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and Food of Denmark
Coastal Authority

Beach Nourishment Effects

An Analysis of Beach Nourishment in Nørlev,
Denmark 2016

Maj 2020



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1. Introduction

This report is a part of the European Interreg project, Building with Nature (BwN), with the objective of analyzing and improving coastal adaptability and resilience to climate changes by means of natural measures. In train of this project the Danish Coastal Authority (DCA) carry out research into different aspects of natural processes and materials in coastal laboratories on Danish coasts. Through the BwN project a better understanding of the interactions within the coastal system is sought.

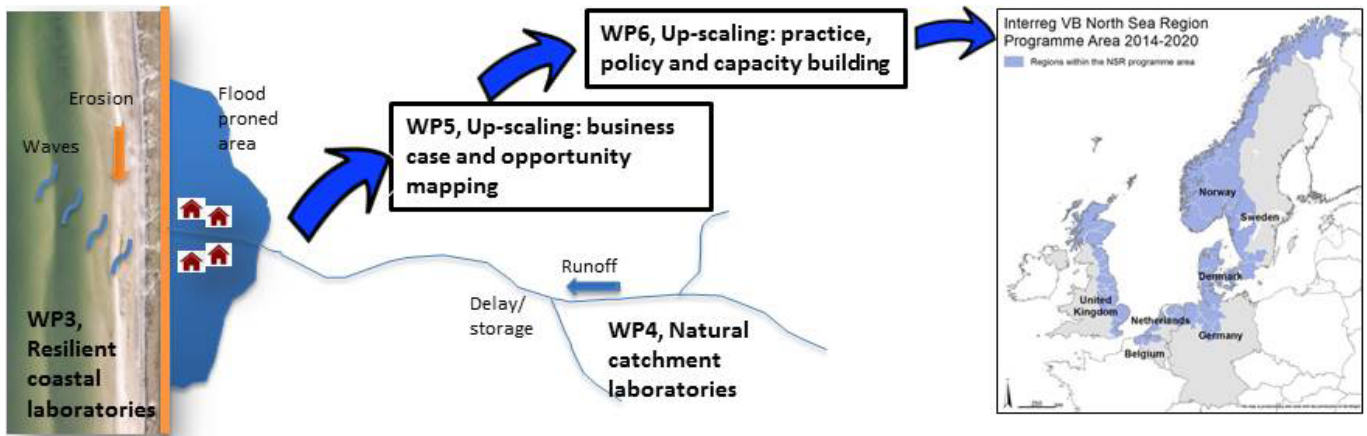


Figure 1.1: The 6 work packages in the Building with Nature project. WP1 - Project Management, and WP2 - Communication are not included, as these WP are in-office activities. The sand buffer with sleeping defense at Nørlev belongs to WP3 which deals with resilient Coastal Laboratories.

The BwN project is a combination of six different work packages, (Figure 1.1). This report on Nørlev in Denmark is part of Work Package 3 (WP3): Resilient Coastal Laboratories.

Work Package 3 (WP3) focuses on the coastal challenges and effects of implementing building with nature methods, in this case beach and shoreface nourishments, which will be demonstrated at seven 'living laboratories' located along the North Sea and the Wadden Sea coasts. The analysis of the local laboratories will improve the evidence base required to incorporate BwN methods into the national investment and policy programs of the North Sea Region countries.

This report focuses on analyzing a beach nourishment in Northern Denmark at Nørlev Beach (Figure 1.2) from 2016. A beach nourishment of 12,475m³ covering a stretch of 340 m is placed in front of the dune and is intended to function as a sand buffer. Between the sand buffer and the existing dune a sleeping defense is constructed, as a rock revetment is installed as an extra safety measure. The sleeping defense is 265 m long. The coastal protection scheme was finalized in November 2016 and the performance of the nourishment and the coastal stretch have been monitored before and after in order to analyze the performance of the nourishment. The results from this analysis will be incorporated in future guidelines for beach nourishments.

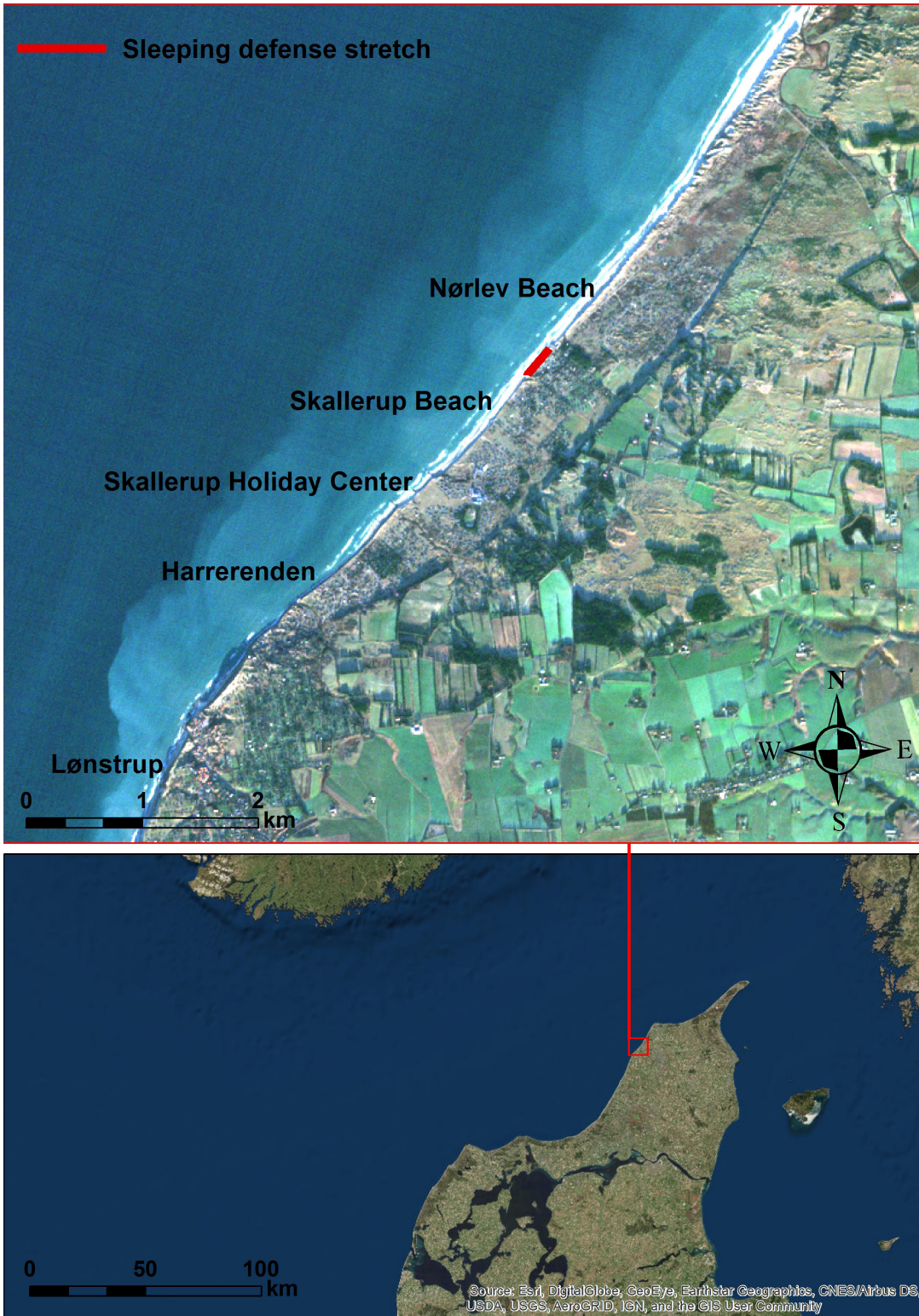


Figure 1.2: Overview of the stretch analyzed during the Nørlev beach analysis.

2. Description of Study Site

Nørlev beach is situated in the municipality of Hjørring which is in the northwestern part of Jutland, Denmark. The beach at Nørlev is popular among locals, as well as tourists, especially due to its recreational values, such as a wide sandy beach, sand dunes and the vast availability of holiday homes. In the summer, the area is characterized by tourism, while few people live there in winter. Nørlev and Skallerup beaches are located in a flat and low lying area which is demarcated at an inland crescentic ridge known as Skallerup Lien, stretching from Lønstrup to Hirtshals. (DNF, 2017) The Lien can be identified in Figure 2.1 by the shades created by the inland curvature and is marking the coastal cliffs from the Littorina Ocean primarily consisting of moraine clay.

This inland ridgeline was once the coastline of the area and it bears witness to the climatic changes during the Stone Age, including rising sea levels and isostatic rebound. But for a period of time, the lower lying areas in northern Jutland were flooded, thus leaving a sea of smaller islands. Since the Weichel Ice Age, Denmark has experienced a relative isostatic uplift of several meters (Sand-Jensen, 2012), which has led to a lift of the marine foreland in front of the Skallerup lien.

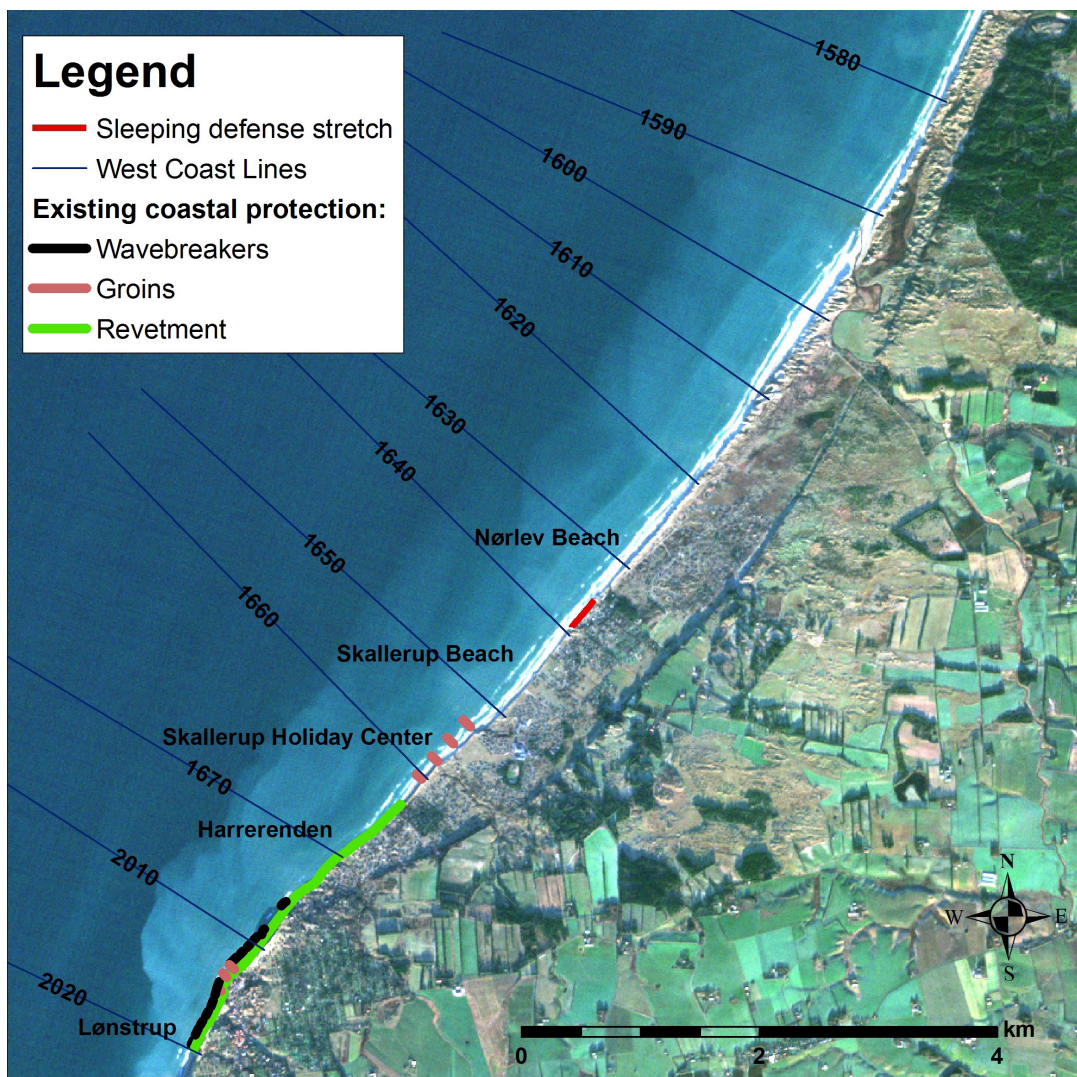


Figure 21: Overview, passive coastal protection west coast survey lines

This area has since then been covered by aeolian sand deposits, and inland from the line vegetated dune fields are found. (Henrik J. Granat, 2005).

The coastal stretch encompassed in this project, as shown in Figure 2.1, is varying with respect to both coastal typology, as well as types of coastal protection measures. The stretch from Lønstrup to Skallerup is expected to have significant influence on the stretch at Nørlev, and therefore a description will follow:

The village of Lønstrup is located SW of the study stretch and is represented by West Coast survey Lines (WCL) 2020 and 2010. The town of Lønstrup is presented from aerial imagery in Figure 2.2. The moraine cliffs facing the ocean at Lønstrup are mostly covered with vegetation. This is a result of continuous beach nourishments in combination with construction of revetments and breakwaters. Coastal protection was initiated in 1982 as a result of a joint agreement between the local municipality and the Danish state in 1982 after a severe storm incident in 1981.



Figure 2.2: Photo of the seaside village of Lønstrup. Direction of sight is NE. Notice that Harerenden begins at the last breakwater.

The erosion risk is managed on the basis of consecutive five year agreements. In the agreement for 2014-18 it is stated that the volume of sand that can be purchased within the designated budget is not sufficient to maintain an equilibrium state at the beach of Lønstrup. Therefore a certain erosion is to be expected in this area during that agreement period (Danish Coastal Authority, 2013). Sediment nourishments have been implemented both as beach nourishments between breakwaters and revetment, and as shoreface nourishments in the upper shoreface.

North East of Lønstrup lies the stretch known as Harrerenden (from Lønstrup to the start of Skallerup). The dunes here were protected by revetments erected along the dune front in the 70-ties and 80-ties. These revetments have been prolonged and maintained ever since, but as a consequence of the ongoing erosion, there is no longer any beach along the coast at the revetments of Harrerenden - a fact that is demonstrated by comparison of the photos in Figure 2.3. The photo from 1963 compared with a drone photo taken from a position above the bunker shown in the 1963-photo. The immobilization of the coastal cliffs also causes a reduction of the sediment supply to the downstream beaches, thus leading to increased erosion. The WCLs describing Harrerenden is 1670 to 1660. Between 2013 and 2016 the landowner association participated in a beach nourishment project, in which 4,000 and 3,000 m³ meters of sand, respectively, were placed on a specific stretch in front of the revetments (Harrerenden, 2016). This nourishment will not be included in this analysis of the coastal protection scheme at Nørlev, as it is located at a considerable distance from Nørlev and since the effects downstream are expected to be negligible due to the limited size of the nourishment.

Early 1960s



26th of May 2016



Figure 2.3: Top photo is taken around 1963 but the precise year is uncertain. The bunker seen in the bottom left corner of the old photograph is still visible today and is part of the northernmost wave breaker from Lønstrup. The bottom photo is taken by drone, just above the bunker's position in 2016.

“Skallerup” is the area between WCL 1660 and 1650. On this stretch, beach scraping has been carried out over several years and four perpendicular groynes was built in the 1980s. When walking from Skallerup to the end of Nørlev beach a distinct change in coastline geology can be noticed. At Skallerup no dunes run parallel to the coast, instead the erosion has reached the inland sedimentary layers of uplifted marine foreland, which are demarcated by a sharply defined line of vegetation. This stretch was not protected by any structures in 1954, as seen from the imagery in appendix B, but during the 1970-ties revetments were built along Harerenden and following the leeside erosion, which was threatening a wastewater treatment plant at Skallerup as well as some houses close to the coastline. Four groynes were installed in 1985 and on multiple occasions they have been maintained by being moved inland in accordance with the profile retreat, by being shortened or by the adding of rocks, also, until recently, beach scraping has been performed between the groynes.



Figure 2.4: Photo is taken from “Morgenvvej” with direction of sight towards NE. The photo is from the 11th of May 2016 which is before the sleeping defense was installed. Nørlev Strandvej is located on the NE side of the sleeping defense stretch.

“Nørlev Beach” will be referred to as the stretch from WCLs 1650 to 1610, it therefore includes part of Skallerup Beach. On Nørlev Beach an L-shaped revetment has been constructed in front of “Nørlev Strandvej” in order to protect the access to the beach. The age of this construction is unknown - this revetment is just NE of the sand buffer analyzed. The SW side of the road is characterized by active dune faces, while the stretch on the NE side of the road has more well developed dune belts and more vegetation cover in the dune face. The two types of fronts are referred to by the same term, dune face, in the following parts of this report. As seen on the photo in Figure 2.4 this is the sand buffer stretch in focus. The sand buffer was in place on the 4th of November 2016, and is located 50 m SW of the road “Nørlev Strandvej”.

2.1 Boundary Conditions

Nørlev Beach is located on a coastal stretch affected by the wind, waves and swell from the Atlantic Sea. The significant wave height is seen to reach levels >5 m with average periods of >6 seconds for storm cycles in the period of monitoring. The predominant wave directions are westerly, resulting in a net sediment transport towards NE. The dominant wind-direction is WSW.

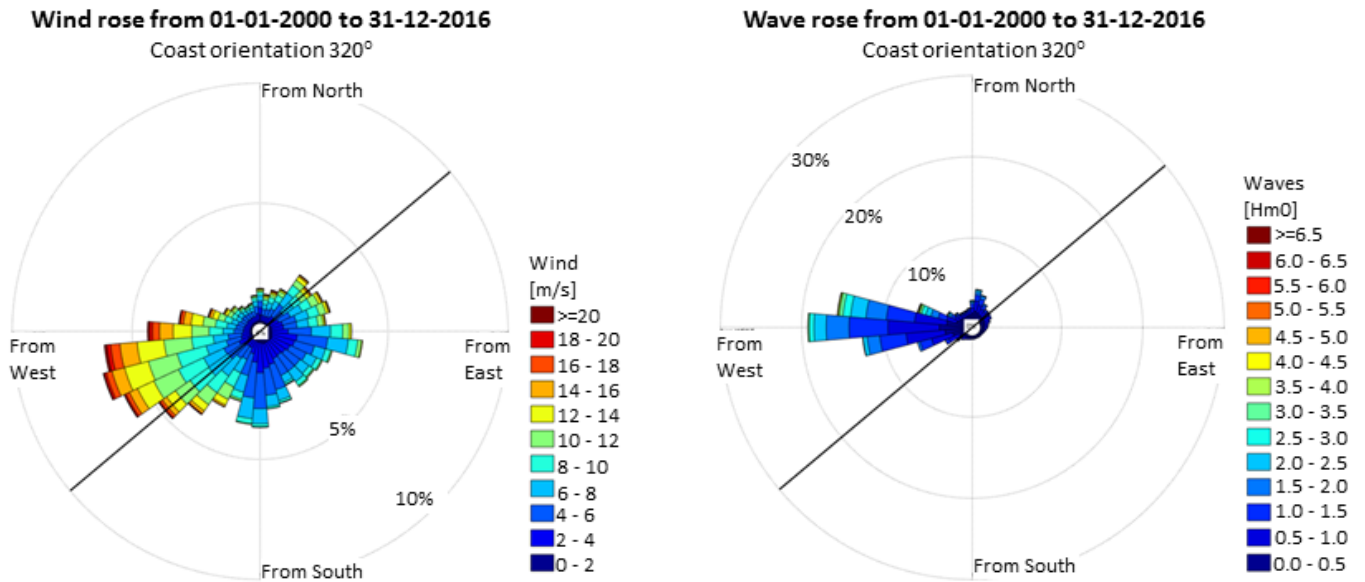


Figure 25: wave- and windroses for the period between 01-01-2000 and 31-12-2016. Wind is measured in m/s and data are from the physical wind gauge in Hirtshals with ID 1410. The Hm0 in the wave rose is measured in m and data are extracted from DHI Met ocean model on deep water outside Nørlev beach.

The tidal range in Nørlev is 0.3m and the tide can be characterized as a micro tidal stretch. The coastal profile variability is not expected to be directly affected by the tides, as the tidal range of 0.3 m have little influence when analyzed as a single parameter. However, the overall water level is considered to be an influence, and if a storm surge pairs with a 30 cm tidal peak, the impact of the tidal range may be significant. The return periods for storm surge events have been presented in table 2.1 (relative to the Danish datum DVR90) with return periods of 1, 20, 50 and 100 years.

Table 2.1: Statistical water levels for different return periods.

Return period (years)	Water levels (DVR90)
1	96 cm
20	135 cm
50	143 cm
100	149 cm

3. Structure of Report

Research Questions

The focus of this report is to quantify the effect of the beach nourishment performed at Nørlev Beach in late 2016. The nourishment in Nørlev is designed as a sand buffer with an overall construction premise and design to ensure that the revetment is never uncovered, not even during extreme erosional events. The landowners in the hinterland wanted additional safety by means of a sleeping defense in the shape of a rock revetment.

In addition to the sand buffer, an annual nourishment of 18,000 m³ sand is also added in Nørlev to counter chronic erosion. This nourishment was performed on the 3rd bar. However, the offshore nourishment has not been measured and will not be included in this analysis.

The chosen design for the nourishment was the first of its kind in Denmark. Therefore it was decided to monitor and evaluate the performance of this coastal protection scheme. The analysis of the sand buffer at Nørlev beach is based on three research questions, presented here:

1. What characterizes the stretch from Lønstrup to Nørlev and how has the coast developed since 1995?
2. How did the nourishment perform during the monitoring period?
3. Has the nourishment influenced the coastal stretch monitored and any stretches downstream from it?

4. Baseline Study

A baseline study of the coastal stretch is performed to present the natural morphological variation at Nørlev in order to be able to quantify the net effect of the sand buffer. The baseline study will also include the stretches both up- and downstream of the sand buffer stretch.

The morphological analysis in the baseline study will be based on both qualitative and quantitative methods. Profile analysis will be included for quantifications while qualitative descriptions and analysis will be based on orthophotos, profile envelopes and satellite imagery.

Having a site specific baseline analysis in place, the net effect of the nourishment can be analyzed. The nourishment effect will be analyzed from a timeline study, including all available data during the monitoring period. This will be based on qualitative and quantitative inspection.

4.1 Data and Coastal State Indicators (CSI)

The analysis of the dynamics of the coast will be based on Coastal State Indicators (CSI) derived from multiple sources.

4.1.1 West Coast Lines (WCL)

Since the 1970-ties coastal profiles have been measured along the west coast of Denmark. Profiles are measured in transect lines perpendicular to the coast. Transects are set with a 1000 m spacing and the profiles are measured from the top of dune or cliff, to about 4 km from the coast. Continuous profile measurements are used for assessing advance/retreat of the coastal profile over time, but the individual measurements are also useful for assessing the current condition of the profile. Resent measurements have been performed in 2016, 2008, 2004, 2003, 2000 and 1995.

Land measurements are carried out using RTK GPS or total station, or a combination of both. The accuracy of the measurements is controlled by using at least two land based fix points: one as a reference station and the other one as a control reference. This technique ensures that the bias error is kept under 3 cm. When RTK GPS and total station are both used for land measurements, an overlapping area is defined and this area is measured with both in order to safeguard quality. The maximum error in the overlapping area is 10 cm. The separation of data points on land depends on the morphology.

Sea measurements are carried out by boat using multibeam echo sounder. At least two reference stations must be used in data control. The expected bias error in height depends on how far apart the reference stations are located, and varies between 2 cm and 4 cm. Spacing between measure points is less than 2 m.

Since each measurement has inherent inaccuracies, the size of these errors must be quantified when performing volume calculations with survey data. These error variations must be taken into account when interpreting the results.

4.1.2 Ortho rectified imagery

Has been included to investigate the dynamics in Nørlev, and also to quantify the retreat rates of the vegetation line from one year to another. Orthophotos have been used for the years: 2018 to 2014, 2012, 2010 to 2008, 2006, 2004, 2002, 1999, 1995 and 1954. The coastal stretches of Skallerup and Nørlev are attached in appendix B. Spatial resolution varies from year to year.

4.1.3 Satellite sensor data

Sentinel 2 satellite imagery (ESA, 2014-2017) have been included for quantification of seasonal changes in the bar behavior and for analysis of the nourishment stretch before, during and after storm. The sensor data is often harvested with a frequency of 7 to 14 days, making it possible to collect multiple plan view images within the same year. Although precision analysis is difficult with a spatial resolution on 10 m x 10 m, the satellite imagery still offers a sufficient spatial resolution to make visual analysis of the coast possible. The data is undoubtedly weather dependent as cloudy weather will render the data useless, but with the temporal frequency of 7 to 14 days, it is possible to obtain multiple images to fill the gaps between orthophotos.

4.1.4 Weather Data

Measurements of wind, water levels and wave data from Hirtshals harbour are available from 2000 and onwards. Hirtshals is located around 12 km NE of the study area, and shown with IDs 1012 and 1410 in Figure 4.1. In addition to the data from Hirtshals, simulated wave data from the DHI MetOcean model are included in this study, as it is possible to extract data in a grid point, which is closer to Nørlev, this point is shown with its ID 1023 in Figure 4.1. Water level measurements are relative to DVR90.

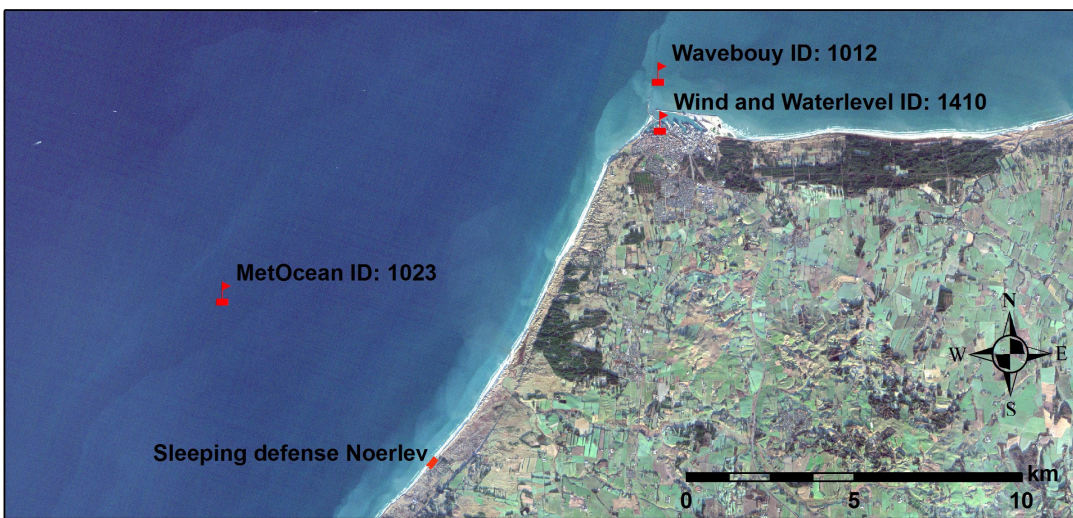


Figure 4.1: Measuring stations used for extraction of wind, wave and water level data. The analyzed stretch at Nørlev is included to illustrate the proximity of the model data and actual measurements. The underlying satellite photo is a composite of band 2,3 and 4 and the date is 14th of December 2016.

