Interreg
North Sea Region
Building with Nature
European Regional Development Fund

EUROPEAN UNION

LKN.SH
Landesbetrieb für Küstenschutz, Nationalpark und Meeresschutz Schleswig-Holstein

National Analysis

Table of Content

1 Introduction

1.1 Background information

The morphodynamics of the sandy coasts leads to different autonomous developments. In some cases the autonomous behaviour doesn't lead to addition coastal measures where in other cases coastal measures had been carried out. The main aim is always to find out the best fit of the proper measures. In the BwN project Schleswig-Holstein investigates the west coast of the island of Sylt, especially the southern part of the island where shoreface nourishments in 2006 were made in order to stable the beach and improve the long shore transport towards the south as well. If it can be seen that the additional sand supply enlarges the sediment transport into the Wadden Sea that would be a great step for the protection of the Wadden Sea due to a sea level rise. This aspect is also investigated by modelling the sediment transport and benthos. Therefore in 2017 an amount of 400 000 m³ of sand was nourished at the shoreface more south of the nourishments of 2006.

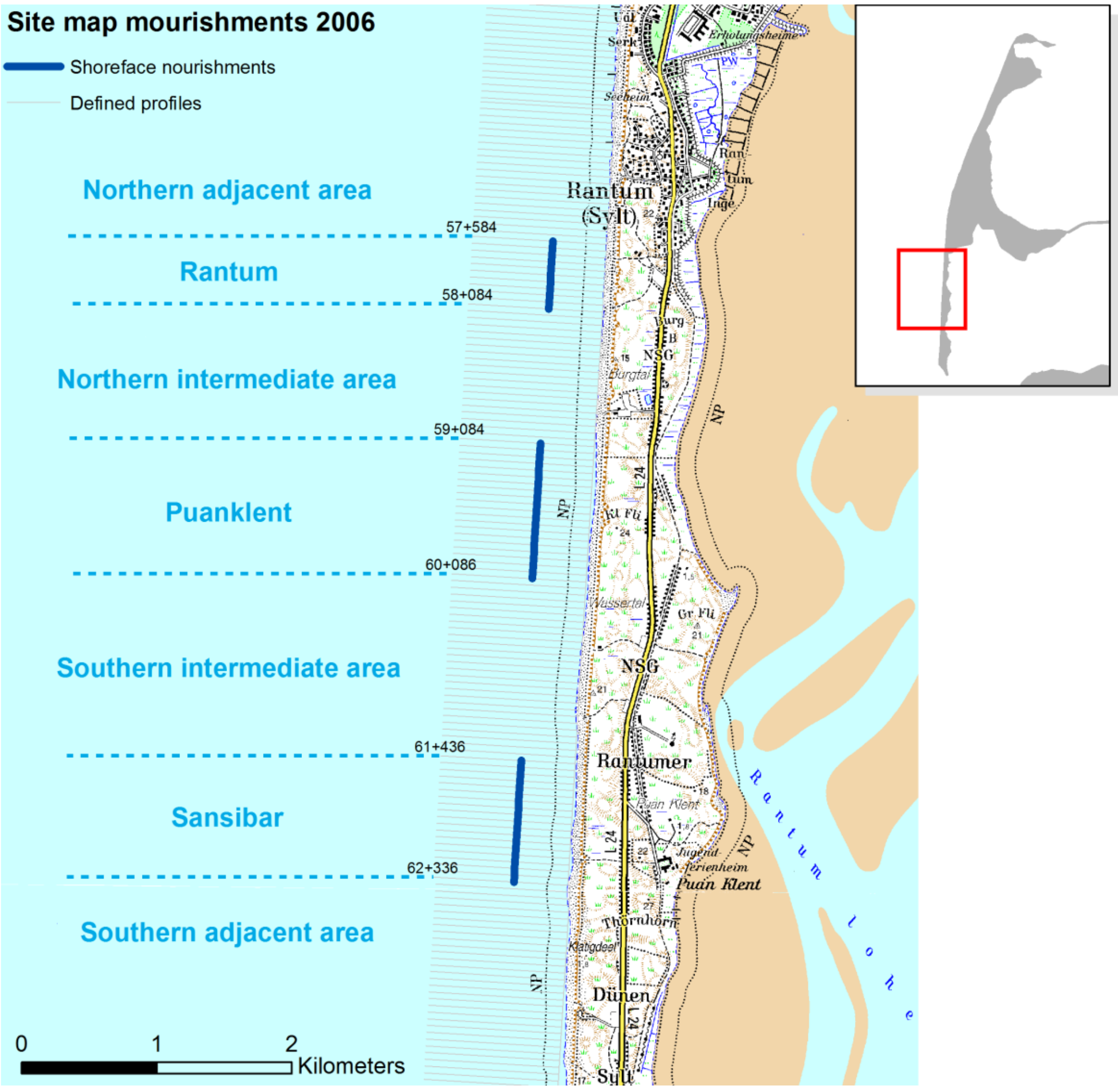

Figure 1: Site map shoreface nourishments 2006.

1.2 Objectives/research questions

The coastal protection on the island of Sylt is done since 1972 mainly by nourishments. The type and amount of nourishments changed during the time in order to develop the best fit. The first nourishment was done at the central part of the island by 1 000 m³/m with the total amount of 1 Mio. m³. The geometric form was built like a sand groyne. Along the coastal stretch a sea wall and different kind of groynes have been constructed since the end of the former last century. In the 1950ies the beach was totally eroded and the safety of the sea wall was at risk. With the aim of tetrapodes it was planned to stabilize the sea wall again. Because all the measures failed, nourishments have been developed in form of a test. The first and the second borrow area could be found as in the Wadden Sea. As a result of the first nourishment a recreation of the beach could be observed. Six years later, the second nourishment was done at the same place, but in form of an alongshore nourishment. With the second nourishment the coastal region started to recreate again. Because to the effectiveness of these nourishments this kind of coastal measures was adopted along the whole west coast that suffered structural erosion, since 1984. In the meantime a new common borrow area was explored that might deliver sufficient sand for the longer future. The geometrical forms of the nourished sand body changed over time in order to have a least disturbance in the natural environment. Until 1996 the nourishments took place only on the beach. In this year a bar nourishment was done. The success was doubtful and thus in 2003 the first shoreface nourishment was made. This kind of measure showed a better behaviour on the beach. Thus, in 2006, at three different locations shoreface nourishments were done. The idea was to compare the effect of length and amount of nourished sand in the shoreface (Figure 1). The morphological development should be observed at least for six years without additional measures. This had been possible and the analysis is the main part of the national analysis. There are four main goals that are searched for: Is it possible to stabilize the beach only by shoreface nourishments? What is the best place to put in the sand in the shoreface? What is the best stretch length for a shoreface nourishment since there are some strong rip currents? Is the long shore transport that is one of the main physical transport mechanisms strong enough to provide material towards the adjacent areas?

2 Study site

The Island of Sylt is formed by the former last ice age and the relocation during the Holocene that led to dunes, marshes and spits of land (Figure 2). The west coast of the island of Sylt suffered a natural retreat of the lower dune foot of 1 to 4 m per year (Figure 3). The dunes save the hinterland to get flooded and protect the fresh water reservoirs for saltwater intrusion. To prevent the further erosion a wide range of coastal measures were established: Groynes, sea walls, revetments and tetrapodes. None of these constructions worked sustainable. The retreat could be stopped only by continuous nourishments. The steady loss of sediment is due to the open sand system that governs the sediment budget at the west coast of Sylt. About 1 Mio. m³ of material is leaving the west coast annually, where the rate of sediment transport increases towards the ends of the island. Along the tidal channels there are accumulations. A part of the material will follow the tidal currents and moves toward the Wadden Sea, the remaining moves towards the ebb deltas.

Figure 2: Study site of west coast of the Island of Sylt at Schleswig-Holstein / Germany (Source of the base map: Copernicus Sentinental Data 2018).

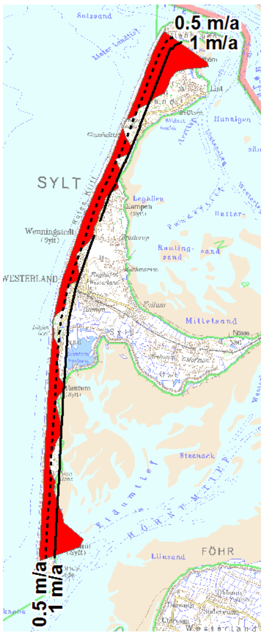

Figure 3: Annual coastal retreat (lower dune foot) along the west coast of the Island of Sylt before nourishments started.

3 Nourishment description

3.1 Coastal infrastructure and earlier nourishments

The first wooden groyne on the west coast of the Island of Sylt was built in 1867 and should enlarge the beach width in order to set up foredunes. Several other types of groynes in kind of iron, steel, concrete and asphalt were implemented until 1968. It was planned to build groynes all along the coast, separated 500 m apart. But only at the middle part of the coast they actually have been performed. In the centre of the island there was built a sea wall in 1906-1946. In the space of time from 1960 to 1967 tetrapodes were put into the front of the sea wall or dune foot in order to reduce the wave attack. In the study area at Hörnum there was built a combination of longshore and cross shore measure out of tetrapodes in 1967/68 that had a serious influence on sediment transport. But all these measures didn’t prevent from further erosion, only the zone of erosion changed. The first nourishment was done in 1972 at the centre of the island (Figure 4). In 1992 almost the total coast was covered at least with one initial nourishment. Since then the main issue was to keep the coast in its shape, whereat the shape includes the whole profile from the upper dune to the outer sand bar. The shoreface nourishments that are considered in this study were carried out in 2006. Due to the autonomous behaviour no further measures were needed at these stretches for the next six years, except planting grasses or putting fences on. Until now only the northern nourishment had to be re-nourished in 2015 (shoreface) and 2016 (beach).

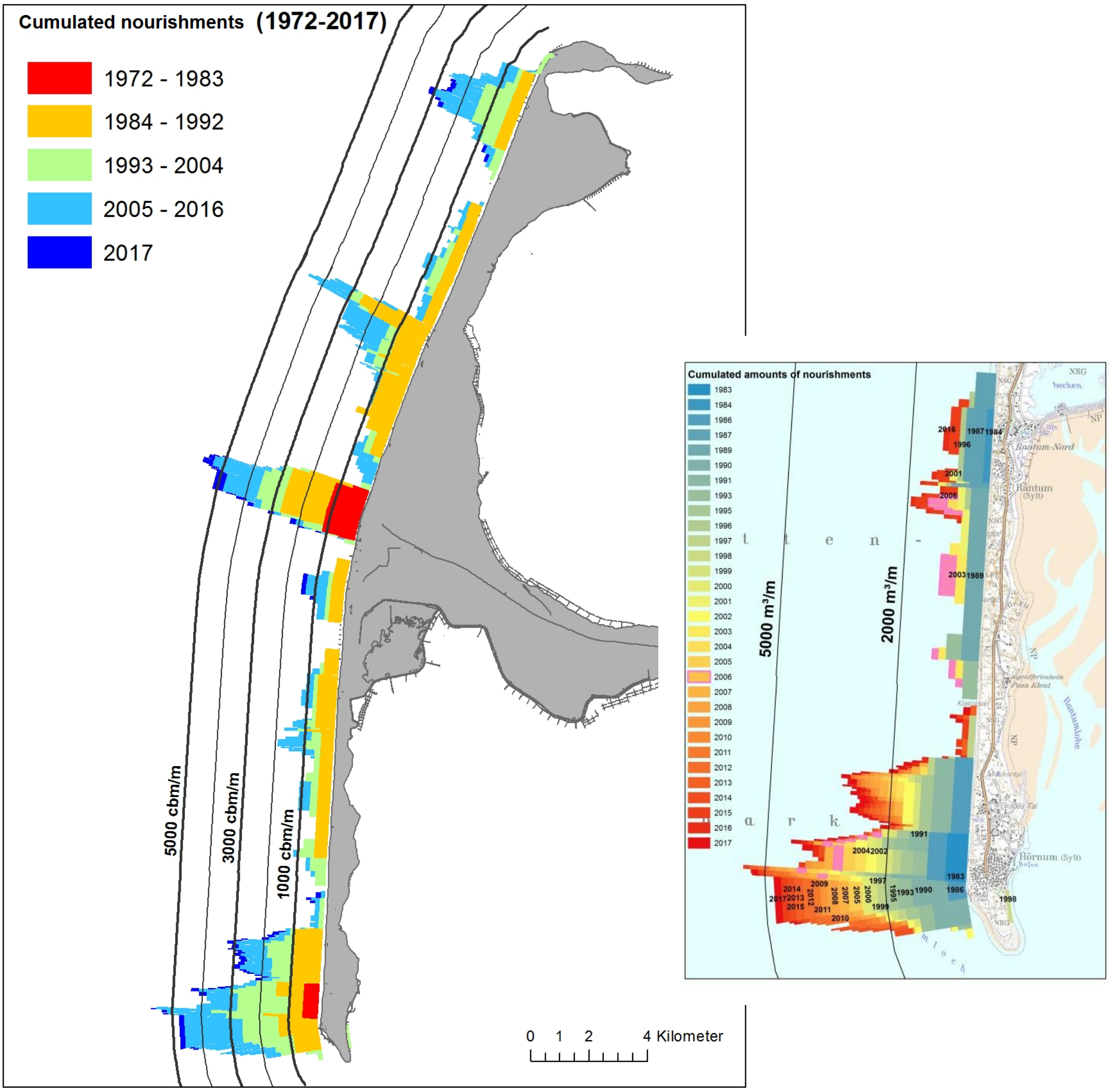

Figure 4: Cumulated amount of nourishment for Sylt from 1972 to 2017, details for Hörnum/Sylt.

3.2 Studied nourishment

In 2006 at three different places shoreface nourishments were carried out: Rantum, Puanklent and Sansibar (Figure 5). The design was the same at all three places: The design parameter were NHN-4m (below the bar top), a seaward slope of 1:200 and a width of 200 m, following a slope of 1:50 down to NHN-6m, from this intersection a slope of 1:10 was assumed in order to have an intersection with the measured profile. The main differences were in the lengths of the stretches and the fit into the natural profile. The main task was to observe the behaviour of the beach from the low water level to the mid dune level for the following six years. The purpose was to stabilize the beach without directly nourishing the beach.

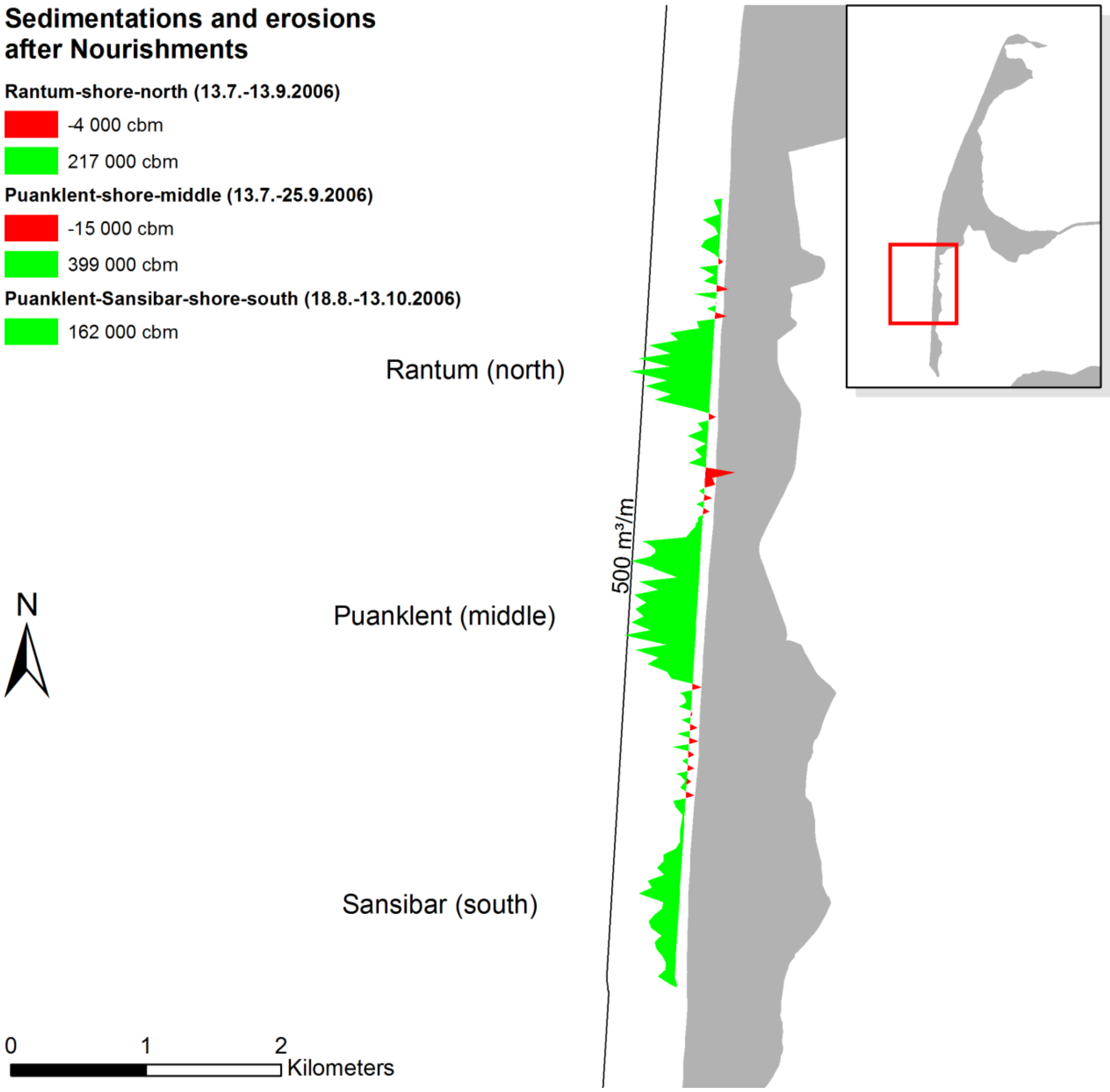

Figure 5: Shoreface nourishments on Sylt in the year 2006.

Besides shoreface nourishments at Rantum (225 000 m³, 452 m³/m), Puanklent (391 000 m³, 391 m³/m) and Sansibar (135 000 m³, 150 m³/m), beach nourishments at Hörnum beach (244 000 m³, 203 m³/m), List-south (132 000 m³, 187 m³/m) and List-north (42 000 m³, 60 m³/m) have been supplied (Beach nourishments are not shown in the figure).

3.2.1 Rantum 2006

At Rantum, 225 000 m³ of sand have been deposited along an approx. 500 m long area seawards the bar resulting in a nourishment of 452 m³/m (Table 1 and Figure 6). 240 000 m³ of nourished sediments could be detected by track surveying in a layer between NHN-1 m / NHN-10 m. Track surveying in 2010 has proven that 91 000 m³ of these sediments still remained in place. That is 38 %. At the beginning of the nourishment campaign sediments have been nourished at a punctual spot seawards the bar top in the northern part of the transect, building a second, artificial sand bar and resulting in a decrease of height of the natural sand bar. The procedure has been immediately revised and sediments have been nourished on the whole seawards slope of the natural breaker bar, according to the original plan.

The sand deposit was installed between NHN -4 m and NHN -8.50 m on a width of approx. 300 meters (Figure 7, Figure 8).

Table 1: Table for Shoreface Nourishment Rantum 2006.

Rantum 2006	
Transect (from)	58+084
Transect (to)	57+584
Track of nourishment	0.500 km
Sediment quantity	0.225 Mio. m^3
Quantity m^3/m	452 m^3/m
Start of nourishment	Jul,15th 2006
End of nourishment	Aug. 13th 2006

Figure 6: Cross section profile comparison, Rantum (shoreface), between 13.07.2006 and 13.09.2006.

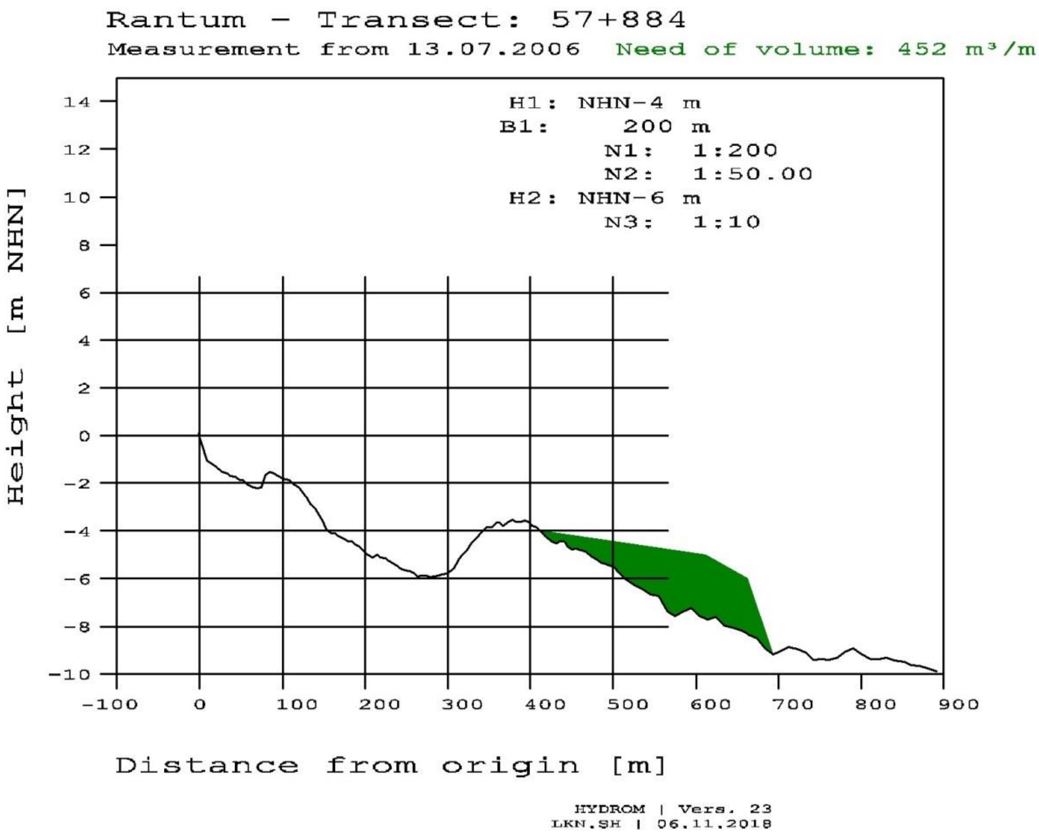

Figure 7: Design profile for Rantum shoreface nourishment 2006, transect 57+884.

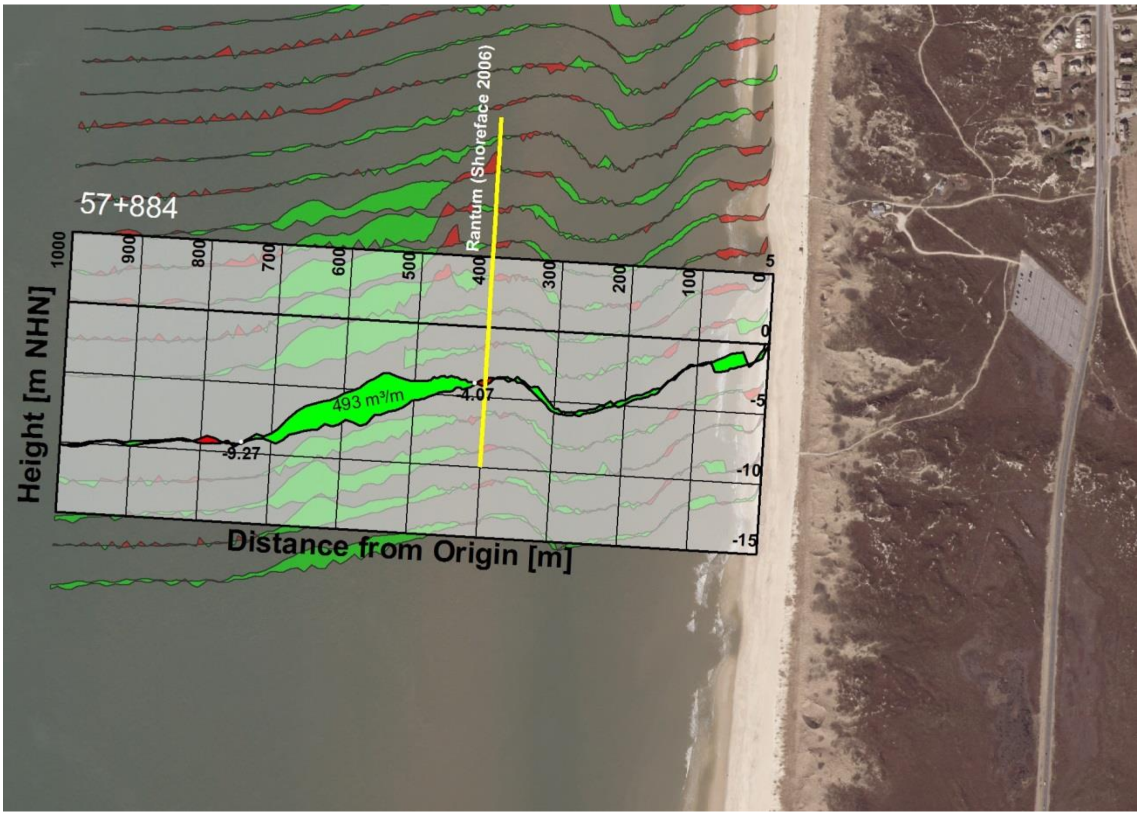

Figure 8: Profiles Rantum (transect 57+884), difference, between 13.07.2006 and 13.09.2006.

3.2.2 Puanklent 2006

At Puanklent, the central nourishment site between Rantum and Sansibar, 391 000 m^3 of sand have been deposited along an approx. 1 000 m long area seawards the bar resulting in a nourishment of 391 m^3/m (Table 2, Figure 9). 380 000 m^3 of nourished sediments could be detected by track surveying in a layer between NHN-1 m / NHN-10 m. Track surveying in 2010 has proven that 252.000 m^3 of these sediments still remained in place. That is 66%.

The sand deposit was installed between NHN -4 m und NHN -8.50 m on a width of approx. 300 meters (Figure 10, Figure 11).

Table 2: Table for Shoreface Nourishment Puanklent 2006.

Puanklent 2006	
Transect (from)	60+086
Transect (to)	59+084
Track of nourishment	1.001 km
Sediment quantity	0.391 Mio. m^3
Quantity m^3/m	391 m^3/m
Start of nourishment	Jul 25th 2006
End of nourishment	Sep 28th 2006

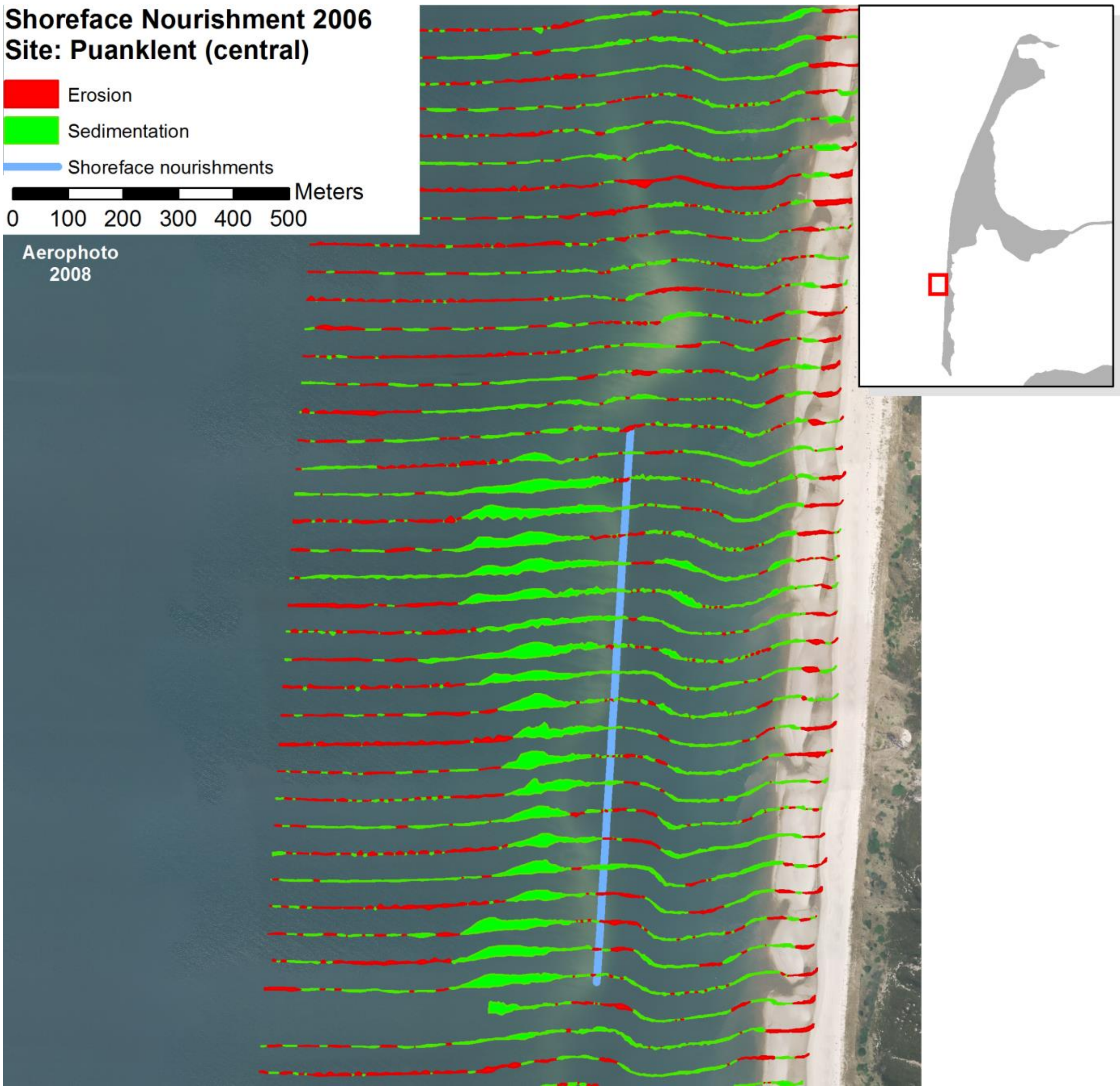

Figure 9: Cross section comparison, Puanklent (shoreface), between 13.07.2006 and 13.09.2006.

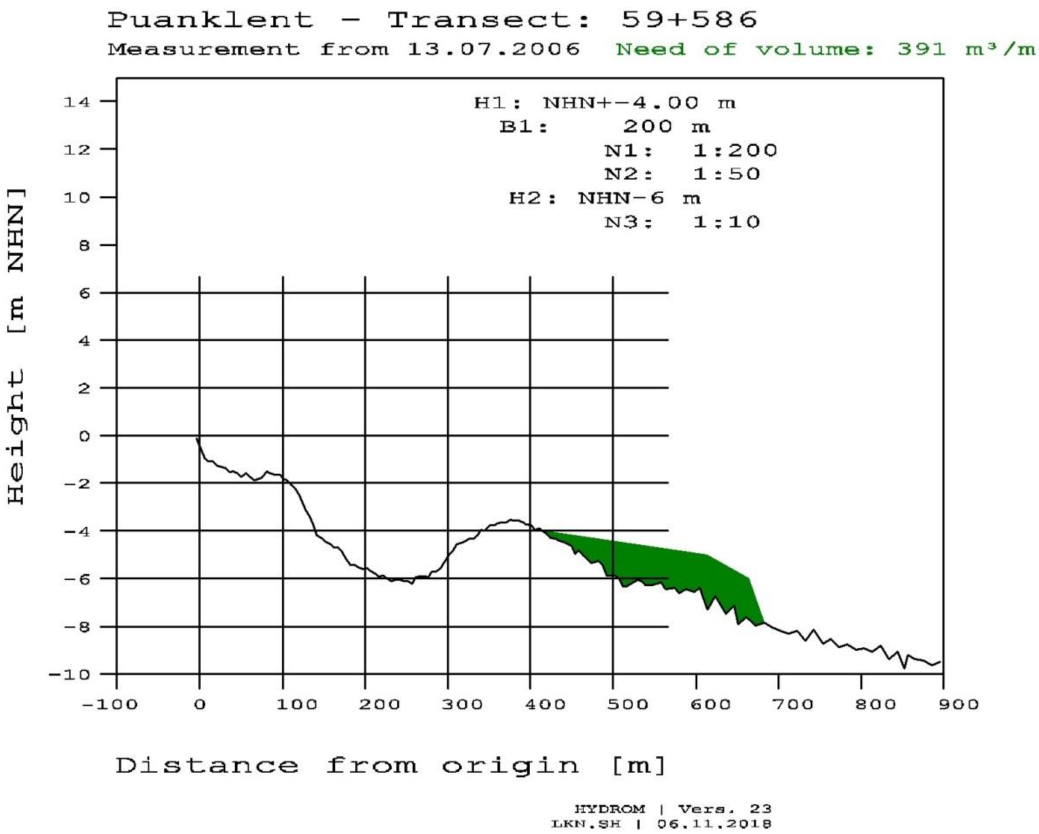

Figure 10: Design profile for Puanklent shoreface nourishment 2006, transect 59+586.

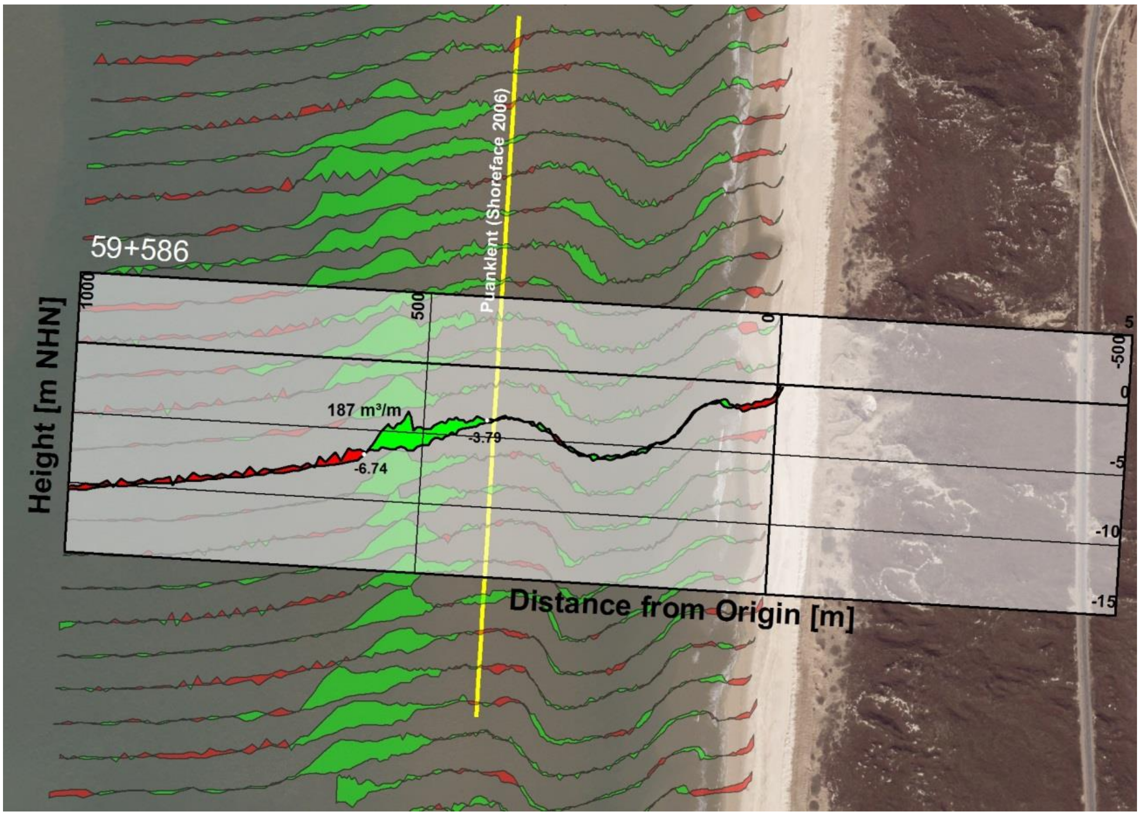

Figure 11: Profiles Puanklent (transect 59+586), between 13.07.2006 and 13.09.2006.

