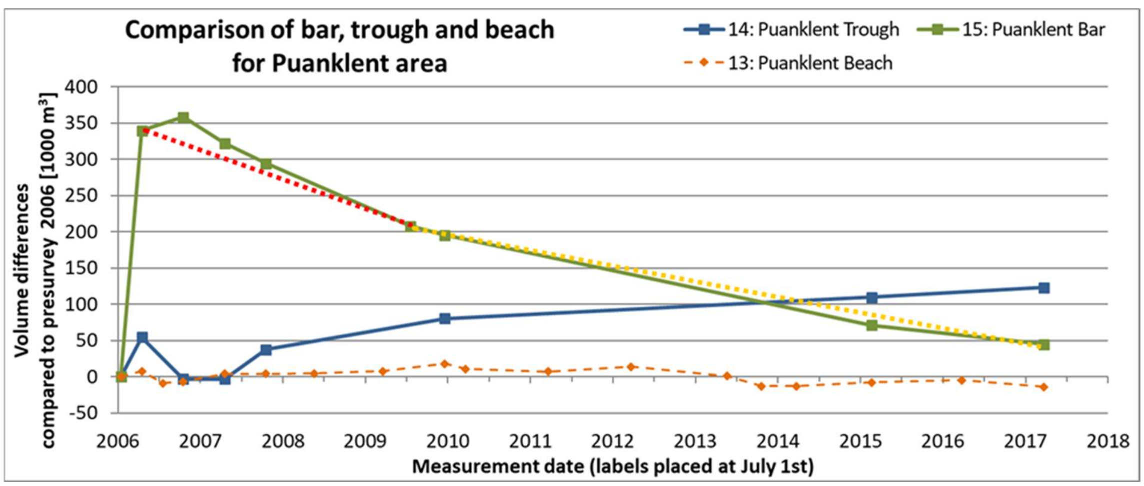


Figure 3.34 *Volume development of shoreface nourishment (Puanklent Bar box) at Puanklent, Sylt (LKN.SH national analysis). Dashed lines indicate rate of change (red=high, orange=intermediate, green=(almost) stable).*

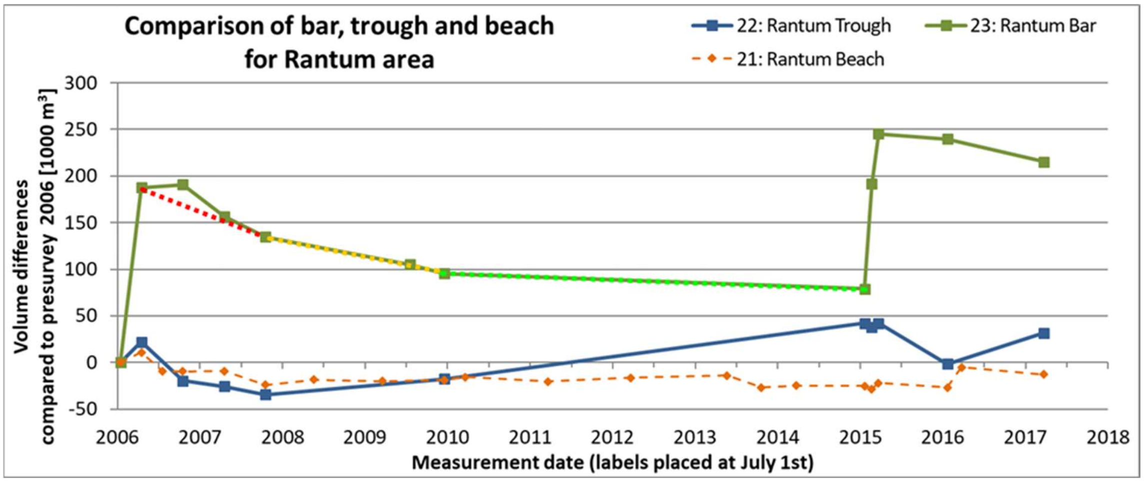


Figure 3.35 *Volume development of shoreface nourishment (Rantum Bar box) at Rantum, Sylt (LKN.SH national analysis). Dashed lines indicate rate of change (red=high, orange=intermediate, green=(almost) stable).*

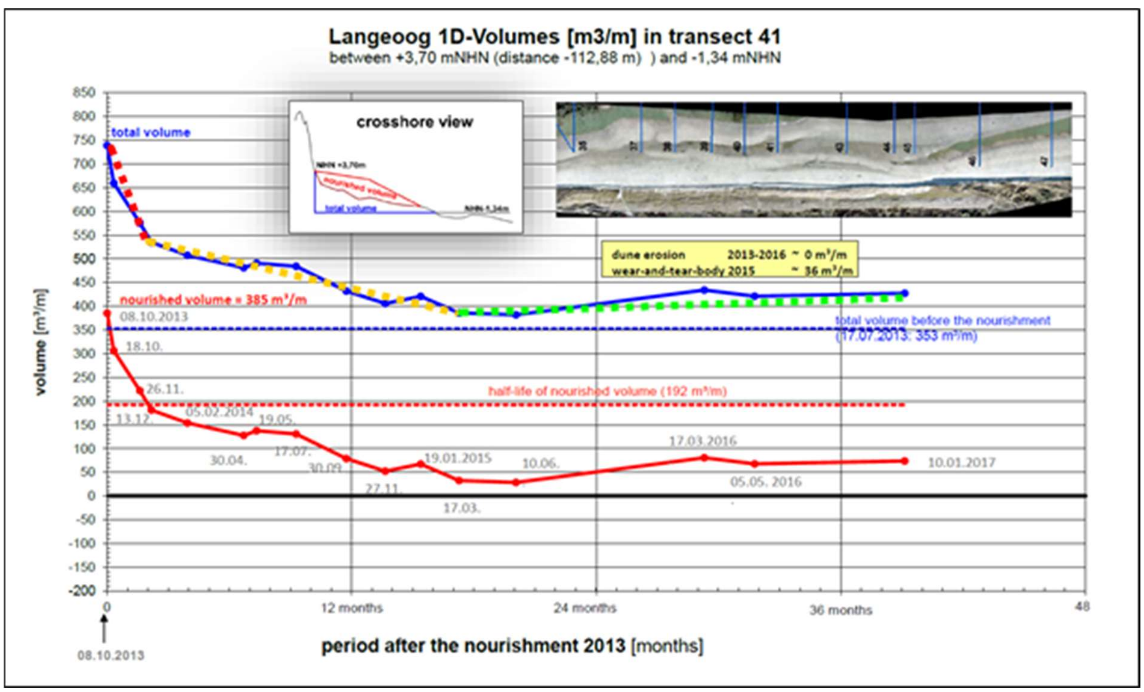


Figure 3.36 *1D-Volume development for transect 41 of beach nourishment at Langeoog (NLWKN national analysis). Dashed lines indicate rate of change (red=high, orange=intermediate, green=(almost) stable).*

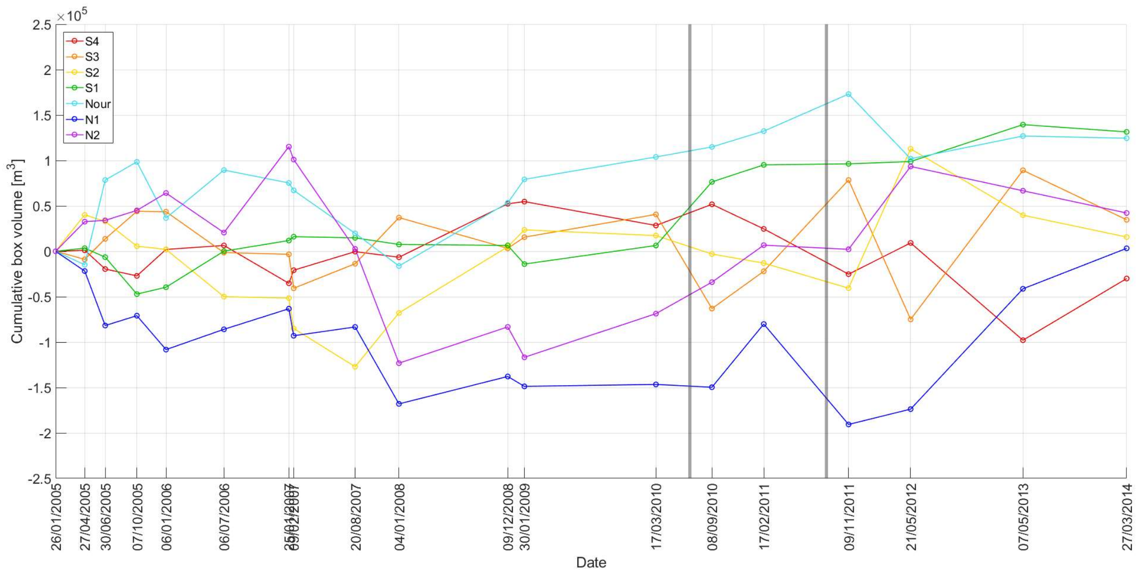


Figure 3.37 Volume development of shoreface nourishment ('Nour' box) at Skodbjerge (DCA national analysis)

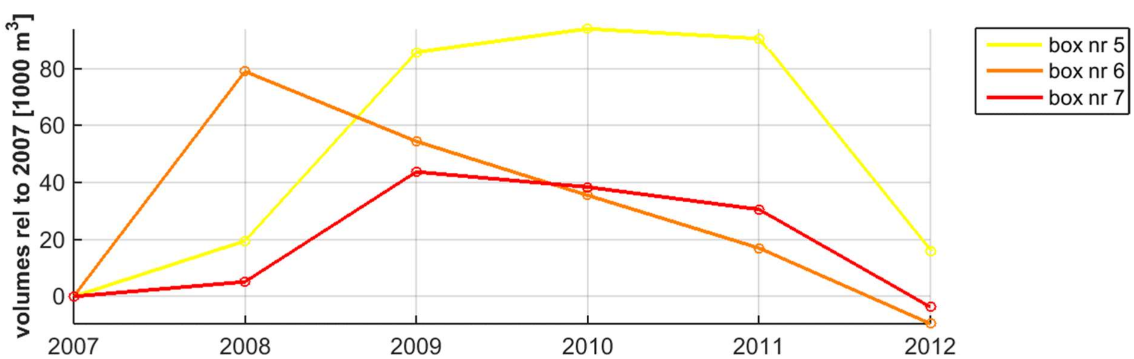


Figure 3.38 Volume development of central part of beach nourishment (box 6) at Domburg (RWS national analysis)

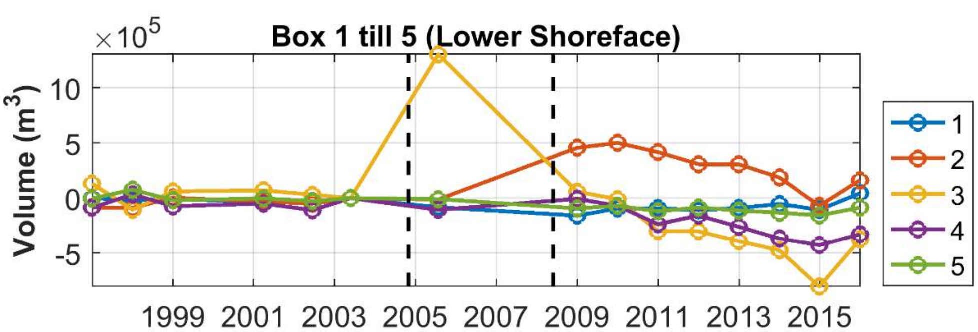


Figure 3.39 Volume development of shoreface nourishment (box 3) at Zandvoort-Bloemendaal (RWS national analysis)

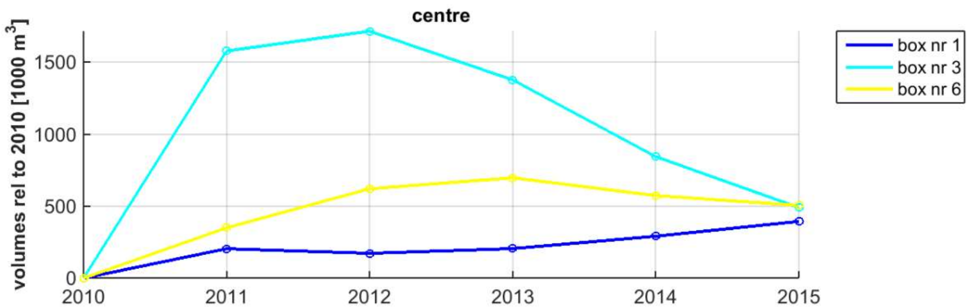


Figure 3.40 Volume development of shoreface nourishment (box 3) at Bergen-Egmond (RWS national analysis)

3.3.7 The coarser the grainsize of the nourishment, the more stable the nourishment is

Explanation

An important parameter for sediment transport is the grainsize of the sediment, besides the flow velocity of the water. Therefore, this is relevant for the behaviour of nourishments: coarser sediment will be transported under higher flow velocities. Therefore, coarser sediment will remain longer at a certain location than finer sediment.

Results

For the studied labs the grainsize is plotted against the diffusion time of the nourishments (time until 50% of the nourishment is transported away from the nourishment location), see Figure 3.41. Although there appears to be a clear trend, with two outliers, there are two important factors that also play a role: 1. the nourishment volume and 2. the hydrodynamic energy. By dividing the total nourishment volume by the ‘relative wave energy’ (total wave energy divided by grainsize) these two are accounted for in some way. This seems to show some relation for some of the labs, but also three outliers (Figure 3.42). Two outliers are the nourishments of Zandvoort and Bergen, with an exceptionally high total volume compared to the other nourishments (2.2 and 3.2 million m^3). Also, the total wave energy might not be a correct measure for the hydrodynamic energy, since tidal flow will also play a role.

Conclusions

Despite the results, when at one location a nourishment would have a larger grainsize, while other parameters are the same (volume, placement, hydrodynamic energy, etc.), the coarser sediment would remain longer at that location.

Besides the effect of grainsize on erodibility, it will also affect the steepness of the coastal profile: coarser sediment will lead to steeper profiles. This can be seen by the steepness of the profiles at Sylt (see 2.2.3).

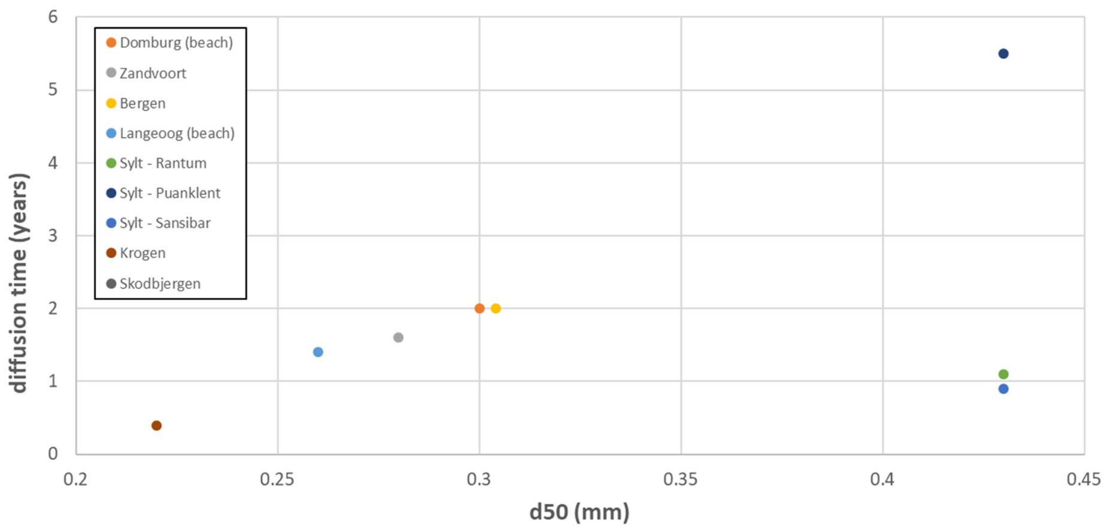


Figure 3.41 *Relation between grainsize (d50) and diffusion time (time till 50% of nourishment volume) for all coastal labs (beach nourishments are specifically noted in the legend,, the others are shoreface nourishments).*

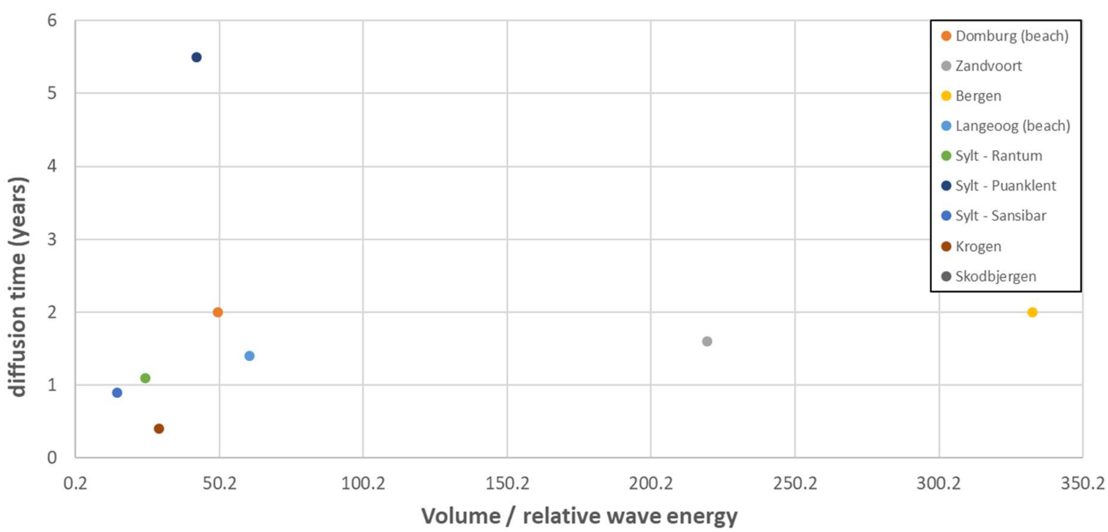


Figure 3.42 *Relation between volume divided by 'relative wave energy' (total wave energy divided by grainsize) and diffusion time (time till 50% of nourishment volume) for all coastal labs (beach nourishments are specifically noted in the legend,, the others are shoreface nourishments).*

3.3.8 Nourishments at exposed beaches erode faster than nourishments at unexposed beaches

Explanation

Exposed and unexposed parts of the coastline respond differently to wave energy. Wave energy on exposed parts cause erosion. Unexposed parts may even benefit from this through longshore transport.

Figure 3.43 illustrates the calculation of the exposure (e) for any point (P) on the coastline.

l [m]:	length of the coastline considered for the calculation
c [m]:	length of a chord (straight line) whose endpoints both are situated on the coastline at chainages l/2 behind and l/2 ahead of P
d [m]:	distance between P and the chord
e = d/c [-] or [m/km]:	exposure

The coastline in this context is defined as the mid dune level (MDL).

Figure 3.43 Definition of exposure

<u>Results</u>

Figure 3.44 shows the exposure (l = 2000 m) for Sylt in comparison with the cumulated nourishment volumes and annual erosion rates[1]. Many of the hotspots with high erosion rates and large nourishment volumes can be explained by exposure (e.g. Westerland, Kampen, Dikjendeel). The high erosion rates and large amounts of nourishments at the island's northern and southern ends are also strongly influenced by tidal currents. Figure 3.45 shows a similar picture for Bergen-Egmond[2] (Noord-Holland). As the most exposed part of the coastline is almost straight for approximately 5 km, l = 8000 m was chosen for the calculations. Figure 3.46 shows the exposure (l = 4000 m) and cumulated

[1] Linear trend (1984 - 2019) of the volume development (0 - 5 mNHN), reduced by nourishments
[2] Erosion rates were not calculated due to different data availability (measurement concept)

nourishment volumes for Domburg (Walcheren). The most western part shows high exposure, but because of a revetment, only low amounts of nourishments.