4.1.5 Definition of Costal State Indicators (CSI)

Costal state indicators (CSI) are based on the idea of using a reduced amount of parameters to determine and describe the dynamic state of a coastal profile, as well as making the coastal profile development easier to understand for decision makers. Here the CSI will be based on quantifiable parameters, which can be determined from profile measurements. The criteria for CSI are presented in (Lescinski, 2016). The CSIs can be seen as physical markers and the relative changes are used when analyzing the variations on the coast and when analyzing nourishment diffusion and effects.

Wave dominated coastal profile (WCP)

The long term development of the active profile is established by using upper and lower levels of +4 m to -8 m. The profile below the -8 m contour is highly dynamic, and it is assessed that the dynamics are caused by the longshore coastal current, and not wave dominated. The upper level is the level that the surveys should at least include.

Momentary Coast Line Position (MCP)

The position is given as a length from an inland fix point on a predefined transect line and is found as depicted in Figure 4.2. The MCP is used to analyze the dynamic behavior of the coastline position. The

boundaries set in this project is +0.5 m and -0.5 m for the baseline study while only +0.2 m and -0.2 m for the nourishment analysis. This is determined by the survey data.

Momentary Dune Face Position (MDP)

The MDP is found in the same way as the MCP, but obviously in the dune face. The MDP describes a position in the dune face and should represent a position well above any water level. The MDP will thus represent a position that will be mostly affected when the dune is undercut and the top of the dune slumps onto the beach or when aeolian processes add or remove sediment. The criteria make the MDP development comparable to vegetation line changes and comparison between the measures will serve to validate the results.

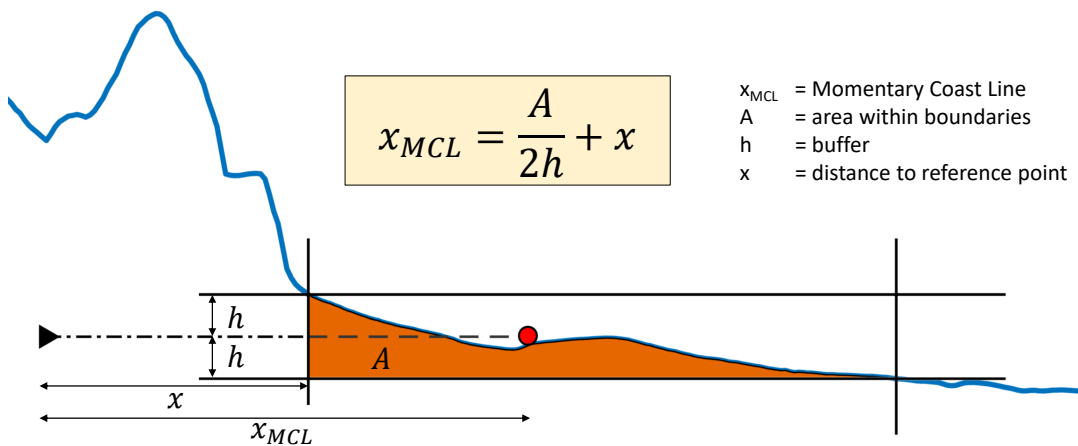


Figure 4.2: Example on how a Momentary coast line is found. The figure is based on the original from (Mulder, 2004) and has been presented in the BwN report from Skodbjerge, as well (Kystdirektoratet, et al., 2020).

Beach Width

The beach width in this report will refer to the horizontal length between the CSI's MCP and MDP. It is included as it serves as an indicator to describe the mutual variations of MDP and MCP over time.

Volume Development 1D Horizontally Fixed

Here the 1D volumes are defined with contours as horizontal boundary layers.

Breaker Bars

Sandy accumulations in the upper shoreface, created as a result of predominant wave and current actions parallel to the shoreline. The spatial position of the breaker bar will rely on visual inspection from high quality imagery such as satellite or orthophoto imagery. In this report the bar closest to the coast will be bar number 1. Description of the breaker system will serve as part of the morphological description of the coastal stretch at Nørlev.

Vegetation line

The boundary between dense vegetation and sandy beach surface is often significant on receding coastal stretches while it is more blurry where dune covers are advancing onto the beach. When sharply defined, the temporal variations can be included for purposes of evaluating the development along a coastal stretch, which is the case for most of the stretch at Nørlev. Although the vegetation line is not easily computed and involves manual drawing in GIS programs, it can be quantified and used for identification of longshore differences in the analysis of advance/retreat along the coast between the survey lines.

Profile Volume

The open source coastal morphology analysis tool MorphAn, is used to analyze transect data from the Danish Coastal Authority (DCA). This tool has been used extensively for profile analysis and visualization.

Results from profile volume calculations are given in m³/m making it possible to assess the volume on the longshore stretch which is represented by the profile measurement. It must be done with caution as MorphAn does not take angles of the transect lines into account, which is problematic as bisectors between the lines are not considered. This could potentially lead to over- or underestimation of volumes.

4.2 Morphological Variations

In order to be able to describe and quantify the effect of the sand buffer, the natural variation of the coastal system must be established, and this is the objective of this section.

Variations of dynamics governing the coastal development causes natural variations on a local scale, both across and alongside a coast. In order to describe and quantify the morphological variations at Nørlev, the baseline study incorporates different analysis approaches, relying both on WCL profile measurements as well as imagery.

WCLs are not suited for investigation of short term fluctuations in the profiles, as there are 1000 m between transect lines and the temporal resolution of the profile measurements are four years on the stretch. The results presented in this subchapter will therefore serve as an investigation of the long-term development. In addition to the WCLs within the Skallerup and Nørlev stretch (WCLs 1650 to 1610) the lines 2010 (Lønstrup) and 1670 (Harrerenden) have been included as they are placed in the upstream stretch of Skallerup and Nørlev.

4.2.1 Profile Development

The profile development evaluation covers the period between 1995 and 2016. Profile measurements are presented in Figure 4.4 and Figure 4.5. The profile changes are estimated within the upper boundary at +4 m, as this is represented in all profile measurements used and the lower boundary is set at -8 m from analyzing the WCL over time.

The profile developments between 1995 and 2016 are presented in Table 4.1 with their respective r^2 values. The r^2 value describes the linear regression trend calculated (profile movement) as described by the data. The profile development relative to the 1995 position is presented in Figure 4.3. As it is seen, it is not unusual that erosion/accretion rates vary over time, but some trends can be seen. These will now be described.

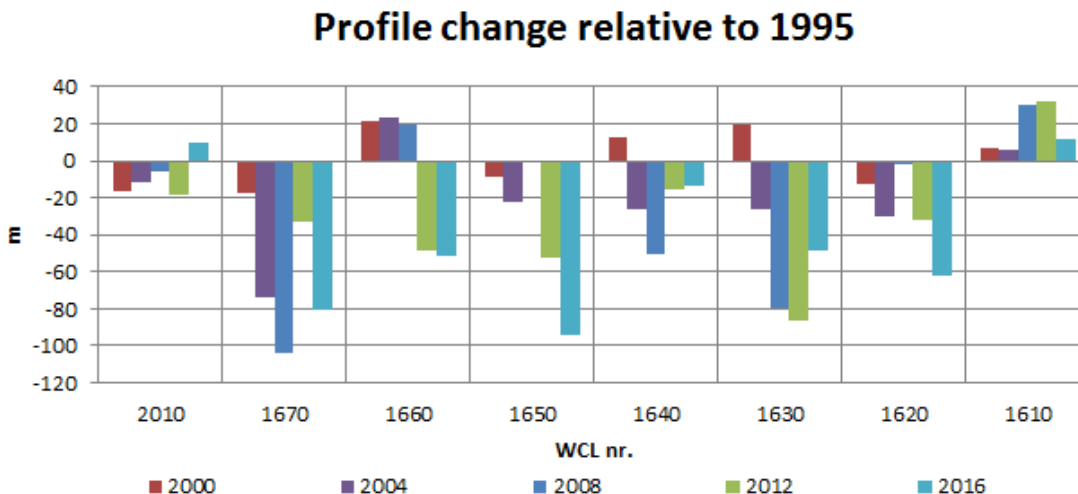


Figure 4.3: Profile movement relative to 1995. Profile defined from +4 to -8m

Line 1010 at Lønstrup shows a clear advancing tendency. The profile has advanced 25 m from 2000 to 2016. The linear fit only describes 0.05 of the variation. The profile envelope in Figure 4.5 also shows that

the general profile between +4 m and -8 m is far steeper than the remaining profiles. It actually shows that the profiles flattens from WCL 2010 to WCL 1610.

West Coast Line	Profile movement +4m to -8m (m/y)	r ²
1610	1.1	0.41
1620	-2.3	0.60
1630	-4.2	0.59
1640	-1.2	0.19
1650	-4.0	0.68
1660	-3.1	0.48
1670	-3.3	0.41
2010	0.3	0.05

Table 4.1: Profile movement (positive value of the advance), and r² value

Line 1670 is measured in front of the stretch “Harrerenden” and includes a revetment. The profile movement at line 1670 shows a total profile retreat in the period, and also periods of profile advance. The advance is explained by the lack of near shore measurements in 2012, which after linear interpolation of the existing points have lessened the slope thus overestimating the profile position. As there are revetments along the full stretch of Harrerenden where line 1670 is measured, the volume deficit is expected to occur in the wet part of the profile.

Line 1660 is straight downstream of the southernmost groyne at Skallerup Klit holiday resort and does show a stable profile for the period between 2000 and 2008. The period between 2008 and 2016 shows a general profile retreat. The profile is relatively stable in the >0 m section while the wet profile is seen to retreat. A small “hump” is present above the -8 m contour around 2300 m seaward, similar to earlier years, but the volume deficit is still found in the wet profile, as several sections have deepened.

Line 1650, located in the downstream (NE) stretch of the 4 groynes, shows the highest profile retreat between 2016 and 1995. This line is directly affected by the leeside erosion from the Skallerup groynes. A total profile retreat of 94 m since 1995 means that average retreat amounts to 4.45 m/y, which is slightly higher than the 4.0 m/y retreat rate found in Table 4.1. The profile advance between 2004 and 2008 could be explained by a buildup of an inner bar, seaward movement of the 2nd bar and a deposition on the seaward slope of the 3rd bar. The profile retreat after 2008 is in the profile above 0 m and a landward migration of 2nd and 3rd breaker while the seaward slope of the 3rd bar has deepened. The profile retreat between 2012 and 2016 is special, as the profile hardly shows any signs of dune face retreat, but the 2nd bar has migrated slightly offshore and the 3rd bar has become almost 2 m lower.

WCL 1640 is found upstream of the nourishment stretch and best represents the local development at the nourishment site. The profile retreat is 1.2 m/y between 1995 and 2016. Looking at the outer part of the profile development of line 1640 it should be noted that in 2004 there are indications of a shoal formation, but in 2008 this hump has moved onshore, and the tidal channel between the breaker systems found in 2004 narrows in 2008 and is completely filled up in 2012. In general the profile appears to be more regularly sloping than the years before. The -8 m contour moves landward in 2016, but two more well-defined breakers have developed in 2016, whereas in 2012 there was only one breaker, but it was deeper than in 2016. This can possibly serve as one possible explanation for the escalated retreat between 2012 and 2016 observed in the profile envelope.

WCL 1630 shows an accretion between 1995 and 2000 and between 2012 and 2016, while the remaining periods show retreat. The highest retreat is found between 2004 and 2008. Between 1995 and 2016 a net erosion of close to 49 m is seen. The shoal formation seen in WCL 1640, Figure 4.5, can also be observed at line 1630 but it seems that the onshore migration is delayed, as a profile advance is found between 2012 and 2016.

WCL 1620 shows a general retreat relative to 1995. But advance between 2004 and 2008 shows that the profile comes close to 1995 levels. The advance between 2004 and 2008 could be a result of sediment addition from 1630 and 1640, as they show retreat during the same period, and there is an accumulation in the outer part of the profile while the breakers in 2008 are far more well-developed compared to 2004, Figure 4.5. The retreat is found again between 2008 and 2016, which is likely to be a result of a landward migration of the -8 m contour and deepening in the seaward slope of the 3rd bar. Line 1620 shows a profile retreat of 62 m between 1995 and 2016 but it is worth noticing that the dune face retreat has decreased compared to WCL 1650 to 1630.

WCL 1610 is at the NE-edge of Nørlev Beach, and it is the only line which shows advance for all periods compared to 1995. This advance is most likely caused by a cyclicity in the hydrodynamics, and cannot be explained in detail by the analysis performed. Between 2004 and 2008 the profile advances. This advance is found to be a response to a seaward extension of the -8 m contours while there is an increase in the breaker system, Figure 4.5. The following period between 2008 and 2012 shows a slight advance despite a landward migration of the -8 m contour and seaward migration of the breakers. This stability and slight increase is explained by measurement inaccuracies in the nearshore shoreface, where a lack of measurements makes the slope linear between -1.5 m and +0.3m.

Legend

— 1995 (12-Oct) — 2000 (27-Sep) — 2004 (28-Oct) — 2008 (25-Sep) — 2012 (12-Dec) — 2016 (20-Dec)

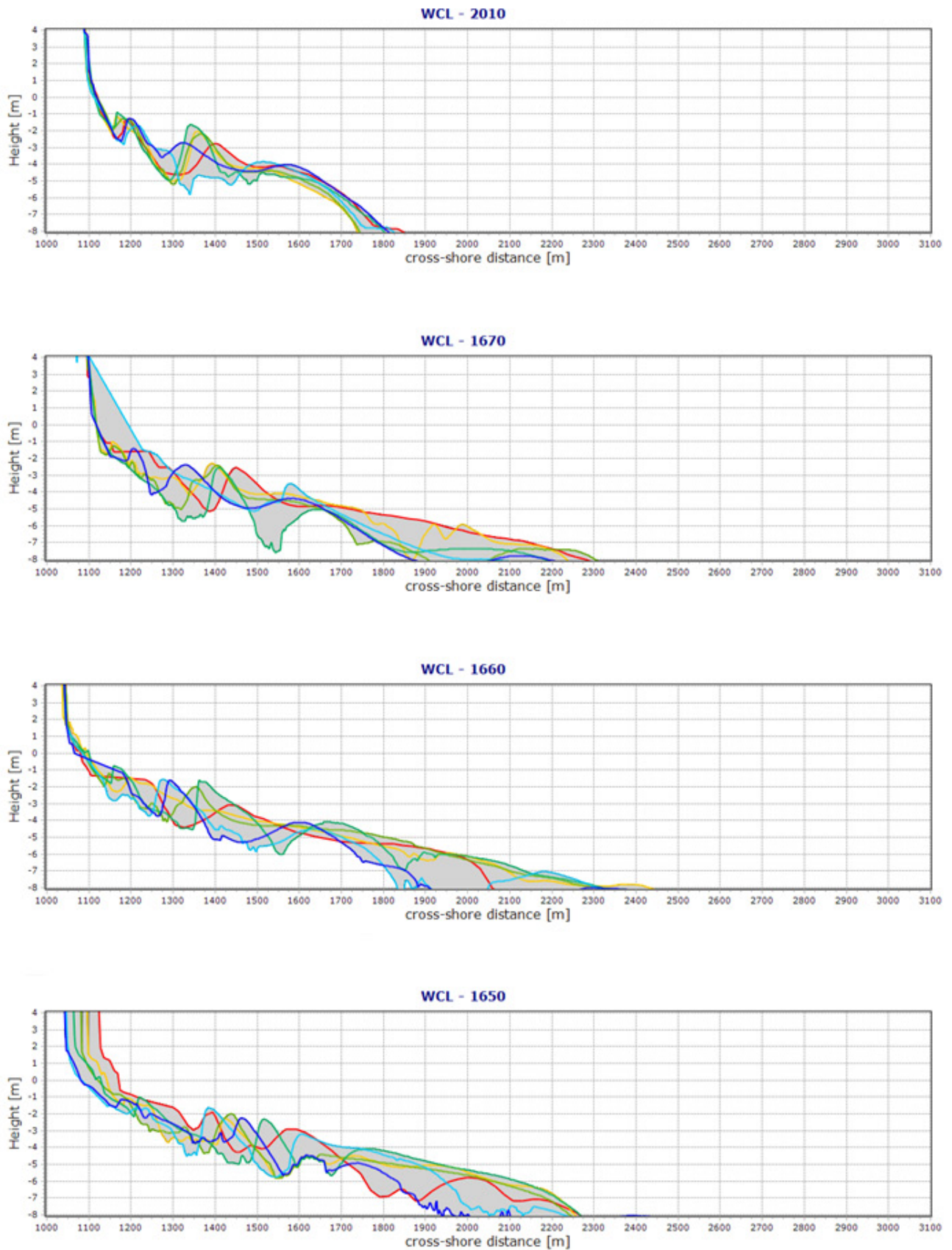
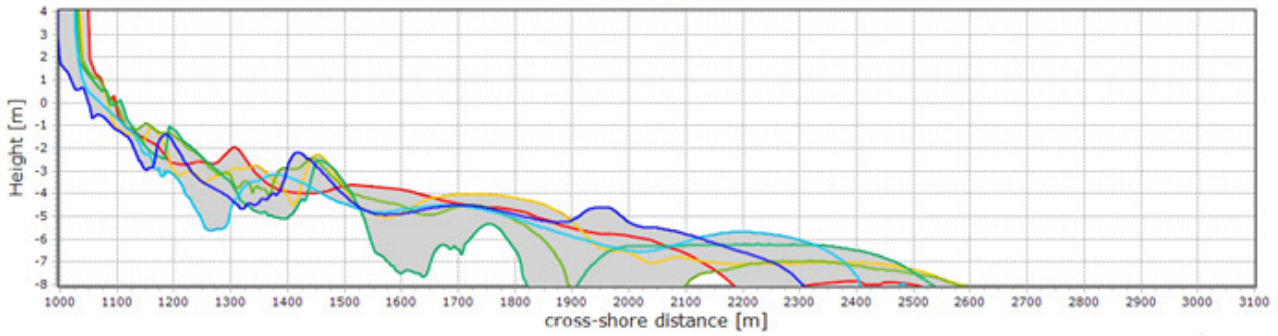


Figure 4.4: Profile envelopes from WCLs 1640, 1630, 1620 and 1610 have been visualized using MorphAn

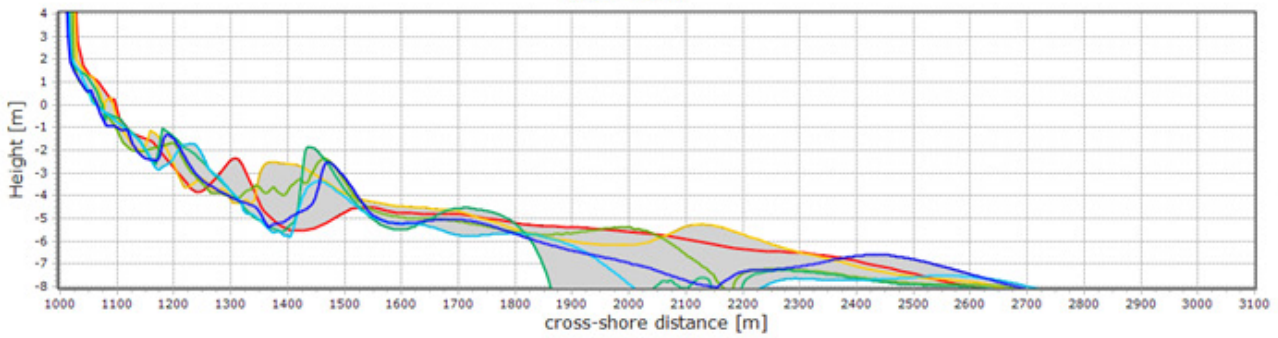
Legend

— 1995 (12-Oct) — 2000 (27-Sep) — 2004 (28-Oct) — 2008 (25-Sep) — 2012 (12-Dec) — 2016 (20-Dec)

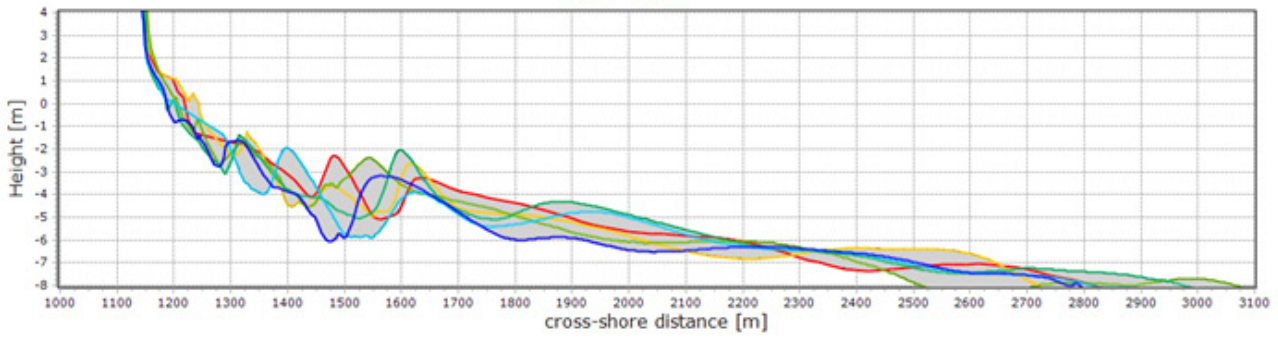
WCL - 1640



WCL - 1630



WCL - 1620



WCL - 1610

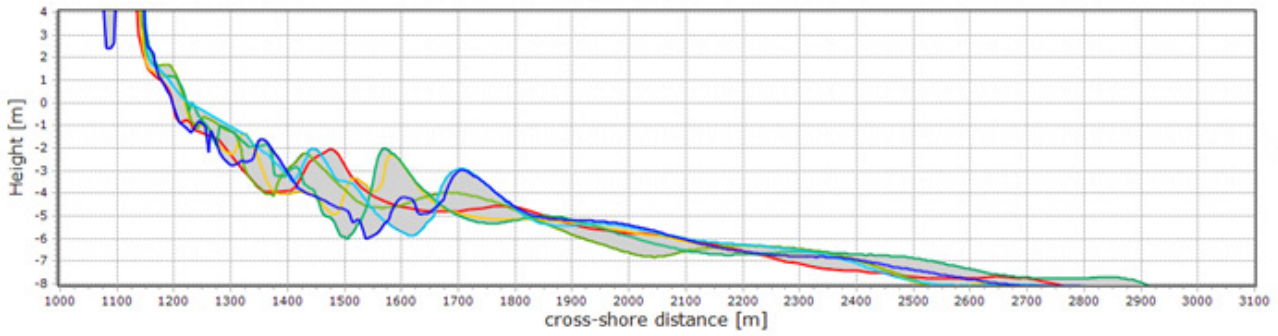


Figure 4.5: Profile envelopes from WCLs 2010, 1670, 1660 and 1650 have been visualized using MorphAn

4.2.2 MCP, MDP and Beach Width

To quantify the changes in beach and dunes the CSI parameters MDP MCP and beach width are used in the baseline study. Positional changes relative to 1995 is presented in Figure 4.6 (MCP) and Figure 4.7 (MDP) while the beach width is presented for all years in Figure 4.8 (beach width). In addition, the development of MDP has been quantified by linear regression and advance/retreat rates can be found in Table 4.2.

Both WCLs 2010 and 1670 appear stationary for both MCP and MDP, but this is to be expected as the coastline is defined by the revetments. The variations in line 2010 at Lønstrup can be attributed to the yearly beach nourishments conducted between breakwaters and revetment. Both MCP and MDP at line 1670 are close to the same position as in 1995, which corresponds with the primary retreat in the wet profile. The beach width at line 1670 is established to be +20 m for the measured years (except for 2012 when measurements are not available). The true width, as found from drone imagery, is 0.0 m of sandy beach on this stretch, but the beach width parameter, based on the horizontal distance between MDP and MCP, demonstrates its weakness here, as the MDP is measured above the revetment and the MCP is found in the revetment toe, therefore reflecting a section that is far too wide. Nevertheless, it is a measurement which can be used to sum up the total movement between MCP and MDP and can also be used to gain insight into local beach width differences between lines. Even at 1670 the beach width measure shows that there is little to no difference in beach width over time, and the existing differences are likely to be caused by variation in profile measurement quality. The beach width parameter also gives a very good indication of a general widening of the beach from WCL2010 towards WCL 1610 when looking at Figure 4.8.

MCP position relative to 1995

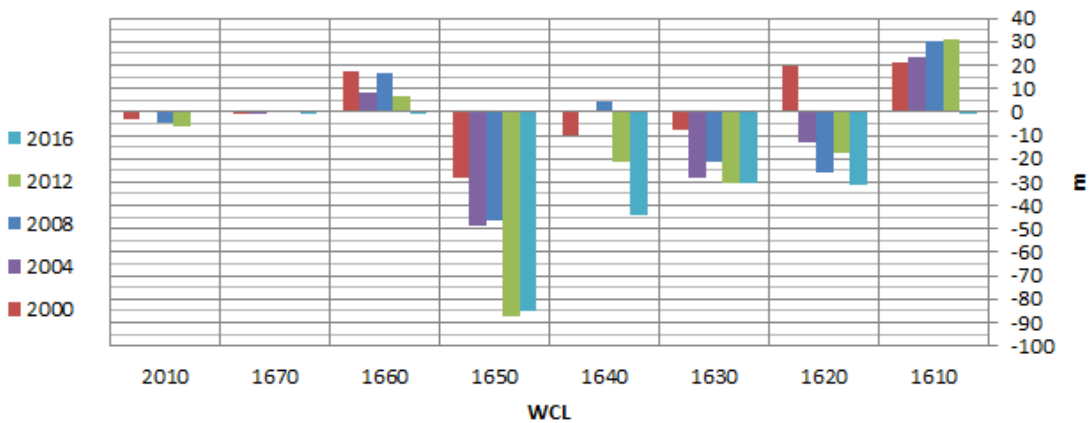


Figure 4.6: The MCP (boundary layers are 0.5 m and -0.5 m) relative to 1995. MCP shows how the shoreline has retreated and advanced relative to the 1995 position.

