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North Sea Region
Building with Nature

Ministry of Environment
and Food of Denmark
Coastal Authority

Shoreface nourishment effects

An analysis of the 2011 nourishment performed at Skodbjerge

December 2018

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1 Introduction

The following report is a product of the EU InterReg project Building with Nature.

The objective of the Building with Nature EU-InterReg project is to improve coastal adaptability and resilience to climate changes by means of natural measures. As part of this project the Danish Coastal Authority (DCA) carry out research into different aspects of using natural processes and materials in coastal laboratories on Danish coasts. Through the EU InterReg project "Building with Nature" (BwN) a better understanding of the interactions within the coastal system is sought.

The Building with Nature project is a combination of six different work packages, see Figure 1.1.

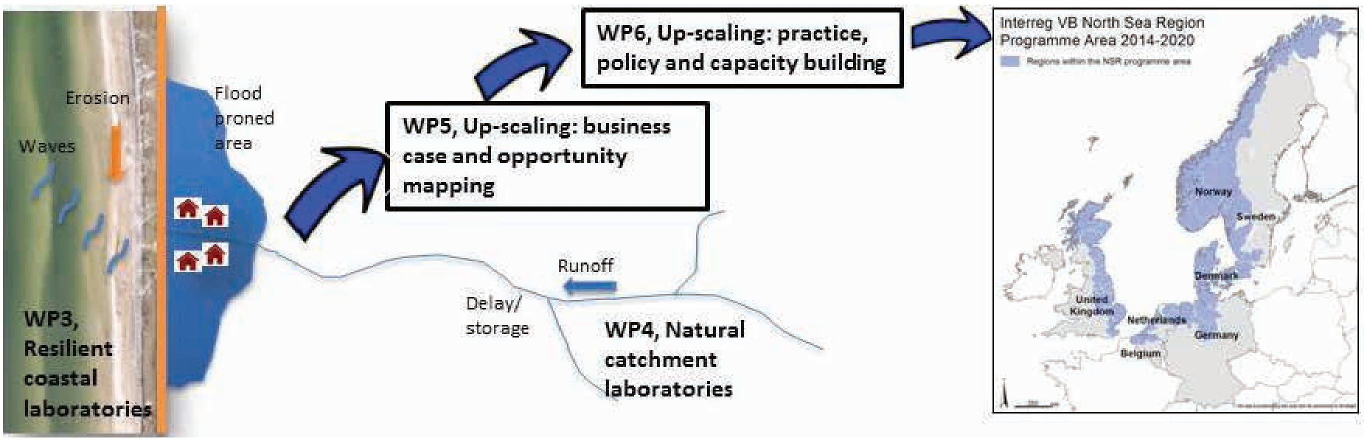

Figure 1.1 The connections between the 6 work packages in the Building with Nature project. WP1 - Project Management, WP2 - Communication Activities, WP3 - Resilient Coastal Laboratories, WP4 - Natural Catchment Laboratories, WP5 – Up-scaling, Business Case and Opportunity Mapping, WP6 – Up-scaling, Practice, Policy and Capacity Building

The Danish Coastal Authority is mainly active in Work Package 3 (WP3): Resilient Coastal Laboratories. In WP3 the coastal challenges and effects of implementing building with nature methods, in this case beach and shoreface nourishments, is represented by 7 'living laboratories' located along the North Sea Coasts and the Wadden Sea. The effects of the nourishments have been analysed using a common transnational methodology, which the members of WP3 have developed during the course of the BwN project. The analysis of the local laboratories will improve the evidence-base needed to incorporate BwN methods into the national investment and policy programmes of the North Sea Region countries.

This report is one of 7 national reports presenting the results from each individual living laboratory, in this case the Danish living laboratory of Skodbjerge located on the Danish North Sea Coast. The results will be compiled into a joint co-analysis providing for comparing nourishment performance and generating a better understanding of the factors that determine nourishment evolution. The report will focus on the nourishment performed in 2011 at Skodbjerge, but the effects of other nourishments, especially the one performed in 2010 at Skodbjerge, have to be taken into account because of the temporal scale of nourishment effects.

1.1 Background

This section provides an insight into the framework of coastal protection along the Danish North Sea Coast, as well as summary of the performance of previous nourishments as recorded by the Danish Coastal Authority.

1.1.1 Coastal protection along the Danish North Sea Coast

The coastal laboratory referred to as Skodbjerge is located on the Danish North Sea Coast, where the Danish Coastal Authority is executive in performing coastal protection.

After a severe storm in 1981 it became apparent that the structural coastal protection in place, mainly consisting of groins and dikes, was not enough to safeguard the Danish North Sea Coast. This is due to the fact that the coastline is subject to chronic erosion, which means that the natural retreat of the active coastal profile will vary between one and eight meters per year, see Figure 1.3. In this area, the combination of substantial natural coastal retreat, a relatively high water level during storms, a narrow dune belt and low hinterlands along long stretches of the coast create a serious flooding hazard; and in case of dune breach homes and property would be destroyed. See Figure 1.2.

The Danish Government and the local municipalities therefore signed a joint agreement to protect the coast in the future. The Joint Agreements are financial agreements usually covering a five year period. This means that the agreement will be up for renegotiation every 5 years.

The overall purpose of the Joint Agreement is to ensure that at the beginning of each winter season the dunes on this stretch of the coast will be resilient enough to withstand the erosion and prevent a breach during a storm with a 100 year return period. The only exception is Thyborøn where the objective is protection against a 1000 year storm. The Joint Agreement for the coastline between Lodbjerg and Nymindegab specifies a safety level for erosion, which includes a protection level against dune breach and floods. This means that the dunes must have a minimum width at the 100 year return period water level. The safety level is also expressed in terms of displacement of the active coastal profile.
Since 1982, thanks to these agreements, protection of the 110 km stretch of coast from Lodbjerg to Nymindegab has been carried out as a joint effort by the local municipalities and the Danish government, see Figure 1.3. The basis for the agreement is the safety level objective.

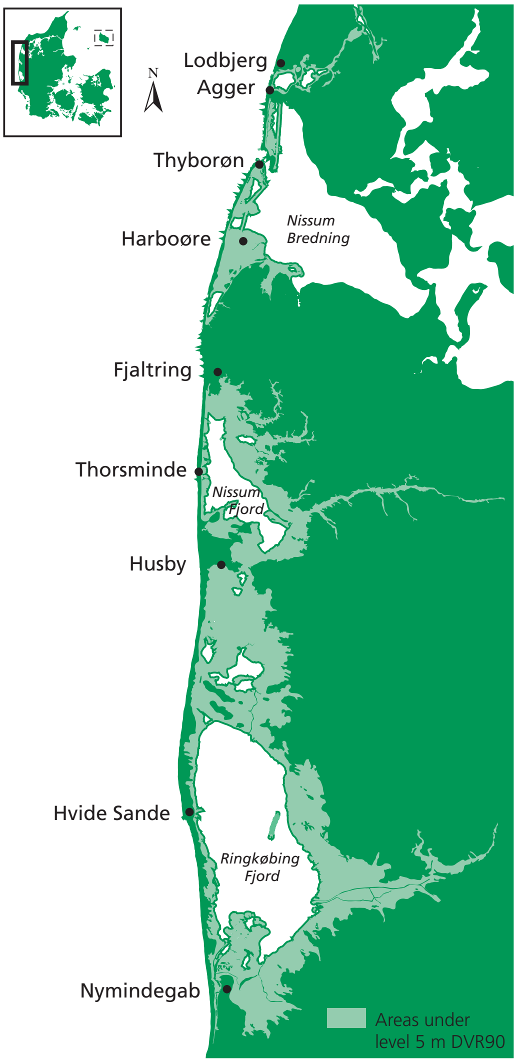

Figure 1.2 The 110 km stretch from Lodbjerg to Nymindegab. The map shows areas below 5 m DVR90

Since the first agreement, 28 km of slope protection have been laid out, 145 breakwaters have been built and the coast has been nourished with 59 million m³ of sand. The current five years joint agreement has been extended until 2019.

Since the 1990s, the coastal protection of the coast stretching from Lodbjerg to Nymindegab has primarily consisted of sand nourishment and slope protection in front of sand dunes and sand dikes. However, today the protective efforts almost solely consist of nourishment.

The building of solid constructions, only, reduced the retreat of the coastline, but not until a nourishment scheme was introduced, was the retreat brought to a halt. The annual coastal protection scheme of the Danish West Coast is planned on the basis of surveys, measurements and analysis of previous coastal development. The Danish Coastal Authority (DCA) is continuously optimizing the coastal protection effort on the western coast of Denmark

In the current Joint Agreement covering the period from 2014 to 2018 (2019) two objectives have been implemented based on assessment and categorization of the impact of coastline retreat. The categorization serves as a means of prioritizing the resources of the joint agreement. Along stretches without hard slope protection measures, where homes and infrastructure are at risk and/or where there is risk of a dune breach during a storm, and this incident could lead to a flooding of the hinterland, the goal is to stop the coastal retreat.

At Havrvig and Skodbjerge, where the dunes have a small, extra sand buffer, the objective is to reduce coastal retreat to a maximum of one meter per year.

On stretches with slope protection, the objective is to reduce coastal retreat as much as possible with the remaining amount of sand for nourishment. Based on a calculation of the amount of sand available for nourishment, the coastal retreat can be limited to 3.2 m/year on the stretches where the natural retreat is above this objective. The objective of the Joint Agreement for the period 2014-2018 (2019) is illustrated in Figure 1.3.

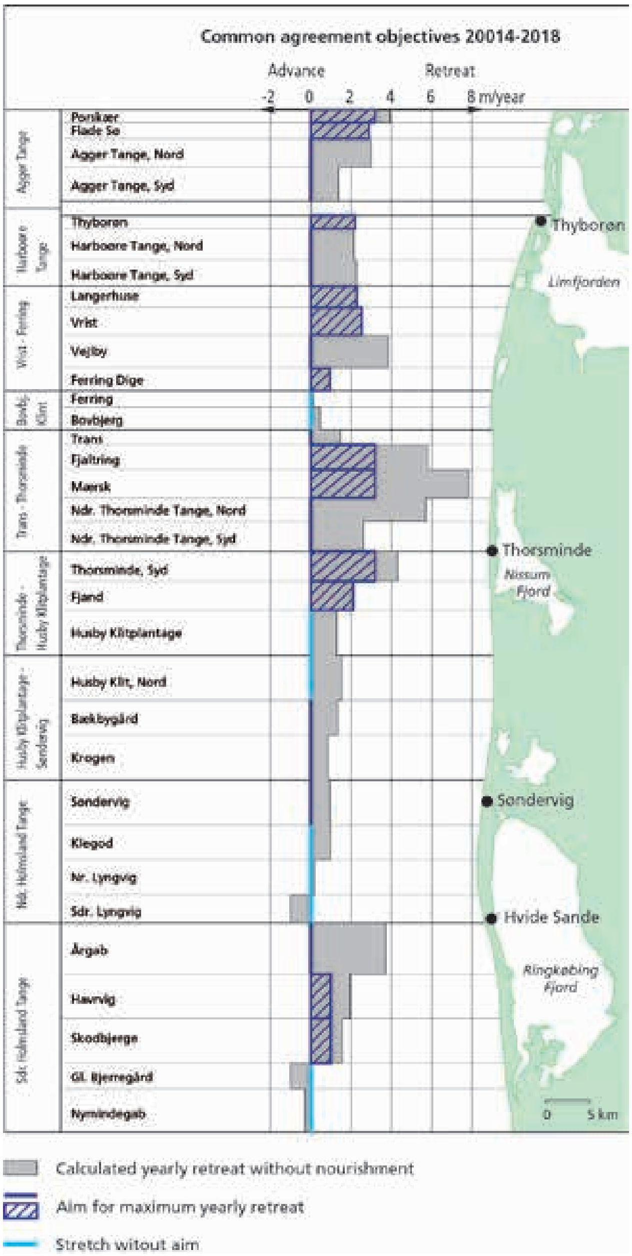

Figure 1.3 Joint agreement objectives 2014-2018

1.1.2 Shoreface nourishment effects

It is complicated to determine the effects of shoreface nourishments. This is due to the fact that the natural coastal variability is large and very stochastic. A direct correlation between the hydrodynamic impact and the coastal response is seldom found by analysis.
The DCA has carried out, monitored and analysed several shoreface nourishments designed to meet a range of design objectives, and some clear conclusions can be drawn based on the analysis of these nourishments:

- Shoreface nourishments can extend the outer bar alongshore. As the outer bar induces wave breaking this reduces the proportion of wave energy reaching the coast. Thereby local dune erosion is avoided.
- Shoreface nourishments can be designed to function as a shore parallel breakwater. The effects are similar to the effects of extending the existing bar, in this case the nourishment creates a new shore parallel elevation, which breaks the waves.
- Shoreface nourishments can be designed in such a way that the nourishment effect results in an onshore transport of sediment onto the beach. This leads to beach widening, which provides better conditions for dune evolution.
- Shoreface nourishment can be designed to act as a feeder berm, adding sediment to the downstream coast.

Even though these effects have been demonstrated, the huge natural variations cause uncertainty when determining the net effect of the shoreface nourishments as well as predicting the effects of planned nourishments. It is the aim of the BWN WP3 to reduce this uncertainty, by analysing more shoreface nourishments in different coastal regimes using the same analytical framework.

1.2 Objectives

The overall aim of this analysis is to contribute to a shared North Sea region evidence base on the effects of beach and shoreface nourishments as a method for improving coastal resilience. In order to provide the relevant information for the co-analysis the focus of the present study is to understand coastal system response to shoreface nourishment and the main governing mechanisms. This will contribute to the continued optimization of the Danish Coastal Authority's nourishment scheme. The study will answer the following questions regarding the nourishment carried out at Skodbjerge:

- What was the lifetime of the 2011 shoreface nourishment?
- How did the 2011 nourishment redistribute along and cross-shore?
- How did the 2011 shoreface nourishment influence the dry part of the coastal profile, especially the safety level?
- How is the nourishment decay correlated with the hydrodynamic forcing?

2 Study site

The coastal laboratory referred to as Skodbjerge is located on the Danish North Sea Coast, Figure 2.1. The Danish North Sea Coast is a micro tidal wave dominated sandy coast. The coast is highly dynamic and the morphology changes responding and adjusting to the predominating climatic conditions. Large alongshore variations in the coastline have been documented along the Danish North Sea Coast, rhythmic bar systems and separating rip currents create coastline perturbations and indentations, which migrate as the bar system migrates alongshore in the sediment transport direction, which is southbound. These coastline indentations, which are characterized by a narrowing of the beach, mark potential erosional hotspots. The number of bars, their size and position in the offshore direction change rapidly, especially during storms.

Figure 2.1 Location and photos of the living laboratory Skodbjerge (© SDFE)

Skodbjerge is located on the southern part of the narrow spit Holmsland Tange which encloses Ringkøbing Fjord, Figure 2.1. The main road, Sønder Klitvej, is the only road connecting the southern part of the spit with the northern Holmsland Tange at Hvide Sande. Along Sønder Klitvej there are several areas with vacation homes in the dunes; as is also the case in Skodbjerge. The road runs parallel to the coast only about 1 km inland, which makes it important in order to safeguard the coastline position. The dunes are generally steep and the naturally developing dunes of between 12 to 18 meters height are backed by a plateau formed by a dune enhancement. The hinterland is protected by dunes and a dune enhancement. The dunes at Skodbjerge have had several wind-scoured blowouts resulting in increased sand drift inland.

The Danish North Sea Coast is recognized as an erosional coast which is subjected to chronic erosion caused by the southbound alongshore drift, but furthermore, large acute erosion events will take place during storms, see Figure 2.2 and Figure 2.3.

Figure 2.2 Photo from Skodbjerge on January 12, 2015 after the storm, Egon. The front of the dune has eroded back and is rendered almost vertical

The chronic erosion at Skodbjerge is about 2 m/yr. As such, this erosion rate is not high compared to other sections of the Danish North Sea Coast, but it is serious, in the light of the risk of acute erosion. At Skodbjerge large blowouts are scouring the dunes, see Figure 2.2 and Figure 2.3.

Figure 2.3 Photo from Skodbjerge on January 7, 2007. The dune front is eroded over a long stretch and there is a local breach

Acute erosion has previously eroded long stretches of dunes at Skodbjerge. In 2007 part of the dunes in Skodbjerge retreated 10 meters during a storm in January. The maximum recorded dune retreat at the Danish North Sea Coast was 60 meters at Thyborøn and a retreat of 46 meters was recorded at Vedersø in 1981; this indicates the scale of potential erosion along the Danish North Sea Coast.

3 Nourishment description

3.1 Coastal infrastructure and previous nourishments

Different types of coastal protection have been performed at Skodbjerge over the past few decades. These include beach nourishments, beach scraping and dune enhancement. Figure 3.1 shows the spatial and temporal distribution of all coastal protection measures carried out since 1980.

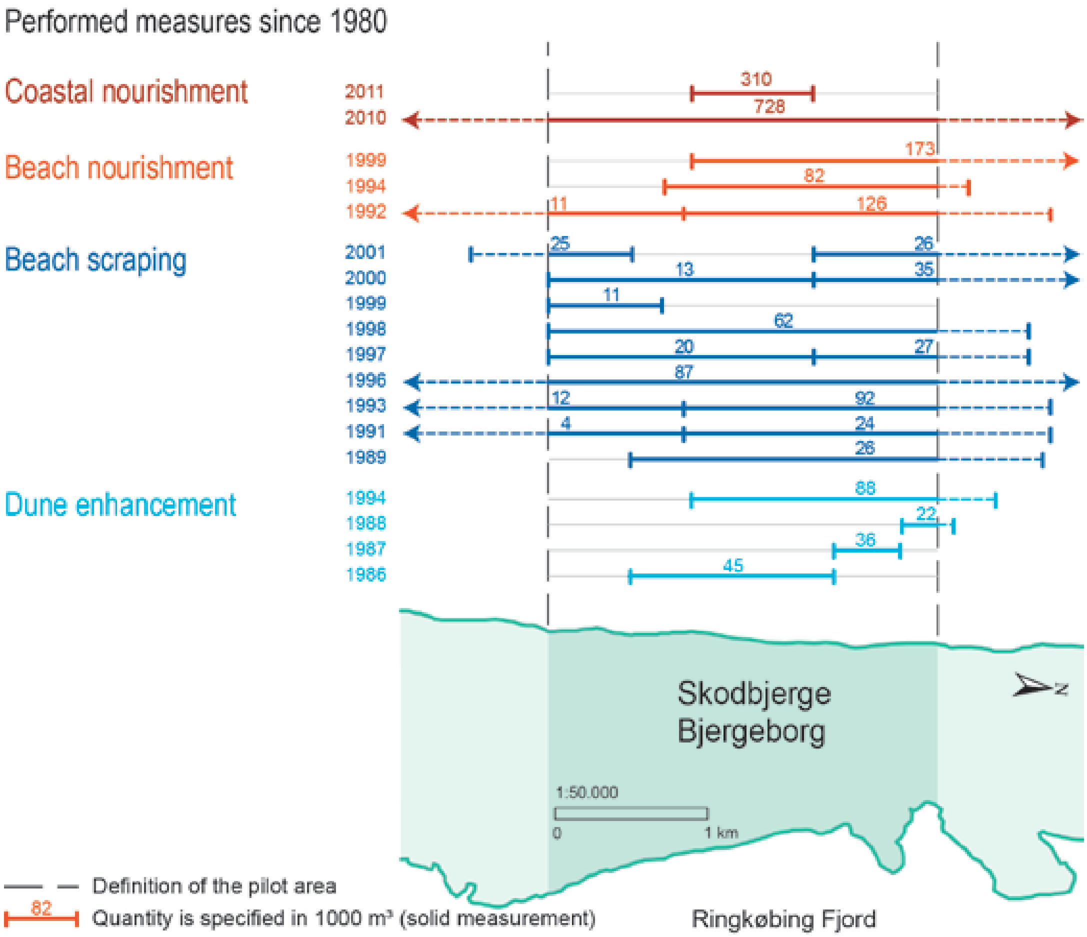

Figure 3.1 Types of coastal protection carried out in the area of Skodbjerge since 1980

No hard coastal protection measures have been erected at Skodbjerge. There was a long period of time between the latest beach nourishment in 1999 and the first shoreface nourishment in 2010. During this period, only beach scrapings were performed - in 2000 and 2001.

Table 1 shows detailed characteristics of nourishments and dune enhancement performed in the area. Information about other interventions performed in the proximity of Skodbjerge is also displayed in the table, since these may influence the natural development of the coastal stretch.

Table 1 Nourishment and dune enhancement characteristics in Skodbjerge area. A hyphen (-) indicates that exact data are unavailable. An asterisk (*) indicates a nourishment outside of Skodbjerge limits, but in the neighbouring area

Year	Method	Finish date	Volume (m³)	Length (m)	Volume (m³/m)	Volume (1000 m³)
1986	Dune enhancement	1986-12-31	45,400	-	-	45
1987	Dune enhancement	1987-12-31	36,000	-	-	36
1988	Dune enhancement	1988	21,500	-		22
1994	Dune enhancement	1994-08-01	87,500	-	-	88
1992	Beach nourishment	1992-06-15	136,768	1,900	72	137
1994	Beach nourishment	1994-08-01	82,345	1,600	51	82
1999	Beach nourishment	1999-07-28	173,185	2,500	69	173
2010	Shoreface nourishment	2010-07-11	727,949	12,774	57	728
2011	Shoreface nourishment	2011-08-03	310,116	775	400	310
2011*	Shoreface nourishment	2011-09-27	310,186	775	400	310

On the 11th of July, 2010 a large bypass project was completed in the area. 727,747 m³ of sand were moved from the northern side of Hvide Sande port and evenly distributed along a 12,774 m stretch of coast south of the port. This equals a sediment volume of 57 m³/m, and a total of ca. 285,000 m³ within Skodbjerge. Part of this stretch of coast coincides with the area in which the investigated shoreface nourishment of 2011 was carried out. Due to this fact, and because there is only a year between the nourishments, understanding the influence of the 2010 nourishment on the coastal system is of great importance to the analysis of the 2011 nourishment.

3.2 The 2011 nourishment

The final evaluation of the nourishment performance will be based on the initial nourishment objectives. In the following subsections the 2011 nourishment will be described according to initial design and nourishment objectives.

3.2.1 Design characteristics

The nourishment in question was carried out from the 11th of June 2011 to the 3rd of August 2011. The total volume of the nourishment was 310,116 m³, located between coastal transect 4014600 and 4013800, see Figure 3.2. The length of the nourishment was 775 m equalling 400 m³ of sediment per meter. This nourishment was carried out between 350 m and 680 m from the coastline.

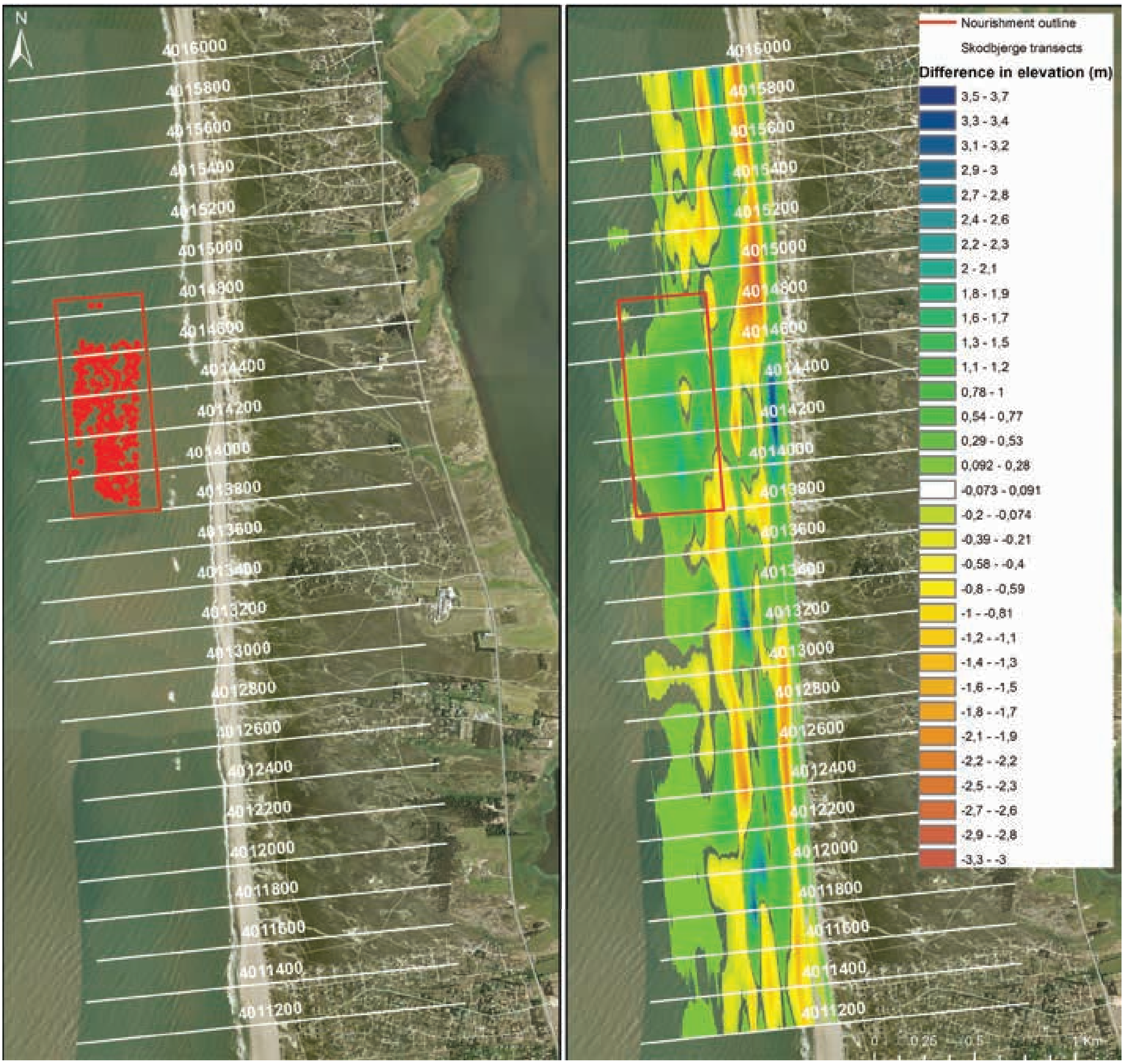

Figure 3.2 Shoreface nourishment placement. The nourishment was carried out between the 11th June and the 3rd August 2011. Right: The area of Skodbjerge including the transect definitions and their profile numbers (white), the nourishment outline and the individual sediment deposits (red). Left: The area of Skodbjerge and a difference calculation based on the pre- and post-nourishment survey showing the areas of erosion and accretion between the 17th January and the 8th November 2011.

