National Analysis

Germany/Lower Saxony

NLWKN Norden

Published by	Interreg VB NSR BwN – NLWKN Niedersächsische Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz - Lower Saxony Water Management, Coastal Defence and Nature Conservation Agency
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Date	27/05/2021
Status	final
Version	V1.5

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1 Introduction

1.1 Background information

This report is an outcome of the EU-INTERREG VB Project Building with Nature (BwN), written during the project and lastly updated in 2021. This is the so-called national analysis for Lower Saxony of the NLWKN (Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz; Lower Saxony Water Management, Coastal Defence and Nature Conservation Agency). It is a result of a shared common approach, presented in "Co-analysis of nourishments; coastal state indicators and driving forces" by Interreg VB NSR BwN – Rijkswaterstaat WVL (Wilmink, et al., 2021). Additionally, a leaflet is presented, combining the outcome of the various national reports in 2021 (Hoogland, Lodder, & Hillmann, 2021). Parts of this report were also presented in the European Geoscience Union General Assembly 2019, Vienna (Hillmann, Blum, & Thorenz, 2019).

2 Study site

In 2007 and 2010 the Master Plans Coastal Risk Management for Niedersachsen, Bremen and East Frisian Islands were issued (NLWKN, 2007) (NLWKN, 2010). Primary objectives of coastal risk management are safeguarding of coastal areas against flooding due to storm surges and guaranteeing the existence of the inhabited islands. New embankments are not planned (Thorenz, 2008).

Since 1955, approximately 2 billion Euro were invested in coastal defence measures. The primary dike line along the mainland coast was significantly straightened and shortened from over 1100 km to 610 km. Seventeen storm surge barriers have been built in order to cut off the tributaries of the tidal rivers Ems, Weser and Elbe from the influence of storm surges. Due to historical reasons, secondary dikes exist for 20 % of this defence line. Wide-stretching coastal areas are protected. Hence, an equal safety standard is defined for all flood protected areas.

Figure 1 Langeoog Living Laboratory. Copernicus Sentinel 2-Image 06.08.2018

The island of Langeoog, which serves as a coastal laboratory "Langeoog Living Laboratory" in BwN, is one of seven inhabited barrier islands situated along the East Frisian German North Sea coast (Figure 1). This coastal area can be classified as mesotidal with semidiurnal tides with a mean tidal range of about 2.7 m at the Langeoog gauge (BSH - Bundesamt für Seeschifffahrt und Hydrographie, 2017). For 2018, the mean low water level (MLWL) is NHN -1.27 m and the mean high water level (MHWL) is about NHN +1.36 m for the period of 11/2000 - 10/2010 (WSV, 2018). The abbreviation "NHN" means "Normalhöhennull" (standard elevation zero) and is handled as the equivalent of mean sea level (MSL) in Germany.

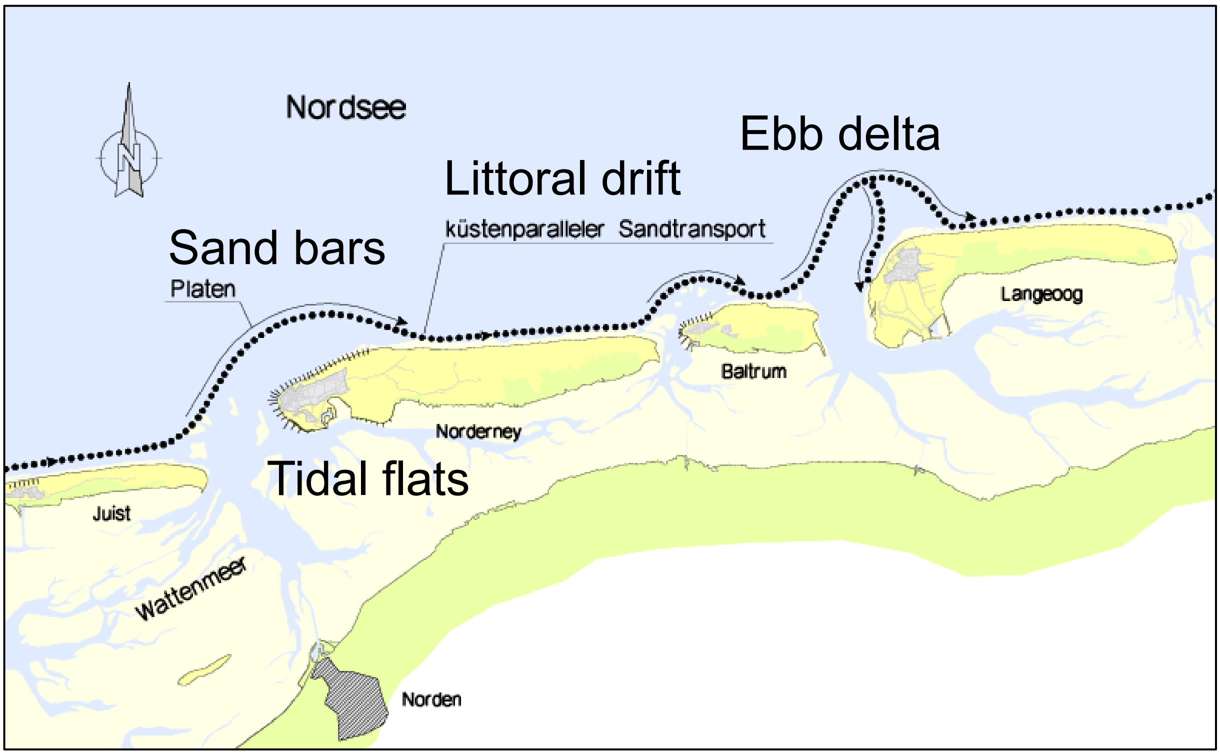

Figure 2 Natural sand transport of the barrier islands

Figure 2 shows the natural littoral drift of sand in a generalized form. The aerial photo taken in 2016 in Figure 3 shows the nourishment areas of 2017 and 2018, situated on the northern beach. The tidal shoals forming the ebb delta of the Accumer Ee can be identified, as bright areas even if a water layer covers these shoals. Time series of aerial photos and additional bathymetry data are used to analyse the drift of the shoals, displayed as blue arrows in Fig 3.

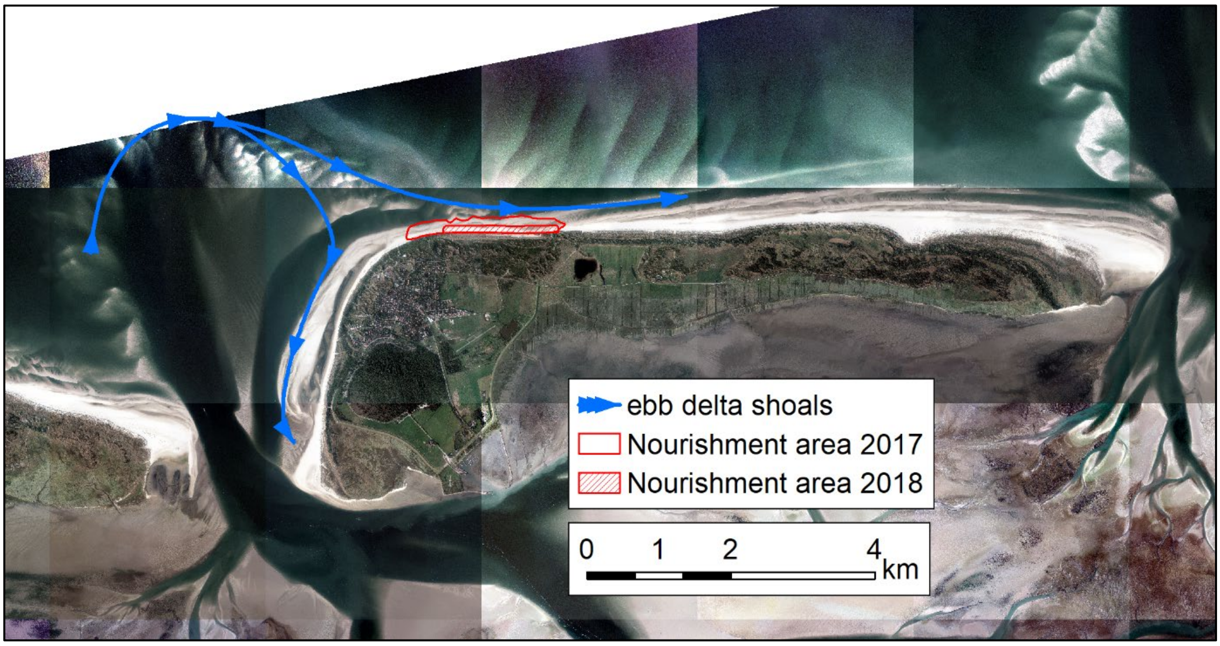

Figure 3 Littoral drift and ebb delta of Accumer Ee (tidal inlet between Baltrum and Langeoog)

The shoals approach the island of Langeoog at its most north-westerly part, approximately between transect 24 and 35 (see Fig. 4). The shoal melding on the beach, is a complex morphological process causing local morphological changes of the beach. In the case of Langeoog, the sediment volume of the former shoal splits in two main directions with different and changing ratios. A southern pathway and an eastern pathway can be identified and result in a sediment supply of the western beach and northern beach, respectively. Since the development of the coastal dunes is very depending on the situation of the connected beach, a reduction of the natural sediment supply often effects the dune (ridge) negatively. Dunes, being the only element of the coastal defence system, are very dependent of the sand bars in front of the island. Since the end of the last century, the main focus of attentions has been on the dune ridge situated northeast of the settlement. This dune ridge protects the Pirolatal and the drinking water supply wells located therein against flooding. The total amount of sediment transported in shoals towards the beach as well as the ratio between the before mentioned pathways is irregular in time.