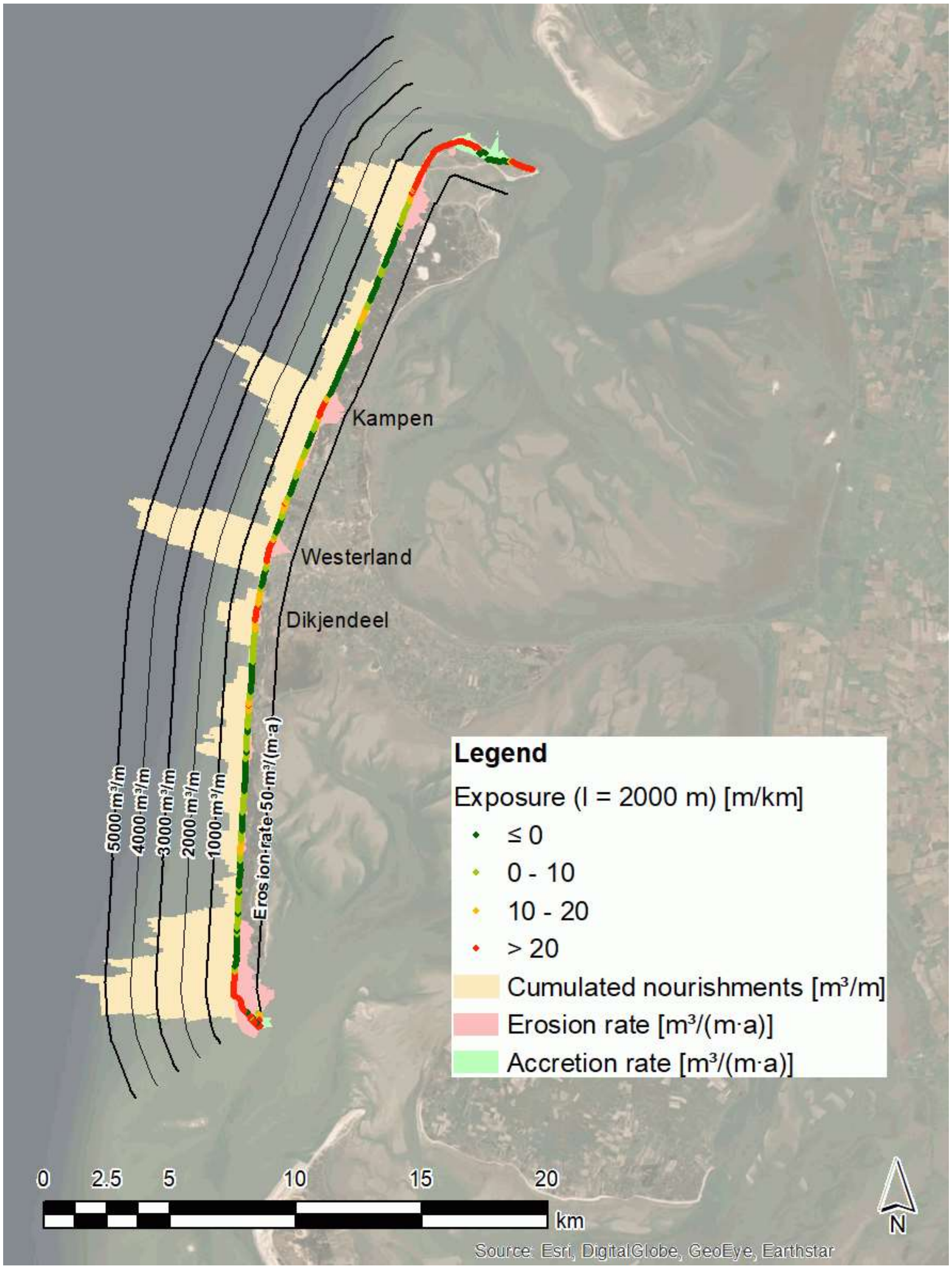


Figure 3.44 *Exposure (l = 2000 m, mid dune level) for Sylt in comparison with the cumulated nourishment volumes (1971 - 2019) and mean erosion rates (1984 - 2019)*

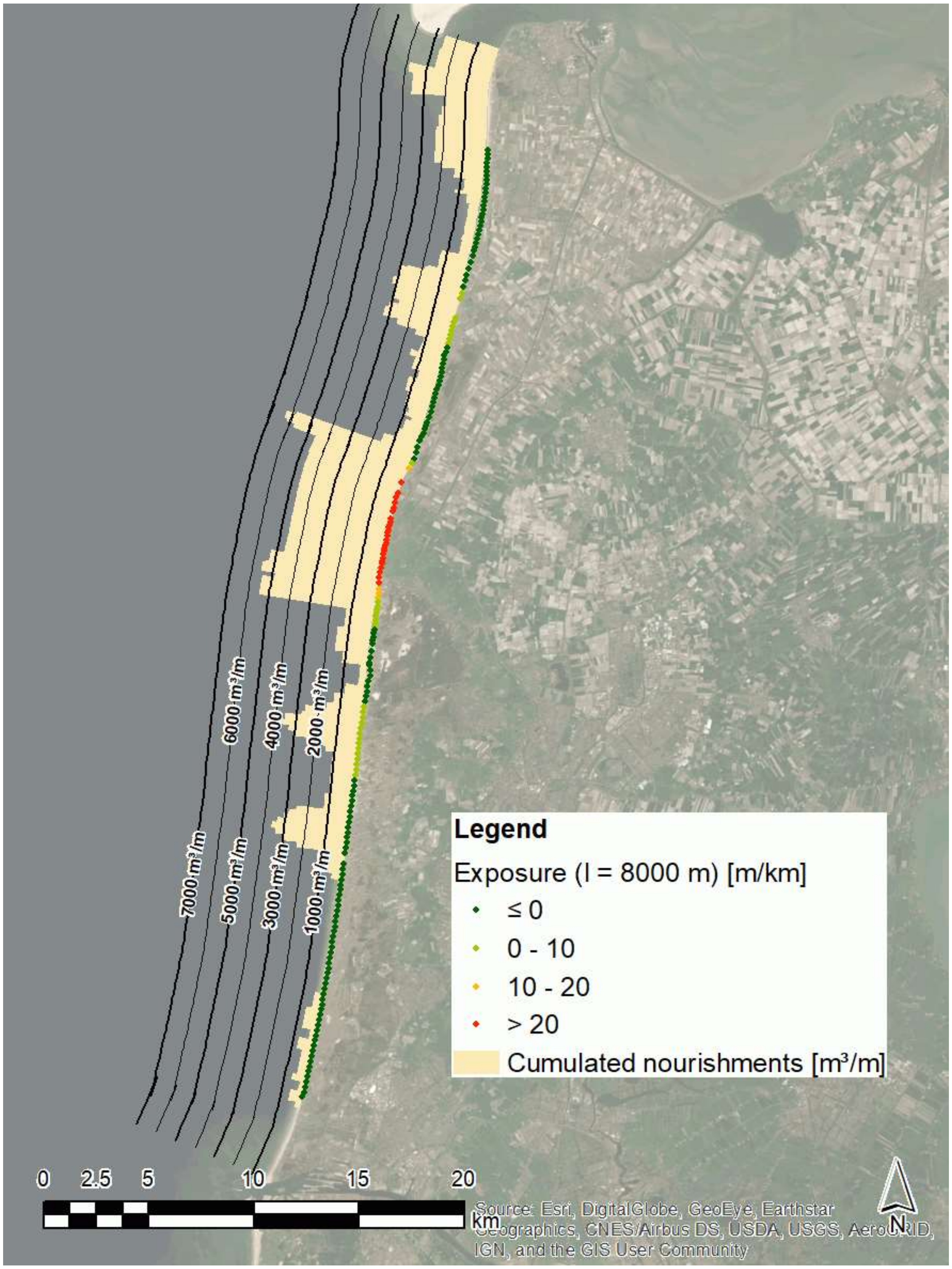


Figure 3.45 Exposure (l = 8000 m, mid dune level) for Bergen-Egmond (Noord-Holland) in comparison with the total accumulated nourishment volumes

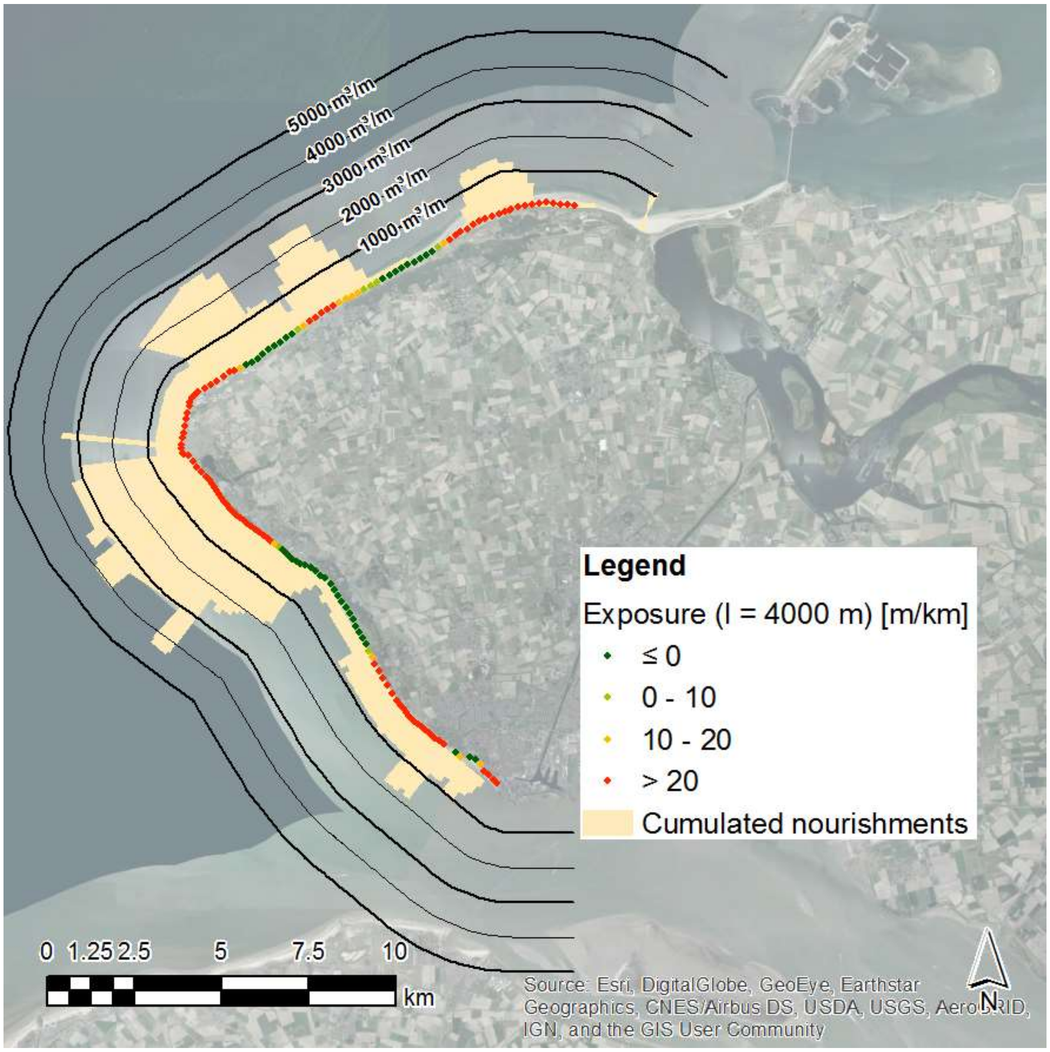


Figure 3.46 *Exposure (l = 4000 m, mid dune level) for Domburg in comparison with the total accumulated nourishment volumes*

Figure 3.47 displays the data shown in Figure 3.44 to Figure 3.46 as graphs. The graphs show a correlation between exposure, erosion rates (Sylt only) and cumulated nourishments. The correlation is lowest for Domburg with a correlation coefficient of r = 0.14 (determination coefficient R^2 = 0.02). Reasons are, amongst others, revetments, groins, different orientations of the northern and southern part of the shore (and therefore different wave energy impact) and nourishments that were not placed for short term erosion compensation (nourishments in the dunes, nourishments in the tidal channel). Correlation is highest in Bergen-Egmond with r = 0.74 (R^2 = 0.54). It must be mentioned, that the large nourishment at the Hondsbossche sea defence (Figure 3.45, central part) is only partly correlated to erosion as it was placed to widen to coastal landscape as a reinforcement. Sylt shows a correlation coefficient of r = 0.54 (R^2 = 0.29) for the cumulated nourishments and r = 0.74 (R^2 = 0.49) for the erosion rates.

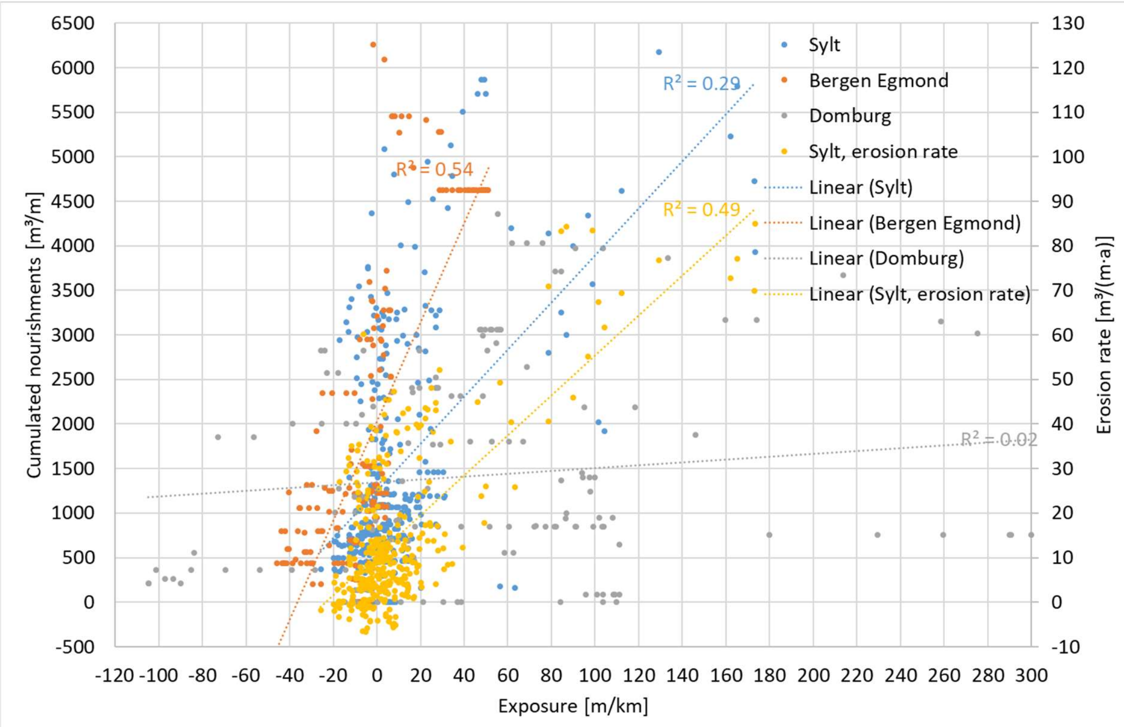


Figure 3.47 Correlation between exposure, erosion rates and cumulated nourishments. Exposures at mid dune level (MDL). Sylt: MDL = 5.00 mNHN, l = 2000 m, erosion rates: 1984 - 2019, 0 mNHN - 5 mNHN; Bergen Egmond (Noord-Holland): MDL = 5,55 mNAP, l = 8000 m, Domburg (Walcheren): MDL = 6,74 mNAP, l = 4000 m

Exposure affects erosion on different scales - from a single edge at Kampen on Sylt to larger morphological structures like for example the peninsula of Domburg. It also depends on the actual spatial extent the analysis is applied to. Table 3.1 illustrates this by displaying the correlation coefficients r for different parameters l and in the case of Sylt also for different extents. The correlation coefficients for the data shown in Figure 3.44 to Figure 3.46 are printed in bold numbers The choice of l for an analysis depends on particular morphological setting of an area and the scale of exposure one is interested in.

Table 3.1 Correlation coefficients for different scales

		Correlation coefficient r		
Location	**Parameter**	**l = 2000 m**	**l = 4000 m**	**l = 8000 m**
Sylt (Central west coast)	Erosion rate	0.48	0.31	0.00
Sylt (Central west coast)	Cumulated nourishments	0.61	0.53	0.37
Sylt (West coast)	Erosion rate	0.70	0.72	0.61
Sylt (West coast)	Cumulated nourishments	**0.54**	0.50	0.51
Bergen-Egmond	Cumulated nourishments	0.34	0.63	**0.74**
Domburg	Cumulated nourishments	0.00	**0.14**	0.33

Conclusion

Exposure in this hypothesis is defined as a geometric feature of the shore. Obviously, it can be only one of many factors influencing erosion. Other factors are: orientation of the shore to the dominant wave direction, amount and direction of wave energy hitting the shore, availability or deficits of sediment at the site itself, gradients in alongshore transport, hard structures such as groins and revetments, lee erosion, tidal currents, etc.. For example, spits are geometrically very exposed. Yet in many cases, they are growing because they have a positive sediment budget due to sediment they receive through alongshore transport.

Where other influencing factors are similar, there is a clear correlation between exposure and erosion. I.e. the sea would like to flatten the coastline. To maintain exposed sites (if that is the policy) an increased effort needs to be made compared to adjacent less exposed sites, e.g. a higher amount (higher number and larger volume) of nourishments, needs to be placed. The adjacent less exposed sites benefit directly from the nourishments in the exposed sites.

The studied labs show for most locations a clear correlation between exposure and nourishment volume, supporting this hypothesis.

3.3.9 Shoreface nourishments (can) increase trough depth

Explanation

Shoreface nourishments are often applied in areas where breaker bars are present. The added sediment will have influence on the existing breaker bar morphology. One possible effect is the development of a new or a larger bar, which can increase the depth of the trough on the landward side. It is therefore the hypothesis that deeper troughs are formed due to the extra sediment available in the system from the nourishment.

Results

For the labs where breaker bars are present the depth of the trough (m to vertical reference) and the surface area (m^2 in the profile) of the bar are calculated automatically for all available transects within a lab (see Figure 3.48). When multiple bars are present in a profile, the parameters are calculated for each bar. For some transects the automated method did not find all existing (visual assessment) bars, especially for the profiles from Sylt.

In several labs where shoreface nourishments have been placed, in the period after the nourishment larger bars with deeper troughs have been observed. For the labs Bergen-Egmond, Zandvoort-Bloemendaal, Sylt and Skodbjerge the depth of the troughs in the measured transects is shown in Figure 3.49 to Figure 3.52. For specific characteristics of the shoreface nourishments shown, see Table 3.2.

Before the shoreface nourishments, the maximum trough depth at Bergen-Egmond was almost always above -7 m, at Zandvoort-Bloemendaal above -6 m, occasionally reaching 0.5 meter deeper. After the shoreface nourishments the troughs reached almost up to -9 m at Bergen-Egmond and almost -7.5 m at Zandvoort-Bloemendaal. For the labs Sylt and Skodbjerge the data do not show a clear difference between the period before nourishments and directly after. At Skodbjerge the depth of the trough even might be slightly shallower in the period after the nourishments than before. At Sylt some periods lack specific data on trough development when the measured transects do not cover the area below low water level. Both Skodbjerge and Sylt have two nourishments, with a total volume that is much smaller than in Bergen-Egmond and Zandvoort-Bloemendaal.

The occurrence of deeper troughs is most likely a direct consequence of the nourishments. There seems to be a relation with the total nourishment volume (Figure 3.53) and no (clear) relation with the volume per stretch of coast (Figure 3.54). However, local differences of the trough depth within the labs are not represented in the graphs.

Conclusions

In general, we expect that the larger bars with deeper troughs are formed due to the extra sediment available in the system from the nourishment. The data from the coastal labs supports this hypothesis. However, several factors play a role in the effect of the nourishment on the bar troughs, including total nourishment volume, volume per stretch of coast, the phase of the bar system (is the outer bar present, decaying or absent) during the placement of the nourishment and the wave climate (e.g. Grunnet & Ruessink, 2005, Van der Spek and Elias, 2013, Vermaas et al., 2017, Bruins, 2016).

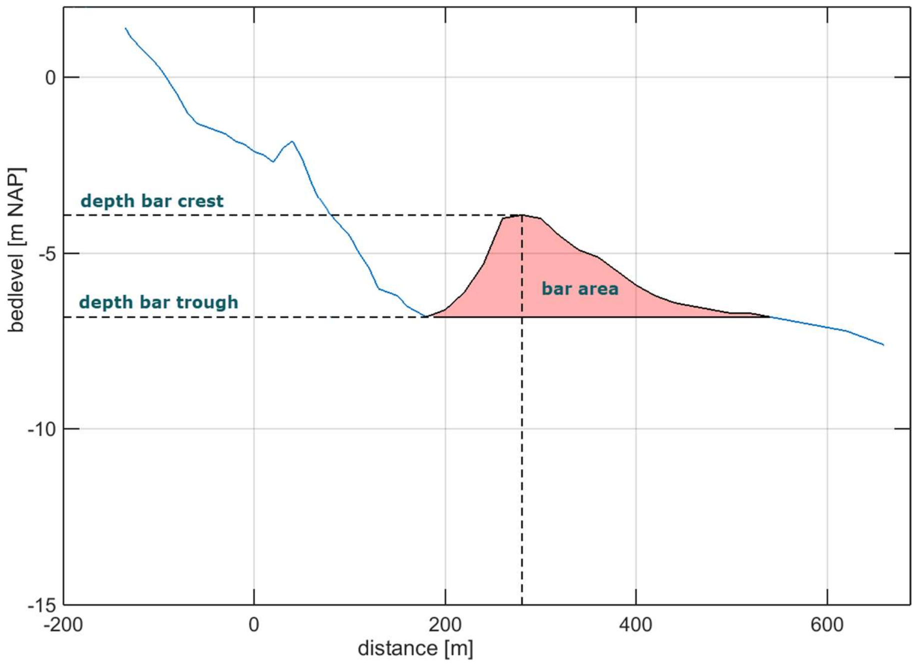


Figure 3.48 Determination of bar trough depth and bar area (red marked area), bar crest depth also indicated

Table 3.2 Characteristics of shoreface nourishments indicated in Figure 3.49 and Figure 3.50

Location	Year of placement	Total volume (million m³)	Volume per m (m³/m)
Bergen-Egmond	1999/2000	1.87	425
Bergen-Egmond	2004/2005	3.11	357
Bergen-Egmond	2010/2011	3.20	355
Bergen-Egmond	2016	2.50	280
Zandvoort-Bloemendaal	2004	2.20	440
Zandvoort-Bloemendaal	2008	1.50	350
Zandvoort-Bloemendaal	2016	2.40	320
Sylt (Rantum)	2006	0.23	451
Sylt (Puanklent)	2006	0.39	391
Sylt (Sansibar)	2006	0.14	150
Sylt (Rantum North)	2015	0.36	256
Sylt (Rantum South)	2015	0.41	325
Skodbjerge	2010	0.73	57
Skodbjerge	2011	0.31	400