3.2.2 Nourishment objectives

The overall objective of shoreface nourishment at Skodbjerge is to maintain the safety level set for the area in order to minimize the risk of coastal retreat and inundation of the low-lying hinterland. This objective responds to the requirements of the Joint Agreement, explained in section 1.1.1

The 2011 shoreface nourishment was part of a nourishment project consisting of two nourishments performed at Søndre Holmsland Tange. One of the nourishments was placed southward within the Skodbjerge area, while the second nourishment was placed at about 2.5 km north of Skodbjerge. The specific characteristics of both nourishments are described in Table 1. These two nourishments had different design goals and were located in their respective sites in relation to the sand bar in order to influence sand bar morphology differently. There were two main research goals for the shoreface nourishments.

The northernmost nourishment – upstream of Skodbjerge - was placed at the middle of the offshore bar. The aim was to test whether it was possible to force an onshore migration of the existing bar system, which would result in an increase of the beach volume, and thereby a decrease in dune erosion. The southernmost nourishment – within Skodbjerge - was placed to the south at the end of the offshore bar, thereby extending the bar in alongshore direction. The aim was to prompt sediment redistribution downstream and displacement of the point of local dune erosion in alongshore direction. The point of local dune erosion is typically found onshore from where the offshore bar ends.

The overall objective of the nourishment design was to place a large enough volume of sediment (400 m³/m), equivalent to the present bar volume, in order to have a significant influence on bar morphology. Figure 3.3 shows transect 4014000 surveyed before and after shoreface nourishment of 310,116 m³ (400 m³/m).

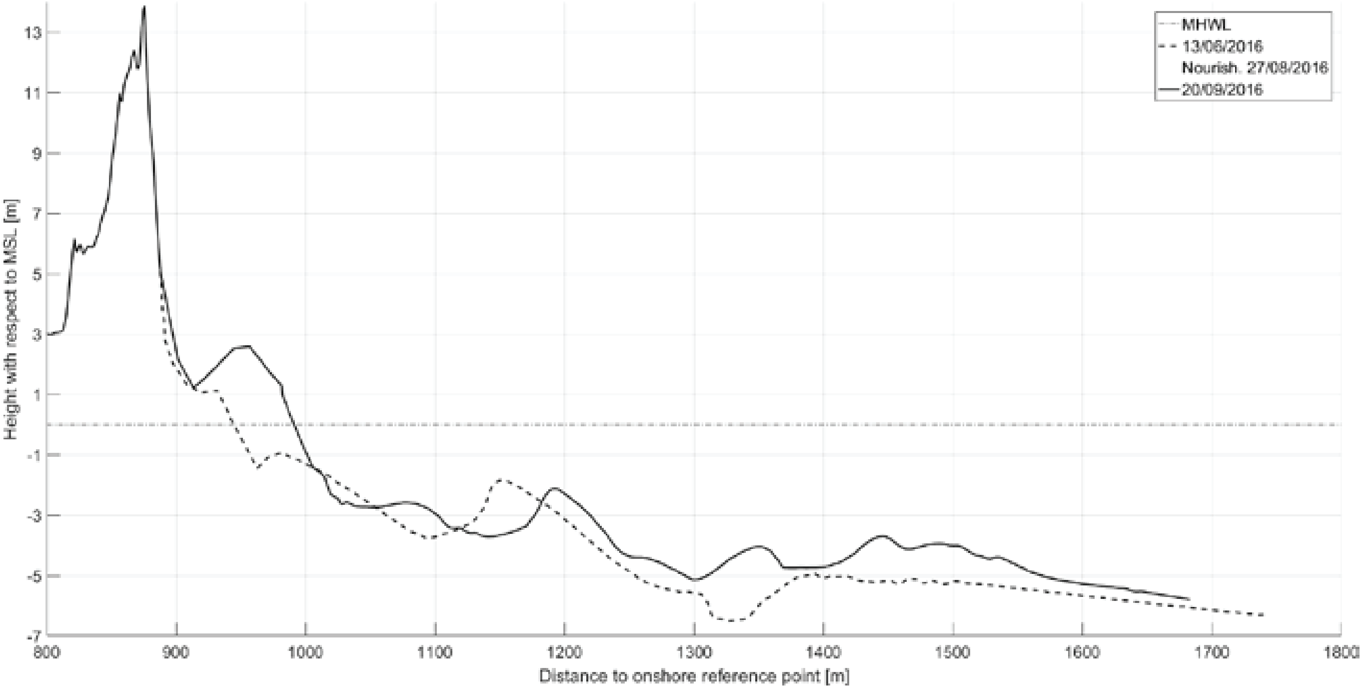

Figure 3.3: Transect 4014000 before and after the 2011 nourishment. It was performed between the 11th June and the 3rd August

4 Data accuracy and processing

In this section the different types of data applied in the analysis of the shoreface nourishment in Skodbjerge are presented according to data source, accuracy and processing prior to analysis.

4.1 Transect data

Skodbjerge has been surveyed in the period 1957 - 2017. Two types of transect measurements have been taken: Local measurements and West Coast measurements. Local measurements are only available from 2005 to 2014, with a spacing of 200 m from each other. This is also the chosen analysis period. Figure 4.1 shows the area covered by local measurements.

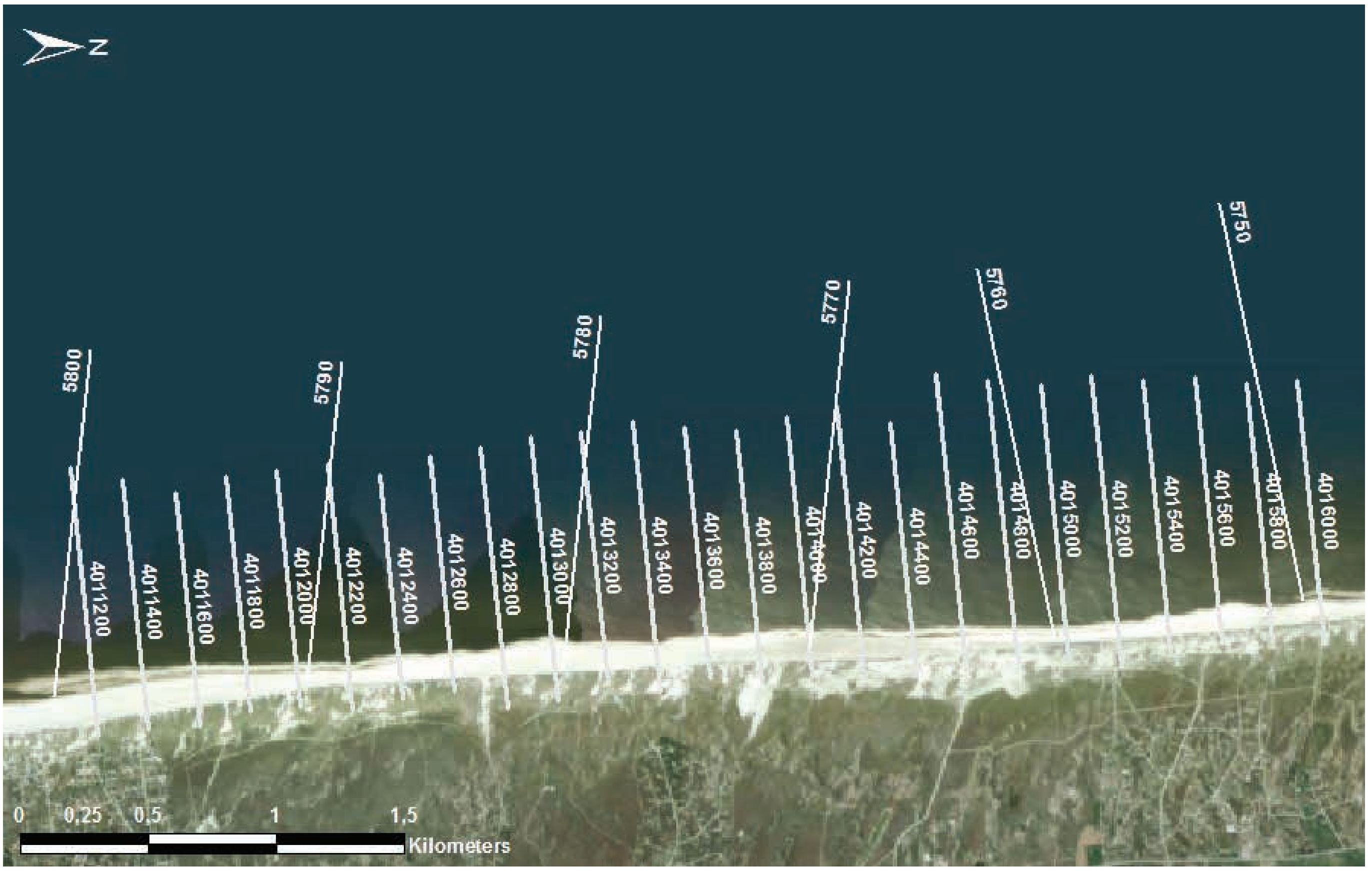

Figure 4.1 Definition of West Coast and local profiles. Distance between local profiles is 200 m, while West Coast measurements are undertaken for every 1 km

Land measurements are carried out using RTK GPS[1] or total station, or a combination of both. The accuracy of the measurements is controlled using at least two inland fix points: One as a reference station and the other one as a control point. With this technique, the biased error is kept under 3 cm. When RTK GPS and total station are both used to carry out land measurements, an overlapping area is defined, and measured with both types of equipment in order to secure quality. The maximum error in the overlapping area is 10 cm. The separation of inland data points depends on the morphology.

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[1] *Real-time kinematic (RTK) positioning is a satellite navigation technique used to enhance the precision of position data derived from satellite-based positioning systems*

Sea measurements are carried out using echo sounder multibeam scans from a boat. At least two reference stations need to be used for data control. The expected biased error in height depends on how far the reference stations are located from each other, and varies between 2 cm and 4 cm. Distance between points under water is 2 m.
Since each measurement has inherent inaccuracies, the size of these errors must be quantified when using survey data for volume calculations with. The survey area spans 5,000 m * 900 m. An error of 5 cm height in a survey means a volume error of 225,000 m³ (5 % of the total volume). The nourishment area is 750 m *400 m, so a biased error of 5 cm in the nourishment areas will result in a biased error on calculated volumes of 15,000 m³. These error variations must be taken into account when evaluating the results.

Local surveys are not evenly distributed in time. From 2005 until 2007, both years included; surveys are performed regularly, up to 6 times a year. From 2008 until 2011, the coastal stretch is surveyed twice a year, normally in spring and in autumn. Finally, from 2012 until 2014, there is only one measurement every year. Not all of these measurements are useful, and some must be filtered according to the use they are going to be given. For instance, some of the 2006 and 2007 surveys cover only dune and beach, offering no data points in the shoreface. Likewise, other profiles are surveyed only until 1 m or 2 m relative to mean sea level (MSL). These profiles can be used if completed with LiDAR data (see Section 4.3.), or if the focus of the analysis is on the shoreface. It is required that all profiles are measured at least up to 8 m relative to MSL, which is the height of the lowest dune in the system.

West Coast measurements are performed annually along the entire West Coast. These measurements are available from 1957 until 2017 at 1000 m intervals. All the surveys contain data points in the wet profile. Regarding the dry part of the profile, after 1978 most surveys are performed up to the dune crest height. Unfortunately, these profiles cannot be extended with LiDAR, since this data is only available from 2005 on. West Coast measurements are not evenly distributed in time. Between 1957 and 1969, there are only surveys in 1962 and 1965. Afterwards, surveys are performed almost every year, with the exception of 1974, 1975, 1985, 1987, 1989, 1991, 1993, 1995 and 1997.

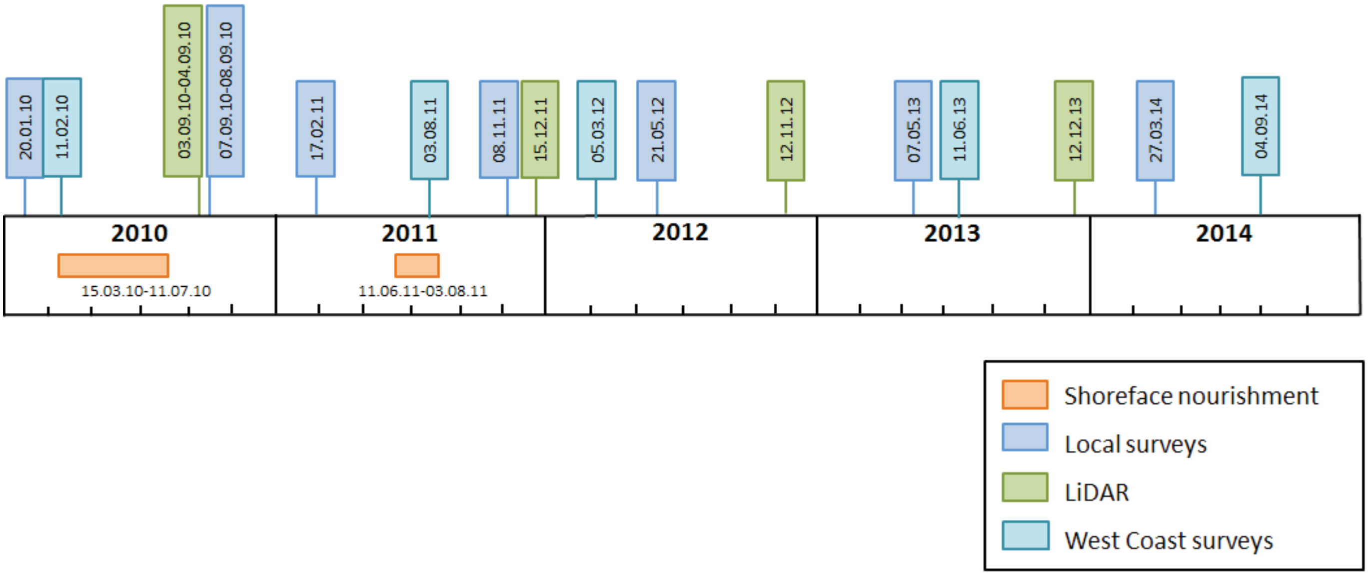


Figure 4.2 Timeline of the shoreface nourishment, LiDAR scans and surveys of West Coast profiles and local profiles.

Figure 4.2 shows a graphic overview of the dates when profile measurements and LiDAR scans were performed, within the period after the recent shoreface nourishments. Time periods in which shoreface nourishments have been executed are also stated.

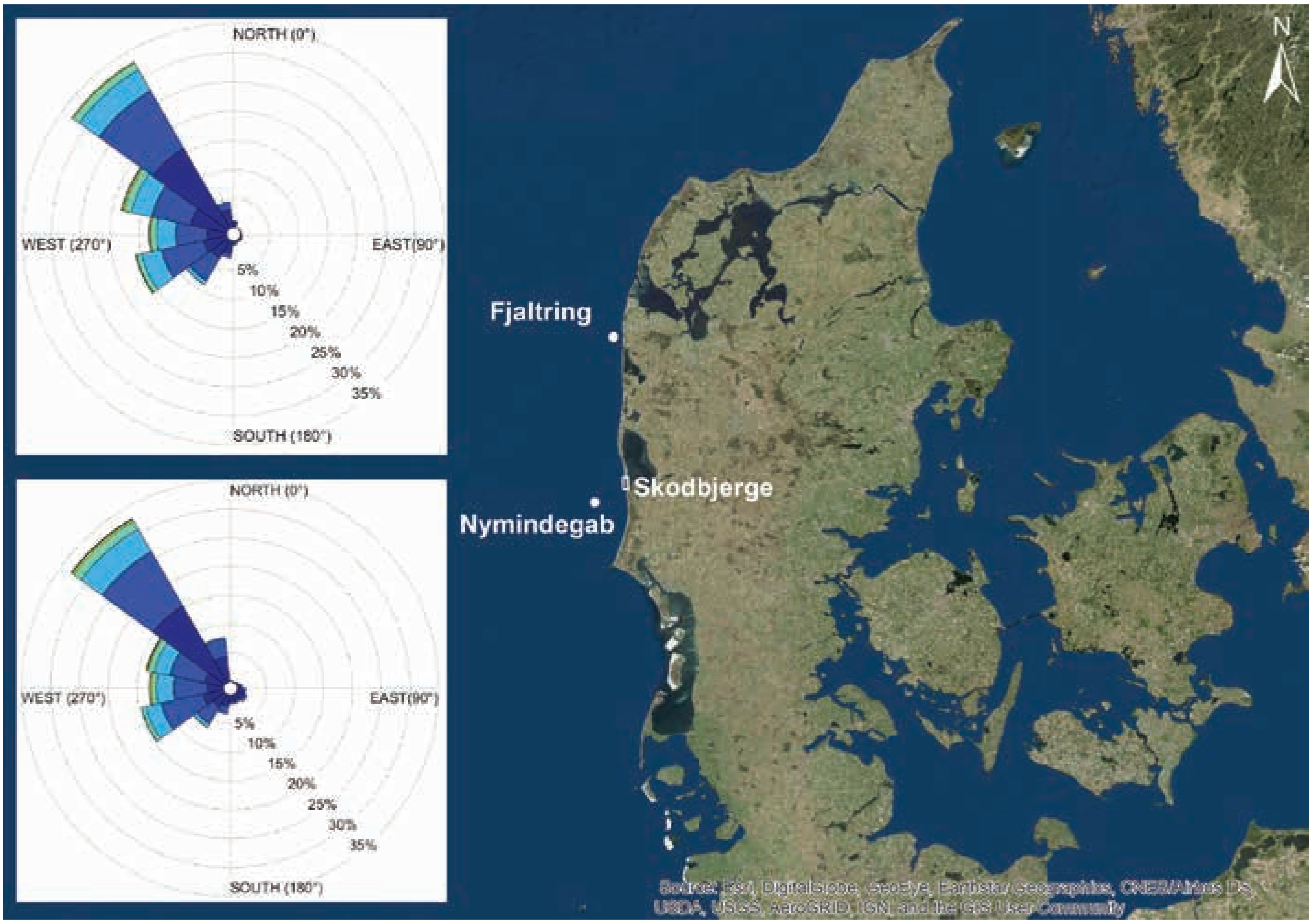
Local measurements are used for different purposes than West Coast measurements. Local measurements offer more detailed information about a short time period (2005 – 2014) therefore they are fundamental to understand the morphological evolution of the beach before and after the nourishment. The morphological evolution observed before the system is altered is called autonomous behaviour. Understanding the implications of nourishments on the system is not possible without understanding the natural variations that occur spontaneously in the coast. Not all natural morphological variations can be understood by studying a period of only 9 years. When the autonomous behaviour of the coastal morphology cannot be determined from local surveys, the analysis of local measurements is supplemented with West Coast measurements.

4.2 Hydrodynamic data

In the following sub sections the available wave and water level data and pre-processing of these are presented.

4.2.1 Wave data

Along the central west coast of Denmark there are two wave gauges. Nymindegab wave gauge is located south east from Skodbjerge, about 15 km away, while Fjaltring wave gauge is located north east from Skodbjerge more than 60 km away. The wave series measured in both buoys are similar; however, due to the geography of this coastal stretch, the direction of the measured waves in Nymindegab is slightly different to those measured in Fjaltring (see Figure 4.3). Therefore the best representation of the maritime climate in Skodbjerge is given by the buoy at Nymindegab.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 4.3 Wave roses from Nymindegab (bottom) and Fjaltring (top), position of the buoys and position of the living laboratory of Skodbjerge.

The Nymindegab buoy has records from the 17th December 1997 until today. Instead of raw data of the wave time series, wave characteristics averaged every 3 hours are given. From the data, spectral significant wave height, H_{m0}, peak period, T_p, and mean wave direction, θ_m are used. The analysis of wave characteristics has two objectives: Describing the average wave climate before and after the studied nourishment, and revealing patterns in the interactions between climate and system morphology.
Wave data is checked for outliers, which are eliminated from the register. The following verifications are done (based on Andersen, T. L., Frigaard, P., & Burcharth, H. F. (2014)):

1. Wave period non-negative and correspondent to gravity waves. Wave periods must be within the range from 1 s to 40 s.
2. Wave height non-negative and non-zero.
3. Wave height is limited due to its relation to water depth. The relation between significant wave height, Hs, and water depth has been observed to be limited to 0.5. Otherwise the wave becomes unstable and breaks, reducing its energy and its height.
4. Wave steepness is limited due to breaking. It is observed that during storms the wave height hardly ever surpasses 1/10 of the wave length.

The data in Nymindegab is quite complete, and not many outliers are found. However, two months of data are missing within the study period. Data from the 3rd May 2007 and the 5th of June 2007, and from the 14th July 2011 and the 24th August 2011 is missing. Since the conformity between wave characteristics in Nymindegab and in Fjaltring is quite pronounced, when possible, wave data from one buoy is used to cover gaps in data from the other buoy. This must be done taking into consideration that there are differences in mean wave direction, see Figure 4.4.

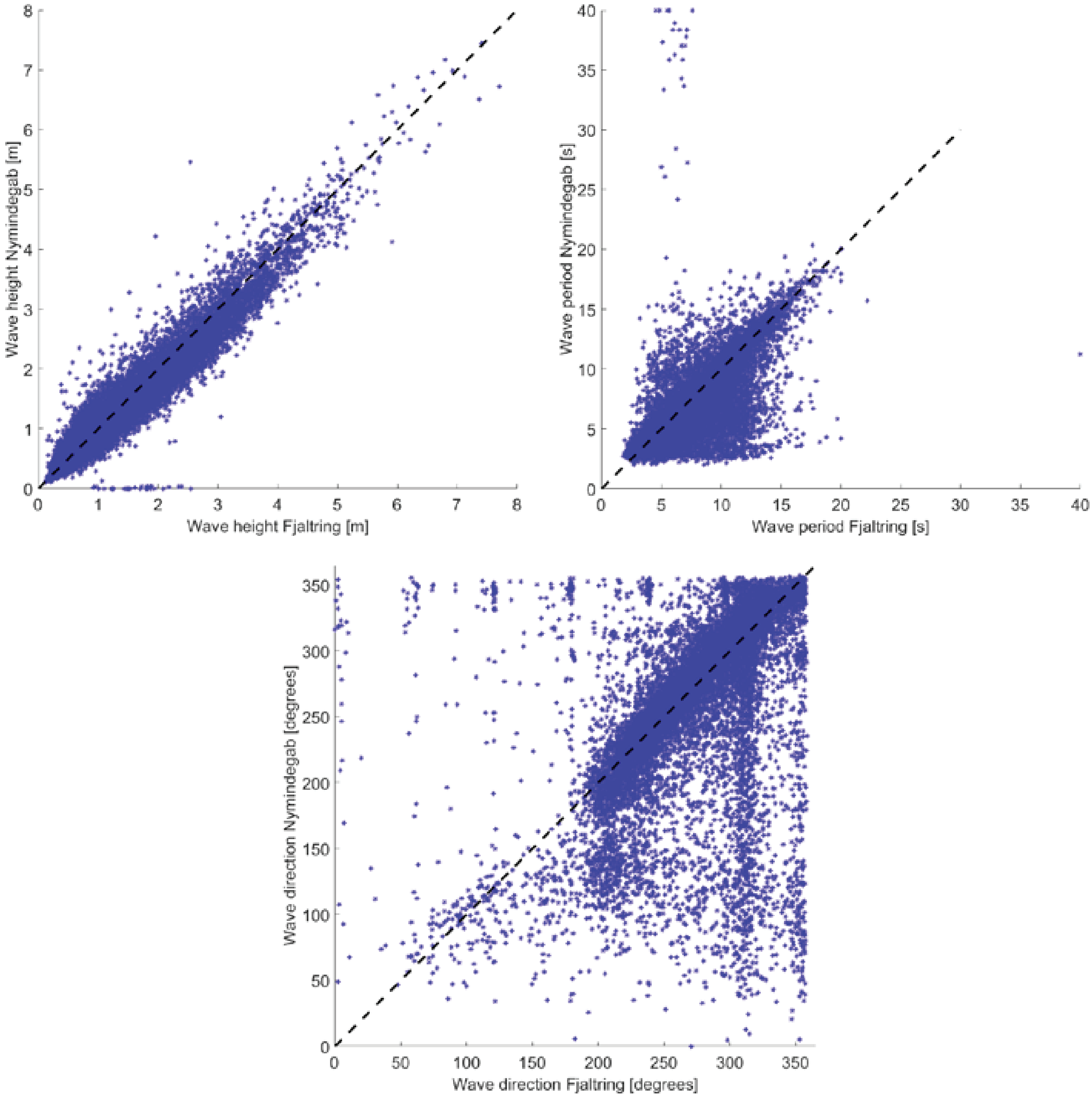


Figure 4.4 Correlation between wave characteristics from Nymindegab (vertical axis) and Fjaltring (horizontal axis). Top left: Correlation of significant wave height. Top right: Correlation of peak wave period. Bottom: Correlation of mean wave direction.