MDP position relative to 1995

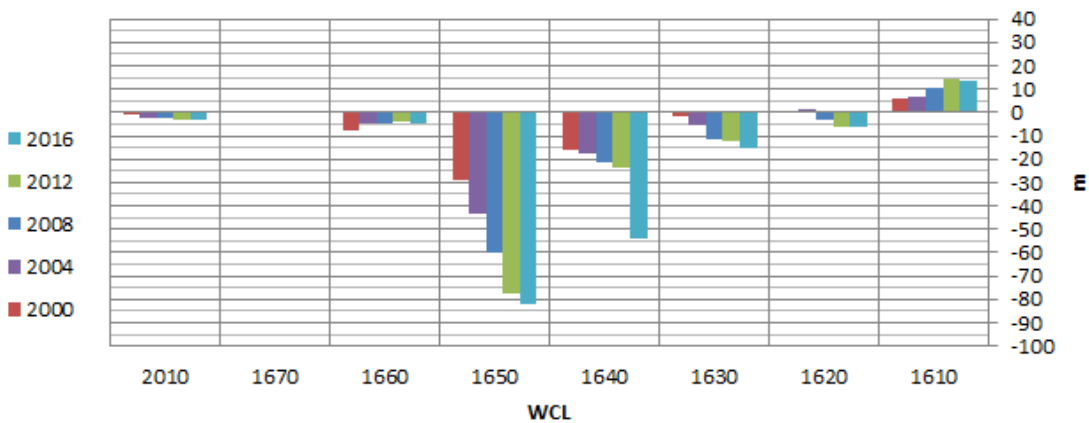


Figure 4.7: The MDP (boundary layers are 4 m and 5 m) relative to 1995. MCP shows how the dune face position has moved in and out relative to the 1995 position.

Beach width since 1995

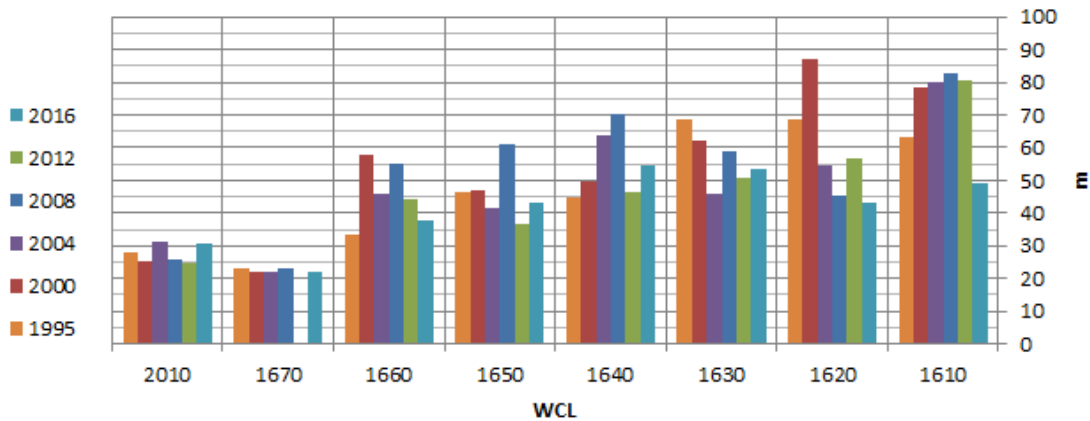


Figure 4.8: Beach Width is determined as the horizontal length between MCP. The x-axis denotes the WCL number and the y-axis denotes the beach width in meters. The graph therefore shows the sum of MCP and MDP movement.

Line 1660 demonstrates advances in the MCP position, but the 2016 position is almost the same as in 1995. The MDP position has seen a net retreat of 4.8 m between 1995 and 2016. Beach scraping has been performed frequently, which explains the stability in the dune face. This also means that the volume deficit found between 1995 and 2016 must have been in the wet profile, as it was found for line 1670, as well.

Line 1650 is measured downstream of the groyne at Skallerup Holiday Resort. Between 1995 and 2016 the MDP at line 1650 has retreated 82 m inland which is equivalent to 3.9 m/y and the MCP has retreated with approx. the same distance. The erosion rate between +4 m and -8 m was found to be 4 m/y and the retreat is expected to take place in the full profile. The MDP retreat seems fairly uniform between periods, but the period between 2012 and 2016 shows only 4 meters of retreat compared to >15 m between the remaining periods. The MCP position is also seen to have advanced slightly between 2012 and 2016, also resulting in a beach widening during the same period. Variations are not unusual but the stability seen in the period between 2012 and 2016 was also found in the profile analysis while WCL 1640 shows increased retreat between 2012 and 2016. It is worth noticing as it could indicate longshore erosional hotspots.

West Coast Line	MDP development +5 to +4m (m/y)	r ²
1610	0.7	0.9
1620	-0.4	0.7
1630	-0.8	1.0
1640	-2.0	0.8
1650	-4.0	1.0
1660	-0.1	0.1
1670	0.0	0.5
2010	-0.1	0.8

Table 4.2: Linear regression of the MDP changes between 1995 and 2016. The r² values are included to illustrate fit of regression

Line 1640 shows a 54 m retreat of the MDP and 43 m retreat in MCP between 1995 and 2016. The beach has generally widened since 1995, but as seen in Figure 4.8 the beach also narrows in between years. The MDP retreats with >15 m between 1995 and 2000 while the profile was found to advance during the same period. This is repeated between 2012 and 2016 when MDP retreats with more than 30 m, while the profile advances slightly during the same period. The retreat is most likely caused by leeside erosion from the groyne, and the fact that the closest groyne has been back-cut leading to increased dune retreat.

Line 1630 lies on the NE-side of the sand buffer. It is clear that in general retreat is predominant in the MCP position, but as for MDP, retreat is found to be 0.8 m/y and shows a high correlation between linear fit and measurements. The beach has generally narrowed since 1995 which could reflect the retreat of the profile which was found to be 4.2 m/y. Taking into account the narrowing beach and the retreat in MDP compared to the retreat rate of 4.2 m/y for the profile between +4 and -8 m (Table 4.1) there is an indication of a deficit of sediment in both beach and in the wet profile at line 1630.

Line 1620 shows advance in MCP between 1995 and 2000, while a slight advance exist in MDP between 1995 and 2004. The beach did narrow in the same period, and the MDP and MCP have retreated since 2004 and 2000, respectively. The total retreat in MDP between 1995 and 2016 is 5.8 m, which is close to one third of the retreat at line 1630. In general, the MCP has moved further inland than the MDP, which has resulted in a narrowing of the beach. Between 2012 and 2016, the MDP is stable, but the MCP retreat of 14 m is combined with a profile retreat of 31 m. Despite the beach narrowing of 14 m and a doubling in the total profile retreat the MDP is stable during this period. But the profile retreat could indicate that a MDP retreat could be imminent if the profile does not re-establish itself.

Line 1610 is generally showing a net accretion in all parameters. The profile advances, the MDP and MCP advances, as well, but between 2012 and 2016 the MCP is seen to retreat back to the position from 1995. This one period of MCP retreat also results in narrowing of the beach, and is combined with a profile retreat over the same period. As MDP shows to be stable in the period, this indicates that sediment has moved from the beach and wet profile.

The beach width proved to be a good measure for the sum of MCP and MDP movements, and it underlines the dynamic behavior of the beach width fluctuations over time. The beach width variations are often found to be more than 10 m between years, which also represents the changing outline of the coast. The hydrodynamic conditions leading up to the single profile measurements will undoubtedly influence the results of MDP, MCP and profile development, and with four years between each measurement the temporal resolution is too high to form the basis for conclusions as to what drivers can affect the morphological changes, but some changes are likely to be inter-connected and the presence of longshore morphological phenomena such as beach and bar undulations are likely at the stretch at Nørlev. If this is the case, it may have affected the erosive patterns along the stretch. Undulation in both beach width and bar position has been studied earlier on other parts of the Danish west coast and their presence have been documented earlier by DCA both at the central part of the west coast as well as in the northern part of Jutland. Beach undulations were analyzed at Husby and Sdr. Holmslands Tange (Kasper Kaergaard, 2011) and there seemed to be a correlation between beach width and bar position demonstrated in a residual bathymetry. Breaker bars, rip current position and acute dune erosion where investigated in (Thorton et. al, 2007), and it showed a likely correlation between acute erosion and rip position. It is therefore likely that some erosional events can be linked to the morphological characteristics of the stretch.

4.2.3 Breaker Bars

The following chapter will focus on a description of the breaker system at Nørlev, but since there are 1 km and 4 years between WCL profile measurements, breaker bar and rip descriptions using profiles would give an incomplete overview. Instead orthophotos will serve as a tool for visual inspections in the following chapter combined with the profile measurements presented in Figure 4.4 and Figure 4.5. Appendix B can be perused before reading, as it includes all available orthophotos from the stretch.

Breaker bars are often found parallel with the coastline, created by wave dynamics. They are one of the main drivers in wave breaking as the waves travel over them. When a wave breaks over the bars, energy dissipates, and the impact on the dunes is reduced compared to a situation when waves run all the way up to the dune face. Their shape, height and position are all a part of the morphological outline, but as the bars are modified by the prevailing hydrodynamic forces, they are dynamic by nature in both long- and cross-shore direction and change over time. The sand buffer and the sleeping defense in Nørlev was installed to protect the existing dune face and the description of the breaker system is included here as

there is an assumption that longshore undulating breakers exist and that they affect the dune erosion by the creation of erosional hotspots.

1954 - Three sandbars are visible. One disruption is seen as a small opening NE from line 1650 and the innermost bar (1st) seems irregular from line 1630 towards NE. Notice that the 2nd sandbar follows the beach undulations.

1995 - Wave breaking indicates two sandbars running parallel with the shore, the 1st bar is in the swash while the 2nd can be identified further out. The breakers are also identified in the profile envelopes. Sediment plumes are seen perpendicularly to the coast and indicate that sediment is removed from the swash to outer bars via rip currents.

1999 - The 1st bar only exists in small sections, but it could also be seen as a flooded berm. The 2nd breaker bar is irregular along the full stretch. The 2nd bar does to some extent follow the beach form. A smaller rip between lines 1650 and 1640 is identified, while a larger section of the bar is missing at line 1620. The 3rd bar can be confirmed in 1999 but the profile envelope only reveals the 2nd bar.

2002 - The 1st bar is detected, but is again irregular along the stretch. A 2nd breaker bar is visible, but despite being more regular, it fluctuates in and out along the stretch. Between lines 1650 and 1640 sandbridges seem to exist between the 1st and 2nd breaker.

2004 - The image quality is low for 2004, but the beach is clearly narrower than in 2002. The 2nd breaker is found to be much closer to the groynes in 2004 than it was in 2002, and the 2004 breaker bar shows a significant "break" towards shore just NE of the groynes.

2006 - Wave breaking indicates two bars: The 1st bar shows smaller fluctuation along the shoreline while the 2nd bar is parallel with the shoreline for more or less the full stretch. The 1st bar is in a more advanced position at line 1640 compared to the neighboring lines 1630 and 1650 and is becoming increasingly pronounced. The 2nd breaker moves landward from SW towards NE.

2008 - The 1st bar is not present on the SW part of the beach, but develops between 1650 and 1640, and migrates seaward in a NE direction. This is likely to be a response to longshore sediment transport and deposition in a bar formation. The 2nd bar is seen to be irregular along the full stretch and again shows a clear break towards shore just NE of the groynes. This is combined with at least one depression in the bar. The 3rd sandbar is again observed and seems to break landward between 1650 and 1640, but is close to regular when moving further NE.

2009 - Photo is from a storm period, and reveals three breaker bars. The 1st bar only exists NE of 1640. The 2nd bar is parallel to the shoreline along the full stretch, and a rip is observed between 1640 and 1630. The rip is also observed in the 3rd bar, which otherwise runs along the full stretch.

2010 - Coloring and reflection in the image makes it difficult to distinguish features in the water. It is possible to determine 2 bars. They seem to follow the undulations of the shoreline along the full stretch. The beach is also noticeably narrow at line 1650, but widens into an undulation in the SW side line 1640. The beach is wide and regular between 1630 and 1620, while the shoreline is close to touching the dunes NE of line 1620.

2012 - The beach varies in width along the full stretch, and seems wider than in 2010 at line 1650, but the dark coloring at the beach could indicate a lower beach in the SW part compared to the NW part. The 1st breaker bar is again seen to develop NW of line 1640, and the 2nd bar shows the same landward break as observed in other years. At line 1640 a rip or depression in the bar is visible and can be found from the profile envelope as well. A crescentic tip is observed at line 1620, which corresponds with a landward migration of the 2nd breaker seen in the profile envelope. The 3rd bar exists for the full stretch but shows irregularities and undulations. In contrast to other years orthophotos from both spring and autumn are

available. The exact days are unknown and it is therefore not possible to estimate a migration speed, but it is clear that the bar system migrates longshore as seen in Figure 4.9. Notice also that the rip in which line 1640 is measured in spring 2012 has moved NE in the autumn.

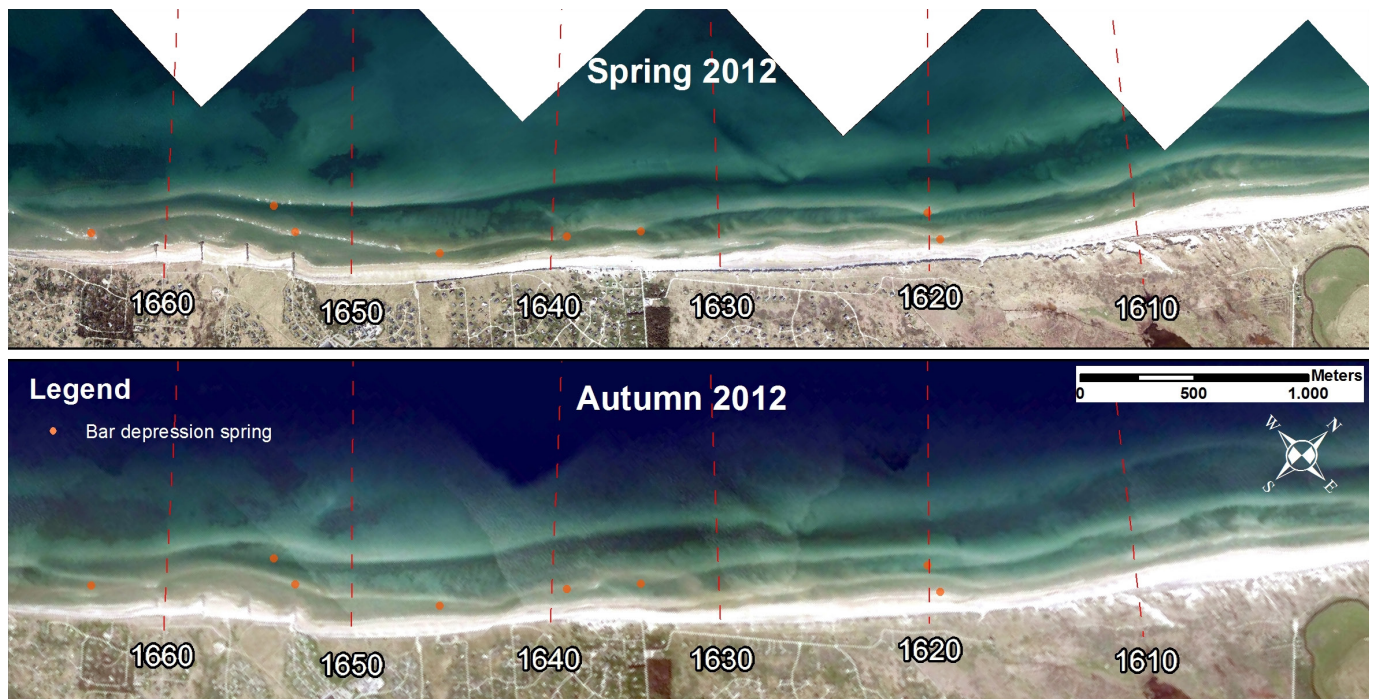


Figure 4.9: - Showing the bar development in 2012 from spring (1st and 2nd of May) to autumn (unknown date).

2014 - The beach widens at line 1650, and narrows between 1650 and 1640 as in 2012. Two bars are found in 2014. The 1st shows to be crescentic for the full stretch. The 2nd again shows a landward break NW of the groyne field, but this time it is observed further NW than in earlier years and is now found between 1650 and 1640. The 2nd bar moves further seaward on the NW side of 1640.

2015 - The beach is seen to be very wide between 1650 and 1640, but as it is seen the wave direction in the photo is from the north, which is likely to induce a SW-bound sediment transport. This is also indicated by the sediment accumulation on the NE side of the groynes, and it would explain the widened beach. Again the 1st bar is found to develop from the beach NE of line 1640 and seems to disappear NE of Line 1620. The 2nd bar is clearly visible for the full stretch and follows the shoreline. The 3rd bar is present but difficult to see for the full stretch. Variations in wave breaking along the 3rd bar could indicate differentiated depth along the bar, but could also just be variations in wave heights and consequently breaking position.

2016 - The beach narrows at line 1640, and the dark colored beach up until line 1640 indicates a lower beach than the one found at line 1630 and 1620. Only the 3rd bar is present along the full stretch. Suspended material in the swash indicate NE-bound sediment transport but generally the bars seem to be weak.

2017 - The orthophoto reveals three breaker bars. The 1st bar is again found NE from line 1630, and is highly irregular. The 2nd bar seems regular and is present for the full stretch. The 3rd bar shows two breaks between line 1660 and 1630. It was possible to get satellite imagery from two specific dates in 2017 with sufficient resolution to once again estimate whether the bars migrate alongshore. Figure 4.10 visualizes the comparison for the bar position change. Between 06-05-2017 and 23-08-2017 all breaker bars have assumed a crescentic form, which could affect the erosion rates locally. Figure 4.10 shows that the bars are migrating between 500 and 350 meters over three and a half months, leaving an estimated migration speed of 3.5 meters per day. Undoubtedly, it will be required to look into parameters such as wave energy, current speed and water level in order to validate the migration, and further study of the autonomous bar behavior could provide a better understanding of the onshore variations.

Summary of Bar Behavior

At the 5 km coastal stretch analyzed at Nørlev, one to three bars are present in the system. A near shore bar is not always present for the full stretch, but it often appears from the beach and outwards between line 1640 and 1630. The extra bar is a response to longshore sediment transport from SW towards NE, which is found to be very much influenced by the revetment and groynes at the upstream part of the coast analyzed. Undulations both in the beach width and in the bars, as well as development of crescentic bars are detected from the orthophotos between years. These shapes have been described to have locally erosive patterns at the embayment of mega cusps or embayments (Thorton et. all, 2007) and this is also expected to be the case in Nørlev - a more extensive study of the stretch is of course necessary to confirm the correlation, but the knowledge of differentiated behavior of the Nørlev breaker bars and beach is likely to have influenced the erosional patterns.

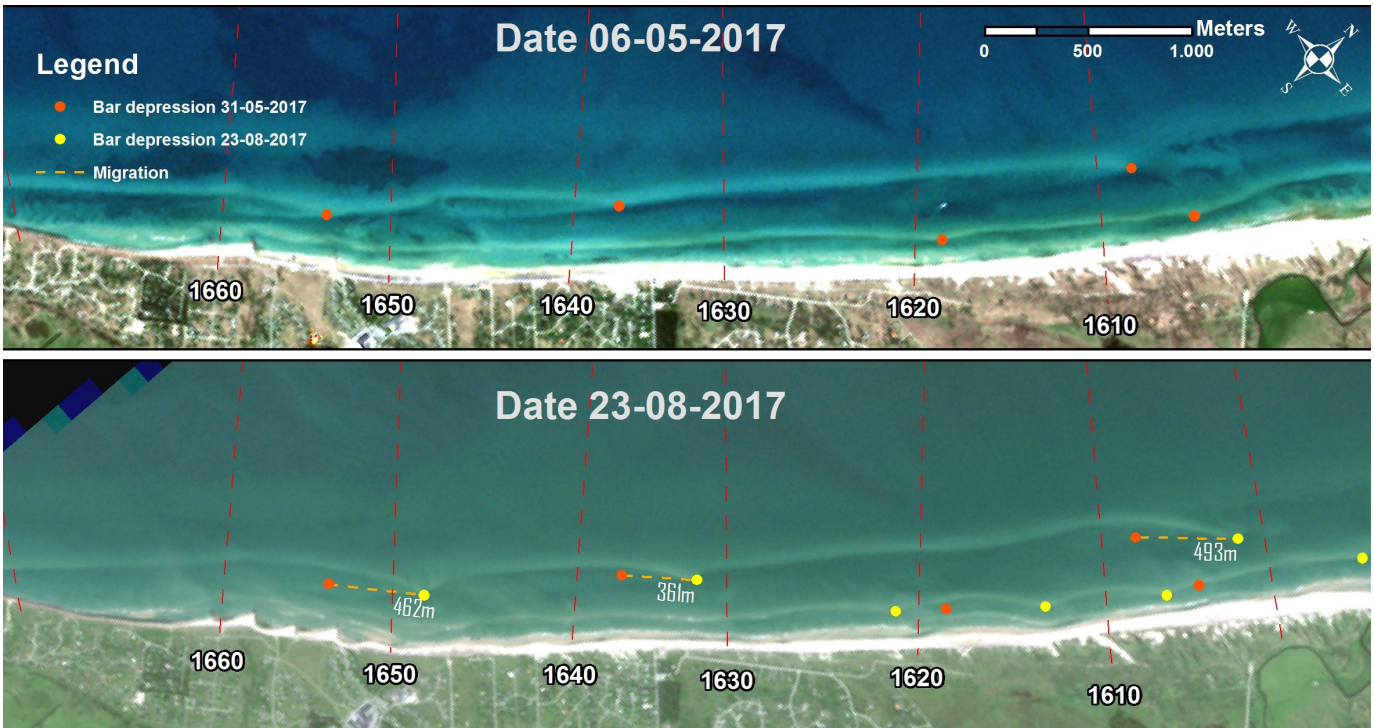


Figure 4.10: The migrations of the sand bars alongshore can be identified from satellite imagery from sentinel 2. Individual crest points have been visually selected and compared with the crest three and a half months later.

4.3 Vegetation Line Analysis

The hypothesis of longshore dynamics in the form of migration in beach undulations and breaker bars has been confirmed both long- and cross-shore, but whether it can be traced to the dune retreat is only analyzed by the MDP at the WCL. Local longshore differences are difficult to analyze using WCLs as their spacing is 1000 m. As a supplement to the WCL MDP analysis the spatial changes of the vegetation line is analyzed over time, as it could reflect local longshore patterns between the WCL and it will also serve as an evaluation of the MDP analysis.

A possible method for analysis would be estimating longshore variations vegetation line advance/retreat as this can be quantified in higher temporal resolution than the MDP due to available orthophotos. The boundary between vegetation and active dune face first needs to be drawn for all available years. This process was manual and performed in ArcMap with a zoom of [2000:1]. The quantifications will serve as rough approximations since slight drawing errors can result in inaccuracies of several meters. After drawing the vegetation lines, the planimetric changes are computed along cross shore lines (CSL). The position of the CSLs are presented in Figure 4.11 together with the sectional separation of the stretch, and the position of the WCL. The CSLs are placed with a 100 m spacing, and are set perpendicularly on an inland boundary line. Workflow and table with retreat rates (m/y) can be found in appendix A, while the retreat given in meters relative to 1995 can be seen in Figure 4.12.

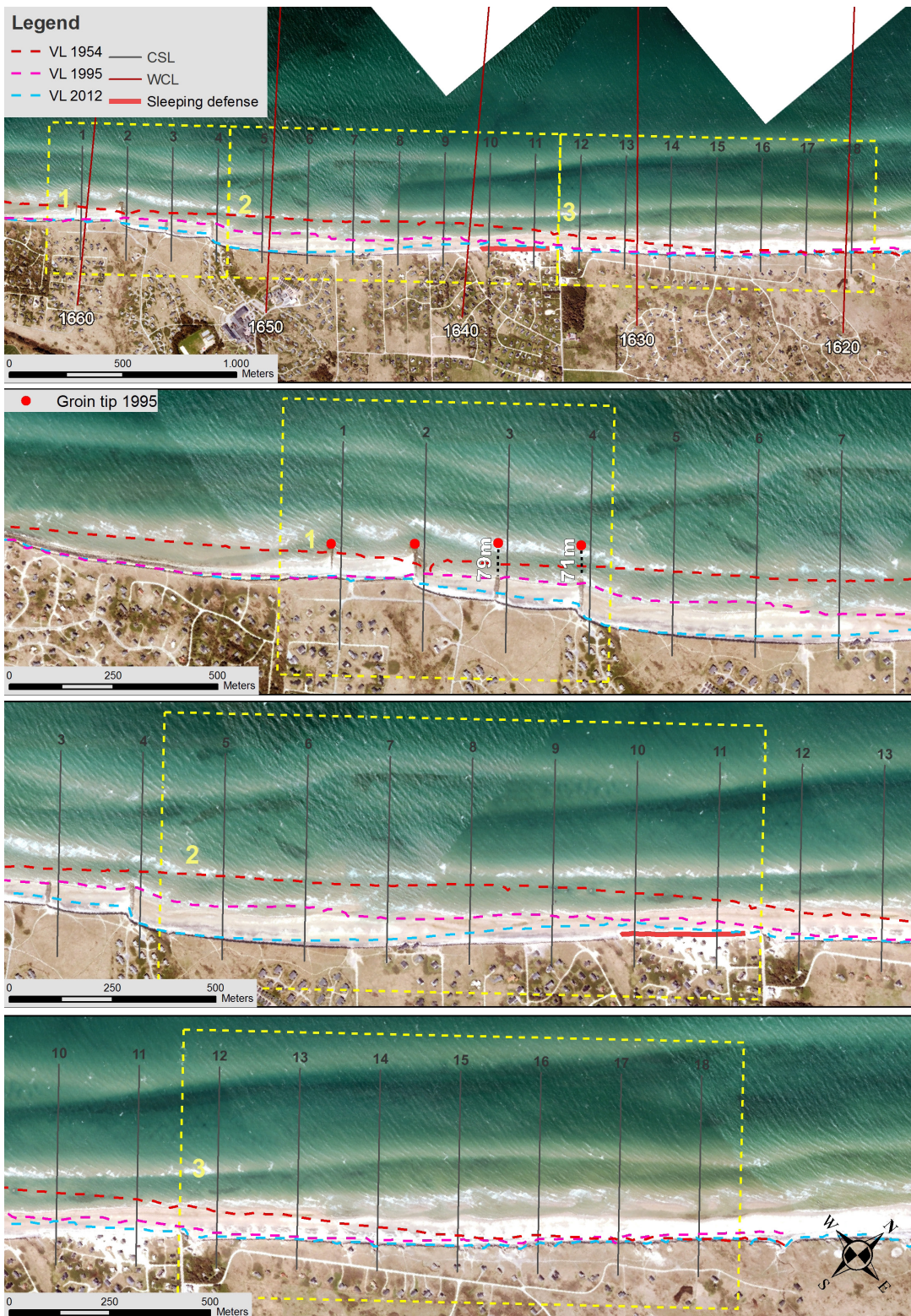


Figure 4.11: The area of interest has been divided into three sections as there is differentiated development along the stretch. CSLs are included to illustrate their position in order to understand where vegetation line (VL) retreat is measured. In section 1 the groyne tip position from 1995 have been illustrated together with the retreat of the groyne tip due to restoration. Background map is from 2017.