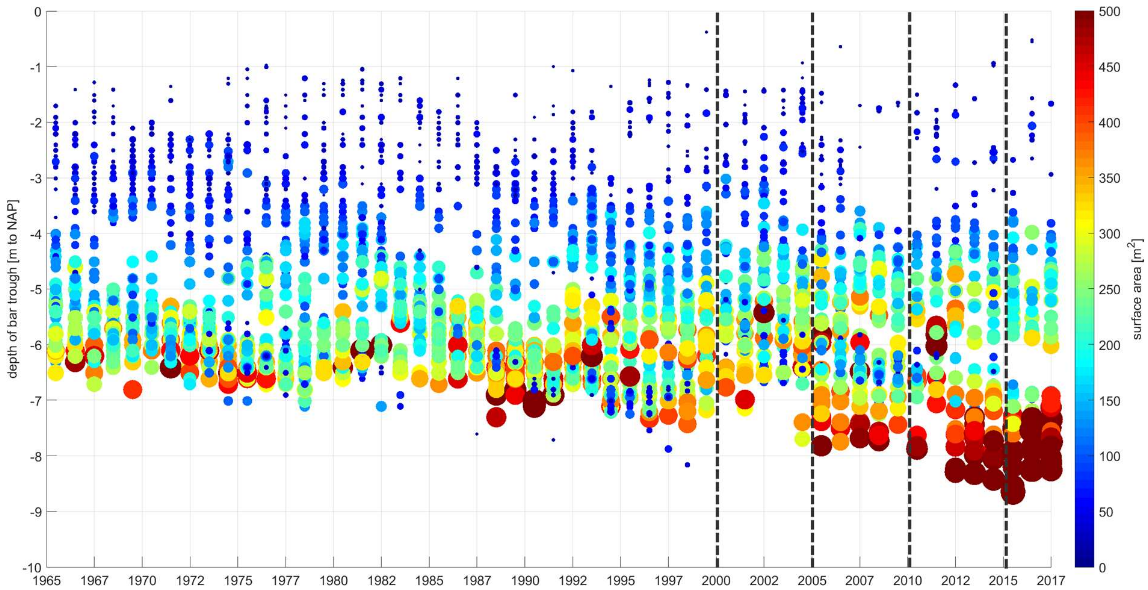


Figure 3.49 *Trough depth in time and bar area (colour and size of circles) for all transects at the Bergen-Egmond lab, dashed lines indicate shoreface nourishments. Each point represents one bar in a profile.*

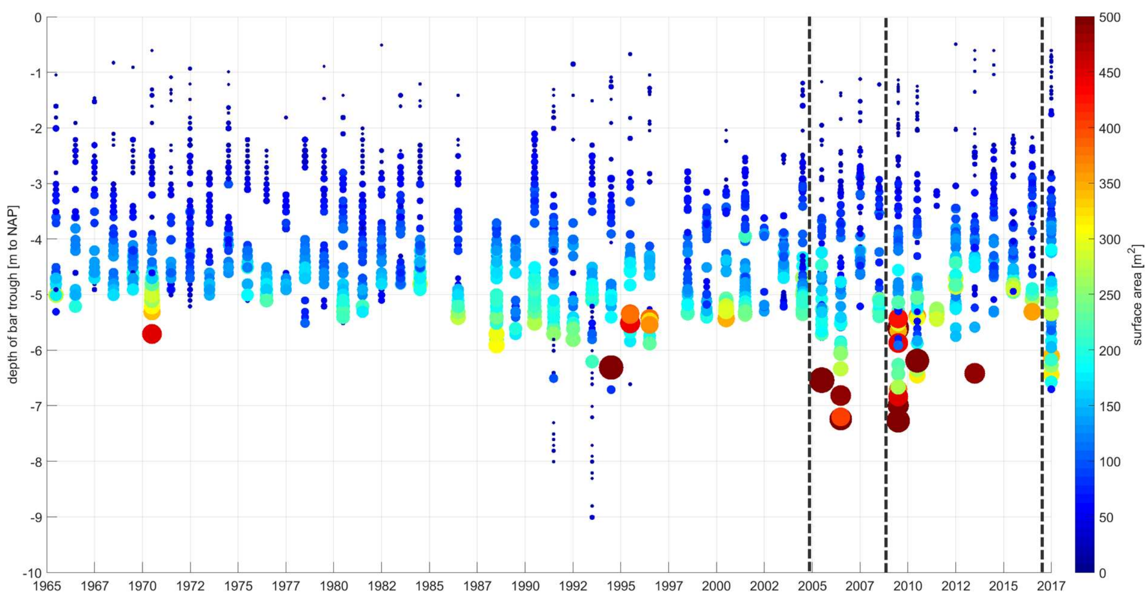


Figure 3.50 *Trough depth in time and bar area (colour and size of circles) for all transects at the Zandvoort-Bloemendaal lab, dashed lines indicate shoreface nourishments. Each point represents one bar in a profile.*

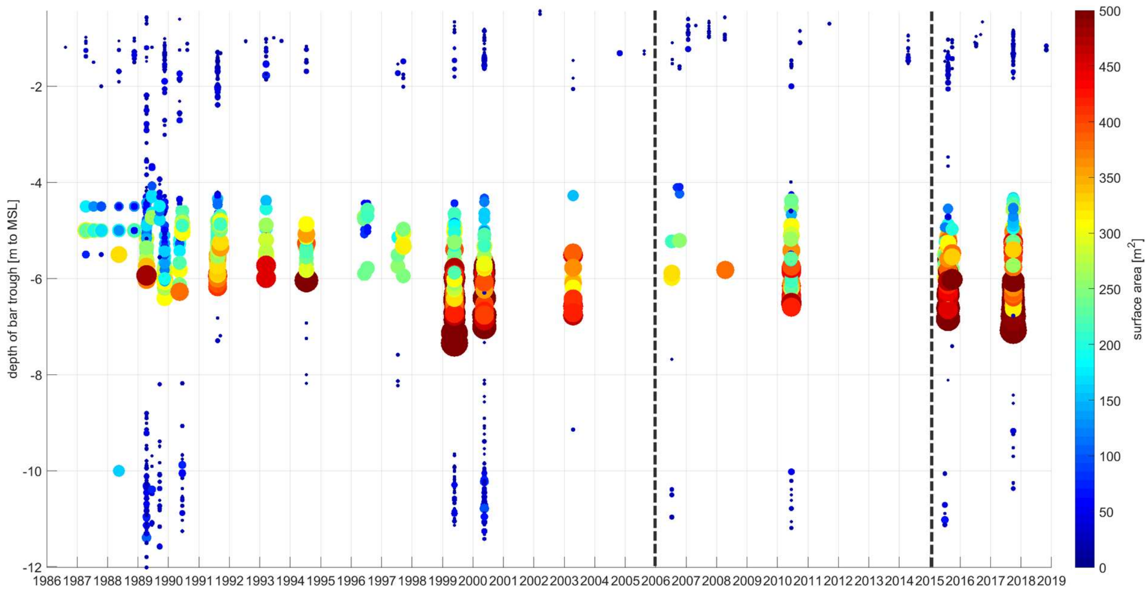


Figure 3.51 *Trough depth in time and bar area (colour and size of circles) for all transects at the Sylt lab, dashed lines indicate shoreface nourishments (last nourishment only at Rantum area). The shallow (above -4m) and deep (below -8m) positions with small bar area (blue color) are artefacts of the applied method. Each point represents one bar in a profile.*

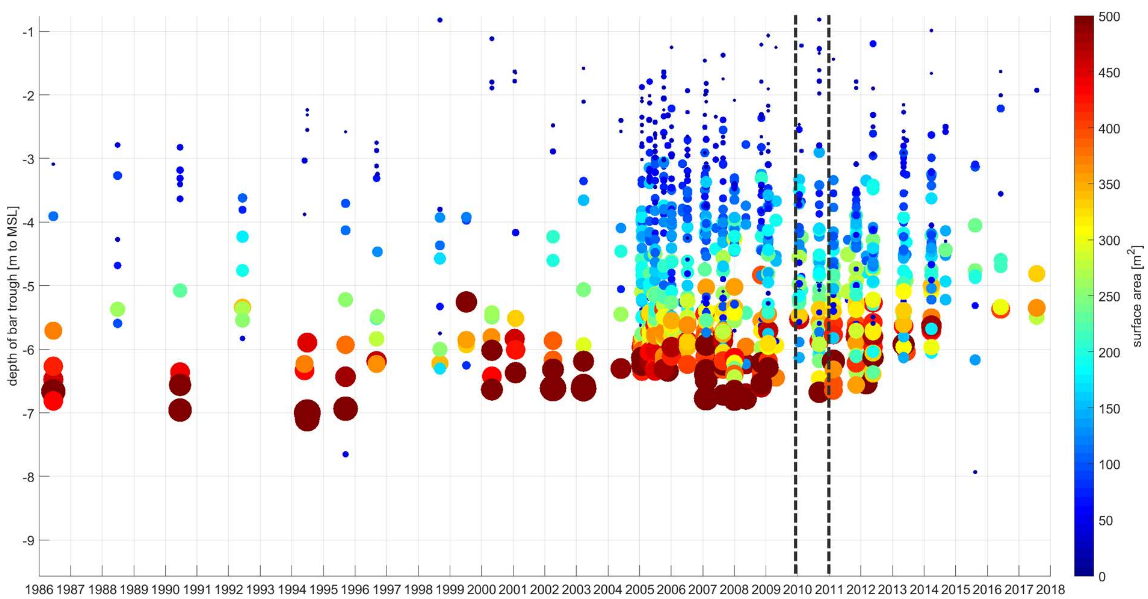


Figure 3.52 *Trough depth in time and bar area (colour and size of circles) for all transects at the Skodbjerge lab, dashed lines indicate shoreface nourishments. Each point represents one bar in a profile.*

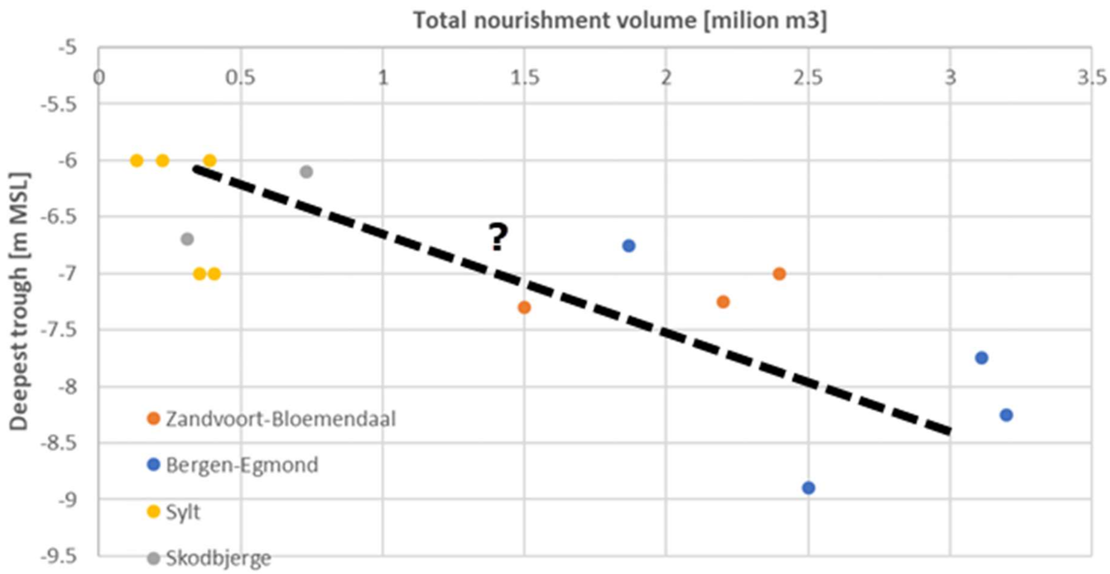


Figure 3.53 *Correlation of trough depth with total nourishment volume, dashed line is an indication and no statistical trendline*

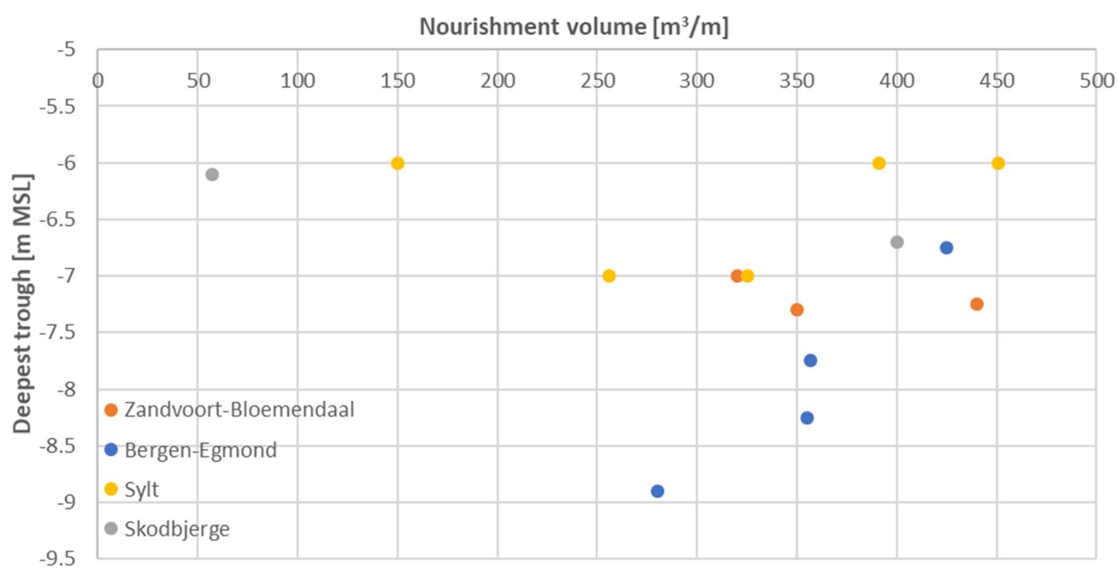


Figure 3.54 *Correlation of trough depth with nourishment volume*

3.3.10 Combined shoreface and beach nourishments have a stronger stabilising effect for the beaches than single measures

Explanation

While a beach nourishment directly increases the sediment volume of a beach, this volume is subject to erosion in a very short time after the measure, depending on the design of the nourishment. Shoreface nourishments in contrast, do not affect the beach volume directly but are often observed as to stabilise it for a longer period. A combination of beach and shoreface nourishments may therefore lead to the benefit of both effects combined: An increased beach volume which shows a higher stability

Method

Ideally, each of the investigated labs has:

- a *time period before* any nourishment,
- a *second period* with beach- or shoreface nourishments alone, and
- a *third period*, where combined nourishments have been applied, sometimes completed by single nourishments.

Here, nourishments are considered as “combined” if they are either designed as combined measures or if they follow-up each other in execution within one year. Within these periods, in the figures, the beach volume development is presented as line plots and completed with a linear regression. Figure 3.55 shows the plot for one lab as an example.

Then, the slope of the linear regressions for every period within each lab are compared. If period 3 is used to have the lowest slope or even an increase in the slope of the regression line, the concept of the combined nourishments is considered the most effective.

In a sub hypothesis it has been investigated if a relocation of the hotspot of erosion from the beach towards the shoreface could at least be partially responsible for the stabilising effect of shoreface- and combined nourishments .

Conclusion main hypothesis

Figure 3.55 shows a lab in the middle of the seaward coastline of Ameland (NL), approx. 6 km to both sides to the ends of the island. It is an example for the created graphs and shows how the situation in a lab typically is. In Ameland there was a time before 1981 with no nourishments and a certain decline of the beach volume (gradient -4.08). This situation is followed by a period with multiple measures, as there were dune enhancements and beach- and shoreface nourishments designed as single measures. They had a stabilising effect. Though, it looks like the first dune enhancement even increased instability. After the second dune enhancement the trend turns to positive. Respectively, there is still a gradient of -0.54 for the whole period. The third period started in 2006 with the first combined measure. The gradient has been raised to its value of 12.34 and therefore has proven that the combined measures have been more effective than the single measures before.

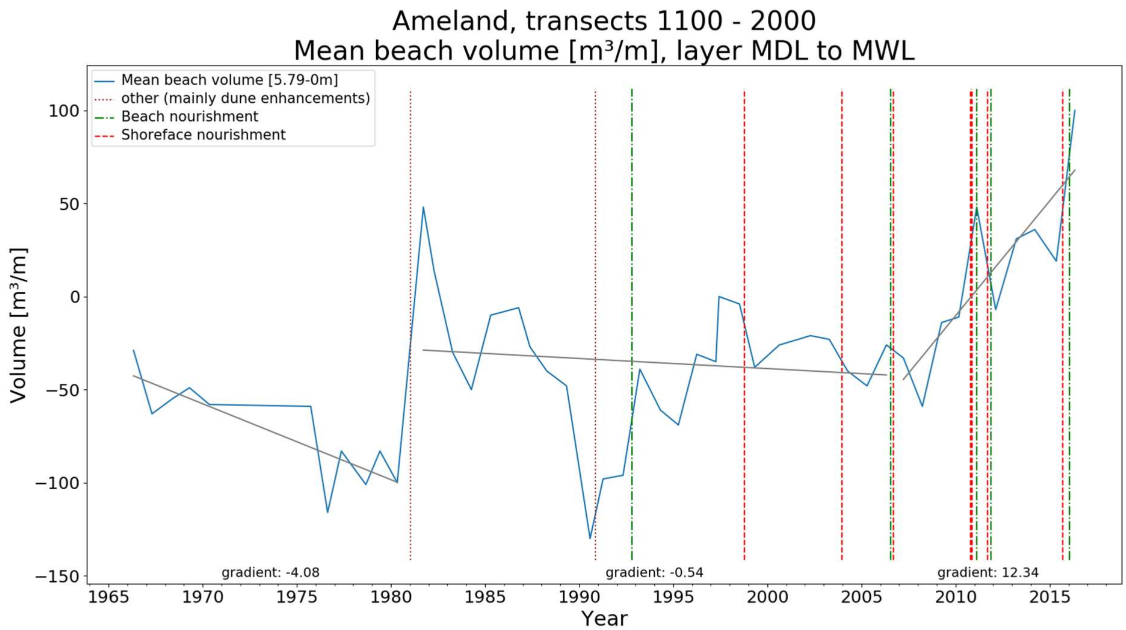


Figure 3.55 *Linear regression for the periods before/single/combined measures plotted over the beach volume development for Ameland, the steepest positive regression gradient is when the combined measures have been applied*

The calculations have been done for all labs where at least one combined measure could be extracted out of the data. To condense the results into one graph, Figure 3.56 shows an overview over all labs. The bars in this bar plot and their values correspond to the gradients of the respective regression lines.

The statement of the gradient should be seen as qualitative, not quantitative. This means that they are comparable within the lab in question. Because all labs are different, the single gradient values should not be compared between the labs (no lab ranking is possible based on the gradients).

Even though, Thorsminde (DK) stands out of this collection of labs due to its different nourishment design[3], all labs show that the nourishment design of the period with the combined measures is the

[3] In Thorsminde the beach- and shoreface nourishment was not performed at one spot but at two spots 2 km apart . Their mutual influence is therefore questionable.

most effective one. Though, as Table 3.3 indicates, the combination of measures is not the only design parameter that has increased the effectiveness.

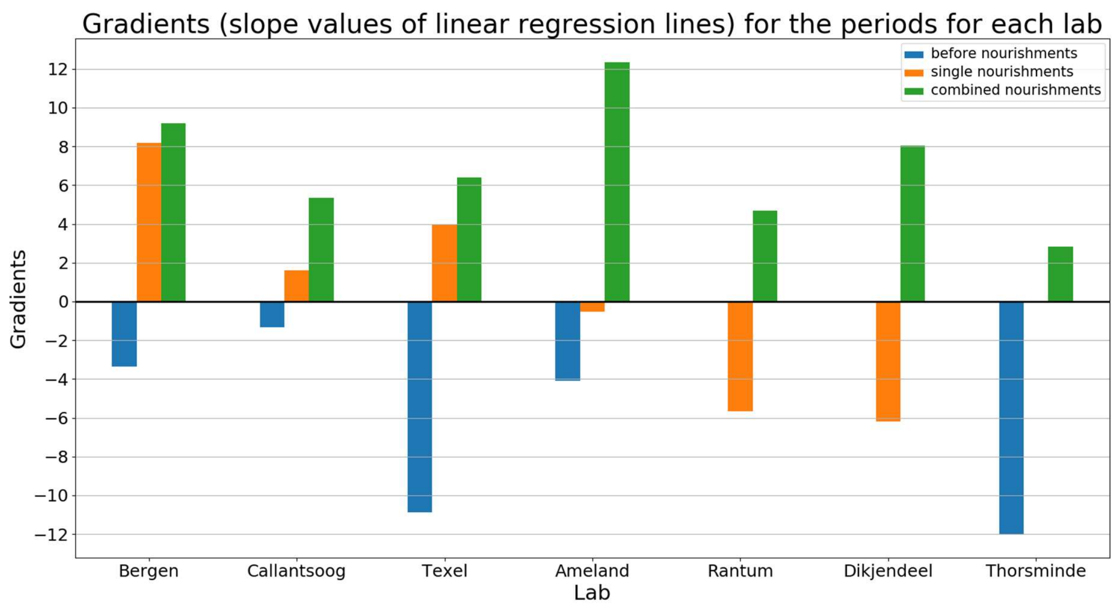


Figure 3.56 *Gradients of the linear regressions plotted as bar plots for each lab. In each lab the combined nourishments show the most positive regression gradient.*

lab	Bergen		Callantsoog		Texel		Ameland		Rantum		Dikjendeel	
period	single	comb.	single	comb.	single	comb.	single	comb.	single	comb.	single	comb.
total vol [m³/m/a]	134	204	30	107	191	349	52	300	57	88	28	43
mean [m³/m/nour.]	167	306	180	289	361	391	267	360	296	222	206	107
beach vol [m³/m/a]	121	97	30	20	124	77	7	79	40	24	28	23
shoref vol [m³/m/a]	0	108	0	87	68	272	23	221	17	64	0	20
other vol [m³/m/a]	13						22					

Table 3.3 *Design parameters of the nourishment volumes for the labs (orange: single nourishments, green: combination)*

All labs received more sediment volume due to nourishing by the combined measures (in m³/m/a) than in the period of single measures. So even the higher nourishment volumes alone should have had a positive effect. Although this is valid for the whole system, it isn't necessarily for the beach volume, which is the focus of this analysis.