Figure 4.4 shows the correlation between wave characteristics for Nymindegab and Fjaltring, during the period from 2005 to 2014. The best correlation is found in wave height, while period and especially directions deviate from perfect correlation. Wave periods measured in Fjaltring are longer, which can be explained by more swells coming in from the NW. This, however, is not properly disclosed by the correlation plots, since there is an error in the directional data in the form of points concentrating in vertical lines. Especially, the wave height plot and the peak period plot both have some points that differ completely in both buoys. They are recordings with very small wave heights – less than 1 m height – and very large peak period – more than 20 s. This is most likely an error in measurements that could not be filtered out by the criteria set up above, because there is no lower limit for wave steepness.

4.2.2 Water level

Water level data is measured in the port of Hvide Sande. Data is available in two gauges, one inside (Hvide Sande Port) and one outside (Hvide Sande Sea) the port. The data from both gauges covers the whole analysis period (2005 – 2014). In fact, data is first measured in Hvide Sande Port on the 22nd August 1974, and first data from Hvide Sande Sea was obtained on the 2nd February 1981. The data is treated for outliers by eliminating negative values, null values and extremely large values. It is also possible to establish whether a value is an outlier by comparing measurements of both port and sea, given that their correlation is very high (see Figure 4.5)

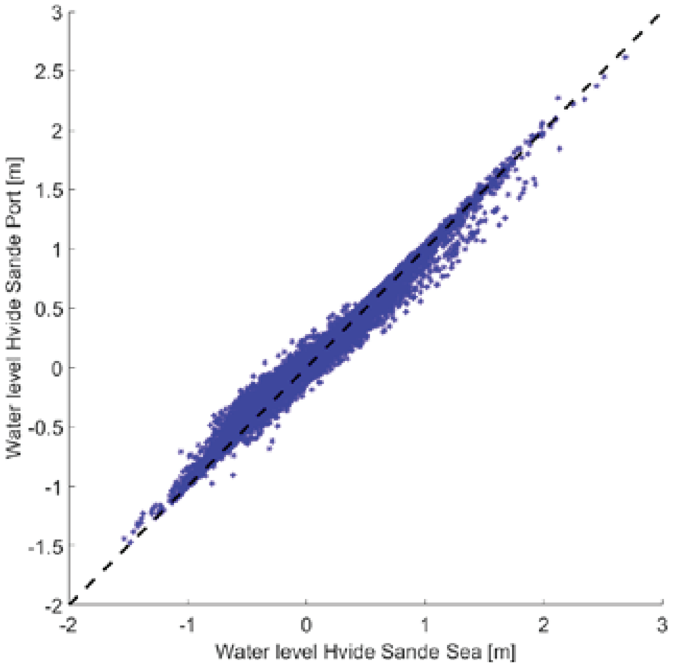


Figure 4.5 Correlation of water level measured at Hvide Sande port and Hvide Sande Sea gauges.

Hvide Sande Sea measurements are used in the analysis, while measurements from Hvide Sande Port are used to substitute missing data. There are two obvious gaps in the sea data. One from the 2nd February 2012 to the 5th March 2012. The second gaps spans the period from the 5th March 2013 until the 4th April 2013.

Astronomical tides are obtained from the Danish Meteorological Institute (DMI). This data is received at the DCA after processing and quality control.

4.3 Additional data

Annual LiDAR data are available from 2005 to 2013 and from 2015 to 2018. LiDAR scans are used to extend transects in cases where the surveyed transects have not been measured up to 8 m height over MSL. LiDAR scans are only performed once a year. In order to perform the reconstruction of profiles, it is assumed that changes at dune level are negligible within the same year. Following this assumption, all surveys performed within the same year are extended by using the same scan data. However, care must be taken, since, by assuming no significant variation within the same year, wind action, human action or storms are not registered when the same scan is used.

The most critical task is to manage the overlap area between scan data and measured points. Points measured in situ offer a higher accuracy than those obtained from LiDAR scans. Therefore these points are used to describe the overlap area. Between the last scan point and the first measurement point, a linear interpolation is done, and it is here, and around 0 m height from MSL, that most errors are found.

5 Environmental characteristics

The environmental characteristics of the system are hydrodynamic forces and grain size. Understanding the evolution of the different hydrodynamic forces and their impact on the system is essential in order to understand the effect and development of the nourishments. The focus is on the description of the average climate characteristics before and after the nourishment.

5.1 Waves

Waves are the hydrodynamic forces which most influence the system. Wave data from the period January 2005 to September 2011 is used to investigate the average conditions of the wave climate at Skodbjerge. This data is compared to wave conditions post nourishment (September 2011 to December 2014) to observe whether there are relevant differences in the hydrodynamics, which affect the nourishment performance. Wave roses representing the climate before and after the 2011 nourishment are presented in Figure 5.1.

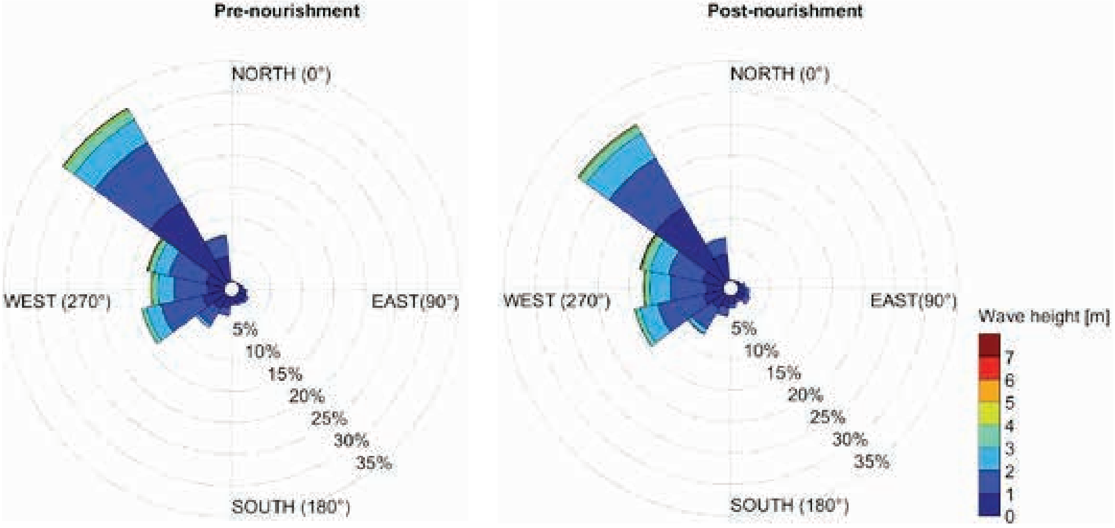


Figure 5.1 Wave height roses in the pre- and post-nourishment periods. The coastline alignment is marked with a dashed orange line. There is a slight change in the share of waves from NW to W directions, especially of waves with medium to small heights (1 m to 4 m)

The predominant wave direction is clearly within the sector from 306° to 330°. The predominant wave direction is the same pre- and post-nourishment, but the percentage of waves coming from each direction changes slightly. The share of waves coming from the north decreases, while the number of waves coming from the south increases. This especially applies to waves from 1 m to 4 m of height. It has to be taken into account that data samples for both plots have different sizes, which may explain some of these disparities.

Additionally, a perpendicular to the coastline forms 264° with the true north. The maximum wave-induced alongshore current occurs when the incoming wave angle is 45° onto the coastline [pp. 41, Aagaard, Nielsen and Nielsen, 2008], which in Skodbjerge corresponds to incident wave angles of 219° and 309°. This means that the predominant incident wave direction generates a southbound alongshore current. When comparing pre- and post-nourishment, the share of incoming waves from the predominant wave direction changes from 32 % pre-nourishment to 28 % after, see Figure 5.2

In addition, waves with an incoming angle between 234° and 258° increase from 13% to 15%, which triggers an increase in the northbound alongshore current. As a consequence, it can be inferred that the alongshore southbound transport is reduced after the sand nourishing.

Following the same principles as for the wave height roses, wave period roses are plotted. The longest wave periods correspond to the highest waves, which generates roses that are very similar to the wave height roses. The longest periods are observed between 306° and 330°. It can be observe that periods longer than 8 s are less frequent post nourishment, while periods longer than 7 s appear more frequently from south-westerly directions. This supports the conclusion that the southbound alongshore transport was smaller post nourishment.

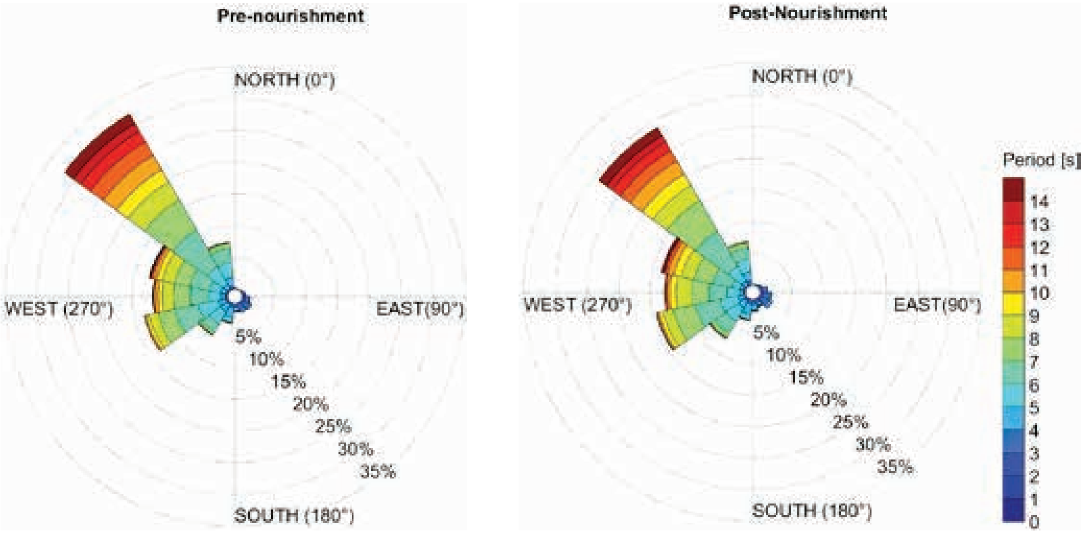


Figure 5.2 Wave period roses in the pre- and post-nourishment periods. Note the redistribution of wave periods, especially in the range of 6 s to 10 s. The coastline alignment is marked with a dashed orange line.

Table 2 contains a summary of the most important wave properties and their bulk statistics during the analysis period, pre- and post-nourishment. The mean and standard deviation are calculated for both H_{m0} and T_p, but for θ_m, the mode is calculated.

Table 2 Table with average wave properties during the whole analysis period, before the nourishment and after the nourishment

Wave property	General		Pre-nourishment		Post-nourishment	
	μ / mode	σ	μ / mode	σ	μ / mode	σ
H_{m0} (m)	1.38	0.86	1.37	0.85	1.39	0.88
T_p (s)	7.12	2.70	7.09	2.56	7.16	2.97
θ_m (°)	315	-	314.3	-	315.7	-

The average and standard deviation of H_{m0}, and T_p are larger post-nourishment than during the whole period and during the autonomous behaviour period. This indicates that not only is the average larger but also the variation. This can be explained by the large peak events that can be observed within the relatively short post-nourishment period (see Table 2)

5.2 Tides

Tide data is used to determine mean high water level (MHWL) and mean low water level (MLWL). These are CSI's defined in table 3. Long-term tidal variations are assumed to be small, even so, ten years of data are used to determine these CSI.

MHWL is calculated as the average of all high tides registered from 2007 to 2017. In the same manner, MLWL is calculated as the average of all low tides in the same period. The following values are obtained:

Table 3 Avarage MHWL, MLWL and Tidal range

MHWL (cm)	MLWL (cm)	Tidal range (cm)
45.55	-27.55	73.10

5.2 Storm surges

Storm surges are the accumulation of water being pushed in a constant direction by the wind [Robert M. Sorensen, 2005]. The water level increases in the wind direction and decreases in the opposite one. In this manner, storm surges and wind conditions are deeply related.

In the stretch were Skodbjerge is located, it is of especial interest the storm surge event of 100-years return period, since the height it reaches is used to monitor the dune safety (see Section 1.1.1). The 100-year water level is 4.5 m relative to MSL.

5.4 Grain size

The grain size has not been studied recently in the area. In December 1999 a large analysis of the sediment characteristics of the whole West Coast was published (Kystinspektoratet, 1999). At Skodbjerge the average D50 is 0.225 mm for the whole coastal profile. In general, the grain size in autumn and winter is larger than in spring and summer. The largest grain size measured was in autumn with a D50 of 0.25 mm. As for distribution in depth, there is larger grain size variability between 2 and 6 m of depth, where D50 moves in the range of 0.4 mm to 0.1 mm depending on the season.

6 Method

In the following sections the BwN common methodology is presented. The common methodology is overall the identical but in each case input to the methods has been adjusted in order to probably capture the morphology of each of the seven living laboratories, as well as the different nourishment designs.

6.1 Terminology and coastal state indicators

The analysis of quantitative morphological development is performed using coastal state indicators (CSI's). CSI's are commonly agreed definitions of features that provide information on the state of a coast at a certain moment in time. The use of CSI's will align the national analyses carried out by each member in WP3 of the Building with Nature project, and will allow them to be joined into one co-analysis.

A CSI is a feature; morphological feature, morphological zone or height level which can be determined using cross-shore transects. When monitored over time, a CSI shows the development of the morphological system and reveals changes in evolutionary trends. The monitored development depends on the type of CSI e.g. Changes in sand volume in a zone, the width of a coastal zone, the cross-shore position of a morphological feature or height level. A description of the CSI's functions and criteria can be found in Lescinski (2010). Below in table 4 the applied coastal terminology, the CSI's and their interrelation is described.

Table 4 Common definitions of Morphological zones (grey) and delimiting height levels – CSI (white). *The seaward and landward limit can be defined as a height level or as a distance.

Coastal-zone	CSI	CSI type and definition
	Landward limit	Not a CSI -The landward limit is not monitored in itself, but sets the limits for calculating dune and system width and volume. The limit is set as a cross-shore position which is measured in all available profiles.
Dune	Upper dune	Coastal sub-section
	Upper dune level	Fixed height level which is highly responsive to dune erosion or human-made reinforcement. The minimum level of dune crests over time must be taken into account.
	Middle dune	Coastal sub-section
	Mid dune level	Fixed height level where aeolian sand transport and aggregation of sand should be of minor relevance. Changes at this level should be likely ascribed to acute dune erosion or man-made dune reinforcement. However, on longer time scales, natural dune growth can be visible, as a response to a positive or negative sediment budget.
	Lower dune	Coastal sub-section
	Dune toe level	Fixed height level where the slope is distinctly changing. Dune growth on shorter time scales can be the result of human-built sand traps or of natural dune growth such as aeolian sand transport.
Beach	Dry beach	Coastal sub-section
	Mean high water level (MHWL)	Fixed height level: MWL + ½ Tidal Range. (If MWL is not available use the astronomical MHW, which is representative for the period after the nourishment was assessed)
	Wet beach	Coastal sub-section
	Mean low water level (MLWL)	Fixed height level: MWL - ½ Tidal Range, (If MWL is not available use the astronomical MHW, which is representative for the period after the nourishment was assessed)
Shoreface	Inner shoreface	Coastal sub-section
	Bar system	Morphological feature: Bar: sand accumulation created by currents and waves. A bar has the following characteristics: Bar top: maxima in the shoreface profile where the slope profile changes from ascending to descending Bar trough: depression between two bar crests, or in between a bar top and a point landward from the bar, at the same depth. Bar height: difference in height between bar top and the deepest point of the bar trough. Bar landward limit: deepest point landwards of the bar top.
	Outer shoreface	Coastal sub- section
	Seaward limit* / Depth of closure	Not a CSI -The seaward limit is not monitored in itself, but sets the limits for calculating shoreface and system width and volume.

The coastal zone terminology in Figure 6.1 will be applied throughout the analysis. The CSI's corresponding to the costal terminology are shown in Figure 6.1 and described in Table 4. The morphological development represented by the CSI will be analysed in order to reveal the morphodynamics and the effects of nourishments.

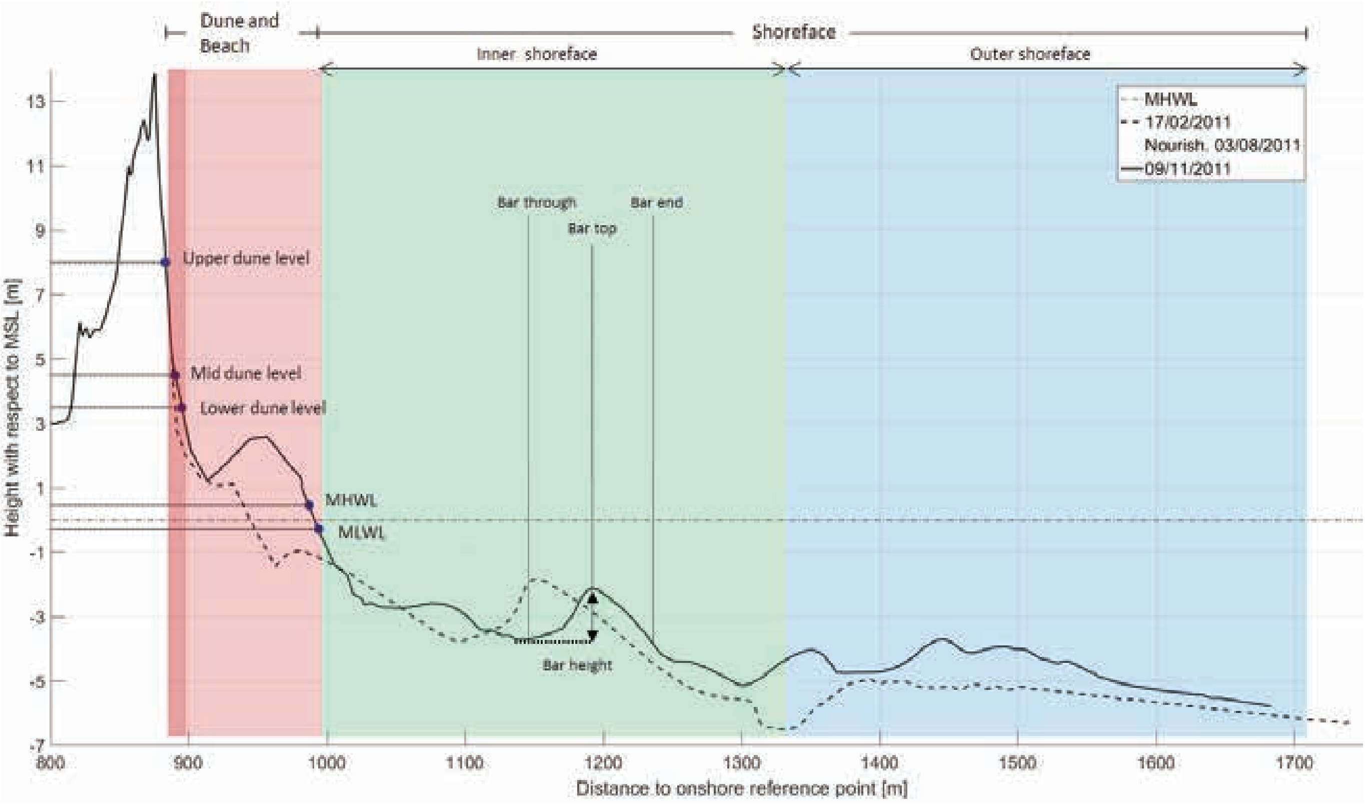


Figure 6.1 General terminology used to describe the coastal profile. On the vertical axis various levels in the profile are shown. The horizontal axis shows different morphological zones in the profile.

The profile is divided into 3 coastal sections: dune, beach and shoreface. The dune section corresponds only to the part facing the shore; hence it is very slim (darker red in Figure 6.1). Since both dune and beach represent the dry part of the profile, they are grouped together in several analyses. In contrast to this, the shoreface zone is extremely wide, thus it is further divided into two sub-sections: inner shoreface and outer shoreface. Both sub-sections are deeply influenced by the dynamics of the breaker-bar system. The vertical levels are set for each living laboratory in order for it to capture the morphology; the relevant levels are presented in table 5.

Table 5 The CSI's selected for the analysis of Physical marks.

Physical marks	Height with respect to MSL (m)
Upper dune	8
Mid dune	4.5
Lower dune	3.5
MWHL	0.46
MLWL	-0.28

In addition, when examining the coastal area in its entirety, a division in alongshore zones is performed.

This division is based on the morphological characteristics of every area at Skodbjerge, considering both their development in the whole study period and their response to nourishment. Every zone has a uniform behaviour; hence, it is possible to represent the alongshore evolution of the whole coast by looking, at least, at one profile from every zone. The zones are named according to their location within the nourishment area; N for those at the northern part, and S for those at the southern part. The numbers increase according to the distance from the nourishment, for instance, zone S1 and N1 are ones the closest to the nourishment, and N2 and S4 are the furthest ones.

When looking at Figure 6.2, cross shore divisions can also be observed. From onshore to offshore these are: mid dune or safety level, MLW level, division between inner and outer shoreface and seaward limit. These divisions are made as part of the analysis of volume development, and are explained in detail in Section 6.4.

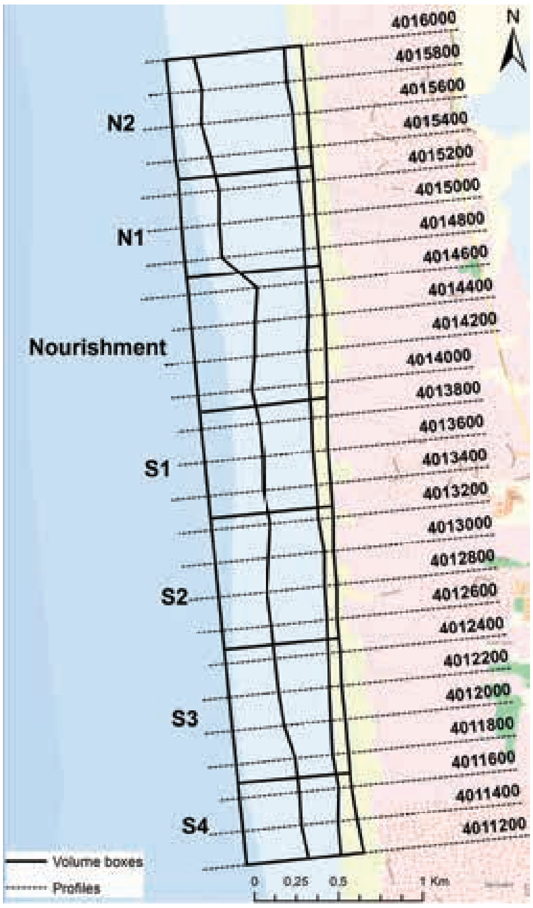


Figure 6.2 Division of the coastal area in alongshore sections. From north to south: N2, N1, nourishment, S1, S2, S3 and S4.

6.2 Physical marks

A wider beach and well-developed dune system provide better protection of the hinterland. To assess the impact of the nourishments on the dry part of the profile the position of the different dune and beach height levels is examined, see Table 5. These levels are defined in points where a certain morphodynamic characteristic can be defined, either as an actual imprint (MHWL and MLWL) or as a point of inflexion in the beach morphology (dune toe, dune face, dune crest). These points are referred to as physical marks.

To extract physical marks from transect measurements, the Momentary Coast Line Model (MCL) is applied (Leidraad Zandige Kust, 2002, Den Heijer, F.). The model determines the position of the physical mark as the centre of gravity of the surrounding sand area. This area is determined by fixing a buffer distance over and under the physical mark. Figure 6.3 shows an example of the MCL-calculation.

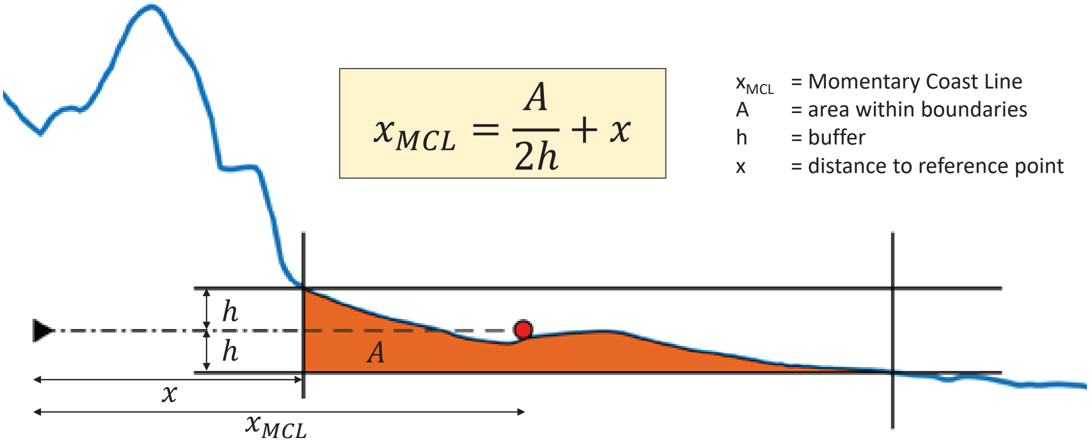


Figure 6.3 Illustration of the of Momentary Coastline (MCL) calculation method.

It is recommended to set the buffer, h, at +/-0.5 m respect to the height level; however, this depends on every specific level. The morphological changes in the wet part of the profile cannot be traced by using the MCL approach, because the MCL position becomes severely affected by the migration of the bar system. This analysis is performed for at least one representative transect in every coastal alongshore zone.

6.3 Bar development

A well-developed bar system improves coastal resilience, since it dissipates wave energy through wave breaking. Therefore the impact of nourishment on the shoreface and its morphological characteristics, especially the dynamics of the breaker bars, are investigated, based on transect measurements.