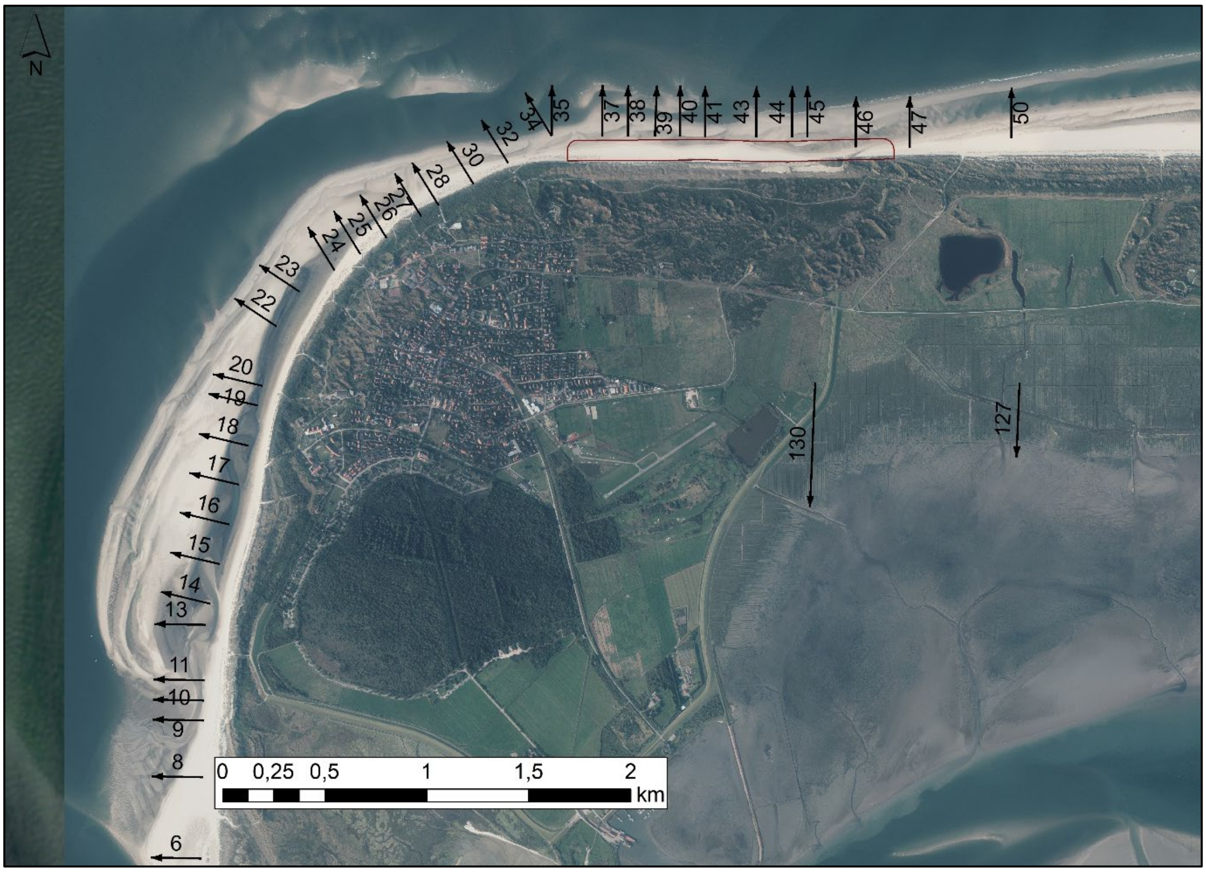

Figure 4 Transect Overview of Langeoog

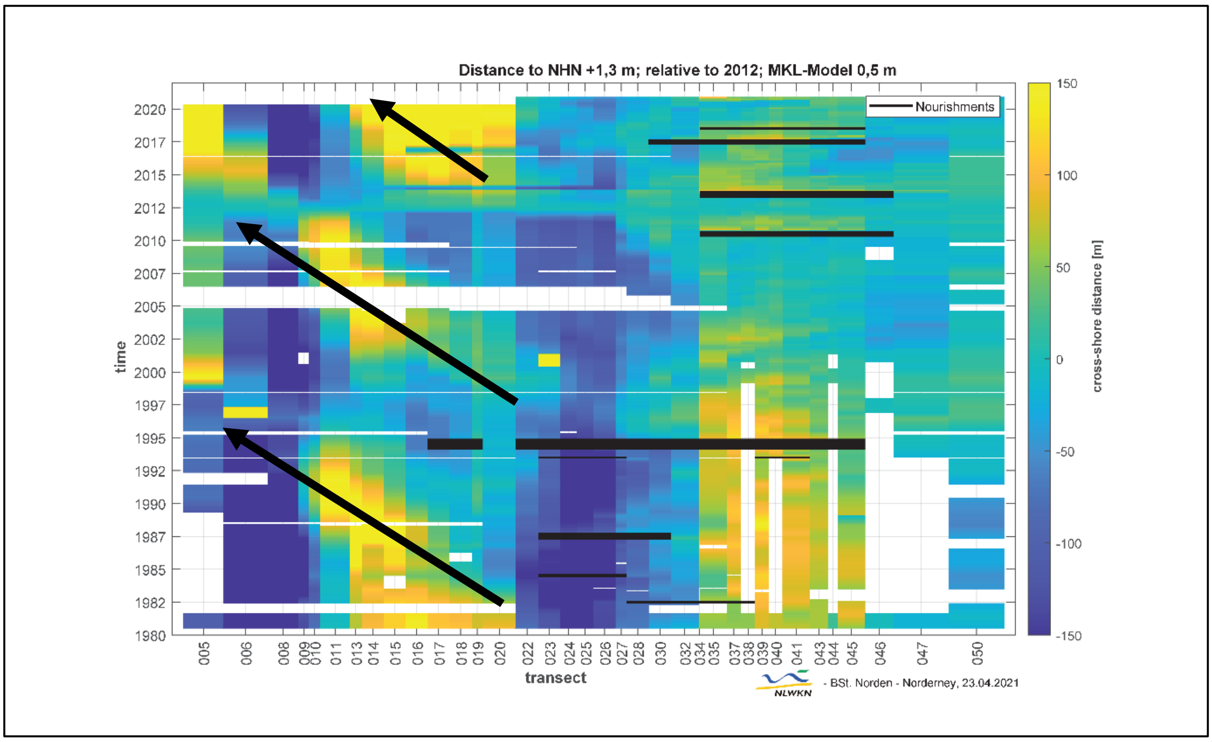

Figure 5 Time-distance diagram of the main transects (locations see Figure 4)

In the last 30 years 3 greater sand bars melted into the north-western part of Langeoog. This development is depicted in a time-distance diagram as presented in Figure 5. Arrows are set manually to indicate sand migrating on the western head of the island from north to south. One part of the sand migrated south is visible as a long extended shoal forming a spit in front of the dunes between transect 10 and transect 28. Although this situation can change in decades, right now the dunes in the north-western part of Langeoog, between transect 35 and 45, have a negative sediment balance, whereas parts of the western dunes profit from the southerly transport.

Figure 6 Sand bars in front of the north-western head of Langeoog. Taken at low spring tide 17.04.2018.

When sand is placed on the beach, whether by natural drift of sand bars or by nourishments, it will be naturally moved. Starting on front of the dunes of the Pirolatal, approximately around transect 39/40, there are bar-through systems developing (Figure 7 and Figure 8). These bars are connected to the beach on their western end and have an angle about 10°- 5° off from the shoreline, visible in the contour line of mean high water. The eastern part of the bar gets shallower as it reaches into foreshore beach. All bars are drifting to the east, where they are finally melting to the beach in their full length. New bars are permanently developing in the area where the tidal shoal is melding at the island’s beach. In front of the bar-through system, other bars are migrating from west to east, which are described as saw tooth bars (“Sägezähne”).

Another considerable part of the sand is transported by wind, known as aeolian sand transport. Every year NLWKN is setting up sand trap fences in front of the dunes, to enhance the dune volume, especially of the lower dune. The sand trap fences consist of brush wood and represent another kind of “Building with Nature” method in a coastal environment.

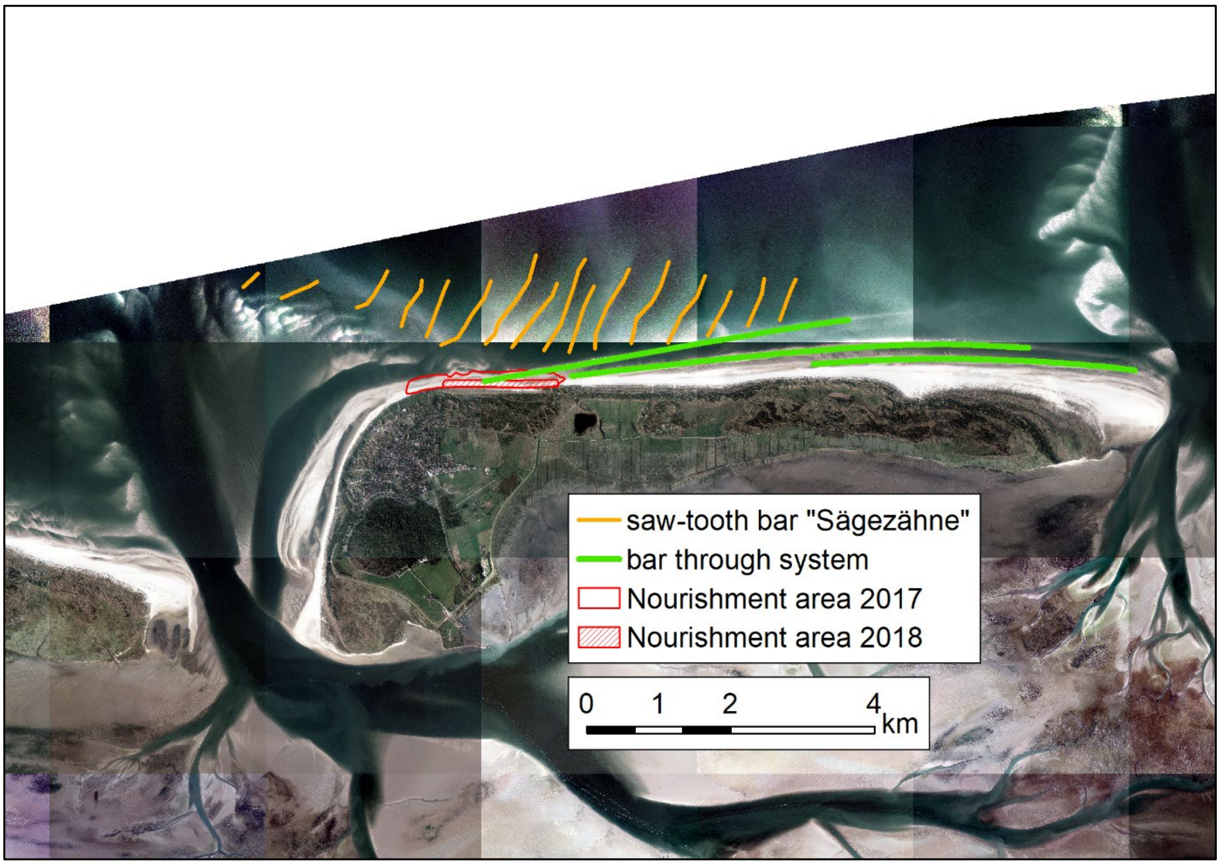

Figure 7 Bar-through system and forshore bars on aerial view

Figure 8 Bar-through system at low tide [17.04.2018 NLWKN]

3 Nourishment description

3.1 Coastal infrastructure and earlier nourishments

On Langeoog approximately 5 million m³ of sand have been nourished since 1971 to ensure the protection of dunes, to bridge temporary sediment deficient phases resulting from temporally and spatially varying approaching of tidal shoals. To protect the inhabited areas against flooding and erosion, the beach-dune system must contain a sufficient volume of sediment. The northwestern and northern part ot Langeoog is only protected by dunes. No hard structures like dikes are present here. Therefore the dunes are of major importance for Langeoog. Due to the location close to the tidal channels with depth over NHN - 20 m and a very shallow shoreface area, mostly beach nourishments are chosen to refill directly the beach sections. See Table 1 and Figure 9 for an overview of beach nourishments on Langeoog.

The sand for the beach nourishments of Langeoog is taken from the nearby tidal inlet Accumer Ee. These areas were, because here large amounts of sufficient sediment is available and the extraction area can regenerate rapidly. Using a cutter dredger, or in some cases a hopper dredger, the sand is excavated and pumped as a sand-water mixture via a pipeline on the beach. On the beach, the sand is spread and profiled by bulldozers.

Table 1 History of nourishments on Langeoog

Location	Start	End	Begin transect	End transect	Length [m]	Volume [m³]	Remark
Pirolatal	07/1971	09/1972	25	45,5	2500	260000	
Pirolatal	07/1982	09/1982	28	40	1200	550000	
Nordweststrand	07/1984	09/1984	22,5	29	1200	290000	
Nordweststrand	07/1987	09/1987	22,5	30	1400	560000	
Nordweststrand	07/1993	09/1993	24	28	650	100000	1/2
Pirolatal	07/1993	09/1993	40	42	450	50000	2/2
Weststrand	07/1994	09/1994	17,5	19,5	450	100000	1/2
Nordweststrand	07/1994	09/1994	25	46	3100	860000	2/2
Nordstrand	07/2010	09/2010	35	47	1750	500000	
Nordstrand	07/2013	09/2013	35	47	1750	600000	
Nordweststrand	07/2017	10/2017	30	47	2000	400000	1/2
Nordstrand	07/2018	09/2018	37	47	1500	200000	2/2
Nordstrand	06/2020	10/2020	37	47	1500	650000	