Change in vegetationline since 1995

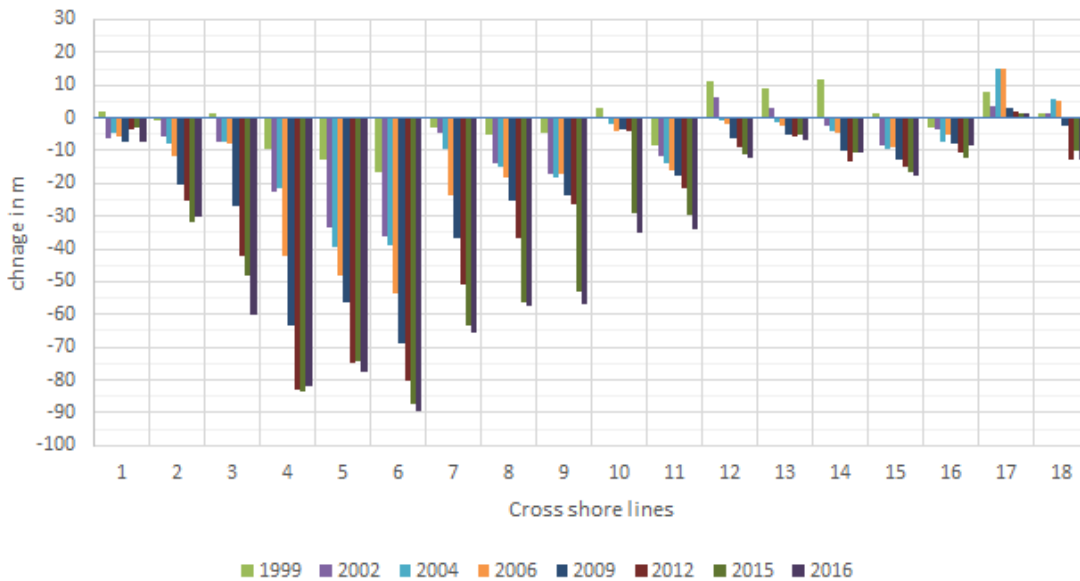


Figure 4.12: The relative location of the vegetation line relative to the 1995 position.

4.3.1 Section 1 - CSL 1 to 4

The CSLs 1 to 4 are found along the groynes at Skallerup holiday resort, and are represented in Figure 4.11. The four groynes at Skallerup have been restored on several occasions and the overall inland relocation of the groyne tips since 1995 is also shown in the figure. As the restorations and changes could not be documented through literary studies, it is described by means of orthophotos, instead.

In the following the groynes in Figure 4.11 will be numbered 1 to 4, with 1 as the one furthest to the SW and 4 furthest to the NE. In 1995 groyne 4 is back-cut, and the inland section is extended with 20 meters, so it reconnects to the dune face. In 1999 both groynes 3 and 4 are back-cut and both are extended approximately 15 m from their inland ends to the dune face. Between 2006 and 2008 both groynes 3 and 4 are back-cut again and orthophotos show that groyne 4 is shortened with 50 m, and groyne 3 is shortened with 15 m. These shortenings were combined with an inland prolonging of 35 m at groyne 4 and 10 m at groyne 3. Between 2013 and 2014 groyne 3 was shortened by 35 m and extended from the end section with 30 m, as it was back-cut again. In 2014 and 2015 both groynes have been extended inland by 15 m and shortened by 15 m. Not all shortenings of groynes 3 and 4 were registered in the inspection, but as shown in Figure 4.11, groyne 3 has been shortened by a total of approximately 79 m and groyne 4 by 71 m since 1995.

The changes in vegetation lines in section 1 is included in Table 4.3 and the retreat rates in vegetation line are increasing from CSL 1 to 4. The low retreat rate at CSL 1 is a response to the beach scrapings which have created a larger gravel paving in the dune face. The profile retreat rate was estimated to 3.1 m/y so the stability in vegetation line and MDP also indicate continued erosion in the wet profile, which was also found from the landward movement of the -8 m contour between 2000 and 2016 at WCL 1660. Groynes 1 and 2 have not been back-cut during the study period, in contrast to groynes 3 and 4 that were both back-cut on multiple occasions. Referring to Appendix A it is found that the retreat is irregular between periods and some periods even show advances of the vegetation lines. These advances are likely to be a response to scrapings or drawing errors. The period between 2015 and 2016 is special as there is a retreat of 5.8 m at CSL 3, while both CSL 2 and 4 show a slight advance. CSL 4 is in the immediate downstream stretch of the groyne field, and therefore high erosion rates could be expected, but the vegetation line is mostly stable at CSL 4 between 2012 and 2016. This was also observed in the profile and MDP analysis, and can possibly be coupled with the fact that an embayment was created during the years up until this period. The stability is also seen a period following a groyne shortening, which have possibly released sediment. Nevertheless, the profile did come out as receding and the -8 m contour migrated landward between 2012 and 2016, so the stability is difficult to explain.

Line	CSL 1	CSL 2	CSL 3	CSL 4
Method	Vegetation line analyses (1995 to 2016)			
m/y	-0.25	-1.66	-2.95	-4.41

Table 4.3: The vegetation line change is based on linear regression of the change between 1995 and 2016

4.3.2 Section 2 - CSL 5 to 11

Section 2 includes CSL 5 to 11, WCL 1650 and 1640, as well as the sleeping defense stretch. This stretch is situated downstream of the groyne field at Skallerup. As a general rule, the leeside effects from groynes are expected to amount to the groyne length multiplied by 10. In 2016 Groyne 4 was approx. 90 m long and CSL No. 9 is close to 1000 m away, giving an indication as to where the effect from the groynes can be expected. If one considers that the retreat of 71 m of the groynes was included, the effect distance would be 1610 m, which from groyne 4 is beyond Nørlev Strandvej. The erosion rates for all CSL in section 2 are found in appendix A and Table 4.4. As seen, all lines show retreat and the retreat decreases from CSL6 towards CSL 11.

Figure 4.11, section 2 clearly shows that the retreat in vegetation line since 1995 decreases from CSL 5 to 11. The highest retreat rates in vegetation lines are found at CSL 4 (4.3 m/y), CSI 5 (3.7 m/y) and CSL 6 (4.3 m/y). This is not unexpected since these lines are in the immediate downstream fetch of groyne 4 at Skallerup. A control of the retreat rates can be undertaken by comparing to the MDP analysis at WCL 1650, which showed retreat of 4.0 m/y.

The leeside erosion from groyne fields is to be expected and erosional peaks combined with storm events are not unlikely on the stretch. Between 1999 and 2002, CSL 5 and 6 retreat with 5 m/y and CSL 8 retreats with 2.2 m/y. In the same period CSL 7 only retreats with 0.4 m/y. The retreat rate at CSL 7 increases to 1.7 m/y (2002-2004) and further to 4.6 m/y (2004-2006).

Between 2004 and 2012 the vegetation line retreats with 61 m at CSL 4, 35 m at CSL 5, 42 m at CSL 6 and 41 m at CSL 7. In comparison the retreat at CSL 8, 9, 10 and 11 was 22 m, 8 m, 2 m and 8 m, respectively. This variation in retreat creates a dune face which stretches further seaward at CSL 8 to 11 than between 4 and 7.

In the following period between 2012 and 2016, CSL 4, 5 and 6 show a decrease in retreat rate. The vegetation lines between 2012 and 2016 have been included in Figure 4.13 to illustrate how the erosional hotspot has migrated towards NE. The maximum retreat in the period from 2012 to 2014 is found between CSL 8 and 9, while it changes in the following period between 2014 and 2016 when the retreat peak is found further to the NE at CSL 10.

The shortenings of groynes 3 and 4 between 2013 and 2014 may have stabilized the retreat at CSL 4 to 6. But the longshore differentiated erosion rates between CSL 7 and 11 are also likely to be the result of headland equalization due to the extensive erosion at CSL 4 to 7 between 2004 and 2012. The profile envelope from WCL 1640 from 2012 and 2016 (Figure 4.14) indicates a larger breaker bar at -3 m in 2012, whereas 2016 indicates two more well defined bars. The 2012 orthophoto in Appendix B reveals that a rip is present in the inner bar system, and that line 1640 most probably has been measured exactly in this depression. The 2014 orthophoto revealed a narrowing beach, as well as depression and landward undulation of the 2nd breaker bar between WCL 1650 and 1640. It is not unlikely that these morphological characteristics have contributed to the increase in retreat of the vegetation lines in the period between 2012 and 2016.

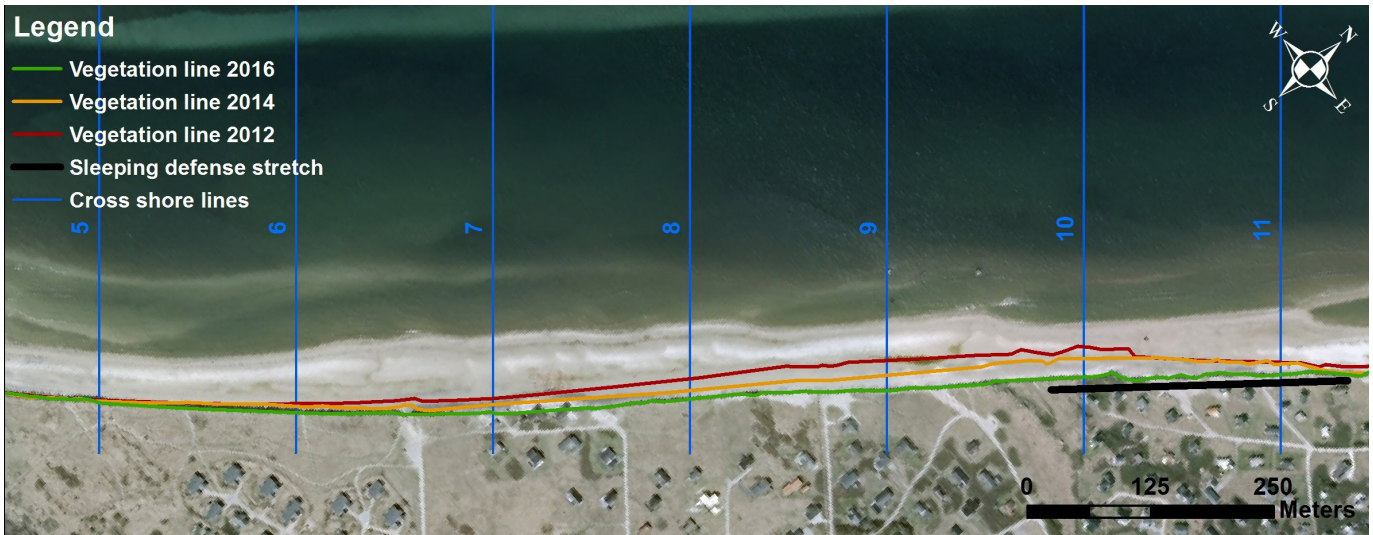


Figure 413: The vegetation lines from 2012, 2014 and 2016 are included to illustrate the longshore movement of erosional hotspots. Erosional peak between 2012 and 2014 is found between CSL 9 and 8. This changes between 2014 and 2016 when peak erosion is found at CSL 10. Notice also the stable vegetation lines from CSL 5 to 6 in this period and the longshore increase in retreat.

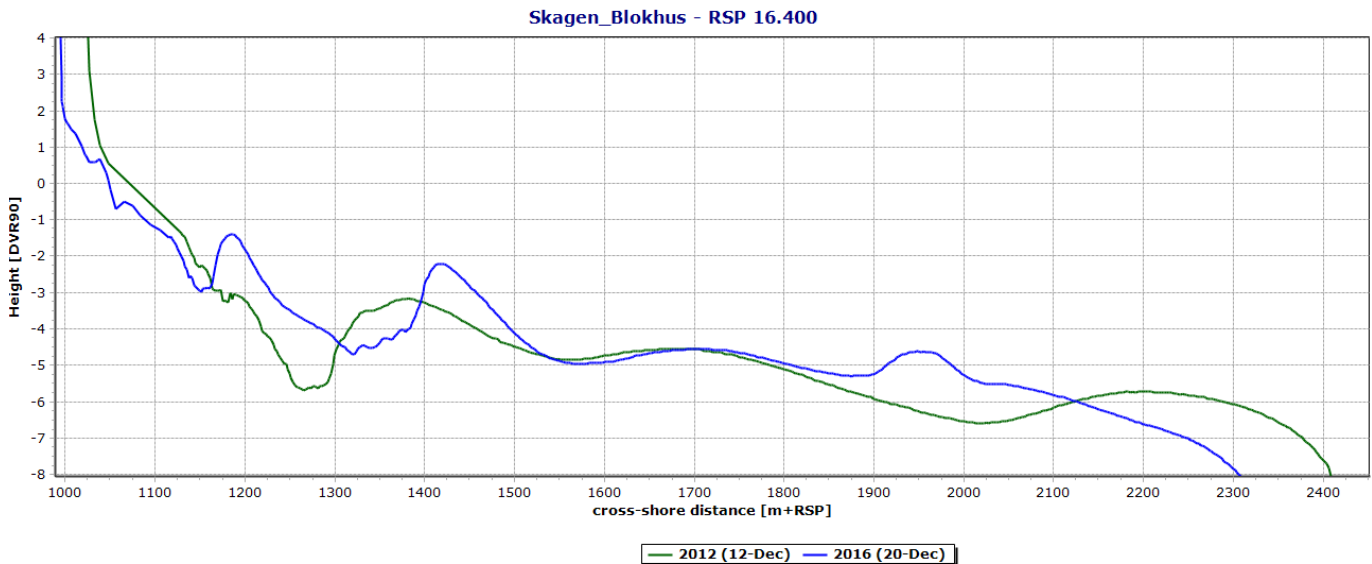


Figure 414: The difference between the profile measurements in 2012 and 2016 at line 1640. Notice the development of two bars in comparison with 2012.

The variation is also influenced by the more seaward position of the vegetation line between CSL 8, 9 and 10 compared to CSL 5, 6, 7, 11 in 2012. This seawards relocation leads to potential higher retreat of the vegetation line between CSL 8, 9 and 10 compared to the surrounding coast.

Line	CSL 5	CSL 6	CSL 7	CSL 8	CSL 9	CSL 10	CSL 11
Method	Vegetation line analyses (1995 to 2016)						
m/y	-3.7	-4.3	-3.5	-2.7	-2.5	-1.5	-1.4

Table 4.4: The vegetation line change based on linear regression of the change between 1995 and 2016.

4.3.3 Section 3 - CSL 12 to 18

Section 3 is enclosing the area downstream of Nørlev Strandvej and includes CSLs 12 to 18. Even though events with increased retreat are found (e.g. 3.0 m/y at CSL 17 from 2006 to 2009), in general the retreat in vegetation lines is lower than the rates found in section 2. Longshore parallel dunes are found on the entire stretch in section 3, and vegetation lines here can be blurred by the advance or retreat of vegetation on the dune face. For some years the vegetation has advanced onto the beach in smaller embryo

dunes, making the fine line between vegetation and sand cover difficult to distinguish. This means that the vegetation line on this stretch may have caused or increased an error in the vegetation line analysis compared to section 1 and 2.

Figure 4.11 shows the vegetation line from 1954 to be almost the same as in 2016 for CSL 15 to 18. The vegetation line have however retreated between CSL 12 and 15. A slight advance in the vegetation at CSL 17 and 18 can be identified between 1954 and 1995. This was a result of seaward advance of vegetation in smaller embryo dunes. Despite the fact that section 3 is showing smaller advances in the vegetation line on several occasions, the overall picture is that the stretch experiences retreat of the vegetation line, which corresponds with the patterns seen for the MDP and profile analysis of WCLs 1630 and 1620. The retreat rates from CSL 12 to 18 range from between 0.9 m/y to 0.2 m/y (Table 4.5) and the MDP analysis at WCL 1630 showed a retreat of 0.8 m/y, and 1620 showed a retreat of 0.4 m. It is worth noticing that line 1610, NE from section 3, showed an advance both in MDP and profile analysis, which could indicate that the eroded sediment is accumulated further downstream. It is also found that there between CSL 15 and 16 is a slight change in coastal orientation. This position represents a separation in retreat rates as the retreat from CSL 16 to 18 is far less than in CSL12 to 15 relative to 1954. Another factor influencing the retreat rates in section 3 could be the additional breaker bar, which on several occasions, have been found to develop from the beach and seaward between CSL 10 and 13.

Line	CSL 12	CSL 13	CSL 14	CSL 15	CSL 16	CSL 17	CSL 18
Method	Vegetation line analyses (1995 to 2016)						
m/y	-0.9	-0.5	-0.8	-0.9	-0.5	-0.2	-0.8

Table 4.5: The vegetation line change based on linear regression of the change between 1995 and 2016

4.3.4 Summary

Strong leeside erosion from the four Skallerup groynes, in combination with sediment deficit at Harerrenden have contributed to the coastal retreat found at CSL 5 to 9, and possibly further on. Periodic stability in the immediate leeside of the groynes between 2012 and 2016 and elevated erosion rates further downstream are expected to be the result of a combination of several factors such as groyne shortening, bar depression, beach narrowing, headland equalization and storm events. The stability downstream of the groynes combined with escalated erosion further to the NE can also be identified in earlier periods but not to the same degree or length. Longshore migration of shoreline undulations in beach and breaker bars was detected in the same periods and on the same locations, as escalated retreats could be documented, and these elements are expected to have affected erosional hotspots in the dune face. Although no complete correlation between erosional events and longshore patterns can be established due to the temporal resolution of data, the knowledge of the existence of these local erosional patterns and longshore dynamics can be utilized in the analysis of the development of the sleeping defense placed at Nørlev Beach.

The combination of profile, MDP and vegetation line analysis has served as a calibration parameter in analyzing the actual profile development, but also in the understanding of the variation across the coastal profile, which is seen to influence the results dependent on where we look and what we look at. The overall conclusion of the baseline study is that the stretch on which the nourishment buffer and revetment have been placed is generally eroding and has been severely exposed to erosional events due to the advanced position of the stretch in response to upstream retreat in earlier periods.

The bar system is very dynamic with migrating sandbars, leading to a situation with erosional hotspots. It has not been possible to quantify the exact bar dynamics because of the sparse density of bathymetric surveys alongshore and in time.

5. Sand buffer with Sleeping Defense at Nørlev Beach

In this chapter the performance of the coastal protection scheme at Nørlev will be assessed using the results of the baseline study as basis for evaluating the net effect.

The design of the coastal protection was based on new requirements from the authorities, and it is the first assessment of whether the objectives can be met by the design criteria.

5.1 Objectives and Design Criteria

The local landowners wanted a rock revetment to protect their holiday houses from being eroded. The long term erosion has resulted in a loss of houses at least since the 1980. After a severe storm the landowners agreed on a coastal protection scheme that provided the safety level they wanted and simultaneously met the requirements of the authorities. This meant that in its lifetime the coastal protection must not cause leeside erosion or make it impossible to walk along the beach. At the same time the coastal protection must fit into the coastal landscape that consists of low sandy marine deposits with small dunes.

As a result the coastal protection scheme consists of three parts. 1) A sand nourishment with a volume of 18,000 m³/year to compensate 100 % for the chronic erosion. 2) A sand buffer that protects the holiday houses on the coastal stretch of 340 m. 3) A sleeping defense of rock placed as a revetment along the dune face, as an extra safety.

If the sleeping defense is exposed it will cause leeside erosion. Therefore the sand buffer must be designed in a way that ensures that the sleeping defense is covered at all times.

A detailed description on the design criteria for the coastal protection scheme is found in appendix D.

The following is a short description on the criteria for the construction of the sleeping defense, as described in the regulatory permit for the installation by the DCA (Kystdirektoratet, 2016).

Compensating nourishment volume was calculated at 18,000 m³ /year based on an chronic erosion rate of 3.8 m/y. The compensating nourishment can be placed anywhere in the active coastal profile. The landowners chose to add the sand just outside the 3rd breaker bar near the groynes at Nørlev.



Figure 5.1: Shoreface nourishment on the shoreface outside of Skallerup Klit. No precise location of the nourishment exist.

The width of the sandbuffer is calculated to be at least 10 m based on a maximum retreat of the dune face under a severe storm of 5 m. The top level must be 4.5 m. At each side of the sleeping defence the width of the sandbuffer is linearly reduced over a distance to 2.5 m ($\frac{1}{4}$ of the maximum width). The distance is longest (50 m) on the upstream coast, while it must be 25 m on the downstream coast.

The total nourishment volume of the sand buffer is 12,475 m³. The grain size distribution of the nourishment sand is unknown. The borrow area was the upstream beach at Hirtshals harbour.

Nourishment volumes and dimensions of the sand buffer must be documented via surveys by the landowners every 3rd year according to the regulatory permit issued (Kystdirektoratet, 2016).

The revetment was designed to withstand a water level and corresponding waves with a statistical return period of 50 years.

Prior to construction the dune face was fluctuating in and out and an additional fill-up in the dunes was carried through before the construction of the revetment in order to straighten out the dune face. This causes the sand buffer to be in a more exposed position than was planned in the design. This addition can also be confirmed in Figure 5.3 when the construction of the revetment is in progress. The average contours of the revetment top was reported to be at the 3.5m contour and the revetment toe was reported to be at the 1.35 m contour.

The beach nourishment was deposited by dumpers, while bulldozers were used to distribute the sediment evenly along the revetment. This method resulted in a lower compaction of the sand compared to pumping via a pipeline. The finished nourishment with underlying revetment or sleeping defense is pictured in Figure 5.2 under strong wind conditions (-10 m/s). In addition to the nourishment, marron grass was planted on the nourishment top to reduce sand drift. The averaged contours for the nourishment was 0.98 m for the nourishment toe, the crest was 3.77 m and the inland top of the nourishment was 4.53 m. Average heights were measured on 4-11-2016 when the nourishment was completed, but it was not reported to be finished until the 21-11-2016. An inspection of the finished construction was made on the 22-11-2016 supported by a drone flight.



Figure 5.2 - Same as Figure 4.1, but here direction of sight is SW. The installation of the nourishment was finished on the 21-11-2016, and was measured on the 22-11-2016.



Figure 5.3: Construction of the revetment. Photo is taken on the 13th of September 2016. Notice how additional sediment has been placed behind the revetment.

The compensating nourishment was also conducted in November 2016 - the specific date is unknown. The nourishment was placed on the 3rd breaker bar from a ship using the rainbow method. A photo from one of the nourishment campaigns can be seen in Figure 5.1. No measurements or position have been made or given for the shoreface nourishment, and therefore the performance of this nourishment and potential influence on the sleeping defense stretch in Nørlev will not be looked into. A plan view presentation of local measuring lines, 1 m and the 3.5 m contour together with the revetment stretch is represented in Figure 5.4.

5.2 Monitoring Program

The monitoring campaign consists of two different methods for following the nourishment performance. Drone videos and imagery have been compiled for different dates during the monitoring period, and local transect measurements have been carried through on several dates along the lines presented in Figure 5.4. More than one nourishment took place during the monitoring period, precise dates are not available, but the months in which they have been carried out are shown in Figure 5.5 together with amounts and a sum up on times when measurements and drone flights have been conducted. Local transects have been used for profile measurements with dGPS.

5.2.1 Local Profile Measurements

Local transects in the area covering the nourishment placed at Nørlev beach have been conducted on four separate dates and the local transects line numbers are between 500000 and 500650 with a spacing of 25 m. These local measurements cover the profile from the top of the dune to a depth of -0.5 meters. It would have been ideal if the measurements were made to a greater depth, but this was impossible due to limited resources. The local profile measurements have been conducted on the following dates:

- 6th September 2016**
- 22nd November 2016**
- 17th February 2017**
- 3rd July 2017**

The accuracy of the data is the same as that of the WCLs as they are measured using RTK dGPS and total station. Since point measurements from measurement campaigns are never perfectly aligned with a predefined transect line, alignment of points to transect lines have been done manually before triangulations or interpolation.

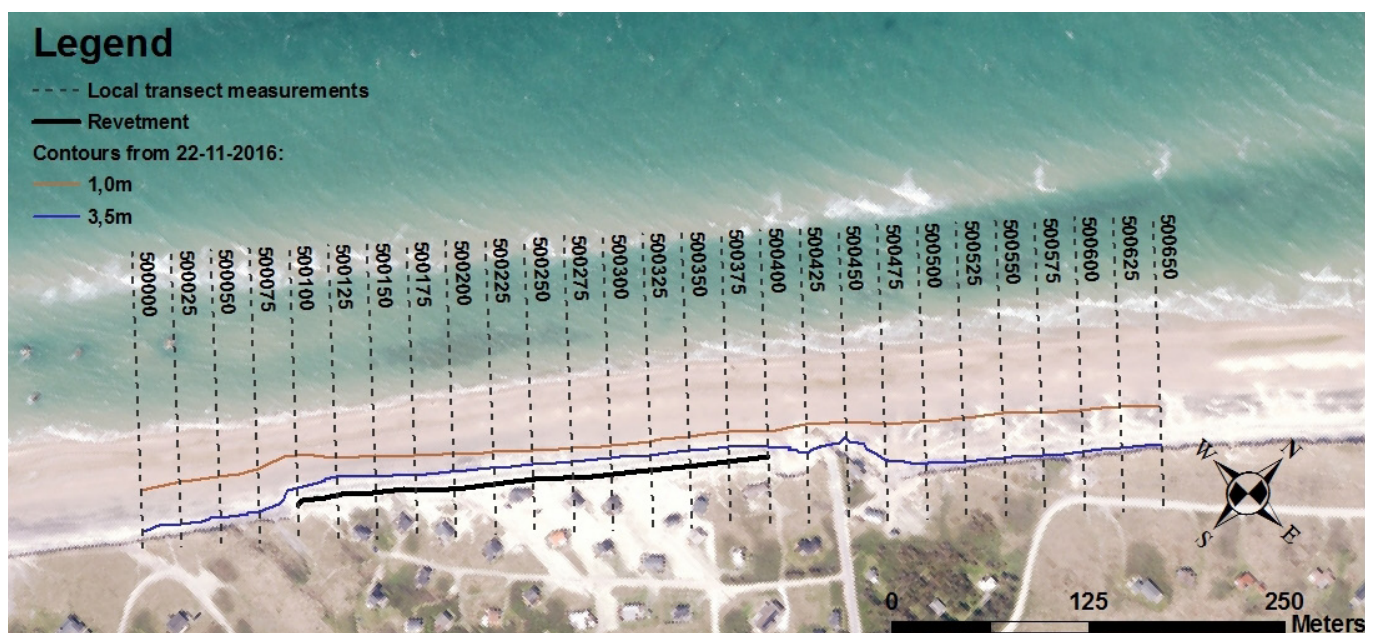


Figure 5.4: Presentation of the measured transect lines together with revetment stretch and contours 1 m and 3.5 m from the 22-11-2016 measurement. Underlying photo is from 2017.