The size and location of bars are examined both cross-shore and alongshore in order to show spatial and temporal evolution in the bar system. This is done by applying two sets of criteria: one to identify the bars present in each coastal transect and one to determine the longshore continuity of the bar.

The characteristics which define a bar are found in Figure 6.4. In order to generically identify the bars within a costal profile the following parameters are defined:

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

6.3.1 Cross shore bar identification

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

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

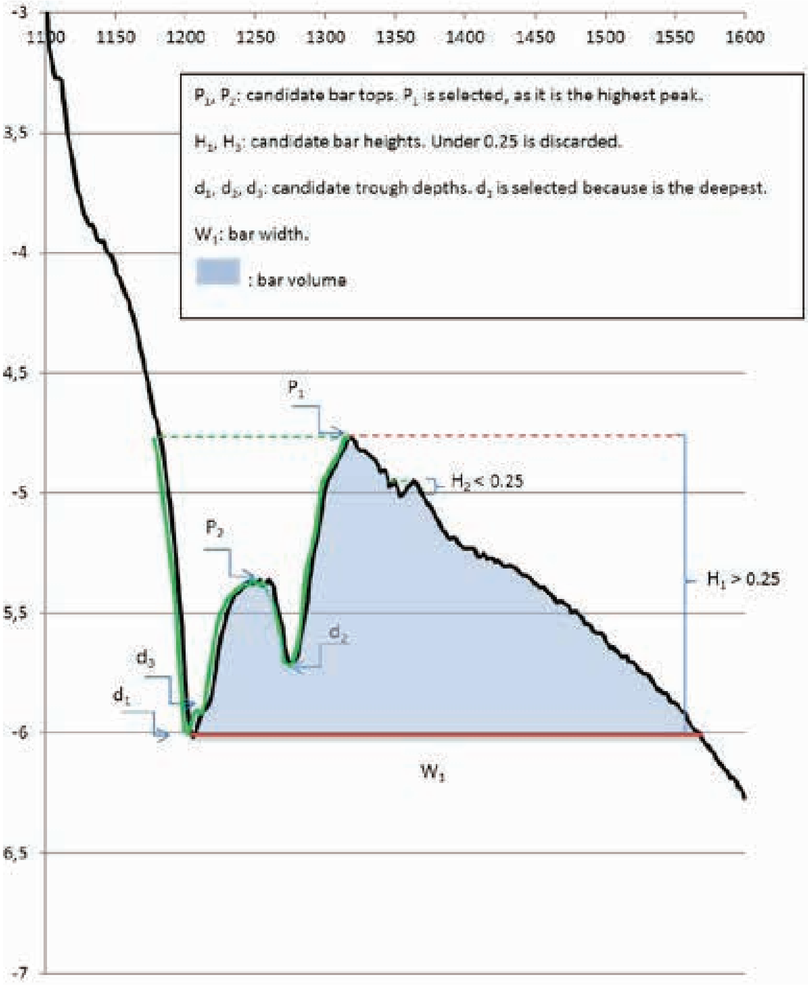


Figure 6.4 Definition of the bar elements: bar top, bar trough, bar width and bar height.
The green line corresponds to the through, the red line signifies the bar width.

These three characteristics have been obtained by iteration. The initial cross-shore criteria are based on the observation of mean wave height, the depth where bars are observed, their width and height. The initial criteria are then refined by iteration, e.g. by finding and afterwards evaluating whether the results match the actual beach morphology.

6.3.2 Alongshore bar connection

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

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

These two conditions are also obtained by iteration. The initial longshore criteria are based on mean wave height, the longshore distance in between transects, and the variation in depth over bar. In the case of two possible bar connections in a neighbouring profile, the one which minimizes distance is selected.

After identifying the bars, both their individual morphological characteristics, as well as their number and migration schemes are evaluated. This is done by quantifying the number of bars in the system and their migration speeds, bar volumes, bar heights, depth over bar, landward and seaward slopes and distances from MLWL. In addition, the longshore variation of bars is evaluated by comparing the plan form evolution before and after nourishment.

6.4 Volume development

Changes in the different coastal zones and height levels, as well as those in the breaker bars, are consequence of sediment redistribution. Sediment redistribution can be divided into alongshore and cross-shore components. Both alongshore and cross-shore components can be examined by dividing the study site into different boxes, and by calculating and comparing the volume change in every box over time. The boxes are obtained by defining coastal perpendicular boundaries and coastal parallel boundaries.

The coastal perpendicular boundaries are defined with the limits of the alongshore zones which are illustrated in Figure 6.2. As explained in Section 6.1, these are based on the morphodynamic behaviour of the coast.

The coastal parallel boundaries are defined based on the coastal sub-sections and vertical heights named in Figure 6.2, in particular in the safety level, the MLW level, the division between inner and outer shoreface, and the seaward limit of the study area. They can be seen in Figure 6.1. These coastal parallel boundaries divide the study area in three parts.

Most onshore areas group together the dune and beach sections demarcated by the mid dune level and the MLW level. Over the safety level or mid dune level (+4.5 m height), no nourishment related impact is expected; therefore, the volume corresponding to the upper dune level is not taken into account within the dune and beach section.

The middle area is the inner shoreface coastal subsection, which is defined by the MLW level and the division inner-outer shoreface.

The division in between the inner and the outer shoreface is defined by to two criteria, depending on whether the nourishment zone is regarded or not. In the nourishment alongshore zone, the division is established in the landward boundary of the observed nourishment. In the rest of the zones (N2, N1, S1...) the division is established between the average position of the inner and outer bars. The inner bar usually moves within a much more dynamic area, while the outer bar usually decays in the outer shoreface subsection

6.5 Energy distribution and identification of storm events

The morphodynamic behaviour at the regarded transects expresses the response of alongshore and cross-shore transport activities which depend on the hydrodynamic impact. The hydrodynamics of the system can be determined by waves and storm surges as the main forcing events. Together with the available grain sizes and the nourishment loads, it is possible to describe a relation between the different interactivities. In the following, the derived hydrodynamic characteristics are explained.

6.5.1 Waves

The wave impact on the coast is regarded through energy flux. The energy flux is defined by the following equation:

$$E = \frac{1}{8} rho \cdot g \cdot H_{m0}^{2}$$

The energy flux can be divided into two components, namely, a coastal parallel component and a coastal perpendicular component.

The coastal parallel component, E_y, is defined as:
$E_y = E \cdot \sin \alpha$

In the same manner, the coastal perpendicular component, E_x, is defined as:
$E_x = E \cdot \cos \alpha$

The angle α is the angle formed between the incident wave and a line perpendicular to the coast.
Thus, from those components, the equation $E_x + E_y = E$, is true.
It must be noted that since the wave parameters are given as 3-hours averages, the energy components are also averaged every three hours.

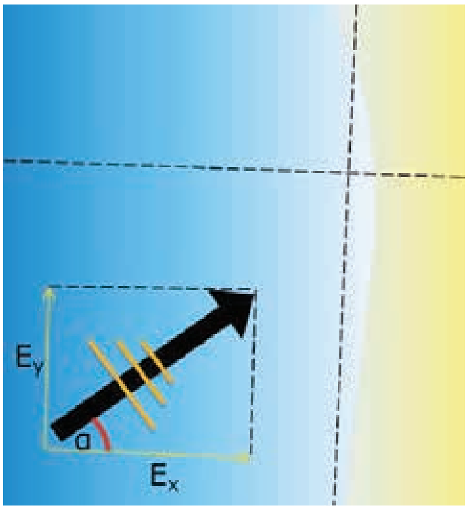


Figure 6.5 Energy decomposition of oblique waves in cross-shore and alongshore components

6.5.2 Storm Surges

During storm surges the coast may suffer erosion, especially if the shoreface lacks sediment and the wave energy reaches the dune foot. The eroded material is transported from the front of the dune to the shoreface. The impact of the storm surges are used to explain the observed coastal evolution.

It is observed that the most significant highly energetic events are those that happened in combination with water levels of at least 1 m height.

6.5.3 Identification of storms

Periods of intense activity can be identified by comparing the time series of the different hydrodynamic forces that impact the coast. Highly energetic periods are normally related to large coastal erosion. Given this fact, it is crucial to identify these periods to facilitate a coastal morphology analysis.

Energetic periods are identified by comparing wave energy flux (total, perpendicular component and parallel component, wave height and water level. By observation, prominent peaks are identified. These correspond to a water level of at least 1.0 m and a wave height of at least 5 m (equivalent to 32,000 kg/s²).

When comparing the energy impact from the waves, with the morphological evolution of the coast, only a group of events are selected. These are selected based on the Peak over Threshold (POT) method , (Leadbetter, M. R. (1991). The peak events are those that exceed a threshold of 32,000 kg/s² (obtained from a wave height of 5 m), and are independent from each other. The criterion of independency is fulfilled by imposing a condition that the peaks must be spaced at least 24 hours from each other. In other words, if two or more peaks (values over the threshold) are found at intervals less than 24 hours from each other, they are consider dependent peaks, and so the largest peak is taken to describe them all.

7 Results

Chapter 7 contains the results of the studies performed using the methodology described in Chapter 6.

7.1 Morphological analysis of the autonomous behaviour and nourishment response

In this section the overall morphodynamic evolution in the area is described based on the available profile data both from West Coast measurements and local measurements. Both are included in order to get the best possible temporal and spatial variation. Three analyses are performed: Section 7.1.1 describes the long-term autonomous evolution of the profiles based on profile envelopes; Section 7.1.2 treats the specific impact of the nourishment between 2011 and 2014; finally, Section 7.1.3 contains a description of the long term behaviour of the breaker bar system, as well as its response to nourishment. The results of this last section are obtained by using the methodology described in Section 6.3.

7.1.1 Long term autonomous evolution of the costal system of Skodbjerge

The long term evolution of the profiles shows coastal retreat from 1957 up until the nourishment scheme starts. During the same period the dune grows in height, while the dune front erodes. The dry profile (beach and dune) becomes more and more concave and the inner shoreface steepens as a result of erosion see Figure 7.1.

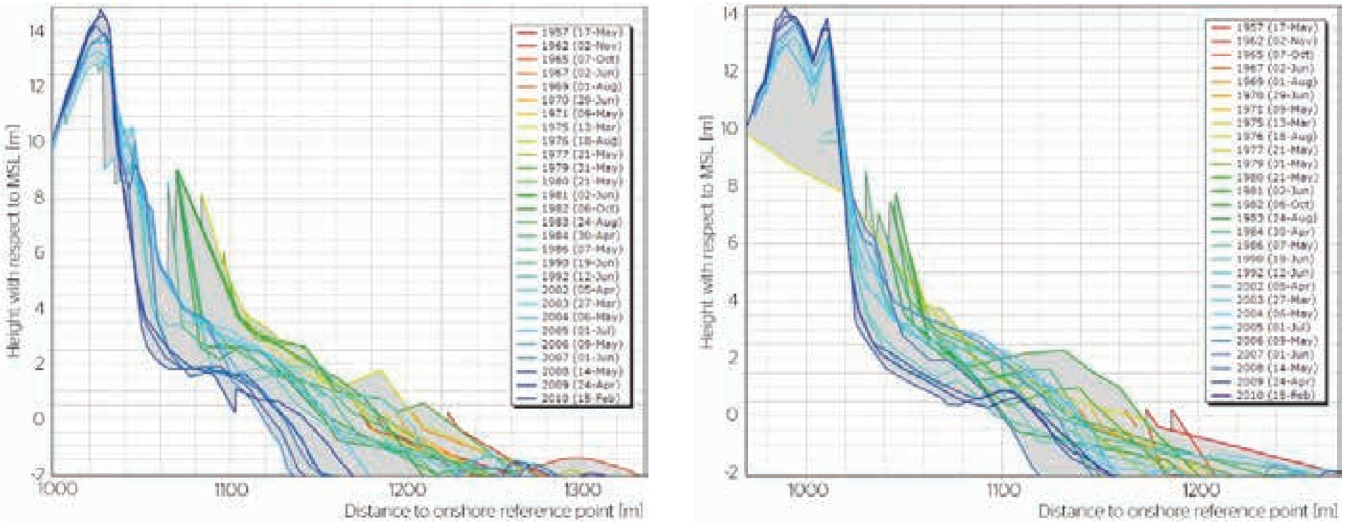


Figure 7.1 Surveys of two west coast profiles exemplifying the autonomous behaviour of the inner shoreface, beach and dune at Skodbjerge prior to nourishment. Left: Profile 5770 (north). Right: Profile 5780 (south).

At Skodbjerge, the bar system moves offshore and the outer bar decays, this morphodynamic behaviour is only visible over longer periods of time, see Figure 7.2. As the outer bar decays a new bar forms along the coastline, this new bar often moves rapidly offshore shortly after the outer bar has decayed. The offshore movement of the outer bar is synchronised alongshore, when considering the autonomous behaviour from 1957-1992, see Figure 7.5. The lifetime of a bar at Skodbjerge is ~12 years.

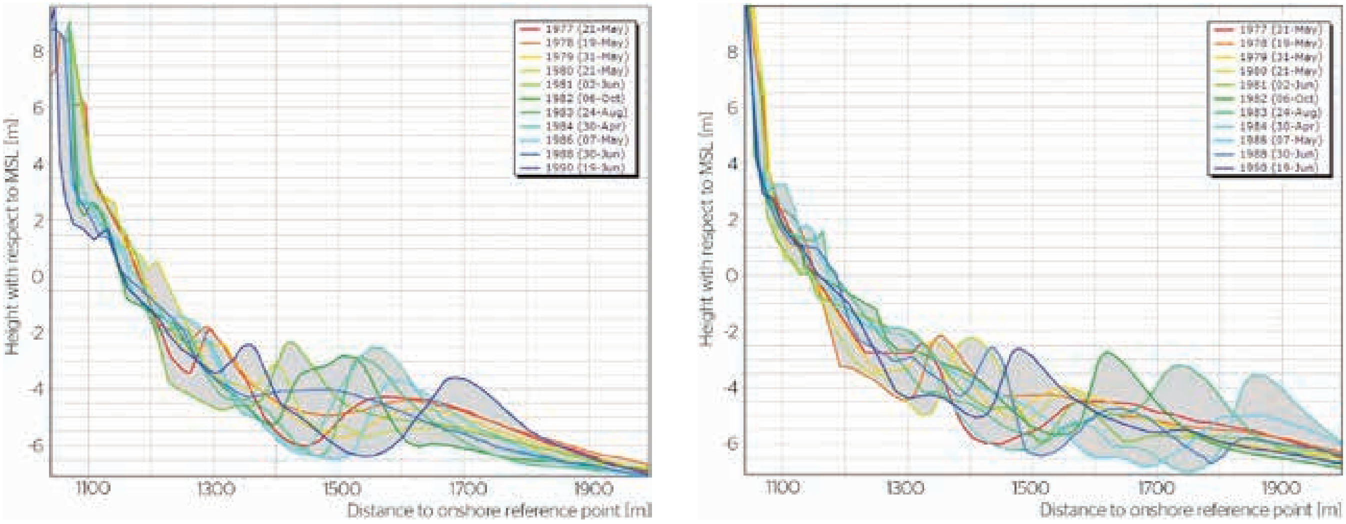


Figure 7.2 Surveys of two west coast profiles, exemplifying the autonomous bar system at Skodbjerge prior to nourishment. Left: Profile 5770 (north). Right: Profile 5800 (south)

7.1.2 Evolution of the 2011 shoreface nourishment from 2011-2014

The post-nourishment survey from the 8th November 2011 shows the nourishment as a slightly uneven outer bar located between 1350 m and 1550 m from baseline, see Figure 7.3. From 2011 to 2014, the bar onshore of the nourishment-induced bar oscillates in and out around its pre-nourishment position at 1200 m from the baseline. A large accretion of the beach and inner shoreface is observed directly after nourishment. The offshore displacement of the beach is ca. 60 m. The dune is stable. See Figure 7.3.

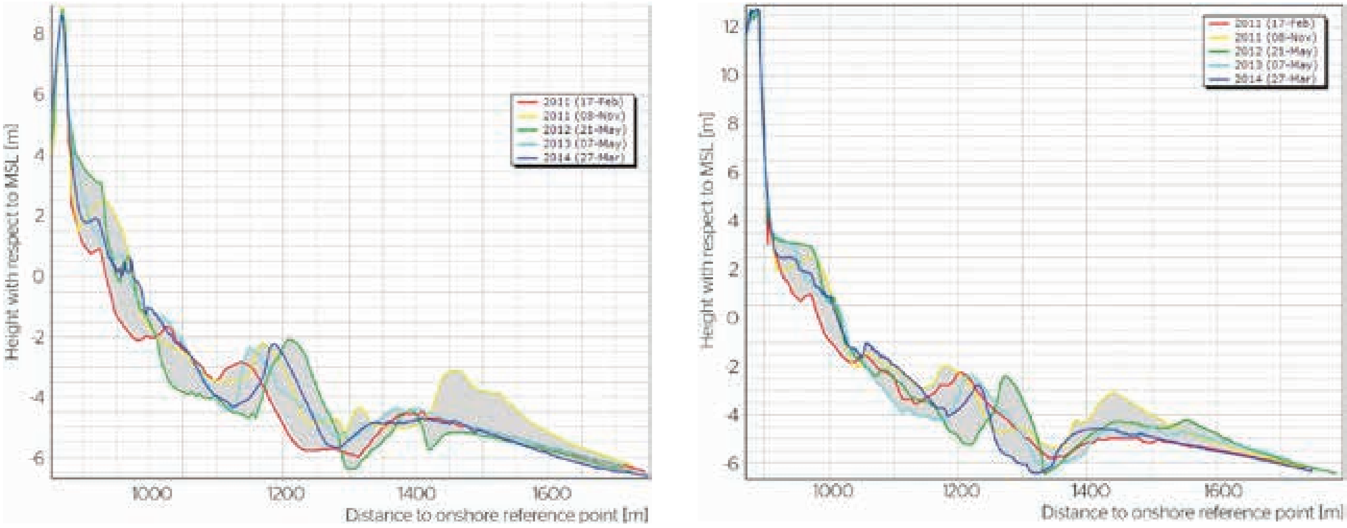


Figure 7.3 Surveys of two nourished local profiles covering the nourishment period, the 2011 nourishment was carried out between February and November 2011. Left: Nourishment profile 4014400 (north). Right: Nourishment profile 4014000, (south).

The coast section north of the nourishment area is represented by profile 4015000, see Figure 7.4 There is no evident nourishment induced bar in November 2011; a new breaker bar emerges onshore of the nourishment at 1070 m from baseline. From the pre-nourishment measurement to 2012, the inner shoreface and beach erode, and then they accrete slightly in 2013 and 2014.

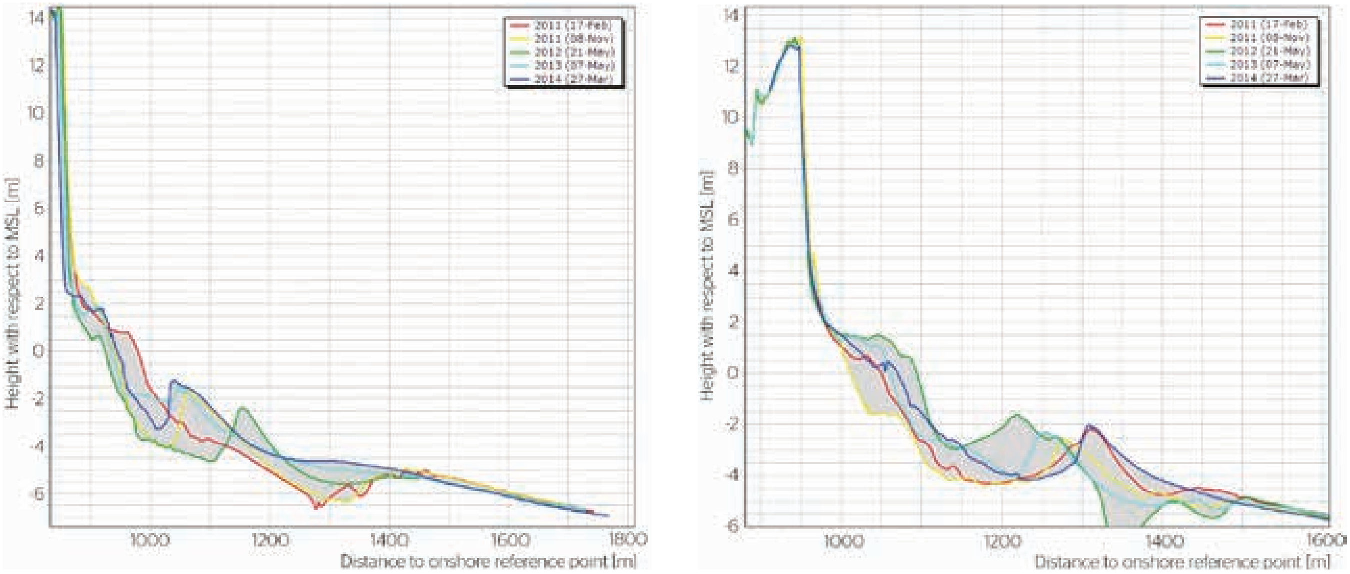


Figure 7.4 Surveys of two non-nourished local profiles covering the nourishment period, the 2011 nourishment was carried out between February and November 2011. Left: North of the nourishment (Profile: 4015000). Right: South of nourishment (Profile: 4013000)

To the south, represented by profile 4013000, there is no evident nourishment induced evolution in the form of a new outer bar in 2011. Right after nourishment, the inner shoreface erodes. One year later, in 2012, the shoreface has accreted beyond its pre-nourishment position with approx. 50 m. From 2012 to 2014 it retreats to its pre-nourishment position. The dune is stable.

In profile 4013000, large changes occur from 2011 to 2012 the bar moves 100 meters onshore from 1300 to 1200 meters from to baseline. It also increases drastically in volume and height and a deep trough is formed at 1350 meters from baseline. The sediment volume eroded from the trough is not enough to compensate for the accreted bar volume, and thus, this extra volume comes from longshore transport. The southernmost profiles included in section S4, see Figure 6.2, all seem to benefit from the longshore sediment transport.

7.1.3 Shoreface nourishment impact on breaker bar system

The 2011 nourishment can be identified in the time stack plot of West Coast profiles, see Figure 7.5, whereas the 2010 shoreface nourishment is not traceable using this method.

The 2011 nourishment is located in line 5770, and it seems that this nourishment creates an artificial bar. This nourishment-induced bar restrains the inner bar from moving offshore up to 3 years after nourishment. After 3 years, the nourishment induced bar is no longer traceable using the bar identification method. A similar restrain of the inner bar can be observed in the neighbouring transects: 5760 and 5780. But here the effect only lasts two years, after which the inner bar moves offshore. The nourishment stays in place; there is no sign of alongshore displacement of the nourishment shape. This indicates that the nourishment is dispersing both from the south and the north. This will be further examined using the local measurements which provide a better temporal and spatial resolution.

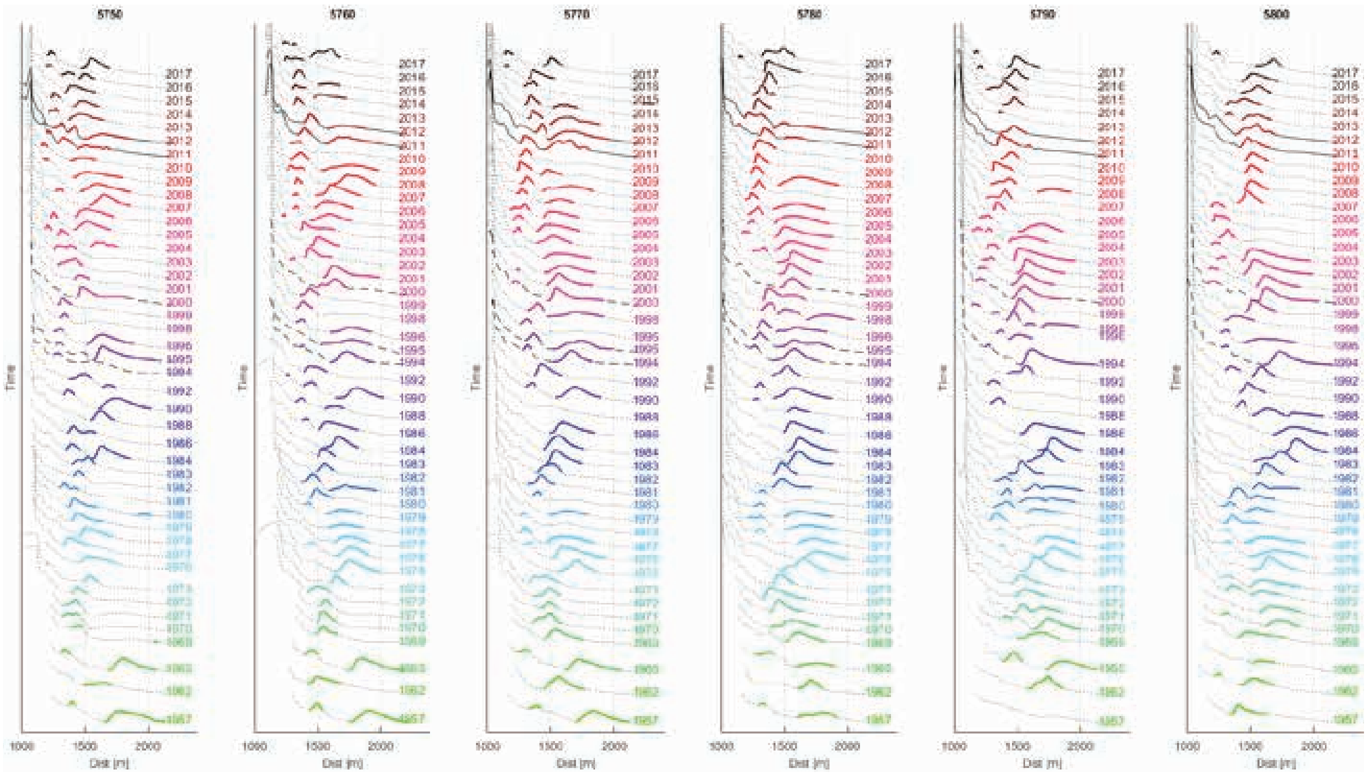


Figure 7.5 Time stack plot of the Skodbjerge west coast profiles which have a spacing of 1000 meters from 1957 to 2017. The profiles are organized left to right from the north to the south. The long-term bar migration is illustrated by colouring the bar shape. Furthermore, years with nourishment are shown: No nourishment since last nourishment (grey profile), Beach nourishment (dashed profile) and shoreface nourishments (black profile).