3.2.3 Sansibar 2006

At the 900 meters long nourishment site of Sansibar, located south of PuanKlent, 135 000 m³ have been nourished (150 m³/m) (Table 3, Figure 12). A total gain of 150 000 m³ of sand could be found by survey in the layer between NHN -1 m and NHN -10 m. In the same layer 90 000 m³ of sediments still remained there in 2010. That's 60%.

The sand deposit was installed between NHN -4 m und NHN -8.50 m on a width of 250 to 300 meters (Figure 13, Figure 14).

Table 3: Table for Shoreface Nourishment Sansibar 2006.

Sansibar 2006	
Transect (from)	62+336
Transect (to)	61+436
Track of nourishment	0.900 km
Sediment quantity	0.135 Mio. m³
Quantity m³/m	150 m³/m
Start of nourishment	Sep 10th 2006
End of nourishment	Oct 2nd 2006

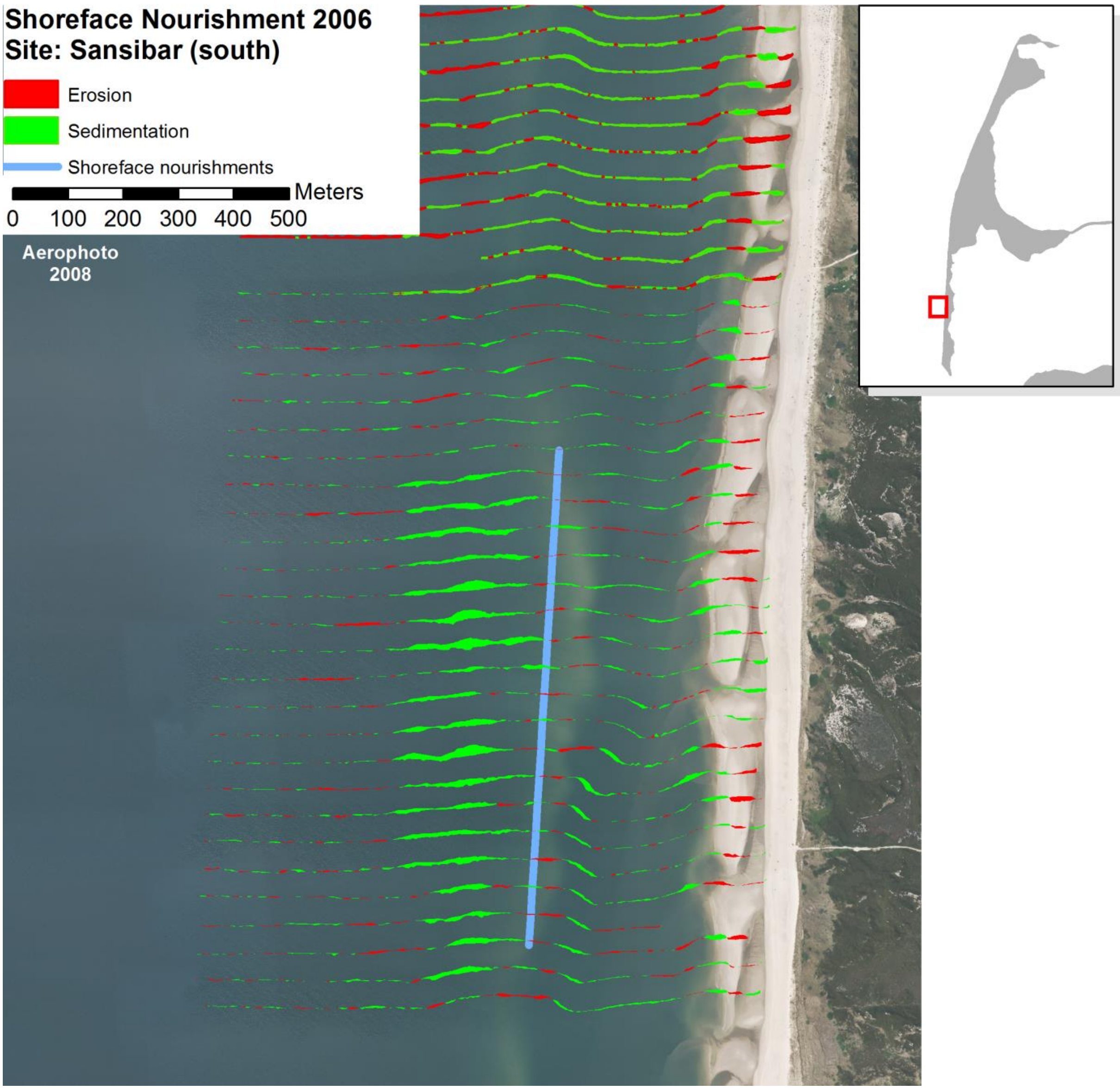

Figure 12: Cross section comparison, Sansibar (shoreface), between 18.08.2006 and13.10.2006.

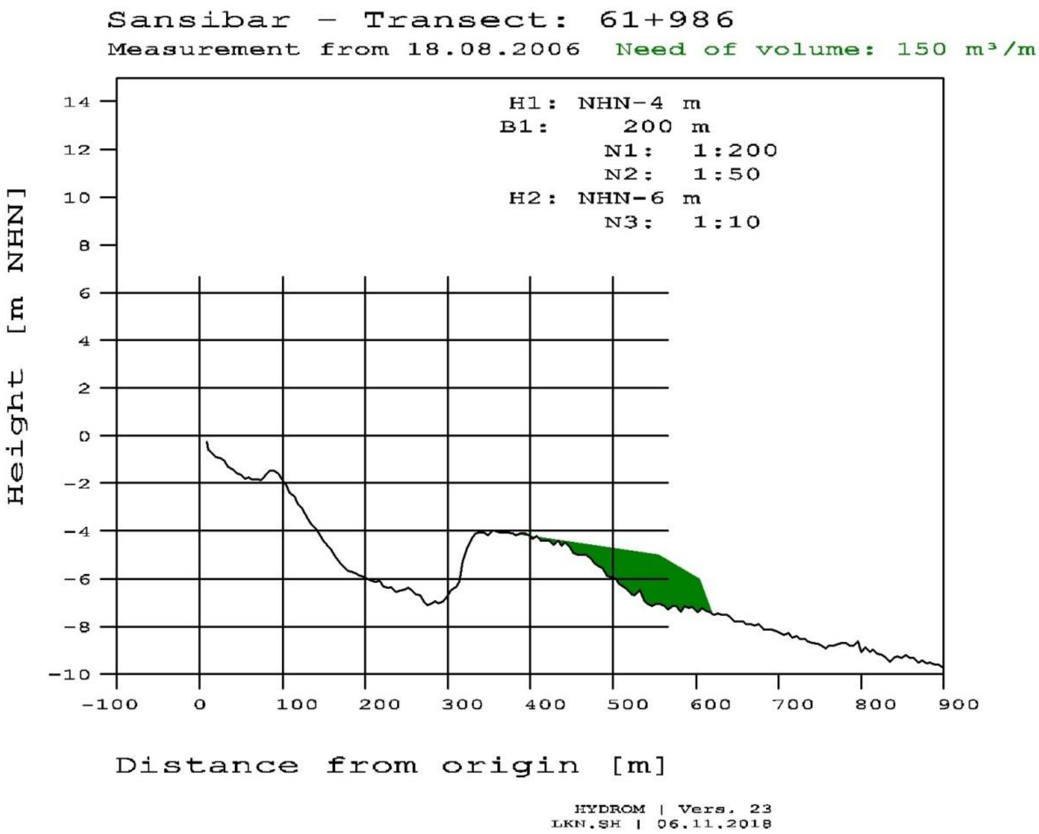

Figure 13: Design profile for Sansibar shoreface nourishment 2006, transect 61+986.

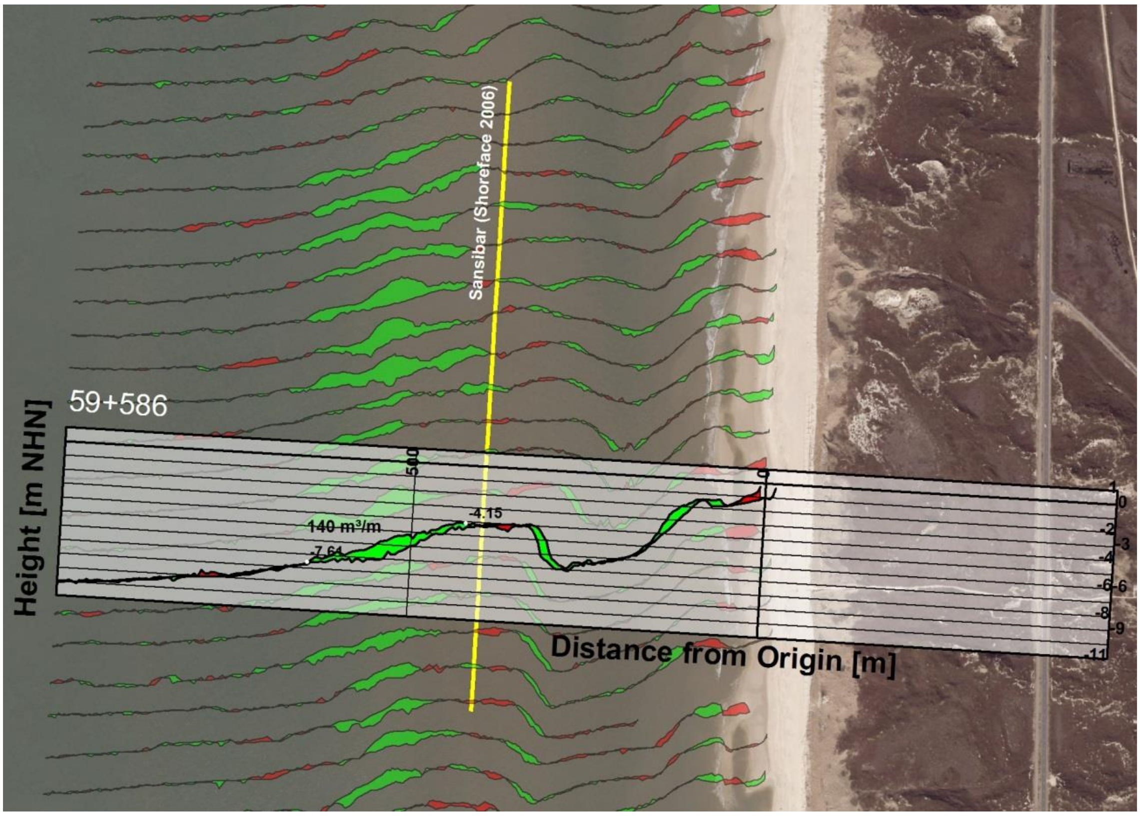

Figure 14: Profiles Sansibar (transect 61+986), between 18.08.2006 and 13.10.2006.

4 Method and data

4.1 Data, availability, accuracy and processing

4.1.1 Transect data

The transect data that are available for the different analysis are put into Table 4 to Table 6.

Table 4: Abstract of measurement campaigns at the site of Rantum 2006.

Date	Beach	Shoreface	Notes
Jul 13th 2006		X	Pre-survey
Jul 19th 2006		X	Check Survey (partially)
Jul 20th 2006	X		Pre-survey
Aug 17th 2006		X	1. Interim Survey
Sep 13th 2006		X	2. Interim Survey
Sep 14th 2006		X	Additional Survey GKSS
Sep 15th 2006	X		LIDAR
Oct 13th 2006		X	1. Resurvey
Jan 25th 2007	X		LIDAR
Mar 29th 2007		X	2. Resurvey

Date	Beach	Shoreface	Notes
Apr 25th 2007	X		LIDAR
Oct 01th 2007	X		LIDAR
Oct 23th 2007		X	3. Resurvey
Apr 07th 2008	X		LIDAR
Apr 15th 2008		X	4. Resurvey
Nov 17th 2008	X		LIDAR
Sep 26th 2009	X		LIDAR
Jan 19th 2010		X	5. Resurvey
Jun 10th 2010		X	Overall survey
Sep 29th 2010	X		LIDAR
Sep 16th 2011	X		LIDAR
Sep 17th 2012	X		LIDAR
Nov 08th 2013	X		LIDAR
Apr 19th 2014	X		LIDAR
Sep 28th 2014	X		LIDAR
Jul 02nd 2015	X	X	Pre-survey
Aug 07th 2015	X	X	Bathymetric LIDAR
Sep 29th 2015	X	X	Resurvey
Jun 15th 2016		X	Pre-survey
Jun 22nd 2016	X		Pre-survey
Jul 13th 2016	X		Pre-Survey
Sep 05th 2016	X		Resurvey
Sep 26th 2016	X		LIDAR
Sep 29th 2017	X	X	Bathymetric LIDAR

Table 5: Abstract of measurement campaigns at the site of Puanklent 2006.

Date	Beach	Shoreface	Notes
Jul 13th 2006		X	Pre-survey
Jul 20th 2006	X		Pre-survey
Sep 13th 2006		X	1. Interim Survey
Sep 15th 2006	X		LIDAR
Sep 29th 2006		X	2. Interim Survey
Oct 13th 2006	X		LIDAR
Jan 25th 2007		X	1. Resurvey
Mar 29th 2007		X	2. Resurvey
Apr 25th 2007	X		LIDAR
Oct 01th 2007	X		LIDAR
Oct 23th 2007		X	3. Resurvey
Apr 07th 2008	X		LIDAR
Apr 15th 2008		X	4. Resurvey

Date	Beach	Shoreface	Notes
Nov 17th 2008	X		LIDAR
Sep 26th 2009	X		LIDAR
Jan 19th 2010		X	5. Resurvey
Jun 16th 2010		X	Overall Survey
Sep 29th 2010	X		LIDAR
Sep 16th 2011	X		LIDAR
Sep 17th 2012	X		LIDAR
Nov 08th 2013	X		LIDAR
Apr 19th 2014	X		LIDAR
Sep 28th 2014	X		LIDAR
Aug 07th 2015	X	X	Bathymetric LIDAR
Sep 26th 2016	X		LIDAR
Sep 29th 2017	X	X	Bathymetric LIDAR

Table 6: Abstract of measurement campaigns at the site of Sansibar 2006.

Date	Beach	Shoreface	Notes
Aug 08th 2006		X	Pre-survey
Aug 21st 2006	X		Pre-survey
Sep 13th 2006		X	1. Interim survey
Sep 14th 2006		X	Additional survey GKSS (3 profiles)
Sep 15th 2006	X		LIDAR
Sep 25th 2006		X	2. Interim survey (part)
Oct 13th 2006		X	1. Resurvey
Jan 25th 2007	X		LIDAR
Mar 29th 2007		X	2. Resurvey
Apr 25th 2007	X		LIDAR
Oct 01st 2007	X		LIDAR
Oct 23rd 2007		X	3. Resurvey
Apr 07th 2008	X		LIDAR
Apr 15th 2008		X	4. Resurvey
Nov 17th 2008	X		LIDAR
Sep 26th 2009	X		LIDAR
Jan 19th 2010		X	5. Resurvey
Jun 16th 2010		X	Overall Survey
Sep 29th 2010	X		LIDAR
Sep 16th 2011	X		LIDAR
Sep 17th 2012	X		LIDAR
Nov 08th 2013	X		LIDAR
Apr 19th 2014	X		LIDAR

Date	Beach	Shoreface	Notes
Sep 28th 2014	X		LIDAR
Aug 07th 2015	X	X	Bathymetric LIDAR
Sep 26th 2016	X		LIDAR
Sep 29th 2017	X	X	Bathymetric LIDAR

The accuracy of the transect data depend on a couple of influences where there is a main difference between terrestrial and hydrographic data on the one side and LIDAR data on the other side. From the LIDAR data the profiles are generated by the defined transects, usually the transects have a spacing of 50 m in order to give a real image of the bar-trough-system and the rip currents. For terrestrial measurements a spacing of 100 m seem to be sufficient in order to get real sand volumes. In the case of echo soundings the vessel might not follow exactly the transect line due to strong currents which leads to a deviation in the position and the difference of different measurements may give additional errors. The corridor for the projection of bathymetric echo soundings at the defined transects is defined to 24 m. In the case of LIDAR data there will be some noise coming from vegetation, buildings or tourism infrastructure. The LIDAR data have to be corrected by water points and as far as water is detected in the profile the more seawards points in the profiles have to be skipped. In general the position and the depth measurement have a natural error that varies in time.

4.1.2 Hydrodynamic data

In order to compare the effect of the different measures over time and detect the influence of climate change hydrodynamic data must take into account. Since tidal gauges are not present at every location around the lab there must be a choice of representative gauges. In the case of Sylt the tidal gauge of the harbour of List is taken because the registration is available since 1900. Studies about interpolation of the water levels between the different points along the west coast of the Island of Sylt had been made and showed an appropriate fit. In the correlation of morphodynamic and hydrodynamic parameters the duration of higher water levels over time is considered. Since the data are sampled in a digital way the values are stored every minute. Because the water levels can be fixed exactly, the main error results from the non-synoptically measurements of the morphodynamics, only with LIDAR a synoptically (some hours) sampling is possible. For the wind and wave data the sampling rate is coarser than for the water levels, but usually at 1 hour. Wind data are available for List since 1950 although the position moved in the meantime a bit. The wave data are gathered at deep water in front of the centre part of Sylt (Westerland) since 1987 whereat the wave buoy failed some times. In this case a wind-wave-correlation helps to fill the gaps.

4.1.3 Nourishment data

The nourishments were carried out by Rohde Nielsen A/S during the regular tender period of several years. The used hopper suction dredgers were "Modi R" (3.493 kW) and "Sif R" (3.052 kW). The distance from the borrow area to the shoreface was about 15 km. In order to get an appropriate fit to the design profile the nourished areas were divided into fixed boxes with 80 m x 80 m, corresponding to the ship length. For each box the amount of shiploads were calculated. This was done in cooperation with Fa. Hahlbrock Marine Technology (HMT) that installed the program and controlled the dredger activities.

4.1.4 Additional data

Together with the LIDAR data there are gathered data from aerial photography with a resolution of about 20 cm. This is useful to correct the LIDAR data for special disturbances (water, vegetation, buildings, touristic infrastructure). Together with the modelling of hydrodynamics and benthos field survey samples are taken from the benthos.

4.2 Method

4.2.1 Terminology and coastal state indicators

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

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

The coastal zone terminology in Figure 15 will be applied throughout the analysis. The CSI's corresponding to the coastal terminology are shown in Figure 15 and described in Table 7. The morphological development represented by the CSI will be analysed in order to reveal the morphodynamics and the effects of nourishments.

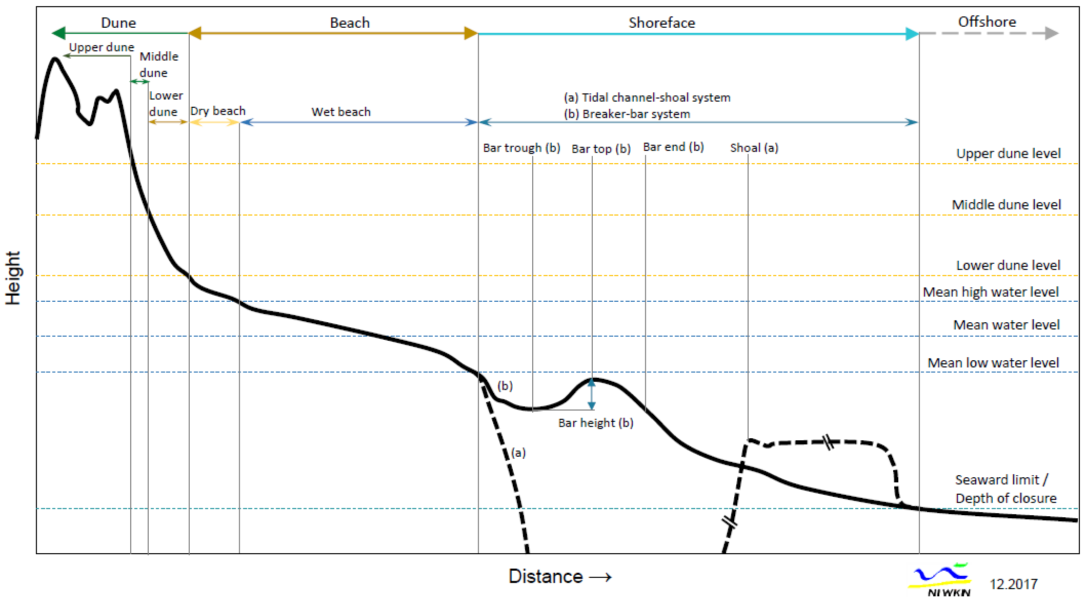

Figure 15: General terminology used to describe the coastal profile. On the vertical axis various levels in the profile are shown. The horizontal axis shows different Morphological zones in the profile.

As there are different environmental and morphological conditions in the analysed coastal laboratories, each partner will adapt the terminology accordingly, still ensuring that a comparison of each adaption and the resulting indicators is possible. The vertical levels are set for each living laboratory in order for it to capture the morphology; the relevant levels are presented in section 6.2. In principle one value is set per vertical level per living laboratory. Only when this gives unsuitable results the level should be differentiated.

Table 7: Common definitions of Morphological zones (grey) and delimiting height levels – CSI (white). *The seaward and landward limit can be defined as a height level or as a distance.

Coastal-section	CSI	CSI type and definition
	Landward limit	Not a CSI -The landward limit is not monitored in itself, but sets the limits for calculating dune and system width and volume. The limit is set as a cross-shore position which is measured in all available profiles.
Dune	**Upper dune**	Coastal sub-section
	Upper dune level	Fixed height level which is most responsive to dune erosion or human-made reinforcement. The minimum level of dune crests over time must be taken into account.
	Middle dune	Coastal sub- section
	Mid dune level	Fixed height level where Aeolian sand transport and aggregation of sand should be of minor relevance. Changes at this level should be likely ascribed to acute dune erosion or man-made dune reinforcement. However, on longer time scales natural dune growth can be visible, as a response to a positive or negative sediment budget.
	Lower dune	Coastal sub- section
	Dune toe level	Fixed height level where the slope is distinctly changing. Dune growth on shorter time scales can be the result of human-built sand traps or of natural dune growth like Aeolian sand transport.
Beach	**Dry beach**	Coastal sub- section
	Mean high water level (MHWL)	Fixed height level: MWL + ½ Tidal Range. A best estimate and fixed height during the time of analysis is recommended for simplicity.
	Wet beach	Coastal sub- section
	Mean low water level (MLWL)	Fixed height level: MWL - ½ Tidal Range. A best estimate and fixed height during the time of analysis is recommended for simplicity.
Shoreface	**(a) Tidal channel-shoal system** **(b) Breaker-bar system**	**(a)** Morphological features. Channel: Deep section between MLWL and the front of the shoal. Shoal: a relatively large shallow area not connected to the beach which is shaped primarily due to tidal forces (e.g. ebb tidal deltas). **(b)** Morphological feature. Bar: sand accumulation created by the action of currents and waves. A bar has the following characteristics: Bar top: maximum in the shoreface profile where the slope changes sign. Bar trough: depression between two bar crests, or in between a bar top and a point landward from the bar, at the same depth. Bar height: difference in height between bar top and the deepest point of the bar trough. Bar landward limit: deepest point landwards of the bar top.
	Seaward limit* / Depth of closure	Not a CSI -The seaward limit is not monitored in itself, but sets the limits for calculating shoreface and system width and volume.

4.2.2 Physical marks

One method to analyse the development of a coastal area in time is to visualize trends in sedimentation or erosion, or periodic changes of both. The development of physical marks, defined in the common coastal terms, can be presented in various ways. One type of figure is a "time-distance-graph", where the y-axis shows the distance of the physical mark (=height level) to a point of reference. The x-axis shows the time of measurement. Multiple lines for different physical marks in one figure are possible. Multiple transects besides each other are also possible, where the y-axis shows time, the x-axis transects and the colour map shows the distances. To see effects of nourishments or dune reinforcements, the date of the nourishment should be displayed in the graph.

To extract physical marks from transect measurements, the MKL-Model (Momentary Coast Line) approach should be used. The model determines the surface area balance point of an area. Figure 16 shows an example of the MKL-calculation.

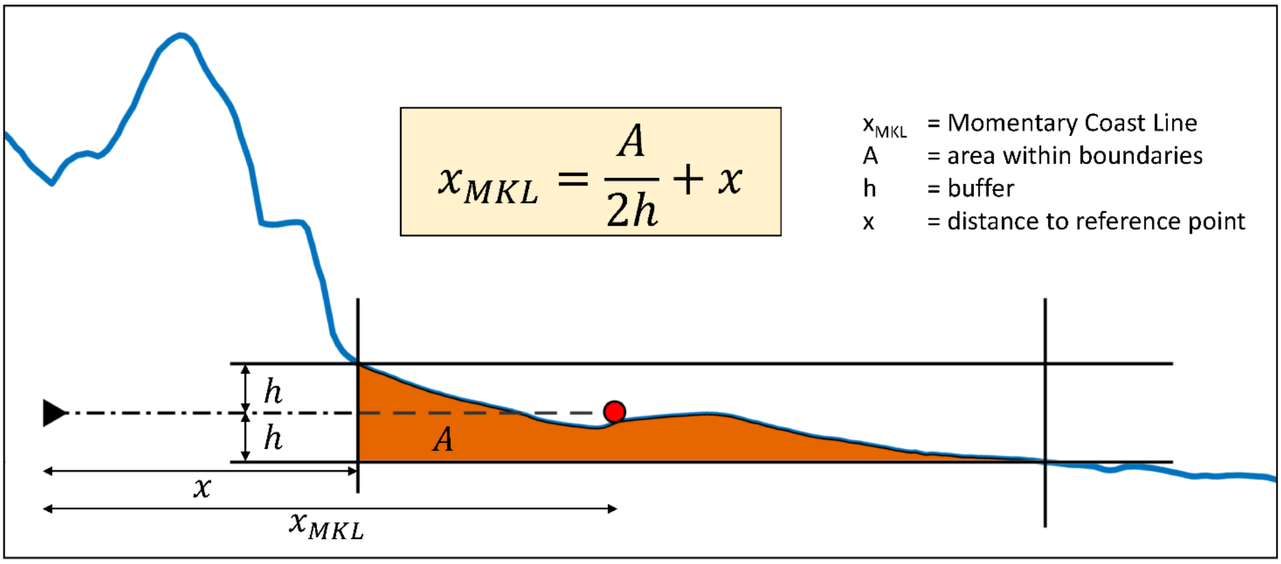

Figure 16: Example of the MKL-Model.

A buffer of at least +-0.5 m for each height level is proposed, but not fixed. For some levels other values can be more utile. However the MKL-Model approach can give good results in the beach and dune area, it is not recommended to use it for physical marks in the shoreface area (e. g. bar detecting). This is because a buffer can sometimes be greater than the actual bar, or a migrating bar is changing in height. Therefore the analysis of physical marks should only be done for the beach and dune area (above MLWL). If the MKL-Model cannot be used, it is possible that one measurement has more than one intersection with a height level. In that case it is important to point out which intersection point is used, or all intersection points are displayed in the diagram. All intersection points can of course be displayed additionally to the MKL-values.

Besides extracting physical marks of the transects, this analysis can also reveal section widths as beach or dune width. The boundaries of the defined width sections are also defined in the common coastal terms. When extracting a section width, the MKL-Model should also be used for extracting the distance of the lower and upper boundary.

This analysis of physical marks and section widths should be done for at least one representative transect in the nourishment area. This is done by HydroM or EXCEL.

4.2.3 Bar development

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

The characteristics which define a bar are found in Table 7. In order to generically identify the bars within a coastal profile the following parameters are defined:

- Shape coefficient: bar width over bar height.
- Depth over bar: difference between MSL and the bar top.
- Bar position: distance between MLWL and bar top position.

4.2.3.1 Cross shore bar identification

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

- Bars are found between 0 and -8 meter height relative to MSL
- Bar height ≥ 0.25 m
- Shape coefficient ≤ 400.

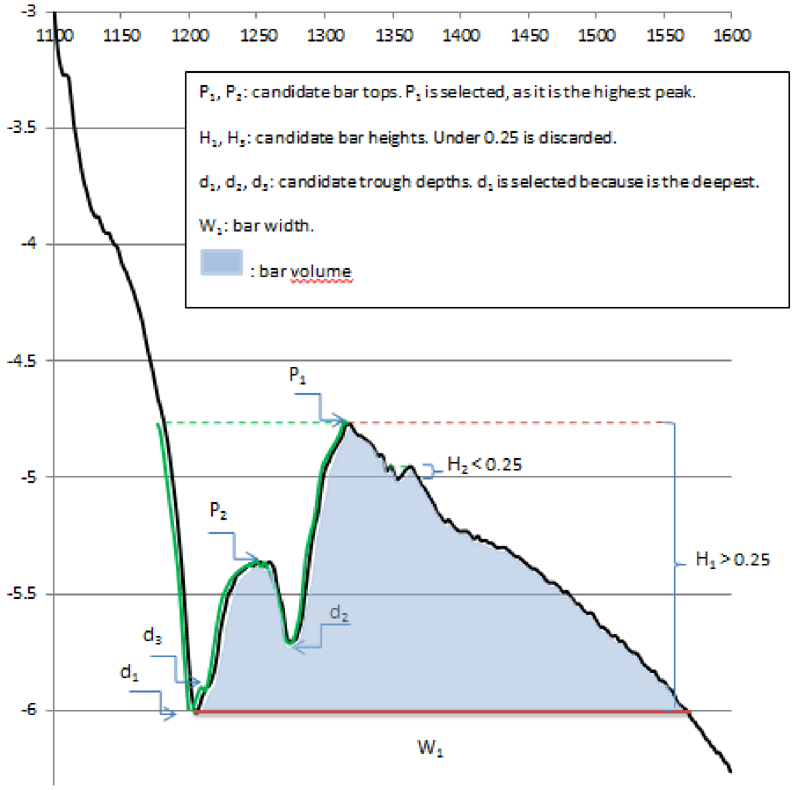

Figure 17: Definition of bar elements. The green line corresponds to the generalized case of through, while the red line shows the bar width.

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

4.2.3.2 Longshore bar identification

Bars are assumed to have an alongshore continuity e.g. another bar of equivalent characteristics must be found in at least one of the neighbouring transect. Alongshore continuity is assumed when:

- Distance between neighbouring bars ≤ 230 m
- Difference in depth over bar ≤ 1.2 m.

In the case of two possible bar connections in a neighbouring profile, the one which minimizes distance is selected.

After identifying the bars, both their individual morphological characteristics, as well as their number and migration schemes are evaluated. This is done by quantifying, the number of bars in the system and their migration speeds, bar volume, bar height, depth over bar, landward and seaward slopes and distances to MLWL. These calculations are performed in HydroM. In addition, the longshore variation of bars is evaluated by comparing the plan form evolution pre and post nourishment. The comparison can be carried out in GIS.

4.2.4 1D volume development: Vertical layers

Another method to analyse the development of a coastal area in time is to visualize trends of volumes in various vertical layers. The layers will show erosion or accretion of volume of a particular vertical layer. The trends in volume development can be used to assess the contribution of various nourishments (size, location) to coastal volume (and indirect coastal safety).

A way of presenting the volume development is by showing the volume of a particular layer over time, where the y-axis shows the volume and x-axis the time. Multiple colour dots are possible to combine multiple layers in one plot (depending on y-axis scale). To see effects of nourishments or dune reinforcements, the date of the nourishment should be displayed in the diagram.

In this method the boundaries for the vertical layers are fixed in the horizontal plane. The boundaries for the vertical layers should reflect the levels presented in Table 7. The calculation can be performed by the volume model of HydroM.

4.2.5 2D volume development: Volume boxes

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

For the coast parallel boundaries a selection of the physical marks levels and the top and bottom level of the nourishment is made based on expert judgement. Using all levels will result in too many and too small areas. For example, for NL beach nourishment placed up to NAP +4 m with a dune foot at NAP +3 m only the +4 m boundary can be chosen: taking both will result in a very small surface area which is too small for the available data resolution. For the landward and seaward boundaries data availability can be leading in the decision, rather than a specific vertical level. About 3 to 4 coast parallel areas will result in a reasonable amount of volume boxes. The boundaries are defined on the last measurement before start of the nourishment.

When raster data is available, in a GIS application depth contours can be created and used to construct a shapefile with the boundaries of the boxes. In HydroM the distance to the chosen vertical levels needs to be defined on the last transect before nourishment, which then can be used in the volume model (Seaward and Landward boundary).

The coast perpendicular boundaries will be based on spatial erosion-sedimentation patterns: transects with similar change will be combined. This will automatically result in boundaries at the beginning and end of the nourishment. In this direction therefore at least three areas will be identified: the nourishment and one on each side.

With raster data a difference map showing the nourishment (the first measurement after the nourishment minus last measurement before) can be used to define the boundaries. In HydromM analysis of the transects before and after the nourishment can be used.

In total about 9 to 15 areas is a reasonable number to use for analysis, although this depends on the size of the research area. Within each of the defined areas the sediment volume will be calculated relative to the last year before nourishment.

Using raster data, best practice is to create difference maps between each measurement and the reference measurement. For each of these difference maps, the volume is calculated by taking the sum of the data within an area multiplied by the surface of one raster cell (make sure to use the same units). In ArcGIS for example the 'Zonal Statistics as Table' function can be used.