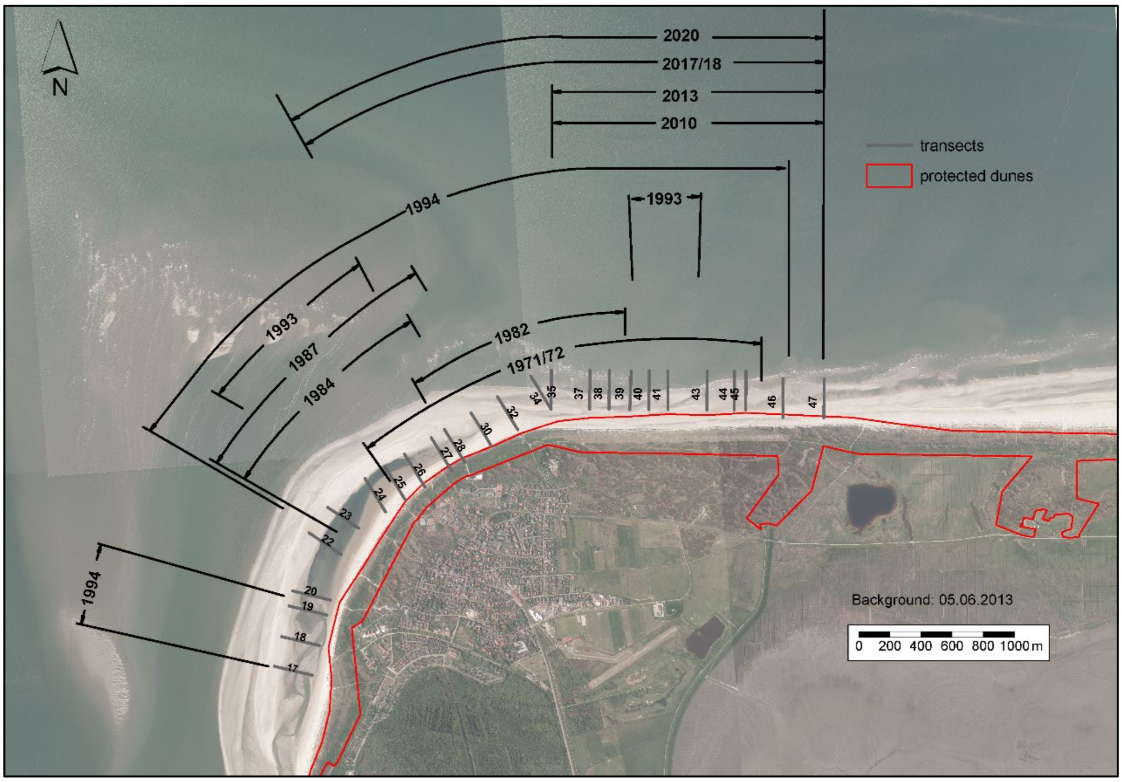

Figure 9 Nourished beach sections at western part of Langeoog since 1971/72 up to 2020

The studied nourishment in this report was designed to be implemented in 2017. Technical design parameters are listed in Table 2. The location of the nourishment area and extraction site is shown in Figure 10. Due to weather conditions and associated technical issues, the nourishment had to be split into two parts. The last part was nourished in late summer 2018. The 2017/2018 nourishment of Langeoog had one main goal: Coastal protection of Langeoog. This can be divided into two sub goals. First, the protection of the dunes for coastal protection by increasing the sediment supply of the northern beach. Secondly, the enhancement of the protective dunes in front of the “Pirolatal”, which were eroded in the years 2014 until 2016.

Figure 10 Langeoog Nourishment extraction site (green) and nourishment area 2017 (red) 2018 (blue)

Table 2 Parameters of the 2017/18 nourishment design

Parameter	Design
Volume	Total: ~600.000 m³
Length	~2000 m
Height	3,5 - 5 mNHN
Slope	1:30-1:10 below mean high water level
Type	Combined beach and foreshore nourishment
Grainsize (Mean d_{50})	Before: 0.26 mm (mean of NHN +2 m level: 0.23 mm; mean of NHN +0 m-level: 0.30 mm Nourished sand: 0.23 mm
Extraction site	Acummer Ee (tidal inlet between Baltrum and Langeoog)

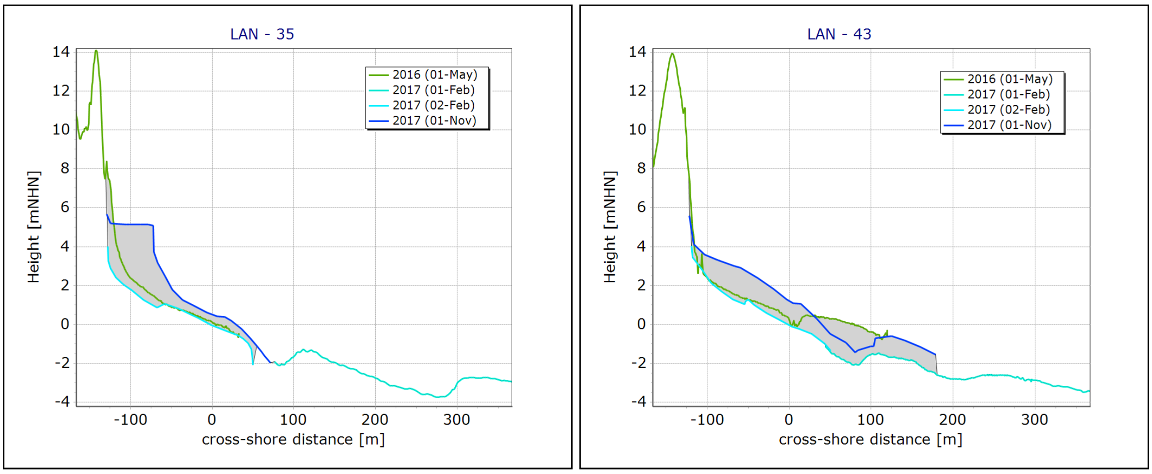

Figure 11 Design of the nourishment 2017 in transect 35 (west) and transect 43 (east)

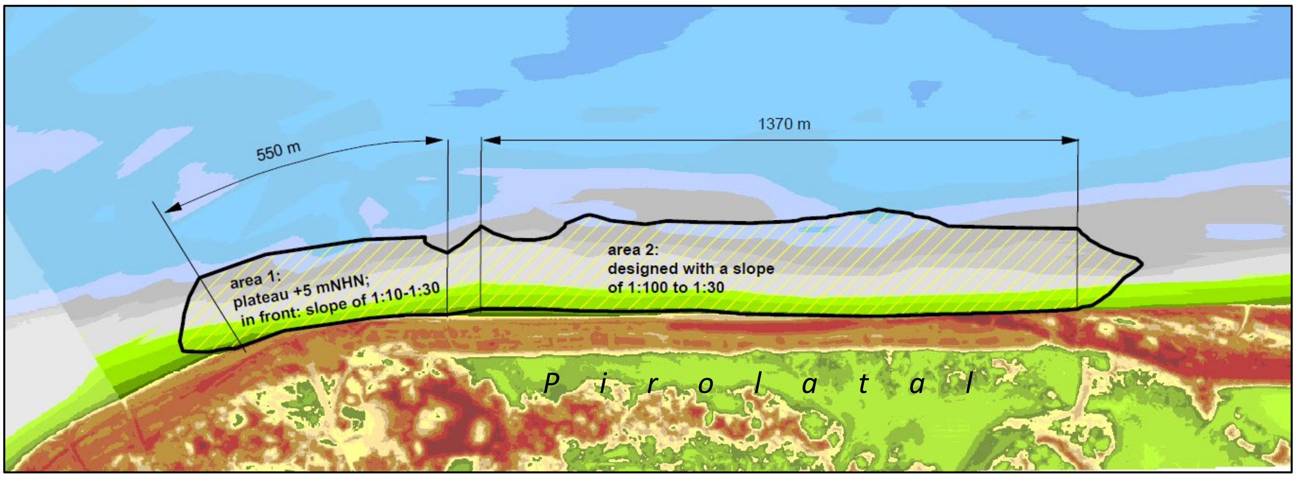

Figure 12 Design of the nourishment 2017

The western part of the nourishment 2017 is partly designed as a plateau with the height of 5 m (see Figure 11 and Figure 12) This is meant to work as a wear and tear body ("Verschleißkörper") to protect the dunes alongside. Additionally, this design concept uses the natural easterly transport direction in this area to feed the north beach including the beach and dune system in front of the Pirolatal.

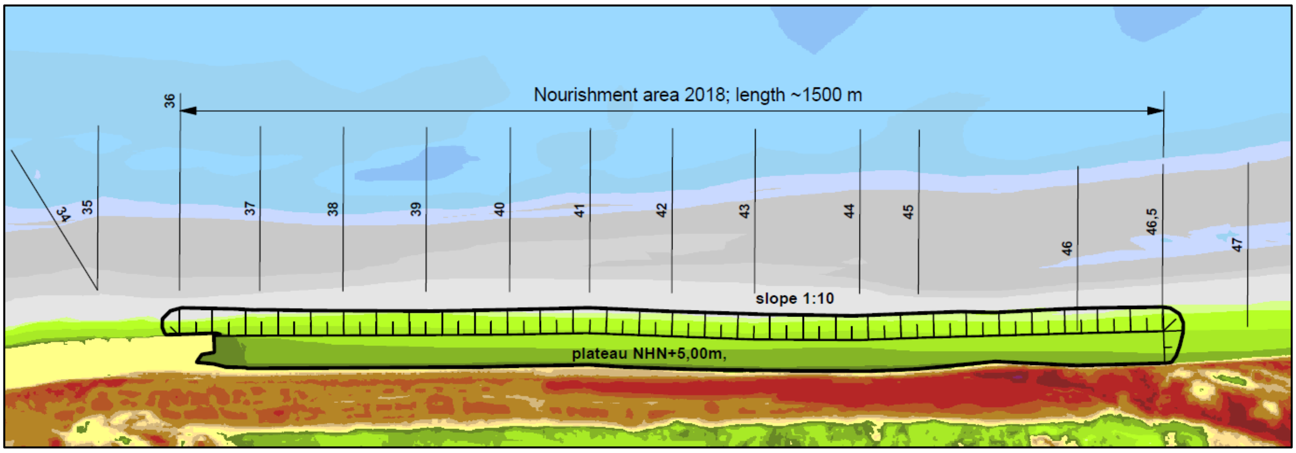

Figure 13 Plateau-design of the nourishment 2018

Due to bad weather conditions in 2017, the nourishment could not be finalized in 2017 and had to be completed in 2018. With help of a numerical model (XBeach) two different designs were evaluated to investigate the further stability of the nourishment under different wave conditions. The results coincided with measurements during the ongoing nourishment and during winter 2017/2018. As a result, it was decided to complete the nourishment in 2018 in a modificated shape, as a plateau-design (see Figure 13).

4 Method and data

4.1 Data, availability, accuracy and processing

4.1.1 Transect data

Transect measurements in this area above the mean low water level are available in high frequency, up monthly RTK-measurements. Below mean low water level it is planned to have measurements at least twice a year. It highly depends on natural circumstances (weather, waves, tide and daylight) to conduct a survey in these shallow areas. Dry areas (above mlwl) are measured once a year using laser altimetry and additionally with RTK-measurements. Wet areas (below mlwl) are measured using singlebeam echosounders by NLWKN or external companies or agencies at least once a year, but on irregular basis. Each measurement is a single dataset, no dataset is a merged dataset of bathymetric and topographic data.

4.1.2 Hydrodynamic data

Long-term hydrodynamic data is available from the FINO1-Platform. In addition, project-related hydrodynamic data is measured with a wave buoy and ACDP, both located in front of Langeoog.

4.1.3 Nourishment data

Detailed information about the extraction of sand during the nourishment is available. This is mainly tracking-data of the dredger.

4.1.4 Additional data

Aerial photography is available within some lidar measurements. Digital aerial photography on a nearly yearly basis is available since 2000. Drone footage of the sand bars and nourishment area is available from the end of 2017 on. Grain size distribution of the sand on the beach before and after the nourishment is monitored.

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 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. hanges 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 14 will be applied throughout the analysis. The CSI's corresponding to the coastal terminology are shown in Figure 14 and described in Table 3. On the vertical axis various levels in the profile are shown. The horizontal axis shows different morphological zones in the profile. The morphological development represented by the CSI will be analysed in order to reveal the morphodynamics and the effects of nourishments.