When the bar system is shown in plan-view, the natural variability in number of bars per profile, as well as bar continuity are evident, see Figure 7.6. Throughout the 14 year period there is a relatively continuous inner bar present, whereas the outer bar undergoes large changes.

From 2005 to 2008, the outer bar decays in the southern part of Skodbjerge. This represents undisturbed autonomous behaviour, as there is no nourishment in the area during this period. In 2008, an outer bar is present in more profiles than in 2007, but it is split into three bar-sections along the coast. From 2008 to 2010, when the shoreface is nourished, the outer bar decays. In 2009 there is no continuous outer bar present at Skodbjerge. Following the two nourishments of 2010 and 2011 the nourishment-induced outer bar erodes from the north and elongates towards the south. In 2014, 3 years after nourishment, the nourishment-induced bar is only present in two profiles. This nourishment evolution was not observed in the time stack plot above because of the 1000 meter spacing between the west coast profiles. During the decay of the outer bar, the inner bar moves slightly offshore.

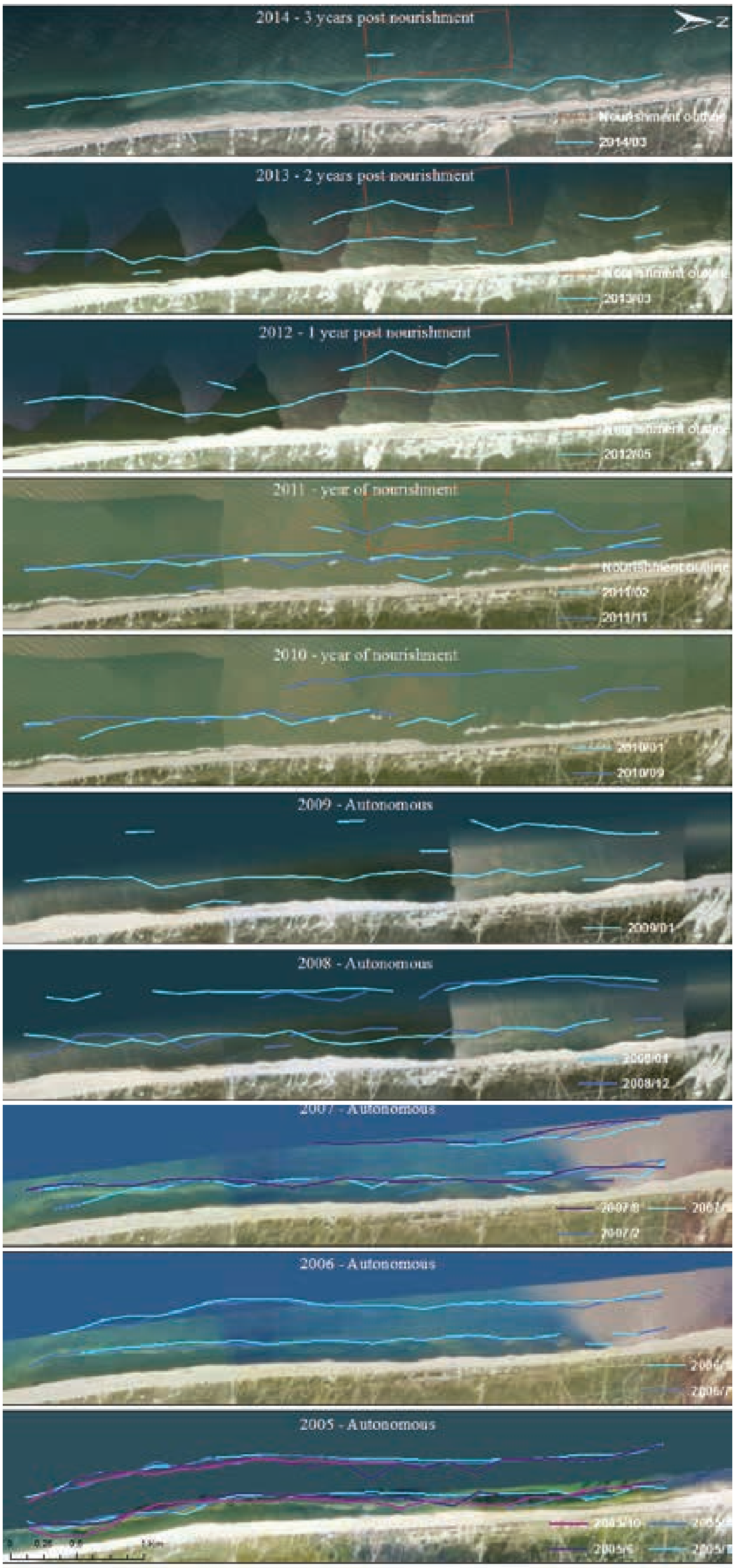


Figure 7.6 Plan view of the bar development. The figure shows the migratory patterns of the bar tops. The original 2011 nourishment location is marked with a red rectangle. The background is from the top aerial photos from: 2015, 2012, 1012, 2010, 2010, 2008, 2008, 2006, 2006 and 2004. The aerial photos are from © DDO 1954-2012, COWI and © DDO 2015-2017, Geodanmark, SDFE).

7.1.4 Conclusions on autonomous morphodynamic behaviour and nourishment response

The shoreface nourishment performed in 2010 cannot be observed from profiles based on the qualitative analysis; this is due to the design, as the amount of sediment per meter coast is so small that it cannot be traced.

The 2011 shoreface nourishment forms a nourishment-induced breaker bar. The sediment is slowly eroded from the initial nourishment position, but there are no signs of off- or onshore migration of the nourishment induced bar shape. The nourishment volume decreases as the sediment is diffused.

It is difficult to determine the up- and downstream effects of the nourishment, because of the large natural variability at the coast during the nourishment period. Within the first year after nourishment, the beach directly in front of the nourishment accretes whereas there is erosion of the inner shoreface and beach both south and north of the nourishment area. Two years after nourishment, to the south there is accretion, while to the north the erosion of beach and shoreface continues, though at a smaller rate than in the first year.

7.2 Quantitative Morphological development

In this section the overall morphodynamic evolution in the area is quantified in order to determine the scale of the natural undisturbed morphological changes and the nourishment induced changes.

Firstly, the evolution of the dry profile is presented based on an analysis of the cross-shore position of selected fixed height levels, referred to as physical marks, see Section 6.2. The physical marks analysis provides insight into if and how the nourishment affected the beach and dune, especially the local safety level at 4.5 meters height.

Secondly, the volume development of the whole coastal area, as well as the volume evolution within each of the morphologically determined sub-boxes are examined providing insight into the magnitude and pattern of the natural volume changes and the redistribution of the nourishment sand. This analysis is based on the methodology of Section 6.4.

7.2.1 Beach and dune response to shoreface nourishment

The phyisical marks considered are MHWL, MLWL, lower dune, mid dune level and finally the upper dune. The evolution of these marks per profile is presented in Appendix B.

In general, the analysis of physical marks shows that MHWL and MLWL fluctuate even on a time scale of a few months. This is expected since this is the most dynamic part of the dry profile, see Appendix B. The lower dune level and the safety level are only one meter apart in height, but still display differences in response time, see Appendix B. The lower dune level erodes and recovers at a faster pace than the safety level at 4.5 meters; the safety level is only affected by large storm events. Almost no changes are seen at upper dune level, it should be noted that the temporal resolution of the changes in the upper dune level is reduced when compared to the more low laying parts of the profile; this is due to the process of elongating the profiles with data from yearly LIDAR scans of the area, see Section 4.3.

When the attention is turned to the nourishment period (March 2010 to November 2011), it becomes evident that there is a natural coastal evolution coinciding with the 2011 nourishment. A coastline undulation is migrating alongshore towards the south of the coastal stretch; this is seen when comparing the position of MHWL, see Figure 7.7. Starting in N2 in March 2010, the beach is widened and this coastline movement progresses through N1 in September 2010, and reaches the nourishment section at the time of nourishment. In order to determine if the undulation is prompted by the 2010 nourishment, the position of MHWL has been calculated for profiles just north of the study area. From this analysis it is evident that the undulation starts migrating prior to 2010 and in N2 it coincides with the 2010 nourishment.

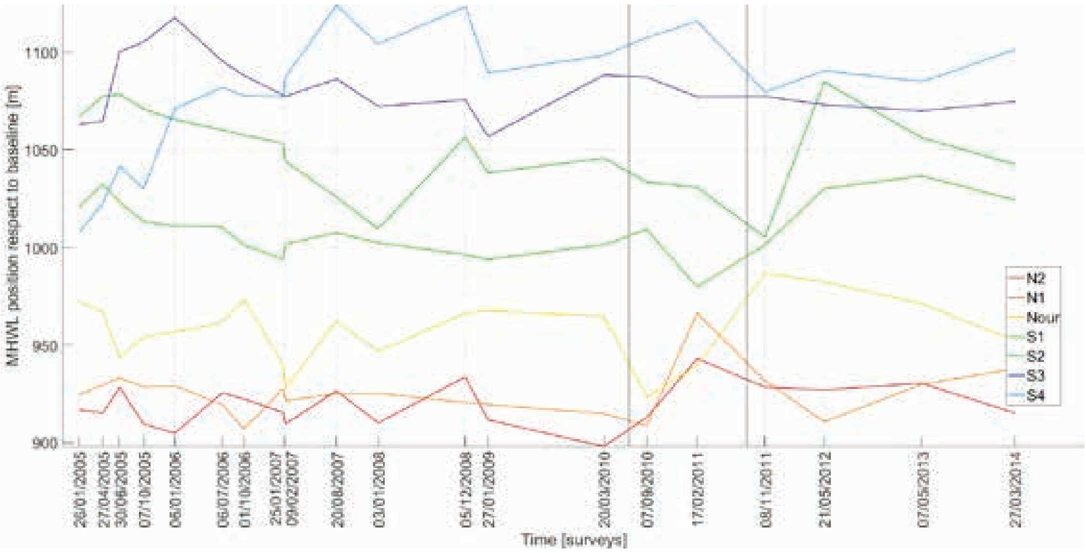


Figure 7.7 Position of the MHWL in relation to baseline. The grey vertical lines represent the date of the nourishment. The natural coastal undulation can be observed from March 2010 in N2. It migrates southwards until it reaches S2 in November 2011. It cannot be found in S3 and S4.

It seems that the nourishment enhances the natural coastal undulation by increasing its lifespan and magnitude, this effect is observed in the nourishment section and S1, where the undulation lasts for more than two years. In S2 the lifespan of the undulation becomes similar to the one observed in N2 and N1 prior to nourishment (less than two years), though the magnitude is much larger, probably due to southward directed sediment migration (see Figure 7.7.)

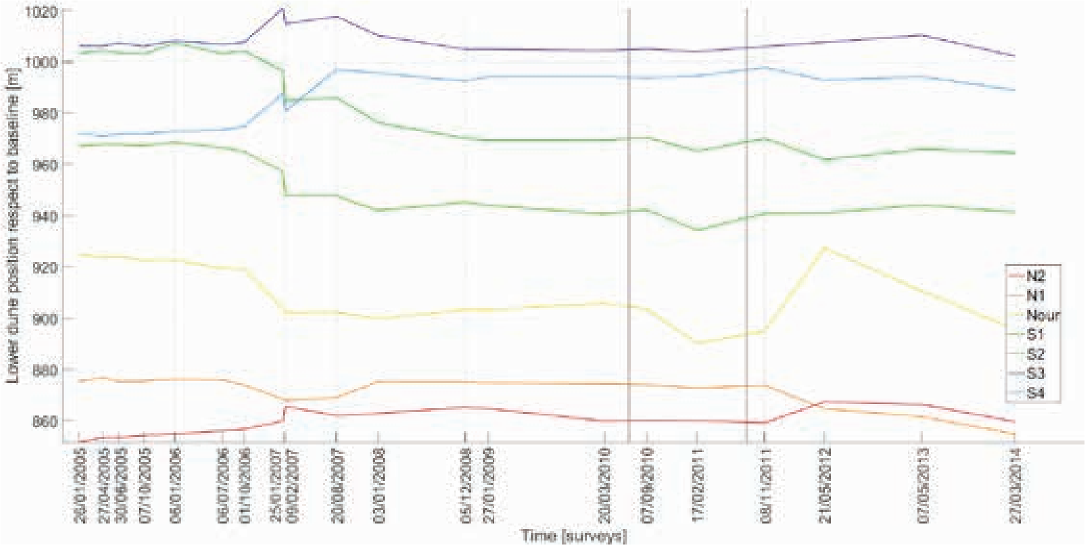


Figure 7.8 Position of the lower dune level in relation to baseline. The grey vertical lines represent the date of the nourishment. The lower dune level advances notably from November 2011 to March 2014.

Since the natural undulation and the 2011 nourishment occurred at the same time, the beach height increases right after the nourishment, reaching the lower dune level, and creating a wider lower dune for at least a year. This effect is only observed in the nourishment section, see Figure 7.8.

7.2.2 Volume evolution and nourishment influence

In order to demonstrate the effect of the nourishment and determine how the nourishment sand redistributes; volume redistribution cross- and longshore has been investigated. The same alongshore division of profiles as in the analysis of physical marks have been applied and the coastal system have further been divided into three cross shore sections: The landward boxes encompass the beach and dune from 4.5 meters to MLW, the middle boxes encompass the inner shoreface from MLWL until the bar trough onshore of the nourishment, the offshore boxes cover the outer shoreface; it is in these boxes that the nourishment volume can be found.

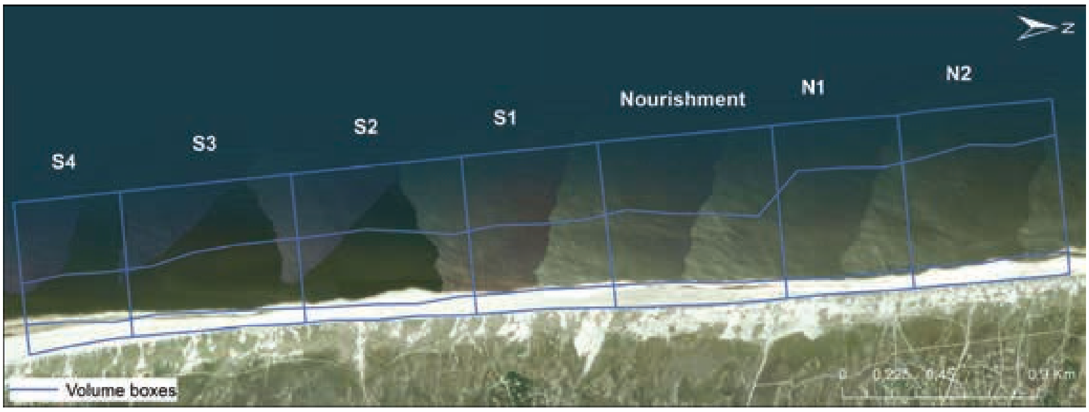


Figure 7.9 Definition of volume boxes Skodbjerge. Alongshore, the boxes are named according to their position relative to the 2011 nourishment. From the north: N2, N1, Nourishment, S1, S2, S3 and S4. In the cross shore direction the landward boxes encompass the beach and dune from 4.5 meters to MLW, the middle boxes encompass the inner shoreface from MWL until the trough onshore of the nourishment, the offshore most boxes cover the outer shoreface, it is in this box that the nourishment volume can be found.

In the following sections, the volume evolution at Skodbjerge from 2005 to 2014 is described. Furthermore, the evolution pre- and post-nourishment is compared in order to uncover the net effect of the 2011 nourishment. First, the evolution in total coastal volume is analysed in relation to the general trend and the influence of the nourishment hereon. Then, the volume redistribution is studied for the different longshore coastal sections displayed in Figure 7.9. Finally, we turn to the 21 boxes shown above and investigate the alongshore and cross-shore volume patterns of beach and dune, inner shoreface and outer shoreface.

7.2.2.1 Total coastal volume evolution

The evolution of total cumulative coastal volume has been calculated based on the local measurements from Skodbjerge comprising 9 years, see Figure 7.10. The plot includes the time of nourishment for the 2010 and the 2011 nourishment, as well as a projected volume development from which the total volume of the nourishments in 2010 and 2011 have been subtracted.

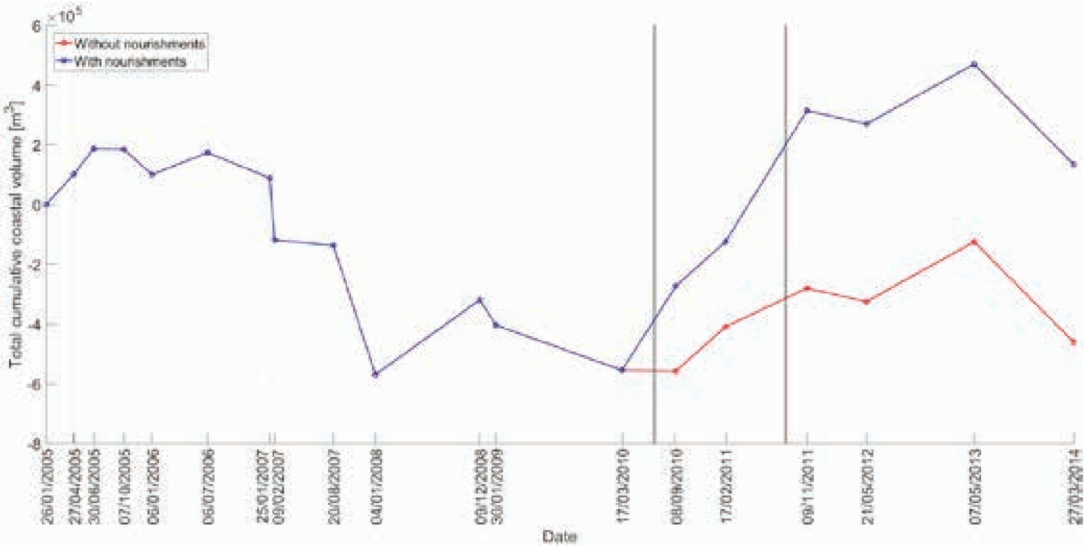


Figure 7.10 Cumulative coastal volume variations from 2005 to 2014 (blue line), the time of nourishment for the 2010 and the 2011 nourishment (vertical grey line). The volume evolution without nourishment has been approximated by subtracting the nourishment volume in 2010 and 2011, leading to a parallel displaced curve (red line).

The erosive nature of the Danish North Sea Coast is evident, especially from July 2006 to March 2010. In this period a total volume of 728,750 m³ of sediment is lost from the area. Also in this period, volume recovery is recorded in one instance, only: From January 2008 to December 2008. The continuous erosion surpasses the recovery.

From March 2010 to September 2010, there was a volume increase of 281,810 m³. This almost corresponds to the 2010 nourishment volume of approx. 285,000 m³. It should be noted that this volume increase is smaller than previously recorded natural variations such as the accretion of 406,920 m³ from January 2008 to December 2008. The post-nourishment evolution differentiates from the pre-nourishment volume evolution, as it increases further during the winter period of 2010-2011, though at a slower rate. From February 2011 to November 2011, the shoreface is nourished with 310,116 m³ sand and the accretion accelerates, exceeding the nourishment volume with 128,914 m³. This means that an additional volume entered the area, a mounting to a total volume increase of 439,030 m³, which is a volume of similar size as the accretion observed in 2008.

The adjusted nourishment volume development in Figure 7.10 shows that the change from erosion to accretion in 2010 is not only a product of the nourishment; the analyses suggest that there was short term natural period of accretion from March 2010 to May 2013, which coincides with the time of both nourishments. this evolution is evident as a change in trend. The projection of a non-nourished volume reaches a remarkably low cumulative volume in March 2014 equal to -460,600 m³. Whereas the real nourished volume in March 2014 is still higher than the initial volume in January 2005.

7.2.2.2 Alongshore redistribution of volume per sections

To better understand the longshore redistribution of sediment from the nourishment area, the coastal volume from seaward limit up to safety level for each section have been calculated, see Appendix E. In this chapter focus is on coastal sections S2, S1, Nourishment and N1 which display the largest nourishment impact, see Figure 7.11. Changes in volume between surveys for sections N1, Nourishment, S1 and S2 can be seen in Figure 7.11.

Firstly, the nourishment section increases with 375,540 m³ in the nourishment period. This shows that the observation of natural accretion in this period is reoccurring in the nourishment section, as the nourishment volume is only 310.116 m³. From November 2011 to May 2012, six months after nourishment, the volume loss is as high as 205,620 m³, which equals 55% of the volume increase detected within the nourishment section. These two volume changes are the largest registered in the study period from 2005 to 2014.

North of the nourishment, in section N1, there is a volume increase of 89,160 m³ pre nourishment from September 2010 to February 2011. During the next two measurement campaigns, N1 loses sediment: in the nourishment period it loses 86,050 m³, equalling the volume gain detected in the previous measurement campaign; the erosive trend continues between November 2011 and May 2012, when N1 losses 105,750 m³ of volume. Therefore, it seems that there is no significant volume redistribution towards the north of the coastal stretch.

Both southern sections S1 and S2 experienced a volume loss during most of the pre-nourishment period. Between February 2011 and November 2011, the nourishment period, section S1 increased its volume of sand with 64,660 m³, while S2 lost a volume of 24,590 m³. This immediate increase in S1 can be a product of nourishment redistribution or a natural variation, since the magnitude of the volume change is of the same order as the natural variations. However, between November 2011 and May 2012, both S1 and S2 increase at a magnitude that surpasses previous natural volume changes. S1 increases 142,060 m³, while S2 increases 184,450 m³. This equals a combined volume of 324,501 m³, which is almost 60% larger than the volume lost from the nourishment section in the same period equalling 205,620 m³.

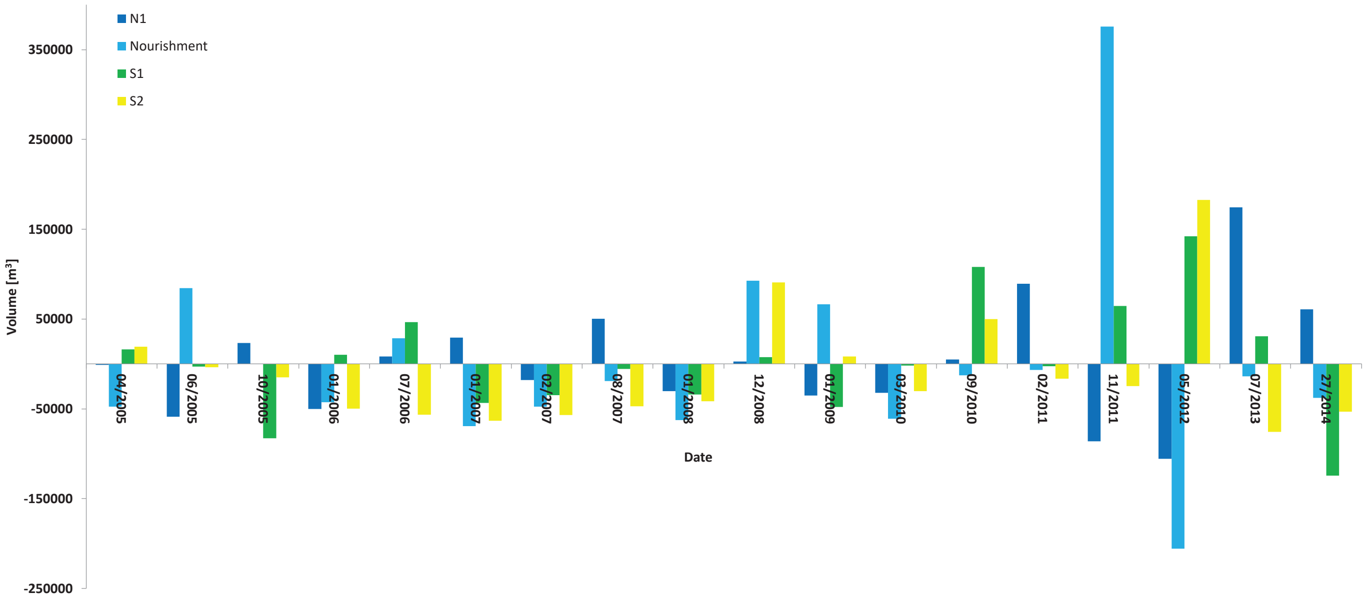


Figure 7.11 Volume change (m³) between surveys for section N1, Nourishment, S1 and S2.

Section N1 and the nourishment section lost a combined volume of 311,370 m³, which is similar to the combined volume gain in sections S1 and S2. This means that within 6 months there is a fast sediment redistribution from the nourishment a towards the south area. This volume transfer is a local phenomenon as the total coastal volume in this period decreases; see Appendix D and Appendix E.

Finally, it is observed that the development in these four sections changes from May 2012 to May 2013. S1 gains 30,860 m³ of sand, which is only 22% of the volume increase in the previous period. S2 loses a volume of 75,660 m³, which equals 40% of the volume gain of the previous period. The nourishment section continues eroding and loses a volume of 13,680 m³. Meanwhile, N1 experiences a sudden increase in volume 174,270 m³, which seems to be a consequence of natural variations in the coastal system. This means that the volume gained during the nourishment continues to redistribute towards the south of the stretch, but the translated volume is spread out or even transported out of the area, as there are no signs of the sediment in any of the southern profiles.