Timeline measurements and nourishment

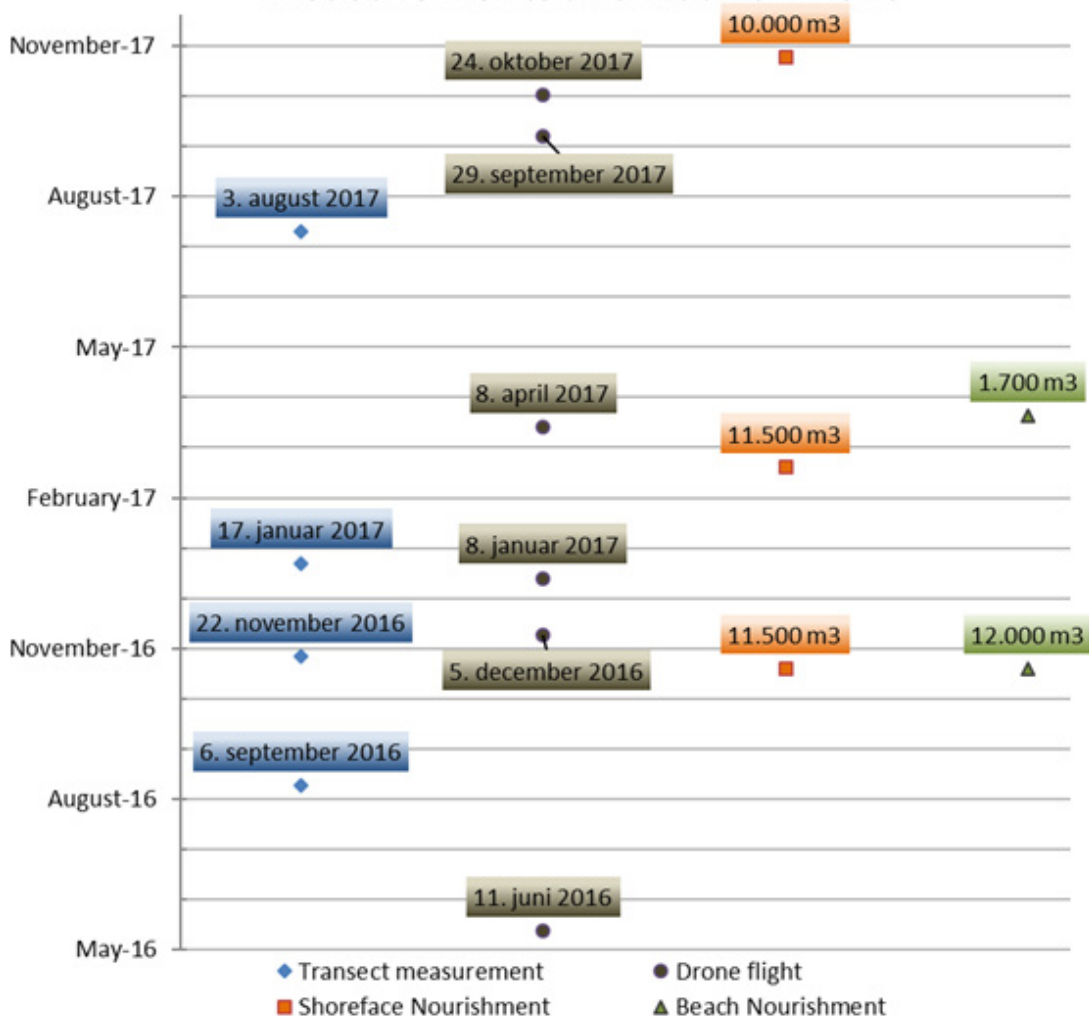


Figure 5.5: The figure serves to give an overview and insight into the timeline over significant events during the period of monitoring. The precise dates of nourishments are unclear but the months and year in which they have been made are used instead.

Originally these pre-defined transect lines have been measured 25 m apart. On four different occasions profile measurements have been conducted along the transect lines and these will be used for profile and volume analysis just as it was the case for the WCL. Transect numbers and placement are presented together with the 1 m and 3.5 m contours from the measurement on the 26-11-2016, which indicates the finished nourishment crest and toe as described in the design. No planview photo is available after the placing of the nourishment, so the underlying photo is from spring 2017 showing the additional nourishment of 1700 m³ placed in April 2017. Notice how beach or nourishment sediment have displaced itself in the hinterland behind the revetment, indicating an aeolian sediment transport over the revetment stretch – this sediment transport must be seen as a sink or loss, as the hinterland is high enough to prevent flooding.

5.2.2 Drone Monitoring Campaigns

have been conducted multiple times over the monitoring period. The drone is used for filming across and along the stretch. These data have been used for visual inspections of the coast and for description of morphological changes in between the more infrequent local measurements. Imagery from the following dates have been included: 11-06-2016, 05-12-2016, 08-01-2017, 08-03-2017 and 29-09-2017.

6. Analysis of Nourishment

Several data sets are available from the periods before and after the nourishment was undertaken. The analysis of nourishment performance and effect can therefore incorporate a more holistic approach in which the performance is studied with different approaches. The analysis structure is presented below.

First of all, the actual nourishment performance will be analyzed from interpolated profile measurements, drone imagery and wave-, wind- and water level data. The study will be subdivided by the profile measurement dates in order to describe changes between measurements.

Analysis and quantification of CSI changes in response to the nourishment and the sleeping defense is also performed. Local profile measurements are used for profile analysis on each measured transect with respect to MDP, MCP, beach width and profile volume. In order to reference the diffusion time of the nourishment, a theoretical approach is incorporated along with the actual development.

6.1 Nourishment Development

The following can be considered as both description and analysis on the development of the nourishment. The performance will be based on the interpolated surface models presented in Figure 6.1. The difference between models will be evaluated and analyzed on the basis of available data between the measurement dates.

Period 1: Between 07-09-2016 and 22-11-2016

Period 2: Between 22-11-2016 and 17-01-2017

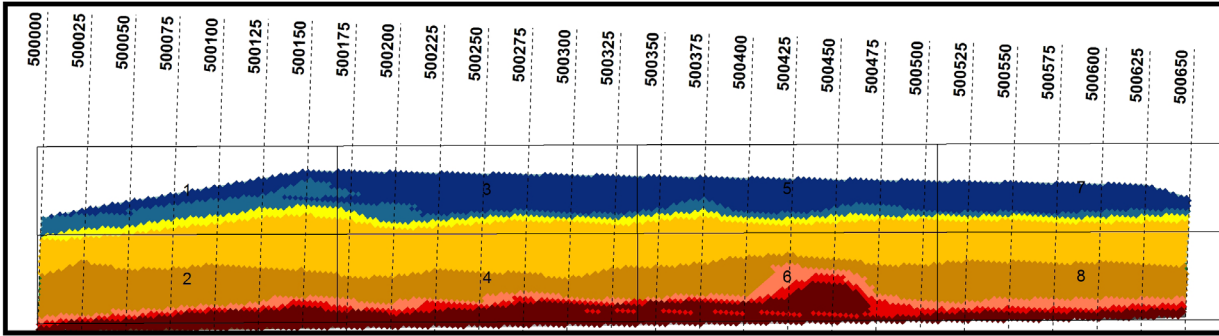
Period 3: Between 17-01-2017 and 03-08-2017

Available drone imagery (Appendix C) and satellite imagery in each period will be described. Surface models have been created using the transect measurements for TIN triangulation, which afterwards have been subjected to a linear interpolation to a Raster format. The extent of the local measurements differs, which also leads to different raster area extents, Figure 6.1. The legend shows different intervals to illustrate some of the values that have been worked with, such as the tidal range of 0.3 m and the MDP levels between 3.5 m and 3.0 m.

The boxes 1-8 and local transect lines serve to provide a solid and comparable reference between the four different frames. All data frames are set to same scale and extent. They will be analyzed for each period with respect to assessment of wind and water level data for the respective periods presented in Figure 6.2 and Figure 6.3.

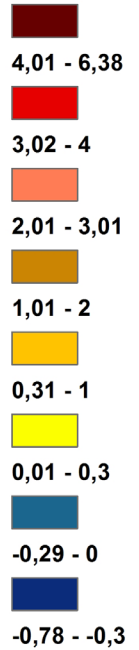
The surface models are based on the local profile measurements. A TIN model is constructed in ArcMap and linearly interpolated into a Raster surface model with 2 x 2 m tiles, presented in Figure 6.1. Notice that the models are based on the same elevation indexes. The elevation intervals are not equidistant, and elevation index value have been manually chosen in order to visualize the varying extension of the beach in high and low water events. E.g. the tidal range of 0.3 m was used on both sides of 0.0 m (intervals between 0.3 m and 0.0 m as well as 0.0 m to -0.3 m) and the 1 m mark was used as the 1 year return was 96 cm.

Date: 06 - 09 - 2016

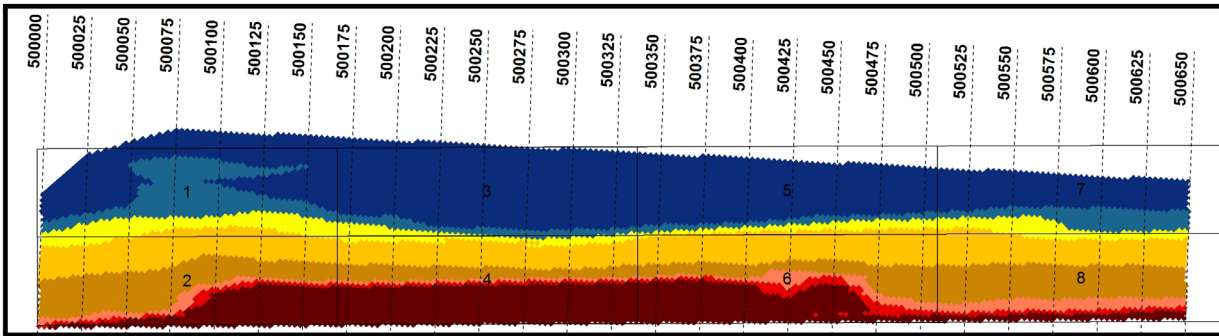


Legend

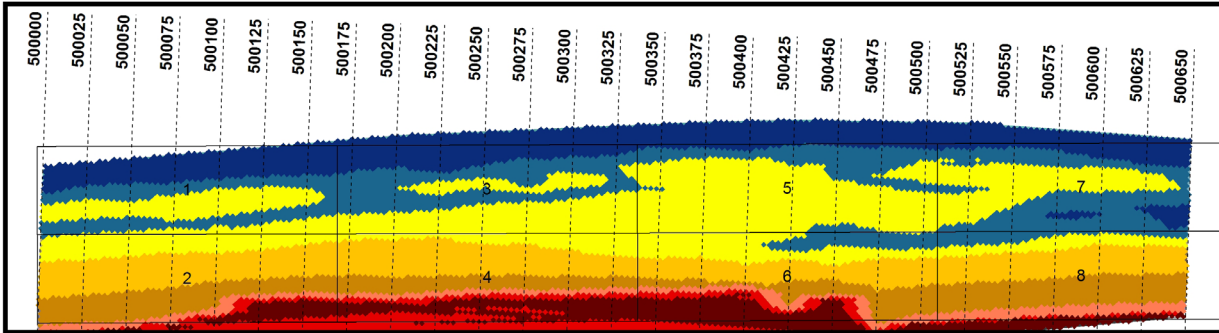
Elevation



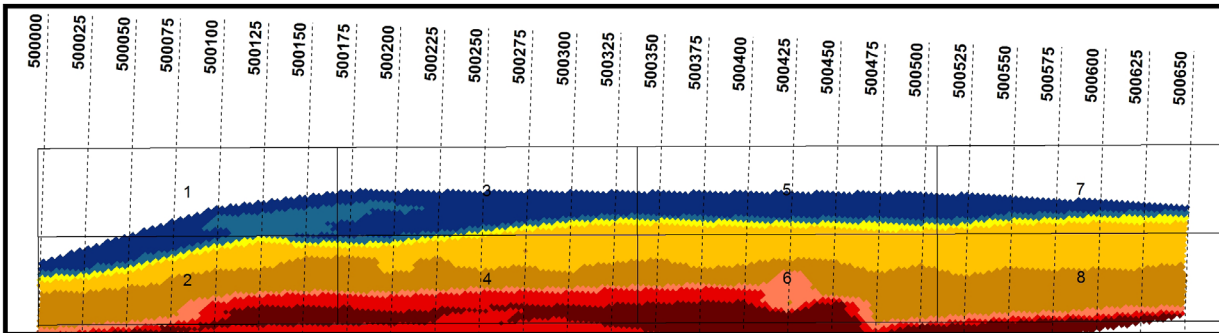
Date: 22 - 11 - 2016



Date: 17 - 01 - 2017



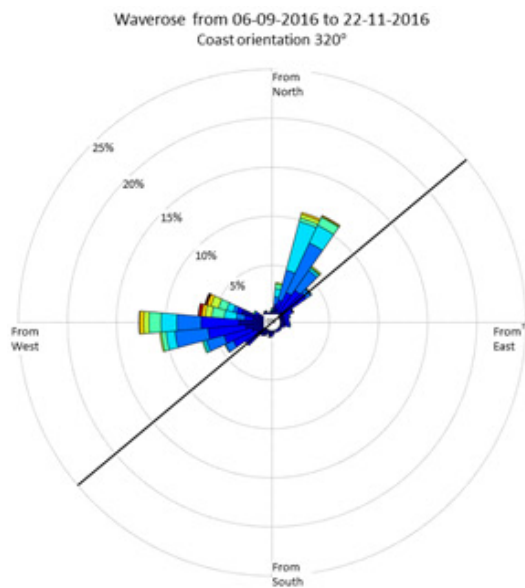
Date: 03 - 08 - 2017



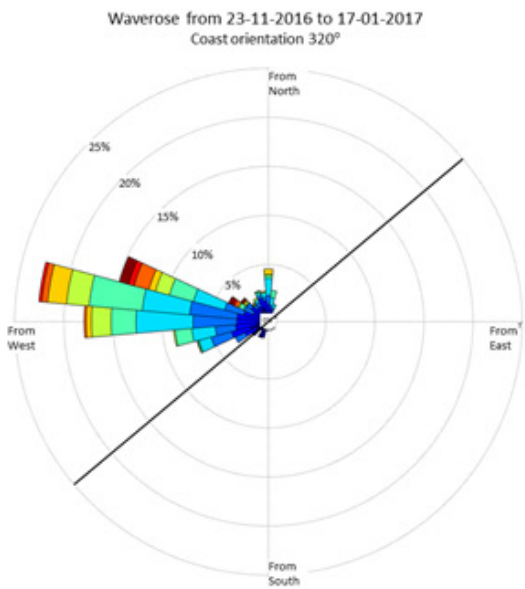
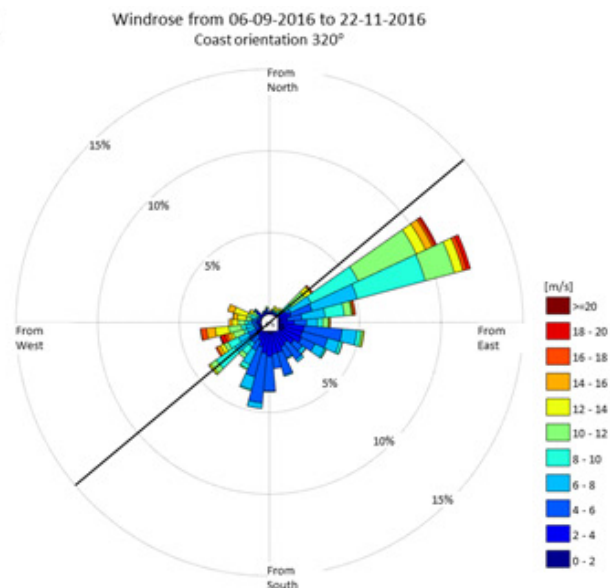
0 0,25 0,5 Kilometers



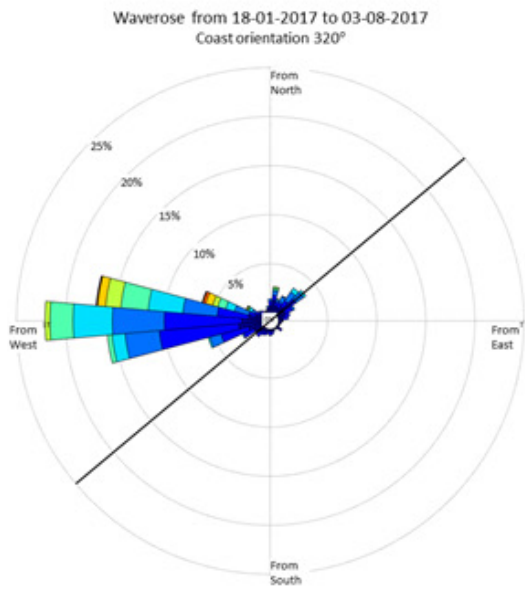
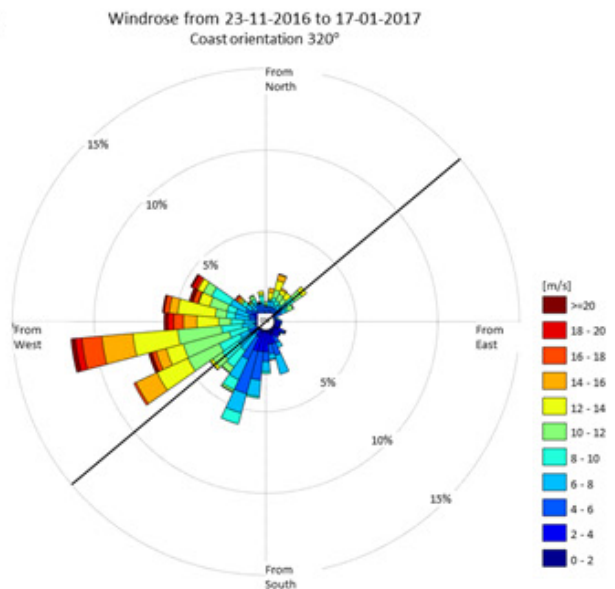
Figure 61: Location of local survey lines and boxes 1-8. The different colors show the different intervals such as the tidal range of 0.3 m (blue) and the MDP levels between 3.5 m and 3.0 m (red/brown).



Period 1



Period 2



Period 3

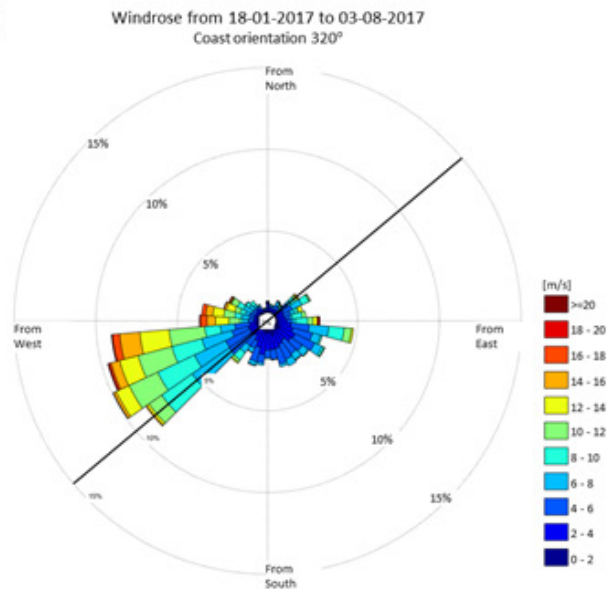


Figure 6.2 Wind roses (left) and waveroses (right) between local surveys.

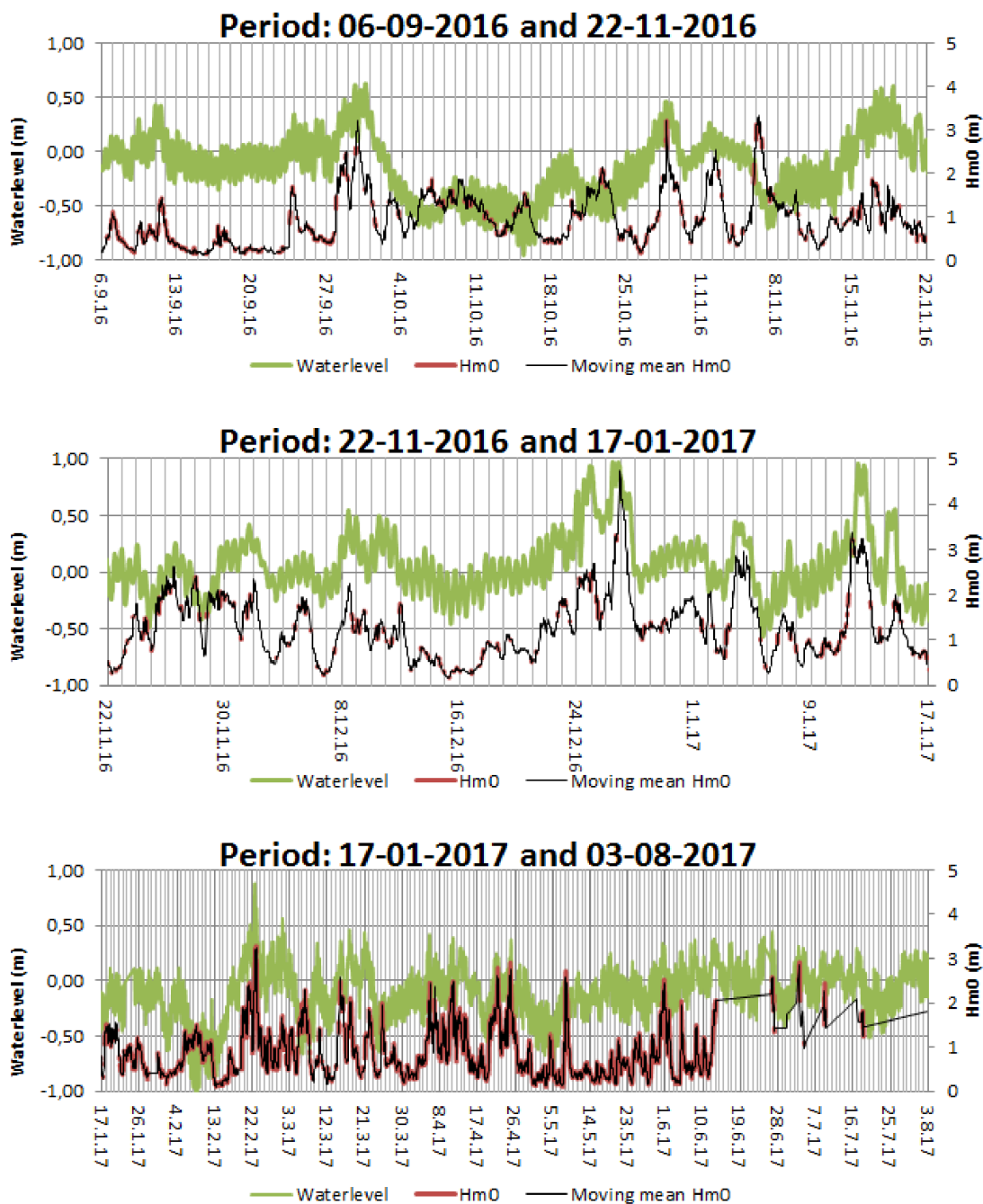


Figure 6.3 Timeseries of wave heights and waterlevel.

6.1.1 Baseline Measurement 06-09-2016

Drone image: 11-06-2016 - around 09:00, water level between -10cm and -14cm.

These drone images are the only drone images available before the measurement from 06-09-2016. The beach is seen to be wide and the low water level allows for identification of a beach runnel with a berm, which is most likely fully submerged at high tide. The vegetation line is seen to fluctuate inwards and outwards along the stretch, which was also noticed in the description of the sand buffer and revetment. The revetment found in the 2nd photo is the one placed in front of Nørlev Strandvej, downstream of the sand buffer stretch.

Shape 06-09-2016 - Figure 6.1

The interpolation of the profiles from 06-09-2016 shows a small headland formation in box 6. This is the revetment found in front of the access road at Nørlev Strandvej also visible on the drone images from 11-06-2016. The beach is close to parallel with the dune face, while the profile below 0.0 m is slightly shallower in box 1, than in 3, 5 and 7.

6.1.2 Period 1: 06-09-2016 to 22-11-2016

Wave- and wind roses for the period are presented in Figure 4.2 and water level in Figure 4.3.

Shape 22-11-2016 - Figure 6.1

No drone imagery is available between the 06-09-2016 and 22-11-2016. The elevation model between 06-09-2016 and 22-11-2016 seen in Figure 6.1 have changed in most of the 8 boxes, and the extent of the profile measurements is shorter compared to 06-09-2016. A general narrowing of the beach is seen in boxes 3, 5, and 7. The sleeping defense is spotted in this measurement as accumulation in boxes 2, 4 and 6 - notice that this is where the beach has narrowed the most. There is an accumulation in the sub 0.0 m part of box 1, but the NE boxes 3 and 5 indicate a deepening - this is most likely due to lack of measurements. No extreme water level observations exists in this period, but three peaks in HmO above 3 m are identified in Figure 6.3. As the dune face is almost in the same position between 06-09-2016 and 22-11-2016, the impacts of these events are not expected to have had significant impact in the dune face, but these wave events combined with multiple water levels above + 0.5 m meters in the period up until 22-11-2016 is likely to be the driver for the narrowing of the beach. There was quite an even distribution of waves from WSW and NNE in this period, which indicates a relatively low net sediment transport rate.