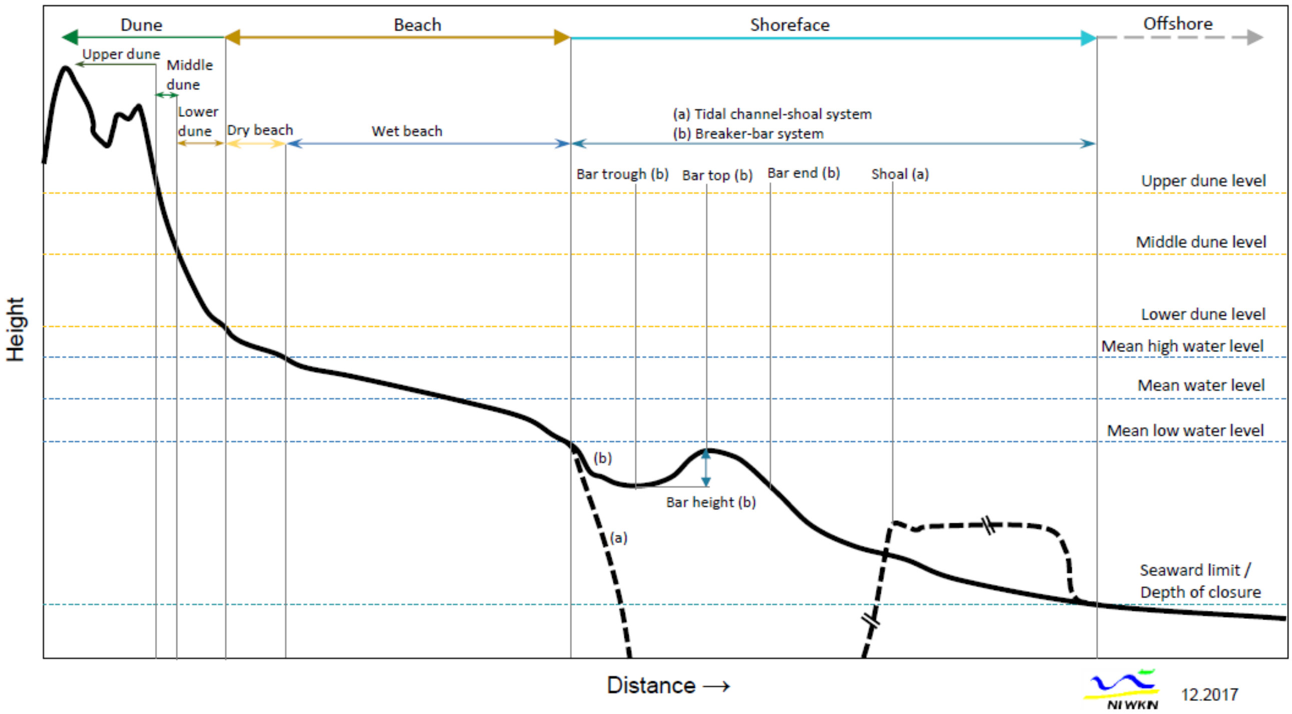

Figure 14 - General terminology used to describe the coastal profile

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 BwN-laboratory. Only when this gives unsuitable results the level should be differentiated.

Table 3 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
Dune	**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.
Dune	**Middle dune**	Coastal sub- section
Dune	**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.
Dune	**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
Beach	**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.
Beach	**Wet beach**	Coastal sub- section
	Mean low water level (MLWL)	Fixed height level: MWL - ½ Tidal Range. A best estimate and fixed height during the time of analysis is recommended for simplicity.
Shoreface	**(a) Tidal channel-shoal system** **(b) Breaker-bar system**	**(a)** Morphological features. Channel: Deep section between MLWL and the front of the shoal. Shoal: a relatively large shallow area not connected to the beach which is shaped primarily due to tidal forces (eg ebb tidal delta's). **(b)** Morphological feature. Bar: sand accumulation created by the action of currents and waves. A bar has the following characteristics: Bar top: maxima in the shoreface profile where the slope changes sign. Bar trough: depression between two bar crests, or in between a bar top and a point landward from the bar, at the same depth. Bar height: difference in height between bar top and the deepest point of the bar trough. Bar landward limit: deepest point landwards of the bar top.
	Seaward limit* / 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 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 "kustlijn" Coast Line) approach should be used. The model determines the surface area balance point of an area. Figure 15 shows an example of the MKL-calculation.

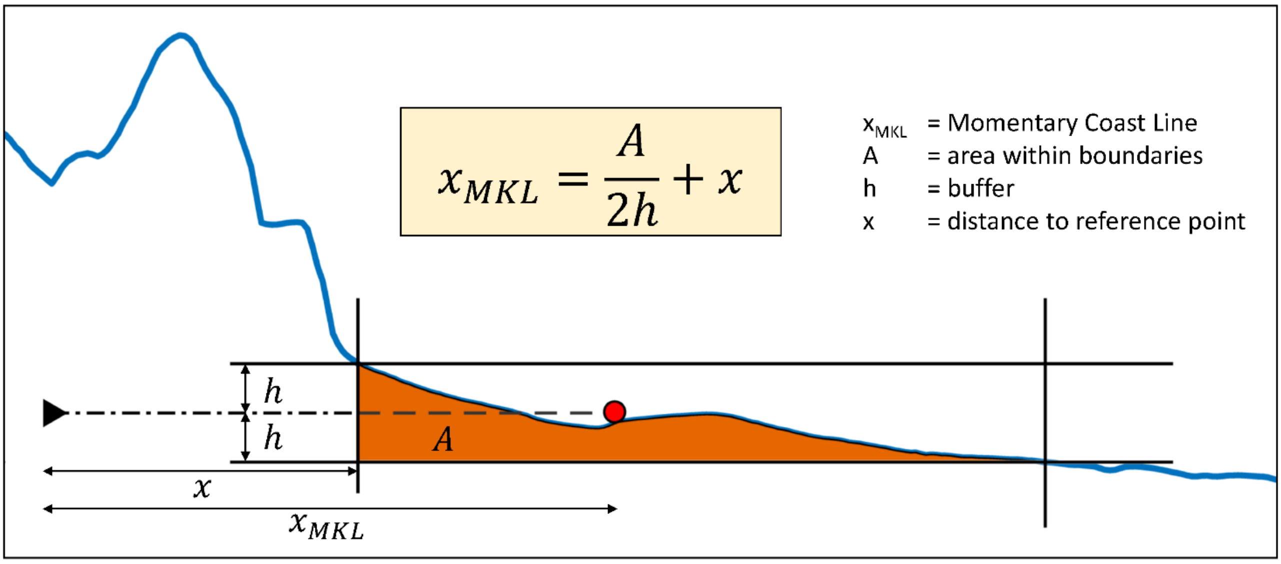

Figure 15 Defenition of the MKL-Model

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 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 conducted for at least one representative transect in the nourishment area. Recommended tools are MATLAB or MorphAn.

4.2.3 Bar development

Not content of this report. On Langeoog there are no typical bar systems comparable to the coastal laboratories in the Netherlands or in Denmark.

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 volume of a particular vertical layer and will show the demand of needed measures. The trends in volume development will result in the contribution of various nourishments (size, location) to coastal volume (and indirect coastal safety).

A way of presenting is 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 multiples 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 (i.e. the horizontal distance corresponding to a certain height level). The calculation can be performed by the volume model of MorphAn. In this analysis, it is carried out with ArcGIS and Excel.

4.2.5 2D volume development: Volume boxes

In the 2D volume analysis method, first the boundaries of the boxes are defined. Coast parallel boundaries (based on vertical level) are chosen based on the physical marks and nourishment properties, while coast perpendicular boundaries are based on morphological patterns of 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 the start of the nourishment.

When digital elevation data grids are available, in a GIS application depth contours can be derived and used to construct boundaries of the boxes. In MorphAn 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 are 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, i.e. up and down stream of littoral transport).

A difference map showing the nourishment (the first measurement after the nourishment minus last measurement before) can be used to define the boundaries. In MorphAn 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 MorphAn 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^2) are subtracted from the volumes calculated in the last measurement before nourishment, resulting in relative volumes (m^3/m^2 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

5.1 Waves

Long term waves characteristics for Langeoog can be described with two measuring locations. FINO1-Platform is located 45 km offshore (FINO1, 2018). For a time period starting in 2017, NLWKN has a wave buoy located 3 km offshore and a ADCP-Platform located in the surf zone, measuring during high tide. In Figure 16 different locations can be compared. Due to technical problems with the measurement buoys and because the final data is not yet fully processed, only a sequence is shown here.

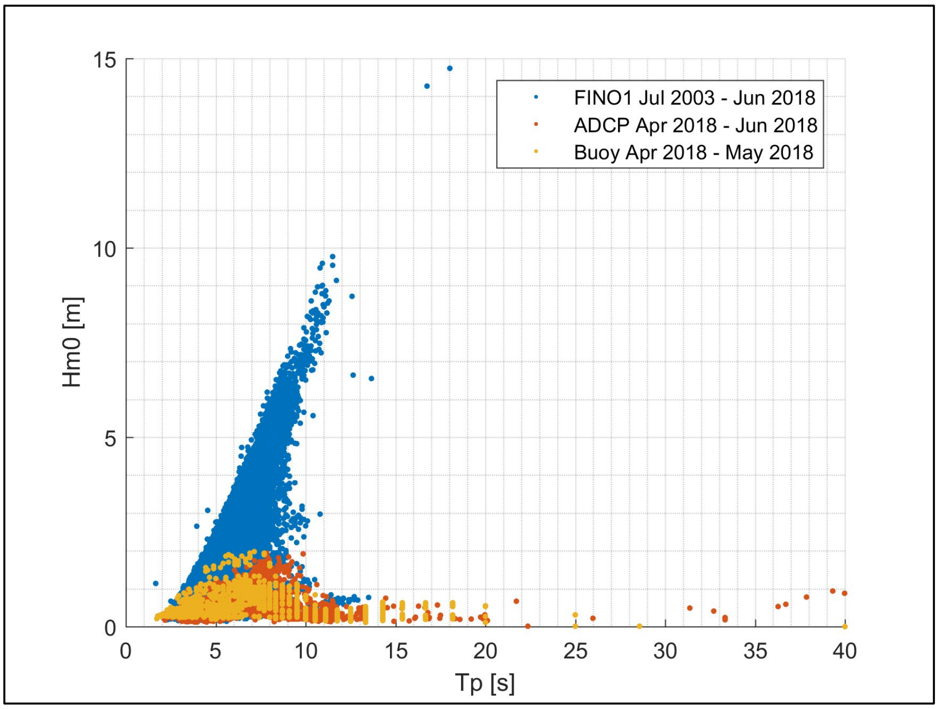

Figure 16 Different measurement platforms to compare results

5.2 Tides

This coastal area can be classified as mesotidal with semidiurnal tides with a mean tidal range of about 2,7 m at the Langeoog gauge (BSH - Bundesamt für Seeschifffahrt und Hydrographie, 2017). For 2018 the mean low water level (mlwl) is about NHN -1,3 m and the mean high water level (mhwl) is about NHN +1,4 m.

5.3 Storm surges

Storm surge events are recorded at two tidal gauge stations: Langeoog and Norderney-Riffgat. The number, the height as well as the time series will be monitored in the assessment of the 2017/2018 – nourishment.

5.4 Wind

Wind conditions for Langeoog can be derived from the platforms of the Deutscher Wetterdienst (DWD), for instance on Norderney. This data is public and can be downloaded from the DWD (Figure 17) (DWD Deutscher Wetterdienst, 2021).

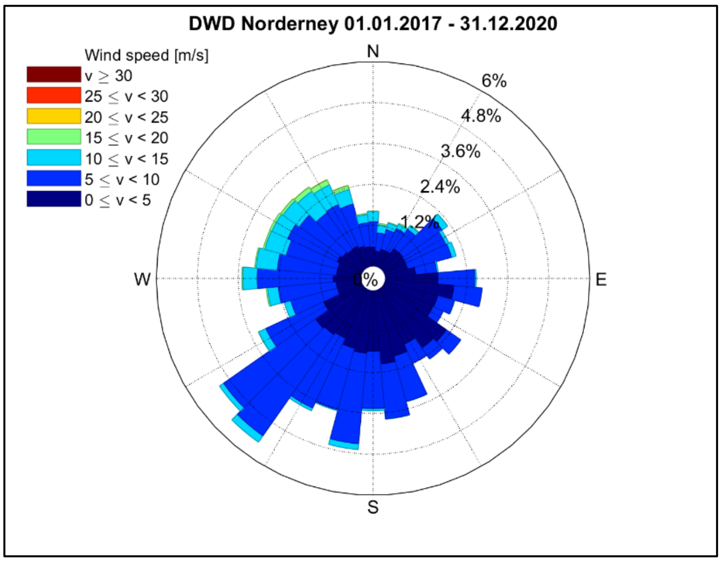

Figure 17 Measured wind at Norderney [DWD, 2021]

5.5 Grain size

The mean grain size for Langeoog (d_{50}) is about 0,25 mm. The upper beach and dune foot area has a mean grain size of about 0,20 mm, whereas in the surf zone it is about 0,30 mm. During the project, grain size distribution is futher monitored.