Between November 2011, first measurement post-nourishment, and March 2014, the last survey, the nourishment section has lost a volume of 257,000 m³, which corresponds to 82% of the nourished volume (310,116 m³) and 68% of the total volume increase in the nourishment period (375,540 m³). This means that there is still a positive volume balance in the nourishment section 3 years after nourishment.

7.2.2.3 Alongshore volume evolution of dune and beach

When observing the volume evolution of the dune and beach at Skodbjerge, two things are evident: first of all, that the accreting trend in box S4 from April 2005 to August 2007 surpasses any other natural accretion in the area. Secondly, the nourishment box sees the largest registered accretion between two measurements when nourished in 2011, see Figure 7.12

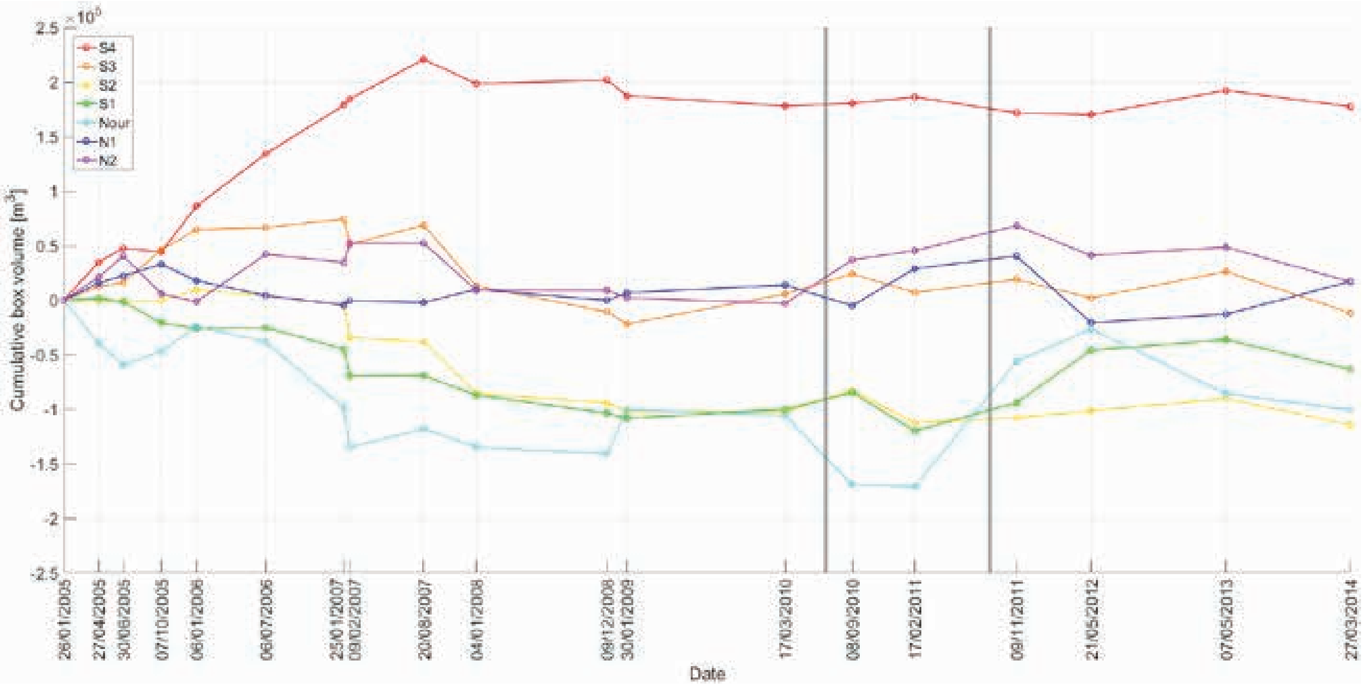


Figure 7.12. Cumulative volume evolution from 2005-2014 for beach and dune. See the exact box locations in Figure 7.9.

After the 2010 nourishment, which covers the whole coastal stretch, all boxes accrete except for N1 and the nourishment box. From March 2010 to September 2010, the nourishment box suffers the biggest sediment loss, which equals 63,520 m³.

From February 2011 to November 2011, during the nourishment period, all boxes accrete except box S4, which is the box furthest south from the nourishment area. As expected, the boxes that increase the most were the nourishment box and S1, with 114,670 m³ and 25,880 m³, respectively. From November 2011 to May 2012, S1 accretes 48,110 m³; the nourishment box and S2 accrete only 29,720 m³ and 6,450 m³, respectively. This can either be an onshore and southward directed translation of the nourishment volume, or a product of a natural variation. Indeed, the analysis of physical marks shows that the nourishment coincides with a natural coastline undulation which is also evident in the beach and dune volume of N2 and N1 pre-2011 nourishment and in the nourishment area, S1 and S2 during and after nourishment.

From May 2012 onwards, the nourishment box is subject to continuous volume loss, but at a smaller rate than in the period 2005 – 2007, when there was a natural, continuous volume loss. Both S1 and S2, which were strongly erosive in the pre-nourishment period, continue accreting until May 2013 and then start eroding. After nourishment, nor nourishment box, neither S1 nor S2, recover the full volume loss from before nourishment. To the north, box N2 sees erosion, while box N1 accretes fast. Finally, box S4 remains relatively stable.

Overall, it should be noted that boxes S4, S3, N1 and N2 have had a positive cumulative volume during most of the study period, proving to be the most resilient parts of the beach and dune system, while the nourishment box, S1 and S2 have eroded the most and have had a negative cumulative volume during the study period.

7.2.2.4 Alongshore volume evolution of the inner shoreface

When comparing the volume evolution of the inner shoreface to the above described evolution of beach and dune, it is evident that the same trends are not recurring.

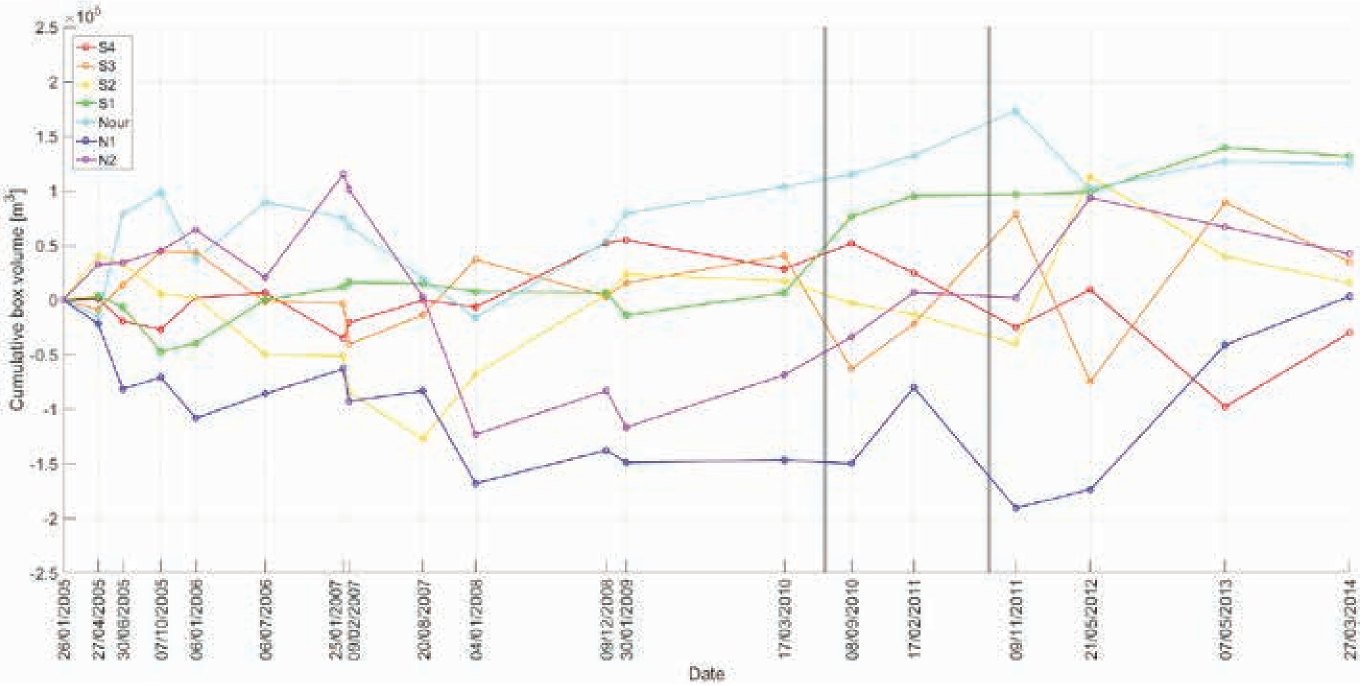


Figure 7.13 Cumulative volume development from 2005-2014 for inner shoreface. See the exact box locations in Figure 7.9.

The nourishment box and N2 reach an all-time volume minimum in January 2008 of -16,130 m³ and -123,170 m³, respectively. S1 starts to accrete continuously from October 2005 when it reached a minimum of -47,110 m³; while S2 accretes from a minimum of -127,020 m³ in August 2007. There does not seem to be a pattern associated with these accretion events.

N1 accretes consistently from November 2011 until March 2014, a volume of 193,890 m³. In the same period the whole area sees a natural volume increase, suggesting that there is a significant input of sediment entering the system form the north.

During nourishment form February 2011 to November 2011 the nourishment box increases with a volume of 40,800 m³ but this is followed by an immediate volume loss of -71,170 m³.

7.2.2.5 Alongshore volume evolution of the outer shoreface

The outer shoreface volume is highly influenced by the bar migration described in Section 7.1.3; the volume increases when a bar migrates offshore and then decreases as the bar decays.

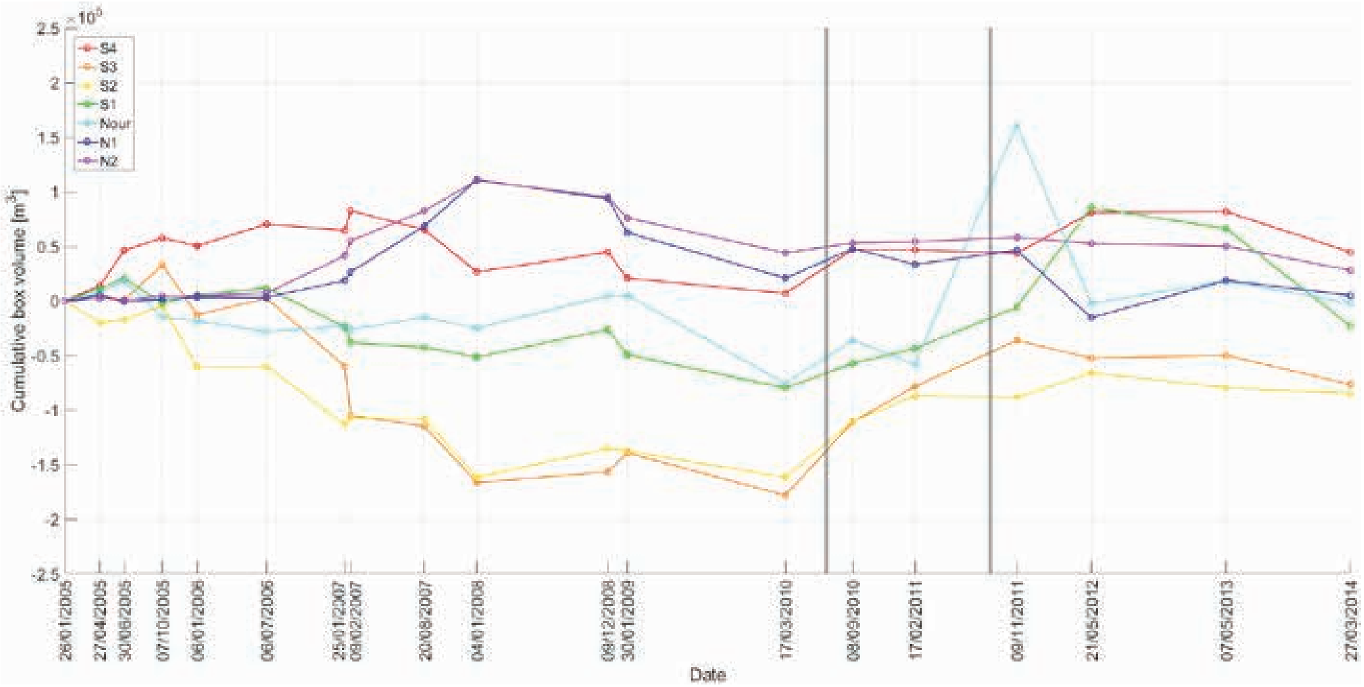


Figure 7.14 Cumulative volume evolution from 2005-2014 for outer shoreface. See the exact box locations in Figure 7.9.

The northern boxes N1 and N2 display the same trend pre-nourishment: they increase from July 2006 to January 2008 with 107,480 m³ and 105,670 m³, respectively; then they decrease until March 2010 right before the 2010 nourishment. This corresponds with the decay of the outer bar. This trend can be seen in a lesser degree in all of the other boxes, which increase from January 2008 until November 2008, and then decrease until March 2010, exemplifying how the bar migrates seawards and decays from the southern end of the bar. The largest natural volume increase between measurements is found in N1 from February 2007 to August 2007 and equals 42,430 m³.

All boxes increased in volume during the 2010 Nourishment. In boxes S1, S2 and S3, this increase is continuous until November 2011, after nourishment. As expected, the nourishment box drastically gains a volume of 220,070 m³ during nourishment between February 2011 and November 2011. This increase by far surpasses any natural variation. After 6 months, ¾ of the nourishment volume, equal to 164,170 m³, is no longer found within the nourishment box. During the same period, S1 and S2 increase with 91,440 m³ and 22,610 m³ respectively. This means that there is a volume translation down drift to box S1, confirming that the nourishment volume redistributes to the south. Both N1 and N2 decrease in the same period with 61,710 m³ and 5,540 m³, respectively.

After May 2012 all boxes display stability compared their behaviour pre-nourishment.

7.2.2.6 Conclusions volume evolution and alongshore distribution of the nourishment

From the total coastal volume evolution it is evident that the nourishment coincides with a natural accretion within the area, but this is enhanced by the nourishment which counteracts the structural erosion. The analysis of section volumes shows that after 3 years the nourished section still has a larger volume than pre- nourishment and that the volumes lost from the nourishment section and N1 move southward.

From the analysis of the 21 volume boxes it can be concluded that ¾ of the nourishment volume is redistributed from its original position within 6 months of nourishment. There is evidence of southward translation of the volume within the outer shoreface. After May 2013, the sediment seems to have dispersed and is no longer traceable as one volume, translating southwards through the boxes.

The beach and dune boxes seem to accrete in the nourishment section, as well as south of the nourishment section. Nevertheless, the volume increase is not only generated by the nourishment, as there are traces of a southwards migrating sand wave, which can also be part of the explanation of why there is a reversed volume trend when the no-nourishment volume evolution is projected.

7.3 Volume response to high energy events

In this section the volume response to the high energy events are investigated. First the high energy periods are identified. Then follows the development in total costal volume and the local differences in storm-response are investigated based on the volume development in each profile. Finally the nourishment response to the 2011-2012 winter is addressed.

7.3.1 High energy periods

Based on the methodology described in Section 6.5, 10 periods with high wave energy have been identified. Three of these periods have been identified in 2007 and two within 2013, which are the two roughest years.

Table 6 contains a summary of hydrodynamic characteristics for each of these high energyperiods. Max H_{m0} corresponds to the maximum significant wave height found in the measurements during the whole period. θ_m and T_p are the mean wave direction and peak periods associated with the maximum wave height. The maximum water level is the maximum found during the period, which does not necessarily occur at the same time as the maximum wave height.

The average energy per day is calculated by adding up the energy of all waves and dividing this number by the number of days in the period. The number of hours where H_{m0} is larger than 5 m is found by a clear count of the hours when this condition is true. Finally, the peaks obtained with POT are the number of peaks within the period that are obtained using the methodology described in Section 6.5.

Table 6 Sum up of the characteristics of the most relevant high energy events.

	Period	Max H_{m0} (m)	θ m (°)	T_p (s)	Max water level	Average energy per day (kg/(s² day))	Count of hours where H_{m0} > 5 m	Peaks obtained with POT
1	29th Oct – 15th Nov 2006	5.5	307	11.7	1.4	74,123	12	3
2	3rd - 25th Jan 2007	6.4	310	13.8	2.1	103,337	42	4
3	19th - 22nd Mar 2007	7.0	311	10.6	2.0	177,358	36	1
4	8th - 29th Nov 2007	6.9	311	13.9	1.4	81,128	36	3
5	3rd Feb -4th Mar 2008	5.2	270	11.3	2.0	56,661	15	3
6	22nd - 25th Dec 2008	5.5	312	13.5	1.2	145,313	12	2
7	5th to 7th Oct 2009	5.7	290	12.2	1.7	209,337	15	1
8	28th Nov 2011-16th Jan 2012	7.2	299	14.1	2.1	94,088	60	6
9	2nd – 3rd Feb 2013	7.4	268	15.6	2.0	279,214	9	1
10	7th - 9th Dec 2013	8.6	245	22.9	2.1	367,286	36	1

It must be noted that table 6 does not include storms outside the study period, which extends from the 26th January 2005 to the 27th of March 2014, since their impact on the morphology cannot be evaluated.

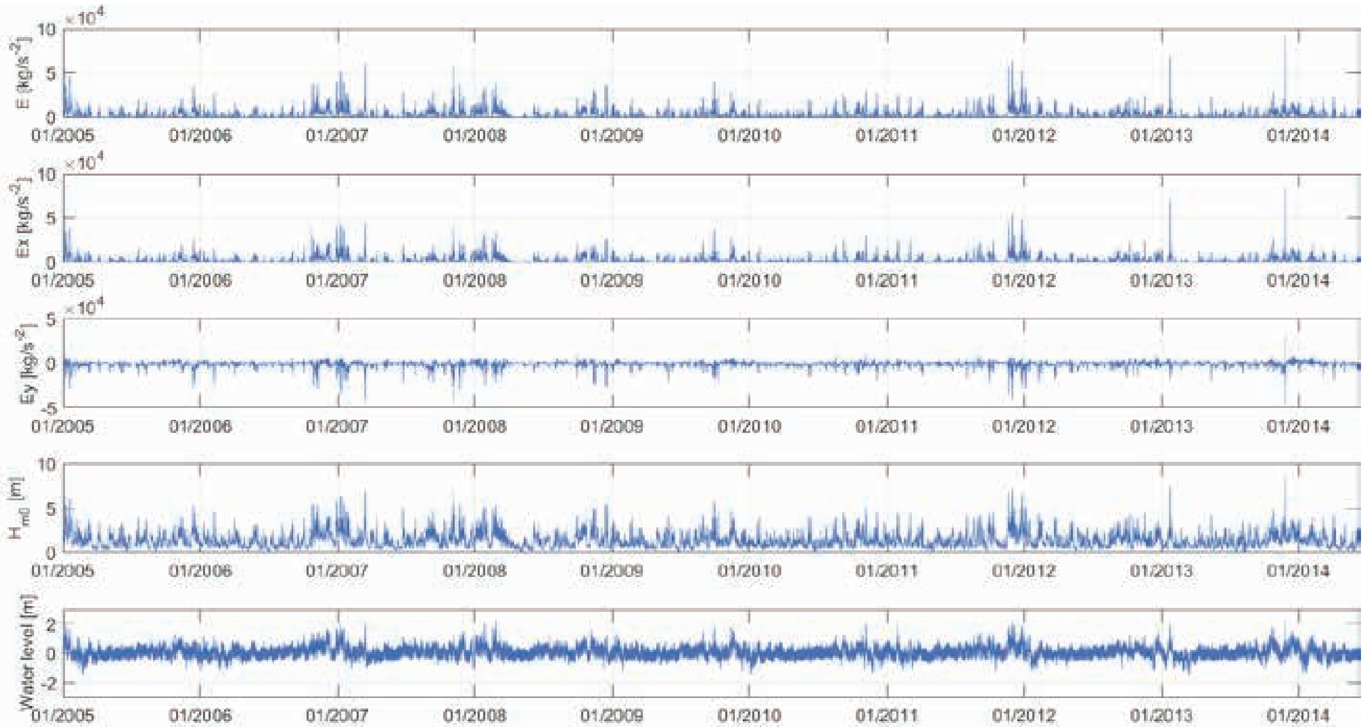


Figure 7.15 Time series of hydrodynamics affecting Skodbjerge. From top to bottom: Total flux, coast perpendicular flux, coast parallel flux, wave height and water level.

7.3.2 General volume response to storm events

In order to understand the volume response to storm events the cumulative volume development is presented together with marks of each of the high energy events identified above, see Figure 7.16.

The largest recorded loss of sediment from the area occurred in the in the winter 2007/2008 with a total volume loss of 432,430 m³ ; during this period three extreme storm events were recorded, combined amounting to 51 hours with significant wave height exceeding 5 m and a maximum water level of +2.0 m with respect to MSL.

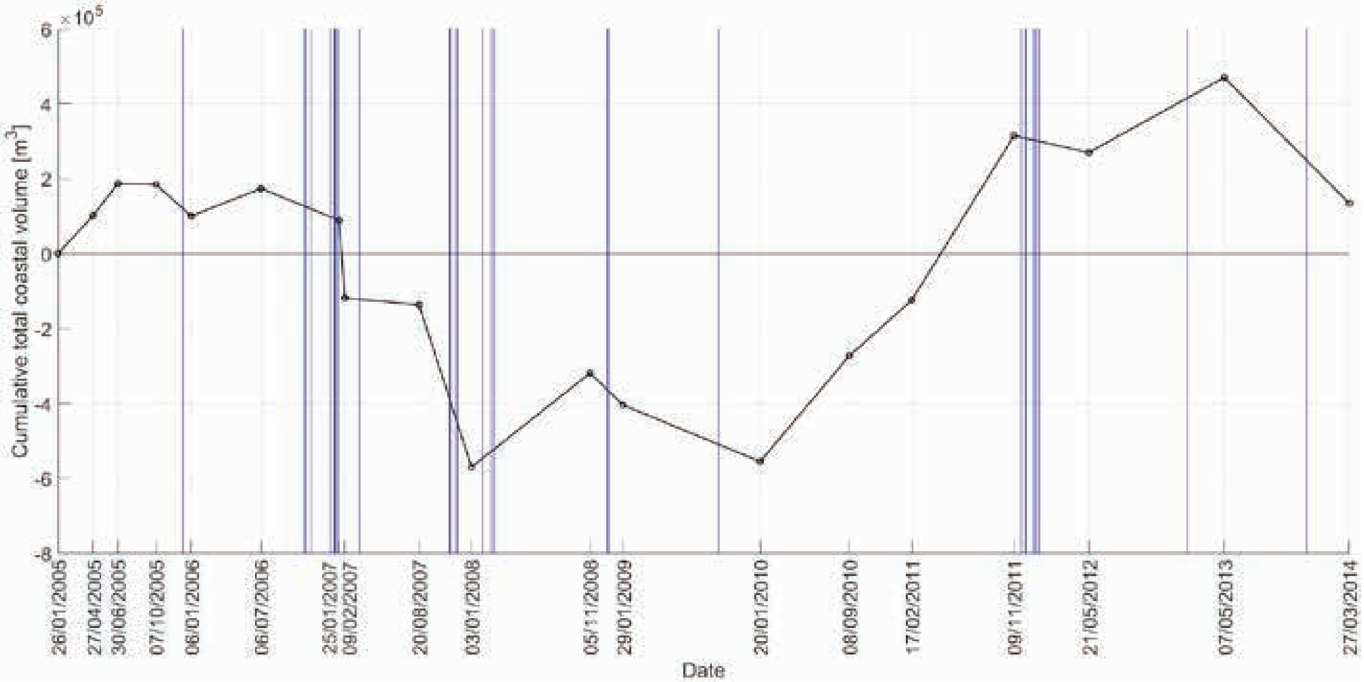


Figure 7.16 Total cumulative volume evolution from 2005-2014 (black line) and vertical blue line signifying high energy events determined by peak over threshold.

From May 2013 to March 2014 a total of 335,820 m³ sediment was lost, during this period only one extreme event was recorded, the storm Bodil. During this event the significant wave height was above 5 m for 36 hours and the maximum water level was +2.1 m compared to MSL.

When considering the impact of extreme events it should be noted that the stormiest period was within the winter of 2011/2012: from November 2011 to May 2012 there were 6 storm events resulting in 60 hours with significant wave heights above 5 m and a maximum water level of +2.1 m compared to MSL. During this period, within 6 months of nourishment, only 44,760 m² of sediment was lost out of the area.

The total energy for each period between measurements have been calculated, see Figure 7.17. This takes into account both calmer periods and periods with rough weather. The total energy distribution between measurements shows that the years post nourishment are relatively high energy. In general, there is correspondance with high energy periods and volume loss.

But it also becomes evident that the energy distribution between measurements, as well as the total energy must be of large importance. Two periods stand out. First, from the 25th of January to the 9th of February 2007, when a volume of 206,990 m³ of sediment was lost from the area. This is the 3rd largest volume loss recorded at Skodbjerge and the shortest time interval between measurements. This development is not explained by storm events, but must be the result of the 4 storm events recorded from the 3rd of January 2007 to the 25th of January 2007 and the relatively high energy weather between the 25th January and the 9th February, which is not classified as a high energy event by the selected criteria, see Section 6.5. Secondly, the second largest total energy between measurements was recorded from the 4th of January to the 9th of December 2008. During this period there was a volume increase of 250,520 m³.