In the Dutch labs also the average volume per running meter has been increased from period 2 to period 3. In the labs of Sylt the opposite took place. The results presented in Figure 3.56 show that larger nourishments are not evident for a larger success of the 3rd period on the effect on the beaches. For example: in Bergen the mean volume per nourishment has been increased by 83% and the gradient could be increased by 1. In Texel the mean volume per nourishment has been increased by 8% and the gradient could be increased by 2.4.

In most labs, except for Ameland (increase), the beach nourishments decreased in volume (in m³/m/a). Despite this, the gradients of the 3rd period are always higher. This proves that the shoreface nourishments have had a positive effect in protecting the beaches.

Conclusion sub hypothesis

Some figures created in this research show a relocation of the erosion hotspot away from the beach and towards the shoreface area. Because of this, a sub hypothesis has been formed that the stabilising effect of shoreface- and combined nourishments can be explained with the mentioned relocation. A reason might be, that a shoreface nourishment protects the beach because the erosion takes place in the shoreface and there is not sufficient energy left to erode the beach. It is also possible that the eroded sediments feed the beach, thereby reducing erosion rates at the beach. Rantum and Ameland are the labs to demonstrate this the best. Figure 3.57 shows this effect in Rantum.

In Figure 3.57, the mean beach volume has been plotted against the mean shoreface volume. After the shoreface nourishment in 2006, the beach erosion has been halted. Instead, after a rapid volume gain due to the nourishment, strong erosion occurs in the shoreface instead of at the beach. See the exclamation mark in the figure. This behaviour can also be observed in some other labs:

Visible	**Not visible**
Ameland (NL)	Thorsminde (DK) tendency, but not clear.
Puanklent (SH)	Dikjendeel (SH) likely disturbed by nourishments Westerland
Rantum (SH)	
Sansibar (SH)	

Texel (NL)	
Callantsoog (NL) only visible if nourishment amounts as m³/m are included as data points (no measurement directly after nourishment)	

The sub hypothesis is most likely to be true. Signals are not always clear and can be overshadowed by other conditions.

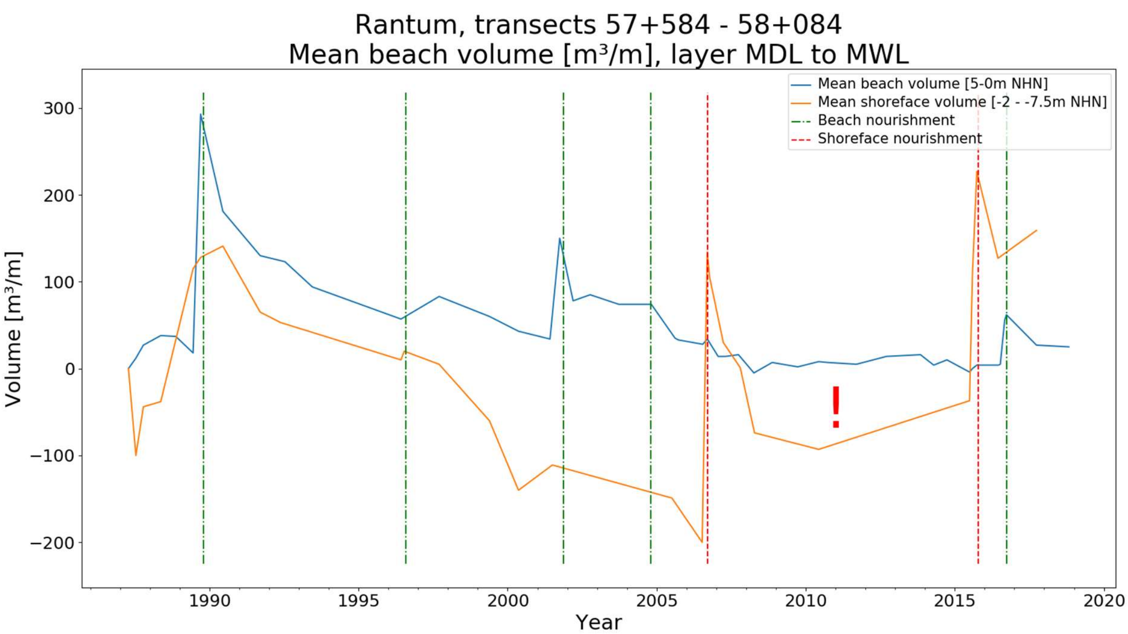


Figure 3.57 Comparison of beach- and shoreface volume development in conjunction with the different nourishment measures, the initial losses after a shoreface nourishment are comparable with the initial losses of the beach nourishments while the beach is stabilised after a shoreface nourishment (see exclamation mark)

<u>Final conclusion</u>

Our analysis indicates that the hypothesis is likely true. Combined nourishments have a stronger stabilising effect for beaches than single measures. One of the major reasons is most likely a relocation of the erosion hotspot from the beach towards the shoreface area after a shoreface nourishment. The erosion in the shoreface will also provide sediment that will be relocated partially cross shore and compensate beach erosion. The ratio between longshore- and cross shore sediment transport and therefore the amount of erosion compensation at the beach, will be different for each lab as it is for all natural parameters .

Each lab has most likely its own ratio between the volumes to use for shoreface- and beach nourishments to be most effective given the coastal management goals. In general, the shoreface nourishment should be larger than the beach nourishment. In the examined labs, beach nourishments could be reduced – or larger nourishment volumes had a big effect on the beach volume increase (example: Ameland). More frequent, smaller and combined nourishments have generally been more effective in beach stabilisation. Whether more frequent smaller nourishments or less frequent larger nourishments are preferred depends on the local situation and other coastal zone management goals like costs, disturbance to the ecosystem and recreation, feeding of down drift locations through diffusion of nourishments sand.

4 Conclusions

In the previous chapter several hypotheses are discussed, based on the results from the national analysis reports of each coastal lab and general system understanding. For several hypotheses additional parameters for the labs were added to be able to do the hypotheses testing. The analyses based on the results from the coastal labs solely does not give scientific solid conclusions for all hypotheses, because there are not enough data-points and also very different conditions in all labs. However, still valuable trends in the data can be distinguished and conclusions could be drawn. These conclusions can help inform coastal zone management policy and practice.

Each hypothesis describes a certain aspect of nourishments, either effects caused by nourishments or factors that influence the (behaviour of the) nourishment. Some aspects were observed in only some of the coastal labs, while others were observed in all or most of the labs. The following conclusions could be made:

Effects caused by nourishments:

- Both beach nourishments and shoreface nourishments ‘stabilize’ the beach (hypotheses 3.3.1 and 3.3.2). Although erosion of the beach continues, adding sand by a nourishment ‘resets’ the volume of the beach and the position of the low and high water lines. I.e. they are moved in seaward direction to a position they were in an earlier stage of the erosion process. Repetitive nourishments even support the natural processes leading to the growth of dunes (by aeolian transport) and neighbouring stretches of coast.
- Shoreface nourishments can influence the morphology, mainly by their effect on breaker bars. At coasts where breaker bars are present, placement of a shoreface nourishment can increase the depth of the trough (hypothesis 3.3.9). Several factors seem to influence the depth of the trough, including the total volume of the nourishment and the volume per stretch of coast.
- The location where shoreface nourishments have influence on morphology, sediment volume, etc. depends on the local processes, like wind, waves and tides. When cross-shore processes are dominant, effects can be expected directly behind the nourishment. If the alongshore component becomes more important, effects will occur more oblique or parallel to the coast (hypothesis 3.3.3).

Factors that influence a nourishment:

- The (design) shape of a nourishment can influence its lifetime. It is suspected that creating a steep beach profile with a nourishment will result in shorter lifetime of the nourishment, however this could not be confirmed by the data (hypothesis 3.3.4). The size (volume) of the nourishment influences the initial erosion rates: larger nourishments have larger initial erosion rates (hypothesis 3.3.6). Larger nourishments will still have a longer lifetime, but the lifetime will not relate linearly with the volume.
- It is suspected, but not supported by the analysed data, that the sediment volume in the ‘active zone’ can influence the lifetime of a beach nourishment: a larger volume can result in a longer lifetime (hypothesis 3.3.5).

- The (median) grain size can influence the lifetime of a nourishment: a larger grain size will result in a longer lifetime (hypothesis 3.3.8). Grain size is known from literature to have other effects as well, including affecting the steepness of the coastal profile.
- Higher exposure of a stretch of coast can lead to larger erosion rates at that location. This also applies for (beach) nourishments (hypothesis 3.3.8).
- Combined beach and shoreface nourishments can have a stronger stabilising effect on the beach than single measures (hypothesis 3.3.10).

5 Recommendations and future directions

In this co-analysis the results from all national analyses have been combined to formulate and test hypotheses on the working of nourishments. This resulted in useful knowledge, as can be seen in the conclusions. However, there are still many aspects we do not (yet) understand, including:

- The insights on correlation between the hydrodynamics and the morphological response of the coast remains limited.
- There direct and indirect effect of nourishments on flood risk (dune and levee breaching during storm) is not studied but very important to make the link between morphology and flood risk management.
- Ecological effects (both positive and negative) are important for Coastal Zone management, but not studied here.
- Effectiveness of nourishments under sea level rise. The analysis shows that nourishments can stabilize beaches in all the coastal labs. It is expected that will remain the case in the coming decades. It is however unknown if that remains the case under strong sea level rise.
- The beneficial effect of shoreface nourishments on the lifetime of beach nourishments when placed together has been shown in hypothesis 3.3.10. However, there are still many questions on the effects of shoreface nourishments on the beach, and how they work in different locations: when is a combination of beach and shoreface the best solution, when is only a shoreface enough?
- Quantification of benefits for other coastal functions besides flood and erosion risk management remains limited.

For the future development and uptake of nourishments as sustainable nature based solutions to make our coasts more resilient to the effects of climate change including sea level rise. It is recommended that future projects aim to reduce uncertainty concerning these aspects. To be able to draft universal conclusions, if possible these projects should be undertaken in an international setting where the responsible coastal authorities collaborate with stakeholders and academia.

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7 Appendix A – Additional information coastal state indicators

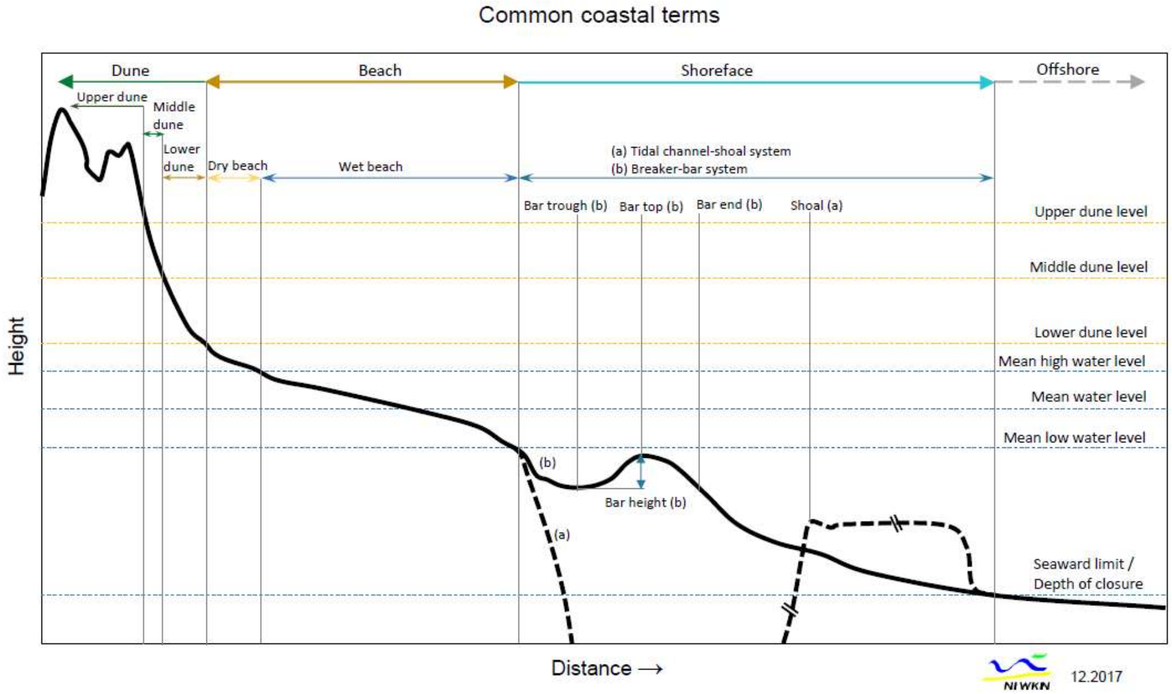


Figure 7.1 General definition/terminology coastal profile used. Source: Simon Hillmann (NLWKN). On the vertical axis various levels in the profile are shown. The horizontal axis shows different zones in the profile.

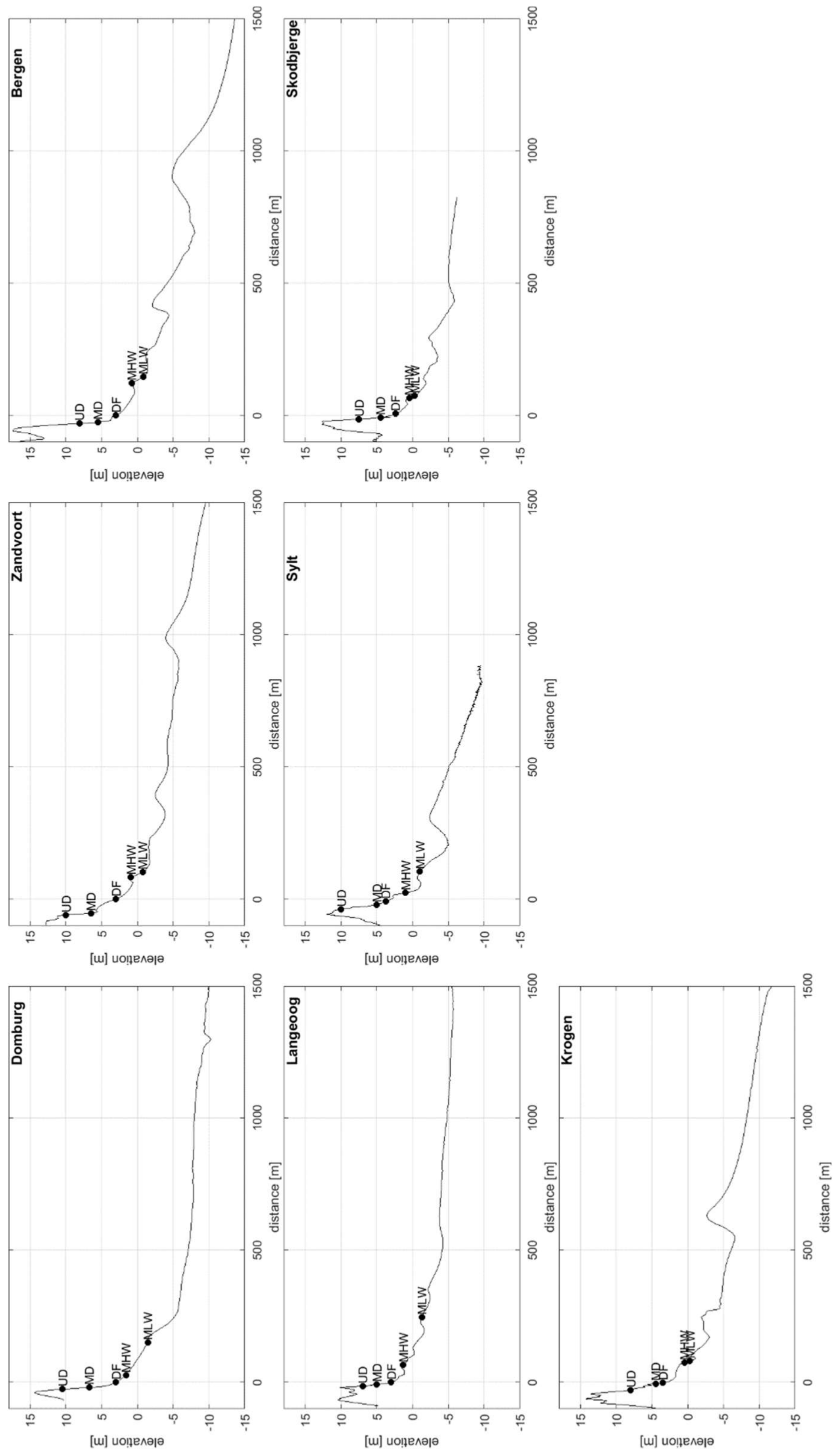


Figure 7.2 *Typical profiles of the labs with indication of the coastal state indicators, distance at MSL +3 m is set at 0 for comparison, x- and y-scale are the same in each subplot.*

Table 7.1 Coastal state indicators (CSI) for each laboratory.

	UDL	MDL	LDL (DF)	MHW	MLW	MTR
Lab	**Upper Dune Level**	**Middle Dune Level**	**Lower Dune Level (Dune Foot)**	**Mean High Water Level**	**Mean Low Water Level**	**Mean Tidal Range**
Krogen	8	4.5	3.5	0.46	-0.28	0.74
Skodbjerge	8	4.5	3.5	0.46	-0.28	0.74
Sylt	10	5	3.75	1	-1	2
Langeoog	7	5	3	1.3	-1.3	2.6
Bergen-Egmond	8.1	5.55	3	0.79	-0.81	1.60
Zandvoort-Bloemendaal	9.98	6.49	3	0.93	-0.74	1.67
Domburg	10.48	6.74	3	1.61	-1.44	3.05

8 Appendix B - Methods and data for wave characteristics

For each lab characteristics of the local wave climate have been derived from two sources: 1) local wave buoys and 2) the CoastDat2 database (Groll and Weisse, 2017). For both sources the wave climate used for calculations is for the period 2000-2014. Although the data from the CoastDat2 database are expected to be less accurate than buoy measurements, they are used to have good comparability between the labs. Both sources are used to calculate the following wave characteristics: average significant wave height, average peak period, average direction, averaged energy parameters (perpendicular and parallel to the coast, both net and gross values). Wave energy is calculated using:

$$Etotal = \frac{1}{8} * \rho * g * Hs^2$$

Where ρ is water density (1025 kg/m^3), g is fall velocity (9.81 m/s^2) and Hs is significant wave height (m). Using the decomposition of incoming waves into cross shore and parallel alongshore components as in Figure 8.1, Ex and Ey become:

$$Ex = \frac{1}{8} * \rho * g * Hs^2 * cos(\alpha)$$

$$Ey = \frac{1}{8} * \rho * g * Hs^2 * sin(\alpha)$$

Where α is the wave angle relative to the coastorientation. Taking the average of the positive and negative part results in the two gross values (to and from the coast, to the left and the right of the coast), taking the average of the total results in the nett values.

From the CoastDat2 database for each lab a location has been chosen perpendicular to the coast, at deepest gridcell above MSL -20 m. This resulted in depths between -16 m and -19 m at the used grids (Table 8.1). The used locations are indicated on the bathymetry in Figure 8.2. To have an indication of the quality of the CoastDat2 data, the values at the Europlatform buoy location have been compared. The values for significant wave height and peak period between 2000 and 2014 are shown in Figure 8.3.

The buoy data and CoastDat2 data follow the same pattern, but the CoastDat2 values are slightly higher for the wave height and significantly higher for the period. This is more clearly visible in the scatter plot (Figure 8.4), also displaying the correlation of the wave direction between the buoy and database. Overall, the wave height (bias = 0.04 m, RMSE = 0.46 m) and direction (bias = 6.38 °, RMSE = 37.9 °) are well reproduced by the CoastDat2 data, whil the period (bias = 1.8 s, RMSE = 2.58 s) is significantly overestimated. For calculation of the wave energy, only the wave height and direction are used, therefore the CoastDat2 data are expected to give reasonable results, fit for the purpose of comparing the labs.