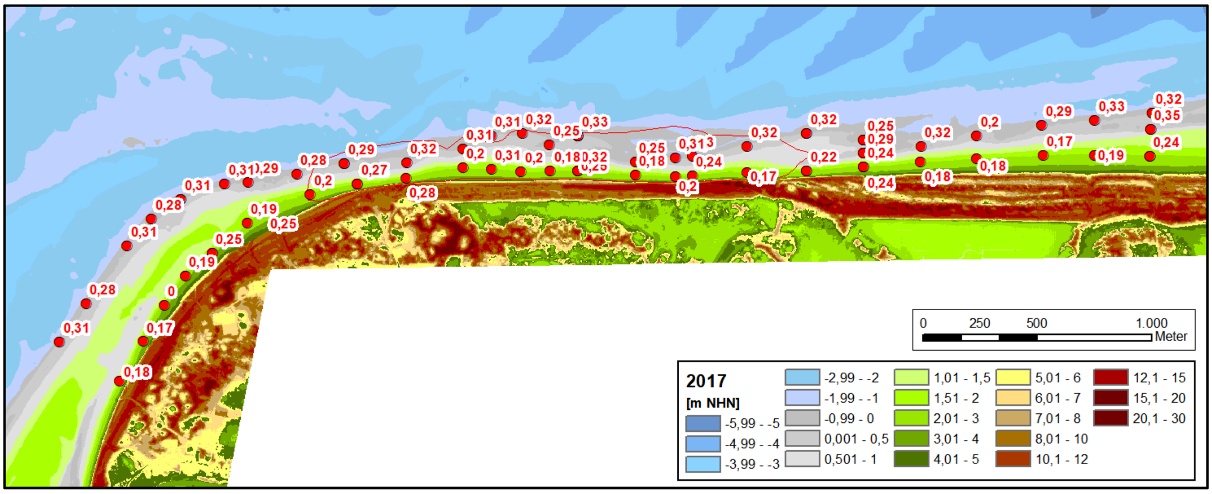

Figure 18 Spatial distibution of d_{50} mean grain size parameter [mm], pre nourishment 2017

6 Results

6.1 Qualitative Morphological development

6.1.1 Shoreface incl. Breaker bars

The shoreface area is mainly dependend of two different morphological features. First, the sand shoals which are migrating through the ebb tidal delta. Secondly breaker bars, which are connected to the beach with their western end. They are migrating in an eastern direction (see Figure 19).

The breaker-bar system is developing from the nourishment area towards the eastern end of the island. Because the breaker bar systems are too deep for manual terrestrial measurements, but the area is too shallow for hydrographic measurements in a high frequency, they are hard to detect in the transect data. Often the measurement is not reaching through the bars neither from the seaside (hydrographic), nor from the dry side (terrestrial).

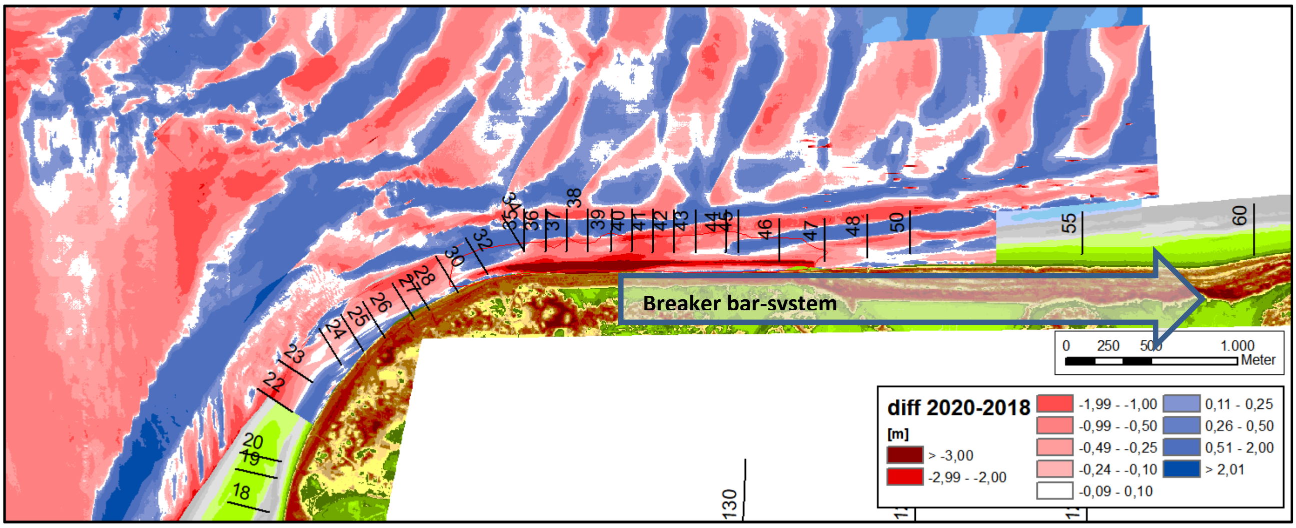

Figure 19 Qualitative differential map of two bathymetry measurements

6.1.2 Beach

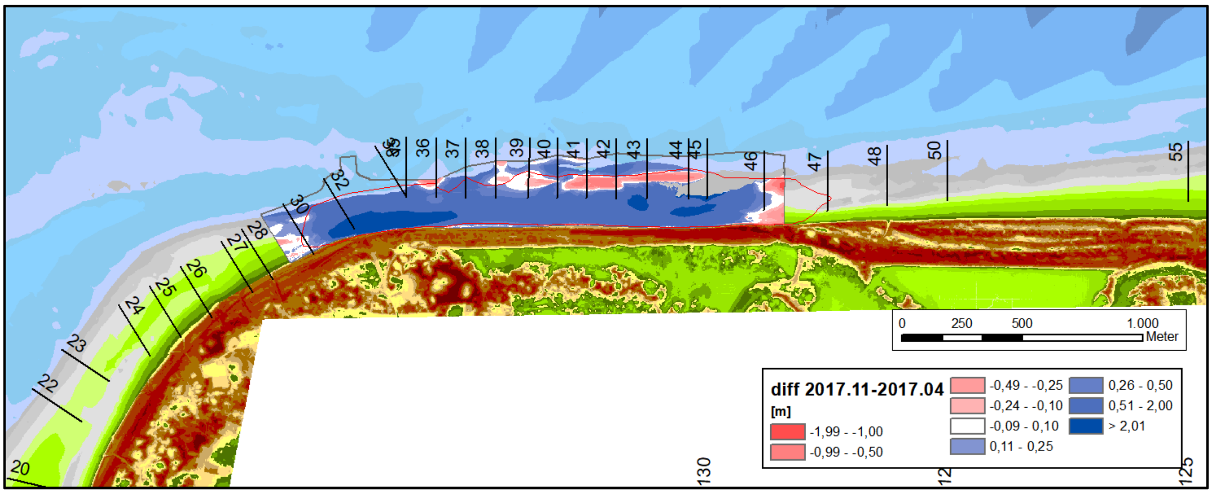

Figure 20 Differential map of before and after the nourishment in 2017

The nourishment in 2017 is clearly visible (see Figure 20). There are measurements before and after each section was nourished. After the nourishment was finished, a high frequency monitoring program was conducted.

6.2 Quantitative Morphological development

6.2.1 Physical marks

Transects 37, 41 and 45 are chosen as representatives. The nourishments, as stated in section 3.1 are visible in the diagrams, primarily in the dune foot line NHN +3 m. During the time of nourishments in a high frequency from 2010 on, in both transects 37 and 41, the beach gets wider and dune erosion is not happening on larger scales like before 2008 (see Figure 21 and Figure 22). Transect 45 however shows a different behaviour (see Figure 23). Although the nourishments can be seen, the beach is not getting instantly wider as the transect is located at the eastern end of the nourishment area

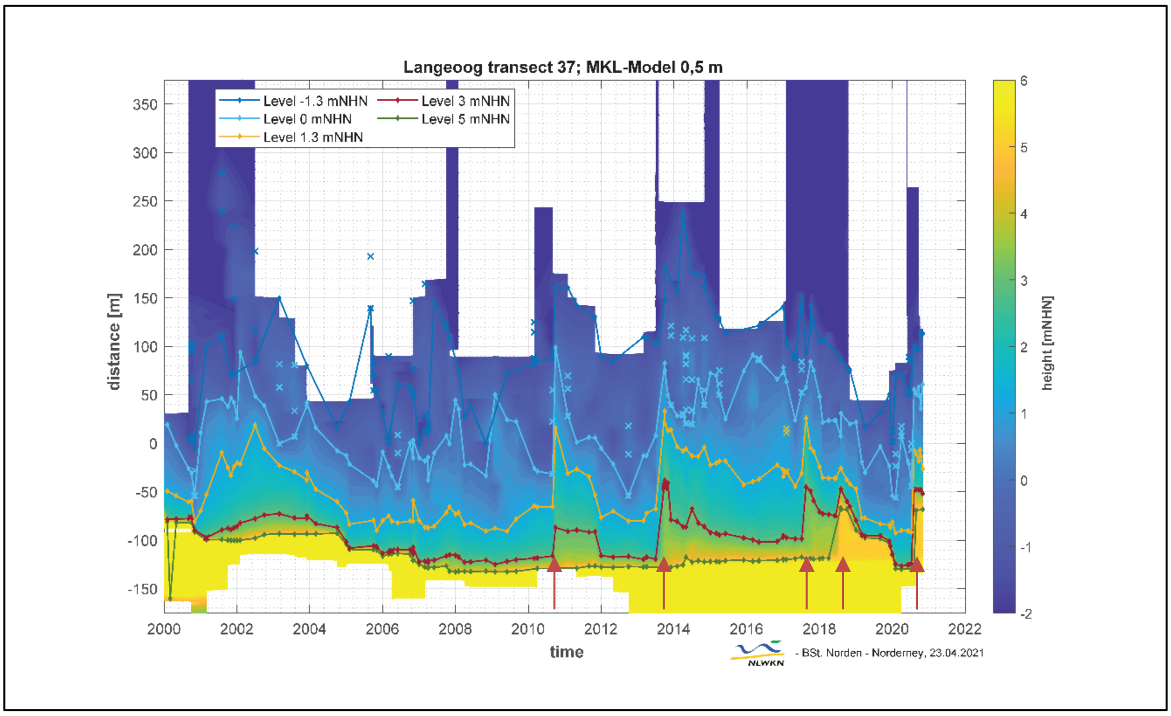

Figure 21 Transect 37. Arrows indicate nourishments.

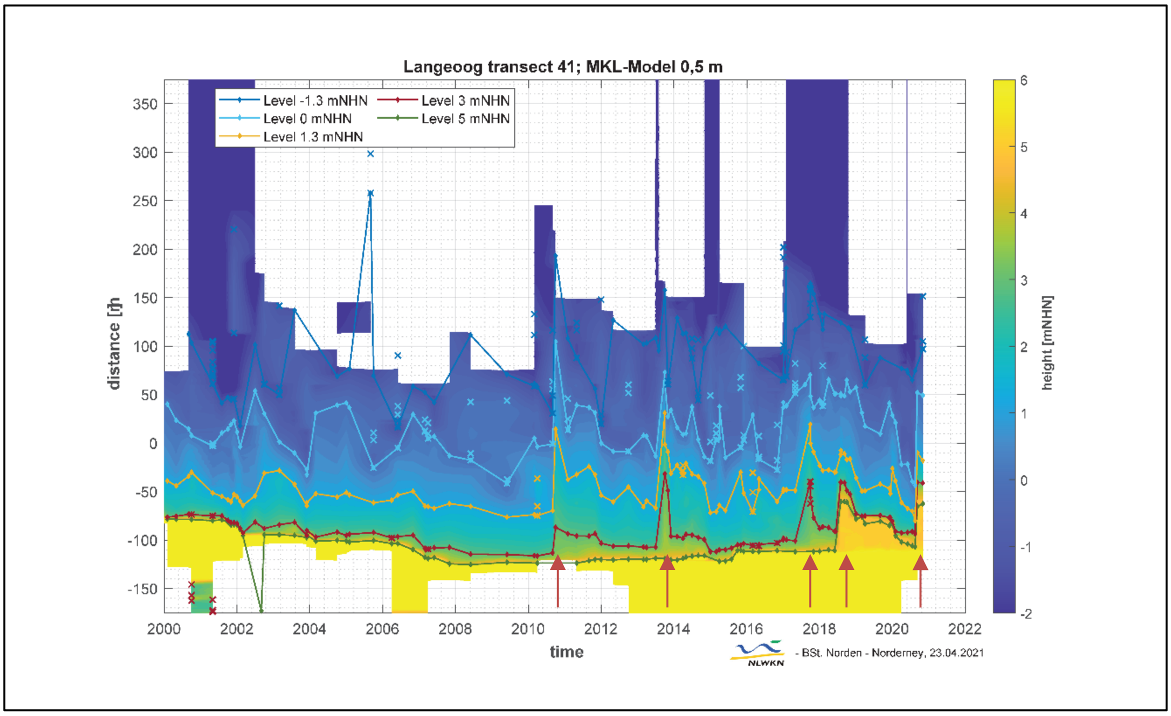

Figure 22 Transect 41. Arrows indicate nourishments.