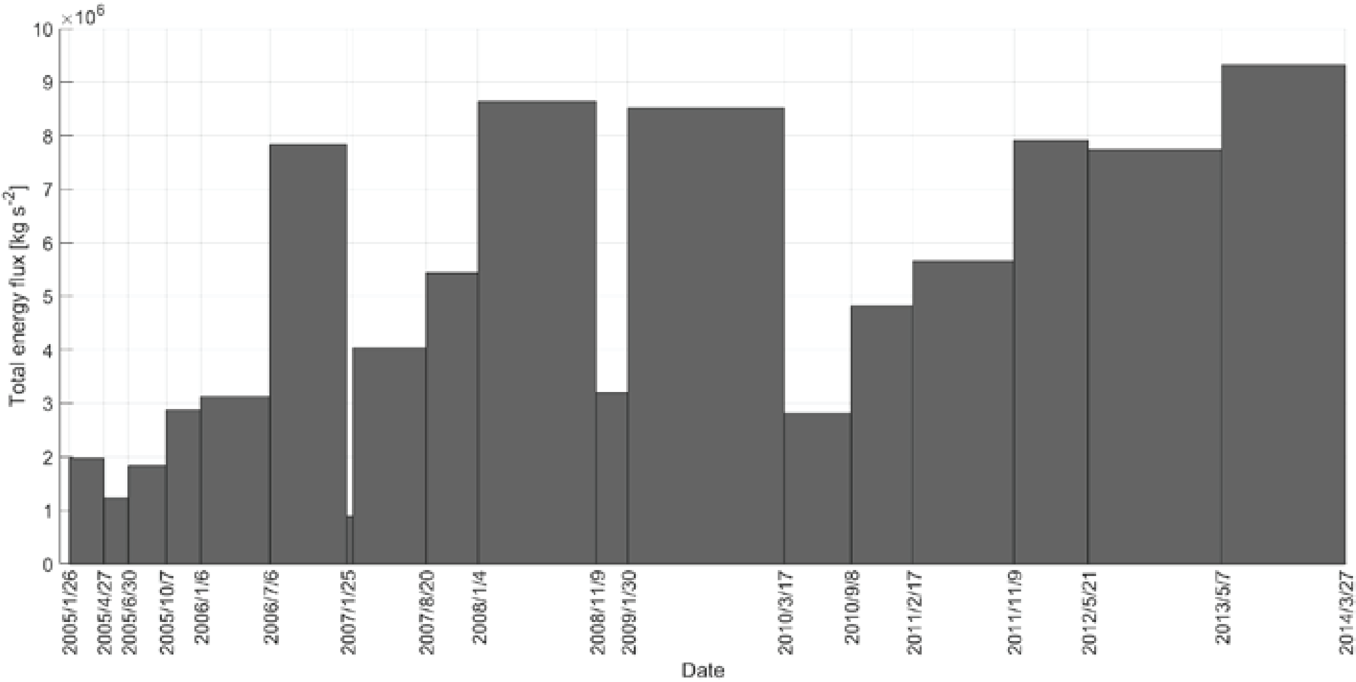


Figure 7.17 Energy distribution: total energy between measurements.

The total volume development highlights the rapid changes, which the system undergoes during high energy events. Even though the system recovers volume, it is obvious that the erosional processes surpasses the accretion (From July 2006 to March 2010). The high energy events do not give a conclusive explanation for the volume evolution. From comparing the erosional response to the total energy between measurements it becomes clear that even though there are cases in which high energy leads to high erosional response, there are also high energy events leading to accretion and low energy events leading to large scale erosion. This highlights the importance of the temporal resolution of the measurements, and opens the question of how well a series of in situ measurements of this resolution captures the actual variability and evolution of the coast.

7.3.3 Local differences in volume development and nourishment response

As described, the volume development shows the eroding nature of the Danish North Sea Coast. From Appendix I, it is evident that 15 profiles out of a total of 25 show a decrease in profile volume when comparing the last measurement of 2014 with the initial 2005 volume. In general, the northern profiles in N2 seem to be the most stable with respect to profile volume. It is obvious that the southern accretion zone displays a different volume evolution than the rest of the coast. They all increase when considering the 9 year period and only two surveys record a smaller volume than the initial 2005 volume. These profiles are less influenced by storms than the rest of the profiles.

The 2011/2012 storm event occurred within 6 month after completion of the nourishment; based on the overall volume development, this event must have influenced the nourishment sediment, redistributing it. This is confirmed by the evolution within each of the nourishment profiles, see Figure 7.18. From November 2011 to May 2012, the nourishment section experiences a sediment loss of 205,620 m³ signifying that the amount of sediment being mobilized from the nourishment profiles surpasses the 44,760 m³ lost from the study area during the same time period. This means that the sediment from the nourishment has been redistributed within the measured area and this might have led to less overall erosion.

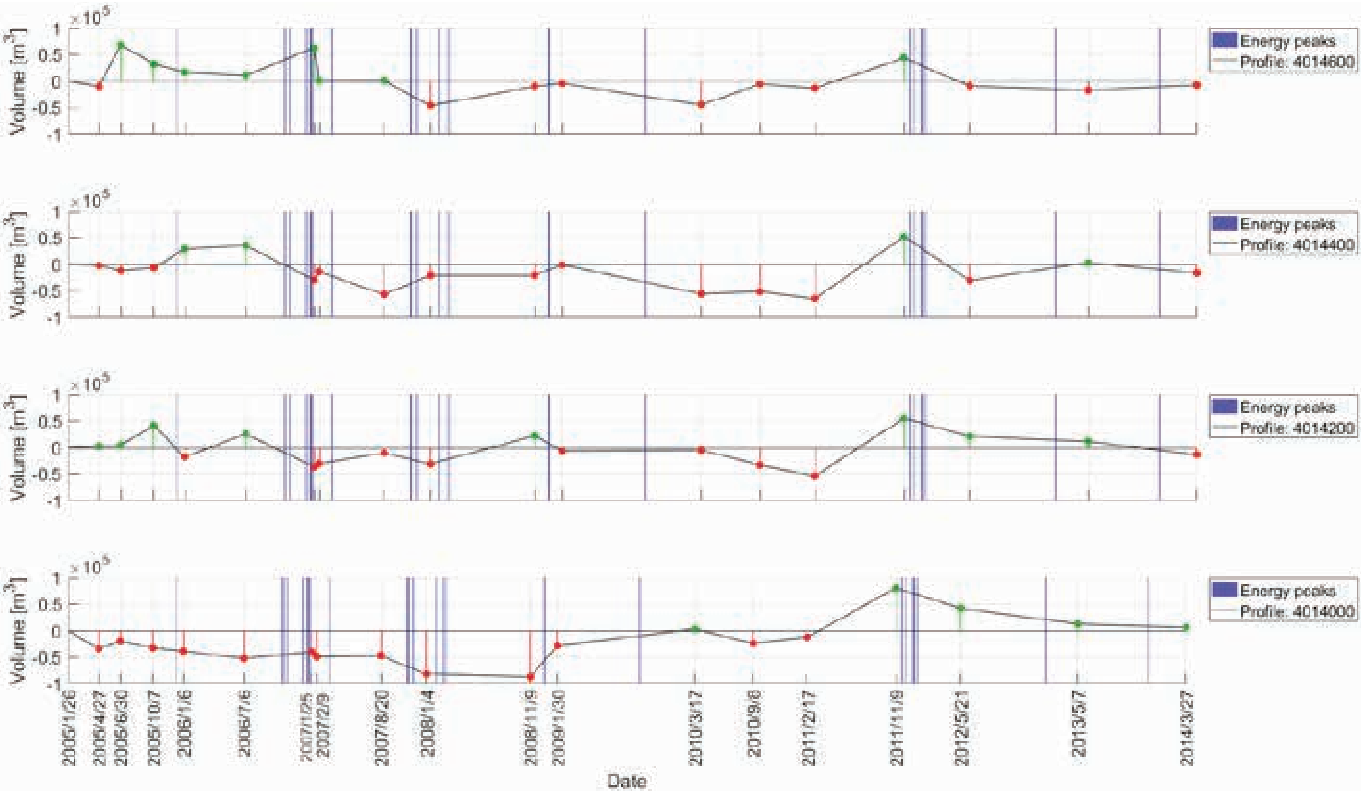


Figure 7.18 Cumulative volume in each of the nourishment profiles from 2005-2014 (Black line) and vertical blue line signifying high energy events determined by peak over threshold. Top profile: northernmost nourishment profile. Bottom profile: southernmost nourishment profile.

It is difficult to deduce the net effect of the post-nourishment storm event. Based on the temporal resolution of measurements, it cannot be decided whether the volume loss within the nourishment profiles took place during the storm event or if it was redistributed gradually during the post-nourishment period. It can be concluded that the storm event post-nourishment led to a smaller volume loss than was expected from previous time periods including storm events of a similar magnitude.

8 Discussion

The performance of the 2011 nourishment at Skodbjerge is now evaluated as to the design objectives:
1) Maintain the safety level and improve storm resilience and
2) Influence the bar system and elongate the existing bar, thereby displacing the local hotspot for erosion.

8.1 Did the nourishment improve the safety level and storm resilience?

The overall objective of shoreface nourishment at Skodbjerge is to maintain the safety level set for the area in order to minimize the risk of coastal retreat and inundation of the low-lying hinterland.

In principle, a direct impact of the shoreface nourishment on the safety level (mid dune level) is not found, as there is no dune development post-nourishment. Considering the beach and lower dune, it becomes difficult to separate the natural coastal variations from nourishment impacts, in particular the coastline undulation described in Section 7.2.1 and in Section 7.2.2. It can be argued that the nourishment enhances the natural variation of the coast by prolonging the period of beach widening and increasing the local beach volume. Hence, this results in a wider beach for longer time, and in the formation of a fore dune in the nourishment area, which are both characteristics of more resilient profiles.

When looking at the wet profile, the presence of the shoreface nourishment is more pronounced, as the nourishment creates an outer bar which is visible for 3 years after nourishment. Furthermore, the nourishment retains the inner bar, creating a two barred profile. The effect of this new post-nourishment profile as flood/erosion defence cannot be quantified but the presence of multiple bars should improve coastal resilience, since it dissipates wave energy leading to less erosion of beach and dune.

Regarding the system as a whole, the structural erosion of the coastal system is halted by the introduction of nourishments. The volume rich systems seems to be more resilient to storms, as it has been seen that the storm of the winter 2011-2012 resulted in less volume loss than what was observed in comparable situations in the pre-nourishment period.

8.2 Did the nourishment influence the bar system?

The nourishment design aimed at significantly influencing the bar morphology by adding a sediment volume equivalent to the present bar volume (400 m^3/m). The bar system is clearly influenced as the nourishment induces a new outer bar, and retains the inner bar from moving offshore.

The 2011 shoreface nourishment was supposed to be placed southward of the end of the offshore bar, with the objective of extending the bar alongshore and thereby prompting sediment redistribution downstream and displacing the point of local dune erosion.

When the nourishment was carried out, the outer bar that was supposed to be elongated had decayed; therefore the design objective of elongating the existing bar was not met. However, the nourishment induced bar itself elongated to the south, while it eroded from the north, thereby partly proving that nourishments could influence the location of erosional hotspots. It must be noted, that the nourishment length was shorter than that of a natural bar, and it did not combine with an existing bar making the nourishment induced bar more susceptible to erosion from the north than if an existing bar had been elongated.

9 Conclusions

One of the benefits of nourishments as a means of coastal protection is the fact that they blend into the natural environment. In turn, this means that the effects are difficult to untangle from the natural variation of the coastal system. This analysis has attempted to identify the effects of shoreface nourishment by taking the autonomous behaviour of the system into account. This has proven important since in depth knowledge of the system is required in order to put the nourishment effects into perspective and thereby reveal which effects are of such a magnitude that they cannot be ascribed to the natural variations and vice versa. In this study, the evolution of the 2011 nourishment has been investigated in depth. In order to do this, the nourishment in 2010 has been taken into account to determine if the observed evolution was influenced by this prior nourishment. Furthermore, the 2010 nourishment functions as a basis for comparison and evaluation of the 2011 nourishment design.

Nourishment lifespan

The main findings regarding the nourishment lifespan are summarized below:

- The 2011 nourishment led to a volume increase of 220,070 m³ within the nourishment box during the nourishment period from February to November 2011.
- By May 2012, 164,170 m³ of sediment had redistributed from the nourishment box. This equals a volume loss of ¾ of the volume detected.
- The 2011 nourishment generated an outer bar which generally decays; this nourishment-induced bar shape lasted 3 years.
- The lifespan of the 2010 nourishment could not be determined as it did not create a nourishment induced bar of which the evolution could be traced through time.
- The 2010 nourishment coincided with a volume increase within the whole system, but the causality between these events could not be determined.

Nourishment redistribution

The nourishment redistributed from the original location and was traced through the system using the volume boxes. From this analysis the following has been concluded:

- The 2011 nourishment redistributed to the south. This is the case for both the bar shape, which elongated to the south, and the volume which could be traced through the southern section.
- The redistribution of the bar shape was very local within the scale of 400 meters downstream.
- The translated volume distribution affected a larger area approx. 1400 m downstream.
- The onshore redistribution of the sediment proved difficult to determine because the nourishment coincided with a natural coastline undulation.
- Offshore distribution could not be rejected due to profile length.
- The 2010 nourishment was only evident when considering the volume of the entire costal stretch and its redistribution patterns could not be determined.

Nourishment influence on the local safety level and general coastal resilience

The effect of the nourishment has been investigated by following the safety level at 4.5 meters height trough time. Furthermore, the derived improvements of coastal resilience have been discussed. Based on this the following have been concluded:

- Neither of the two shoreface nourishments directly influenced the safety level at 4.5 meters height.
- The 2011 nourishment lead to the formation of an artificial bar which must have locally dissipated energy, thereby sheltering the coastline and improving coastal resilience.
- The presence of the nourishment induced bar seems to have locally enhanced and prolonged the beach widening associated with the natural coastline undulation. Thereby leading to a more resilient coastline.

Nourishment influence on the bar system

The 2011 nourishment was designed to influence the bar system by adding a sediment volume similar to the volume within the existing bar and specifically elongating the existing bar towards the south. The influence on the bar system have been analysed over time and the following can be concluded:

- The 2011 nourishment did not elongate the existing bar, because the natural bar had decayed prior to the nourishment.
- The 2011 nourishment did influence the bar system as it created an artificial outer bar.
- The nourishment induced bar retained the inner bar from naturally migrating offshore during its 3 year's lifetime.
- The nourishment induced bar eroded from the north and elongated to the south.

System response to storm events

It has proven difficult to find a correlation between the hydrodynamic forces and the costal response. The effect has been investigated in relation to high energy events and total energy between surveys. From this the main findings are:

- There is no direct correlation between total energy and volume loss from the coastal system, but in general high energy periods lead to a volume loss.
- The effect of high energy events is difficult to determine because of the temporal resolution of the measurements.
- From the stormy period of January 2007 for which we have post storm measurements the volume response is minor. But during the following three weeks a large volume of sand is lost from the area. This is not explained by the energy input alone.
- The post-nourishment period is generally high energy but the coastal volume increases, even when disregarding the nourishment volume.
- The 2011/2012 winter storms led to less erosion than expected. This might be an effect of the nourishment.

Nourishment behaviour

As described, the nourishments along the Danish North Sea coast have displayed a variety of different behaviours depending on their design, see section 1.1.2. The 2010 and the 2011 nourishments can be categorized as follows:

- The 2011 nourishment induced bar acts as a shoreline parallel breakwater, leading to prolonged and enhanced widening of the beach.
- The 2011 nourishment sediment redistributes downstream effectively feeding the downstream costal sections.
- From the 2010 nourishment, only the input of sediment can be observed. There are no derived effects like the ones found from the 2011 nourishment.

Influence of the temporal and spatial resolution of the survey program

Throughout the analysis it has become evident that, potentially, the temporal resolution of the surveys may have considerable influence on the result of the analysis. There can be large fluctuations in the system volume within weeks. From this study the following should be noted with regards to the available surveys:

- Volume changes calculated based on one measurement per year can potentially lead to an over interpretation of the system development, based on the in-situ state of the system rather than an expression of the overall evolution.
- The available measurements did not fully cover the active part of the costal profile making it difficult to determine if some of the nourishment sediment is redistributed offshore.

What can be learned from the nourishments at Skodbjerge?

Untangling the nourishment effects form the natural variations have proven difficult, especially on two counts. First of all, it is necessary to understand the natural variation of the system. And secondly, understanding the complex effects of shoreface nourishments requires survey data at a high temporal resolution to fully understand the redistribution of sediment.

The effect that the 2010 nourishment had on Skodbjerge is completely different from that of the 2011 nourishment, this is seen as a function of the nourishment design, specifically the volume distribution along the coastline (m^3/m). This highlights that the initial nourishment design can enhance the effect of the nourishment from solely being an addition of sediment to a sediment starved system, to also having derived effects when the dynamics of the natural system is taken into account. In order to get the full benefits of shoreface nourishments, the nourishment design should be scale based taking into account the size of the natural system. This can help ensure that the system will respond and adapt to the nourishment rather than having the natural dynamics overrule the nourishment.

10 Bibliography

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Appendix A:

Surveys at Skodbjerge

Table providing an overview of surveys of local transects performed at Skodbjerge from 2005 to 2014.

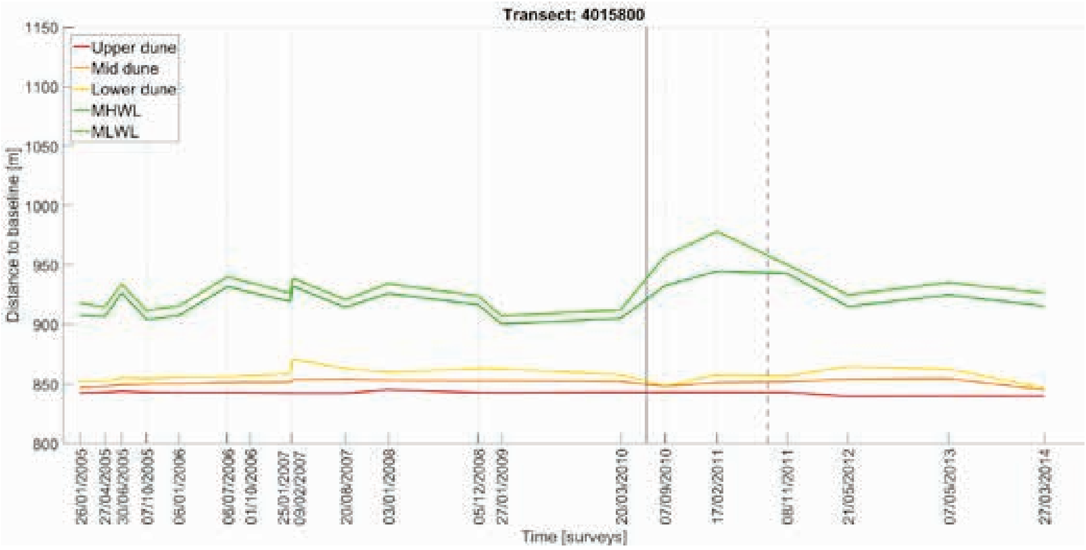
Table - Finalization dates and available measurements of surveys executed at Skodbjerge

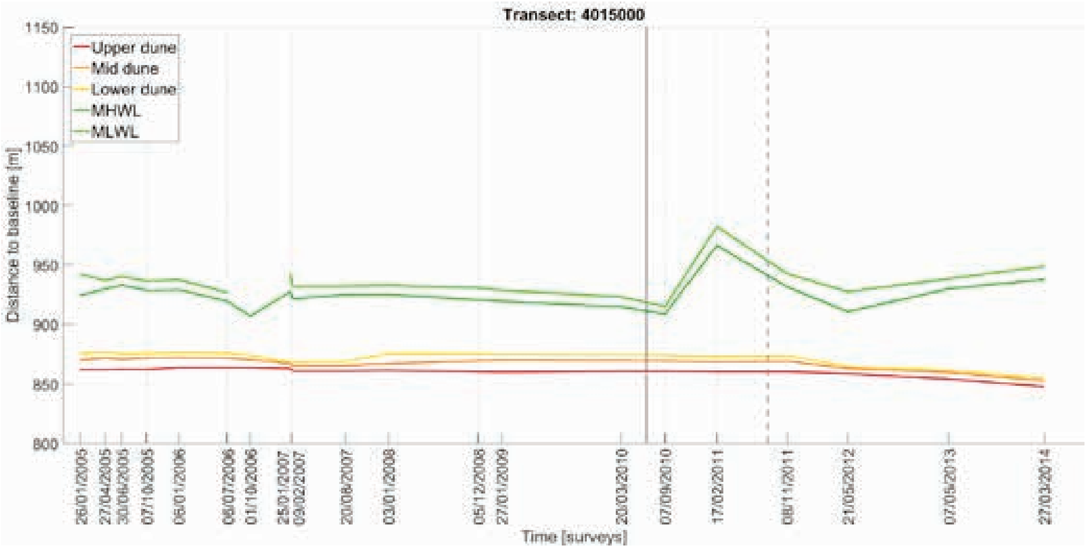
Survey name	Finalization date	Missing wet profile	Insufficiently measured dry profile
2005.01	26.01.05		
2005.02	27.04.05		x
2005.03	30.06.05		
2005.04	07.10.05		
2006.01	06.01.06		x
2006.02	01.04.06	x	x
2006.03	06.07.06		x
2006,04	01.10.06	x	x
2006,05	21.11.06	x	x
2006,06	19.12.06	x	x
2007.01	25.01.07		x
2007,02	22.01.07	x	x
2007.03	09.02.07		x
2007,04	30.03.07	x	x
2007.05	20.08.07		x
2007,06	28.09.07	x	x
2008.01	04.01.08		
2008.02	09.12.08		
2009.01	30.01.09		x
2010.01	17.03.10		
2010.02	08.09.10		
2011.01	17.02.11		x
2011.02	09.11.11		x
2012.01	21.05.12		x
2013.01	07.05.13		
2014.01	27.03.14		

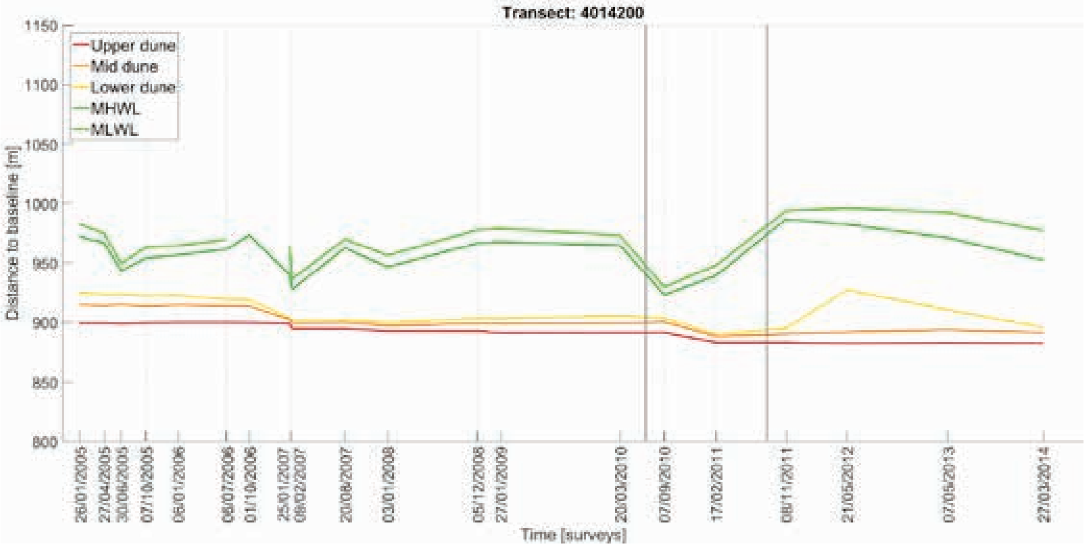
Appendix B:

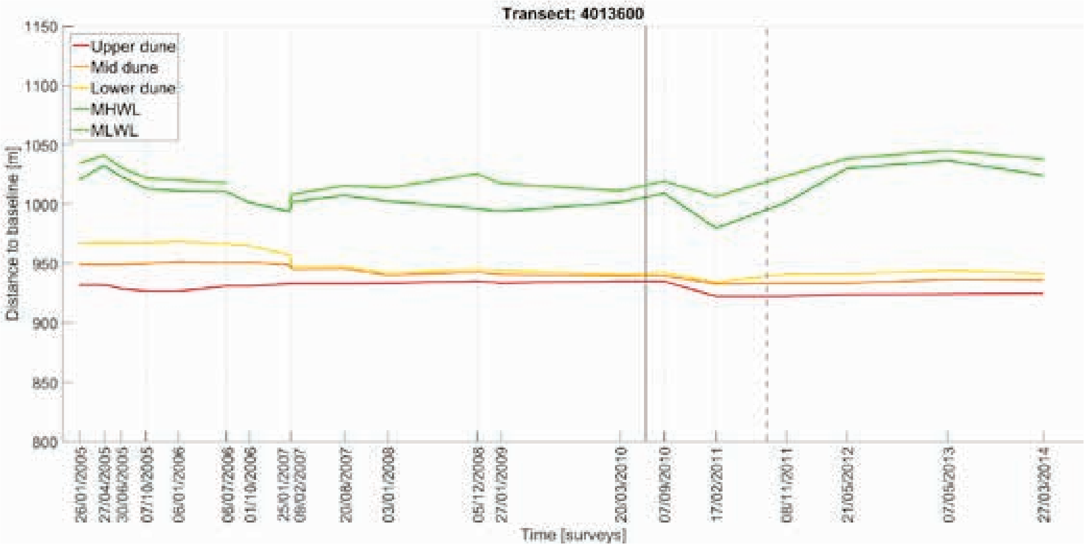
Physical marks for representative profiles

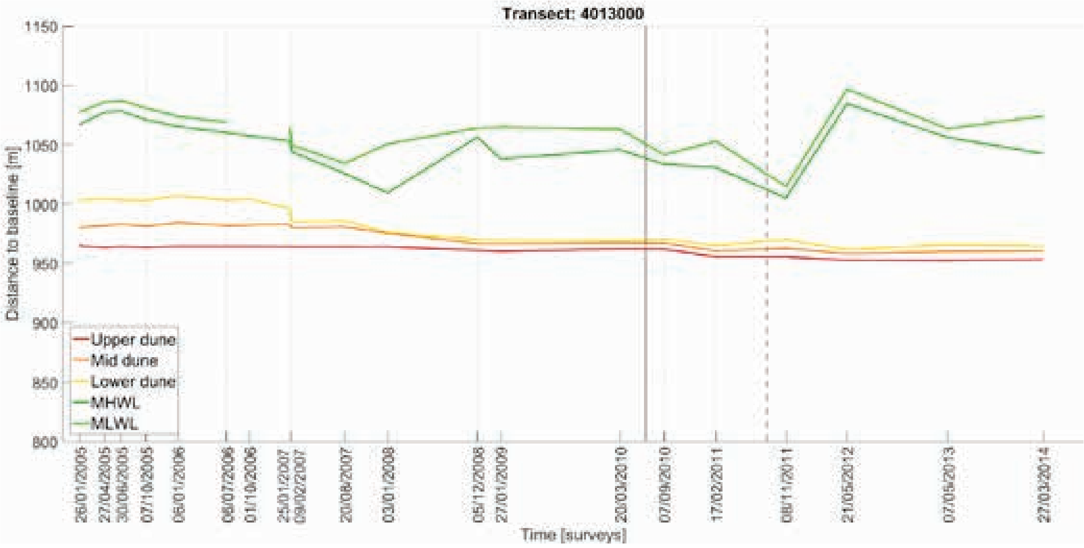
Below the position of the Physical Marks are plotted as a function of time: Upper Dune, Mid Dune, Lower Dune, Mean high water level (MHWL), Mean low water level (MLWL) for each of the profiles representing each of the coastline sections. N2: profile 4015800, N1: profile 4015000, Nourishment: Profile 4014200, S1: 4013600, S2: 4013000, S3: 4012000, S4: 4011400.