In HydroM for each coast parallel area a volume model needs to be created. Each volume model needs to be run for all transects and all measurements. Then the calculated volumes (m^3/m) are subtracted from the volumes calculated in the last measurement before nourishment, resulting in relative volumes (m^3/m relative to reference year). Taking the average of the relative volumes for the transects within one coast perpendicular area and multiplying with the alongshore length results in the final volumes (m^3 relative to reference year).

5 Environmental conditions/characteristics

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

5.1 Waves

If the wave climate is measured or determined by wind-wave-correlation the energy flux along the coast can be calculated. The energy flux can be separated into the following components:

F_{tot}: Total,

F_n: Normal to the coast,

F_l: Parallel to the coast along the opposite direction.

Following equation yields everywhere: $F_n + F_l = F_{tot}$

The calculation of the energy flux consists of the steps: 1) pre-processing, 2) processing and 3) post-processing. These steps are explained underneath.

1. Pre-processing: A transect has to be selected. The wave data and tidal data at a nearby location must be available. If the wave data contains gaps, it can be filled by a wind-wave-correlation.
2. Processing: The transect data have to be interpolated into equidistant points and be completed from the -13 m depth to the lower dune foot. The energy flux into the surf zone can be calculated for e.g. every hour. The data are stored in a database, making later use for other purposes possible.
3. Post-processing: The cumulative sum of the energy flux is calculated for each hour and stored for each week. The energy impact between two measurements can therefore directly be derived. Also the annual distribution of the energy flux can be calculated. This procedure is sometimes not possible due to lack of data or transformation. Then, these parameters are calculated for a location that is best representative for the coastal lab. In this way the inter-annual changes in forcing can be assessed.

As can be shown in Figure 18 und Figure 19 there is an annual fluctuation in the wave impact. Especially in 2002/03 there was a very low energy flux along the west coast of the island of Sylt.

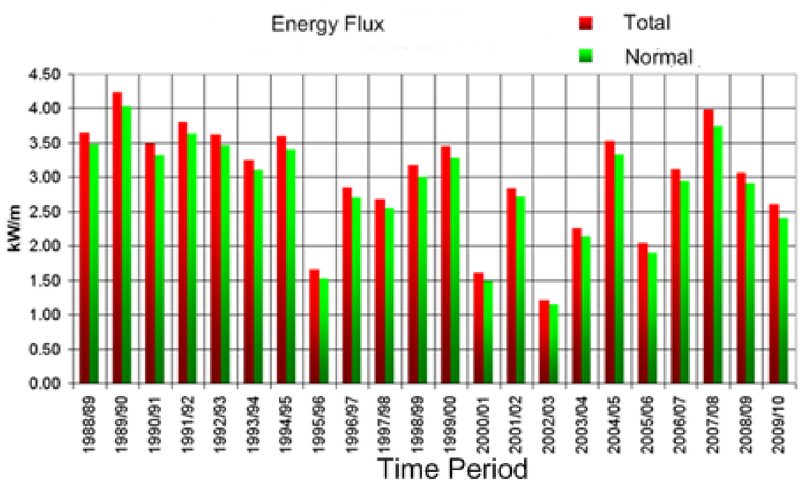

Figure 18: Part of the normal energy flux on the total energy flux for Sylt (annual averages between 1988-2010).

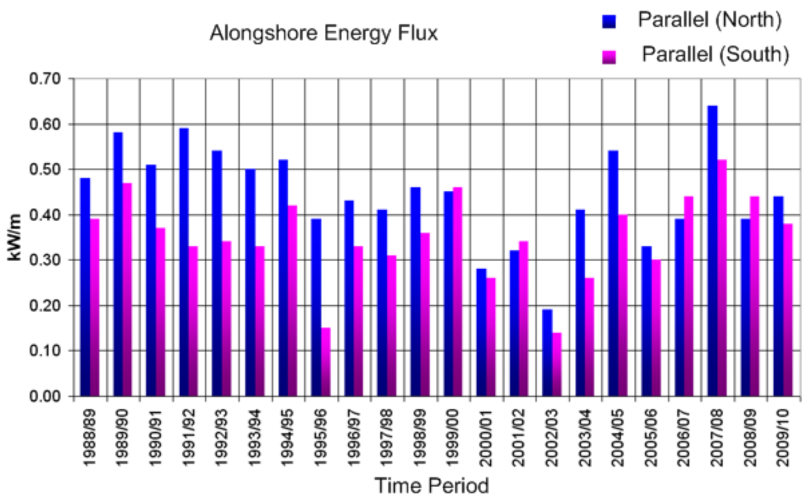

Figure 19: Coastal alongshore energy flux towards the south and north for Sylt (annual averages between 1988-2010).

The average energy flux between 2001 and 2010 is put into Table 8.

Table 8: Parameter settings for the load by energy flux for Sylt.

Parameter wave load	Unit	Average wave load at Rantum/Sylt (2001-2010)
Total energy flux	kW/m	2.73
Normal energy flux	kW/m	2.57
Parallel energy flux towards south	kW/m	0.39
Parallel energy flux towards north	kW/m	0.37

5.2 Tides

Tides are one of the most important agents shaping coastal landscapes. It is therefore important to understand the tidal characteristics for the coastal labs and their surrounding coastal area. The local tidal characteristics are shown in Table 9.

Table 9: Tidal parameters for Sylt at the tidal gauge harbour List from astronomical tidal analysis.

Astronomical tide	Water Level (NHN m)
HAT - Highest astronomical tide	1.17
LAT - Lowest astronomical tide	-1.33
MHWS - mean high water springs	1.00
MLWS - mean low water springs	-1.10
MHWN - mean high water neaps	0.80
MLWN - mean low water neaps	-0.90

5.3 Storm surges

During storm surges the coast may suffer severe erosion, especially if the shoreface has a lack of sediment. The wave energy penetrates in full amount to the dune foot and above in that case. The eroded material will settle in front of the beach, mainly below the high water level. To get parameters from storm events it is needed to assess the time of exceedance (per set time frame, year/decade/century) for set water levels.

Table 10: Parameter settings for the storm surge load (Harbour List/Sylt).

Parameter storm surge load	Water level (NHN m)	Time exceeding water level (hours/year)	Frequency *) (n/year)	Frequency *(Gauge Westerland)*	Water level (NHN m) *(Gauge Westerland)*
	>= 2.0	8.55	6.3	1/25	3.62
	>= 2.4	1.93	1.7	1/50	3.79
	>= 2.8	0.58	0.5	1/100	3.94
	>= 3.2	0.02	0.1	1/1000	4.33

***) Due to the stochastic nature of storm events and possible changes over time in storminess the frequency of storms is time dependent. The time period was taken as 2001-2010.**

The water levels used for this analysis depend on the tidal range and the distribution of the storm events.

5.4 Wind

The wind is the overall dominating driving force for waves and storm surges. Since the wind action varies in direction and magnitude it is useful to extract a scalar parameter out of the wind. From empirical research the wind directions that lead to higher water levels and stronger waves are generally well known. For Sylt the main wind direction that leads to chronical coastal erosion is from northwest to southwest. On the other hand it can be stated that wind from easterly directions stabilizes the west coast. Also the wind speed is important; only wind speeds above a certain threshold generate enough friction with the water to generate wind waves and water set-up. Also the wind driven sand transport (Aeolian Transport) depends on the wind speed and the existing grain sizes and the soil moisture, among others.

For each hour the wind characteristics are calculated at a location representative for a coastal lab. From these characteristics the accumulated sum of the wind load for different directions is calculated. The calculated results can be used to assess whether a correlation between the (response) the coastal state indicators and wind parameters can be found.

5.5 Grain size

The grain sizes of the nourishments on Sylt are homogeneous as far as the borrow area is the same since 1984 (Table 11).

Table 11: Mean grain size percentile in the borrow area Sylt (Pleistocene).

Percentile	Grainsize (mm)
D_{10}	0.200
D_{50}	0.430
D_{90}	0.600

6 Results

6.1 Qualitative Morphological development

6.1.1 Shoreface incl. Breaker bars

The development of the shoreface is determined by the fluctuation of the bar-trough-system as shown in Figure 20 to Figure 22 for the three different nourished areas. The large undulation can be seen very clearly.

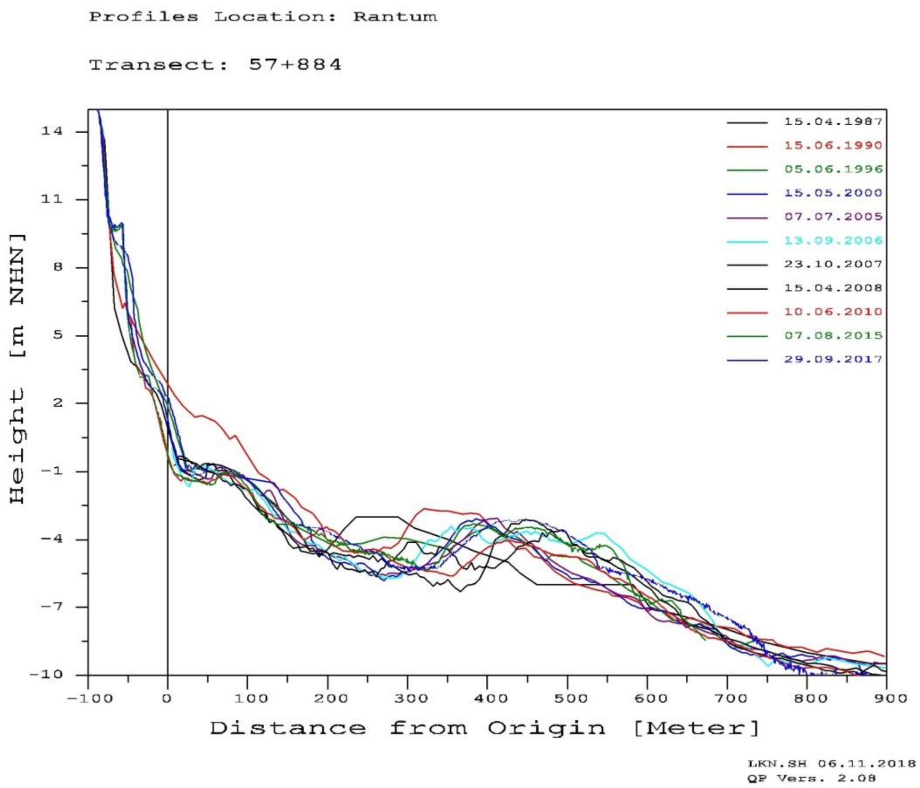

Figure 20: Temporal variations of the bar-trough-system at transect 57+884 between 1987-2017. The shoreface nourishment at Rantum was made in 2006.

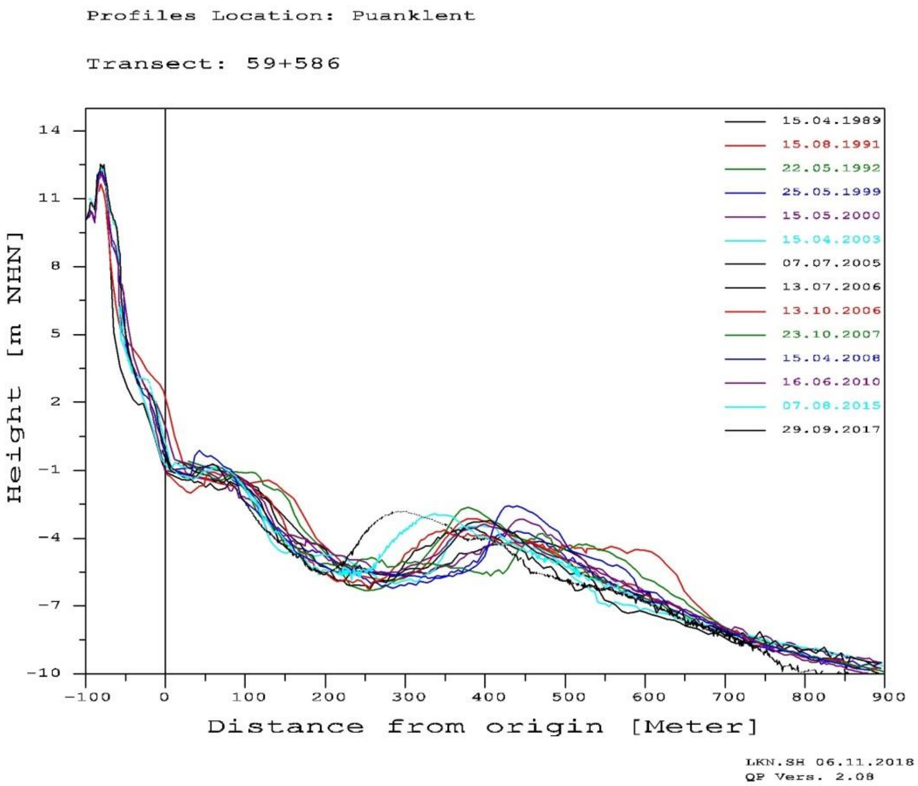

Figure 21: Temporal variations of the bar-trough-system at transect 59+586 between 1989-2017. The shoreface nourishment at Puanklent was made in 2006.

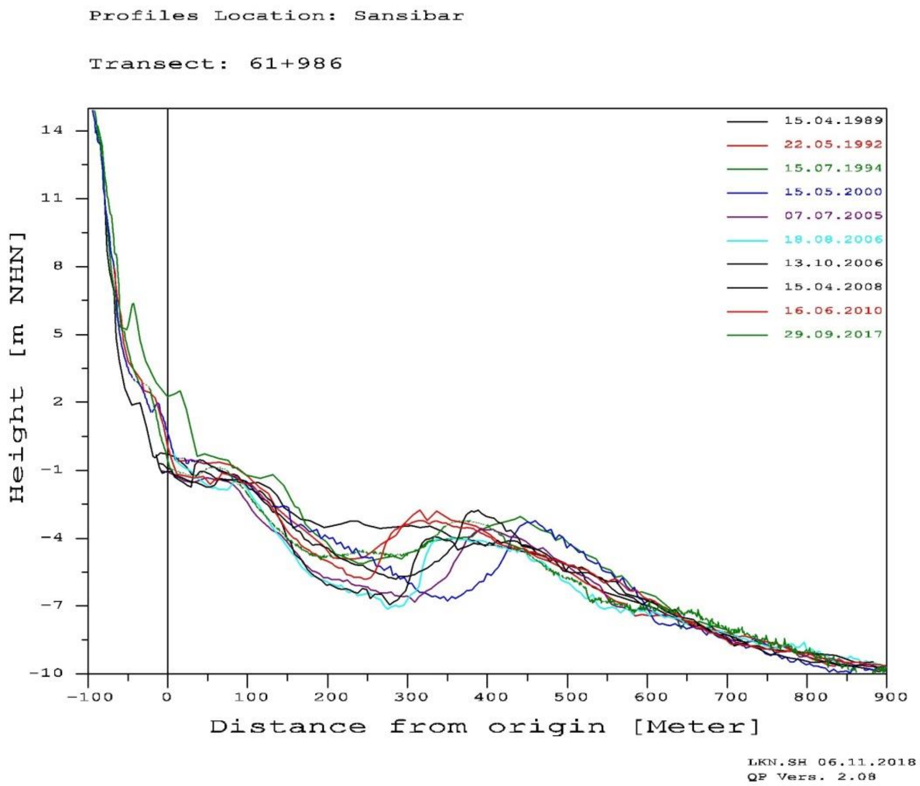

Figure 22: Temporal variations of the bar-trough-system at transect 61+986 between 1987-2017. The shoreface nourishment at Sansibar was made in 2006.

6.1.2 Beach

The beach is represented by the dune toe level, high water level, mean sea level and low water level. The lateral variation of the coastal state indicators (CSI) shows the influence of the shoreface nourishments, see Figure 23. The stabilization of the beach can be seen especially in relation to the intermediate areas.

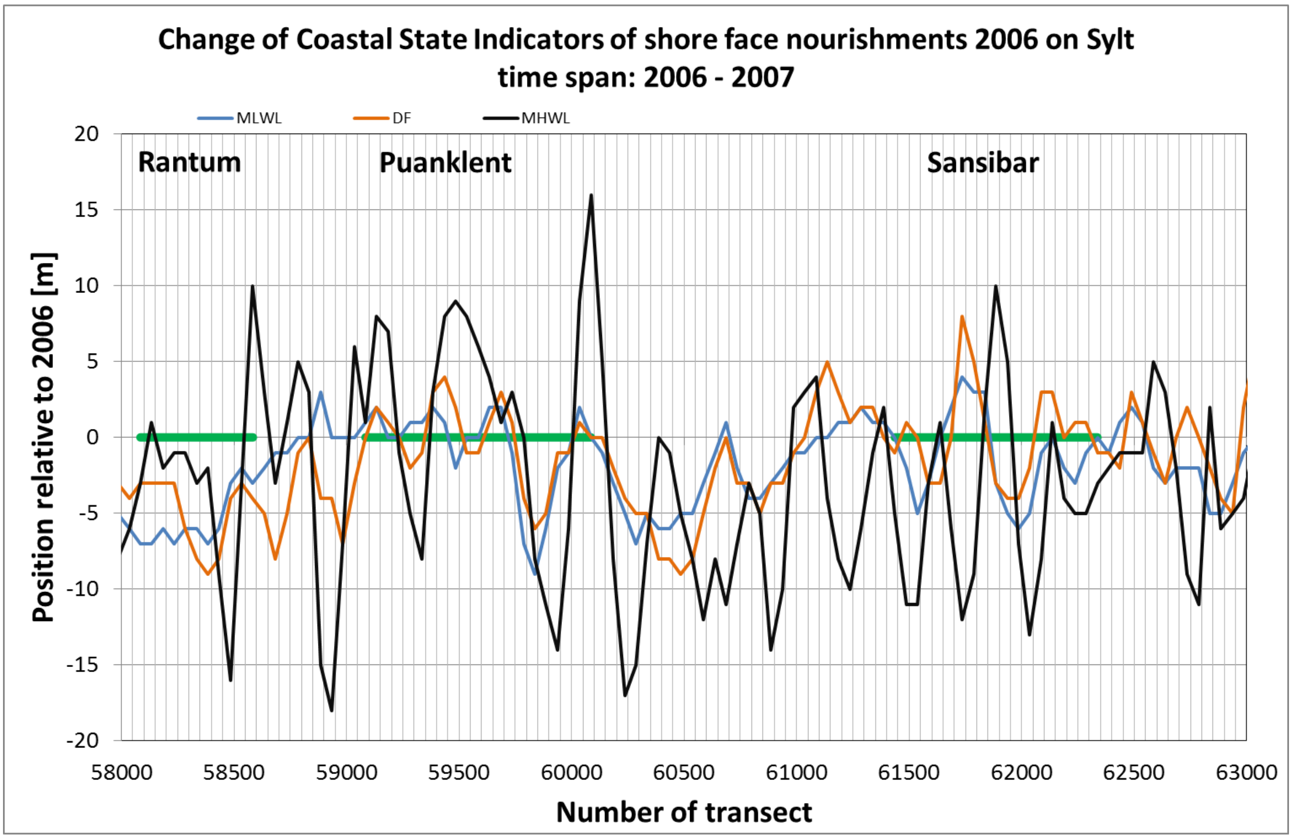

Figure 23: Change of coast state indicators for the beach (before and after shoreface nourishments).

6.1.3 Dunes/Cliff

The dunes/cliffs are represented by the coastal state indicators upper dune level (UDL), mid dune level (MDL) and dune toe (DF). The variations of these CSIs are shown in Figure 24. Although the dune toe and the mid dune level retreated the upper dune level shows an increase that is probably due to the Aeolian Transport.

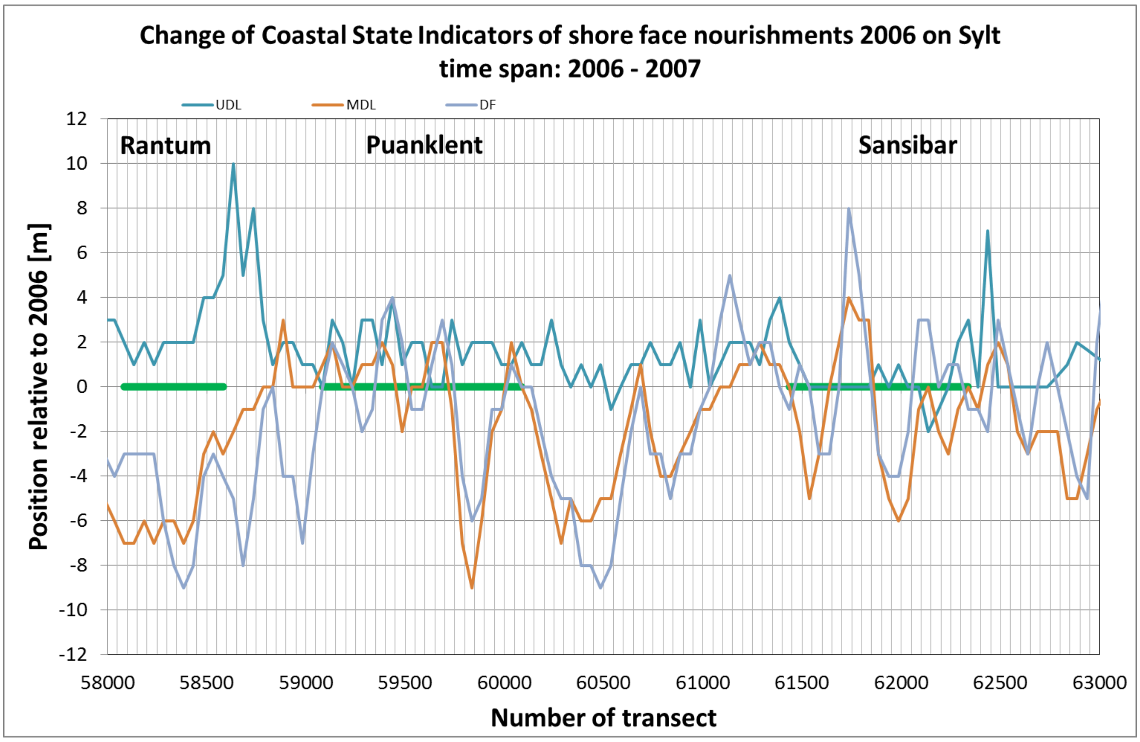

Figure 24: Change of coast state indicators for the dunes (before and after shoreface nourishments).

6.1.4 Overall

As can be seen in the previous figures there is some dynamics in the changes of the coastal state indicators during one year of observation an also in longshore direction. Especially, the shoreface nourishments have had some influence in the morphodynamics.

6.2 Quantitative Morphological development

6.2.1 Physical marks

The physical marks are defined in Table 12 for the lab of Sylt in Schleswig-Holstein.

Table 12: Physical marks taken for the lab Sylt.

Coastal state indicator	Physical Mark
Upper dune level	NHN+10 m
Mid dune level	NHN+5 m
Dune toe level	NHN+3.75 m
Mean high water level (MHWL)	NHN+1 m
Mean low water level (MLWL)	NHN-1 m

6.2.2 Bar development

In order to describe the development of the bar it is distinguished between the depth of the bar top (Figure 25) and the position from the origin (Figure 26).

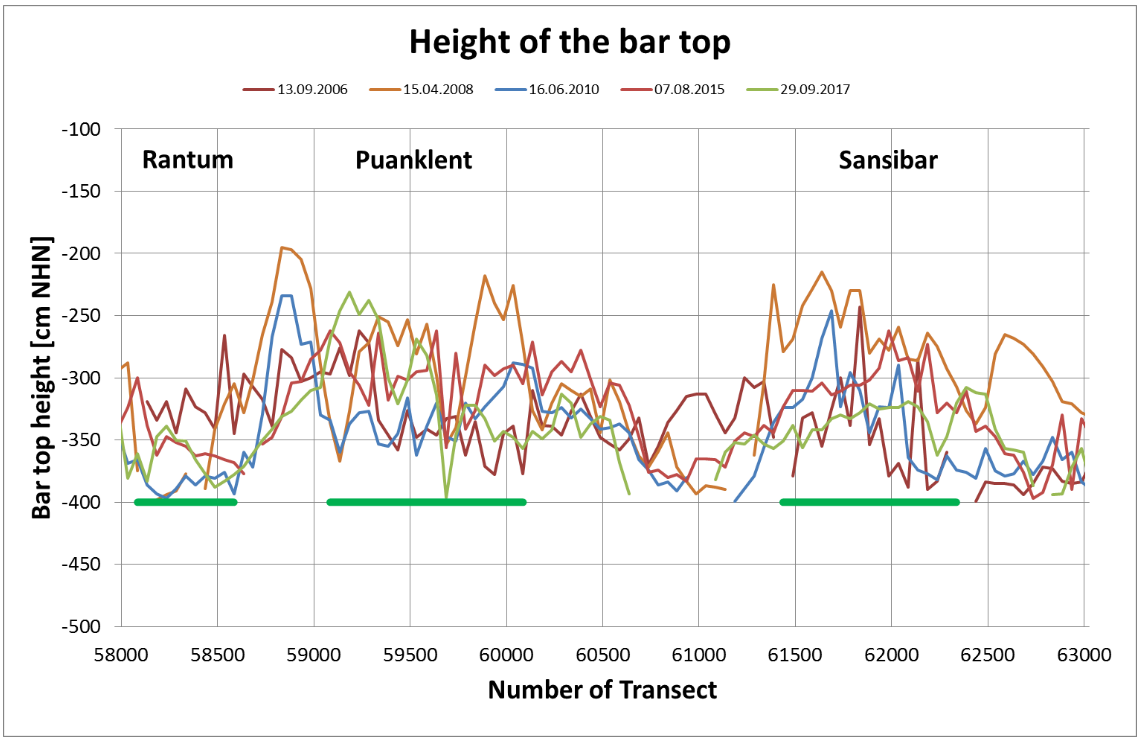

Figure 25: Heights of the bar tops 2006-2017.

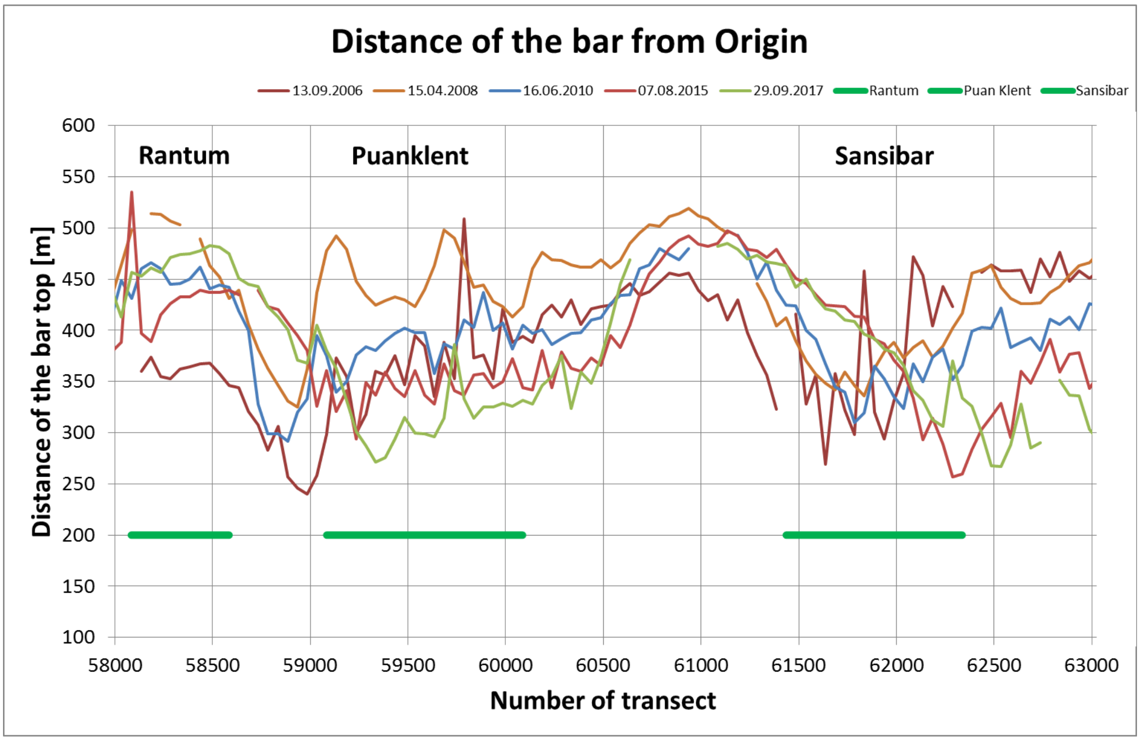

Figure 26: Distances of the bar top from the origin.

6.2.3 Volumes 1D

The mean volume between the mid dune level and the mean water level (NHN+5m/MWL) is shown as a path-time diagram in Figure 27 for the shoreface nourishment Rantum 2006. The difference between both graphs is due to the reduction of the amount of nourishments. In this way it can be seen that the shoreface nourishment in 2006 stabilized the beach for a while.

The chronological sequence of the sediment volumes graph in the height layer between NHN +5 m and NHN 0 m shows a natural decline of the beach level where the volume curve has been reduced by the nourished sediment amounts. In comparison to that, a second graph of the non-reduced volumes shows how nourishments in 1989, 2001, 2004 and 2016 led to interim reversals of this decline while the shoreface nourishments in 2006 and 2015 stabilized the beach within a longer time period without significant ups and downs.

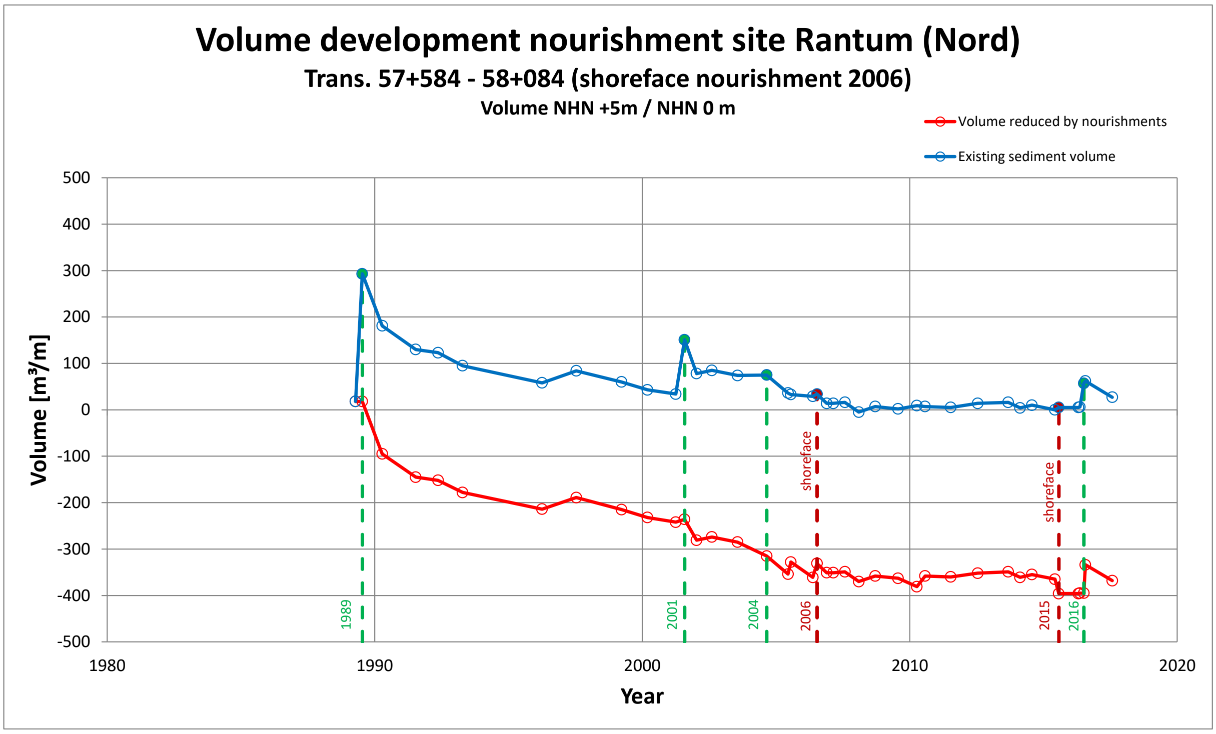

Figure 27: Path-time diagram of volume between mid-dune level and mean water level for the shoreface nourishment Rantum 2006.

The according path-time diagram for the shoreface nourishment Puanklent 2006 is shown in Figure 28. The chronological sequence of the sediment volumes graph in the height layer between NHN +5 m and NHN 0 m shows a natural decline of the beach level where the volume curve has been reduced by the nourished sediment amounts. In comparison to that, a second graph of the non-reduced volumes shows how nourishments in 1989 and 2003 led to interim reversals of this decline while the shoreface nourishment in 2006 stabilized the beach within a longer time period without significant ups and downs.

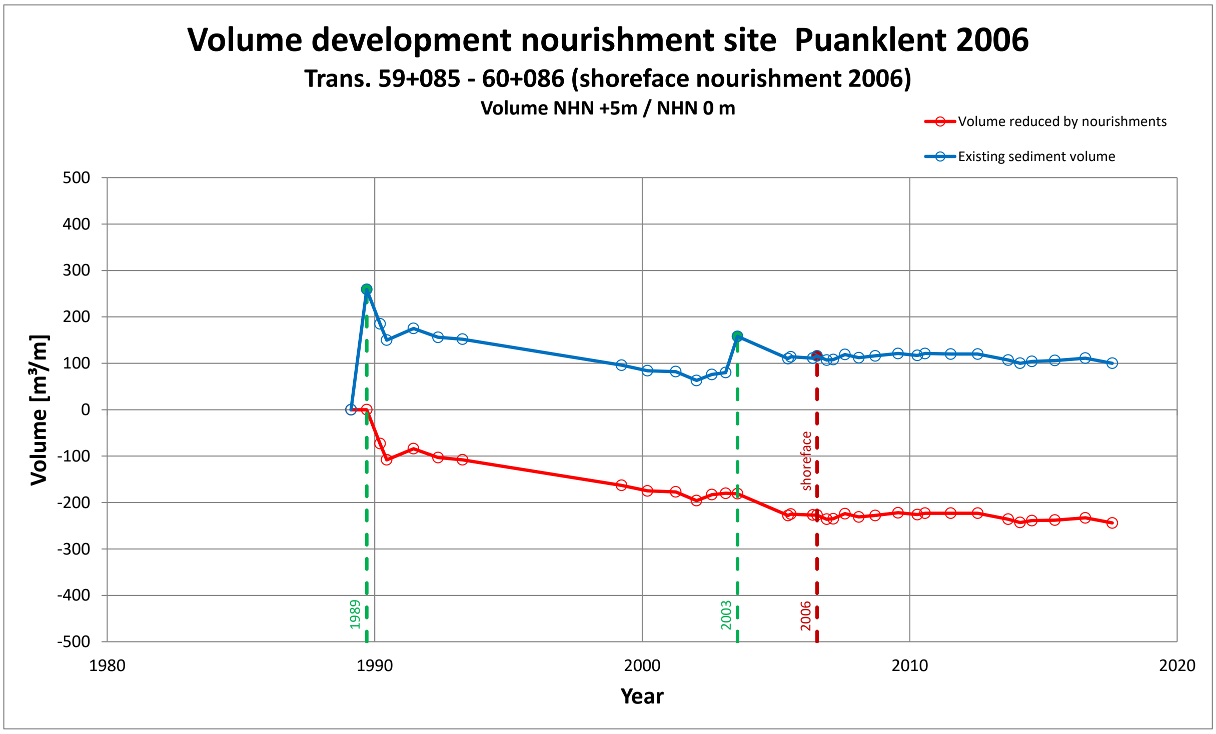

Figure 28: Path-time diagram of volume between mid-dune level and mean water level for the shoreface nourishment Puanklent 2006.