6.1.3 Period 2: 22-11-2016 to 17-01-2017

Drone image: 05-12-2016 - around 09:30, water level between +12cm and +16cm.

The images are recorded a months after the nourishment was concluded, and as it is to be seen, no erosion has yet taken place in the nourishment front. The beach width in front of the nourishment has narrowed significantly, also if the beach width in front Nørlev Strandvej (at the revetment) is considered, compared to 11-06-2016 images. This narrowing is a combined effect of the seaward extension due to the sediment placed behind the revetment, as well as the retreat of the beach. The water level is also found to be 30 cm higher than on the 11-06-2016, and as waves are breaking in the images it is possible to identify at least three breaker bars in front of the stretch. The 1st bar might be the berm noticed in the images from 11-06-2016 while the two others have been confirmed from orthophoto analysis.

In Dec 2016 the water level peaked on the 23rd at 22:30 hours with +106 cm while the wave peak was found to be 4.73 m on the 26-12 at 23.00 hours. The water level itself is only 10 cm above the 1-year return period, but when combined with deep-water waves peaking at 4.73 m, the setup at the beach has resulted in an even higher water level. The averaged wave period was measured between 7.6 sec and 8.4 sec. The water level peaked above 1 m both on the 24th December and again on the 26th December, while the HmO values have decreased for the 2nd water level peak.

Drone image 08-01-2017 - around 14:00, water level between 0 cm and +5 cm.

This flight is conducted in between 2 storm periods, (24th to the 26th of Dec-2016 and 11th to 13th of Jan-2017), and the sand buffer in front of the revetment had been redistributed already before the storm in January. The sleeping defense is almost completely visible, and its advanced position is clearly seen. There are still some nourishment sediment left on top and behind the revetment, which the wave run-up has not been able to reach. A wide beach is present in the SW end of the revetment and the stretch shows a well-defined hill edge/vegetation line indicating erosion in the dune face. A large undulation in the beach is seen in the SW corner of the sleeping defense in contrast to the beach narrowing to 0m in the NE corner of the revetment. The vegetation line has retreated between Nørlev Strandvej and the revetment which is close to back-cut. At least two breaker bars can be identified, the first is close to the beach in the SW stretch, but as the beach narrows in the NE corner of the revetment the bar continues in a regular line along the revetment.

Shape 17-01-2017 - Figure 6.1

The sand buffer was confirmed to have been redistributed already on the 8th of January, which corresponds well with the retreat of the dune face in boxes 2, 4 and 6 (Figure 6.1) and this is probably a result of the storm in late December 2016. The non-existing beach in front of the revetment, shown in the drone images from the 08-01-2017, does not correspond to the shape seen in Figure 6.1, as a seaward advance of the 0.0 m contour is identified with respect to the position on the 22-11-2016. Since the water level maximum is +5 cm in the drone image from the 08-01-2017 it is possible that the beach is submerged in the images, but a bar or berm can be identified in the shape from 17-01-2017 in Figure 6.1 which corresponds with the 1st breaker seen from the drone image. As a storm passed between the 11th and 13th of January with waves predominantly from W it is likely that the undulation in the beach seen in the SW end of the revetment stretch from 8th of January 2017 has migrated towards the NE and to the front of the revetment. The period between 13th and 17th of January showed average HmO of 1 m and an averaged 325° wave direction which is close to the coast normal. Buffer sediment redistributed across shore is therefore likely to have migrated back to the beach between the 13th of January and the 17th of January 2017.

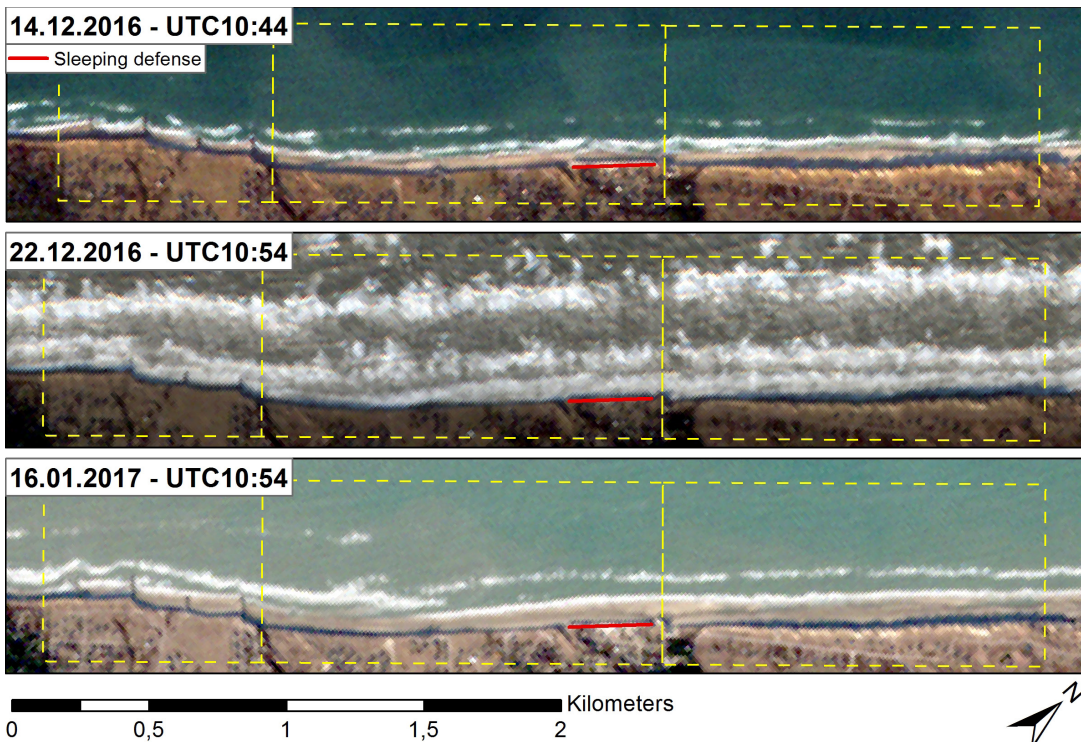


Figure 6.4: Satellite imagery collected from the sentinel 2 satellite in 10X10 m grids. The dates in upper left corner is in UTC times meaning that the local time is -1hour. Water levels: 14.12.2016 - local time 09:40 was -33cm, 22.12.2016 - local time 09:54 was +33, 16.01.2017 - local time 09:54 was -23cm.

Satellite imagery from the sentinel-2 satellite has been scrutinized in order to find imagery from between the storm periods and possibly during storms. Satellite imagery was available without cloud cover for three dates in period 2. On the 14th and 22nd of December 2016 and also on the 16th of January 2017.

From the satellite imagery in Figure 6.4 it is possible to identify a narrow beach in front of the sleeping defense stretch already on 14.12.2016 and the 2nd breaker bar seems weak in front of the stretch, as well, since no wave breaking is taking place despite wave breaking on each side. In the 22.12.2016 imagery most of the beach seems to be submerged under swash, and a depression can be identified in the 3rd bar between section 2 and 3. On the imagery from the 16.01.2017, the beach seems much wider, compared to the 14th of December 2016. This corresponds with the measurements from the 17th of January 2017. It is also visibly clear that a beach widening has taken place between 14.12.2016 and 16.01.2017, also when taking into account the water level which was 10 cm lower on the 14.12.2016. Furthermore the beach runnel suspected from the shape on the local measurement on the 17th can be visually identified

just NE of the sleeping defense pin line in Figure 6.4 on the satellite imagery from 16.01.2017. This beach berm could act as a breaker in when submerged and sediment accumulated here must be a result of NE-directed longshore transport, also some of the sediment is likely to originate from the nourishment.

A relatively calm period was experienced between the 13th and the 16th of January 2017, resulting in a build-up, possibly caused by nourishment sediment re-entering the lower profile section of the local profile measurements from cross-shore depositions. The breaker bar is also identified from wave breaking and is straight and uniform. The development of an additional inner bar was also identified in the orthophoto analysis in the baseline study, underlining the NE directed transport of nourishment sediment. Besides retreat of the sand buffer, the dune face is also seen to have retreated for the stretches in boxes 2 and 8. The interpolated surface model shows a beach widening on the 17th of January, while narrowing was identified on the 8th of January from drone imagery (Waterlevel -0.2 m) and the satellite imagery from the 16th of January confirmed the beach widening.

6.1.4 Period 3: 17-01-2017 to 03-08-2017

Drone image 04-03-2017 - around 14:30, water level between -33 cm and -36 cm.

With a water level of -30 cm the 1st breaker bar is seen to be dry and now shows up as an actual berm with a seaward undulation in front of the revetment stretch. It may be difficult to see but an excavator is conducting a re-nourishment on the revetment and can be seen to have covered half of the revetment again. This re-nourishment was reported to be finished in April 2017 as seen in the timeline (Figure 5.5). The re-nourishment was 1700 m³. It is not easy to distinguish from these images, but already at this stage there has been aeolian deposition of sediment behind the revetment, which means that not all the nourishment sand is redistributed in the wet zone. The maximum water level in the period between 17-01-2017 and 03-08-2017 occurred on the 22nd of February when the water level reached +87 cm and HmO peaks at 3.8 m in Hirtshals, but it is not possible to distinguish from the drone image if this event had any impact in the dune face.

Surface model 03-08-2017 - Figure 6.1

Shows a beach widening in boxes 3, 5 and 7 as the 0m contours extend seaward and the height of the beach seems to increase in comparison with the post storm measurement from 17th of January 2017. As it is seen, the outer berm or bar observed on the 17th of January was not measured, most likely as it had lowered, due to an overall onshore directed sediment transport. In the upstream stretch (box 2) the beach has narrowed, but there is still an increase in beach height. The dune face advances in front of the sleeping defense stretch, reflecting the re-nourishment placed in April 2017 (1700 m³). This was also confirmed from drone imagery. Another slight advance can be witnessed for the +2 m contour since the 17-01-2017, which could indicate that occasionally the swash is reaching the upper beach even in situations of onshore directed sediment transport. It could also be a response to aeolian deposition between the measurements.

Drone image 29-09-2017 - around 14:00, water level between +14 cm and +18 cm

The re-nourishment conducted in March is still intact in front of the nourishment. Furthermore, the beach in front of the nourishment stretch is wide and attached to a partly submerged berm. Looking to the SW end of the nourishment stretch the beach is darker, which indicates a lower beach compared to that in the nourishment stretch and NE of it. The leeside erosion which took place during the winter storms in Dec. 2016 and Jan. 2017 is still visible and can be compared with the two cars parked between the revetment and Nørlev Strandvej. It is to some extent noticeable that the aeolian deposition is larger than that which was seen on the 4th of March 2017, but it is especially clear in the orthophoto from 2017 between WCL 1640 and WCL 1630 (Appendix B), which was taken in the spring of 2017. The extent of the aeolian deposition stretches close to 100 m inland from the revetment and the width is also approximately 100 m.

6.2 CSI Analysis

To quantify the changes between models the CSIs are analyzed for the local profile measurements. The analysis and quantification will be based on momentary dune face position (MDP), momentary coastline position (MCP), beach width (horizontal length between MDP and MSP) and a profile volume analysis. The results will be set relative to the baseline measurement from 06-09-2016 and the analysis of the CSI changes will be made for each parameter divided into the same periods as used in chapter 4.1. The sand buffer was placed between lines 500100 and 500400 while the revetment is found between lines 500125 and 500400.

6.2.1 Momentary Dune Face Position (MDP)

The MDP position is defined by the top level of the revetment (avg. 3.5 m), and a lower boundary set at 3 meters. Some local measurements have not been made to the full height of the dune and nourishment, therefore the top boundary was set at 3.5 m as most lines are presented at this height. These boundaries also ensure that the revetment is caught as MDP when all the nourishment sediment in front of the revetment is redistributed after a storm. In Figure 6.5 the MDPs are set relative to those found for the baseline measurement from the 06-09-2016, and have been plotted from line 500000 (SW) to line 500650 (NE).

Period 1: 06-09-2016 to 22-11-2016

The first measurement after construction of the sleeping defense was on 22-11-2016 and it therefore reflects the maximum extent of the sand buffer, which is the advance seen for lines 500100 to 500400. The advance of the sand buffer is irregular and ranging between 16 m and 10 m which is explained by the slight fluctuation of the dune face before the coastal protection was installed. The difference in advance is caused by the straightening of the sand buffer which can be seen on the drone imagery from December 5th 2016. The exposed position (15 m) of the sand buffer is clearly to be seen.

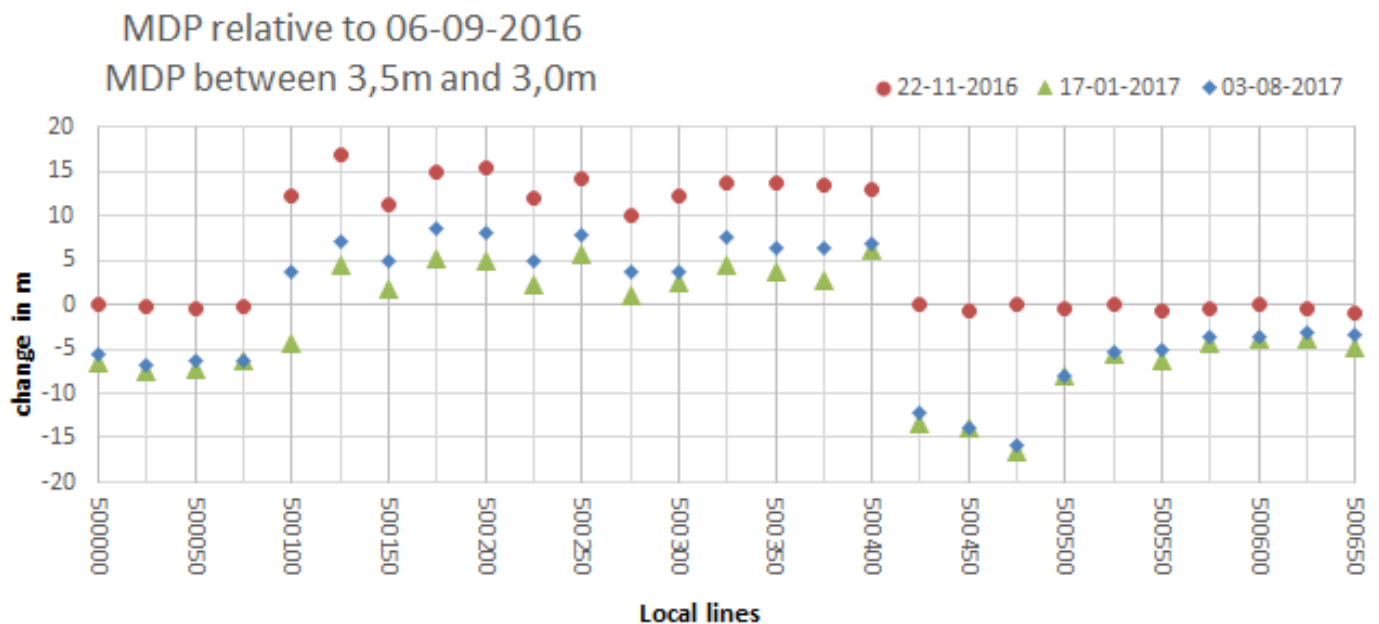


Figure 6.5 - MDP has been visualized by idealizing lines between the MDP points of each period. The revetment is not to scale, and merely illustrates the transect extent. The 17-01-2017 line from 500125 to 500400 illustrates the revetment position to scale.

Little changes are found in the MDP for up- and down-stream lines, but there have been smaller retreats, which were not found from the surface analysis. Although dune face erosion or slumping cannot be ruled out, no storm impacts or significant high-water events (maximum = +60 cm) have occurred between 06-09-2016 and 22-11-2016, and these small fluctuations could reflect differences in the profile measurements. If the point density in dGPS measurements differ it may have resulted in a different slope for the dune face than the one in earlier measurements, which affects the MDP measure.

Period 2: 22-11-2016 to 17-01-2017

As the period between 22-11-2016 and 17-01-2016 can be characterized as a storm period (On the 26-12-2016 max water level was +106 cm, while the waves peaked at +4 m waves avg. period of 8 s), a retreat in the dune face is not unexpected, but the retreat rates are unusual in comparison with the average rates found in the baseline study. On the upstream side of the revetment (Lines 500000 to 500100) the average retreat between 06-09-2016 and 17-01-2016 is found to be 6.4m.

The downstream stretch (Lines 500425 to 500650) shows a retreat of 8.1 m for the same period. However, the downstream stretch can be divided into two different stretches: the stretch between 500425 and 500475 which is affected both by the sleeping defense and the revetment in front of Nørlev Strandvej, shows an average retreat rate of 14.7 m, while the stretch from line 500500 to line 500650 shows a retreat rate of 5.3 m. Even though this division changes the retreat rates, the 5.3 m retreat rate is still far above the vegetation line retreat rate found at CSL 12, which was 0.9 m and the 0.8 m retreat found for WCL 1630. The maximum retreat found for CSL 12 in vegetation line was seen between 2002 and 2004 and averaged 2.5 m (appendix A).

The sleeping defense stretch shows a retreat for all lines since 22-11-2016, but the MDP still extends further seaward compared to the 06-09-2016 measurement. As all nourishment sediment in front of the revetment was redistributed after the December storm, the difference between 06-09-2016 and 17-01-2017 is the actual advance of the revetment relative to the pre-existing dune face - The average advance of the revetment relative to the original dune face is 3.8 m. The actual retreat in the nourishment must therefore be the difference between 22-11-2016 and 17-01-2017 which for all lines between 500125 and 500400 averaged 9.7 m (also average width of nourishment along the revetment). The retreat rates are close to double of the maximum acute erosion rate used in the regulatory permit (5m/y), and well above the maximum erosion in MDP at WCL 1640, which was 7.7 m/y and maximum vegetation line retreat between 2012 and 2015 at CSL 9, which was 6.7 m/y.

Period 3: 17-0-2017 to 03-08-2017

Both up- and downstream of the revetment the stretches show a slight advance on 03-08-2017 compared to 17-01-2017. These advances could be a response to the deposition caused by aeolian transport, which was confirmed from orthophotos and drone imagery. The advances could also reflect differences in point density between profile measurements. Even though a smaller storm event occurred on the 22nd of February 2017 with water level peak at +87 cm and HmO peak at 3.28 m, no retreat in the MDP can be identified between 17-01-2016 and 03-08-2017.

The 1700m³ re-nourishment concluded in April 2017 can be identified as the advance between 17-01-2017 and 03-08-2017 on lines 500125 to 500400. This means that the difference in MDP between the above dates must be the width of the additional nourishment. If line 500100 is counted into the nourishment stretch, the average nourishment width is 3.0 m for the re-nourishment in April 2017.

Between 06-09-2016 and 03-08-2017 retreat rates in MDP at the upstream stretch (lines 500000-500100) are found to be between 5.5 and 6.2 m. The retreat rates in MDP on the downstream stretch (Lines 500425-500650) was found to range between 15 and 3 m. These rates are higher than those found in the baseline, which showed 2 m/y WCL1640 (upstream) and 0.8 m/y at WCL 1630, and also above the maximum acute erosion in the permit, which was set at 5 m.

The erosion rates are not unexpected, as it is seen in Appendix A that the period between 2012-2015 reveals an average erosion rate of CSL 10 of +6 m/y, and it is not unlikely that between 2012 and 2015 an event may have occurred in which the maximum retreat has been above 6 m. An interesting observation is that the nourishment was fully diffused after the December storm, especially since the peak water level in the December storm was measured at +106 cm which is only 10cm above a 1 year return event. However, the satellite imagery from the 22nd of December 2016 revealed that the swash was well up the beach even though the water level was only +33 cm and this was also more than two days before the storm

peaked. The intensity of the storm, combined with a narrowed beach, bar depressions and headland formation of the nourishment and combined also with a lower degree of compaction in the sediment (far from the native), have exposed the sand buffer to the erosive forces of the surging waters in the lower dune section. It is also interesting to note that the maximum retreat rates were found immediately downstream of the revetment, caused by to leeside erosion.

6.2.2 Momentary Coastline Position (MCP)

The MCP boundaries were originally defined between +0.3 m and -0.3 m as outlined in the surface models in chapter 4.1. Unfortunately, these boundaries proved not to be appropriate since 25 % of the surveyed profiles were not below -0.2 m, therefore the MCP upper and lower boundaries were defined between 0.2 m and -0.2 m. In Figure 6.6 the MCP are set relative to those found for the baseline measurement from the 06-09-2016, and have been plotted from line 500000 (SW) to line 500650 (NE).

Period 1: 06-09-2016 to 22-11-2016

A small advance in MCP can be identified at upstream lines 500000 to 500100 and 500575 to 500600. Retreat in MCP is decreasing from line 500100 to 500500 and from 500550 to 500650. Between lines 500125 and 500400 the retreat ranges between 0.5 m and 11.5 m, while the average retreat is 6.8 m. An undulating motion in the beach can be identified in the MCP changes - notice the peak in advance at line 500050 to 500075 and the peak in retreat between 500275 and 500375 which again is ended by a peak advance at line 500550. The narrowing of the MCP at lines 500125 to 500400 indicates an overall narrowing of the beach. The combined effect of MCP retreat and MDP advance will also be seen under the beach width section.

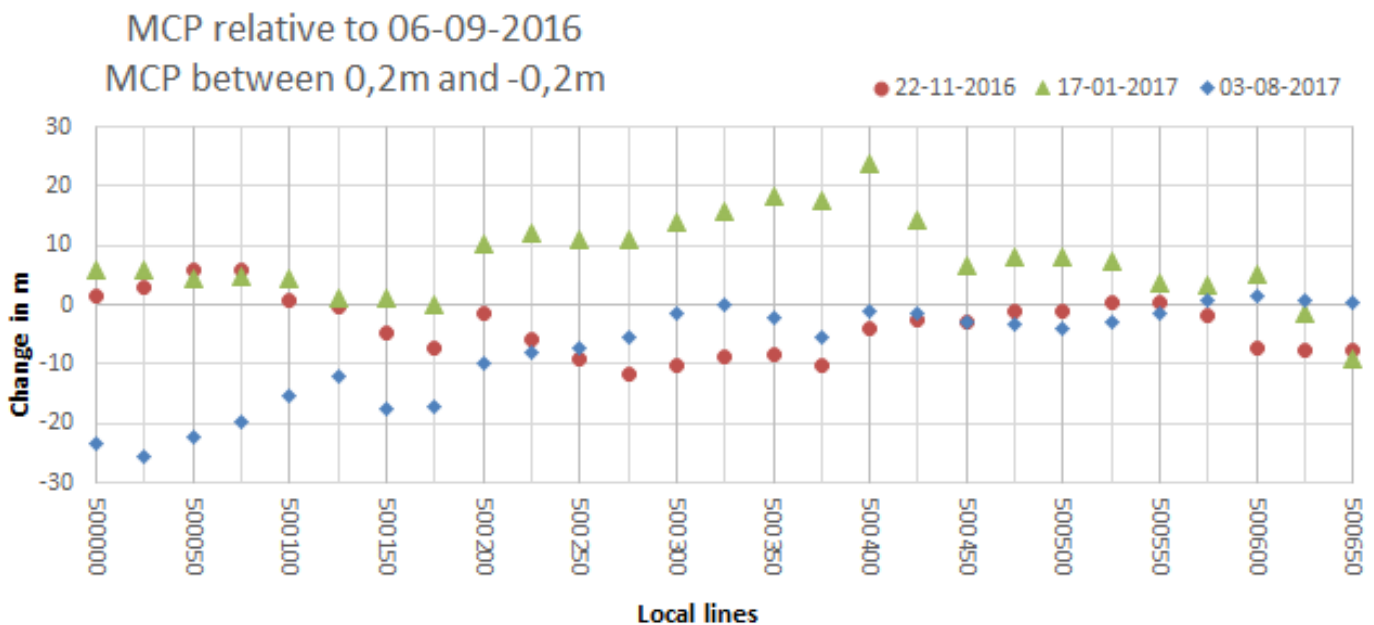


Figure 6.6: The momentary coastline has been found for every transect measurement in MorphAn. The position for each line was given in meters from a defined fix point inland. The purple box represents the revetment and is not to scale. It merely illustrates the transect extent.

Period 2: 22-11-2016 to 17-01-2017

All lines with exception of 500625 and 500650 show an overall increase in beach width relative to 06-09-2016 and especially in front of the revetment on lines 500200 to 500400. Here the advance is found to be between 10 m and 25 m relative to 06-09-2016, but relative to 22-11-2016 the advance can be seen to be an even increase from Figure 6.6. The advance is smaller on the upstream side on lines 500000 to 500175 and also on the downstream side from line 500450 to 500575 but when compared to the MCP on 22-11-2016 there is a significant advance in MCP. All the nourishment sediment was redistributed from the revetment front after the 2016 December storm and it is therefore likely that the sediment has been redistributed in the beach section or in a tidal berm/breaker.

Period 3: 17-0-2017 to 03-08-2017

In the upstream side at lines 500000 to 500125 a significant retreat in MCP can be identified, possibly as an undulation. This narrowing is also seen in front of the revetment stretch, especially if compared to 17-01-2017 MCPs. It is seen to decrease from line 500175 to 500325 where the MCP is almost the same as found on 06-09-2016. The upstream stretch is seen to fluctuate inwards and outwards with a couple of meters from line 500375 to 500650 and an advance is actually found at lines 500575 to 500650. Despite the retreat relative to 17-01-2016 the surface models indicate that the volume increased in the upper beach section on the 03-08-2017 model, so although the MCP has retreated the beach might still contain the same volume.

The MCP is expected to show natural fluctuations as this has been observed in the baseline study. The advance in MCP between 22-11-2016 and 17-01-2017 in front of the revetment stretch could indicate that nourishment sand has been redistributed in the lower part of the profile, and therefore leading to seaward extension of the shoreline. The MCP retreat rates between 17-01-2017 and 03-08-2017 decrease steadily from line 500000 to 500600. This could indicate that an undulation of sand has travelled towards the NE. As the measurement from the 03-08-2017 is much shorter than the rest, another possibility is that a bar might have built up outside of the measured area, thus compromising the results.

6.2.3 Beach Width

The beach width is found as the horizontal distance between MDP and MCP, changes in beach width therefore reflects the combined movements of MDP and MCP - beach widths relative to 06-09-2016 is presented in Figure 6.7.