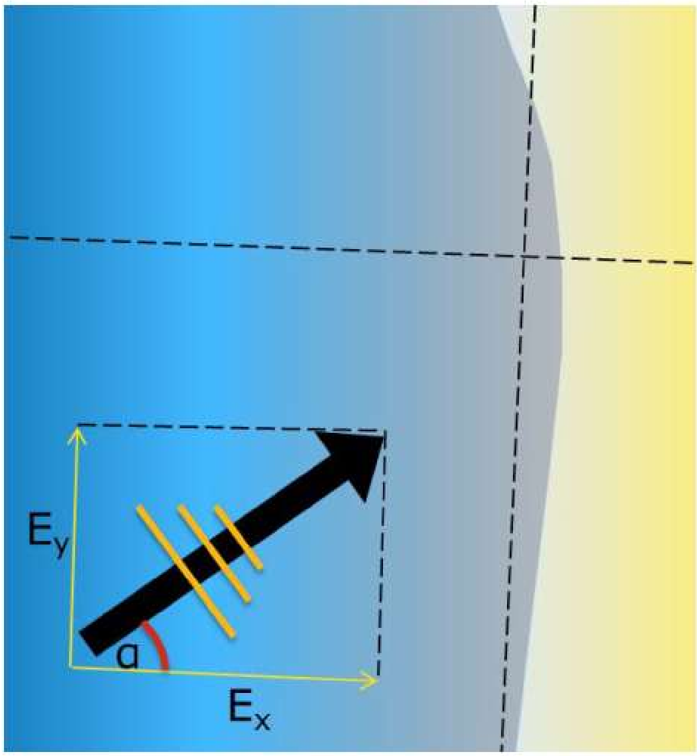


Figure 8.1 Energy decomposition of oblique waves in cross-shore (perpendicular) and alongshore (parallel) components

Table 8.1 Depth at used locations from wave buoys and CoastDat2 database

Location	Depth at buoy (m)	Depth CoastDat2 gridcell (m)
Skodbjerge	20	17
Krogen	18	18
Sylt	13	19
Langeoog	30	16
Bergen-Egmond	30	19
Zandvoort-Bloemendaal	30	19
Domburg	30	19
Europlatform buoy	30	27

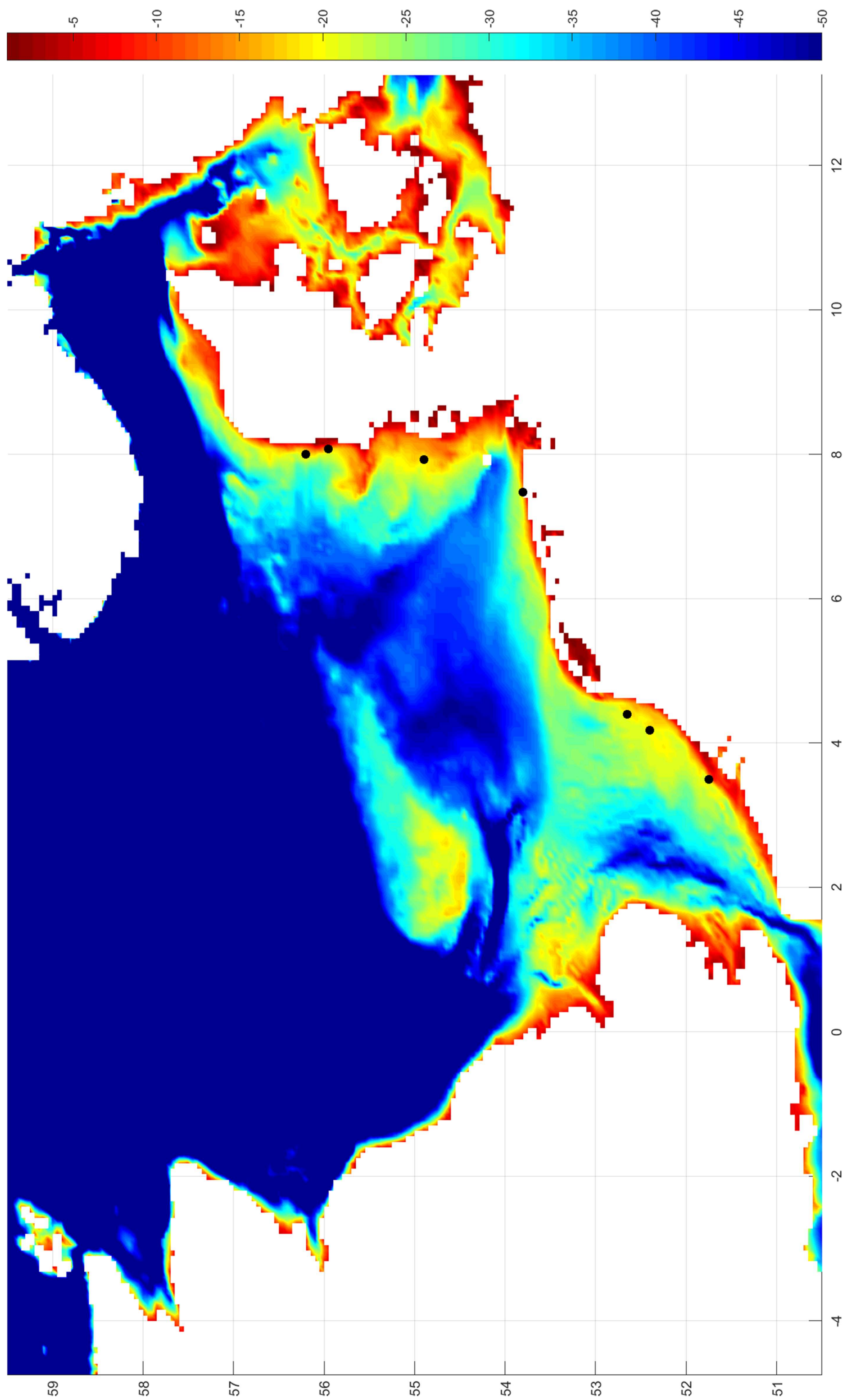
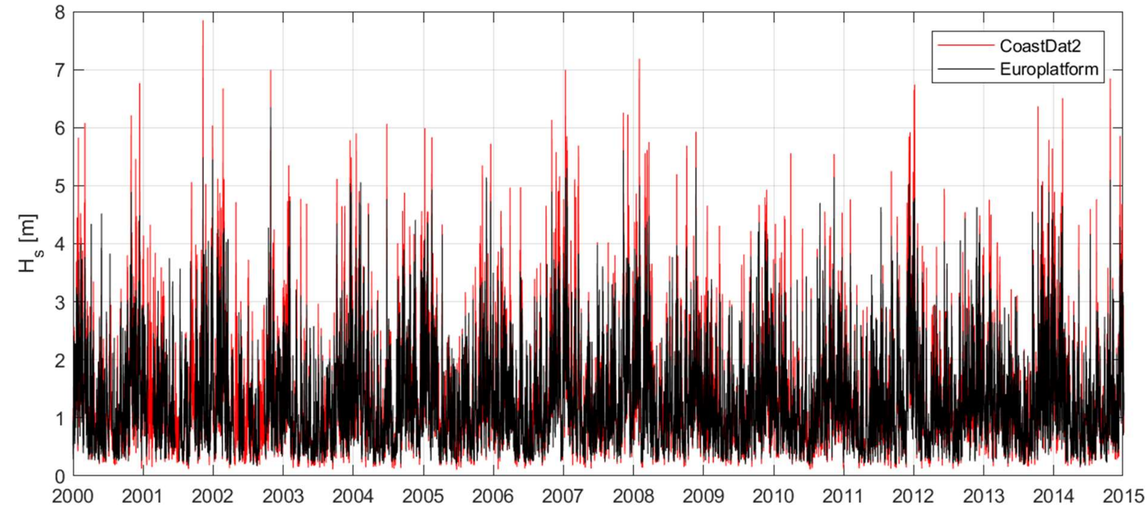


Figure 8.2 Selected locations to derive wave characteristics



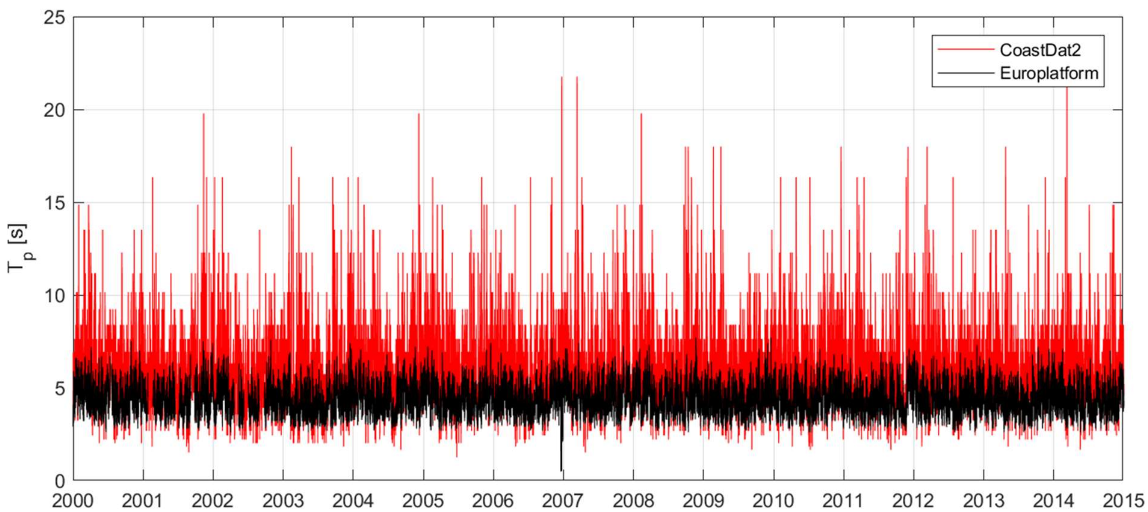


Figure 8.3 Timeseries of significatn waveheight (top) and peak period (bottom) at the Europlatform buoy, data from buoy and CoastDat2

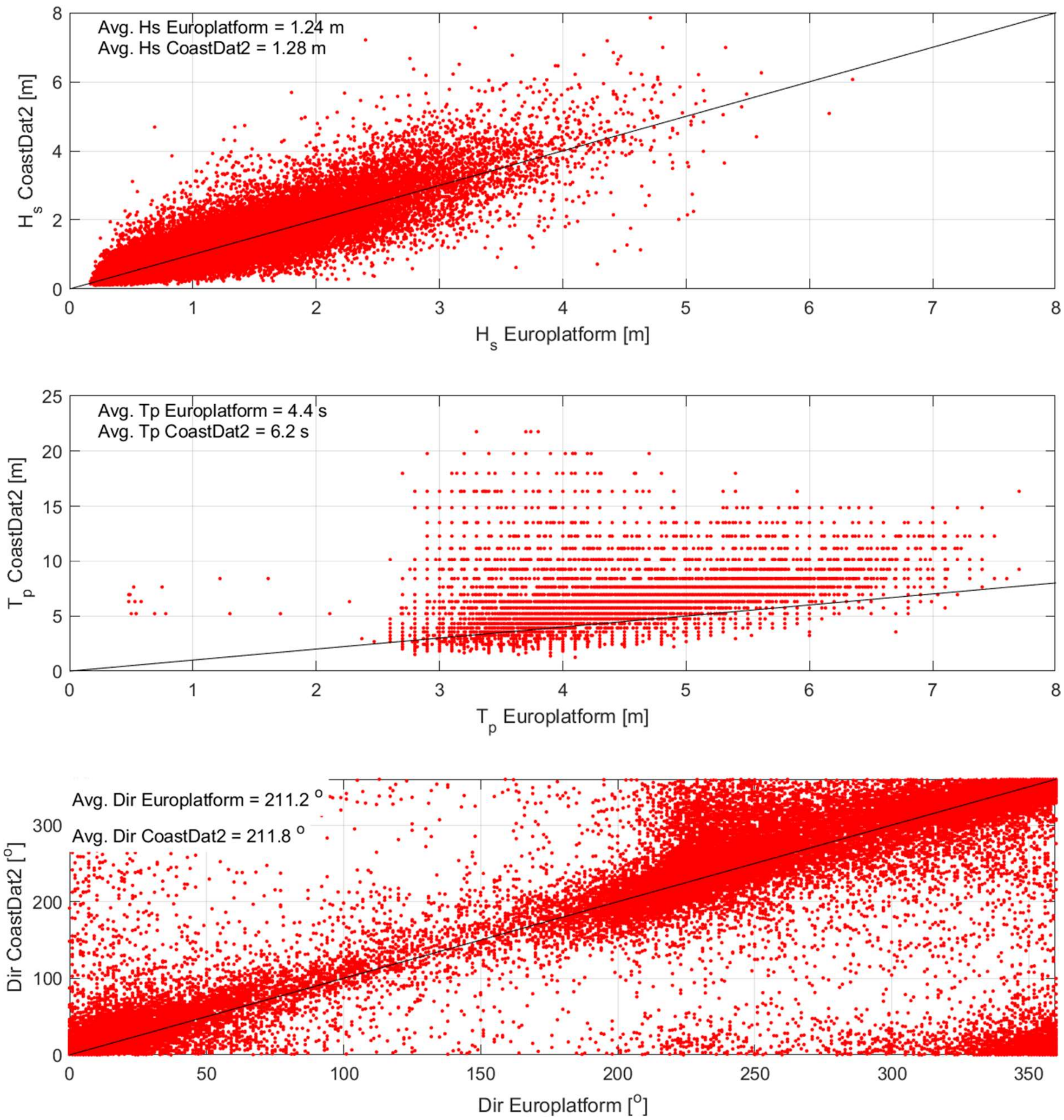


Figure 8.4 *Scatterplot of significant wave height and peak period and wave direction at the Europlatform buoy, data from buoy and CoastDat2, black line is the 1:1 line.*

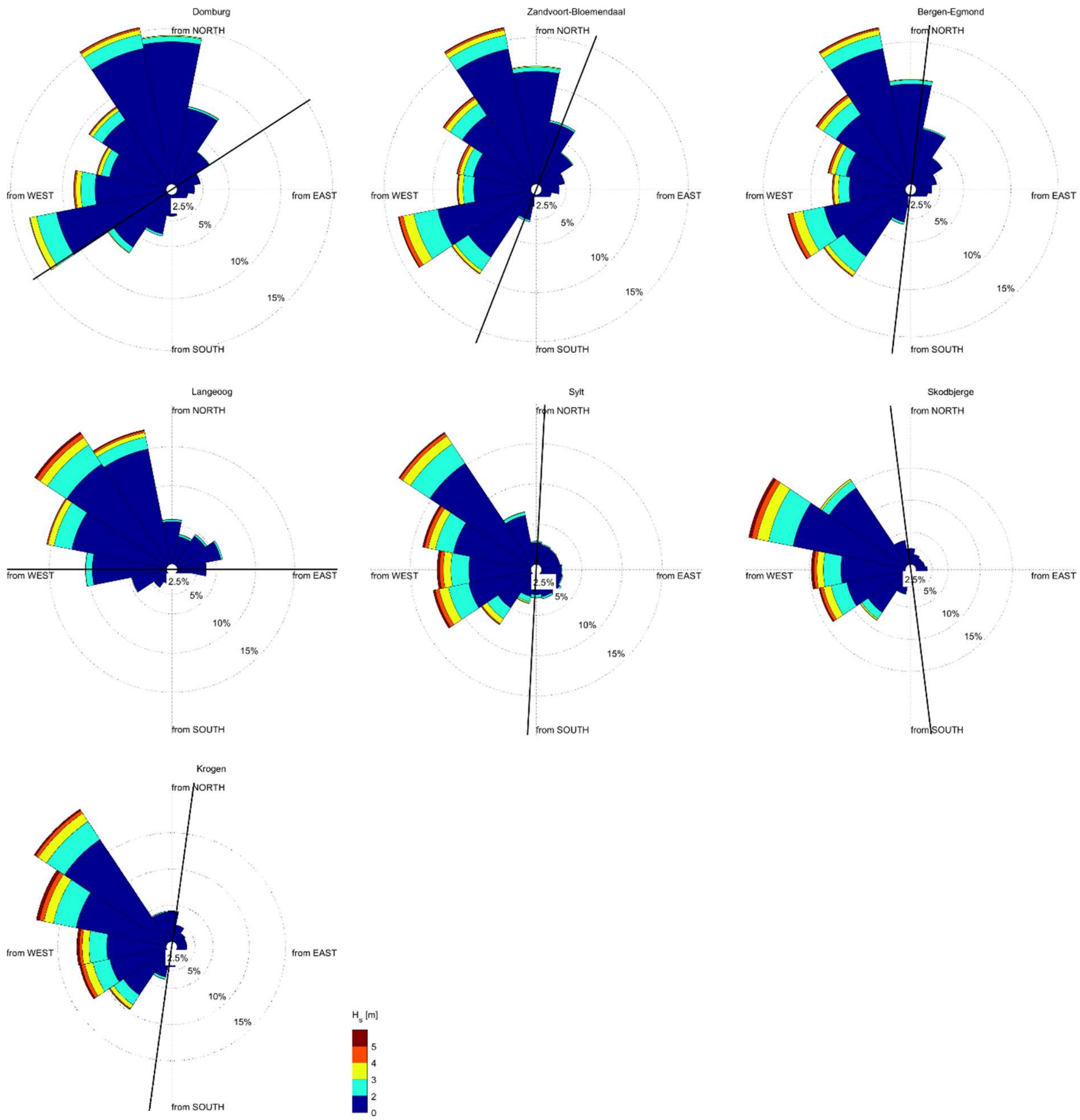


Figure 8.5 *Wave roses based on the CoastDat2 data for the period 2000-2014, black line indicates shoreline orientation*

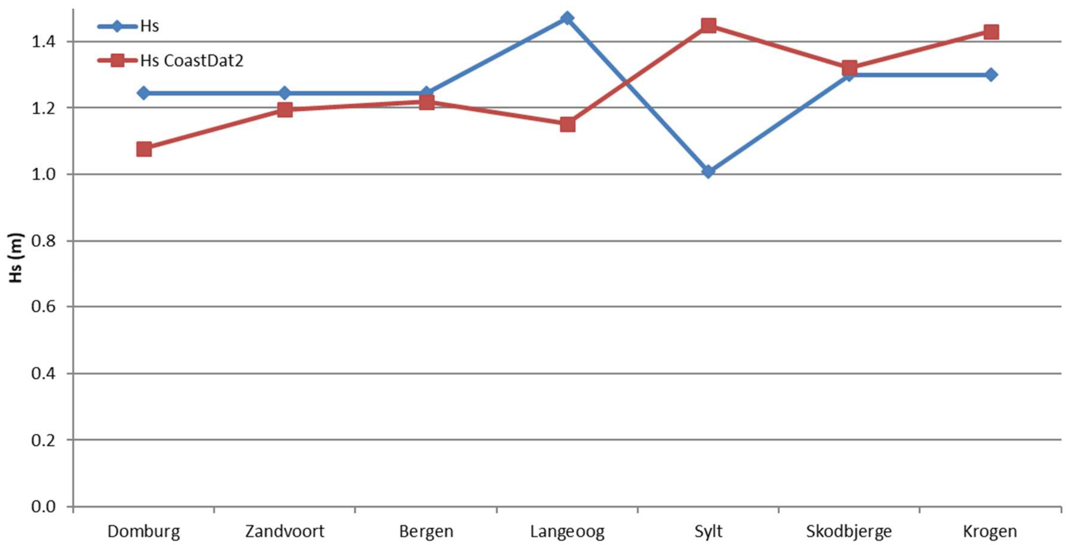


Figure 8.6 *Average significant wave height for the labs, from the local buoy and the CoastDat2 database for the period 2000-2014*

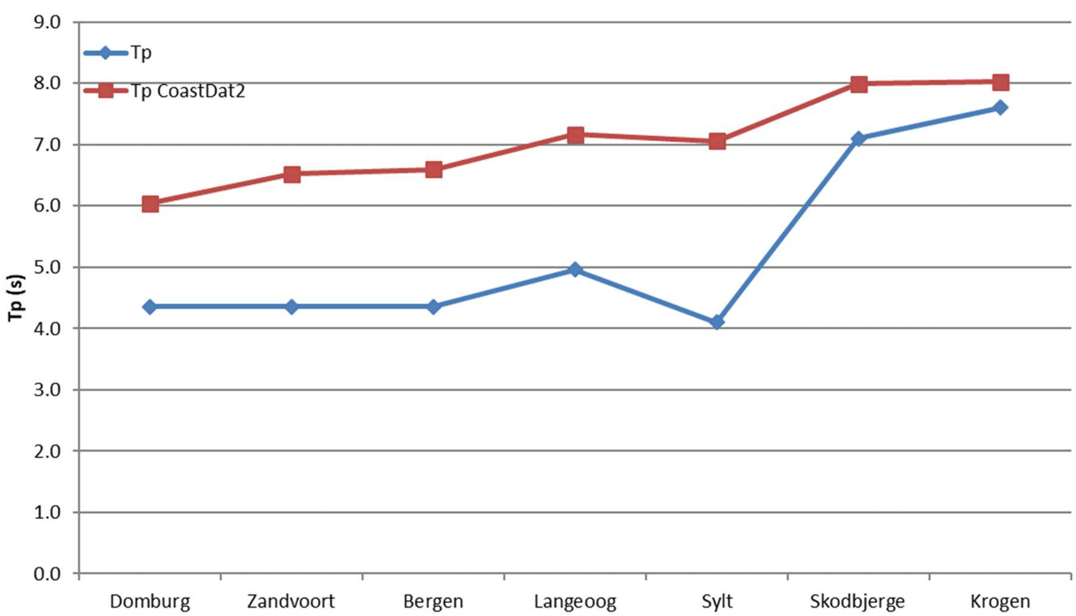
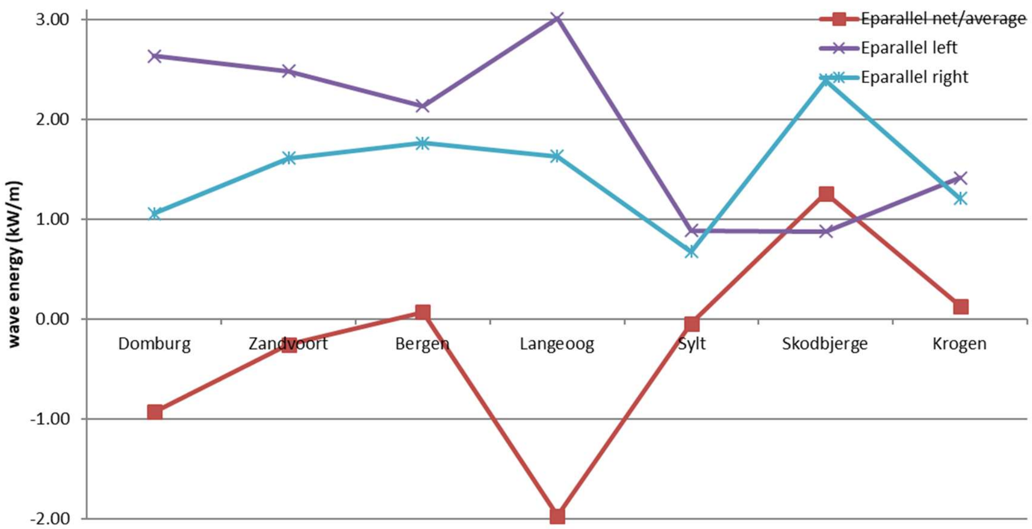