The path-time diagram for the shoreface nourishment Sansibar 2006 is shown in Figure 29. The chronological sequence of the sediment volumes graph in the height layer between NHN +5 m and NHN 0 m shows an autonomous decline of the beach level for both graphs. The graphs also show how beach nourishments in 1989, 1993 and 2003 led to interim reversals of this decline while the shoreface nourishment in 2006 not even stabilized the beach within a longer time period but also led to a growth of the sand volume.

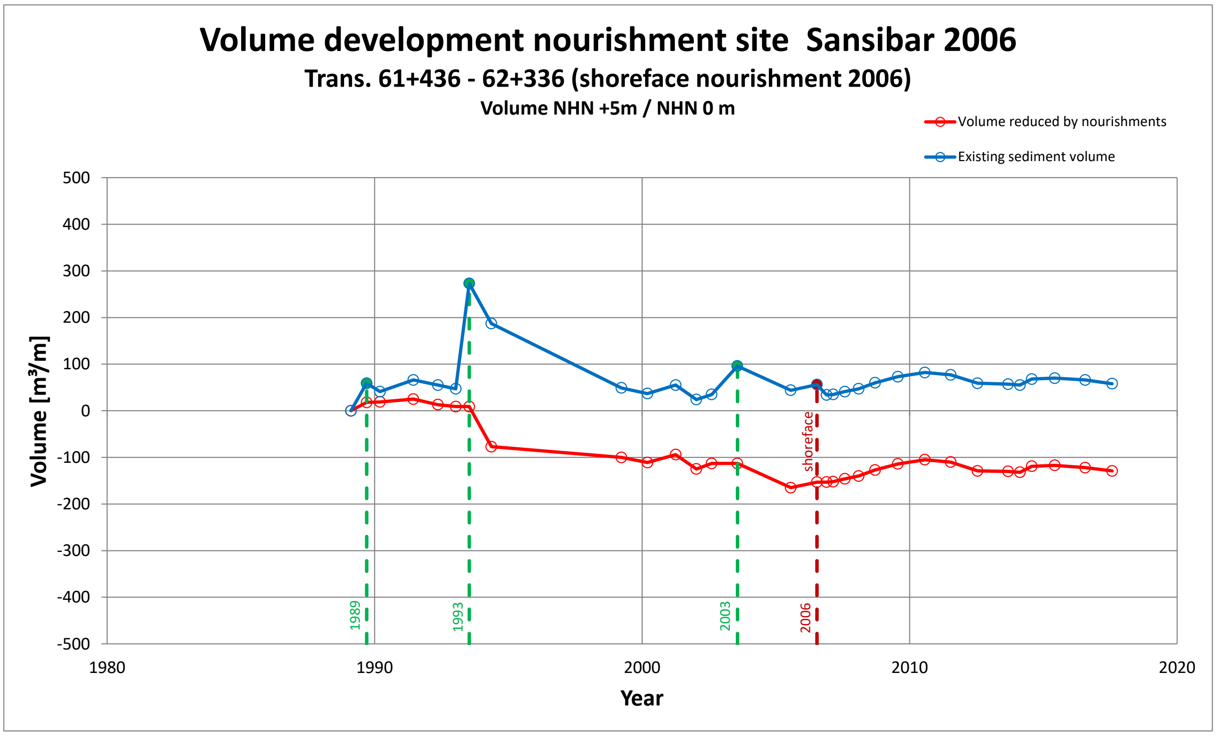

Figure 29: Path-time diagram of volume between mid-dune level and mean water level for the shoreface nourishment Sansibar 2006.

The **northern adjacent area** extends from the nourishment site of Rantum up to 900 meters to the north. Between the pre-survey and the first resurvey a sedimentation of sands of approx. 50 000 m³ could be observed in the layer between NHN +5 m and NHN 0 m. But from the pre-survey up to the year 2010, this area incurred a loss of 100.000 m³ of sand. Neither the beach nor the shoreface had benefitted from the sand nourishment. According to the longshore transport in this area which is directed mainly to the south, the placed sediments have not been relocated to the northern adjacent area. The time series is shown in Figure 30.

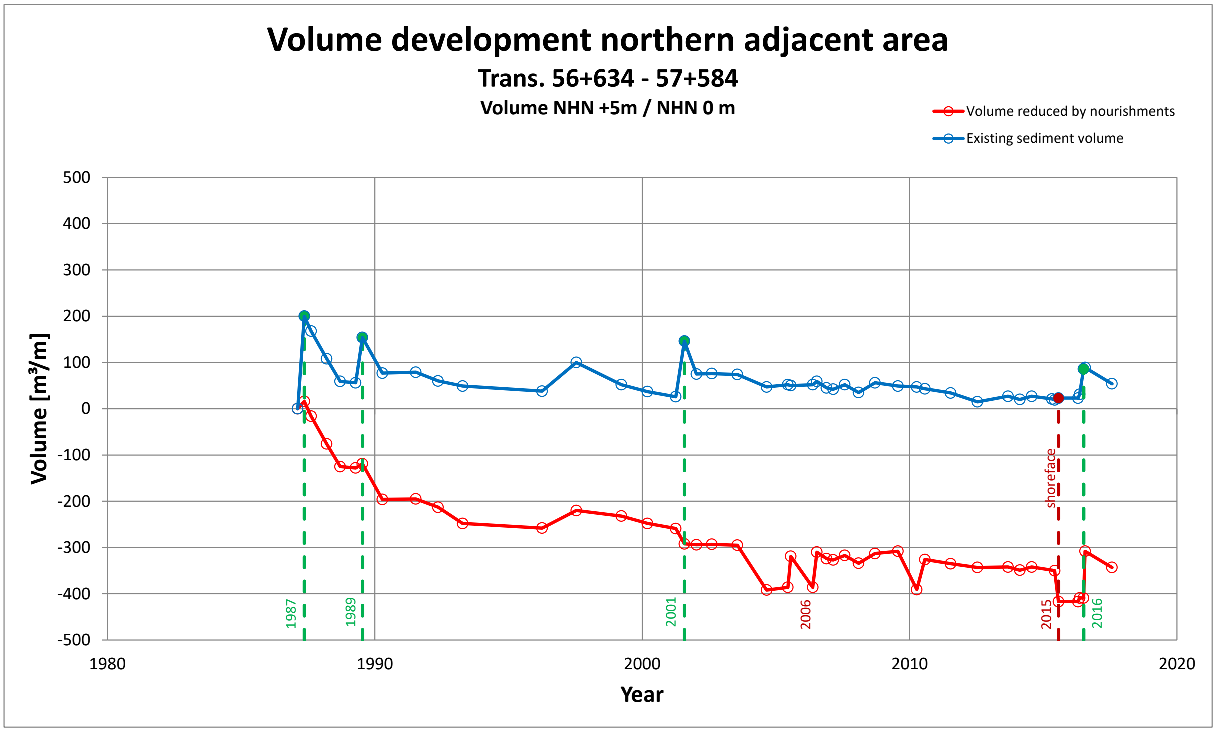

Figure 30: Path-time diagram NHN+5 m / NHN+0 m (northern adjacent area).

The volume trend over time in the layer between NHN +5 m and NHN 0 m shows the natural overall tendency of volume decline that is well known as the natural behaviour for the west coast of Sylt. Interruptions of short duration can be seen in the years of 1987, 1989, 2001 and 2016, when beach nourishments have been applied. The curve of volumes reduced by nourishments shows the tendency of coastal decline even more clearly. Nourishments at this site and also the applied shoreface nourishment in the adjacent south could reduce this natural decline to nearly zero.

In the **northern intermediate area** (between Rantum and Puanklent) sedimentation of approx. 40.000 m^3 has been detected between the pre-survey and the first resurvey for the hypsometric layer of NHN +5 m and NHN 0 m (Figure 31). In 2010 the accretion in this area reached approx. 75.000 m^3. In particular the shoreface below NHN -4 m benefitted from the nourishments in the adjacent areas.

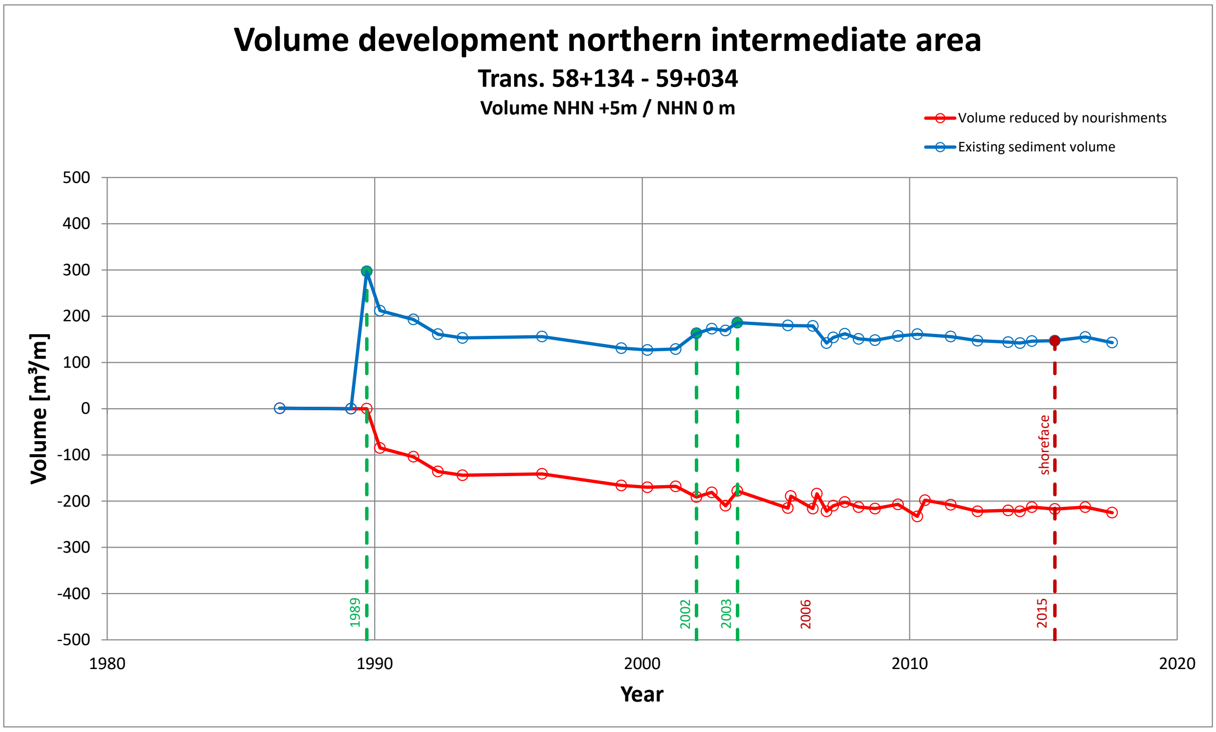

Figure 31: Path-time diagram NHN+5 m / NHN+0 m (northern intermediate area).

Also in the northern intermediate area, the volume trend over time in the layer between NHN +5 m and NHN 0 m shows the natural overall tendency of volume decline. This is shown particularly by the curve of the volume reduced by nourishments. The curve for the existing sediments shows the impact of the beach nourishments from 1989, 2002 and 2003. From 2006 on especially the existing sediment volume curve gets smooth and nearly horizontal and therefore shows the beach stabilizing effect of the shoreface nourishments in the areas to the north and south.

In the **southern intermediate area** (between Puanklent and Sansibar) a sedimentation of approx. 30 000 m^3 has been detected between the pre-survey and the first resurvey for the hypsometric layer of NHN +5 m and NHN 0 m (Figure 32). A survey in 2010 revealed in this area a loss in volume of 180 000 m^3 in comparison to the pre-survey in 2006, most significant in the layer of NHN -4 m.

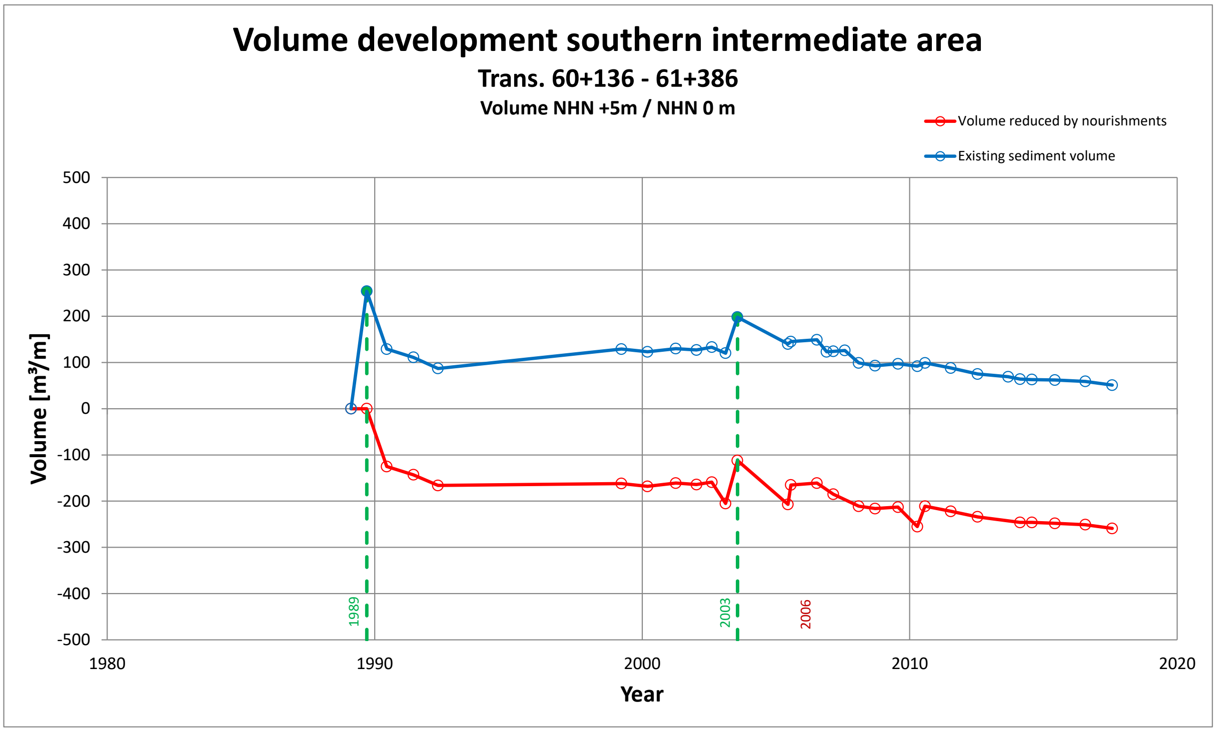

Figure 32: Path-time diagram NHN+5 m / NHN+0 m (southern intermediate area).

The time curve of the volume trend in the layer between NHN +5 m and NHN 0 m shows times of stability alternating with times of coastal retreat. Beach nourishments took place in 1989 and 2003. Since 2006 there is a decline of the beach volume curve that can partially be explained with erosions in the shoreface area.

For the **southern adjacent area** the volume balance between the pre-survey and the first resurvey could not be determined because of an insufficient data situation.

The volume curve for the layer between NHN +5 m and NHN 0 m shows a slight natural decline of the beach volume for the majority of time after the nourishment in 1993 (Figure 33). Though, this beach nourishment provided enough sediment to keep the volume balance in the positive range until 2013, when the next nourishment took place. No enhancement for the beach in this area, resulting from the shoreface nourishment in 2006, can be observed.

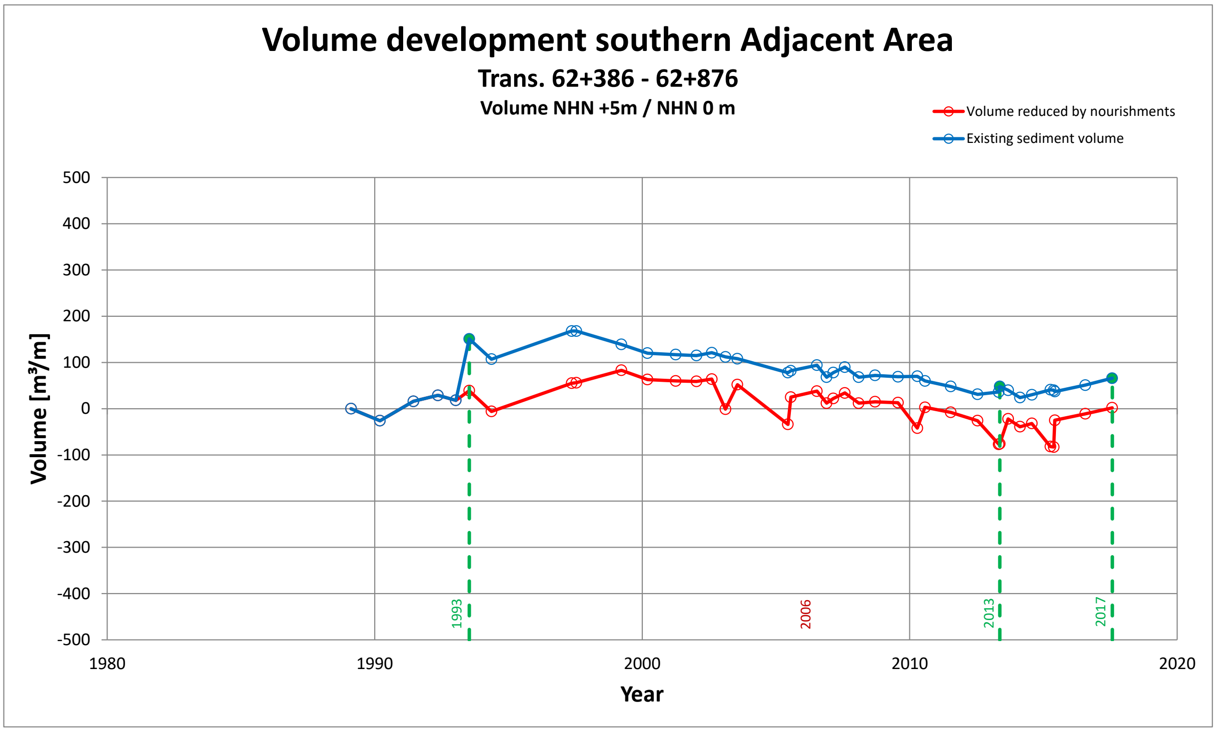

Figure 33: Path-time diagram NHN+5 m / NHN+0 m (southern adjacent area).

6.2.4 Volumes 2D

The 2D volume boxes have been created according to the method described in chapter 4.2.7.

The coast parallel boundaries of the volume boxes have been defined partially according to physical marks, nourishment properties and availability of data. Form land to sea the boundaries have been created as follows:

1. The landward boundary has been established according to the location of the NHN 5m contour (mid dune level – CSI). Because in the majority of cases this would lead to extremely narrow boxes, except for the southern adjacent and Sansibar areas, the boxes are designed to be at least 50m in width.
2. The next boundary is the MWL, also a CSI, and set to the NHN -0.05m contour. It has been calculated out of transect data 2006 with the use of the MKL model.
3. The next two boundaries are based on the landward and seaward extent of the nourishments. The intersection of design of the nourishment with the transects of the presurvey have slightly been modified according to the intersections in transects for the presurvey and the first resurvey to generate a smoothened but reasonable polygon around the deposited sediments.
4. The seaward boundary has been set according to data availability and has been fixed approx. 1300m seaward the beach.

The perpendicular boundaries divide the overall area in the three nourishment areas, the two adjacent areas and the two intermediate areas. In total every of the 7 sites consists of 4 boxes resulting in 28 volume boxes in total. These boxes surround:

- the beaches, referred as “beach”
- the bar system area between beach and the beginning of the nourishment area with the trough as the main morphologic feature in it, referred as “trough”
- the seaward slope of the bar with or without nourishments, referred as “bar” and
- the shore behind the bar system, referred as “shoreface”.

Figure 34 shows the volume boxes as well as the morphologic situation at the time of the presurvey. In general, the landward boundaries of the bar-boxes follow the top of the bar, but because the bar-trough-system does not follow a straight line and particularly the trough itself is crossed three times by shallow areas (Sansibar, northern intermediate and northern adjacent), the box boundaries and the bar areas do not perfectly match. Though, the nourished sediment bodies, derived from the difference plot between resurvey – presurvey, fit very well into the appropriate boxes.

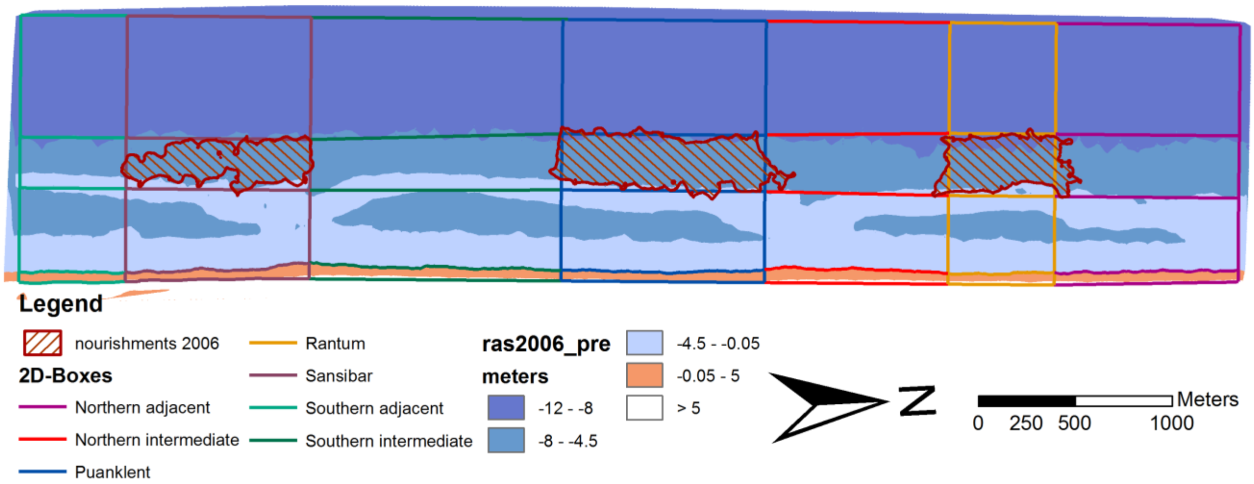

Figure 34: Volume boxes on categorized presurvey raster 2006, overlayed with nourishment bodies.

It has been tried to optimise the investigation of longshore sediment transport processes by splitting up the intermediate and adjacent area boxes perpendicular to the coast into smaller sub boxes. This did not give useful results due to two reasons. At first there is an intense interaction between the bar boxes and the trough boxes, so that sediments continuously switch between bar boxes and trough boxes and only the resulting direction of relocation is longshore. At second the time deltas between the measurements are too large to tag the tracks of the sediments in detail.

For the statistics, difference plots of raster data with $1m^2$ cellsizes are used and are processed further on with the “Zonal Statistics as Table” tool from ArcGis. The difference plots are all calculated against the presurvey.

In the year 2015 a second shoreface nourishment became necessary and in 2016 a beach nourishment followed. Figure 35 shows the locations where the shoreface nourishments took place. It affects mainly Rantum and the northern adjacent area but also further to the north. The beach nourishment was done at the same section. These measures are clearly visible in the data and the effects should not be mixed up with the effects of the original measure from 2006. For this reason this time period has been excluded for some investigations where the effects are not clearly assignable.

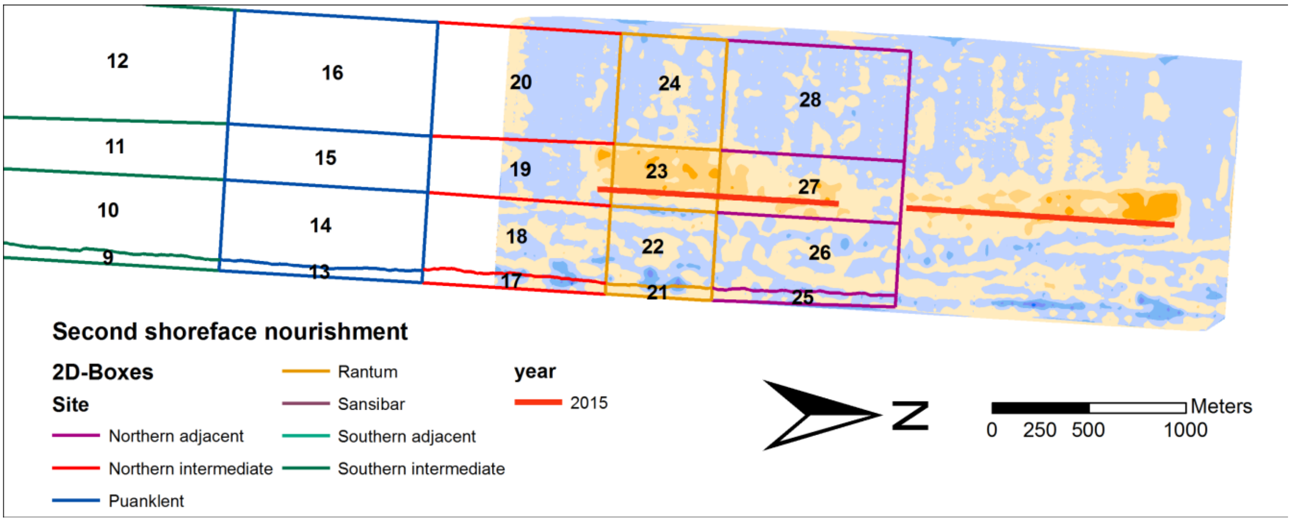

Figure 35: Additional shoreface nourishment 2015 (beach nourishment 2016 took place at the same section).

The zonal statistics over difference rasters are combined into time series like plots. Because the boxes differ in size, the mean differences of cell values are stated to be more suitable to compare the trends of the boxes contrary to the absolute volumes, depending to the particular question to be answered. Plots are referred to as time series for convenience but show measurement campaigns in chronological order instead.

As a major overview over the sediment balance in the whole area longshore “superboxes” have been created by combining all beach boxes into one, all trough boxes into one and so on. To investigate the tendency of the whole area balance all boxes have been merged into one “whole area box”. This is displayed in Figure 36 for the mean raster cell height differences as well as for the volumes. Because the surveys for the nourishments of 2015 and 2016 only have been done for the affected sites, no sums and means for the whole area could be calculated. This is the reason why these measures are not visible in the graphs.

The **black dotted line** for the **whole area** shows that there is no trend in the volume summed up for the whole investigation area. Beginning with the presurvey 2006, the nourishment measure from 2006 adds volume to the whole area box before the graph declines until April 2008 where the sediment volume ends up nearly at the level it had before the nourishments. After 2008, the volume does not change any more. Keeping in mind that there are only 2 valid datasets for the whole area box after April 2008, a first result is that the whole area only lost the sediments that have been nourished. With a view on the other graphs however, one can say, the nourishment has settled an enduring change in the terrain that mainly results in a volume gain of the bar boxes. Unfortunately, the data gap between June 2010 and September 2017 obscures the course of the overall bar volume graph. Especially the shoreface nourishment from 2015 is not visible here although the data point for September 2017 should include a slight effect coming from the partially supplied sediments. The overall trough box does not seem to change in volume. This box has to be viewed together with the overall bar box because both of them form the track of transport for the longshore sediment transport. It has to be shown later on, that the bar-trough-system moves partially seawards and landwards and especially at the southern end it performs a meandering movement. So, there is a strong sediment exchange between bar and trough boxes and parts of the bar sometimes lay more in the trough boxes and vice versa. This is not an effective relocation of the bar-trough-system as a whole, because it can be seen in the trend of the overall bar box that the volume continues to be high. With the trend of the trough boxes and the bar boxes presented here it should be obvious that also a combined overall-bar-trough box should show the same pattern of the bar box but on a lower level. This means that the bar-trough system does not move in total. It also is an indicator for longshore transport.

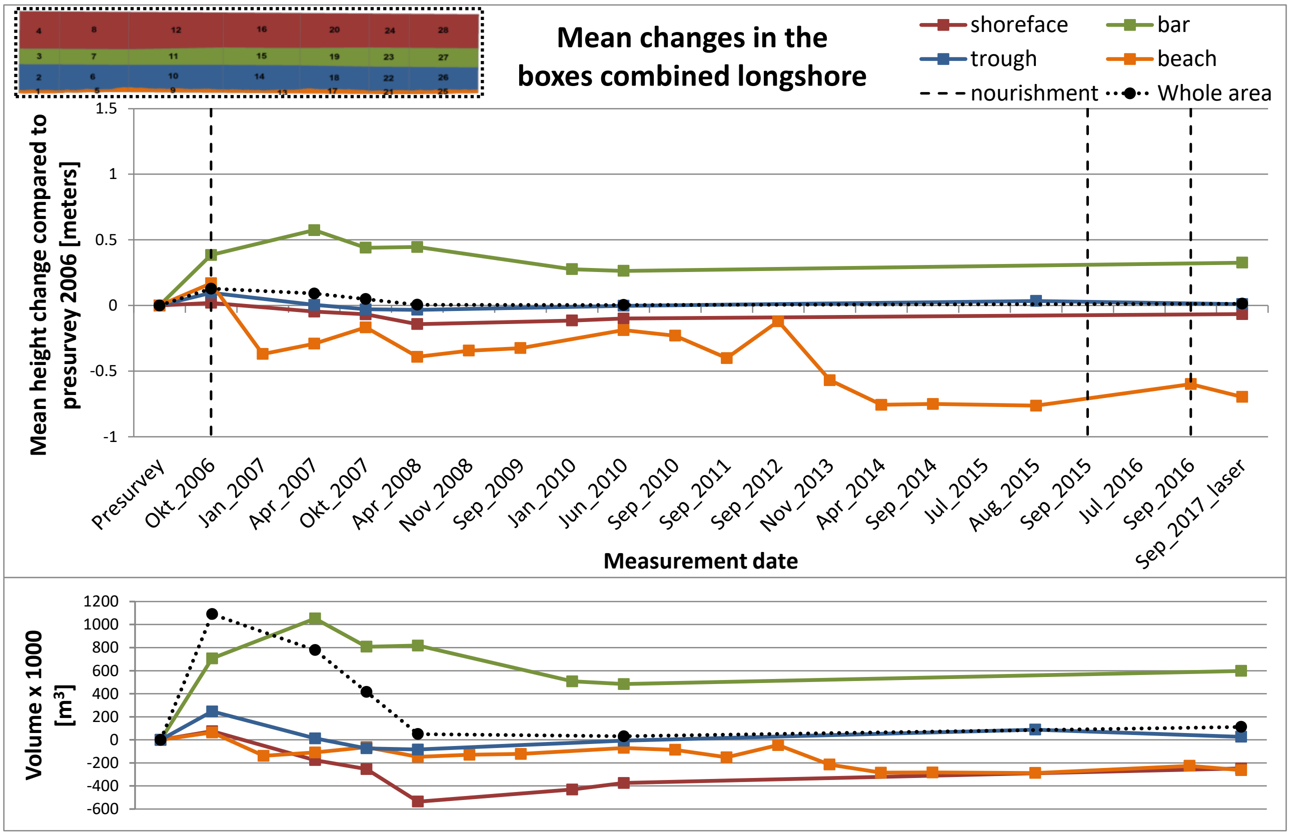

Figure 36: Mean changes in longshore boxes and in the whole system

Keeping in mind that the whole area box does not lose sediments over time and the bar boxes sustainably gain sediments there must be a counterpart with erosion to fulfil the equation. With a look at the volumes at the bottom of the above figure a combination of the overall beach box and overall shoreface box seem to supply the required sediments for that. While the majority of the sediment losses come from the overall shoreface box, it is important to keep in mind what areas the beach and the shoreface boxes cover. So, the mean height change for the overall shoreface box is low enough to state the volumes there as generally stable. The overall beach box however significantly loses volume over time, but not continuously. One may observe two steps in the trend of the overall beach. The first occurs in January 2007 while the second step occurs in 2013. Because between these steps the overall beach looks stable, special incidents like storm surges should be responsible for a relocation of sediments into the foreshore while calm periods should reverse these storm inducted erosions. A look at energy fluxes, e.g. wind velocities, wind directions and wave dynamics, may provide more information about this topic but is not covered in this chapter.

As already announced, a stable volume in the overall bar box is an indicator for longshore transport along the bar, because due to the hydrodynamics going on in the area there must occur sediment transport, but the transported sediments do not seem to outgo the overall bar box. In the special case of this investigation, we also have a very stable volume balance for the overall trough. Because these superboxes lay adjacent to each other and the sum of both also has no significant trend it is valid to say that they form a system with an inner, yet unspecified sediment dynamic, and this system performs a partial and equally balanced sediment exchange with the adjacent boxes in the long term. In the first two years after nourishment however, the bar attracted sediments from its adjacent boxes.

Because the bar and trough boxes together appear to hold the key to the sediment dynamic of the whole system the next step is to investigate the single bar boxes and compare them with each other, then compare them with the trough boxes. Because in Figure 37 the bar boxes are shown individually, some of the graphs have more data points because there are more regional surveys available.