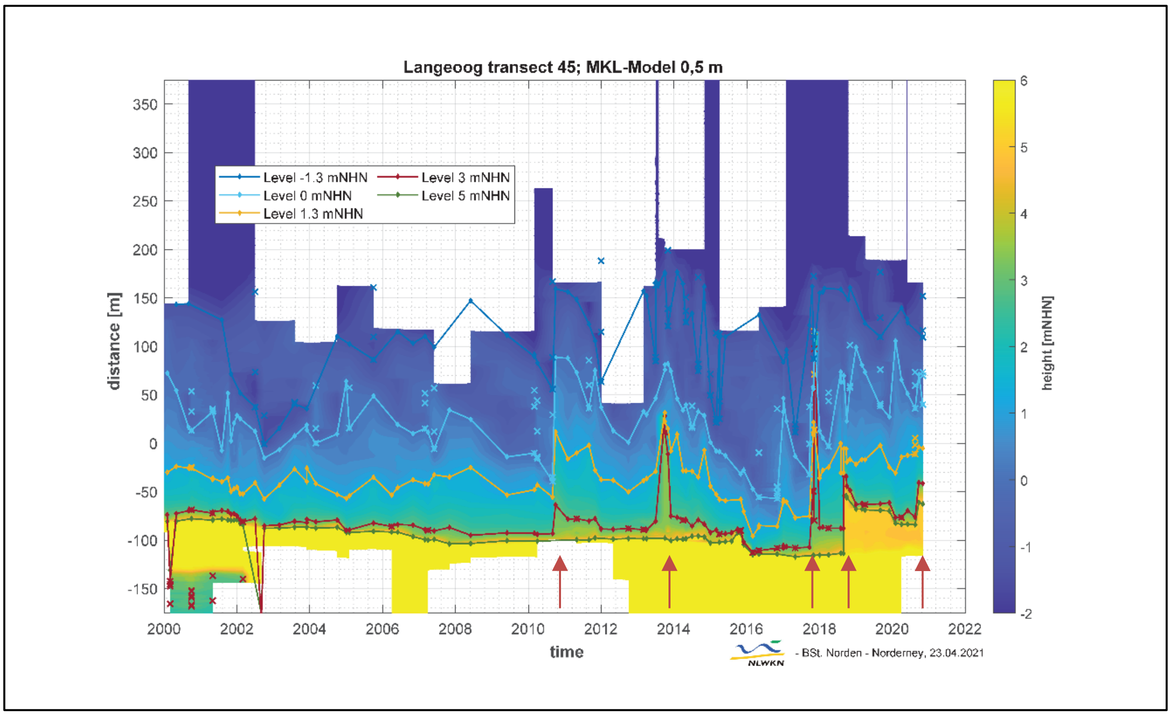

Figure 23 Transect 45. Arrows indicate nourishments.

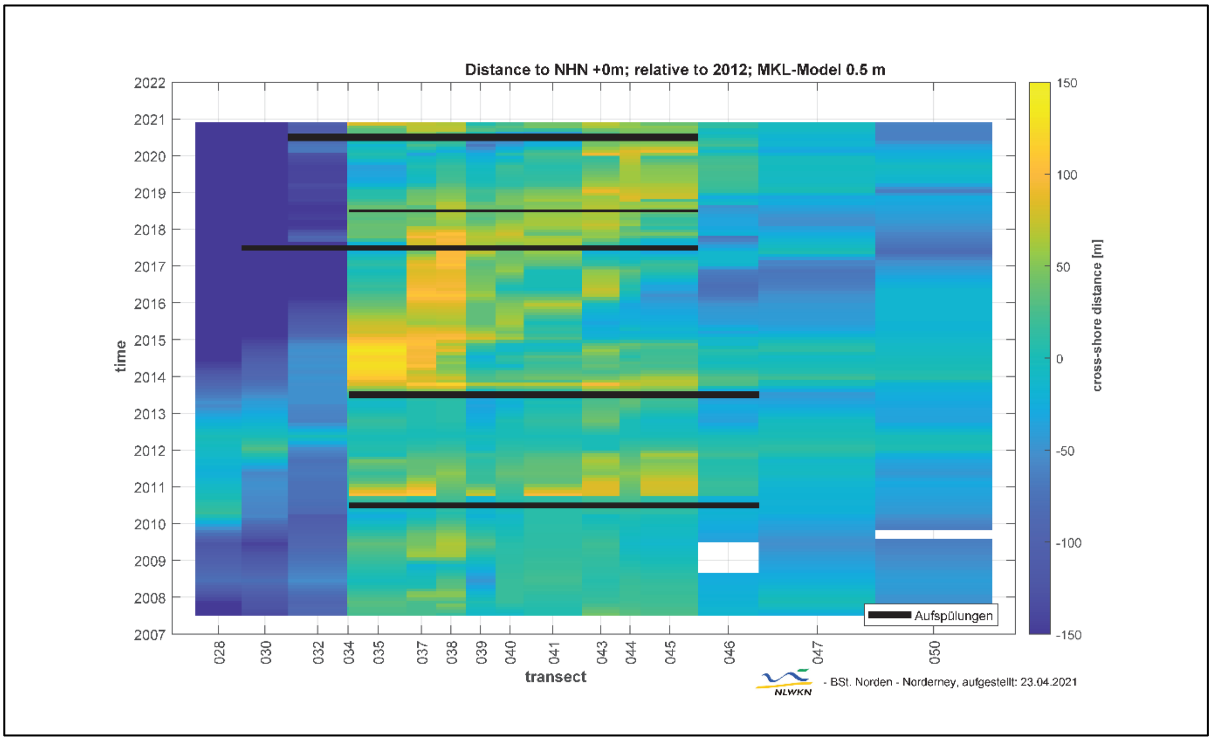

Figure 24 Physical mark for all transects of the nourishment area.

Figure 24 shows the physical mark of 0 mNHN for the area of nourishment and the surrounding transects. As in the single transect diagrams, the nourishment can be seen as an increase of the cross shore distance. Between 2013 and 2017 sand volumes appear to migrate from west to east.

6.2.2 Volumes 1D

The calculation of 1D-Volumes show the actual development of the volume of sand in the nourishment area. In Figure 25, Figure 26 and Figure 27 this is shown for the transects 37, 41 and 45 for the nourishment 2017/18. The volume development varies in the transects. The nourishment placement in 2017 and 2018 is visible with two peaks in volume and the following decreasing. The future development varies from a high decreasing in transect 37 up to the year 2020, to a more moderate decreasing in transect 45. In transect 37 and 41 the volume in 2019 is below the volume before the nourishment has been placed. In transect 45 the volume in 2020 is still higher than before the nourishment. In all transects a volume decrease can be seen in the beginning of 2020. This is related to a severe storm surge event in February 2020, which led to large erosion especially in transect 37.