Figure 8.7 *Average peak period for the labs, from the local buoy and the CoastDat2 database for the period 2000-2014*



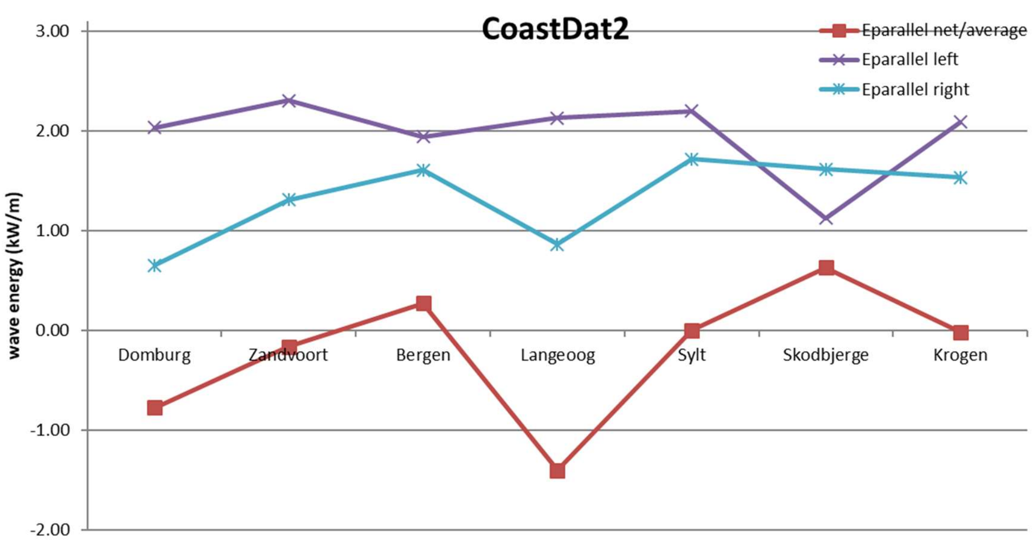


Figure 8.8 Wave energy parallel to the coast, direction as seen from wave (for the labs left is east/north, right is west/south), based on local buoy data (top) and CoastDat2 data (bottom)

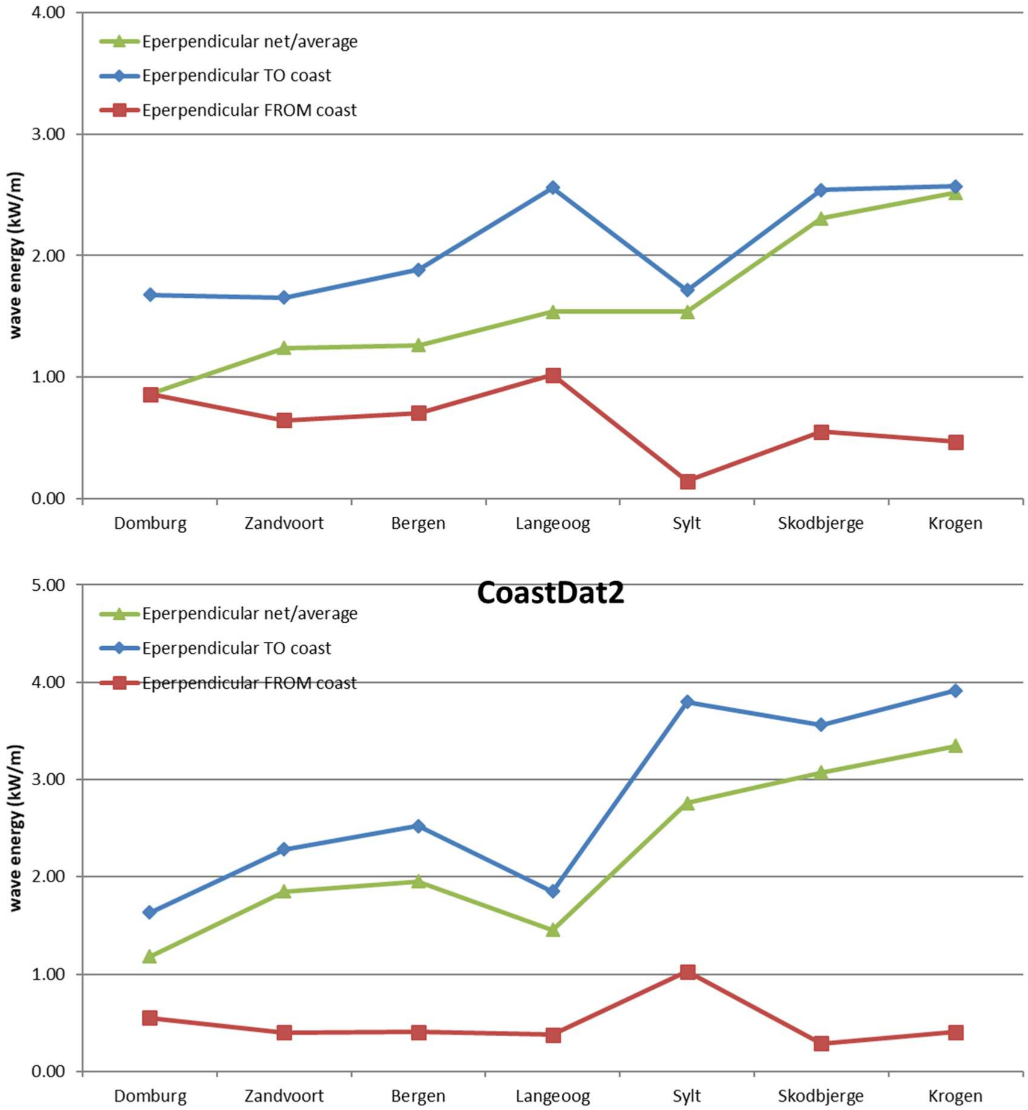


Figure 8.9 Wave energy perpendicular to the coast, based on local buoy data (top) and CoastDat2 data (bottom)

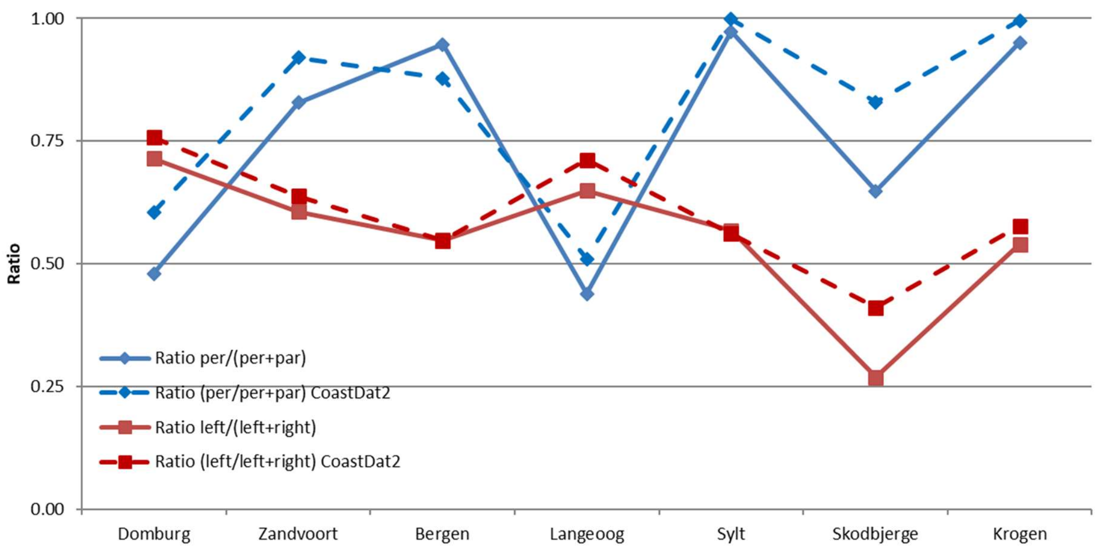


Figure 8.10 *Ratio of shore perpendicular and shore parallel wave energy (blue line, 1=only perpendicular wave energy, 0.5=equal energy perpendicular and parallel), and of parallel energy left and right (red line, 1=only wave energy to the left, 0.5=equal energy to right and left)*

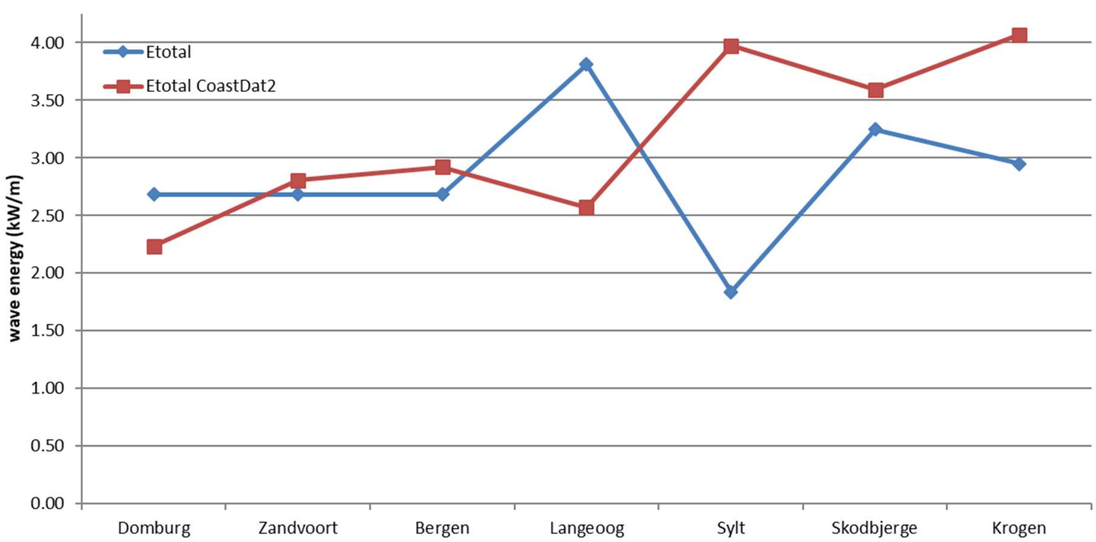


Figure 8.11 *Total wave energy, based on local buoy data and CoastDat2 data*

9 Appendix C - Nourishment data of main BwN nourishments

Nourishment properties	Bergen-Egmond 1	Bergen-Egmond 2	Domburg	Zandvoort 1	Zandvoort 2	Langeoog 2010	Langeoog 2013	Langeoog 2017/18	Krogen	Skodbjerge
Transects	3100 – 3400 3400 – 3900 3900 – 4000	3150 – 3400 3700 – 3900	1406-1633	62.75 – 65.75 65.75 – 67.75	61.00 – 63.00 67.75 – 70.25	35-47	35-47	30-47 37-47	390600 - 393000	4014000 - 4014600
Type	Shoreface	Beach	Beach	Shoreface	Shoreface	Beach	Beach	Beach & Foreshore	Shoreface	Shoreface
Volume (m3)	1.124.348 1.713.913 360.870	500.000 400.000	369.565	1.202.332 1.001.095	1.002.957 509.913	500.000	600.000	400.000 200.000	440.000	310.116
Length (m)	3000 5000 1000	2500 2000	2265	3000 2000	2000 2500	1850	1850	2000 1500	4500	775
Volume (m_3/m)	375 340 360	200 200	160	400 500	500 200	270	324	200 133	98	400
Start nourishment vertical level	-5 mNAP	3 mNAP	4 mNAP	-5 mNAP	-5 mNAP	3,5 mNHN	3,5 mNHN	5 mNHN	-3	-3

End nourishment vertical level	-8 mNAP	-1 mNAP	-1,9 mNAP	unknown	unknown	~ -1,3 mNHN	~ -1,3 mNHN	-2 mNHN	-6	-5
Begin construction (mm-yyyy)	11-2010 08-2010 08-2011	11-2010 03-2011	05-2008	11-2004 10-2004	06-2008 06-2008	09-2010	07-2013	07-2017 07-2018	07-2016	06-2011
Finished construction (mm-yyyy)	02-2011 08-2011 09-2011	08-2011 04-2011	07-2008	02-2005 12-2004	09-2008 11-2008	10-2010	10-2013	10-2017 09-2018	08-2016	08-2011

Nourishment data information for Sylt

Hoehenlamelle: 3.75/-.50 [m³/m] | Sylt (West): alle Profile														
Nr_Aufsp	Stat_Beginn	Stat_Ende	Aufspuelstrecke [km]	Aufspuelname	Aufspuel_Beginn	Aufspuel_Ende	Hoppermenge [Mio. m³]	spezif. Hoppermenge [m³/m]	Datum_VV	Datum_NV	V_Null [m³/m]	T_n [a]	dVTn [m³/m/a]	Kind of Nourishment
69	58,084	57,584	0,5	69. Rantum (Vorstrand)	15.07.2006	13.08.2006	0,225	451	23.09.2005	15.09.2006	378,75	1	188,77	Shoreface
70	60,086	59,084	1,002	70. Puan Klent (Vorstrand)	25.07.2006	28.09.2006	0,391	391	20.07.2006	25.01.2007	304,58	2,58	58,96	Shoreface
71	62,336	61,436	0,9	71. Sansibar (Vorstrand)	10.09.2006	02.10.2006	0,135	150	21.08.2006	25.01.2007	344,37	0,95	181,78	Shoreface

Beach widths during the nourishment construction

Location	Transects	DF to MLW	Date	Slope	1/Slope	Width	Minimal width	Maximal width
Bergen-Egmond (Nord-Holland)	3150 – 3400 (mean)	3 - -0,81 [mNAP]	**2010-04-13**	**0,032**	**30,9**	**118**	**101**	**132**
			2011-01-27	0,027	37,7	144	96	168
			2012-01-31	**0,030**	**33,5**	**128**	**120**	**135**

Domburg (Walcheren)	1406-1632 (mean)	3 - -1,44 [mNAP]	**2007-03-09**	**0,027**	**36,8**	**141**	**108**	**186**
			2008-06-18	0,028	35,4	137	85	186
			2009-03-17	**0,027**	**36,7**	**141**	**105**	**169**
Zandvoort-Bloemendaal (Rijnland)	6275-6775 (mean)	3 - -0,74 [mNAP]	**2004-03-25**	**0,030**	**32,2**	**123**	**65**	**143**
			2005-04-24	0,035	27,7	106	67	137
			2006-04-05	0,033	29,4	112	86	150
			2007-03-09	0,031	31,9	122	82	152
			2008-05-21	0,030	32,3	123	85	142
			2009-01-01	**0,028**	**34,7**	**132**	**96**	**161**
Langeoog 2010	35-47 (weighted mean, regarding distance to neighbouring transects)	3 - -1,3 mNHN	2010-03-02	0,023	44,0	189	167	237
			2010-04-01	0,023	43,4	187	162	235
			2010-09-01	**0,026**	**37,8**	**163**	**91**	**211**
			2010-10-01	**0,017**	**58,4**	**251**	**223**	**280**
			2011-02-01	0,020	50,5	217	141	276
			2011-05-01	0,018	54,1	232	184	272
Langeoog 2013	35-47 (weighted mean, regarding distance to neighbouring transects)	3 - -1.3 mNHN	2013-03-01	0,020	50,1	215	162	254
			2013-04-01	0,020	49,6	213	163	241
			2013-07-01	**0,021**	**46,9**	**202**	**146**	**265**
			2013-10-01	**0,022**	**44,7**	**192**	**148**	**238**
			2013-10-02	0,022	45,2	194	163	226

			2013-11-01	0,030	33,5	144	109	186
			2014-02-01	0,020	50,8	219	179	280
			2014-04-01	0,017	57,6	248	180	324
			2014-05-01	0,020	51,1	220	161	301
Langeoog 2017/18	32-46 (weighted mean, regarding distance to neighbouring transects)	3 - -1,3 mNHN	2017-01-01	0,022	46,4	200	152	297
			2017-01-02	0,021	48,3	208	143	302
			2017-02-02	**0,022**	**46,2**	**199**	**159**	**247**
			2017-05-01	0,024	40,8	176	119	265
			2017-11-01	0,022	44,7	192	123	285
			2018-01-01	0,022	45,0	193	132	245
			2018-02-01	0,023	43,1	185	127	243
			2018-11-01	**0,028**	**35,7**	**154**	**107**	**209**
Skodbjerge	4014000 - 4014600	3,5 - -0,28	2009-01-29	0,062	16,1	61	43	71
			2010-03-17	0,060	16,5	62	51	83
			2010-09-08	0,089	11,3	43	23	67
			2011-02-21	**0,058**	**17,2**	**65**	**54**	**71**
			2011-11-09	**0,041**	**24,2**	**91**	**77**	**101**
			2012-05-21	0,083	12,1	46	36	62
			2013-05-07	0,055	18,2	69	66	71
			2014-03-28	0,043	23,0	87	73	93
Krogen	390600 -393000	2,4 - -0,28	2015-03-13	0,033	30,4	81	65	104
			2015-08-10	0,036	27,7	74	57	102

			2016-05-10	0,031	32,8	88	75	105
			2016-06-13	**0,030**	**33,2**	**89**	**74**	**113**
			2016-09-20	**0,031**	**31,9**	**86**	**68**	**97**
			2016-11-09	0,027	37,5	100	62	240
			2017-02-07	0,028	35,3	95	67	109
			2017-05-23	0,032	31,3	84	59	121

Slopes

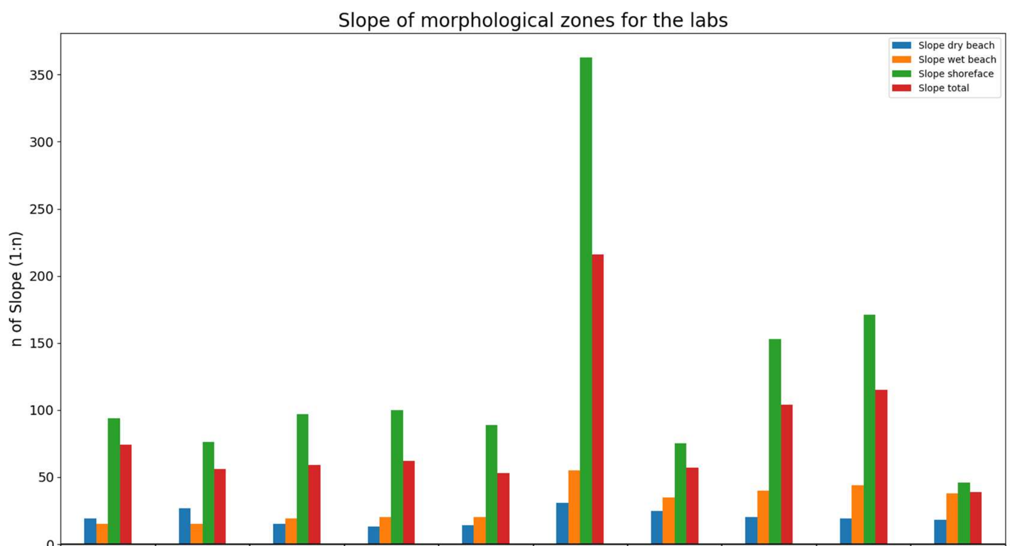
Location start end	Kind of Nourishment	Beach slope before Nourishment Sb	Beach slope after Nourishment Sn	Ratio Sb/Sn	Diffusion Time (50%) [years]	Remarks
Bergen-Egmond	Beach+Shoreface	0,032	0,03	1,07	2(shoreface)/ ∞(beach)	beach is increasing in volume
Domburg	Beach	0,027	0,027	1	2	influenced by neighbouring nourishments
Zandvoort-Bloemendaal	Shoreface (both)	0,030	0,028	1,07	1,6	Diffusion time based on combined 2004/2008 nourishments
Langeoog 2010	Beach	0,026	0,017	1,53	1,08	Diffusion time based on 3D-Volume calculation (in profiles ranges from 3 to 18 months)
Langeoog 2013	Beach	0,021	0,022	0,95	1,25	Diffusion time based on 3D-Volume calculation (in profiles ranges from 2 to 20 months)
Langeoog 2017/18	Beach & foreshore	0,022	0,028	0,79	1,4	50% diffusion only reached in 9 of 13 profiles
Skodbjerge	Shoreface	0,058	0,041	1,41	-	Diffusion time could not be determined
Krogen	Shoreface	0,030	0,031	0,97	0,4	
69. Rantum (Vorstrand) 15.07.2006 13.08.2006	Shoreface	0,024	0,024	1,000	1,0	NHN+3.75m/NHN-0.5m
70. Puan Klent (Vorstrand) 25.07.2006 28.09.2006	Shoreface	0,023	0,016	1,409	2,6	NHN+3.75m/NHN-0.5m
71. Sansibar (Vorstrand) 10.09.2006 02.10.2006	Shoreface	0,021	0,021	1,021	1,0	NHN+3.75m/NHN-0.5m

10 Appendix D – General characteristics of the coastal labs

In Figure 10.1 the mean slopes of the different hypsometric layers are shown. The slopes differ from lab to lab and between the different hypsometric layers (see Table 7.1 for levels of the layers). The main characteristics for the slopes are as follows:

- Dry Beach: The labs on Sylt (Rantum, Puanklent, Sansibar) have the steepest slopes of the dry beach (1:13 to 1:15), while Langeoog has the flattest one (1:31).
- Wet beach: The lab on Holmsland/DK (Skodbjerge, Krogen) have the steepest slopes of the wet beach (1:15), while Langeoog (1:55) and the Dutch labs (1:35 to 1:44) have flatter wet beaches.
- Shore face: The steepest shore face slope is at Domburg (1:46), followed by Bergen (1:75) and Krogen (1:76), while the flattest slopes of the shore face is on Langeoog (1:363), followed by Zandvoort (1:171 to 1:153).
- Total (beach and shore face down to -6.5 m): At the whole profile (beach and shore face) the steepest slope is on Domburg (1:39), while the flattest slope at the whole profile is on Langeoog (1:216), followed by Zandvoort (1:115 to 1:104).