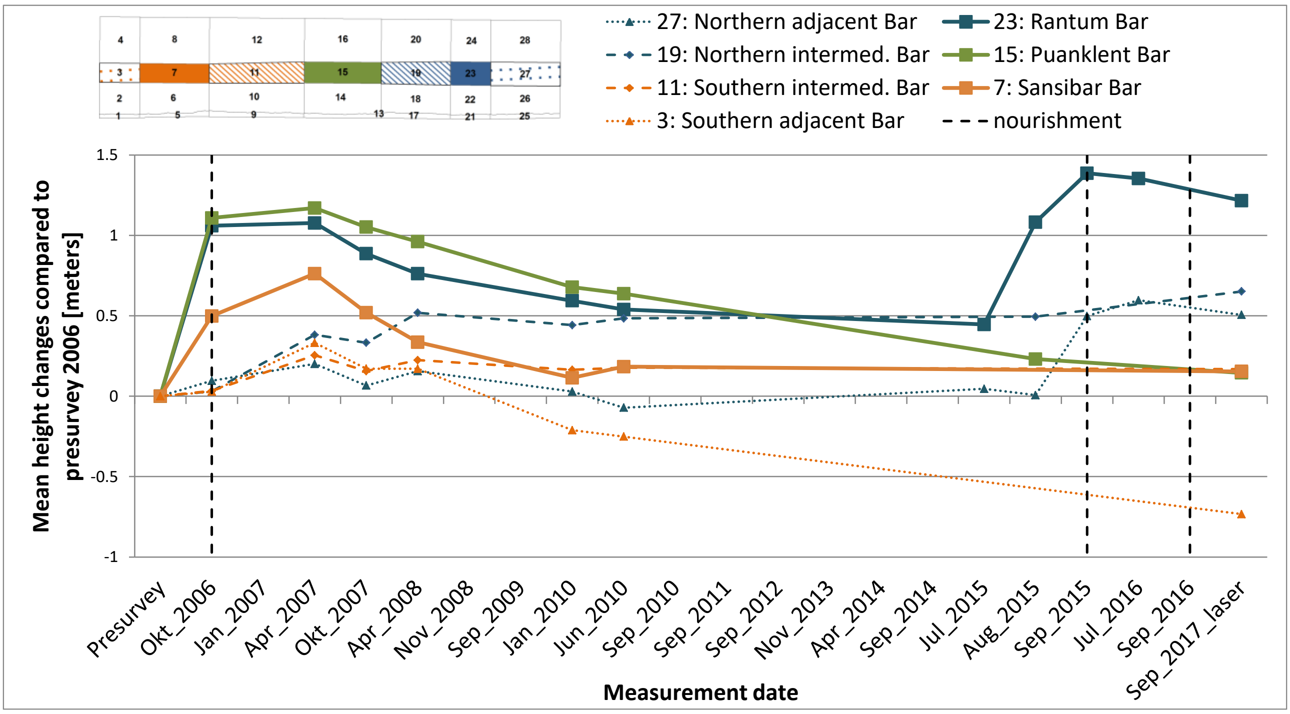

Figure 37: Comparison of bar boxes

To understand the details it is useful to remember some data for the nourishments:

Nourishment 2006:			Nourishment 2015:		
Sansibar	10.09.06 to 02.10.06	134883 m^3			
Puanklent	25.07.06 to 28.09.06	391346 m^3	Rantum	16.07.15 to 16.09.15	406194 m^3
Rantum	15.07.06 to 13.08.06	225472 m^3	north of area	16.07.15 to 16.09.15	355528 m^3

The nourishment areas (bolt lines with square markers in Figure 37) show the increase of volume according to the nourished amounts of sediments. After one year the graphs decline. After 11 years the volume balance is close to zero except for Rantum, where the nourishment 2015 took place. A tendency to evenly spread the sediments along the bar is not undisturbed because of the nourishment, but still visible.

From 2006 to 2008 all adjacent (dotted lines in Figure 37) and intermediate (dashed lines in Figure 37) bar boxes gain sediments from the nourishment areas and after that it gets diverse. With lateral sediment transport in mind one expects the **northern intermediate bar box** to get the most increase in volume because it is located between the two nourishment sites where more sediments have been dumped. The graph for this box therefor shows a behavior as expected. Additionally, after the nourishment of 2015, this bar box shows a second period of volume increase. So, the process of volume gain from the adjacent nourishment boxes was repeated. The volume increase after the nourishment 2015 appears to be slightly. At first hand there is only one adjacent nourishment site this time, and at second hand, there may be a slight overestimation of the volume before the measure because there is no data point for this box before the nourishment started. The first data point after the long data gap is August 2015, and that is directly in the middle of the nourishment measure.

The **southern intermediate bar box** behaves like the northern intermediate bar box but on a lower level. Again, this is as expected, because the southern adjacent nourishment box (Sansibar) got the lowest amount nourished. From June 2010 on, the Sansibar bar box and the southern intermediate bar box are equal in volume gain and this surplus of sediments stays there for the whole study time. This means that the morphologic structures in these boxes do not perform noticeable shifts between 2010 and 2017.

Both **adjacent bar boxes** show a slight positive response to the nourishment in 2006, while the northern adjacent bar is stable and the southern adjacent bar looks not. While lateral sediment transport shortly supports the southern adjacent bar box and its volume gain even overtops the volume gain of the southern intermediate bar box for the data point for April 2007, the volume loss in the southern adjacent bar box is the most drastic. The most obvious explanation to this behavior should be found in a movement of the bar-trough-system as a whole, and in this particular case a movement towards the coast. This however, cannot be determined without a look at the trough boxes and their interactions with the bar boxes.

Figure 38 is about the southern adjacent area and the already mentioned drastic volume loss in the southern adjacent bar box. From 2010 onwards the graphs for the trough and the bar diverge as if they are mirror-inverted. So, it seems obvious, that there is a shift of sediments from the bar box to the trough box. This figure shows direct volumes instead of height differences, and also the volumes in m^3 shifted from the bar box to the trough box match.

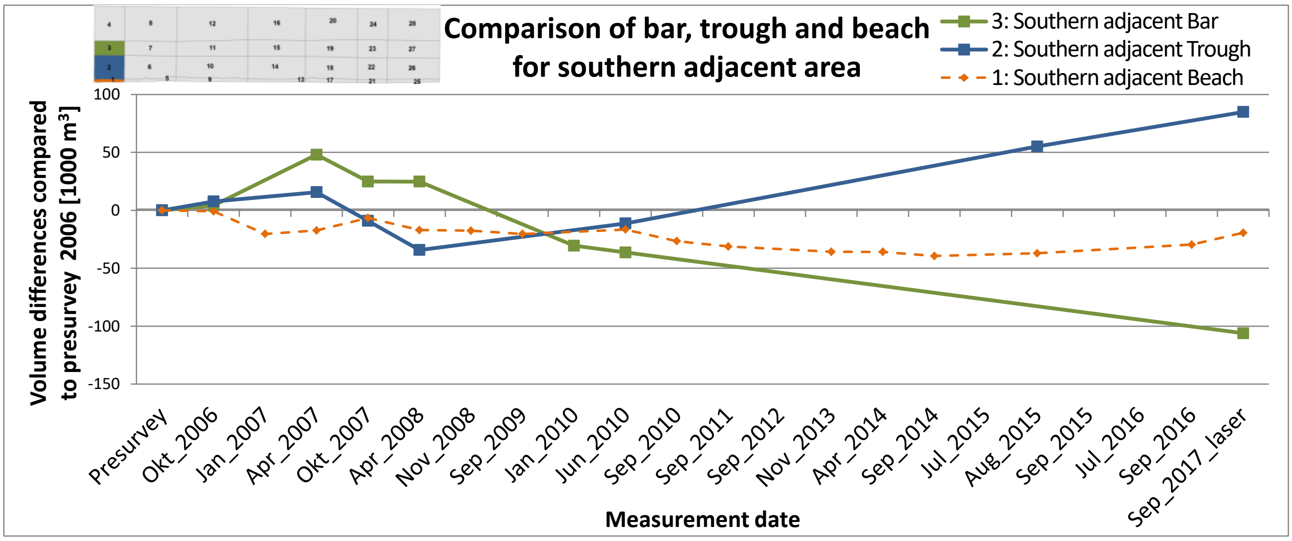

Figure 38: Trends of bar, trough and beach boxes for southern adjacent aera.

This symmetry indicates the shift of a whole structure instead of just a relocation of some sediments and in this case it is a shift of the bar itself in the direction to the beach that can also be observed in the raster data and has already been referred to as meandering of the bar-trough system earlier in this document. The trend of the southern adjacent beach box is also displayed in the figure to show that even though the bar migrates towards the beach the sand does not seem to reach the beach box before 2015. Therefore, an undisturbed and narrowed trough should be expected in the southern adjacent area for most of the time.

Going one site to the north, the Sansibar graphs (Figure 39) look quite different and more vital. After the nourishment the bar box attracts some additional sediments, partially from the trough box. But then, the bar migrates towards the beach, reaching and filling up the trough box. The two measurement dates from April 2007 and April 2008 are outstanding. The first is the lowest measurement value for the trough and the highest value for the bar. Then, in April 2008, the bar loses roundabout 100 000 m^3 sediments and the trough gains the same amount. At this timestamp, the trough volume gain overtops the volume gain of the bar until 2015. Then the system changes again. Because the trough box loses volume but the bar does not, it is not a cross shore sediment shift but rather a longshore instead. In the raster data it is visible as a longshore sediment drift to the southern adjacent bar which is then located in the southern adjacent trough box (forming a part of the sediment enhancement for the trough box in Figure 38).

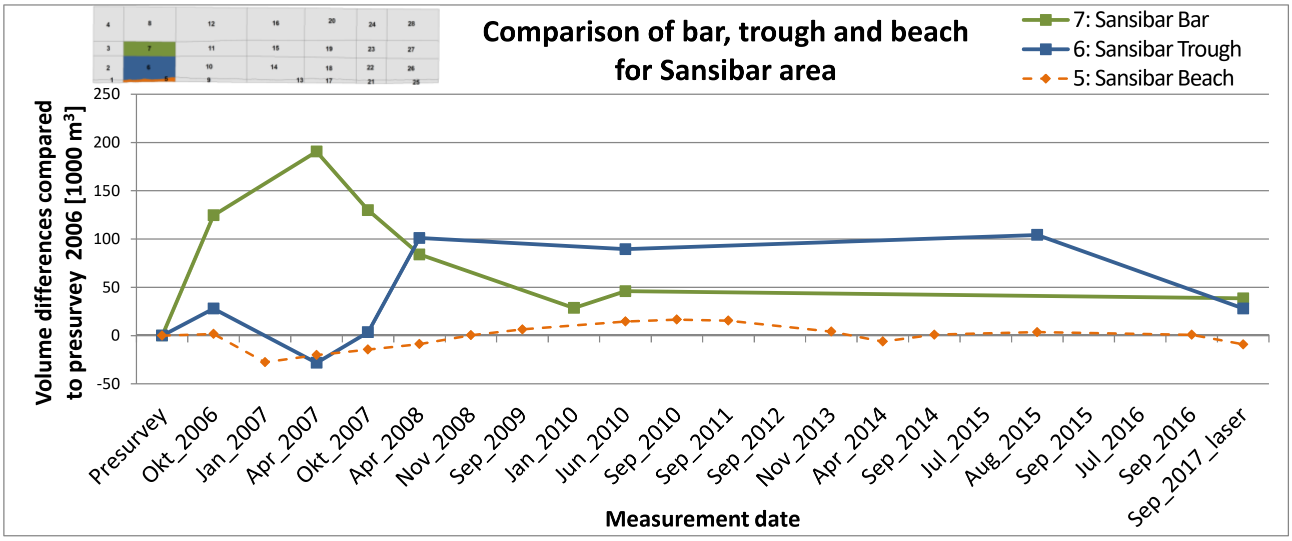

Figure 39: Trends of bar, trough and beach boxes for Sansibar.

A look at the beach box graph shows that there is a minimal sediment impact from the trough to the beach, especially in the time of 2009 to 2011 (0.9m mean height gain from January 2007 to September 2010). So, in the Sansibar site there is a sediment transport line (a shallow area in the trough, visible in the raster) from the bar-trough system to the beach.

The pattern for the southern intermediate area (Figure 40) shows a decline of volume in the trough and a volume gain for the bar. The latter is quite half the size than the first, so there is a net volume loss at this site even if the volume loss of the beach is not taken into account. That means that a pure relocation of the bar-trough system seawards which actually took place, cannot explain the whole of the volume balance. If the southern intermediate site pattern is compared with the figure from Sansibar, presented above, it is obvious, that sediments from the southern intermediate trough box migrated into the Sansibar trough box. This began from April 2007 to April 2008. The deepening of the southern intermediate trough seems to have terminated the sediment supply for the southern intermediate beach. That demonstrates that sediment losses in the trough involve sediment losses at the beaches if there are no additional factors active (compared to the northern adjacent site, mentioned later in this text).

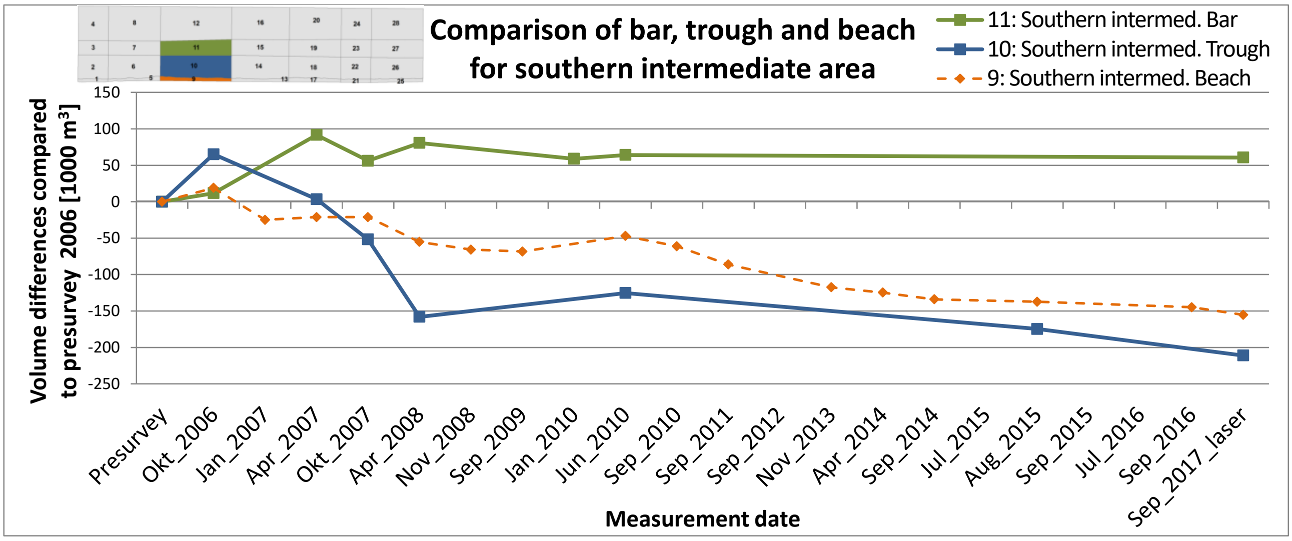

Figure 40: Trends of bar, trough and beach boxes for southern intermediate area.

At Puanklent (Figure 41) nearly 400 000m^3 of sediments have been nourished 2006. This amount can be found in the combination of bar and trough volume gain for the resurvey of October 2006. It resulted in a seaward shift of the bar top and a deepening of the trough (deepening is visible in the rasters since April 2007). After April 2007 the bar volume decreases but the increase of the trough volume starts not earlier than one year later. So, the initial relocation of sediments after the steepening of the bar-trough slope must have been lateral between bar boxes. In April 2008 the movement of the bar in direction to the beach (and its former location) starts. The beach box volume balance of Puanklent is stable. The small but visible volume gain of the beach box in Puanklent took place between November 2008 to November 2013 and resulted in a bit more than 0.3m mean height increase. The time period is the same as for Sansibar.

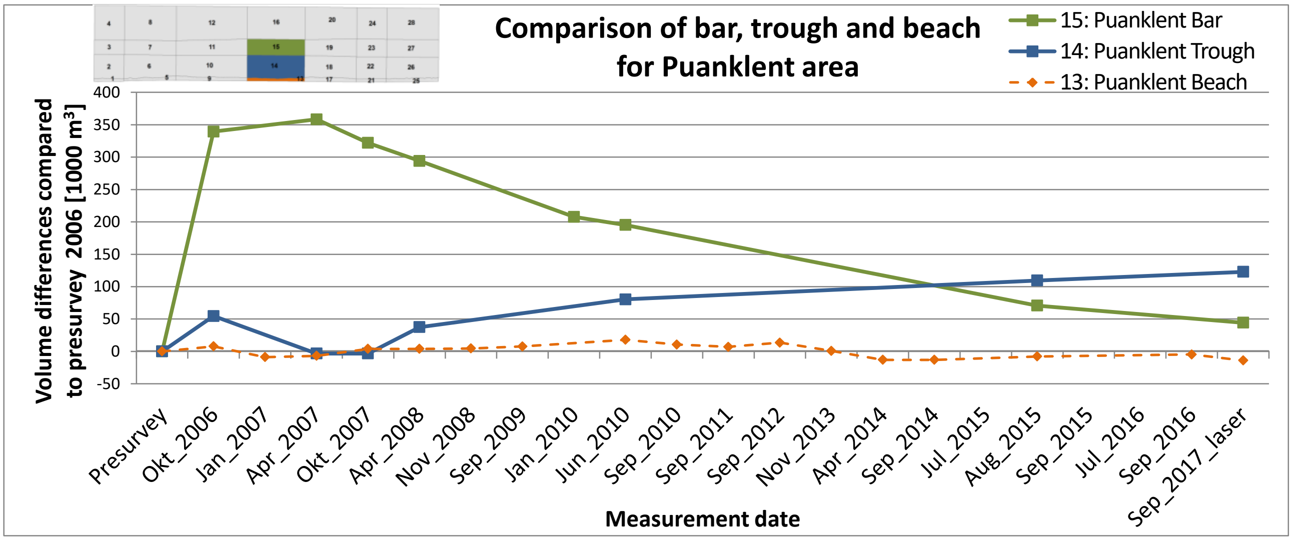

Figure 41: Trends of bar, trough and beach boxes for Puanklent area.

While the bar box of the northern intermediate area (Figure 42) gained the largest sediment increase for all non-nourished sites, the trough box suffered a slight erosion that becomes evident with the data point for August 2015 with a mean cell height loss of 0.3m in comparison of a mean height loss of 0.05m for the data point

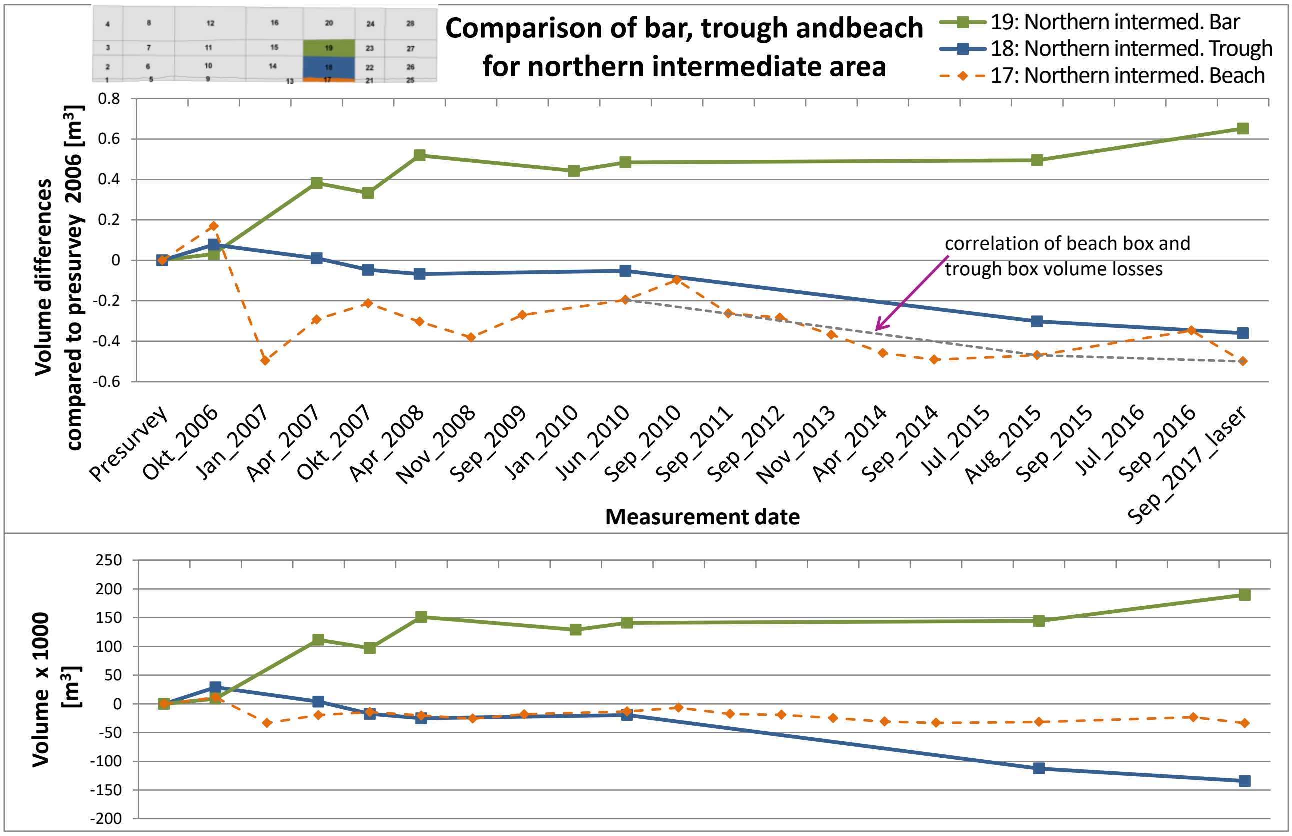

Figure 42: Comparison of bar, trough and beach for northern intermediate area.

from June 2010, which is not yet evident. In the above figure the mean cell height differences and the total volumes are displayed together because the small beach box in comparison to the relative big trough box leads to an underestimation of the beach erosion, which is not much in volume dimensions but more evident if expressed in height loss since presurvey 2006. Again, a volume loss in the trough box is combined with a volume loss in the beach box. The extremely low beach box volume data point for January 2007 is related to storm surges (see Figure 18 and Figure 19 for energy fluxes). After this data point the beach recovers until September 2010 before it erodes again. This second erosion period is perfectly correlated to the volume loss of the trough box if only the common data points are taken into account. This is demonstrated by sketching the parallelity between the relevant beach data points and the trough data points with a grey dashed line. The last data point for the northern intermediate area reflects the shoreface nourishment from 2015 at the Rantum site and demonstrates again that the nourished sediments are spread longshore to the adjacent bar boxes.

Also the Rantum site (Figure 43) bar box shows a continuous decline after the nourishment inclination in 2006. While the trough box also lost sediment volume between 2007 and 2010, the increase of the volume after 2010 is as unspectacular as the loss before. So, in general, the trough volume balance looks balanced, but at least the erosion at the beach indicates that the part of the sediment relocation that is not aeolian, takes place in the trough box. There are also sediments coming from further north because the nourishment from 2015 took place in Rantum and northwards.

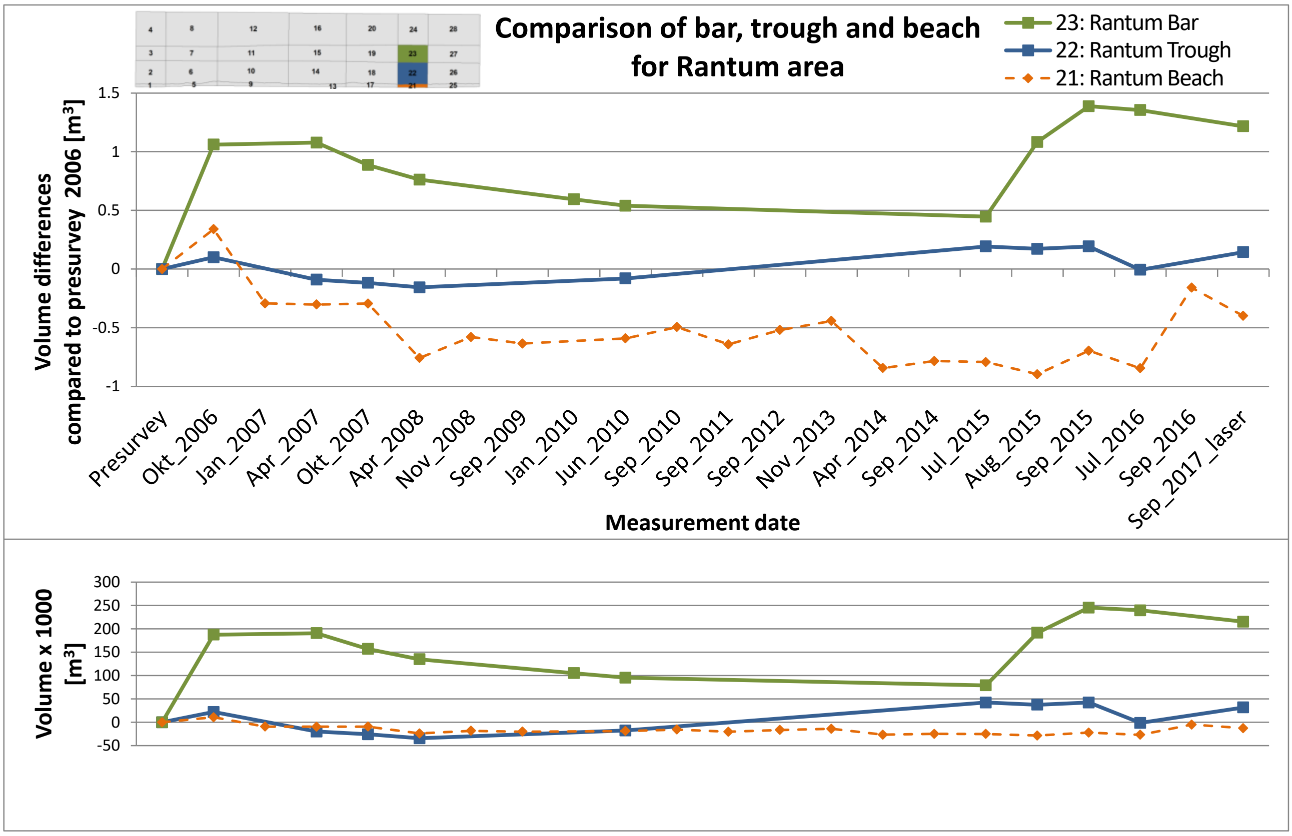

Figure 43: Comparison of bar, trough and beach for Rantum area.

At the northern adjacent area (Figure 45) there are stable conditions in the bar- and trough box. Until September 2010, the beach was also generally stable. From 2011 on, the beach erosion was slightly increased and the volumes eroded at the northern adjacent beach are in the same scale as the gains of the Rantum trough after the data gap. In the figure for the northern adjacent area, 0.85m mean cell height means 50 000m^3. The mean cell heights have been chosen contrary to the absolute volumes for this graph because the small size of the beach box inhibits the differences between before and after September 2010 to be clearly visible.

The increase in volume for the northern adjacent trough box in July 2015 cannot be explained by nourishments, because it occurs too early. Unfortunately, due to the data gap we do not know how the trend is before. Because the data presented here is based on the differences compared to the presurvey, the graphs indicate that the trough box gained sediments especially from 2015 on (0.2m is equal to 75 000m^3 for the trough box) and the bar does not show an evident change if 2015 is compared with the presurvey. These sediments cannot be shifted from Rantum to the north as the volume graphs proof. Contrarily, they may come from the north due to longshore transport or they come from the beach. Of course, the longshore transport is active at the whole west coast of Sylt, but with a look at the raster data presented later, it can be determined that the beach grew seaward and supplied an extra amount of volume to the balance of the trough box. The data for the beach box, shown in the figure for the northern adjacent area, indicates that the broadening of the beach may have started in 2011, but because the excel-graphs do not contain data for the trough and bar for the surveys in question, we cannot determine this. Figure 44 however, shows that the sediments that formed the broader beach originated in an erosion of the dunes, indicated by an increase of the dark red areas at the lower border of the beach boxes (see also chapter 6.1.2 for a different view on the topic of dune erosion).

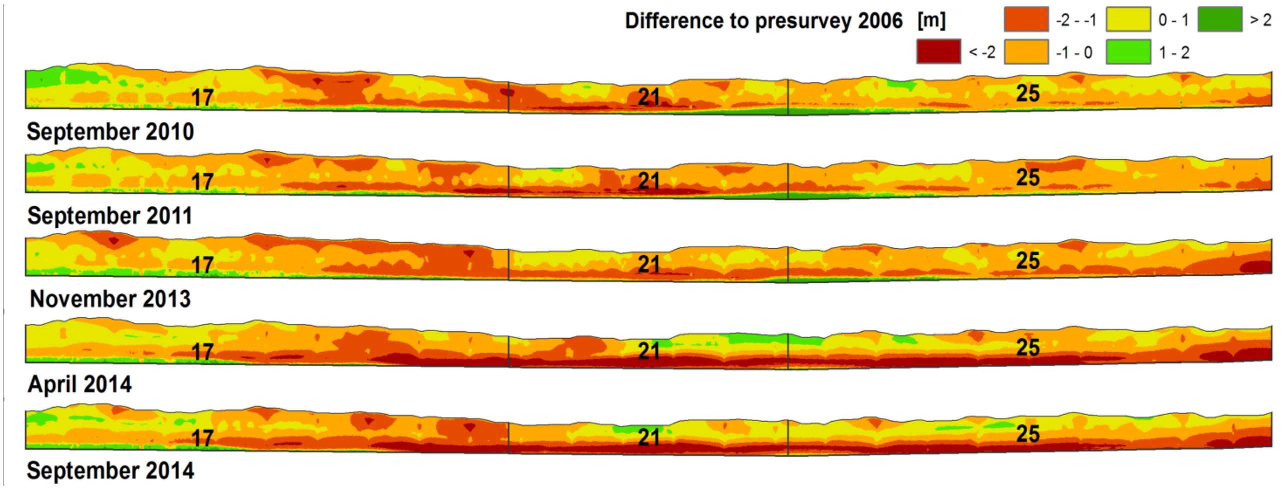

Figure 44: Increasing dune erosion for northern adjacent, Rantum and northern intermediate sites.

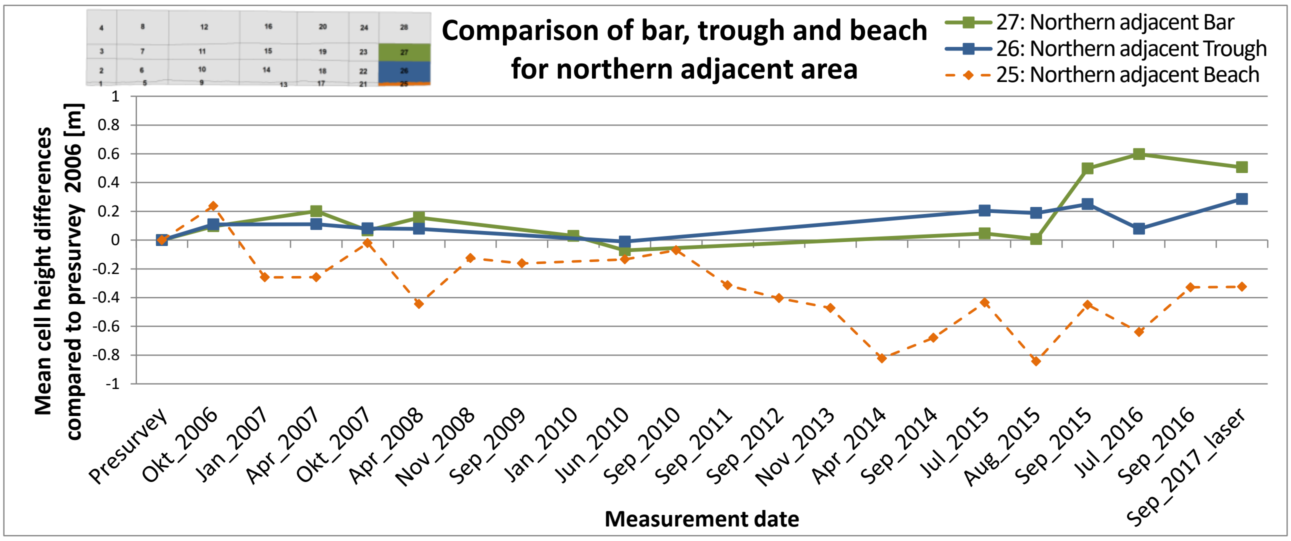

Figure 45: Comparison of bar, trough and beach for northern adjacent area.

To get a clearer picture of the morphologic development of the investigation area the raster data that is the basis for the figures above is presented here. Every of the following figures show the terrain raster of a special year on the top compared with the difference of this terrain raster to the presurvey raster. The difference raster are overlayed by a shape of the area higher than -4m NHN extracted from the terrain raster.

Figure 46 for Oct. 2006 mainly shows the nourishment placements seawards the bar top. The bar top is represented by the dotted shape for areas > -4m NHN. Between the bar and the beach is a trough with a depth of mainly between -4 and -6m NHN. The bar top declines in height from north to south. Yet, there is no reasonable sediment relocation visible. At the northern adjacent, northern intermediate and Sansibar trough boxes the bar comes close to the beaches and there are slight volume gains at some spots in the beach boxes, mainly where the bar is close to the beach.

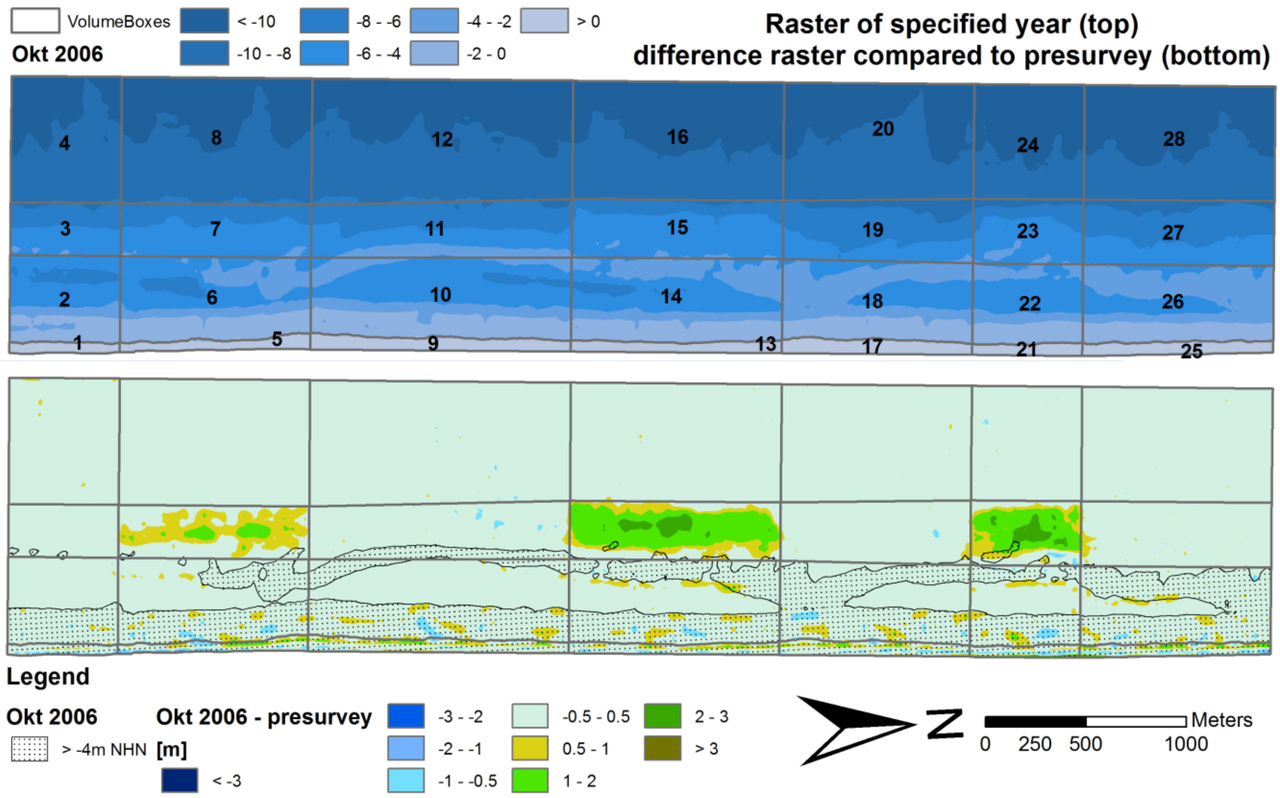

Figure 46: Comparison of terrain raster and difference raster for Oct. 2006.