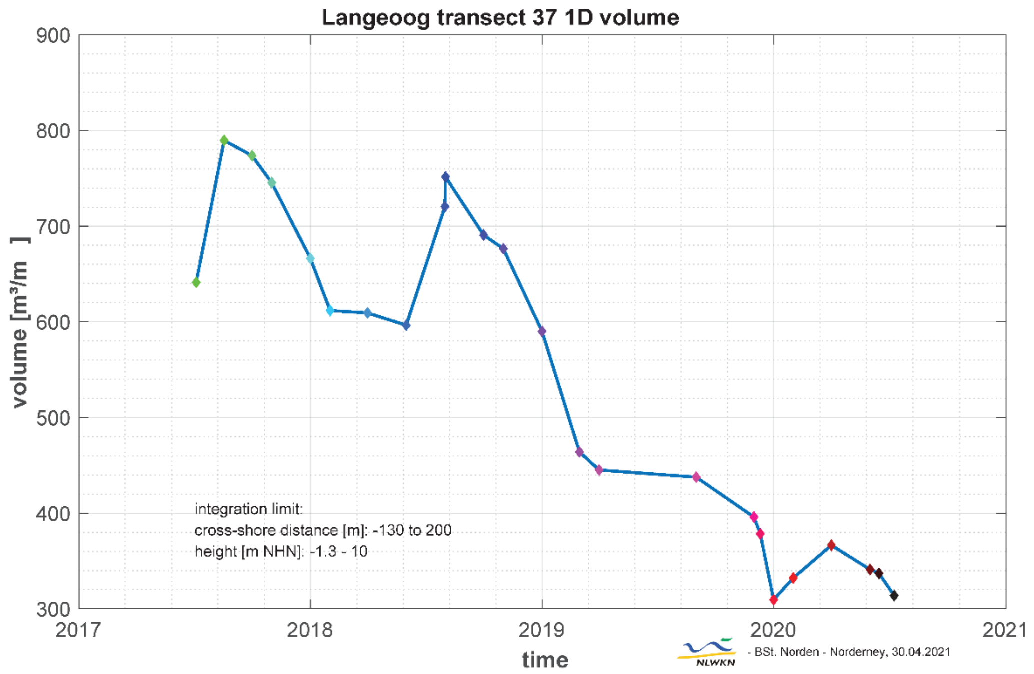

Figure 25 1D-Volumes in transect 37 for the nourishment 2017/18

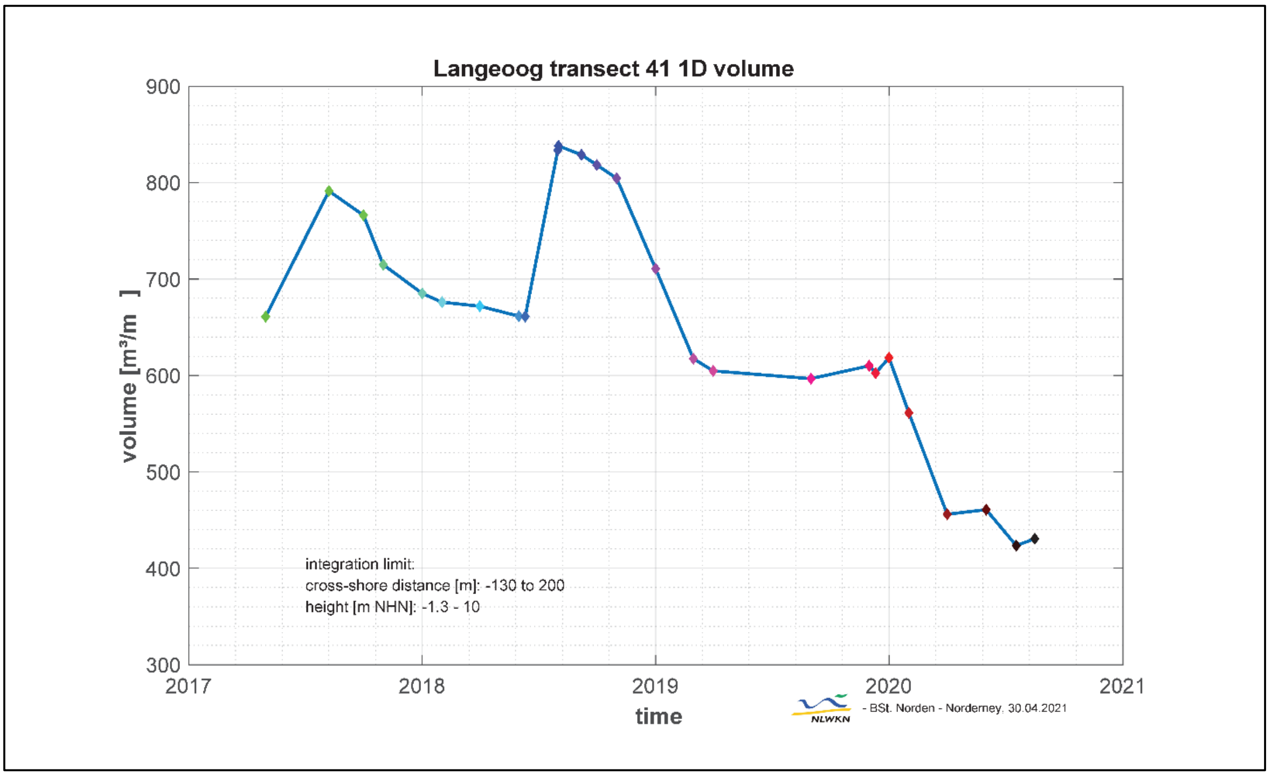

Figure 26 1D-Volumes in transect 41 for the nourishment 2017/18

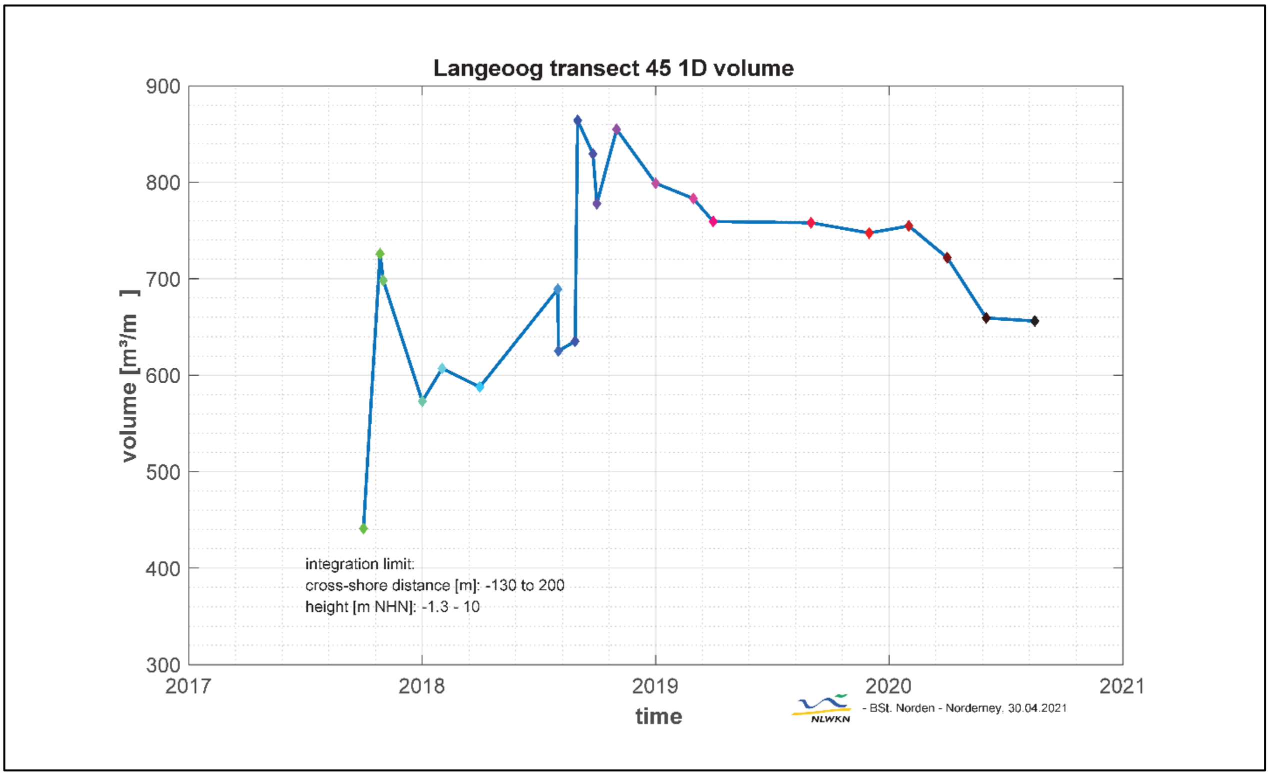

Figure 27 1D-Volumes in transect 45 for the nourishment 2017/18

6.2.3 Volumes 2D

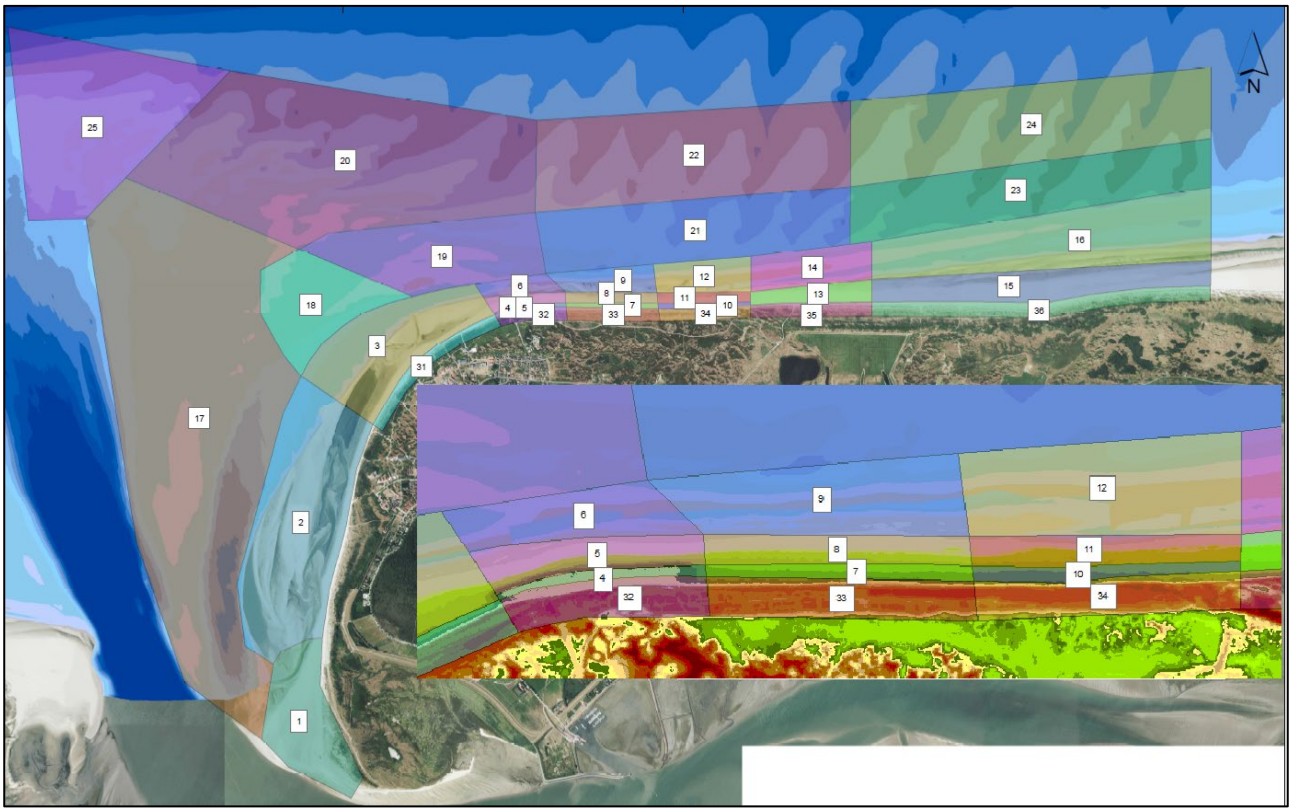

Figure 28 Volume Boxes.

In Figure 28 the selected volume boxes are shown. The design of the boxes is the result of an iterative process. The boxes are shaped in reference to morphological systems taking data avaiablity into account.

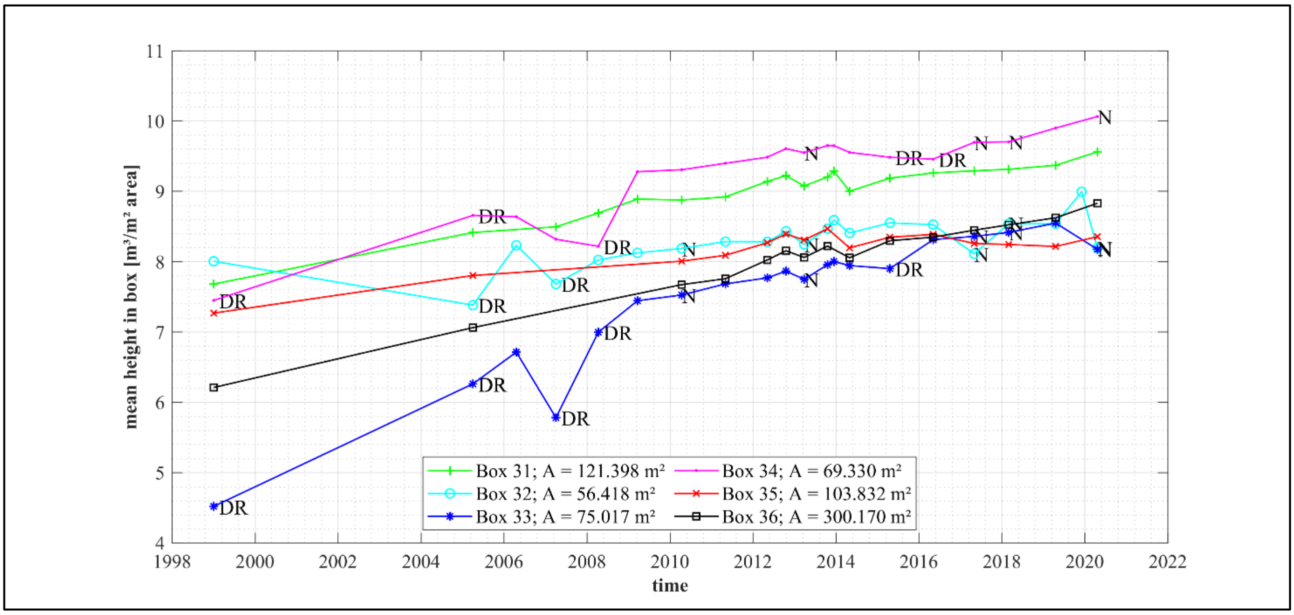

Figure 29 Boxes in the dune area. DR marks a dune reinforcement, N a nourishment.

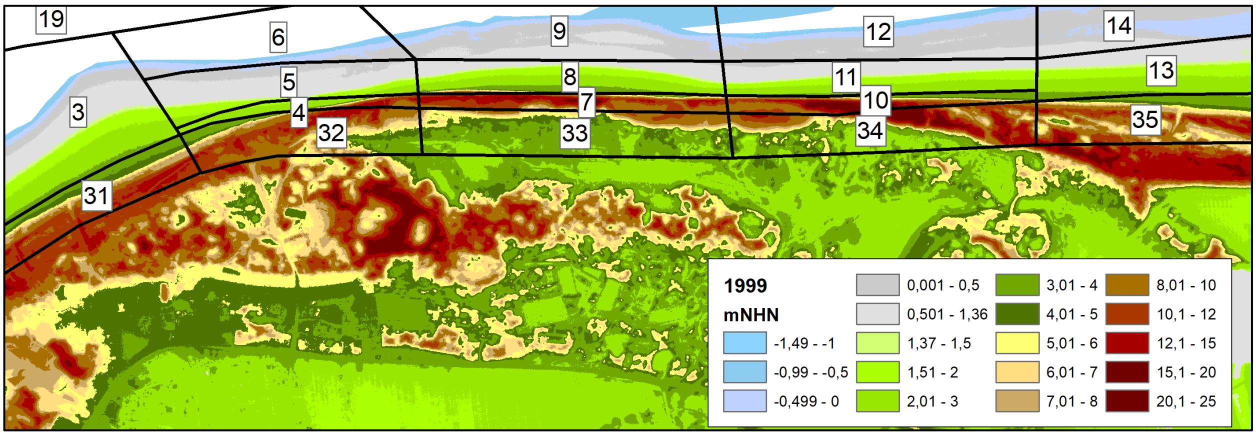

Figure 30 Digital Terrain Model of dune area in 1999

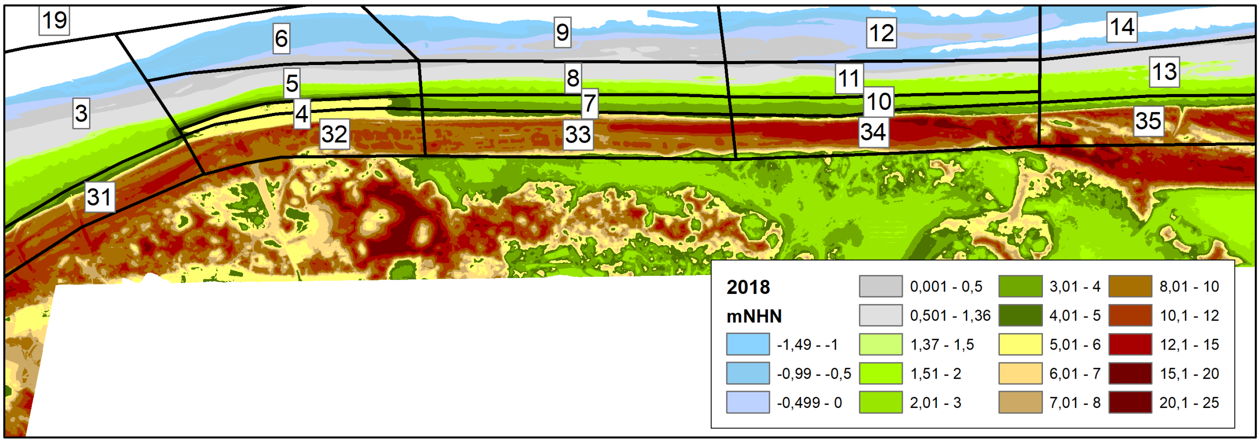

Figure 31 Digital Terrain Model of dune area in 2018

Figure 29 shows the development of the mean height in the ”dune”-boxes. Each box must be covered by the measurement by at least 99% w.r.t. the box area, to be shown in the figures. Box 33 shows a mean height of around 4,5 mNHN in 1999, where most of the area was a low-laying valley called ’Pirolatal’. However in 2018 the mean height of around 8,7 mNHN is the result of serveral dune reinforcements that were necessary to protect the Pirolatal. Figure 30 and Figure 31 show this development in measurements of 1999 and 2018. The ”dune”-box 33, 34 and 35 became partly a ”beach”-box in 2018. As a result the ”beach”-nourishment of 2018, which was located in front of the actual dune is also visible in the ”dune”-diagram. While the dune foot moved landwards, the dune height increased because of human-made reinforcements, although a additional dune growth resulting from aeolian sand transport cannot be excluded.