Period 1: 06-09-2016 to 22-11-2016

The beach width increases between lines 500000 to 500075 and 500525 to 500550. The remaining lines show decrease in beach width. The nourishment stretch between 500100 and 500400 shows a significant decrease ranging from 11.5 m to 23 m. This narrowing in beach width is the combined effect from the establishing of the nourishment and retreat in MCP.

Period 2: 22-11-2016 to 17-01-2017

In the following period between 22-11-2016 and 17-01-2017, the beach is found to widen for all profile lines. As the MDP was found to retreat on all lines it is not unexpected, but reflecting on the advance in MCP on revetment lines, the beach widening is found to be between 10 m and 34 m increasing from SW towards NE.

Period 3: 17-01-2017 to 03-08-2017

The last period between 17-01-2017 and 03-08-2017, shows a general narrowing of the beach for all lines except 500625 and 500650 which are the lines located furthest to the NE. It is not unexpected as the MDP is advancing on the revetment stretch due to re-nourishment and the MCP is retreating for all lines except 500625 and 500650. Compared to the baseline from 06-09-2016 the beach width on 03-08-2017 is seen to have narrowed between 500000 and 500400 at the end of the revetment stretch. The beach have widened for all lines NE of the revetment. This downstream widening of the beach is likely to be a response to longshore transported sediment since MDP retreats during storm, but the MCPs in the last measure was close to the baseline.

Beach width relative to 06-09-2016

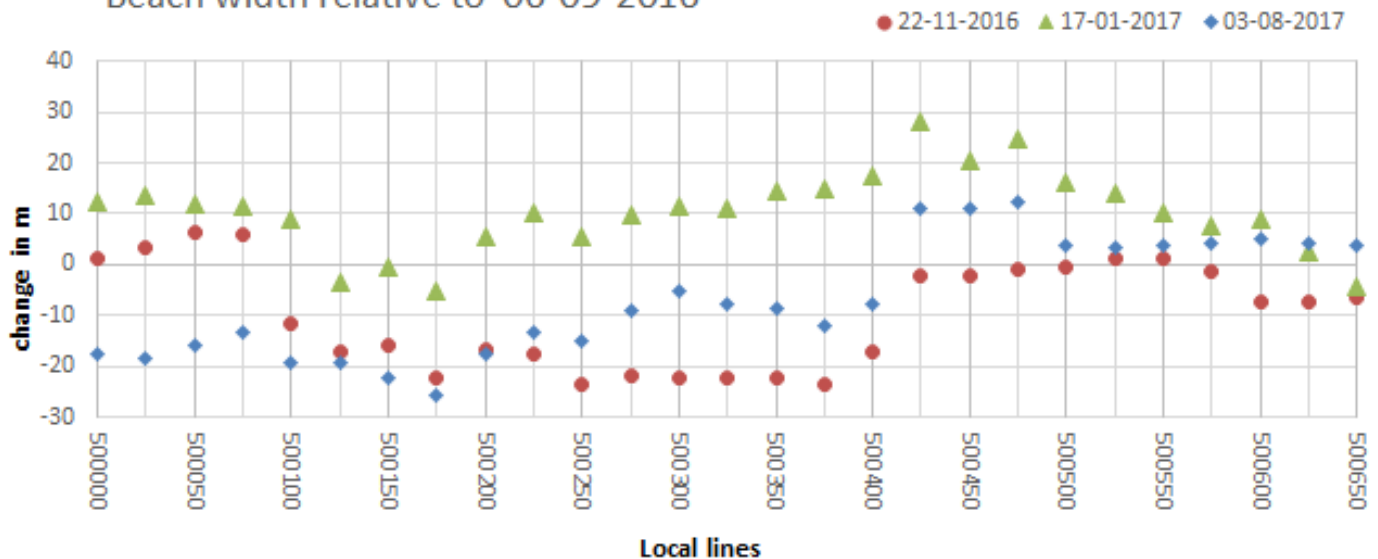


Figure 6.7: Beach width boundaries have earlier been set as the horizontal difference between MCP and MDP for all lines measured. By subtracting the MDP from the MCP a positive horizontal length is found, here defining the beach width.

6.2.4 Nourishment Diffusion

Comparing the nourishment diffusion time with the natural retreat rates along the entire stretch showed that the nourishment diffused faster than expected. In this section the actual nourishment diffusion time and a theoretical approach is implemented.

The theoretical approach is presented by Silvester & Hsu (Silvester & Hsu, 1997) and argues that the averaged disturbance on a beach due to nourishment will retreat faster than native stretches. The disturbance retreat rate is considered to be exponentially decreasing in the time after nourishment. This is due to profile equilibration in response to beach widening and longshore diffusion of sediment. Silvester and Hsu proposes the following formula for calculating the width of the beach over time:

$$Z_t = \left(0,2 + \frac{0,8^{kt}}{10}\right) - (t * \tan \alpha) / Y$$

Where Z is the remaining width at a given time step, k is rate of exponential decay, Y is the width of the beach after placement of buffer, t is time and $\tan \alpha$ is the long term erosion rate at the location.

k: set to 0.64 - The value was found by Silvester&Hsu in a test on multiple stretches.

Y: Set as average beach width along the nourished stretch on 22-11-2016

Tan a: Set to 3.8 m/y the value on which the buffer size is based

Please note that Silvester and Hsu's approach is based on an average condition, since it does not include the actual impact on the beach nourishment.

The theoretical lifetime of the nourishment is also described by Silvester & Hsu:

$$t_e = \frac{Y}{\tan \alpha} * 0,2$$

Which in the case of Nørlev results in:

$$t_e = \frac{41,6m}{3,8m/y} * 0,2 = 2,19y$$

The model is modified from Winston et al. (Winton et. al., et al., 1981) and is originally based on field measurements. The value of k (the decay rate) is originally based on the disturbance of MLW, MSL and MHW contours relative to original after nourishment. These are plotted on semi logarithmic paper against the time after nourishment - the slope of the best linear fit to contour retreat defines the rate of decay and thereby the value of k. As the nourishment did not extend the contours since all buffer sand is placed above the water line, the k constant found by Silvester & Hsu of 0.64 is used.

The theoretical model described above has been developed on the basis of nourishments placed in the swash, thereby extending the water/land boundary seaward. This is not the case for the nourishment at Nørlev, but the model is applied as the exponential retreat is useful in the description of results from the buffer sediment. The model is applied for the buffer width.

The nourishment width is defined as the horizontal distance between MDP from 17-01-2017 and MDP at any other measurement, meaning nourishment width is 0 on the 17-01-2017 as the nourishment was fully redistributed at this measurement. As the revetment front is expected to be fixed in position, the comparison with other MDPs will reveal the buffer width. The width is found as the average width between lines 500100 and 500425. The width of the re-nourishment (1700 m³ placed in April 2017) is measured as the difference in MDP between 17-01-2017 and 03-08-2017, which was measured to be 2.9 m. This is slightly wider than expected, since the nourishment contained 1700 m³ for a 300 m stretch distributed evenly between contours 1 m and 3.5 m would result in a width of approx. 2.25 m. It is not unlikely that some aeolian deposited sediment has widened the nourishment slightly, but it is also likely that measurement inaccuracies and differences in point density may have caused the variation.

Figure 6.8 includes both background erosion and the Silvester & Hsu model, and both includes the added buffer from April 2017 of 2.9 m. The background erosion is found as "Nourishment width at time t = Nourishment width - long term erosion rate*time". The long term background erosion has been set to 3.8 m/y.

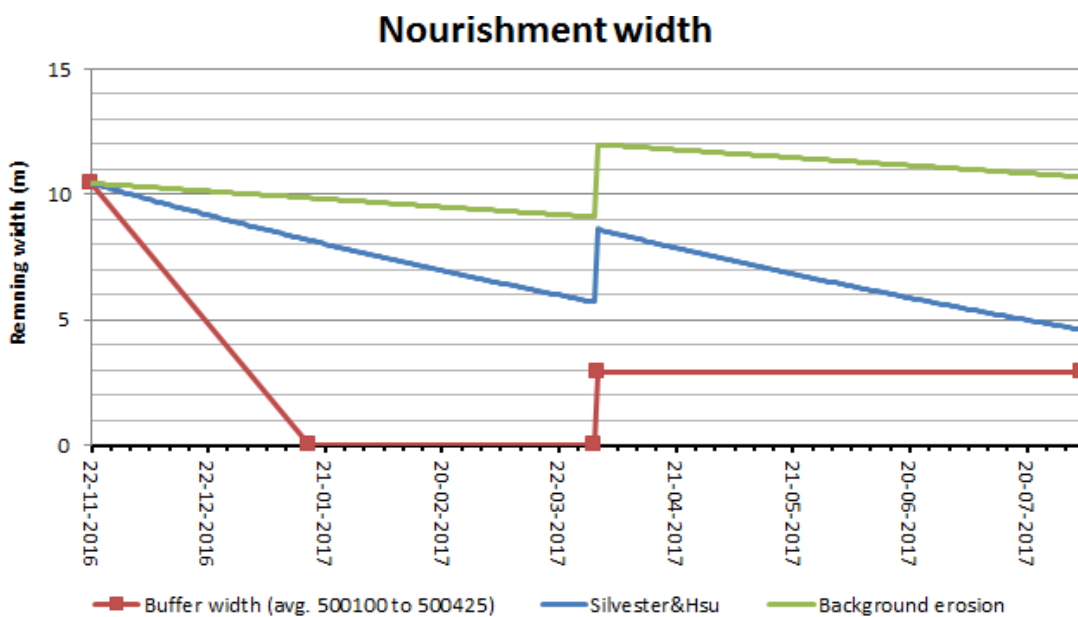


Figure 6.8: The figure presents the nourishment width at the nourished stretch for both measured, theoretical and if inly background erosion had been present.

The observed erosion rate at the Nørlev Stretch is found to be above average as all nourishment sediment is redistributed within few months. The model described by Silvester & Hsu does not show a good fit for the first part of the period, but with the re-nourishment the actual retreat and the model are closing on each other in the late summer of 2017. It is not unlikely that model fit will increase as a calm winter season with minimal acute erosion would leave some of the nourishment sediment in the buffer. The model is not an ideal fit as the parameters included are few and the actual development is dependent

on various elements. Some examples are that acute retreat in the dune face is a response to increase in energy impact water level, surges etc. The model neither includes the presence of local features such as beach undulations which could possibly blur the results if measured on the actual beach width. However, the model can describe the difference between the long term background erosion and excursion deposited sediment which is found to retreat at an increased rate.

6.2.5 Profile Volume Analysis

The profile volume (m^3/m) relative to the baseline measurement from 06-09-2016 is presented in Figure 6.9. The figure presents both an upper and lower profile section as well as a total profile volume. Total profile volume is found between the lower boundary of -0.2 m (minimum value of MCP) and the upper boundary of 3.5 m (maximum value of MDP). Division into two profile sections are conducted to analyze if the nourishment volume can be identified below the average sand buffer toe, and whether the retreat/advance in MCP also dictates a volume loss/increase. The 1 m separation is chosen on the basis of the average lower section of the buffer toe.

Period 1: 06-09-2016 to 22-11-2016

The volume change on lines 500100 and 500400 found in this period is influenced by the volume addition of revetment and nourishment. The upper profile volume clearly shows the added volumes compared to the baseline. Despite the linear requirements to revetment and sand buffer, volume additions are seen to vary depending on which profiles are analyzed. As mentioned earlier, this variation in volume addition is a result of straightening of the dune face before construction of the revetment and sand buffer.

The lower profile section (1.0 m to -0.2 m) shows erosion on all lines except 500075 which shows slight accretion. This corresponds well with the retreat in MCP and the beach narrowing observed earlier. The lower profile volume erodes at rates between 0.5 m^3/m and 12 m^3/m and it is noticed that erosional peaks and troughs form an undulating volume change along the measured profiles, which again fit well with the MCP undulation observed. Profile 500275 is found in the center of the revetment, and it has the maximum erosion rates in the lower profile section which corresponds to the largest retreat in MCP at the same line. The lower profile volume and MCP are not dependent on each other as an MCP advance or retreat does not necessarily mean an increase or decrease in volume, and it is seen that there is advance in MCP on lines 500000 to 500050 despite volume decrease in the lower profile section. However, the undulating advance/retreat in MCP may possibly be compared with the lower profile volume.

The total profile volume in the up- and downstream profiles of the revetment (lines 500000 to 500075 and 500425 to 500650) shows few changes, and the maximum change is seen to be 2.5 m^3/m . The erosion/accretion found on these lines is a result of redistribution in the lower profile and possibly aeolian deposition/erosion in the upper profile section. Measurement inaccuracies may also influence the volume changes.

Period 2: 22-11-2016 to 17-01-2017

The entire amount of original sand buffer sediment was redistributed on the 17-01-2017 and all lines show volume decrease compared to the 22-11-2016 measurement, and in general most volumes are found to be lower than the baseline. However, there are some lines on the revetment stretch which show a volume increase. This is naturally due to the sleeping defense and the fill material behind it.

The upstream stretch (500000 to 500100) saw erosion rates between 25 and 30 m^3/m relative to the baseline from 06-09-2016. This means that the measured profile retreat with up to 8 m in the native upstream stretch.

The total profile volume is both above and below the baseline volume. Despite the fact that all lines show the structural volume additions in the upper profile (revetment and fill), the opposite is the case for the lower profile section which shows a volume decrease relative to the baseline. This also explains the deficits seen for some lines in the overall profile volume. In general, the lower profile volume is decreasing compared to the baseline, and seems to show the same undulating motion as the MCP. The undulation

peaks are found at - max 500100, min 500225, max 500450, min 500600 - which places the undulations at wavelengths between 350 m and 375 m.

However, the volume in the lower profile section is not decreasing when looking at the difference between 22-11-2016 and 17-01-2017. Here an increase in volume of the lower profile section for all lines between 500200 to 500375 is seen. This corresponds well with the seaward extension of the MCP on the same lines and this also corresponds well with nourishment re-distribution and fits with a longshore movement of beach undulation. This is the same for lines 500400 to 500650 which decrease in MCP advance while the volume in the same period is decreasing. This volume deficit is partly explained by the beach runnel and seaward movement of the berm, as seen from Figure 6.1 in the surface model and from the satellite imagery from the 16-01-2017.

Line 500425 and the upstream line 500100, which was also inside the sand buffer, show the highest erosion rates when compared to the 22-11-2016 measurements as erosion rates are close to 50 m³/m for both between the 3.5 m and -0.2 m contours.

The nourishment buffer placed in front of line 500100 can therefore be seen to have decreased the potential retreat. The downstream erosion is more than 20 m³/m higher for the downstream profiles 500450 and 500475 compared with the upstream profiles 500000 to 500075. These lines are affected by the revetment in front of Nørlev Strandvej. Downstream lines 500500 to 500650 have comparable or lower erosion rates than the upstream profiles, which could be the result of a sheltering effect from the inner bar/berm which was shown in the shape analysis.

Period 3: 17-01-2017 to 03-08-2017

The upstream lines 500000 and 500075 show a continued volume decrease compared to all other measurements. The volume decrease between 17-01-2017 and 03-08-2017 is restricted to the lower profile section, which corresponds to the retreat in MCP. The total volume at profile 500100 is still lower than the baseline measurement, but between 17-01-2017 and 03-08-2017 the volume increases. This increase is found in the upper profile section and is a response to the re-nourishment conducted in April 2017.

The revetment stretch from 500125 to 500400 shows volume increase to the baseline with exception of line 500150. The increase is a response to the re-nourishment in April 2017, which is found in the upper profile section. The lower profile section shows a continued volume decrease for lines 500150 to 500250. The lines from 500275 to 500400 increase in lower profile volume compared to 17-01-2017 despite a retreat of the MCP, which indicates an accumulation in the upper beach, possibly in the nourishment toe as aeolian deposition. The inner bar/berm found from surface model analyses, drone imagery and satellite photos seems to have disappeared from the 03-08-2017 measurements, and it is likely that the sediment has been transported onshore from there during the summer months.

On downstream lines from 500425 to 500500 volume increases in the upper profile section are found, relative to 17-01-2017. This is not unexpected as stabilizing nourishment has been undertaken and rocks added within these lines after the erosion in the winter storms. The volume increase in the profile between 500525 to 500650 is unexpected as there has only been two occurrences of high water levels above 0.5 m. This volume addition is therefore expected to be a result of longshore and onshore directed sediment transport and very likely some aeolian deposition in the dune toe. Generally, the total volume in the downstream stretch of the sleeping defense and the sand buffer is negative compared to the baseline which is due to dune face retreat. The lower profile section is found to increase in volume compared to the 17-01-2017 measurement, and in general stays close to the baseline.

The predominant wave direction in the period is W and WSW and the incoming waves have resulted in a NE bound sediment transport. It is likely that the volume deficit in the upstream stretch has been transported along the sleeping defense stretch and into the downstream stretch of Nørlev Strandvej, where accretion is also found.

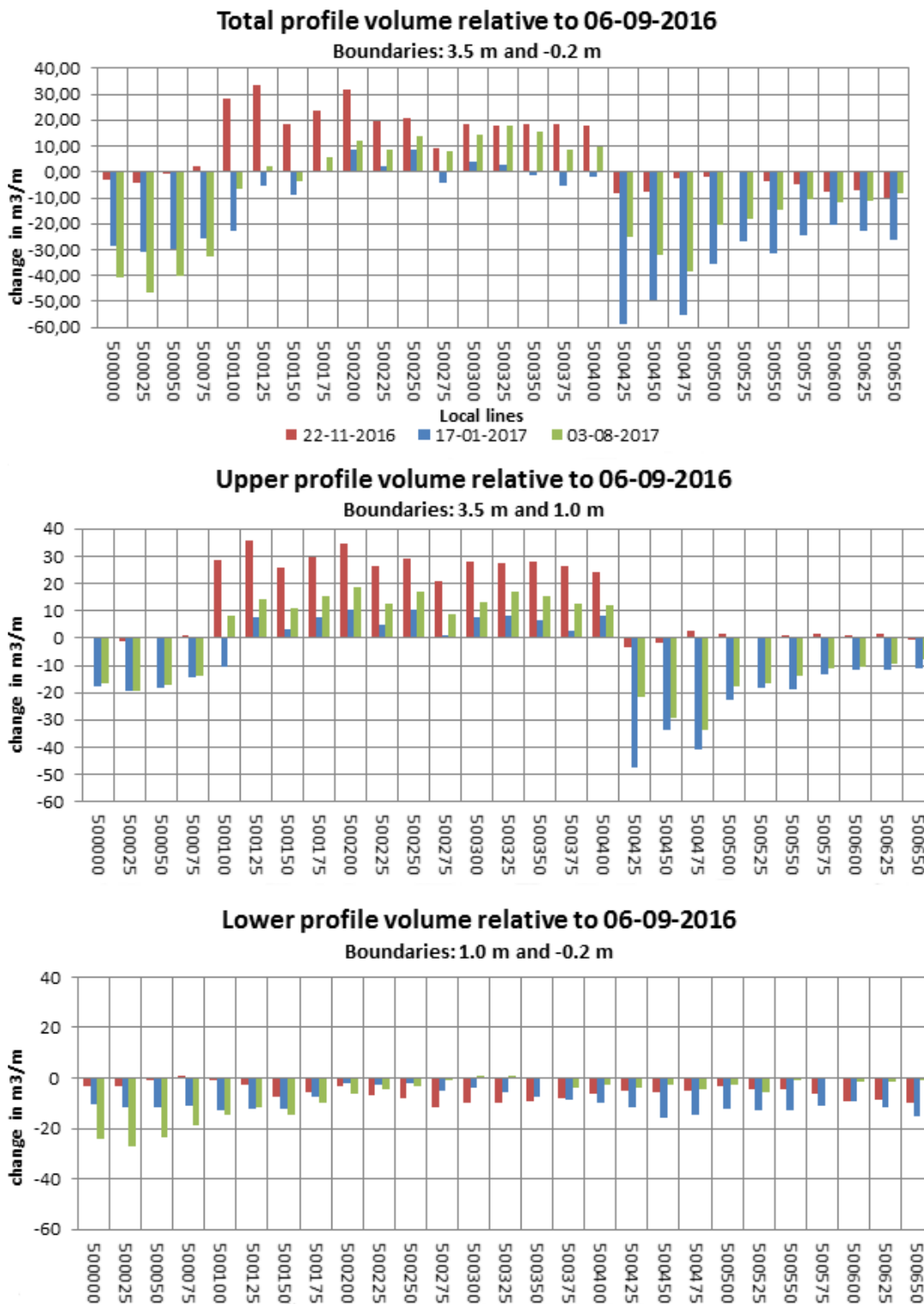


Figure 69: The volumes have been calculated from MorphAn. In the coastal development tool an MCP is returned between 3.5 and -0.2 m. The volumes shown here is the volume from the inland fix point at 900 meters and seawards between the heights of 3.5 m and -0.2 m. All sand lost or gained, above 3.5 m and beneath -0.2 m is lost in this definition. The volume extension to the inland reference point at 900 meters was done manually in excel.

6.2.6 Nourishment Diffusion

The buffer sediment at Nørlev was expected to be redistributed over time, but the rate of diffusion was higher than first expected, compared to the maximum acute erosional rate set to 5 m/storm. The volume development is therefore tested against a simple theoretical model for nourishment diffusion. Dean presents an analytical approach for estimation of beach nourishment performance on long straight beaches (Dean, 2002). The equation is based on the assumption that multiple nourishments have been required

on a given stretch and can be used when estimating the re-nourishment time. The equation is based on an assumed exponential nourishment decay, as with Silvester & Hsu, and multiple nourishments in the same stretch will be self-similar:

$$M(t) = e^{-kt}$$

Where M is the remaining proportion of sediment fill at time t, and k is an empirical constant estimated from the decay rate of the first nourishment in the same stretch. As there were no nourishments before the buffer, a theoretical test against its own decay rate would give a misleading result with a close to perfect fit. Instead k will be implemented as the daily estimated erosion rate based on the long term background erosion rate set to 3.8 m/y, which means that k is

$$k = \frac{3,8m/y}{365days} = 0,0104m/d$$

This means that the nourishment diffusion is tested against the expected long term diffusion. It is noted in the literature that the model has been seen to over-predict the decay. The model does not include length, positioning or shape of the nourishment but assumes an exponential decrease of nourishment sediment due to equilibration to native profile, a longshore distribution and is based on long straight, non-obstructed stretches with rectangular nourishment designs. The model does not reflect hydrodynamic forcing, storminess, erosional hotspots or residual bathymetry (Dean, 2002), and it is therefore a fairly simple model. Despite upstream groynes and a newly constructed revetment the model is applied due to its simplicity. The theoretical and measured diffusion have been plotted in Figure 6.10, please note, that the volume development is only tested for lines 500100 to 500425. The upper boundary of the volume analysis is increased to 4 m since this height is available on these lines, while the lower boundary is still set to -0.2 m.

The nourishment was reported to be placed with a top level of 4.5m, meaning that the nourishment on top of the revetment is not caught in the analysis. Also, the average bottom contour of the nourishment was reported to be 0.98 m, meaning that the volumes included here also take into account the lower profile changes, as volume increase was seen for some of the profiles in the post-storm measurement.

The volumes presented in Figure 6.10 have the 22-11-2016 measurement as baseline. In order to estimate the diffusion between the baseline and the two following measurements, it is assumed that the buffer volume of 12,475m³ is intact and that the volume changes in the 2017 measurements are then compared with the 22-11-2016 measurement. In addition to the measured and modelled values the long term erosion rate has been included in the figure. The long term erosion rate is based on a profile retreat of 3.8 m/y.

It was confirmed that all buffer sediment covering the revetment was re-distributed from the sleeping defense already on the 8th of January, before the storm between 11th and 13th of January 2017, but as it was found in the volume analysis of the lower profile section that some of the volume from the upper section was likely to be traced in the lower section. This is confirmed here as the total diffusion between lines 500100 and 500425 was 85 %. This indicates that 15 % of the buffer sediment can still be traced within the measured stretch, between contours 4 m to -0.2 m. The diffusion of the remaining 85 % is expected to be across- and alongshore in a NE direction. The buffer sediment is therefore not gone, but has been redistributed. If the volume analysis had been extended to the -0.5 m contour the submerged profile could possibly have reflected a larger deposition. The re-nourishment of 1700 m³ were placed in April 2017 and it is clear that an accumulation took place between 17-01-2017 and 03-08-2017. However, the volume increase in the overall volume analysis between 17-01-2017 and 03-08-2017 was found to be above 1700 m³, in fact the volume increase between the measurements in 2017 was close to 4000 m³, which can be interpreted as re-entering of buffer sediment to the lower profile section, aeolian re-distribution from swash to dune toe, onshore directed sediment transport and/or possibly slight measurement inaccuracies.

The test results against Dean's formula shows that the nourishment diffusion is faster than the model predicts. This is not unexpected since the k-value was set to the long-term retreat rate of 3.8 m/y at the stretch, and retreat experienced during storm was above the long-term rate. Nevertheless, the model showed that after storm incidents 15 % of the nourishment sediment still remained within the stretch and the remaining sediment was re-distributed across and along shore in the downstream direction. With the re-nourishment and the volume increase experienced in the lower profile section between 17-01-2017 and 03-08-2017 the remaining volume is actually above the prediction in the Dean model, though 23% lower compared to the long-term erosion. The addition in volume between 17-01-2017 and 03-08-2017 is in the form of re-nourishment and is also likely to be a results of re-entering of nourishment sediment or along-shore beach undulations to the profiles. The model is therefore highly dependent on the beach state at the given measurement period.