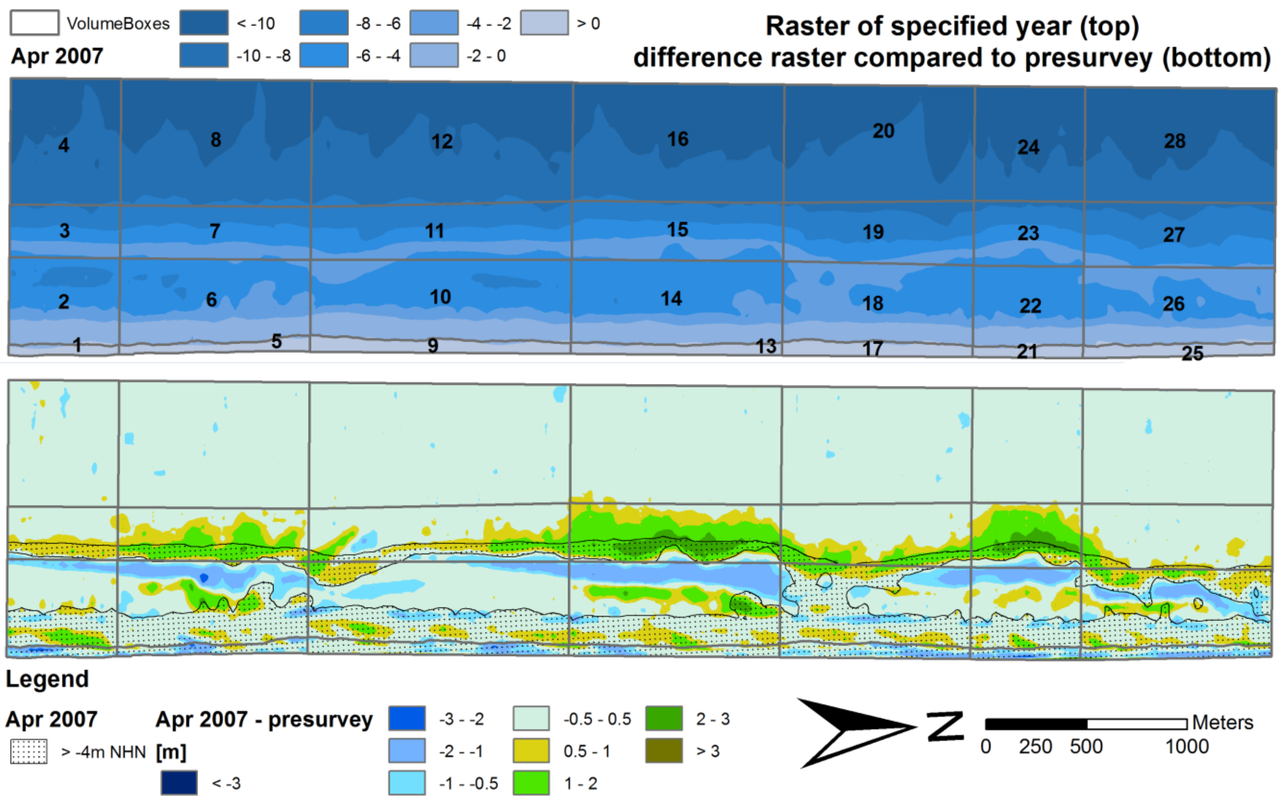

Figure 47: Comparison of terrain raster and difference raster for Apr. 2007.

In April 2007 (Figure 47) the bar has been strengthen, bar tops have been increased, the bar level over -4m NHN has been closed over the whole area and the trough has been deepened. Sediments from the bar and the trough boxes of the three nourishment areas have been relocated into the bars of the adjacent and intermediate areas. The connection to the beach has been disturbed in the Sansibar site and the northern adjacent site and beach erosion occurs. Landwards the deepening of the trough, near the beaches, accumulation is visible. This is stronger at the nourishment sites, where both, the erosion in the deep trough and the accumulation in the shallow areas are stronger as in the adjacent and intermediate sites.

This accumulation progresses in Oct 2007, especially in the Puanklent trough box where it seems to be nourished by the former beach erosion (Figure 48). The peaks of the nourished sediments in Rantum and Puanklent, which have been increased in April 2007 flattened and gaps occur in the -4m NHN and above height level. The sediments fill up the bar box of the northern adjacent area. The trough deepening grows longer and starts to cut off the connection to the beach in the northern intermediate area.

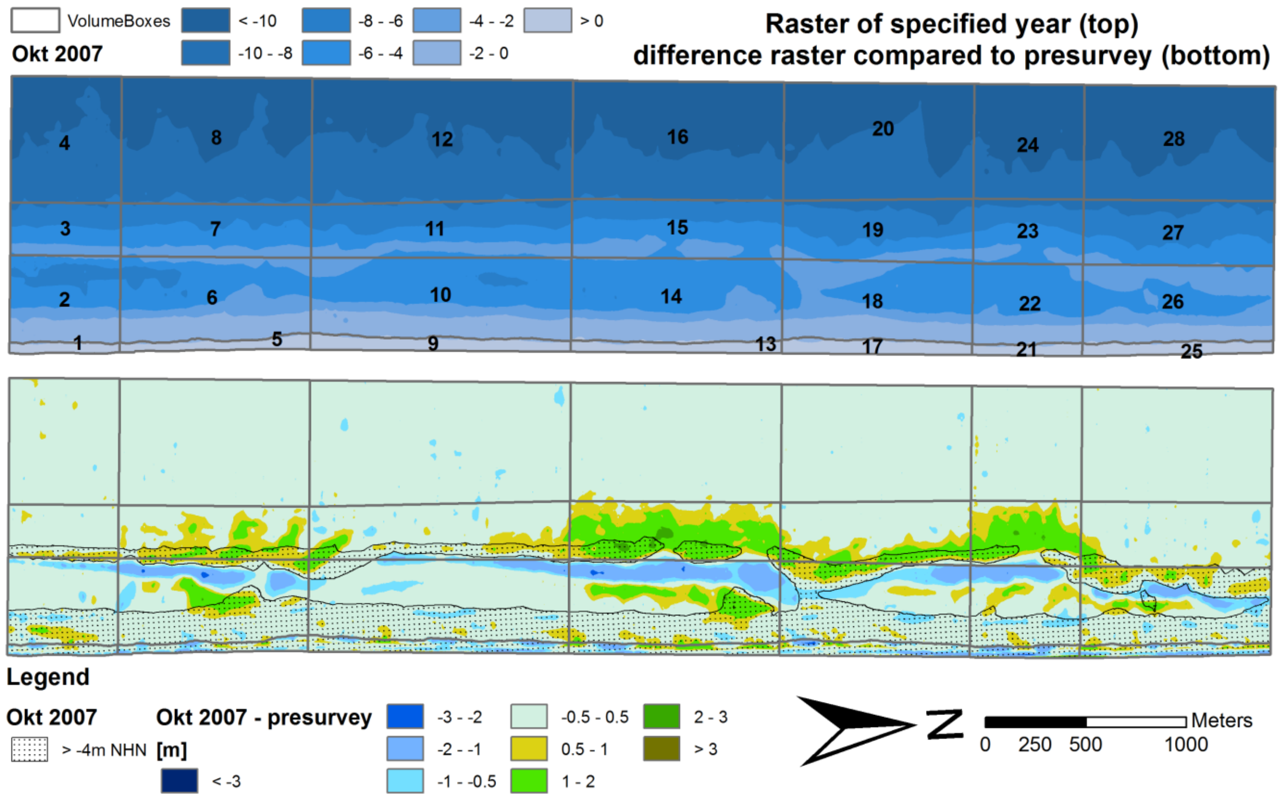

Figure 48: Comparison of terrain raster and difference raster for Oct. 2007.

In April 2008 the nourished sediments from Sansibar mostly have been integrated into the bar (Figure 49). The bar itself begins a shifting: At Sansibar it moves to the beach and the beach grows. At the southern adjacent site the bar moves seaward and the beach erodes. At Puanklent the bar moves to the beach and the sediments migrate towards the beach but have not reached it yet. At the northern intermediate area the trough deepens, the same happens in Rantum. In the northern adjacent area the bar grows and the beach grows strong. The deepened areas in the trough are connected and form a long and deep channel.

In January 2010 most parts of the bar have moved towards the beach (Figure 50). In the difference raster a tendency to establish a second bar is visible. The terrain raster instead shows that this did not happen.

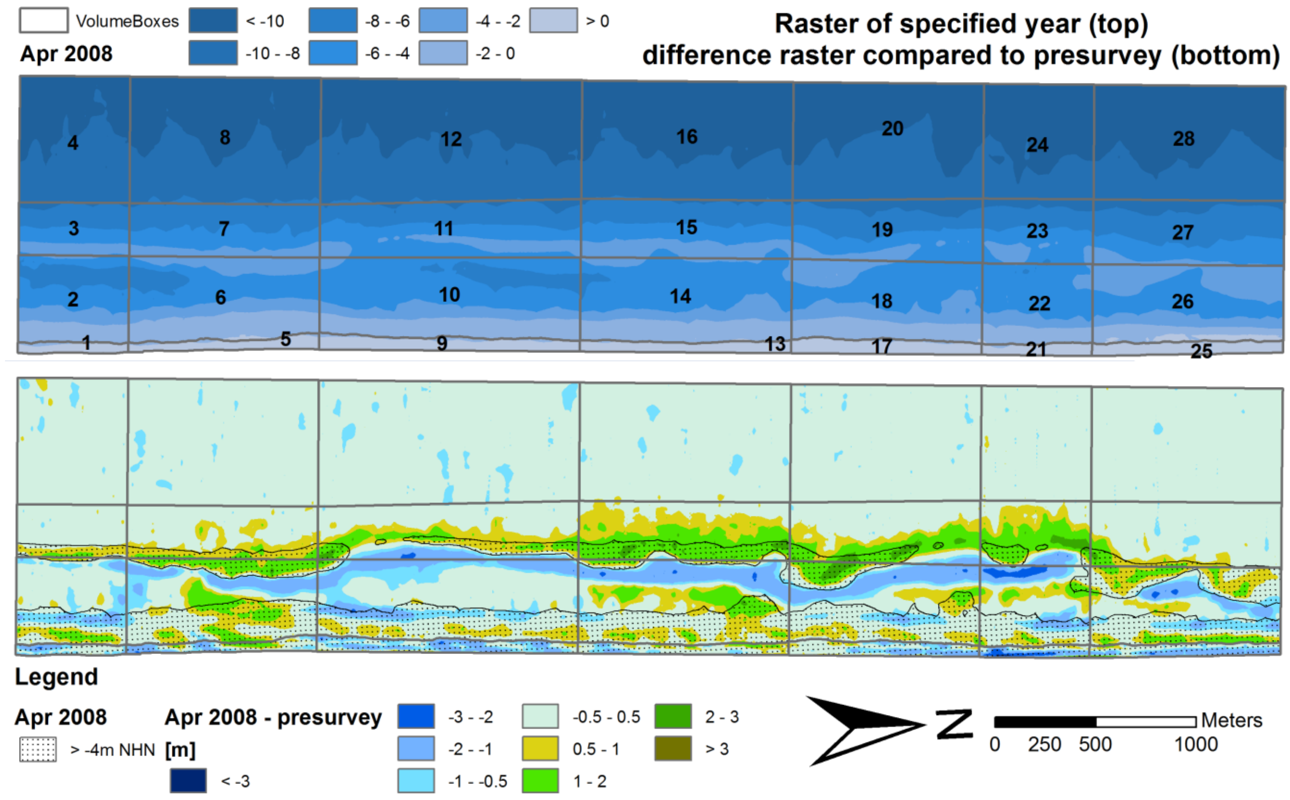

Figure 49: Comparison of terrain raster and difference raster for Apr. 2008.

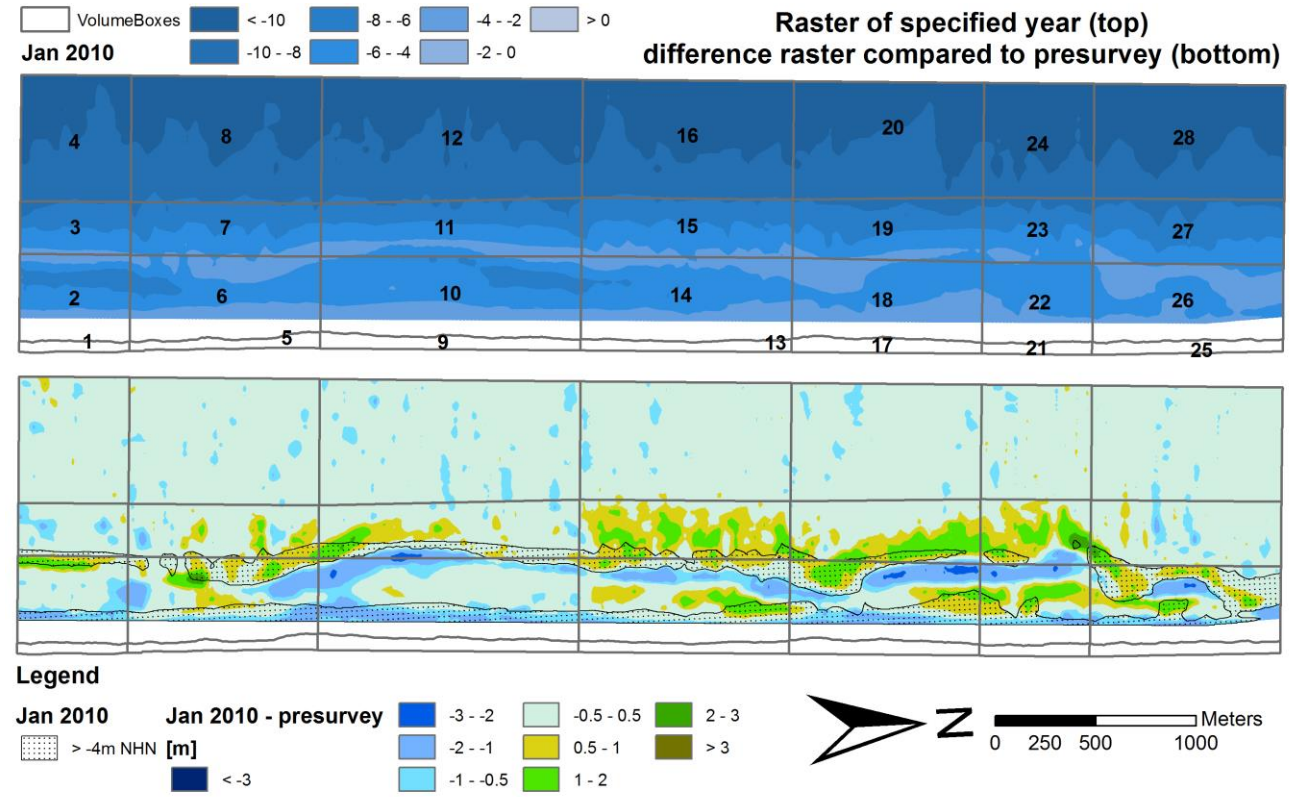

Figure 50: Comparison of terrain raster and difference raster for Jan. 2010.

In June 2010 the beach boxes of Sansibar and Puanklent grew and at least the sediments that ended at Sansibar beach came from the bar (Figure 51). The cavity of the trough declined. Large parts of the beaches recovered.

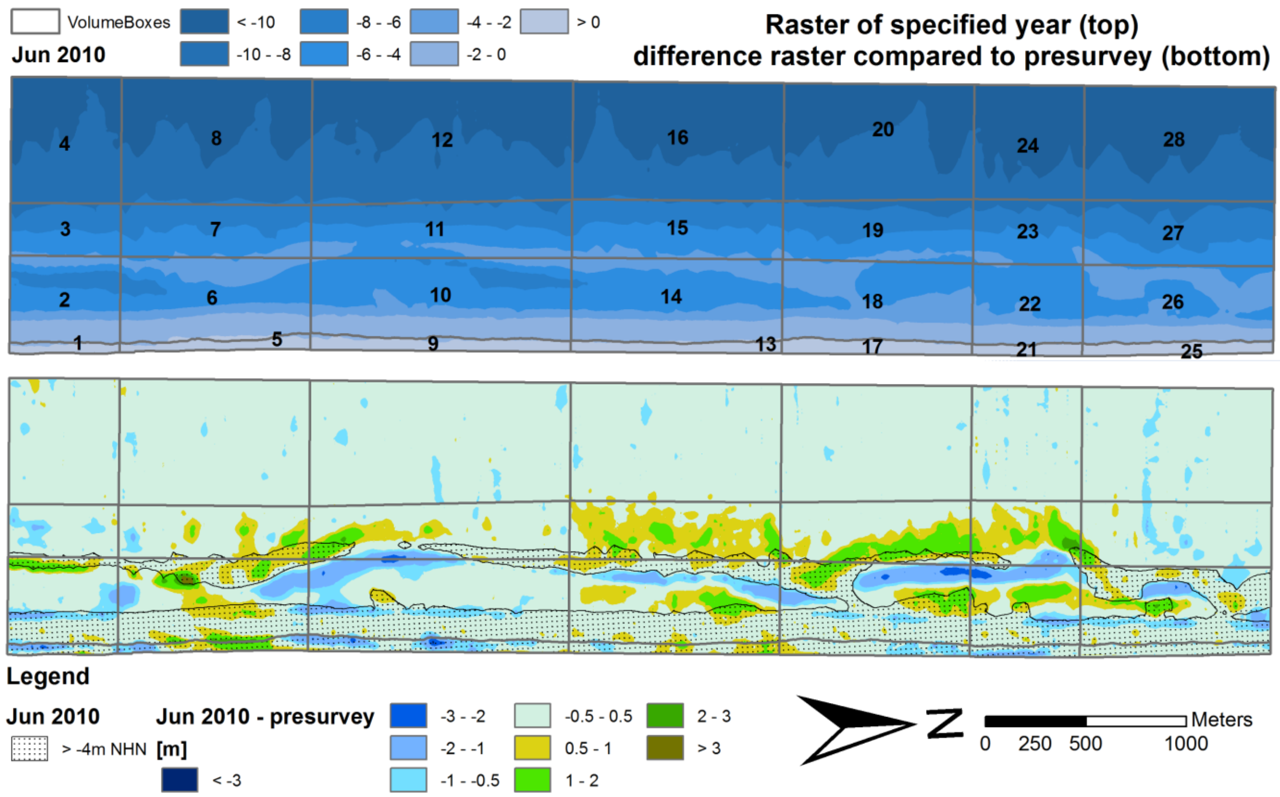

Figure 51: Comparison of terrain raster and difference raster for Jun. 2010.

The figure for 2015 shows the situation right in the middle of the new nourishment (red line in Figure 52). In the southern adjacent and Sansibar area the bar has moved to the beach even further and increased its volume. The beach at the northern adjacent area had dune erosion. The beach is broader now but grows out of the beach box. This results in a net. Volume decline for the northern adjacent beach box which seem to indicate a loss at this beach, but in fact the beach is partly in the trough box now and the loss, if any, is overestimated.

Figure 53 shows the situation in September 2017. There is still more sediment volume in the bar boxes than at the time of the presurvey. The bar itself is partly located closer to the beach. The trough directly behind the bar is still depressed. At the southern intermediate site a big cavity has been formed. Eroded sediments from the beach have been accumulated landwards the trough in the trough boxes. The beach at the southern intermediate site has been eroded, obviously due to the big cavity in the trough directly seaward. The beach sites at Sansibar and Puanklent have more sediment volume than at the beginning.

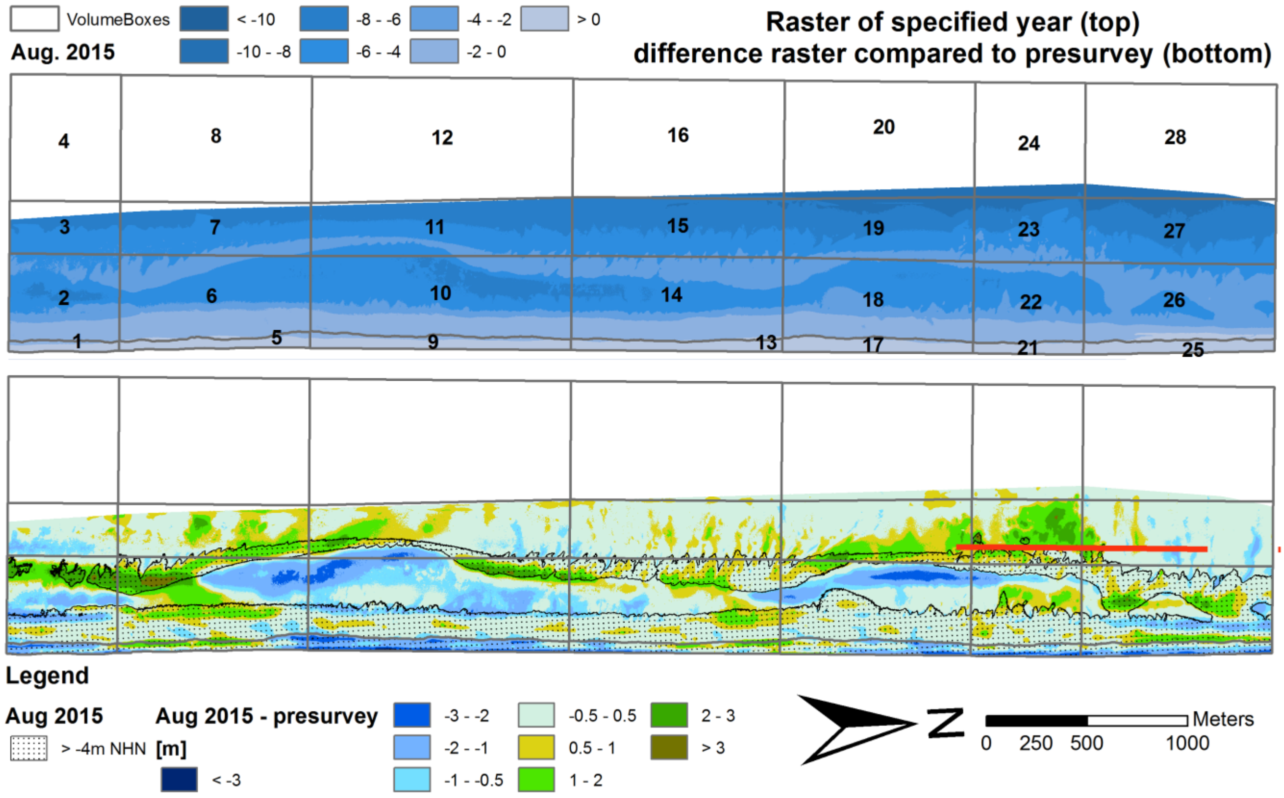

Figure 52: Comparison of terrain raster and difference raster for Aug. 2015 (red line is nourishment site).

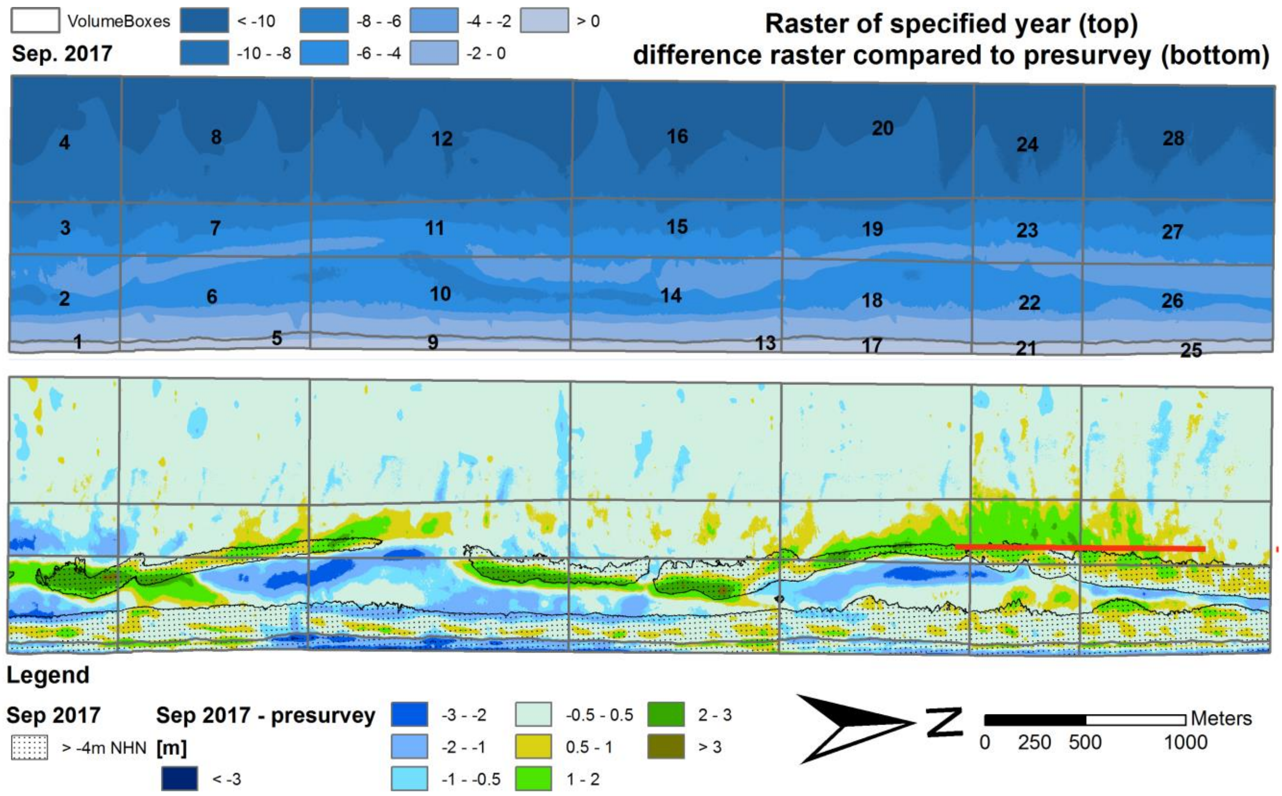

Figure 53: Comparison of terrain raster and difference raster for Sep. 2017 (red line is nourishment site).

6.3 Relation between nourishment development and hydrodynamic characteristics

To evaluate the measure the application of energy has to be taken into account. This is possible through the parameters water level, sea disturbance and wind. Because of a long term downtime of the measurement device to track for the sea disturbance, located seawards Westerland, and this parameter cannot be taken into account for the time period of the shoreface nourishment 2006 and thereafter.

6.3.1 Water levels

For the overall time from 1900 to 2018 peak flood water levels and length of stay for storm events above NHN +2 m exist for the tidal gauge in List harbour (Figure 54). Generally there is a relation between the storm surge water-levels and the length of stay (duration) at these levels, although sometimes the flood is coming soon and passing quickly which leads to some heavy damages also. For the observation time (2006-2012) there appeared some storm events (Figure 55). In the winter half years of 2006/07, 2007/08 and 2011/12 dwell times of high water levels lasted longer than usual (Figure 56). 2008/09 had no occurrences of higher water levels while 2009/10 and 2010/11 were average years.

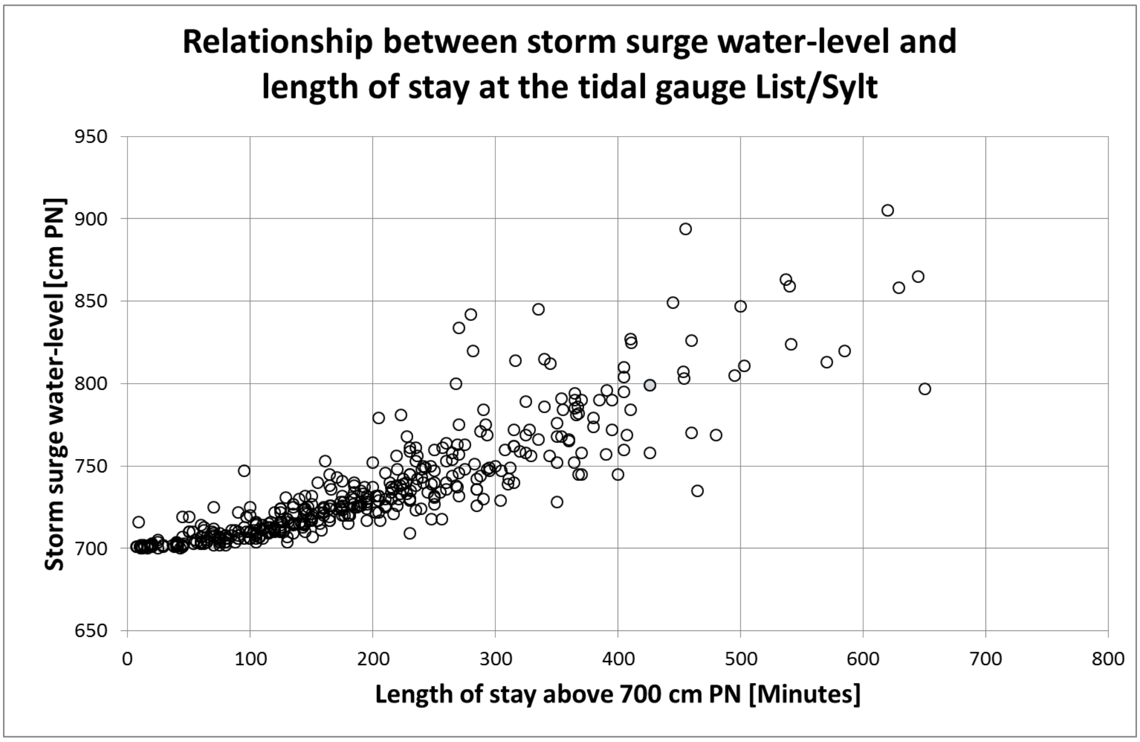

Figure 54: Relationship between storm surge water-level and length of stay at the tidal gauge harbour List/Sylt between 1900 and 2018.

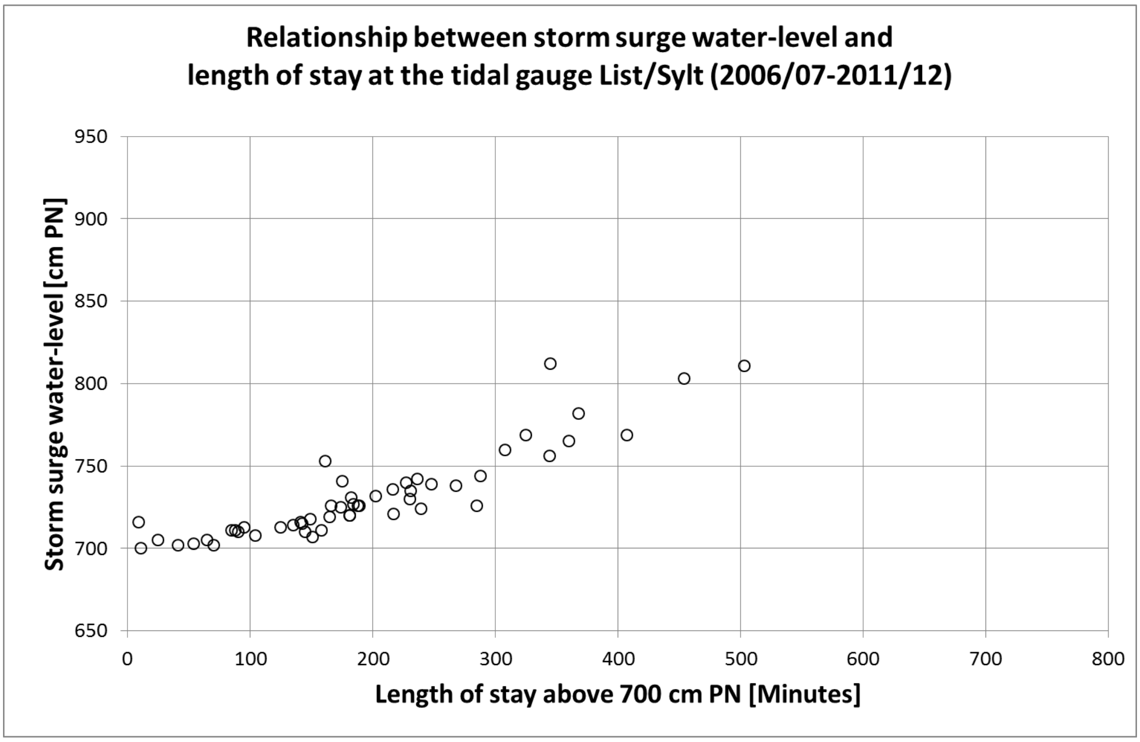

Figure 55: Relationship between storm surge water-level and length of stay at the tidal gauge harbour List/Sylt between 2006/2007 and 2011/12.