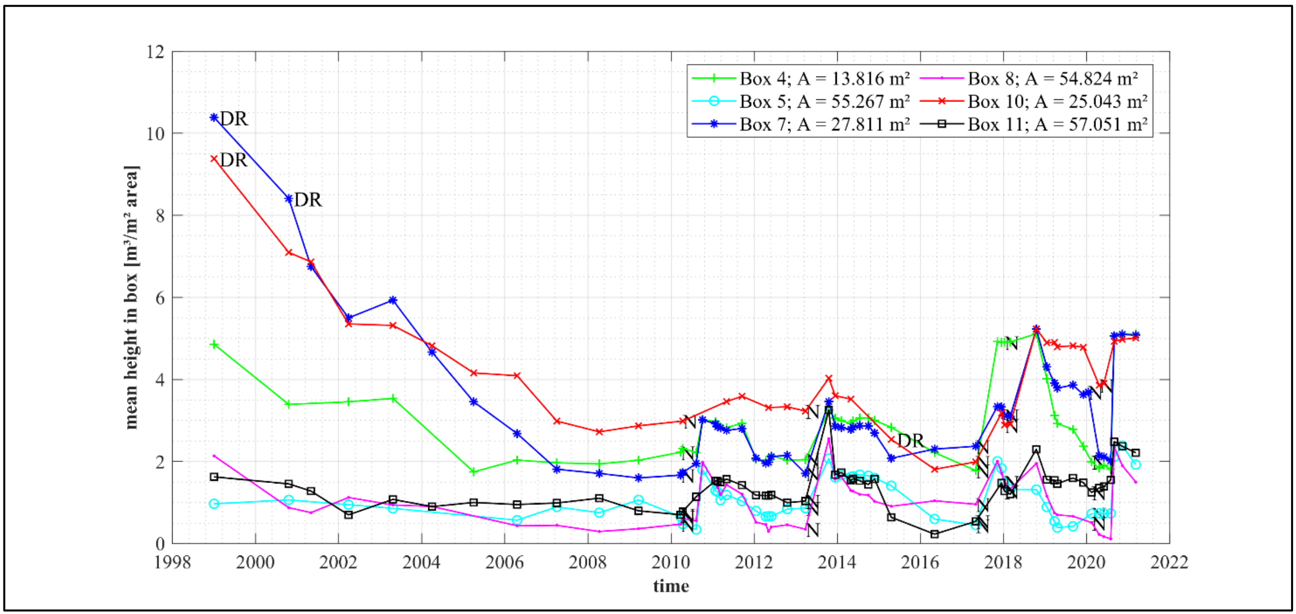

Figure 32 Boxes in the beach. DR marks a dune reinforcement, N a nourishment.

Figure 32 shows the development in the beach area. As previously stated and visible in Figure 30 and Figure 31, the position, height and extend of the dunes changed in time. As a result, boxes 4,7 and 10 started as ”dune”-boxes, whereas now the main part can be stated as a beach area.

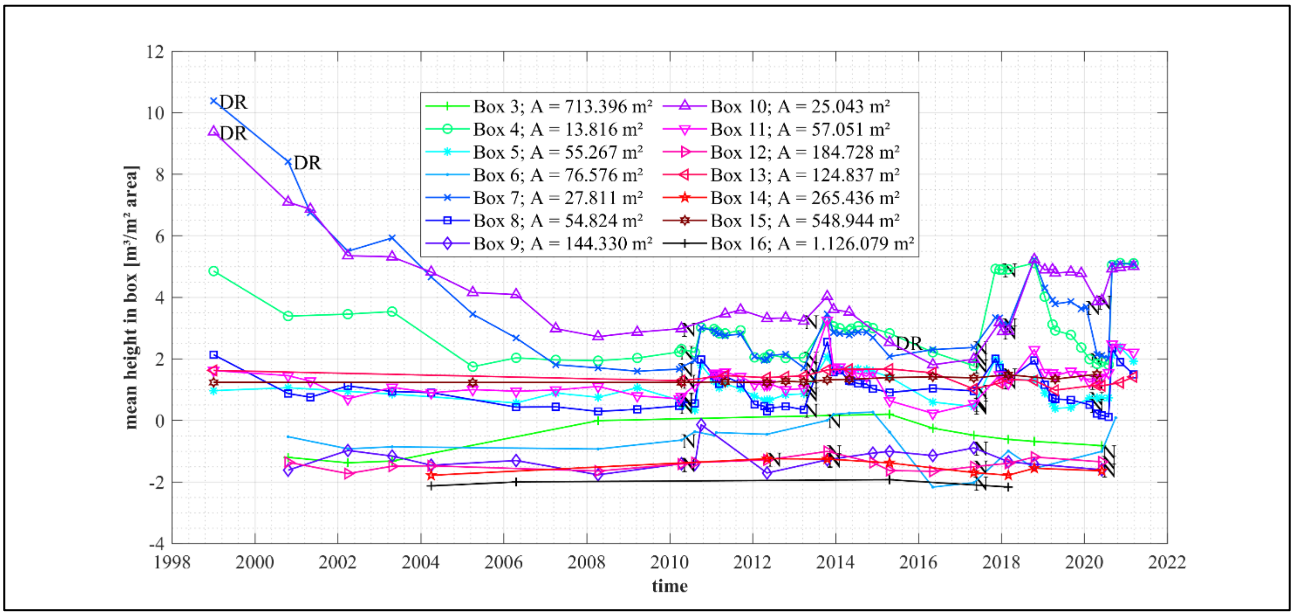

Figure 33 Boxes in the beach and foreshore area. DR marks a dune reinforcement, N a nourishment.

Figure 33 shows the development of the beach in combination with the foreshore area. Boxes 6, 9 and 12 are located in the foreshore area in front of the nourishment. Whereas box 6 might underlie big influence by the migrating tidal shoals, variations in boxes 9 and 12 can be dedicated to the sand of the beach nourishment. Boxes 9 and 12 show an increase in the mean height in 2013.

7 Synthesis

7.1 Nourishments performance

The nourishments themselves can clearly be detected in the data. The autonomous behaviour can be separated from the nourishments, although this depends on the area. High volumes of sand migrate through the tidal shoals onto the northwestern head of the island. The wet beach and foreshore area is affected in a greater speed by the natural morphodynamics than the dry beach. The autonomous behaviour of sand shoals migrating on the island, has a longer time scale than the nourishment lifespan.

The nourishment lifespan of the nourishments in 2010 and 2013 is about 3 years, but can differ because of many reasons (e.g. storm surges, location on the island). The nourishment of 2013 for example was completed right before a storm surge of the highest category ("sehr schwere Sturmflut") with a level of 3,80 mNHN at gauge Borkum (BSH - Bundesamt für Seeschifffahrt und Hydrographie, 2013) and nevertheless served also 3 years.

The performance of the nourishment design (2017/2018) has been monitored during this project. Measurements in higher time frequency and of a wider area made it possible to supervise the development in a detailed way. As a result, some main conclusions can be drawn:

- The nourishment reached its goal to protect the dunes and water extraction area of Langeoog in total.
- Distribution of nourished sand on the beach and foreshore area is highly dependent of natural morphologic processes for instance bar-through systems. That is seen in the longshore variation of nourishment erosion. In some sections, the nourishment eroded completely, whereas in other sections the nourishment has lost only half of its original volume. Additionally, other areas profit from the nourishment due to longshore sediment transport, although they are outside the nourishment area.
- The decision to nourish in a plateau design fulfilled its aim to protect the dunes while developing the expected beach cliff.
- Storm surges are a major driver of dune and beach erosion on Langeoog as seen in February 2020.

7.2 Strategic goals

The strategic goal for the nourishments on Langeoog is subject of coastal risk management. This means protecting the inhabitants of the island against flooding due to storm surges and especially on Langeoog the protection of the fresh water supply. This goal is reached, if the dunes provide a sufficient level of protection, which is reflected in the ability to resist a certain level of dune erosion. Due to nourishments, the dune position in total is in a safe position.

7.3 Source Pathway Receptor (SPR) Approach

During the project extension, we use the Source-Pathway-Receptor approach to gain more insight into morphological and hydrodynamic processes of Langeoog (Table 4).

The source 'water' is describing the basic forcing conditions of the morphological system of Langeoog: The changing water level resulting of tides, wind induced waves and the resulting currents. The pathway is the shoreface, beach and dune area, which is opposing these forces. The result is the creation of a flood level safety, which is the receptor.

The sediment source for Langeoog are sand nourishments and the natural sand supply from the ebb delta. This finds its pathway by influencing the volume of the beach and dune area. This will lead to a flood level safety as a receptor.

Table 4 Source-Pathway-Recepter Elements for Langeoog

Area	**Source**	**Pathway**	**Receptor**
Water	Tide Waves Currents	natural erosion/accumulation processes in the “active zone”	Creation of a flood level safety
Sediment	Nourishments Natural sand supply	Influencing the “active zone” (shoreface/beach/dunes)	

Building with Nature techniques often aim at influencing the SPR both for long-term sediment processes and for storm surge events. XBeach is a numerical model for wave propagation, long waves and mean flow, sediment transport and morphological changes of the nearshore area, beaches, dunes and back-barrier during storms, especially focusing on dune erosion during storm conditions.

Different scenarios of nourishment designs as well as scenarios related to effects due to future climate change are investigated using the Xbeach model. The model results of Langeoog and from other BwN-project partners are described in a separate report published in May 2021 (Hillmann, Geertsen, Quataert, Hoogland, & Frederiksen, 2021).

8 Conclusion & Outlook

In this report, a comprehensive description of the study site Langeoog is presented. Various morphological systems are described in their function and current trends were outlined. To conclude, Langeoog is highly dependent on natural morphological patterns like morphological speed and magnitude of movements in the ebb tidal delta.

During the BwN project, common methods have been developed to approach coastal state indicators, which give the possibility to compare morphological features from different coastal laboratories. In this report, the morphological features on Langeoog are described qualitatively and quantitatively. The evaluation of physical marks and 1D/2D volume calculations lead to a highly improved system understanding. Especially sediment movements resulting from nourishments are visualised and described in detail. This analysis profits from more frequent measurements, which were made during the project.

Concluding, nourishments are an efficient and working method for ensuring coastal protection on the island of Langeoog. The performance of the nourishment is established and approved for this area. The design of the nourishment is adapted to different morphological settings. Therefore, new improvements on the nourishment technique and design can still be elaborated in future. Experience from other coastal laboratories can give input here.

The outcome of this report is also used in the Co-Analysis Report (Wilmink, et al., 2021), lastly updated in 2021 and a leaflet “Lessons Learned in the Building with Nature project” (Hoogland, Lodder, & Hillmann, 2021), published in 2021.

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