Diffusion of nourishment volume

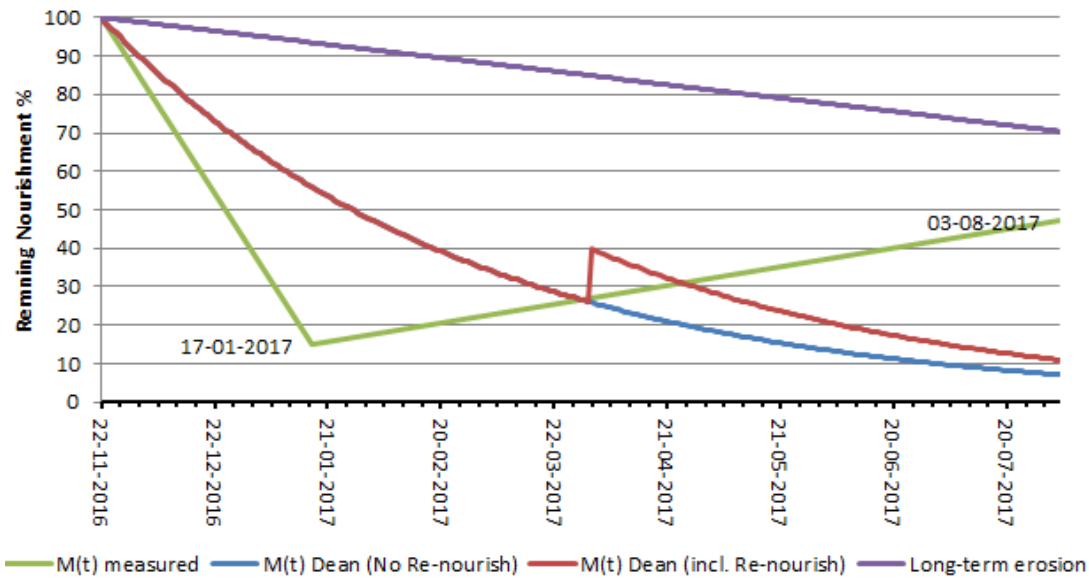


Figure 6.10: The figure presents two diffusion models, one including the re-nourishment of 1700 m³ set to be finished on April 1 2017 and a model which does not include it. The Measured Volume is found as described in the text. Measured Volumes were found in MorphAn between 4 m and -0.2 m, to an inland fixed set to 900 m, and have been normalized to percentage.

7. Considerations and Remarks

The stretch at Nørlev Beach is found to be highly dynamic and lies within a complex coastal stretch affected by several hard coastal protection measures. Variation in erosion rates over time is not unexpected, as seasonal variation results in differentiated profile outlines which can give way for erosional hotspots or equalization. The variations are the result of several factors such as longshore undulating breaker bars and coastline and erosional hotspots due to depressions in the breaker bar. The system is found to contain up to three breaker bars dependent on the year of measurement, but the outline and position is dynamic and changes over the course of months. The breakers also took different forms such as crescentic, ripped, parallel and undulating. The beach is found to have longshore dynamics, as well, and though the bars were changing, there was often a residual bathymetry. These natural occurring elements affect the coastal development on the stretch, and erosional hotspots are found to travel alongshore, possibly in combination with the creation of headland due to leeside erosion from the groyne field at Skallerup.

The design of the revetment was originally to build it in the existing dune face but as it was seen, infill was placed on most of the stretch behind the revetment, possibly to straighten the revetment or stabilize residences on top of the dune. This leads to a more exposed sand buffer, hence leading to a shorter lifetime. The compaction of the nourishment sediment was during inspection confirmed to be considerably lower than that of the native dunes. The nourishment design in itself as a rectangular box with triangular segments formed as a headland on an already narrowing beach section made the nourishment very exposed to the oncoming surges. The sediment in the buffer was placed with the buffer toe at approx. +1 m and no natural re-distribution could therefore be expected before storm. The maximum water level in the study period was found in combination with a storm from SW-W, but the peak water level was +107 cm, which is lower than a 1 year event. The water level at >1 m in itself meant that the water table has been at the toe of the buffer, which combined with setup and wave action must have resulted in a run-up on the buffer. It was seen from satellite imagery on 22-12-2016 that white water was already close to the dune toe, if not touching, and the water level was only found to be +33 cm at this point - two days before the storm peaked.

The nourishment design in combination with natural occurring undulations in the beach, rips in the bar system and pre-existing headland on the stretch have increased the exposure of the nourishment and the expected erosion rate. This being said, the overall erosion on native stretches was found to be higher than many of the extremes documented in the baseline study and for all local lines the rate of retreat was above 5m/y which was set as the maximum acute erosion. The maximum retreats found in MDP for the local lines was indisputable on the stretch with the sand buffer and in the immediate leeside. This was not the case if the volume development were considered. The maximum volume decrease at 17-01-2017 was in the immediate downstream stretch of the revetment. The upstream lines also showed volume decrease above normal after the storm compared to the revetment stretch. This is explained by the addition in the lower profile section along the revetment and the fact that the sleeping defense blocks further erosion above 1.5 m, the erosion increase in the rest of the active profile, most of which has not been surveyed.

From an overall perspective, the nourishment functioned as designed, and the nourishment has been redistributed cross-shore in the lower profile section and alongshore. The protective effect of the nourishment was proven, but the design of the nourishment combined with naturally coastal variations are likely to have increased the retreat locally at the time of the storm after the nourishment was completed. In order to meet the objectives, the design criteria must be modified to include larger volumes of sand and perhaps longer nourishments at the sides of the sleeping defense.

8. Future perspective for the coast

The rock revetment has been prolonged in 2017/2018 and now stretches further NE beyond Nørlev Strandvej with additional nourishment on the extension. One main consideration in regards to the future development on the stretch is that the upstream and downstream coastal stretches will continue to retreat at least at the same rate as before. The revetment will remain in its now fixed position, until renovation will be required in the future. The natural concern is that the continued retreat up- and downstream of the revetment stretches will create embayment around the revetment, unless retreat is stopped by compensating measures. It could eventually result in the upstream section back-cutting the revetment or the revetment would simply remain as a headland. Also, in 2017 a comparable coastal protection has been established on a shorter stretch at "Morgenvej", which is located between the revetment at Nørlev Strandvej and the groynes at Skallerup. Until now, no documented sand buffer has been installed or any compensating nourishment undertaken, and the effect from this would be an increase in the retreat rate at the downstream stretch between the rock revetments of Morgenvej and Nørlev Strandvej.

The landowners from Harrerenden to Udemarken participate in a cooperation initiated by Hjoerring municipality and the Danish Coastal Authority with the aim of initiating shoreface nourishments on the stretch to compensate for the chronic erosion.

References

COWI, 2016. Kystbeskyttelse ved Nørlev strand, Kongens Lyngby: COWI.

Danish Coastal Authority, D., 2013. Fællesaftalestrækningen Lønstrup - Bilag til fællesaftale mellem staten og Hjørring Kommune om kystbeskyttelsen for perioden 2014-18, Lemvig: Danish Coastal Authority.

Dean, R. G., 2002. Beach nourishment - Theory and Practice. New Jersey : World Scientific Publishing Co. Pte. Ltd.

DNF, D. n., 2017. fredninger. [Online]

Available at: <http://www.fredninger.dk/fredning/lien/>

[Senest hentet eller vist den 09/10/2017].

ESA, 2014-2017. scihub.copernicus.eu. [Online]

Available at: <https://scihub.copernicus.eu/>

Harerenden, S., 2016. Orientering vedr. udførelse af sandfodring i en 3-årig forsøgsperiode. Lønstrup: Sommerhusforeningen Harerenden.

Henrik J. Granat, U. G. L. K. S., 2005. GEOLOGI OG JORDBUND - NORDJYLLANDS STATSSKOVDISTRIKT, s.l.: Skov- og Naturstyrelsen & Danmarks og Grønlands Geologiske Undersøgelse.

Kasper Kaergaard, J. F. S. B. K., 2011. Coastline undulations on the West Coast of Denmark: Offshore extent, relation to breaker bars and transported sediment volume. Coastal Engineering 60, 1 Nov, pp. 109-122.

Kystdirektoratet, A., 2016. Tilladelse til tildækket skråningsbeskyttelse med kompenserende fodring ved Nørlev Strand. Hjørring kommune, s.l.: s.n.

Kystdirektoratet, Karlsson, H. V. & Larsen, B. G., 2020. Aeolian Sediment Transport and Natural Dune Development, Skodbjerg, Lemvig: Kystdirektoratet.

Lescinski, J., 2016. Description of coastal state indicators. [Online]

Available at: <http://www.conscience-eu.net/documents/deliverable09-coastal-state-indicators.pdf>

Mulder, M. v. K. a. J. P. M., 2004. Sustainable coastal policy developments in The Netherlands. A Systematic Approach Revealed. Journal of Coastal Research, Vol. 20, No 2., Spring, pp. 375-385.

Rivero, O. Y., 2017. Coastal erosion and climate description of Nørlev Strand area - Thesis, Aalborg: Aalborg University.

Sand-Jensen, K., 2012. Naturen i Danmark - Geologien. København: Gyldendal.

Silvester, R. & Hsu, J. R. C., 1997. Coastal stabilization. Singapore: World Scientific Publishing Co. Pte. Ltd.

Thorton et. al, E., 2007. Rip Currents, mega-cusps and eroding dunes. Marine geology, 16 february, pp. 151 - 167.

Winton et. al., et al., 1981. Analysis of Coastal sediment transport processes from wrightsville beach to fisher, North Carolina, Fort Belvoir: U.S. Army, Corps of Engineers.

Appendix A

- Averaged Retreat Rates in Vegetation Line (CSL analysis)

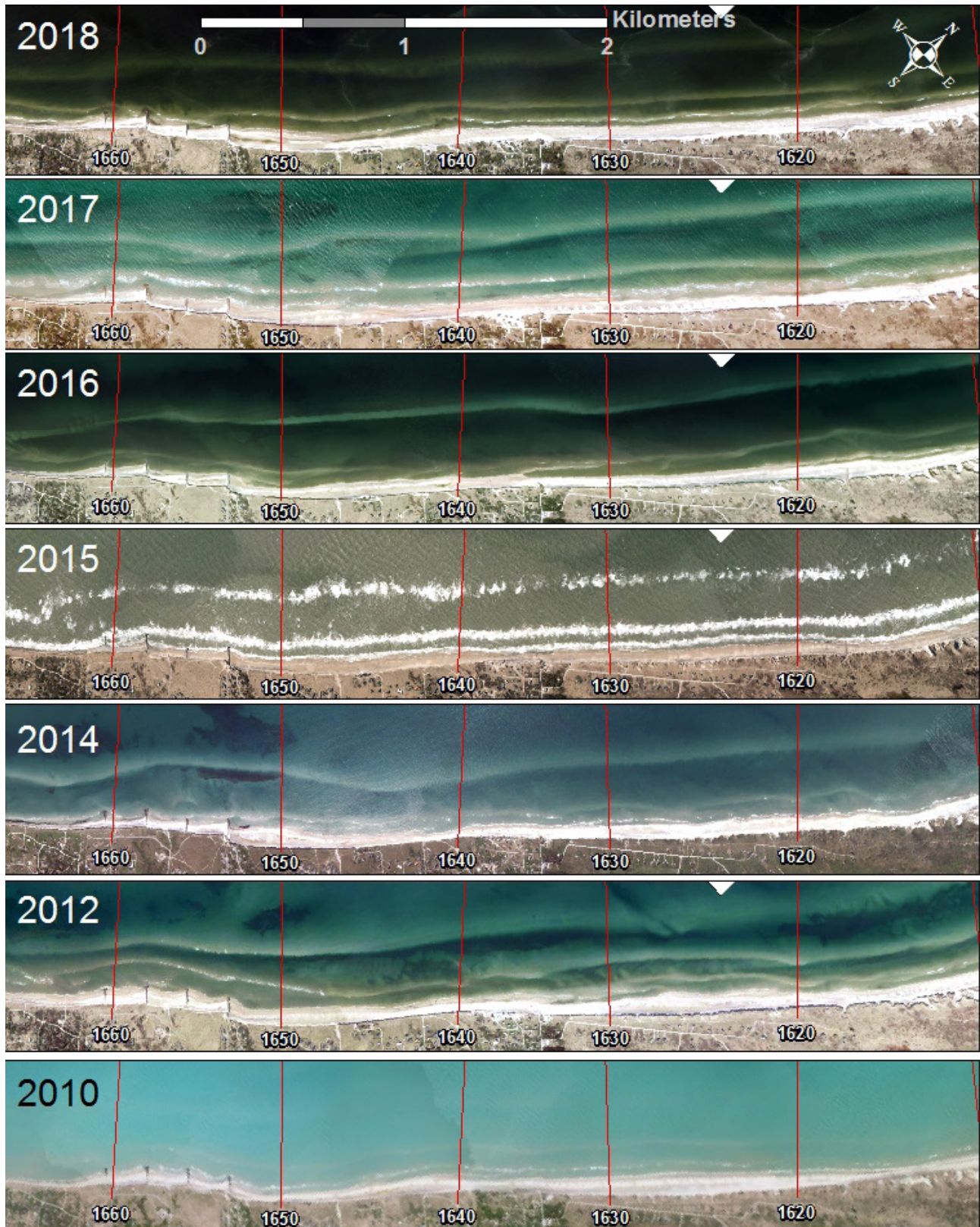
Total erosion is divided with the number of years within the period, which gives erosion rate in m/y for every CSL. Retreat in m was found from the following analysis conducted in ArcMap.

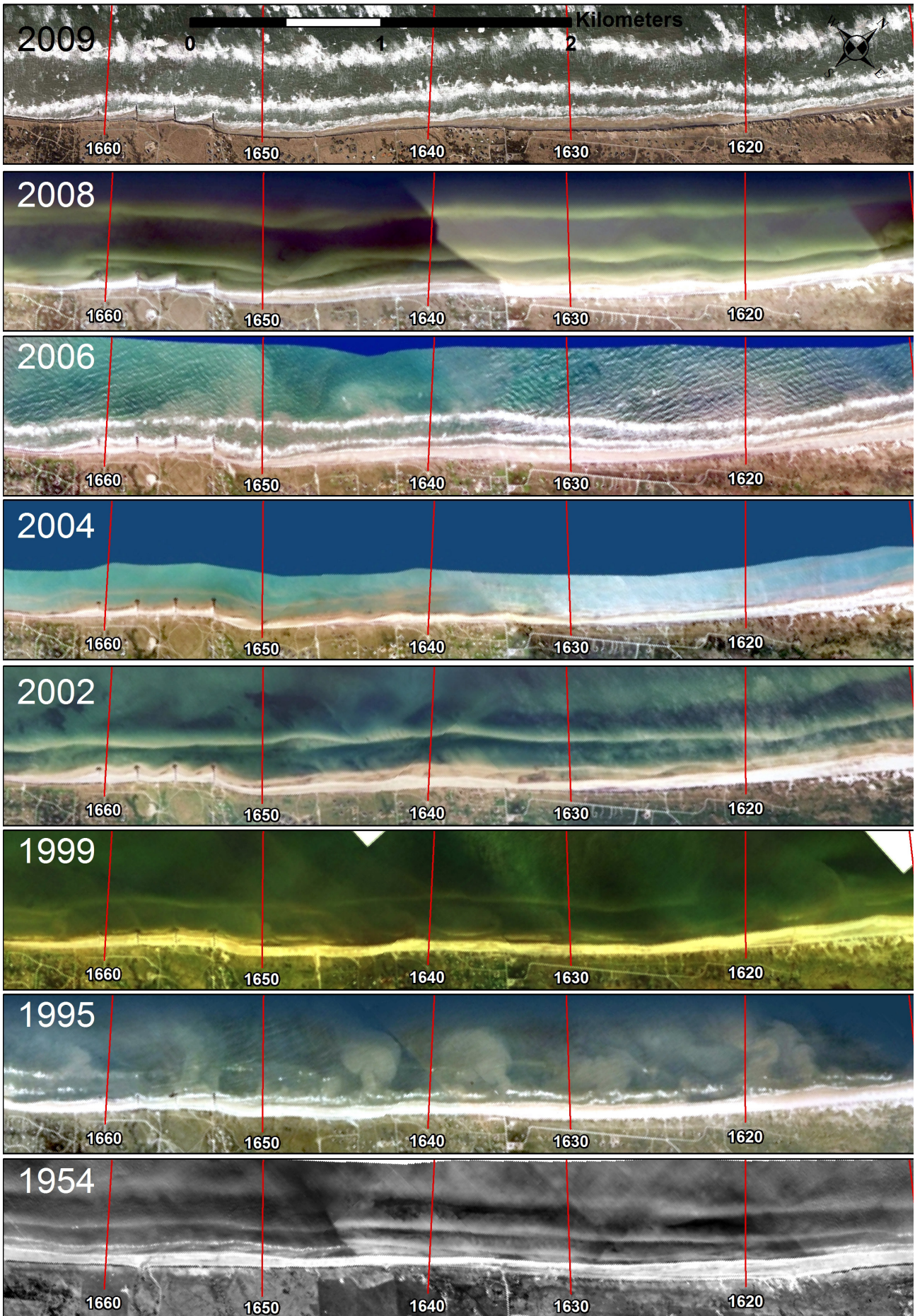
From an inland line, perpendicular line features are constructed for every 100 meters. These Cross Shore Lines (CSL) cross the drawn vegetation polylines. Using the intersect tool, point features were created in the intersections between CSL and vegetation lines. By using "Generate near Table" the distance from station line to the points could be found.

Development on coast (m/y)	2015 - 2016	2012 - 2015	2009 - 2012	2006 - 2009	2004 - 2006	2002 - 2004	1999 - 2002	1995 - 1999	Total movement 1995-2016 (m)	Avg movement 1995 - 2016 (m/y)
NR 18	-1.4	0.7	-2.5	-1.9	-0.2	1.5	-0.1	0.3	-12.8	-0.6
NR 17	0.1	-0.2	-0.2	-3.0	0.0	3.9	-1.1	1.5	1.5	0.1
NR 16	1.8	-0.3	-0.8	-0.7	0.9	-1.3	-0.3	-0.5	-8.3	-0.4
NR 15	-0.5	-0.4	-0.5	-1.0	0.1	-0.3	-2.4	0.3	-17.6	-0.8
NR 14	0.0	0.7	-0.8	-1.4	-0.1	-0.5	-3.5	0.6	-19.1	-0.9
NR 13	-0.8	0.1	-0.2	-0.7	-0.4	-1.5	-1.4	0.4	-13.9	-0.7
NR 12	-0.5	-0.5	-0.7	-1.2	-0.2	-2.5	-1.2	0.6	-20.2	-1.0
NR 11	-2.3	-2.0	-1.0	-0.4	-0.7	-0.7	-0.7	-1.7	-34.2	-1.6
NR 10	-3.0	-6.2	-0.1	0.2	-0.8	-0.7	-0.7	0.6	-34.9	-1.7
NR 9	-2.0	-6.7	-0.6	-1.7	0.4	-0.5	-3.0	-1.0	-57.0	-2.7
NR 8	-0.5	-4.9	-2.9	-1.8	-1.0	-0.4	-2.2	-1.0	-57.4	-2.7
NR 7	-1.0	-3.1	-3.5	-3.4	-4.6	-1.7	-0.4	-0.5	-65.6	-3.1
NR 6	-1.2	-1.7	-2.9	-3.8	-5.0	-0.8	-5.0	-3.3	-89.6	-4.3
NR 5	-1.4	0.0	-4.6	-2.1	-2.9	-1.9	-5.1	-2.6	-77.3	-3.7
NR 4	0.8	-0.2	-4.9	-5.3	-6.9	0.5	-3.3	-1.9	-82.0	-3.9
NR 3	-5.8	-1.6	-3.7	-4.8	-0.3	0.0	-2.1	0.3	-59.9	-2.9
NR 2	0.7	-1.6	-1.3	-2.2	-1.2	-0.6	-1.4	0.0	-30.4	-1.4
NR 1	-2.2	0.1	1.0	-0.5	-0.4	0.6	-2.0	0.4	-7.3	-0.3

Appendix B

- Orthophoto Collection





Appendix C

- Drone Images from Nørlev











Appendix D

- Criteria for Design of Sand Buffer with Sleeping Defense

The coastal protection scheme consists of three parts.

- 1) A sand nourishment with a sufficient volume to compensate 100 % for the chronic erosion.
- 2) A sand buffer that protects the holiday houses on the 340 m.
- 3) As an extra safety: A sleeping defense of rock placed as a revetment along the dune face.

If the sleeping defense is exposed it will cause leeside erosion. Therefore the sand buffer must be designed in a way that ensures that the sleeping defense is covered at all times.

The overall premise for including a sleeping defense (revetment) as part of coastal protection is that in principle the revetment never will be visible, so negative effects from the revetment are avoided. The nourishment volume will therefore be the same as if no revetment were installed. A local assessment must always be undertaken for every individual coastal protection scheme, but as a general rule a sleeping defense in Denmark must be designed as follows. A term-diagram is presented at the end of this appendix.

The sleeping defense at Nørlev beach is established along a 265 m stretch in front of the existing dune face at Nørlev Beach.

$$L_{\text{Revetmet}} = 265\text{m}$$

The maximum acute erosion $W_{\text{Max acute erosion}}$ is the basis for the determination of nourishment quantities, as well as the morphological scale in which the nourishment is set. Based on analysis of WCL and ortofotos $W_{\text{Max acute erosion}}$ was determined to be 5 m/storm.

$W_{\text{Nourishment, revetment}}$ is the width of the nourishment in front of the revetment and if nourished every 3rd year it must be at least:

$$W_{\text{Nourishment, revetment}} = 2 \cdot W_{\text{Max acute erosion}} = 10 \text{ m}$$

The nourishment was required to be established between contours 0.5 m and 4.5m which equalled 40m³/m along the revetment.

When referring to the morphological scale it is referring the nourishment end-segments. These must be constructed so the width is set to $W_{\text{Nourishment, morfological scale}} = 0,25 \cdot W_{\text{Nourishment, revetment}}$

The length of the morphological scale section (end sections of nourishment which compensates for longshore morphological effects) the length of the weather side must be longer than the lee side. The general rule is

$$L_{\text{windward side}} = 2 \cdot L_{\text{Lee side}} \quad \text{Where } L_{\text{Lee side}} = 10 \cdot W_{\text{Max acute erosion}}$$

They are found to be, respectively:

$$L_{\text{Lee side}} = 25\text{m}$$

$$L_{\text{Windward side}} = 50\text{m}$$

$W_{Nourishment, morfological\ scale} = 0,25 \cdot 10m = 2,5m$ Which equals a nourishment volume of $10\ m^3/m$ at the outer ends of the end-segments. The stretch in-between the end of revetment nourishment to the end segment should decrease in a linear way from $40\ m^3/m$ to $10\ m^3/m$ meaning an addition of $1250\ m^3$ in the windward side and $625\ m^3$ in the leeside.

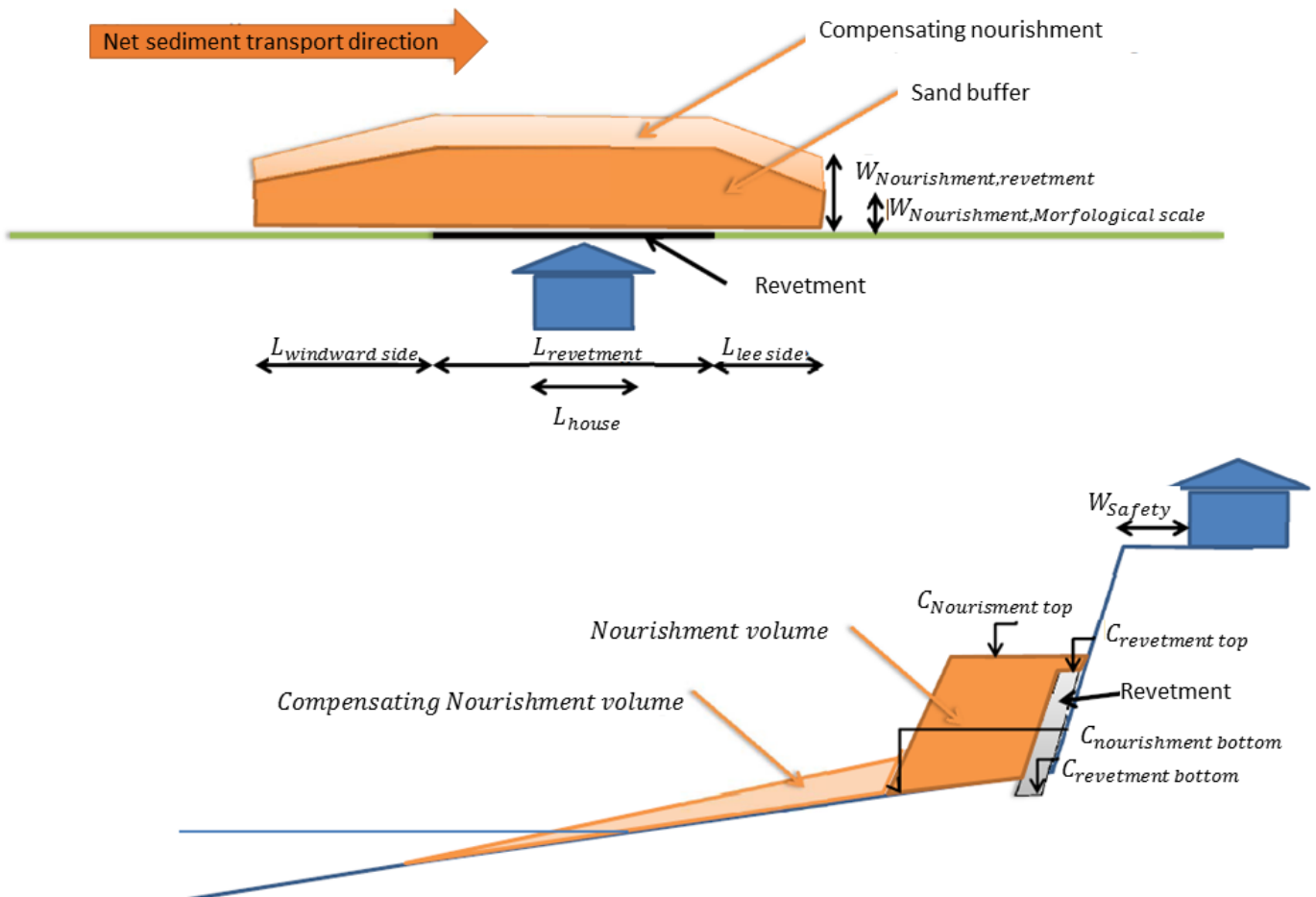
This equals a total nourishment volume of $12,475\ m^3$.

Compensating nourishment volume was set to $18,000m^3$ as the regulatory permit was based on an chronic erosion rate of $3.8\ m/y$ and the compensation nourishment was therefor set to be $53\ m^3/m$ for the full nourishment stretch of $365\ m$ ($18.000\ m^3\ pr.\ year$). The compensating nourishment was not placed on the beach, but was instead added onto the 3rd breaker bar near the groynes at Nørlev.

However, nourishment volumes are required to be documented by the landowners every 3rd year according to the regulatory permit issued (Kystdirektoratet, 2016).

The level the nourishment $C_{Nourishment\ top}$ must be at least $1m$ above the top level of the revetment $C_{Revetment\ top}$, or higher. The bottom contour of the nourishment $C_{Nourishment\ bottom}$, must be at least the same as the bottom contour of the revetment $C_{Revetment\ bottom}$ or lower.

Sandbuffer with sleeping defense





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