All in all the labs on Langeoog (flat) and Domburg (steep) show the main extreme differences.



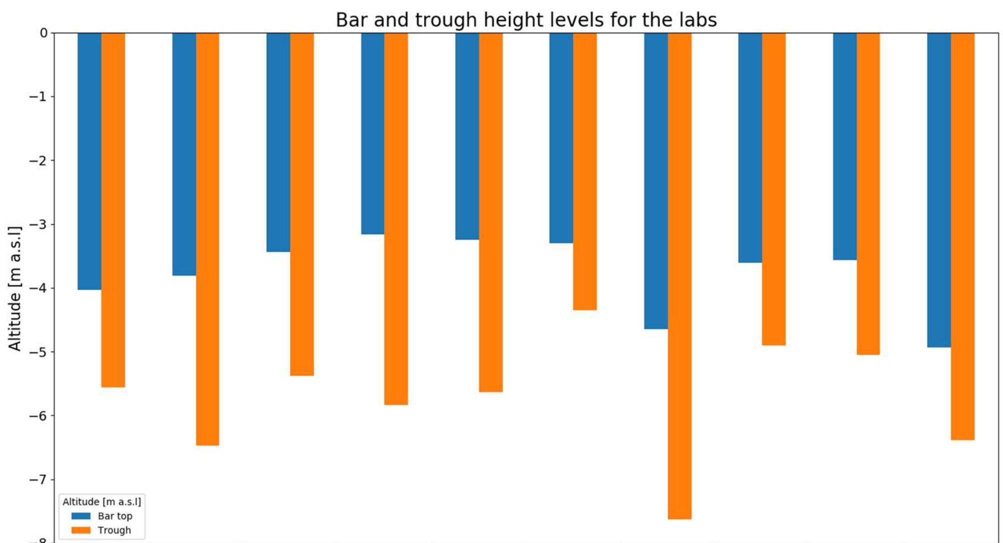
	Skodbjerge	Krogen	Rantum	PuanKlent	Sansibar	Langeoog	Bergen-Egm.	Zandvoort 2004	Zandvoort 2008	Domburg
Slope dry beach	19	27	15	13	14	31	25	20	19	18
Slope wet beach	15	15	19	20	20	55	35	40	44	38
Slope shoreface	94	76	97	100	89	363	75	153	171	46
Slope total	74	56	59	62	53	216	57	104	115	39

Figure 10.1 Slopes for different hypsometric layers (morphological zones) for the single labs.

In Figure 10.2 the mean bar heights and depths of trough are shown. For the coastal labs Domburg and Langeoog the parameters were calculated, although these locations have no breaker bars since the morphology is tide-dominated. The bar heights and depths of trough differ from lab to lab and between the different hypsometric layers. The main characteristics for the bar heights and the depths of trough are as follows:

- Bar height: The highest bar tops are placed at the labs on Zandvoort (a.s.l. -3.16 m to a.s.l. -3.44 m) and Langeoog (a.s.l. - 3.3 m), while the deepest bar tops are found in Bergen (a.s.l. -4.65 m), followed by Krogen (a.s.l. -3.81 m).
- Depth of trough: The shallowest troughs are found at the labs on Langeoog (a.s.l. - 4.35 m) and Zandvoort (a.s.l. -4.9 m to a.s.l. -5.05 m), while the deepest bar tops are found in Bergen (a.s.l. -7.63 m), followed by Krogen (a.s.l. -6.47 m).

Due to the high dynamics of the bar-trough system the calculated averages give only a slight hint on the value of the bar top und depth of trough.



	Skodbjerge	Krogen	Rantum	PuanKlent	Sansibar	Langeoog	Bergen-Egm.	Zandvoort 2004	Zandvoort 2008	Domburg
Bar top	-4.03	-3.81	-3.44	-3.16	-3.25	-3.3	-4.65	-3.61	-3.57	-4.93
Trough	-5.56	-6.47	-5.38	-5.84	-5.64	-4.35	-7.63	-4.9	-5.05	-6.39

Figure 10.2 Bar Height and depth of trough for the single labs.

In a next step the time series of the different morphological parameters are calculated and presented as stacked graphs.

In Figure 10.3 the time series of the slope of the dry beach are shown. The main characteristics for the temporal development of the slopes of the dry beach are as follows:

- For Skodbjerge, Krogen and Langeoog the slope of the dry beach flattens since 2005, while for the other labs the slope seems to be more or less stable.

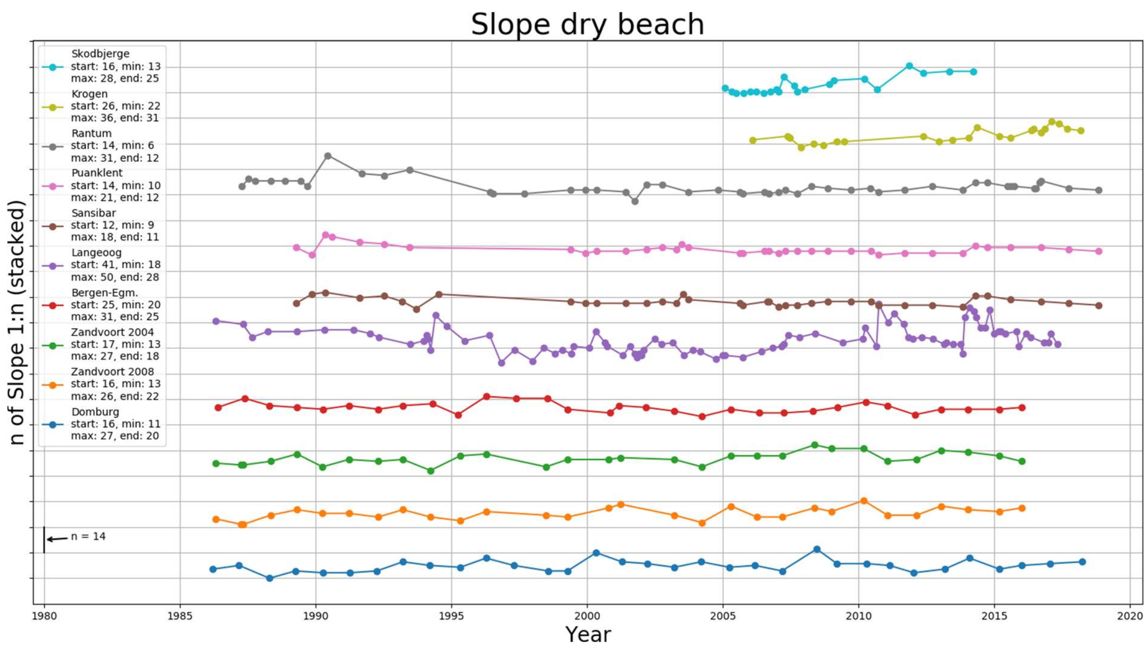


Figure 10.3 Time series of the slopes of the dry beach.

In Figure 10.4 the time series of the slope of the wet beach are shown. The main characteristics for the temporal development of the slopes of the wet beach are as follows:

- For Bergen-Egmont the slope of the wet beach flattens 2005 and is stable since then, while at the other labs the short period temporal fluctuation of the slope of the wet beach occurs.

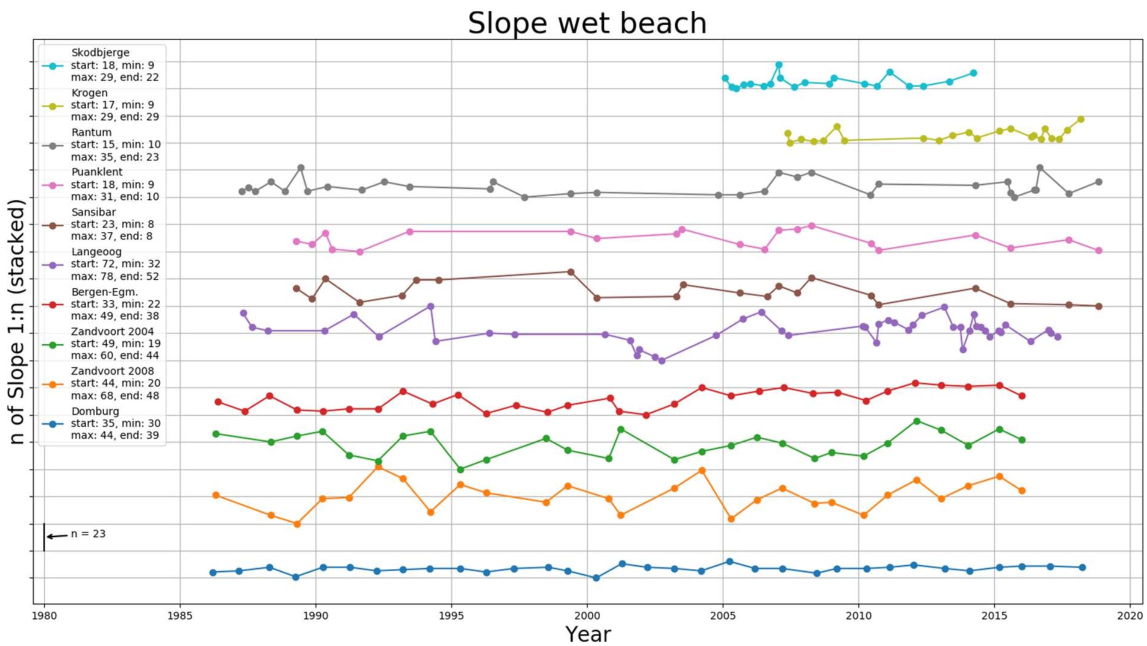


Figure 10.4 Time series of the slopse of the wet beach.

In Figure 10.5 the time series of the slope of the shore face are shown. The main characteristics for the temporal development of the slopes of the shore face are as follows:

- The fluctuation of the slope of the shore face seems to have a longer period, which is also a matter of fact due to the more rare measurement activities at the shore face. At Langeoog the slope of the shore face steepens and for Bergen-Egmont it flattens.

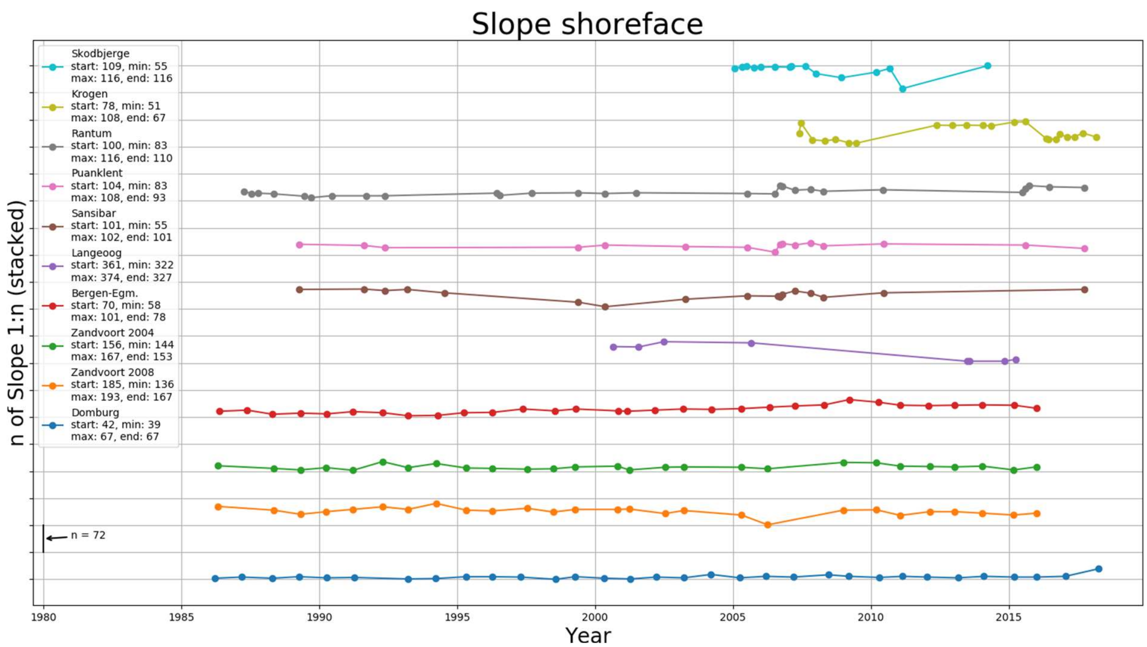


Figure 10.5 Time series of the slopes of the shore face.

In Figure 10.6 the time series of the slope of the beach and shore face are shown. The main characteristics for the temporal development of the slopes of the beach and shore face are as follows:

- For the lab at Langeoog the total slope (Beach and shore face) steepens, while at Bergen the slope flattens.

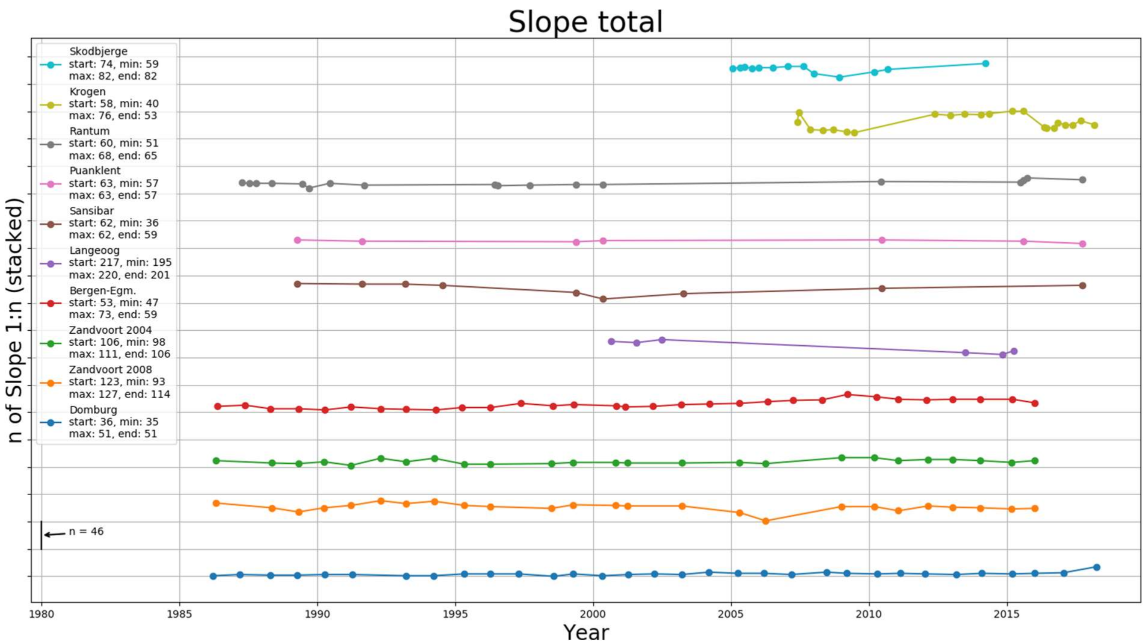


Figure 10.6 Time series of the slopes of the beach and shore face.

In Figure 10.7 the time series of the volumes of the dry beach are shown. The main characteristics for the temporal development of the volumes of the dry beach are as follows:

- The volumes of the dry beach show the effects of nourishments and energy impacts clearly. At Krogen, the labs on Sylt and in The Netherlands the volumes of the dry beach show an increase between 1985 and 2018, while at Skodbjerge and Langeoog the volumes decreased a bit.
- In the Dutch labs there is an almost steady increase of the volumes of the dry beach. At the labs on Sylt the volumes are stable since the shore face nourishments 2006. At Krogen the volume increased abrupt in 2014 due to the shore face nourishment.

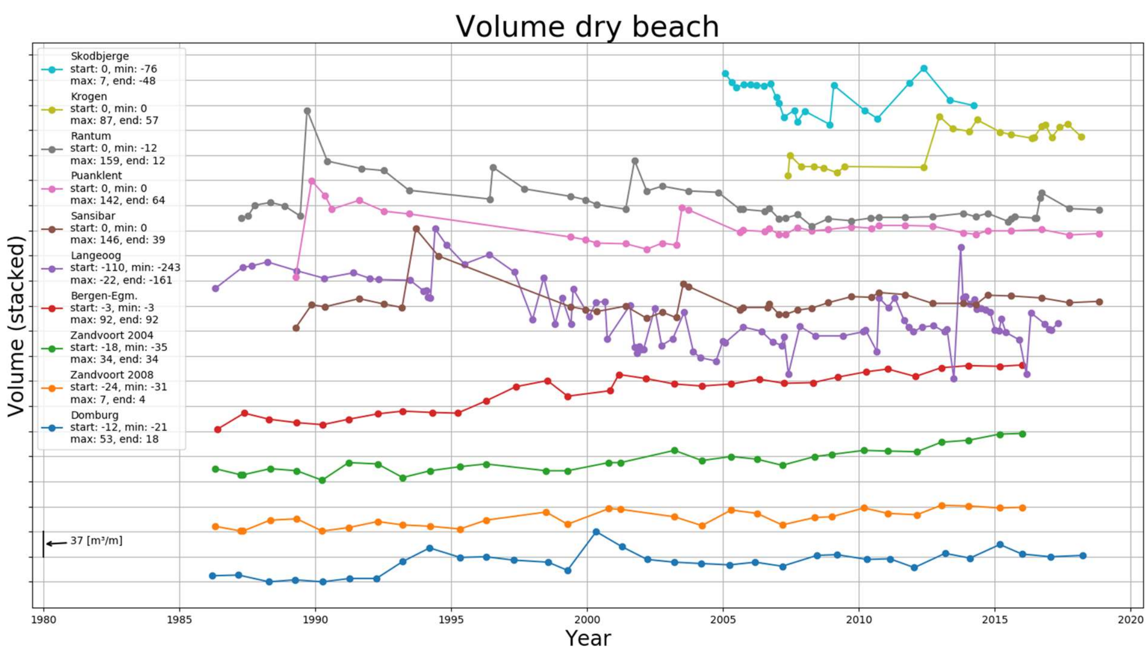


Figure 10.7 Time series of the volumes of the dry beach (in relation to an arbitrary time of reference).

In Figure 10.8 the time series of the volumes of the wet beach are shown. The main characteristics for the temporal development of the volumes of the wet beach are as follows:

- The volumes of the wet beach show a steady increase at Bergen-Egmont. At Domburg was an abrupt increase of the wet beach volume in 1993/94 and 2000 due to nourishments.
- At the Dutch labs there is an almost steady increase of the volumes of the wet beach. At the labs on Sylt the volumes of the wet beach are influenced by the beach nourishments as well, since beach nourishments shift the low water level towards the sea. After the shore face nourishments 2006 the volumes of the wet beach are stable. At Skodbjerge and Krogen the volume of the wet beach increased almost slowly. At Langeoog the influence of the different beach nourishments can be seen.

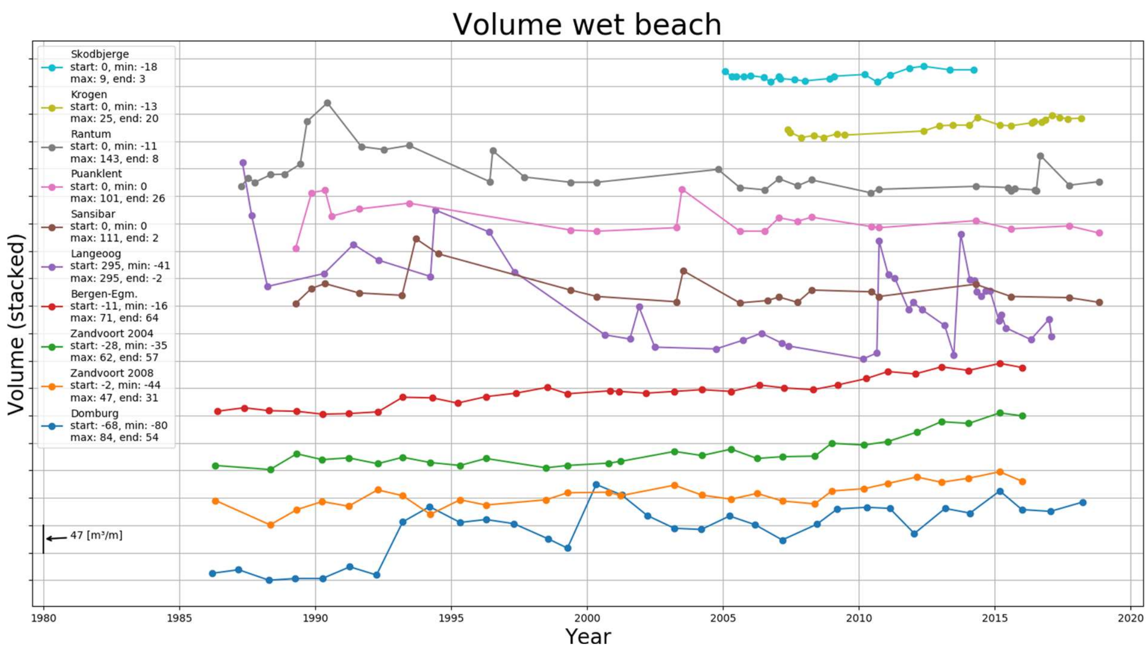


Figure 10.8 Time series of the volumes of the wet beach (in relation to an arbitrary time of reference).

In Figure 10.9 the time series of the volumes of the shore face are shown. The main characteristics for the temporal development of the volumes of the shore face are as follows:

- At the lab of Sylt the volumes of the shore face show a steady decrease that could be stopped in 2006 by the shore face nourishments. At Langeoog the shore face volume decreased after 2003.
- At the Dutch labs (Bergen-Egmont and Zandvoort) and Krogen the shore face volume increased significantly.