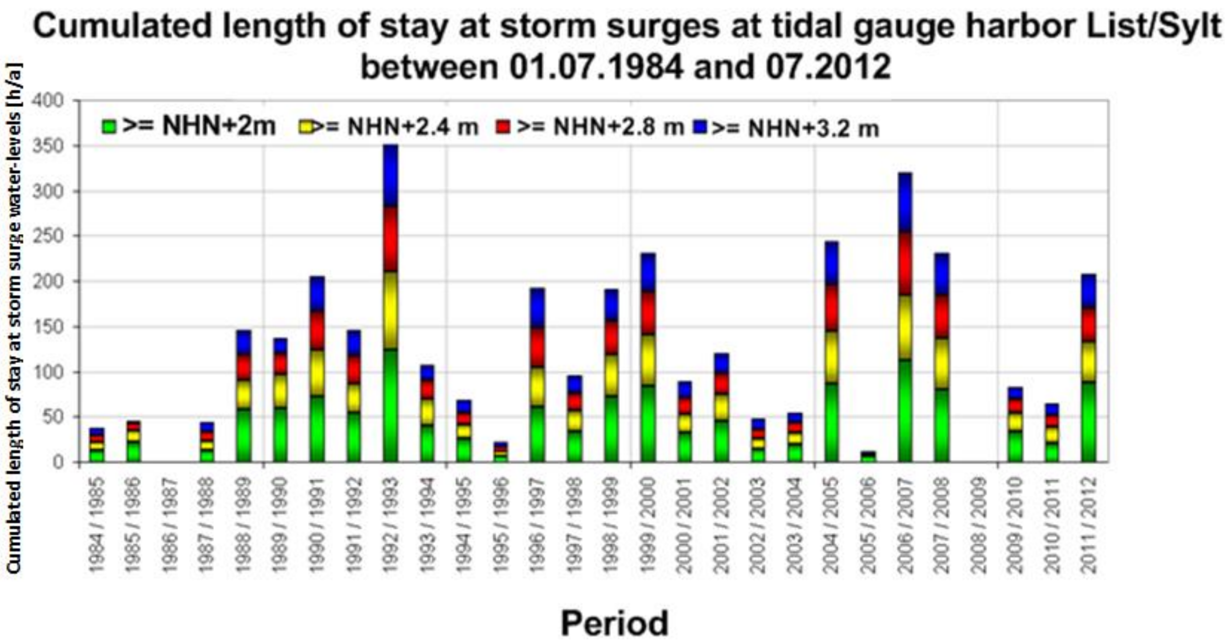

Figure 56: Cumulated length of stay at storm surge water-levels at the tidal gauge harbour List (1984-2012), operated by: WSA Tönning.

The length of stay at storm surges and the peak storm surge water-levels in the period from 1984 to 2012 (since nourishments have been applied regularly) show moderate to high impact on the beaches and shoreface (Figure 57).

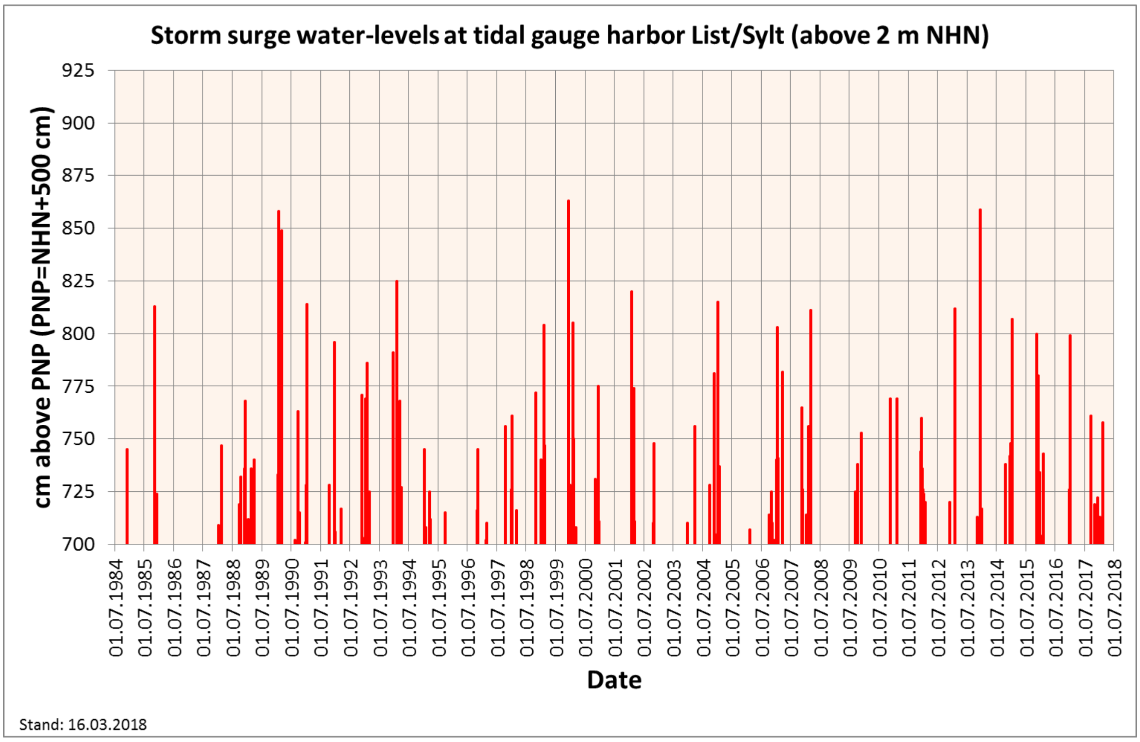

Figure 57: Highest storm surge water-levels at tidal gauge harbour List (1900-2012), operated by: WSA Tönning.

The highest storm surge water-levels from Jul. 1st 2006 to Jul 1st 2012 occurred at the tidal gauge harbour List as follows:

- Jan. 12th 2007 NHN+3.03 m (rank 23 in the time period 1900-2012) with 7 hours and 34 minutes over NHN+2 m (rank 18 in the time period 1900-2012)
- Mar. 03rd 2008 NHN+3.11 m (rank 19 in the time period 1900-2012) with 8 hours and 23 minutes over NN+2 m (rank 10 in the time period 1900-2012)

In the period between 2006 and 2012 occurred energy-rich surges, therefore it is proved that the measures had to stand up also against stronger attacks.

6.3.2 Waves (Energy flux)

The energy flux is calculated from the wave buoy at deep water to the bar top at transect 56+004. For the different years the annually (period 01.07 to 30.06.) variations can be seen in Figure 58.

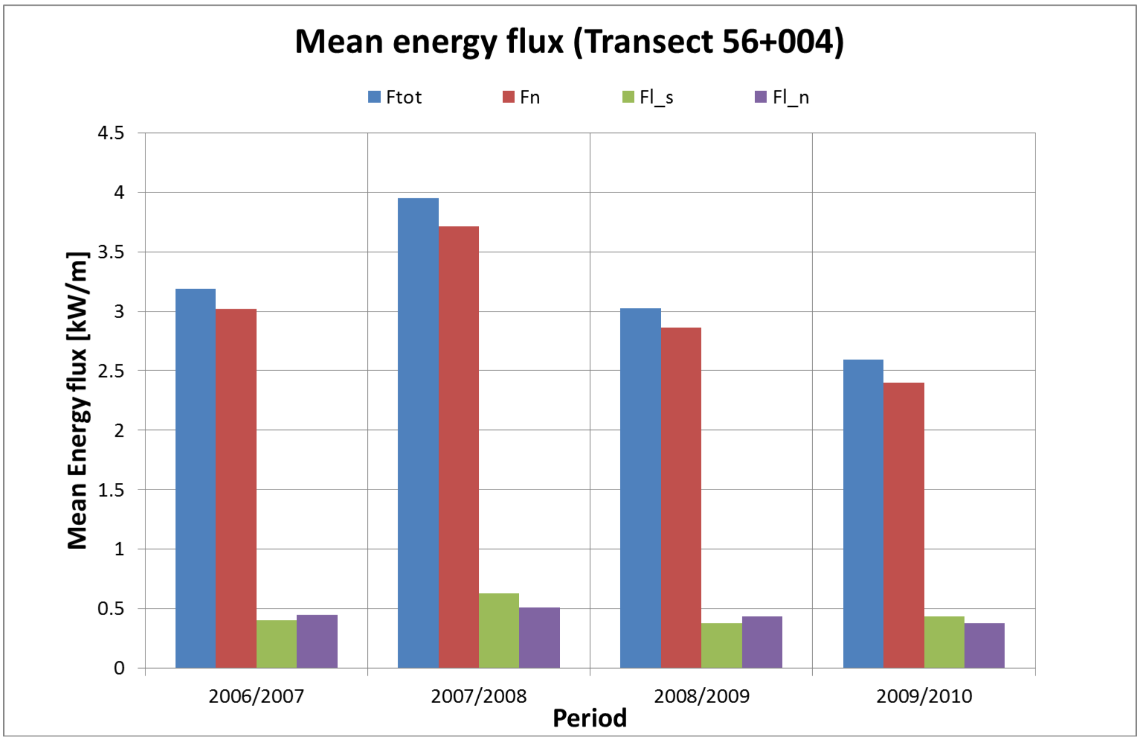

Figure 58: Wave energy flux in the period 01.07.2006 to 01.07.2010 at the transect 56+004.

In der winter half year (2007/2008) a higher wave energy flux was registered.

6.3.3 Wind

The distribution graph for wind directions and intensities at the monitoring station List for the time period from 1984 to 2011 (since nourishments have been applied regularly) shows prevailing West winds with strength mainly in the range between 5 m/s and 10 m/s (Figure 59).

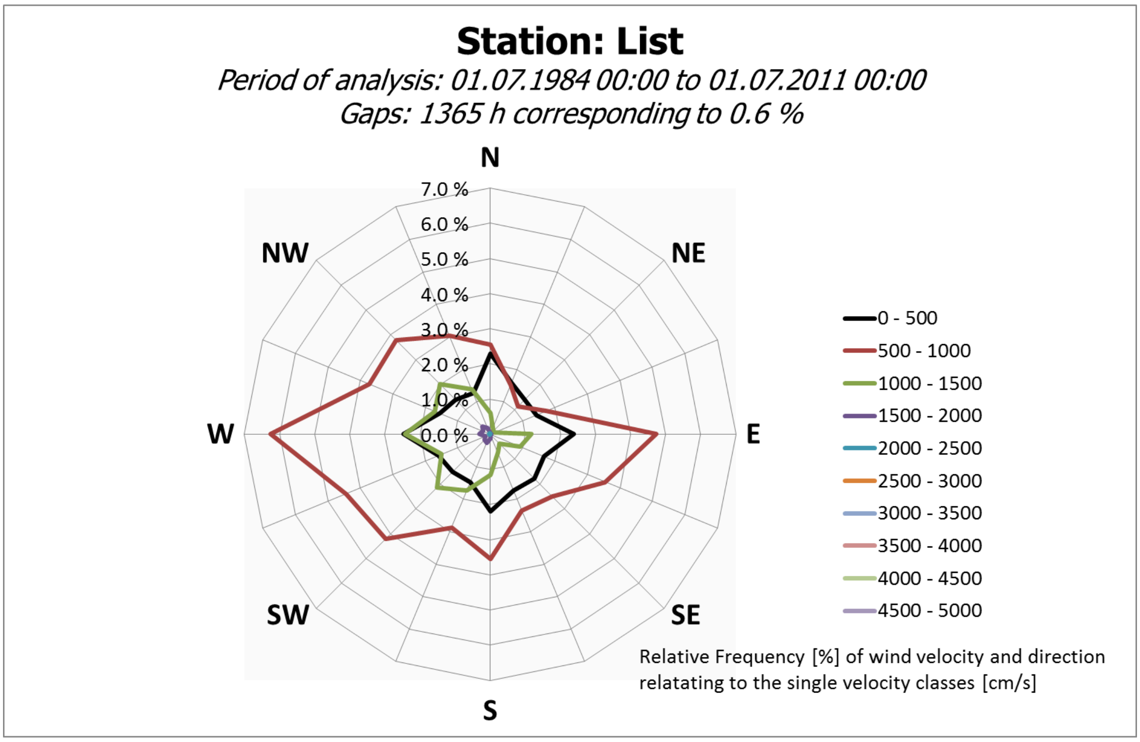

Figure 59: Wind statistics at the monitoring station List (1984-2011), operated by: DWD.

In the time period from 1984 to 2006 (start of regular nourishments up to the shoreface nourishment 2006) the wind directions and intensities don't show notable variations compared with the time period from 1984 to 2011 (Figure 60).

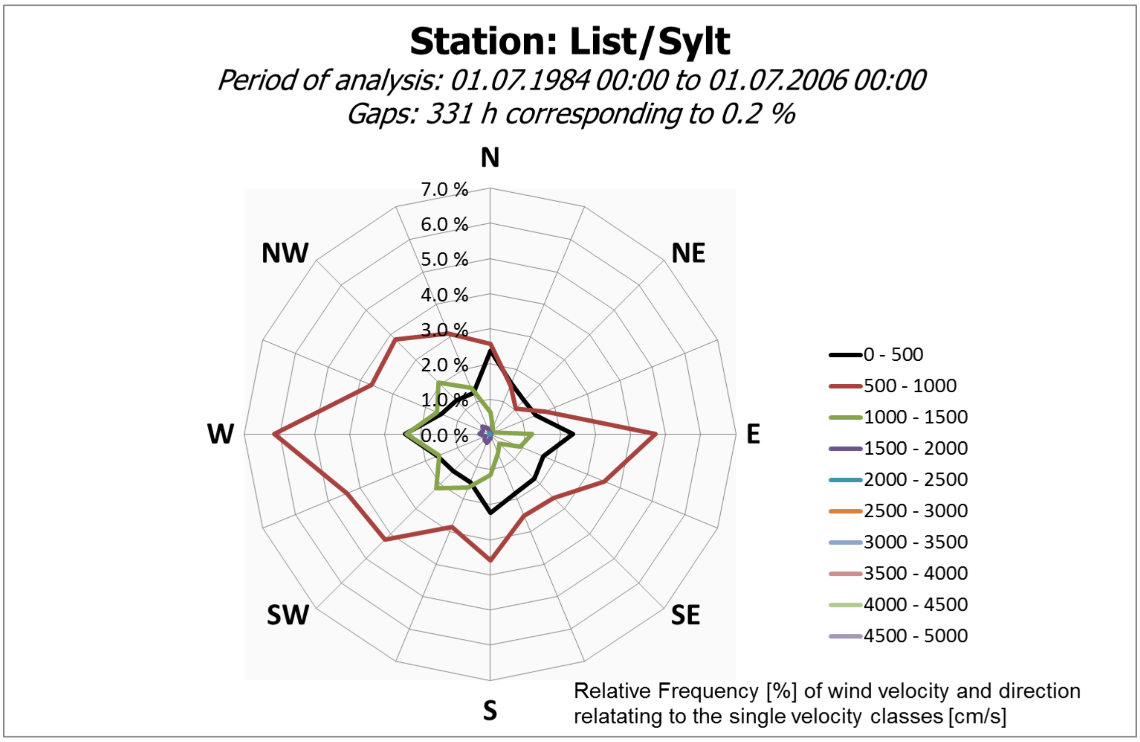

Figure 60: Wind statistics at the monitoring station List (1984-2006), operated by: DWD.

In the time period from 2006 to 2011 (from shoreface nourishment 2006 up to 5 years after) the wind directions and intensities correspond to the values in the time period from 1984 to 2011 (Figure 61). In comparison to the period from 1984 to 2006 a higher percentage of wind from west could be observed and the percentage of winds from the east was slightly decreased.

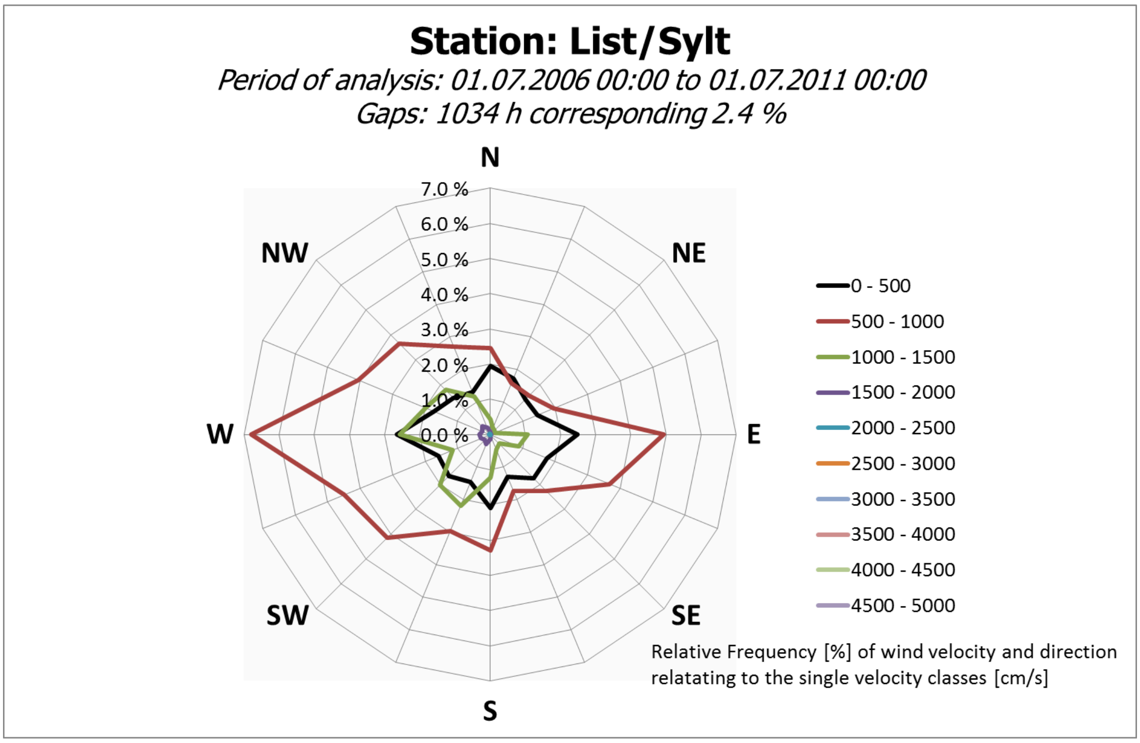

Figure 61: Wind statistics at the monitoring station List (2006-2011), operated by: DWD.

6.4 Additional analysis

The visualization of the bar-trough dynamics can be shown by the graphs from Figure 62 to Figure 64, in addition to Figure 20 to Figure 22. There seems to be an almost periodic behaviour in the shoreface movement. The nourishments in 2006 give for Rantum and Puanklent some other impacts as for Sansibar, regarding the development of the trough.

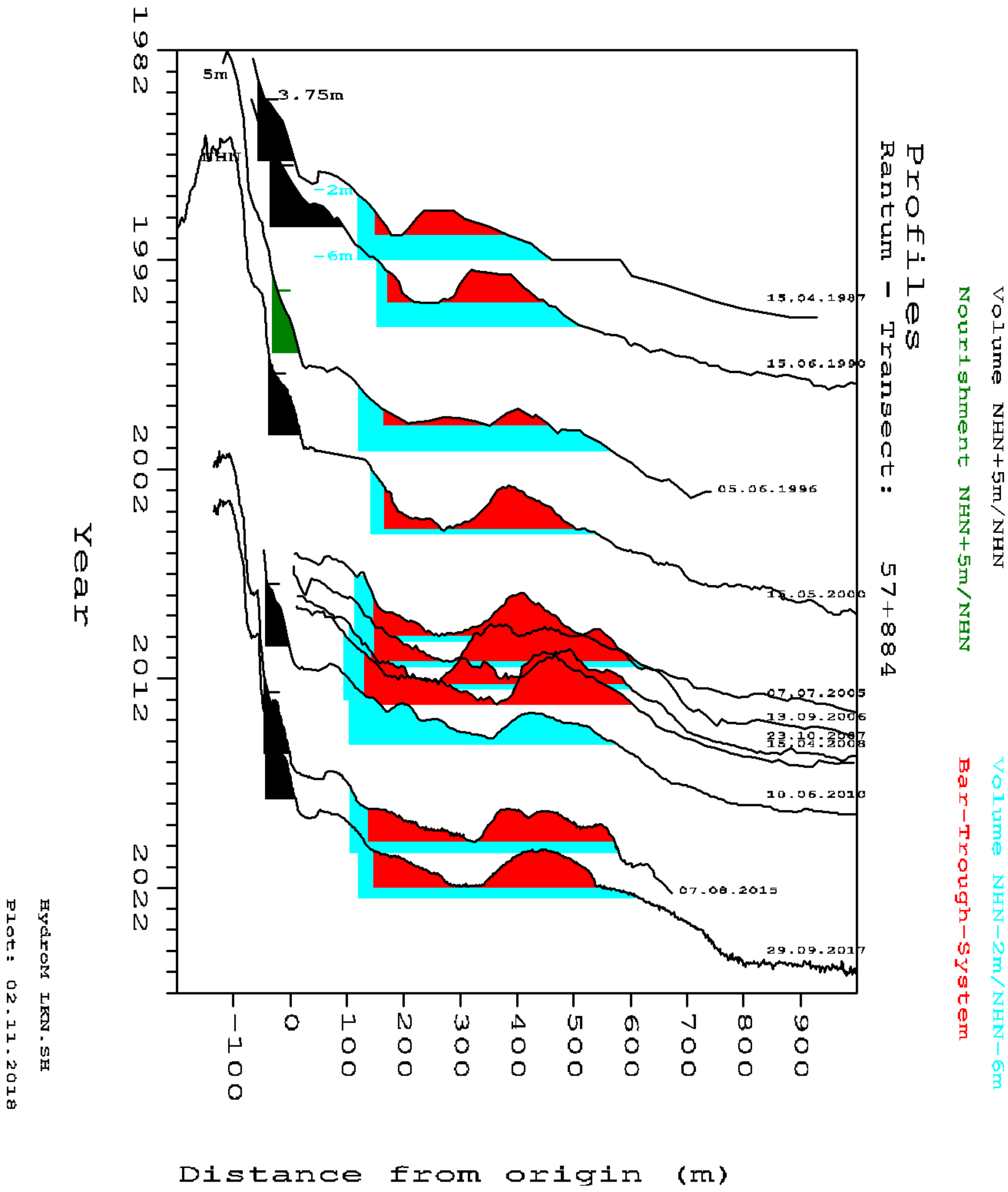

Figure 62: Temporal variations of the bar-trough-system at transect 57+884 between 1987-2017. The shoreface nourishment at Rantum was made in 2006.

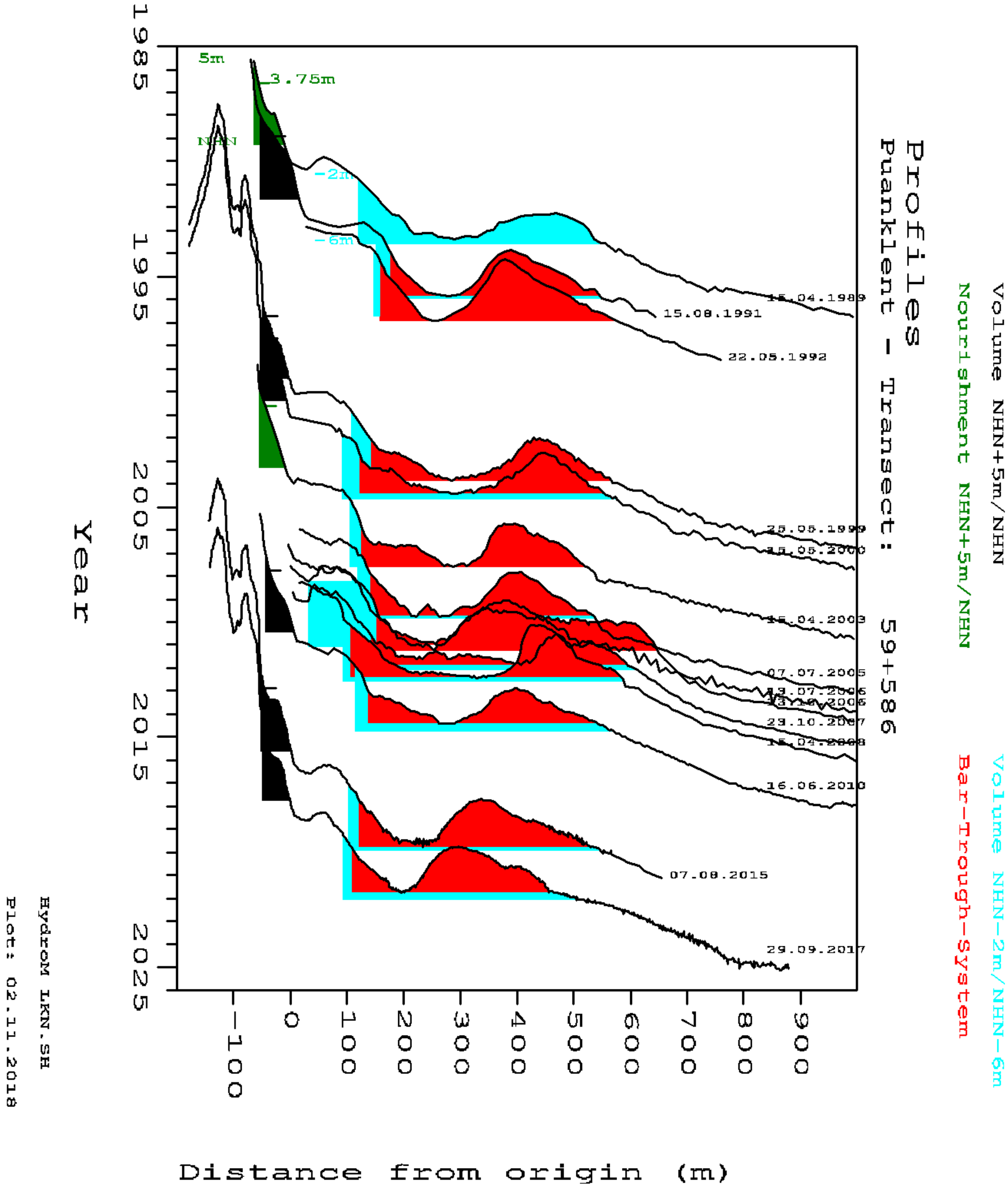

Figure 63: Temporal variations of the bar-trough-system at transect 59+586 between 1989-2017. The shoreface nourishment at Puanklent was made in 2006.

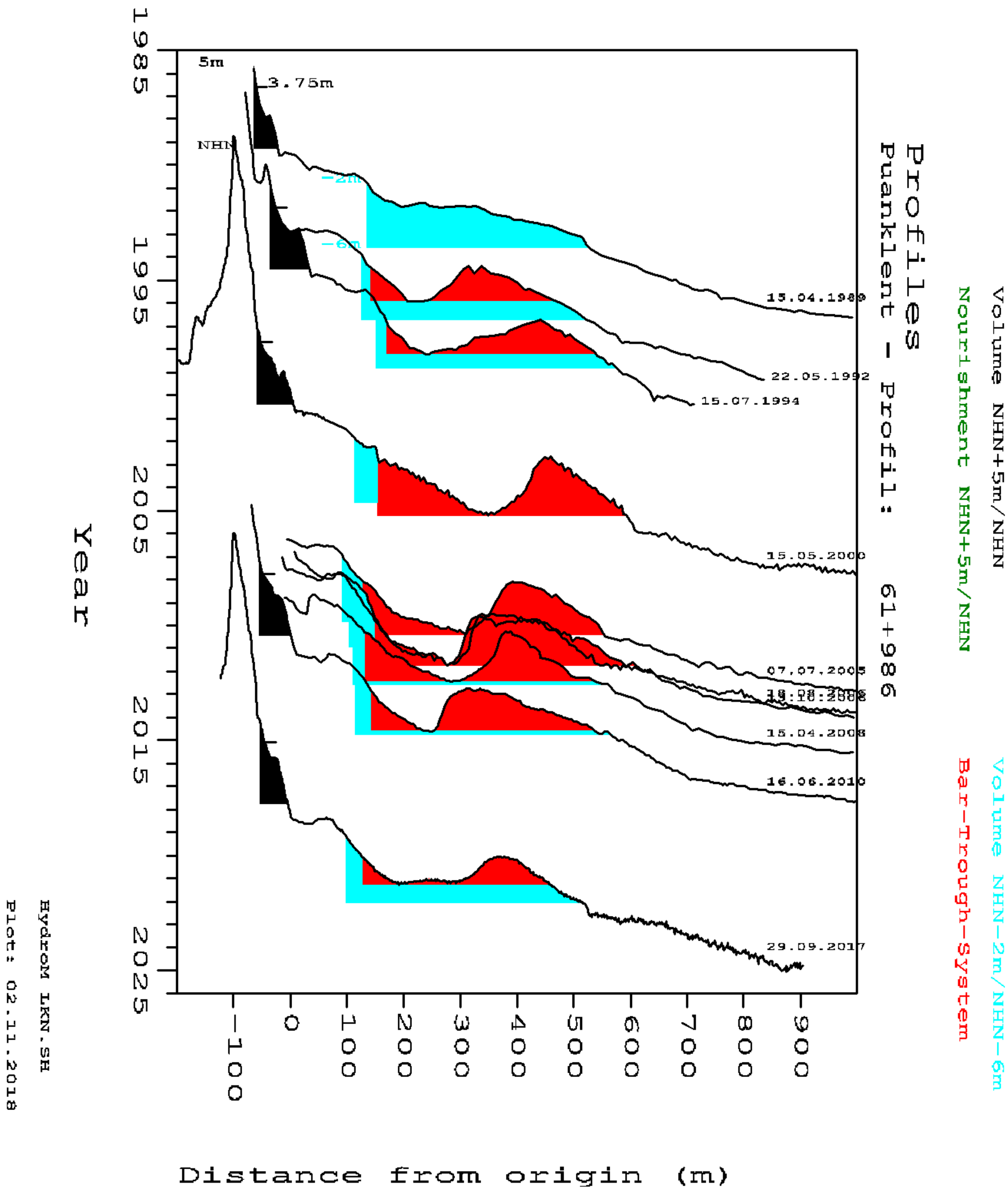

Figure 64: Temporal variation of the bar-trough-system at transect 61+986 between 1987-2017. The shoreface nourishment at Sansibar was made in 2006.

The spatial variation of the volumes (beach, Figure 65 and shoreface, Figure 66) for different time periods shows that there is a slight longshore transport towards the south.

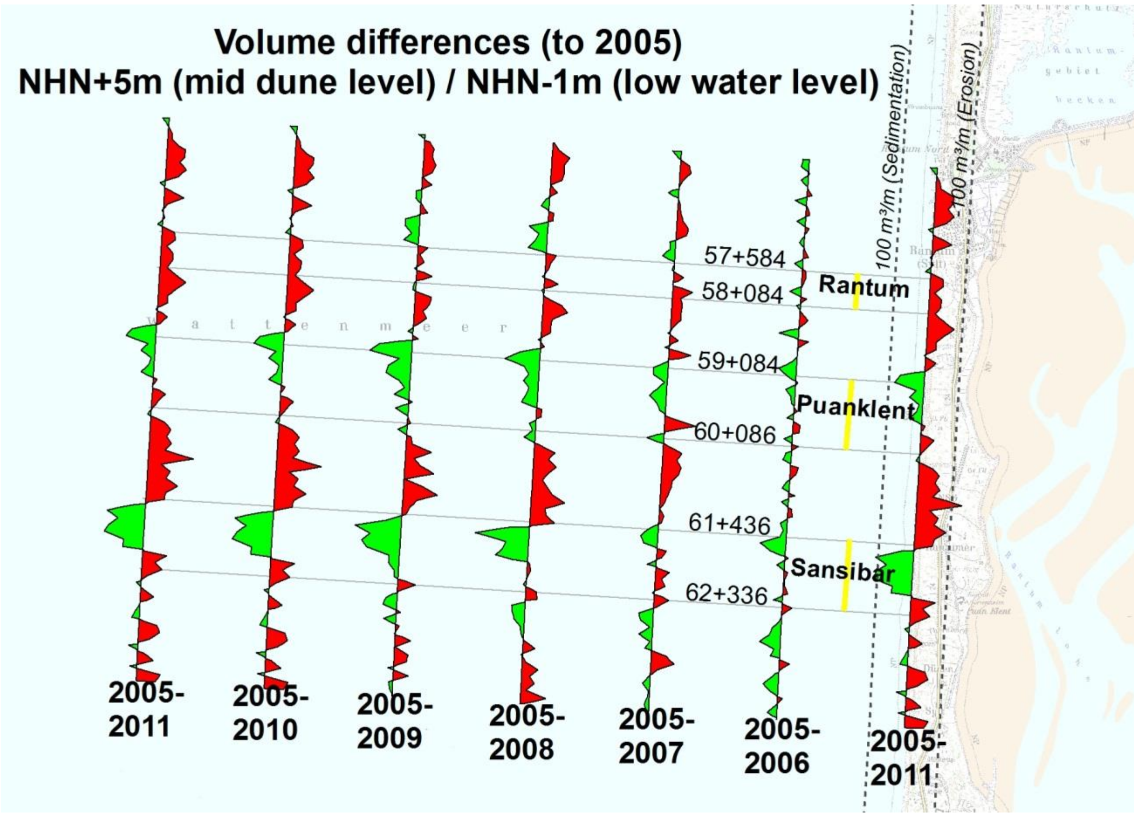

Figure 65: Spatial variation of the beach sand volume (NHN+5m/NHN-1m for different time periods between 2005 and 2011.

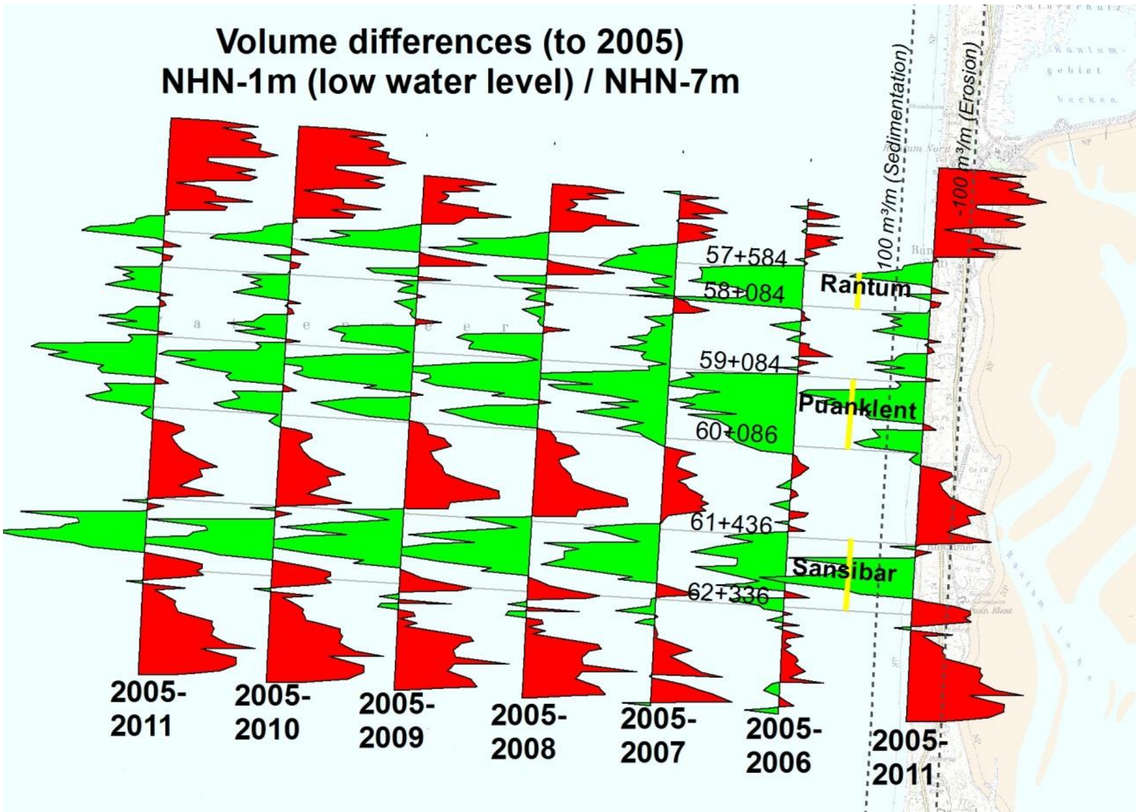

Figure 66: Spatial variation of the shoreface sand volume (NHN-1m/NHN-7m) for different time periods between 2005 and 2011.

The comparison of the annual rates of volume development as shown in Figure 67 gives some evidence that there is an increase of sand volume at least for the shoreface nourishments at Puanklent and Sansibar.

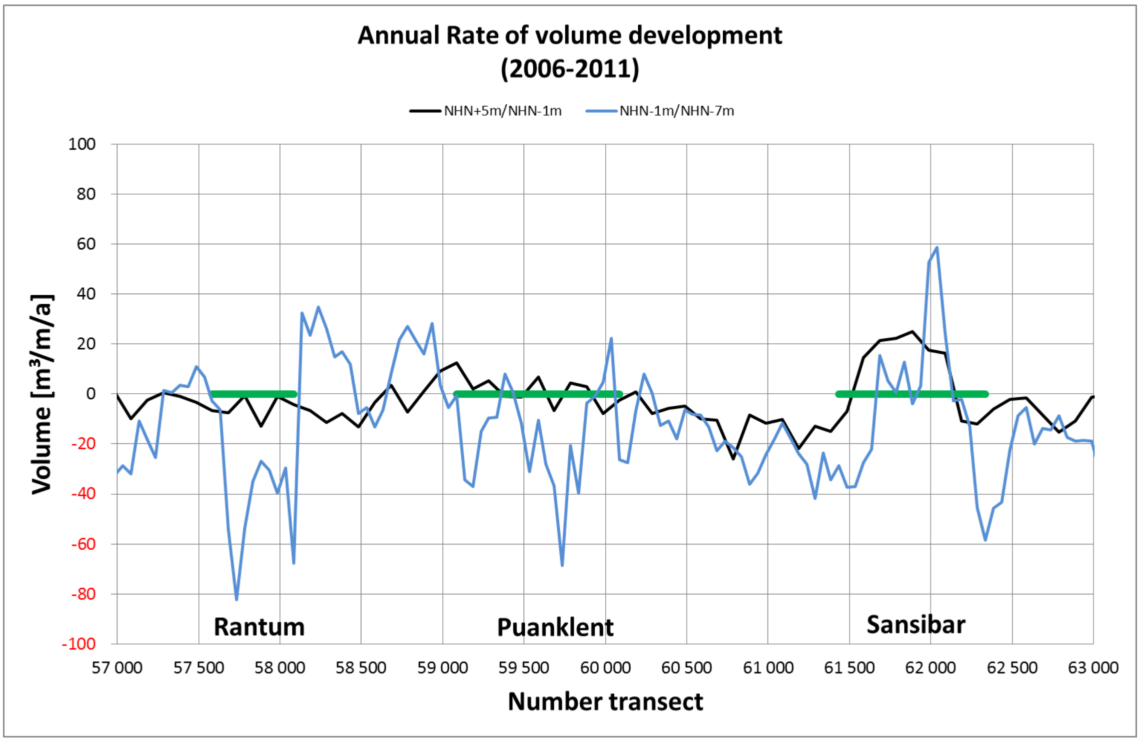

Figure 67: Annual rate of volume development between 2006 and 2011.

7 Synthesis

7.1 Nourishments performance

Beach nourishments on the west coast of the Island of Sylt are performed since 1972, annually since 1984. A lot of different geometric forms to put the sand on the beach were created. It was identified that a massive amount of sand led to large redistributions. Therefore the specific amount of sand (m^3/m) was reduced. On the other side the stability of beach nourishments depend on the morphological situation in front of the beach. If there is a lack of sediment in the shoreface a shifting of sand from land so sea will be initiated in order to get an equilibrium profile. The main reason to perform shoreface nourishments in 2006 at three different locations was to see whether the additional sand impact will help to stabilize the beach. There is evidence that the nourished sand has to be placed seaward of the bar top, otherwise the trough would be enlarged. Also the stretch of the sand body shouldn't be too long, since the rip currents may exist about each 1 000 m. The measures should not be disturbed by additional measures for the next six years in order to observe clear signals. All this constraints were fulfilled and the results of the shoreface nourishments 2006 could be stated with the measurement made in 2011.

It turned out that the shoreface nourishment at Sansibar had the more stabilizing effect for the beach, regarding the volume from the mid dune level to the mean water level (NHN+5m/NHN 0m). The mean differences to the both other nourishments exist in the less specific amount of nourished sand and the shorter chosen stretch. Besides the higher accumulation of sand above the mean water level (NHN 0m) the change of the trough was much less. Therefore it can be concluded that a smaller amount of sand at shorter stretches will have less redistribution in advance. In addition it has to be mentioned that nourishment at Sansibar is the most south one and does benefit from the usual longshore transport. Up to now, 11 years after the shoreface nourishment was done, the beach is still in a stable condition.

The shoreface nourishment Puanklent 2006 led also to an almost stable beach although the autonomous behaviour shows a slight decrease of beach volume. But in this case the trough was enlarged.

In case of the shoreface nourishment Rantum 2006 the beach developed stable, but the buffer volume in the northern intermediate area wasn't enough so that in 2015 and 2016 another shoreface nourishment and beach nourishment was done nearby. At the southern intermediate area there can be observed a steady decrease of beach volume. In the southern adjacent area there was a steady autonomous volume loss at the beach so that beach nourishment was done in 2013.

As a result of all measures it can be stated that shoreface nourishments have an additional effect in order to maintain the beach and the shoreface as well. The specific amount of nourished sand should not be greater than 240 m³/m in order to keep the bar-trough-system stable. The nourished stretch should not be longer than 1 000 m if rip currents are present.

As long as there is a stable beach and the wind is blowing onshore the dune toe, mid dune level and upper dune level will grow. Figure 68 to Figure 70 show the variation of the position of the coastal state indicators between 2006 and 2011. Especially the low water levels indicate a main increase of the position towards the sea.

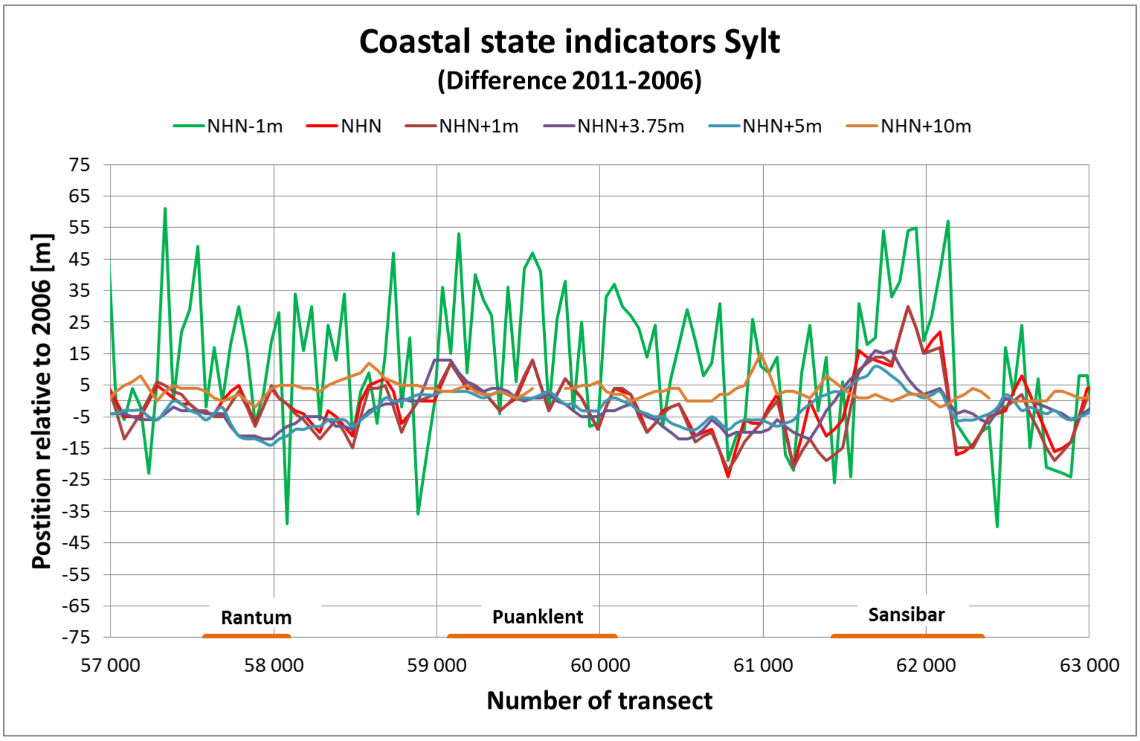

Figure 68: Position of the coastal state indicators in 2011 relative to 2006 (overall CSIs).

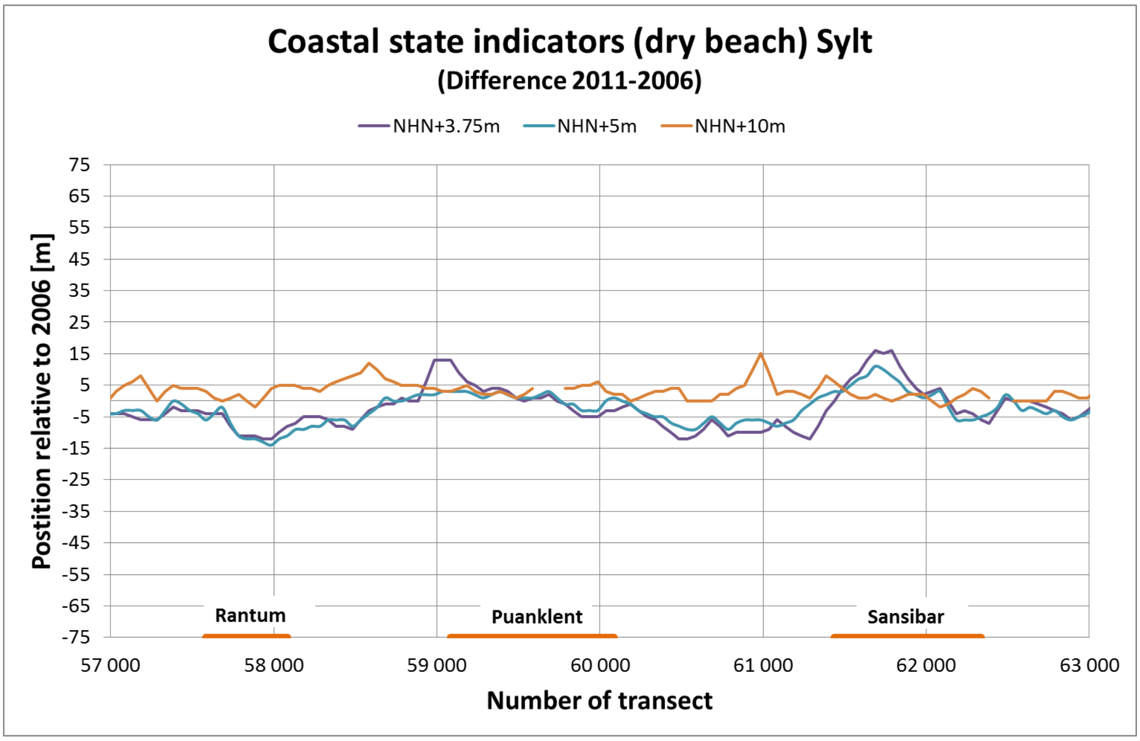

Figure 69: Position of the coastal state indicators in 2011 relative to 2006 (CSI dry beach).

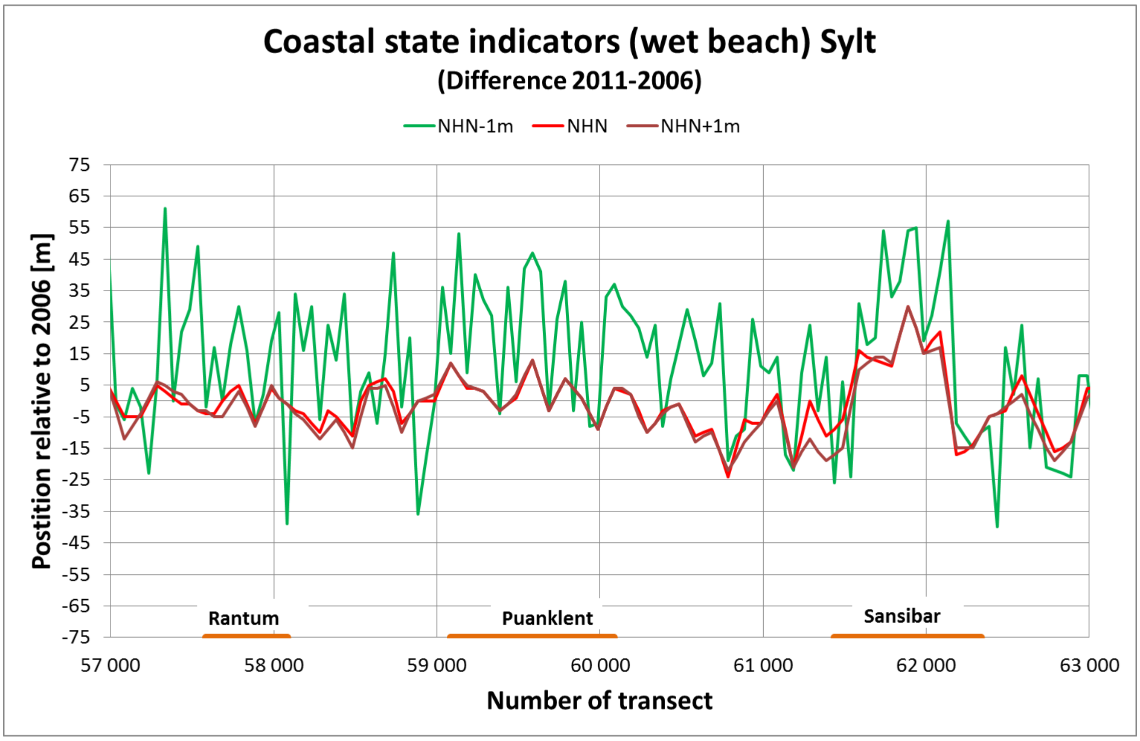

Figure 70: Position of the coastal state indicators in 2011 relative to 2006 (CSI wet beach).

The bar is moving towards the trough and the bar height deepens. This seems to be part of an autonomous behaviour since it can be seen at many cases. In general the migration pattern might be periodic (bar is moving back and forth).

7.2 Relation between nourishment development and hydrodynamic characteristics

The interaction between hydrodynamic impact and morphodynamics is evident. At higher water-levels (storm surges) material is relocated from the dry beach down to the wet beach. On the other side high wave events might reshape the bar-trough-system. The steady longshore transport supports material towards the south of the lab. The strong westerly winds let the dunes grow, especially if the sand is dry. It seems as if the shoreface nourishments give an additional onshore transport due to the normal energy flux which makes the beach more stable.

7.3 Strategic goals

It was shown that the shoreface nourishments in 2006 made the beach more stable and prevented the island of Sylt from further structural erosion. The effectiveness of the measure last for at least 10 years and is comparable with beach nourishments as well. The cost benefit is better as long as the sand supply for shoreface nourishments is somewhat cheaper, depending on the tender.

8 Source-Pathway-Receptor

In this national analysis the primary focus is set on volume changes and movements of coastal state indicators to describe the system and the outcome of the performed nourishments. A Source-Pathway-Receptor approach can add information about the interrelations between the subsystems the whole lab consists of, e.g. beach, trough-bar system, shoreface. The best way to analyse these interrelations is to set up a model to get to a most complete understanding about the development of a nourishment by modelling the trajectories of sediment bodies. Besides, the general concept of Source-Pathway-Receptor can also describe in an easy understandable way the effect of nourishments and why the coastline benefits from them, even if there are no resources to run a full model, like it is the case for this report. In this chapter we analyse the Sources, Pathways and Receptors for the Sylt coastal laboratory.

In the Rantum-Puanklent-Sansibar system the sources are wind, waves, water level, wave driven and tidal currents and storm surges. The pathway is the coastal profile as far as it is relevant for nearshore sediment dynamics. The receptor can be defined as the area where flooding might have an impact, e.g. the natural reserve, infrastructure of which the main road to Hoernum is essential, and touristic and recreational infrastructure. Also the village of Rantum is located directly behind the northern edge of the labs and would also be at risk in the case of a dune breach. While the coastal protection policy is not exactly to hold the coastline, it is sufficient to say that a relocation of the mid dune level landwards can be interpreted as an impact to the receptor.

As long as the pathway can dissipate the forces of the source, the receptor is sufficiently protected against storm surges. While aeolian transport is the driving force for sediment redistribution from the beach towards the dunes, there is no direct connection with the shoreface nourishments in the lab. This link is indirect. Vice versa, tidal currents should only have a minor impact in beach nourishments, taking into account that these nourishments can reach from +3,50m to -1,00m NHN. Waves and water levels on the other hand, are effective over the whole pathway, either by flooding the hinterland or through wave induced bottom currents. Therefore, the seaward boundary of the pathway is linked to the combination of wave climate and the water level.

Shoreface

To determine the range of effectiveness of the wave induced bottom currents, we use the range for the highest astronomical tide, mentioned in chapter 5.2 (table 9), the water levels during storms as presented in chapter 5.3 (table 10), and the wave climate derived from the dataset that formed the basis for chapter 5.1. This data was taken by a buoy at 9m water depth and has been filtered to select the days with storm events, to determine representative wave heights for storm days and normal conditioned days. Here, storm days are those with a water level setup (water level minus astronomical tide) of at least 2m. Besides water level the data has been filtered on wave directions from the south to the north (180 to 360 degrees) . Waves from east are generally small and do not create mentionable erosion on the western beaches. It is important to mention, that a whole day has been filtered as “storm day” if a storm occurred within, not only the “storm occurrence” itself. There are still calm hours on these storm days. This is a quick-and-easy solution to reduce calculations, because without modelling all considerations remain schematic anyway.

The representative wave height during storms is determined by the most frequent wave height above the 90% percentile for the time span 31.01.2006 to 31.12.2015, filtered by only storm days. The determined value of 4.76m was rounded up to 5m because the highest value was 6.41m and the highest 90% percentile for a single storm day was 5.96m. So, 5m (at the buoy, 9m water depth) is a rounded value that can be called common for stronger storms in the Sylt labs. For normal conditions, the dataset was filtered by days without water level setup over 2m. The 50% percentile for this subset is 0.93m, the mean over all values is 1.06m. A mean wave height of 1m under normal conditions is therefor reasonable. Based on this calculation we can derive two depth values for wave induced bottom currents: For storm events it is 2 times wave height minus 2m water level setup = -8m NHN without tidal effects. For normal conditions it is 2 times wave height = -2m NHN, also on mean water level. These two depth values are plotted in figure 71 as red dashed lines against three representative profiles, each for one BwN-lab.

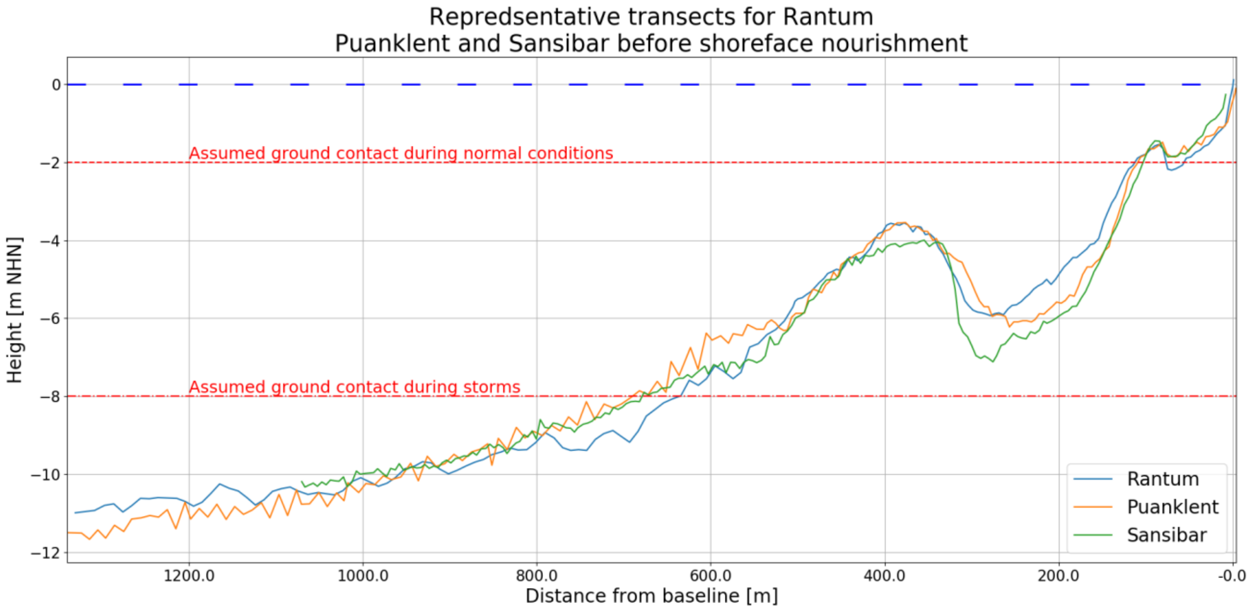

Figure 71: Assumed ground contact plotted over three representative transects before nourishments

This figure illustrates, that under normal conditions only little sediment dynamics are to be expected at the bar and that results in a relatively stable bar. Under normal conditions, wave induced shoreface sediment dynamics take place only in the shallowest area, roughly within the first 110m seawards the waterline. Due to the used definition, under normal conditions, only this short part of the pathway is active in dissipating wave energy. Under storm conditions, the active pathway is much longer (630 to 690m seawards waterline), and the bar system is within. This is the reason why we observe the major erosion- and relocation events in the bar during storms. And this means also, that a much longer part of the pathway is active in dissipating wave energy during storm conditions. This can be called a compensative mechanism of the pathway. Figure 72, focussing on Rantum, shows this mechanism. Due to the resemblance of all representative transects, the other labs have been omitted.

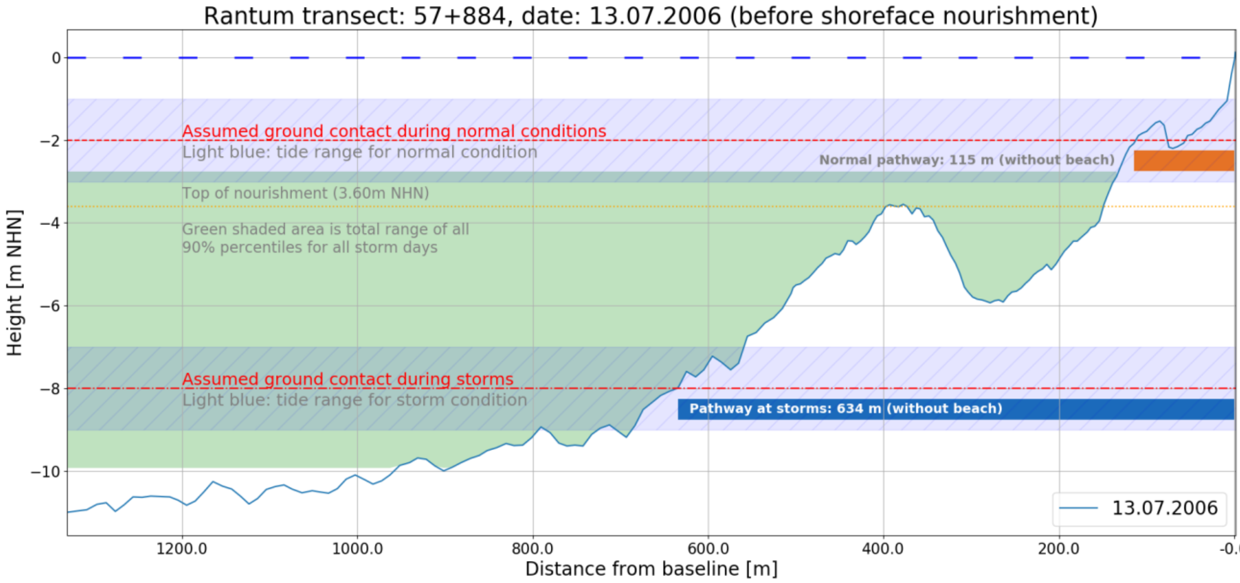

Figure 72: Variability of ground contact of wave energy for Rantum before nourishments

Shoreface nourishment

If a shoreface nourishment is applied like it has been done in Rantum, additional sediments are located at the seaward slope of the bar, which has an effect that can be described in three mutually dependend ways:

- The additional sediments increase the total amount of sediments that are available to dissipate wave energy. The nourished amount in m³ in Rantum is shown in the header of figure 73.
- It can be said that the active part of the pathway is enlarged. In Rantum at -8m NHN the active pathway was only 50m longer(shown in figure 73). At -6m NHN, the difference was as much as 144 m (horizontal distance between orange and blue profile at 6m). The increase of wave energy dissipation due to the longer active pathway should have been largest at a depth of -6 to -5 m NHN.
- The same effect can be seen as a reduction of the resulting average slope of the shoreface in the area of nourishment. While this is trivial because of the increased bar volume, it is still mentionable because of the general knowledge that a flatter slope in the shoreface generally means more wave dissipation until the waves reach the beach. Of course this is valid for all waves whose energy actually reach the ground, what leads to the consideration of the active pathway again.

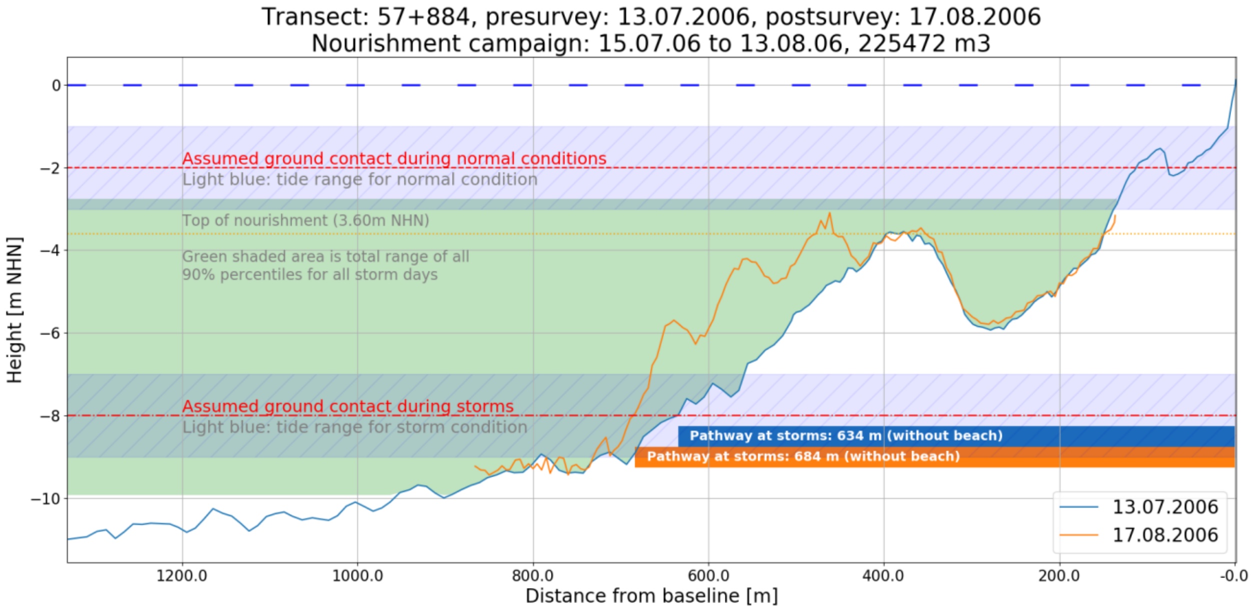

Figure 73: Extension of the pathway due to the shoreface nourishment in Rantum

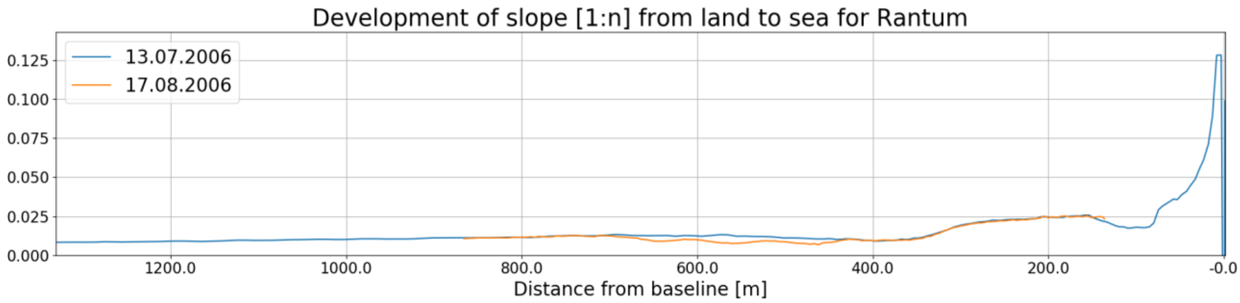

Figure 74: Decrease of slope steepness due to shoreface nourishments in Rantum

The above three points of view all describe an effect for waves whose energy at least reaches to the depth of the top of the nourishment, which is -3.60m NHN. From the wave statistics we can conclude, that on no-storm-days, on mean water level, 87% (low wl: 69%, high wl: 95%) of the waves did not reach the nourishment. On stormdays, assuming a 2m setup on mean water level, 41% (low wl: 22%, high wl: 56%) of the waves did not break at the shoreface nourishment.

These simplified calculations should give an overview over the additional protection a shoreface nourishment can provide, and that it tends to attenuate the effect of stronger storms. The discussed effects that changes in water level have for the status of protection, e.g. length of active pathway, can also be linked to other topics, e.g. the effects of climate change and sea level rise. What this calculation can not predict is, how the protection level actually changes when nourished sediments are relocated, and where these sediments finally settle, their receptor area.

Beach and dunes

The beach and the foredunes are the part of the pathway that provide a protection level not only by wave energy dissipation, but also by flood protection during storm water levels. The area called the “dry beach” is also essential in foredune recreation due to aeolian transport. It has been observed, that after a storm surge that affected the dune foot, the eroded sediments could be found in the dry and wet beach and in the very near shoreface directly after the storm. During calm periods, preferably with easterly winds blowing, sediments can be relocated from the nearshore and the wet beach towards the dry beach. From there on aeolian transport driven by westwinds leads to a rebuild or enhancement of the foredunes.

In Rantum, a beach nourishment was undertaken from Jul. 31th 2016 to Aug. 25th 2016 with an amount of 150451 m³ (120 m³/m). In figure 75, the resurvey is plotted against the presurvey.

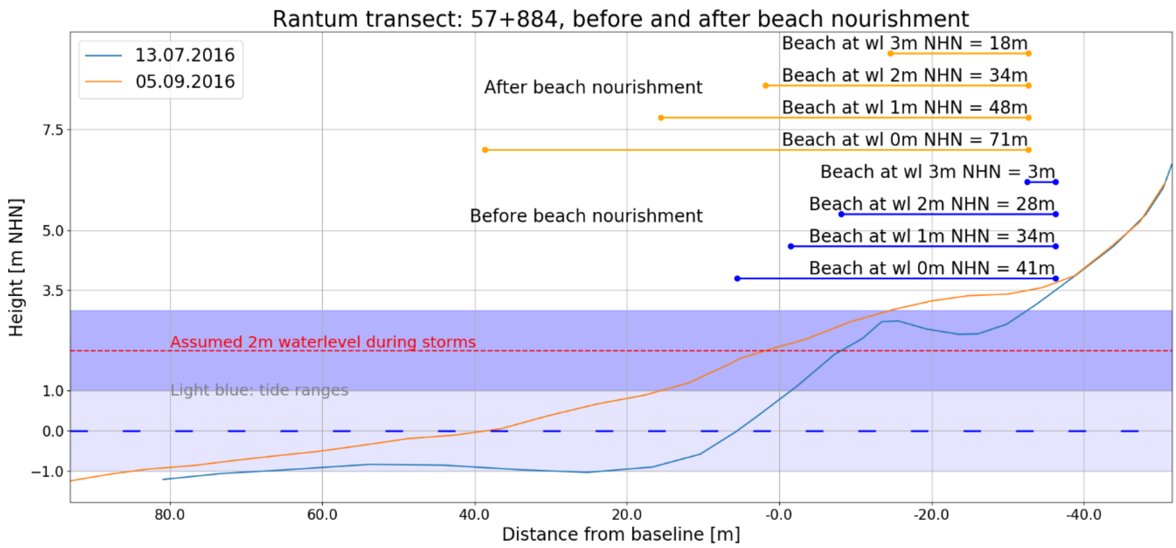

Figure 75: Extension of beach widths due to beach nourishments in Rantum

The plotted beach widths in the graph of figure 75 have significantly been enlarged due to the nourishment. The “dry beach”, which is the beach at the level over 1m NHN, has been widened by 14m, which is mainly the area where sand gets blown out and transported into the dunes, or the dune foot to create new initial dunes. Concerning the water level of 3m NHN, which is a storm surge of 2m setup plus a high tide, the increase in beach width from 3m to 18m can be quite important to keep the swashing of broken waves away from the dune foot.

Conclusions

The topics discussed in this chapter give a comprehensive overview of the services the pathway provides in terms of coastal protection and in what way a nourishment can strengthen the pathway. Dependent on the design as a shoreface- or beach nourishment, the measure adds sediments to the pathway, potentially elongates its active part for energy dissipation, provides sediments for dune recreation due to aeolian transport, widens the beach by relocating the coastal state indicators seawards and strengthens the protection of the dunes due to a wider upper beach.

Describing a system like this, where the status quo is continuously changing, this chapter could only highlight schematically, under which conditions what interactions between the pathway and the energy, provided by the sources, take place. This chapter cannot add new insights in the relocation processes after a nourishment without repeating what has already been provided in the other chapters of this analysis. It is instead, another view to the general functions of nourishments in the BwN labs of Sylt.

9 Conclusion & Recommendations

In making shoreface nourishments the placement and specific amount of material is important. It seems as if much sand is put into the system stronger redistributions are activated, especially in the trough. The sand must be placed at least seaward of the bar top.

Together with the modelling that is done within the BwN-project the longshore transport capacities can probably be used in the future in order to compensate the budget deficit due to the sea level rise in the Wadden Sea and to protect the west coast of the island of Sylt as well. In this way the nourished sand works in more different ways. In order to minimize the gas consumption shoreface nourishments and the use of the longshore transport are sustainable method, partly done by nature itself.

10 References

LKN.SH: “Fachplan Küstenschutz Sylt”

LKN.SH: „Morphologischer Abschlussbericht Vorstrandaufspülungen 2006“

MELUND: „Strategie Wattenmeer“