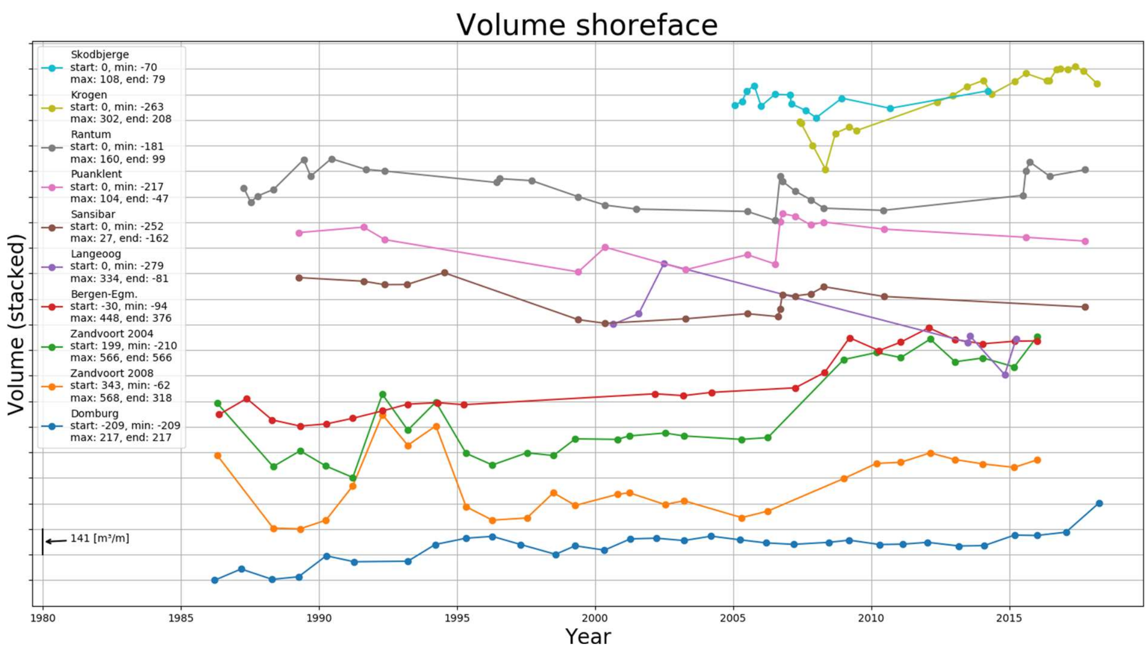


Figure 10.9 Time series of the volumes of the shore face (in relation to an arbitrary time of reference).

In Figure 10.10 the time series of the volumes of the beach and shore face are shown. The main characteristics for the temporal development of the volumes of the beach and shore face are as follows:

- The development of the volumes of the beach and shore face is mainly dominated by the volumes of the shore face since the amount is much higher than in the beach.

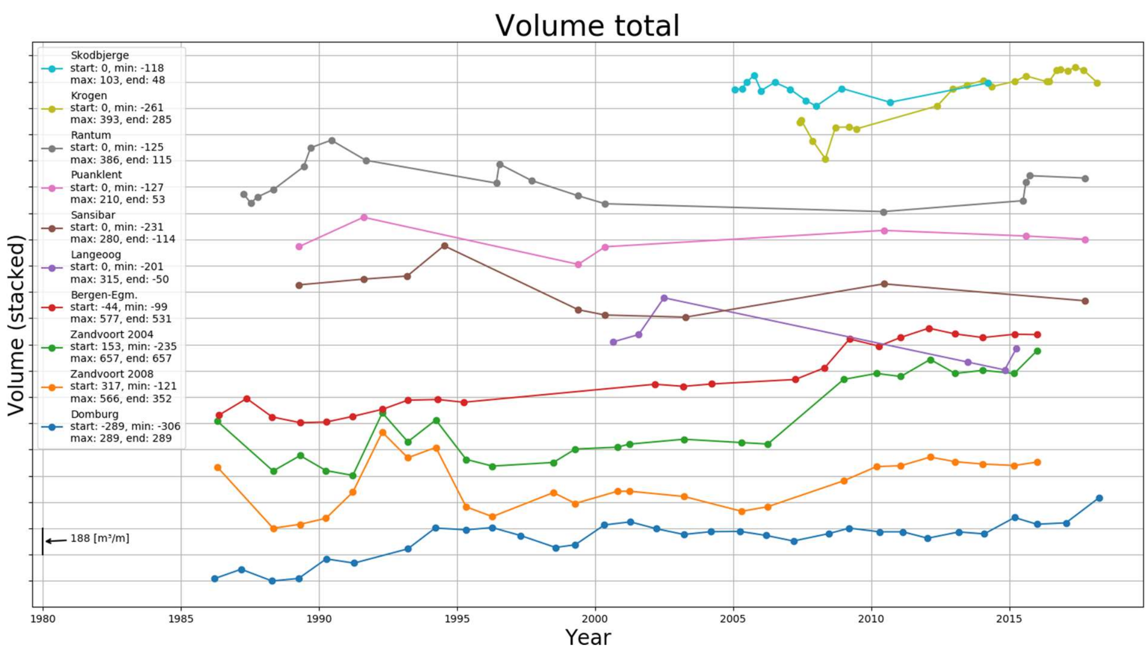


Figure 10.10 Time series of the volumes of the beach and shore face (in relation to an arbitrary time of reference).

In Figure 10.11 the time series of the system volumes of the dry beach are shown. The main characteristics for the temporal development of the system volumes of the dry beach are as follows:

- Significant increases of the system volume on the dry beach are seen at the Danish labs and at Zandvoort.

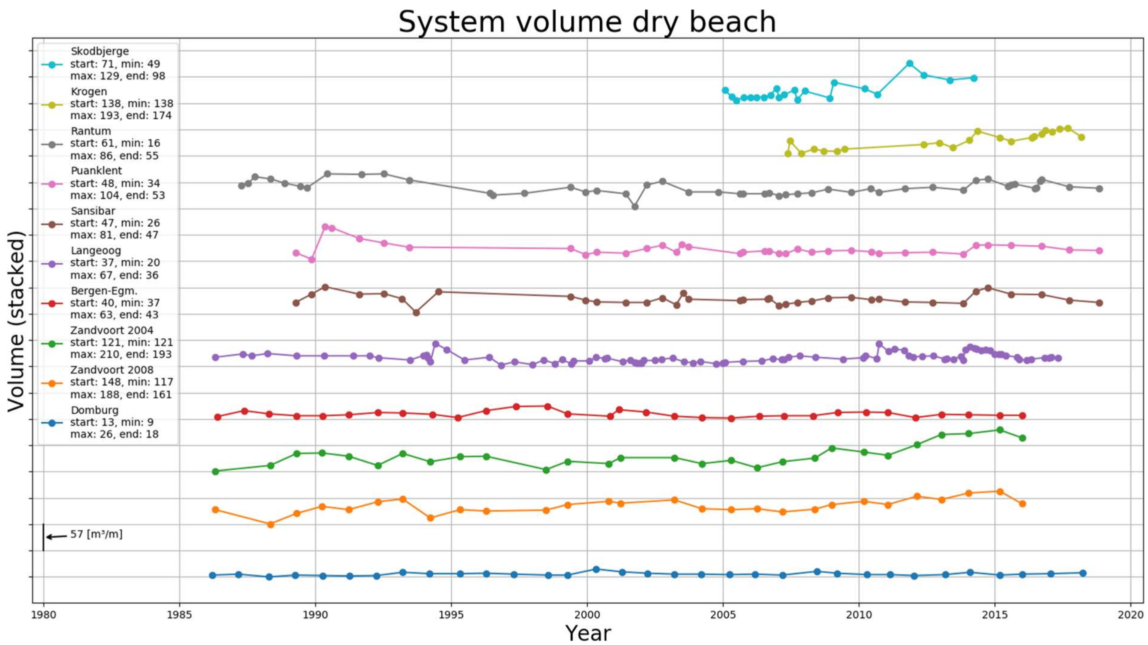


Figure 10.11 Time series of the system volumes of the dry beach.

In Figure 10.12 the time series of the system volumes of the wet beach are shown. The main characteristics for the temporal development of the system volumes of the wet beach are as follows:

- The system volume of the wet beach increased at Bergen-Egmont and Domburg.

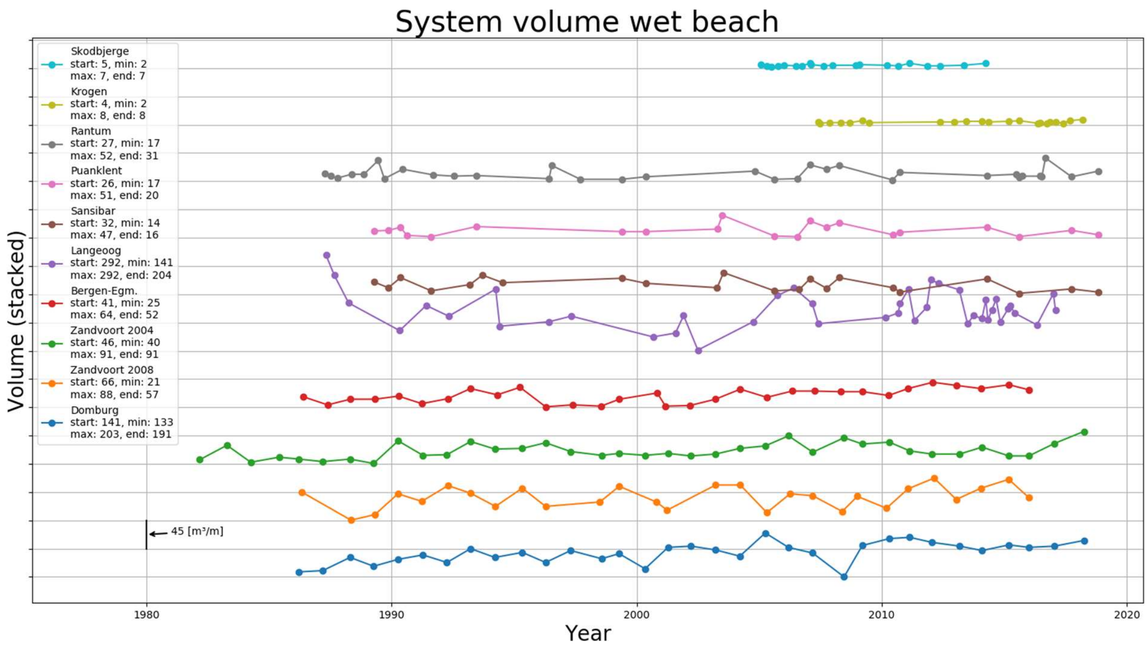


Figure 10.12 Time series of the system volumes of the wet beach.

In Figure 10.13 the time series of the system volumes of the shore face are shown. The main characteristics for the temporal development of the system volumes of the shore face are as follows:

- The system volume of the shore face doesn't variate so much. Only at Langeoog the system volume of the shore face decreased between 2006 and 2014. At Langeoog there is influence of shoaldynamics - migrating shoals supplying the beach with sediment in a cyclic way. A slight increase of the system volume of the shore face is seen at Zandvoort (2004).

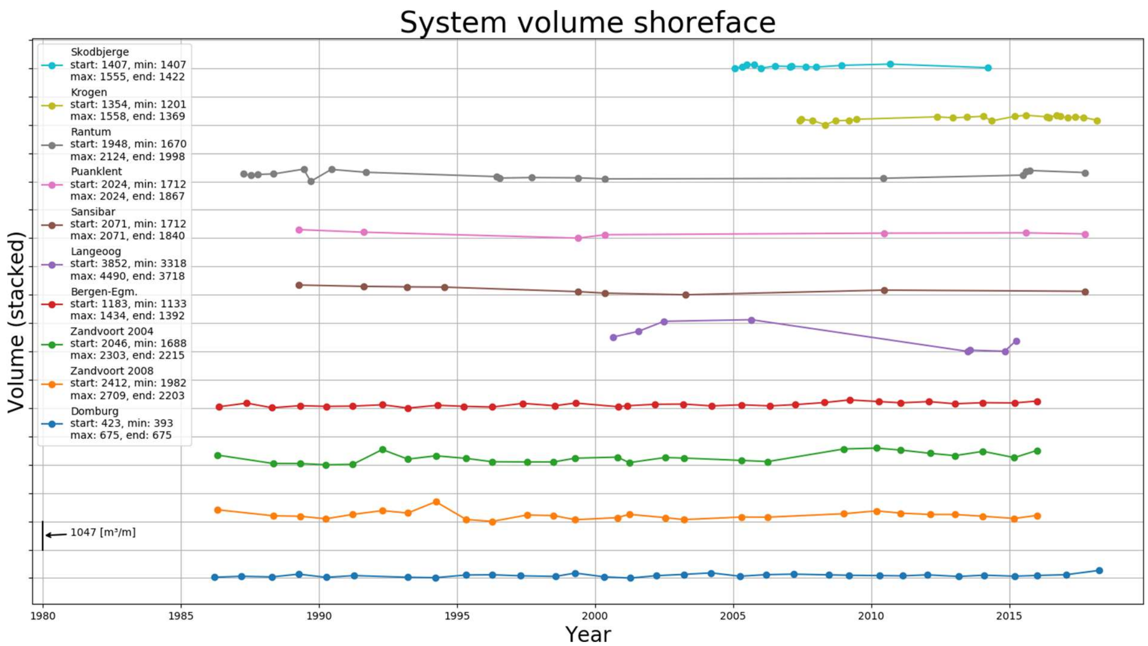


Figure 10.13 Time series of the system volumes of the shore face.

In Figure 10.14 the time series of the system volumes of the beach and shore face are shown. The main characteristics for the temporal development of the system volumes of the beach and shore face are as follows:

- The development of the system volumes of the beach and shore face is mainly dominated by the system volumes of the shore face since the amount is much higher than in the beach.
- Especially at the Dutch and Danish labs there exists a slight tendency of increase in system volume of the beach and shore face.

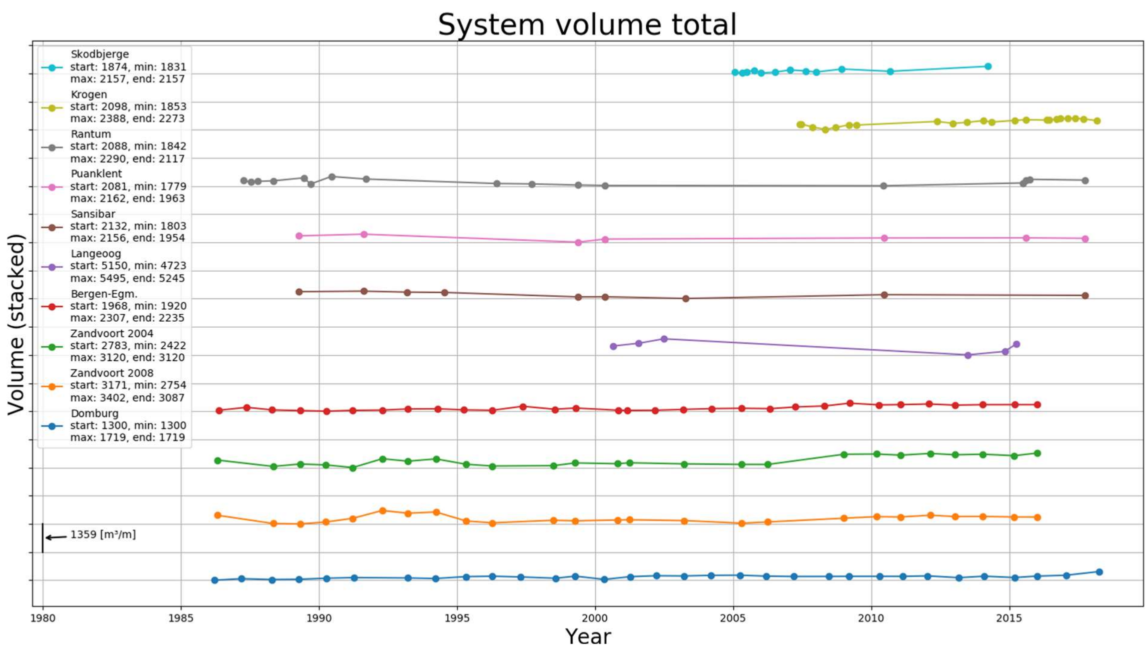


Figure 10.14 Time series of the system volumes of the beach and shore face.

In Figure 10.15 the time series of the heights of the bar top are shown. The main characteristics for the temporal development of the heights of the bar top are as follows:

- The development of the bar top varies in time and doesn't show any special tendency.

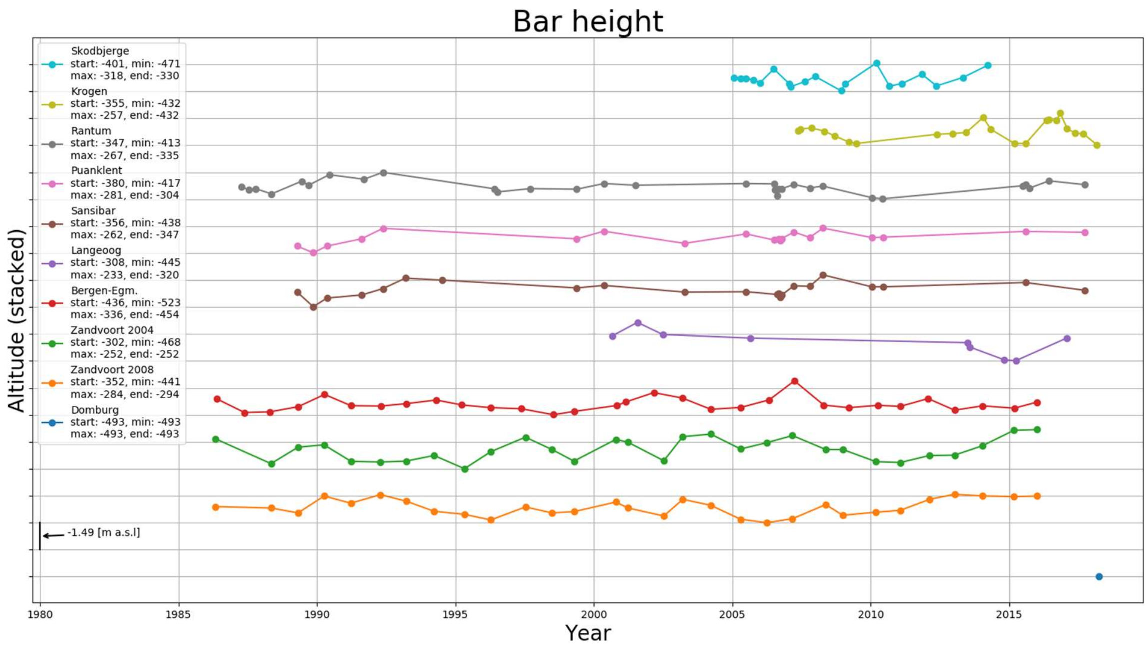


Figure 10.15 Time series of the heights of the bar tops.

In Figure 10.16 the time series of the heights of the depths of the trough are shown. The main characteristics for the temporal development of the depths of the trough are as follows:

- The temporal evolution of the depth of trough is dominated by long term fluctuations.

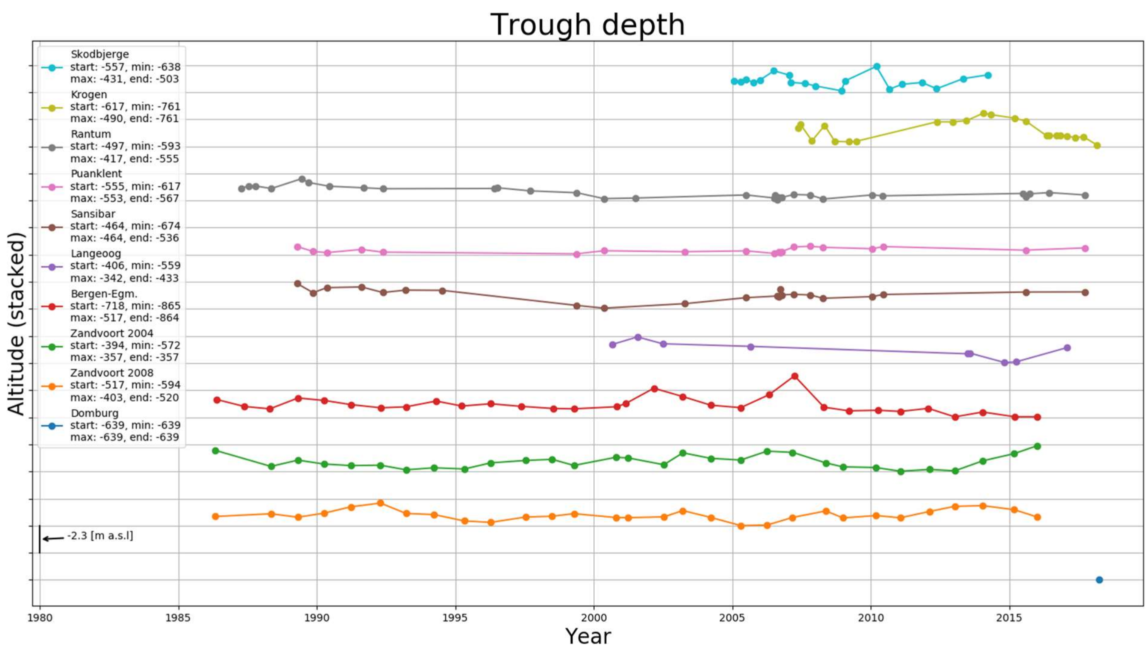


Figure 10.16 Time series of the depths of the troughs.