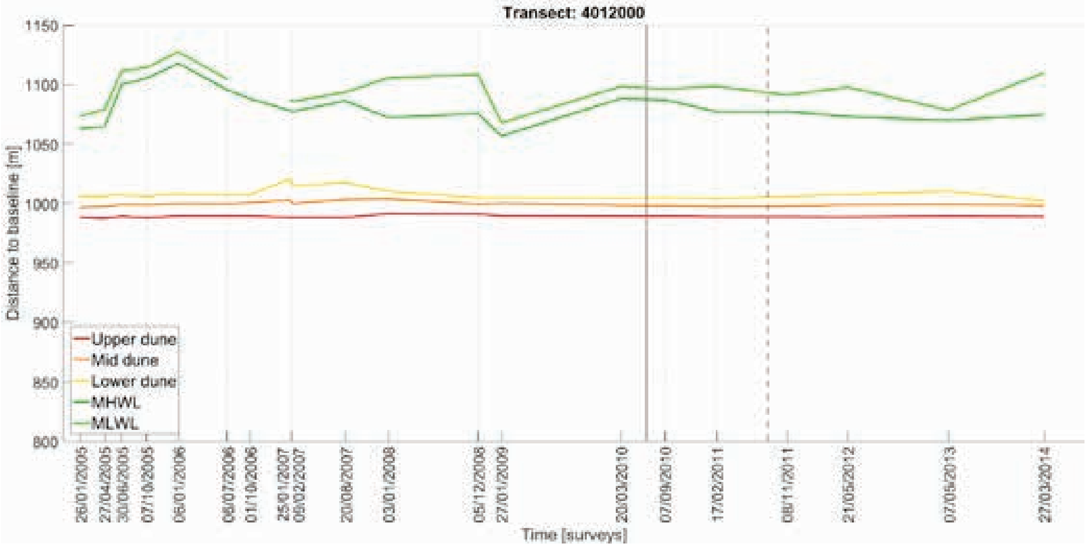


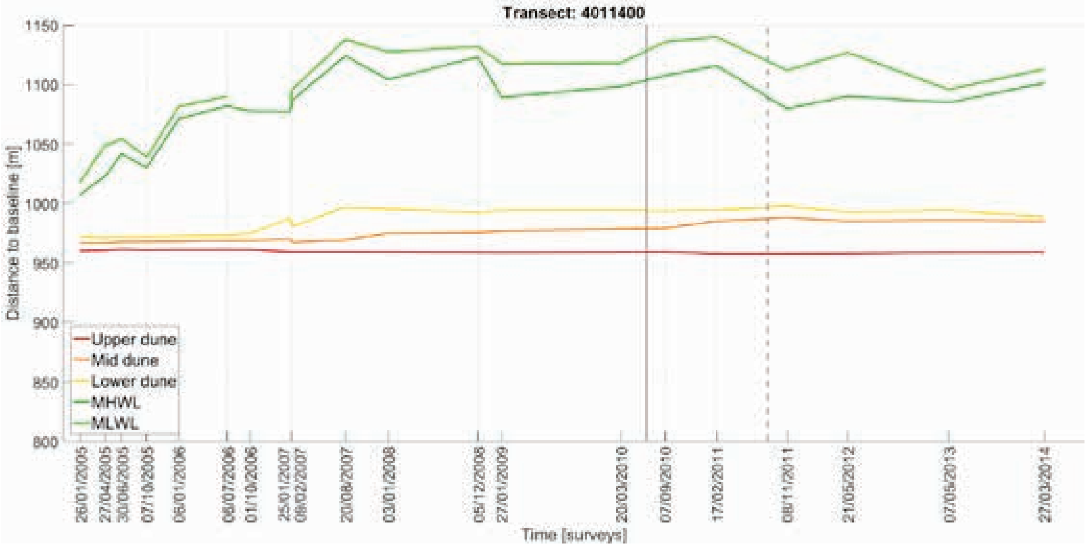



Transect: 4014200
1150
1100
1050
1000
950
900
850
800
Distance to baseline [m]
Upper dune
Mid dune
Lower dune
MHWL
MLWL
26/01/2005
27/04/2005
30/06/2005
07/10/2005
06/01/2006
08/07/2006
01/10/2006
25/01/2007
08/02/2007
20/08/2007
03/01/2008
05/12/2008
27/01/2009
20/03/2010
07/09/2010
17/02/2011
08/11/2011
21/05/2012
07/05/2013
27/03/2014
Time [surveys]


Transect: 4013600
1150
1100
1050
1000
950
900
850
800
Distance to baseline [m]
Upper dune
Mid dune
Lower dune
MHWL
MLWL
26/01/2005
27/04/2005
30/06/2005
07/10/2005
06/01/2006
08/07/2006
01/10/2006
25/01/2007
08/02/2007
20/08/2007
03/01/2008
05/12/2008
27/01/2009
20/03/2010
07/09/2010
17/02/2011
08/11/2011
21/05/2012
07/05/2013
27/03/2014
Time [surveys]


Transect: 4013000
1150
1100
1050
1000
950
900
850
800
Distance to baseline [m]
Upper dune
Mid dune
Lower dune
MHWL
MLWL
26/01/2005
27/04/2005
30/06/2005
07/10/2005
06/01/2006
08/07/2006
01/10/2006
25/01/2007
08/02/2007
20/08/2007
03/01/2008
05/12/2008
27/01/2009
20/03/2010
07/09/2010
17/02/2011
08/11/2011
21/05/2012
07/05/2013
27/03/2014
Time [surveys]


Transect: 4012000
Distance to baseline [m]
1150
1100
1050
1000
950
900
850
800
Upper dune
Mid dune
Lower dune
MHWL
MLWL
26/01/2005
27/04/2005
30/06/2005
07/10/2005
06/01/2006
08/07/2006
01/10/2006
25/01/2007
09/02/2007
20/08/2007
03/01/2008
05/12/2008
27/01/2009
20/03/2010
07/09/2010
17/02/2011
08/11/2011
21/05/2012
07/05/2013
27/03/2014
Time [surveys]


Transect: 4011400
Distance to baseline [m]
1150
1100
1050
1000
950
900
850
800
Upper dune
Mid dune
Lower dune
MHWL
MLWL
26/01/2005
27/04/2005
30/06/2005
07/10/2005
06/01/2006
08/07/2006
01/10/2006
25/01/2007
09/02/2007
20/08/2007
03/01/2008
05/12/2008
27/01/2009
20/03/2010
07/09/2010
17/02/2011
08/11/2011
21/05/2012
07/05/2013
27/03/2014
Time [surveys]

Appendix C:

Physical marks for representative profiles

Below the position of the Physical Marks: Upper Dune, Mid Dune, Lower Dune, Mean high water level MHWL, Mean low water level MLWL for each of the profiles representing each of the coastline sections. N2: profile 4015800, N1: profile 4015000, Nourishment: Profile 4014200, S1: 4013600, S2: 4013000, S3: 4012000, S4: 4011400.

Profile Nr. 4015800																				
Position	Date																			
	26-01-2005	27-04-2005	30-06-2005	07-10-2005	06-01-2006	06-07-2006	01-10-2006	25-01-2007	09-02-2007	20-08-2007	04-01-2008	09-12-2008	30-01-2009	17-03-2010	08-09-2010	17-02-2011	09-11-2011	21-05-2012	07-05-2013	27-03-2014
Upper dune	842,44	842,64	843,88	842,87	842,67	842,67	842,67	842.1	842.1	842.1	845,23	842,68	842,56	842.9	842.9	842,88	842,88	839,6	839,88	839,91
Mid dune	847,03	847,94	849,49	849,95	850,4	851,32	851,41	851,51	853,67	854,22	853,13	852,89	852,91	852,19	848,01	851,24	852	854,05	854,65	845,07
Lower dune	852,12	852,4	855,17	854,53	855,62	855,97	857,01	858,59	870,73	862,96	859,83	862,91	862,56	857,78	848,46	857,78	856,56	864,55	862,4	846,75
MHWL	907,66	906,73	926,49	904,07	13.55	931,81	927,19	919,38	932,09	914,45	926,11	916,72	900,29	905,17	932,59	944,65	942,94	915,24	924,91	915,48
MLWL	917,94	914,68	934,03	911,85	915,43	939,99	935,23	926,3	938,94	920,96	934,25	924,04	907,36	912,22	957,71	978,18	950,37	924,84	935,2	926,41

Profile Nr. 4015000																				
Position	Date																			
	26-01-2005	27-04-2005	30-06-2005	07-10-2005	06-01-2006	06-07-2006	01-10-2006	25-01-2007	09-02-2007	20-08-2007	04-01-2008	09-12-2008	30-01-2009	17-03-2010	08-09-2010	17-02-2011	09-11-2011	21-05-2012	07-05-2013	27-03-2014
Upper dune	862,03	862,05	862,28	862,18	863,81	863,81	863,76	863,02	861,01	861,01	861,4	860,22	859,84	860,61	860,61	860,26	860,26	858,58	854,28	847,75
Mid dune	870,26	871,83	870,9	871,75	872,23	871,71	870,62	866,92	864,94	865,32	867,02	869,4	870,18	869,58	869,52	868,5	869,13	863,14	859,62	852,75
Lower dune	875,32	876,96	875,34	875,49	876,31	875,98	873,98	868,48	867,98	869,11	875,34	875,31	874,76	874,47	874,14	872,88	873,89	864,62	861,63	854,89
MWHL	924,55	929,58	933,19	928,53	929,18	919,61	907,07	927,6	921,55	925,13	925,26	920,72	919,61	914,94	908,8	966,44	931,68	910,77	929,93	937,85
MLWL	942,41	937,07	940,35	936,54	937,62	926,85		943,12	932,21	932,34	932,87	930,69	928,73	923,29	915,29	982,33	942,74	927,55	938,43	948,94

Profile Nr. 4014200																				
Position	Date																			
	26-01-2005	27-04-2005	30-06-2005	07-10-2005	06-01-2006	06-07-2006	01-10-2006	25-01-2007	09-02-2007	20-08-2007	04-01-2008	09-12-2008	30-01-2009	17-03-2010	08-09-2010	17-02-2011	09-11-2011	21-05-2012	07-05-2013	27-03-2014
Upper dune	899,43	899,58	898,79	899,73	900,12	900,13	900	899,05	894,78	894,78	892,89	892,84	891,33	891,56	891,56	883,3	883,3	882,31	883,06	882,49
Mid dune	914,71	914,23	914,88	913,79	914,65	913,9	913,7	902,58	899,65	900,21	897,19	899,2	899,07	899,48	900,37	888,48	890,37	892,06	893,83	891,63
Lower dune	925,04	923,57	924,11	922,56	922,83	919,43	919,22	903,8	902,26	902,46	899,81	903,51	903,27	905,86	903,63	890,19	895,07	927,49	910,64	895,69
MWHL	972,13	966,81	943,54	954,17	956,8	961,6	973,39	940,07	927,85	962,51	946,73	966,55	967,67	964,71	923,41	939,45	986,8	982,46	971,2	952,37
MLWL	982,82	974,92	949,62	963,37	964,6	969,51		963,7	936,6	969,97	956,48	977,69	979,01	973,13	929,84	948,08	993,84	996,15	992,39	977,17

Profile Nr 4013600																				
Position	Date																			
	26-01-2005	27-04-2005	30-06-2005	07-10-2005	06-01-2006	06-07-2006	01-10-2006	25-01-2007	09-02-2007	20-08-2007	04-01-2008	09-12-2008	30-01-2009	17-03-2010	08-09-2010	17-02-2011	09-11-2011	21-05-2012	07-05-2013	27-03-2014
Upper dune	932,06	932,22	928,9	926,73	926,73	931,06	931,06	933,15	933,15	933,15	933,49	934,98	933,65	934,97	934,97	922,43	922,43	923,99	924,4	925,01
Mid dune	949,27	949,03	949,17	949,89	951,23	950,51	950,85	948,97	945,28	945,63	940,04	942,82	940,73	939,54	939,56	932,96	933,45	933,45	936,5	936,06
Lower dune	967,18	967,7	967,61	967,26	968,59	966,47	964,99	957,26	947,75	947,79	942,05	945,32	944,12	940,73	942,3	934,37	940,89	941,04	944,22	941,36
MWHL	1020,71	1032,39	1023,26	1013,29	1011,06	1010,44	1001,35	993,93	1001,8	1007,46	1002,42	996,31	993,92	1001,39	1009,17	979,78	1001,4	1030,13	1036,74	1024,38
MLWL	1034,58	1040,97	1030,86	1021,95	1020,15	1018		1000,9	1008,29	1015,69	1013,75	1025,55	1017,49	1011,3	1019,29	1006,34	1023,77	1038,27	1045,23	1037,97

Profile Nr 4013000																				
Position	Date																			
	26-01-2005	27-04-2005	30-06-2005	07-10-2005	06-01-2006	06-07-2006	01-10-2006	25-01-2007	09-02-2007	20-08-2007	04-01-2008	09-12-2008	30-01-2009	17-03-2010	08-09-2010	17-02-2011	09-11-2011	21-05-2012	07-05-2013	27-03-2014
Upper dune	964,92	963,56	964,28	963,69	964,55	964,55	964,55	964,3	964,2	964,2	964,16	961,19	960,17	962,34	962,03	955,74	955,74	952,64	952,43	953,33
Mid dune	980,37	981,76	983,24	981,43	984,4	982,01	982,39	983,23	980,21	981,02	975,46	966,82	966,51	967,56	967,34	960,58	962,93	958,22	960,06	960,61
Lower dune	1003,39	1004,49	1003,61	1003,08	1007,34	1003,27	1004,34	996,43	984,86	985,98	976,31	970,17	969,47	969,45	970,5	965,22	970,08	961,83	965,98	964,6
MWHL	1066,61	1077,44	1078,53	1070,9	1065,54	1060,18	1057,65	1053,28	1044,04	1025,8	1009,56	1056,36	1038,17	1045,76	1033,63	1030,79	1005,28	1084,69	1056,16	1042,56
MLWL	1077,46	1085,9	1087,24	1080,86	1073,83	1068,99		1065,41	1049,59	1034,42	1050,74	1064,15	1065,11	1063,22	1041,59	1052,91	1014,93	1096,76	1063,63	1074,15

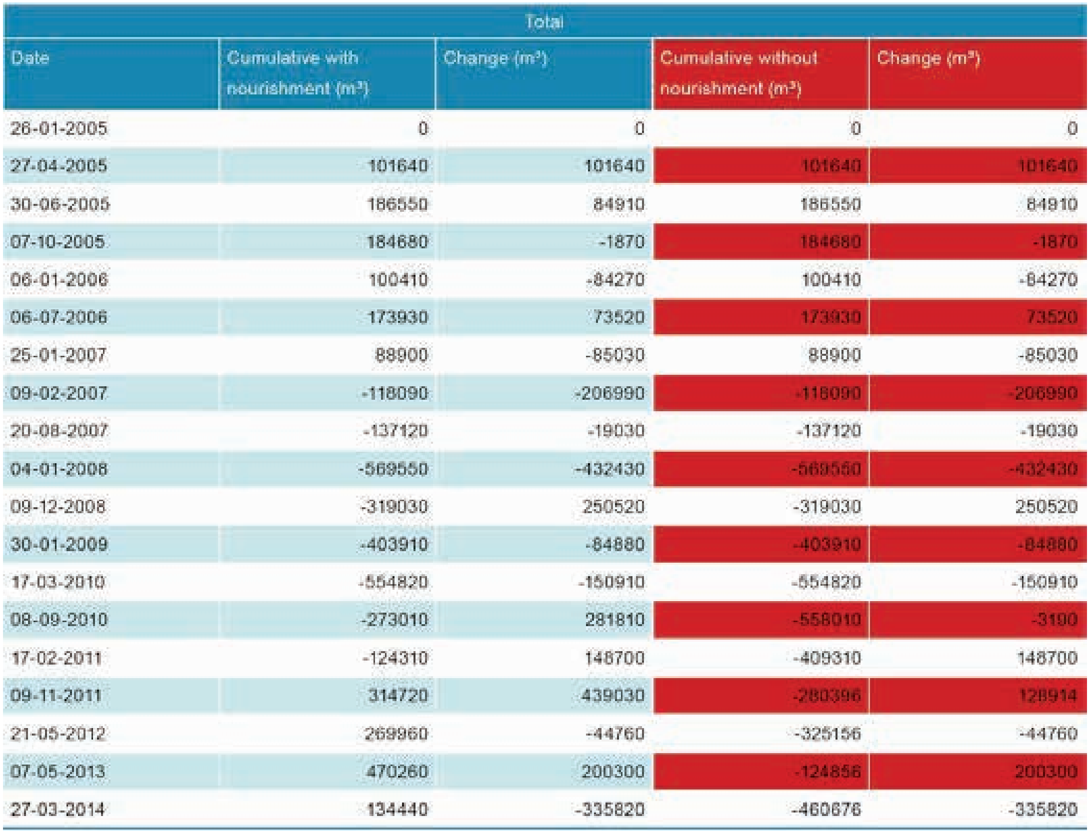
Profile Nr 4012000																				
Position	Date																			
	26-01-2005	27-04-2005	30-06-2005	07-10-2005	06-01-2006	06-07-2006	01-10-2006	25-01-2007	09-02-2007	20-08-2007	04-01-2008	09-12-2008	30-01-2009	17-03-2010	08-09-2010	17-02-2011	09-11-2011	21-05-2012	07-05-2013	27-03-2014
Upper dune	988,37	987,69	989,33	988,08	989,57	989,57	989,57	988,33	988,36	988,36	991,33	991,08	989,69	989,41	989,41	988,97	988,97	988,82	989,32	989,05
Mid dune	996,96	997,43	999,09	998,61	1000,1	999,91	1000,65	1003,02	1000,01	1003,44	1003,88	999,64	1000,39	998,41	998,22	997,45	997,64	998,83	999,23	998,29
Lower dune	1006,23	1006,16	1007,36	1006,08	1008,3	1006,83	1007,59	1020,78	1014,82	1017,64	1010,25	1004,91	1004,94	1004,45	1005,03	1004,02	1005,99	1007,64	1010,38	1002,3
MWHL	1063,14	1064,68	1100,21	1105,23	1117,75	1095,56	1088,09	1078,01	1077,38	1086,24	1072,35	1075,56	1056,84	1088,24	1087,18	1077,17	1077,34	1073,14	1069,93	1074,71
MLWL	1073,48	1078,87	1111,6	1114,32	1127,58	1104,36		1087,42	1085,88	1093,53	1105,56	1108,32	1067,91	1098,37	1096,37	1098,43	1091,18	1097,77	1078,46	1109,94

Profile Nr. 4011400																				
Position	Date																			
	26-01-2005	27-04-2005	30-06-2005	07-10-2005	06-01-2006	06-07-2006	01-10-2006	25-01-2007	09-02-2007	20-08-2007	04-01-2008	09-12-2008	30-01-2009	17-03-2010	08-09-2010	17-02-2011	09-11-2011	21-06-2012	07-05-2013	27-03-2014
Upper dune	959,96	960,29	961,27	960,59	960,98	960,98	960,98	959,11	959,11	959,11	959,05	958,75	958,47	958,97	959,06	957,69	957,69	957,92	958,55	958,85
Mid dune	966,94	967,1	968,02	968,08	968,4	968,98	969,07	970,2	967,67	969,51	974,9	975,52	976,7	978,68	979,16	985,25	988,33	985,26	986,12	985,33
Lower dune	971,95	971,09	972	971,9	972,83	973,55	974,77	987,63	980,85	996,96	995,62	992,52	994,19	994,27	993,74	994,6	997,74	992,89	994,27	988,94
MWHL	1007,66	1022,59	1041,69	1030,19	1071,08	1081,95	1077,77	1077,16	1087,26	1124,05	1104,24	1123,25	1089,41	1098,38	1107,48	1115,84	1079,62	1090,5	1084,92	1101,22
MLWL	1017,51	1048,51	1054,4	1038,88	1081,59	1090,24		1085,88	1096,14	1137,84	1127,58	1132,08	1117,51	1118,05	1135,99	1140,04	1111,99	1126,93	1095,87	1112,93

Appendix D:

Total coastal volume evolution

Table 6 Total cumulative coastal volume. The cumulative volume and the change from date to date

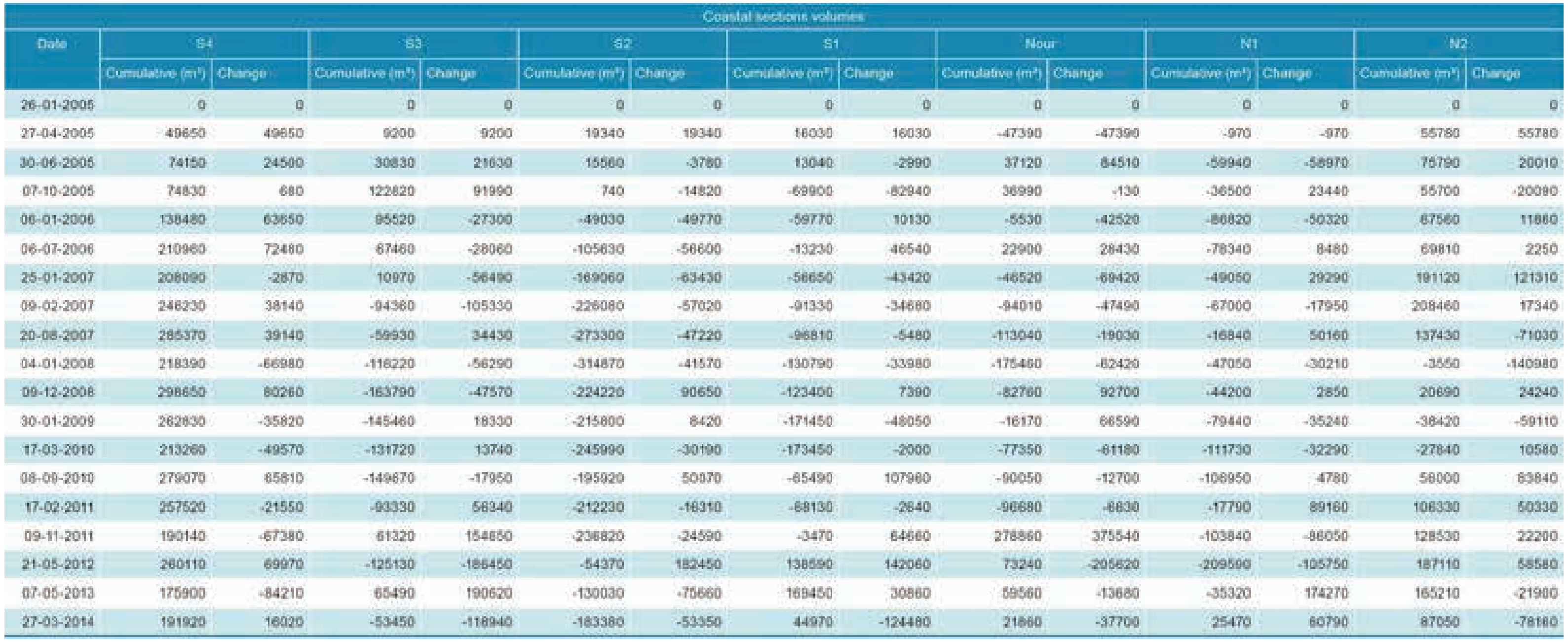


Total				
Date	Cumulative with nourishment (m^3)	Change (m^3)	Cumulative without nourishment (m^3)	Change (m^3)
26-01-2005	0	0	0	0
27-04-2005	101640	101640	101640	101640
30-06-2005	186550	84910	186550	84910
07-10-2005	184680	-1870	184680	-1870
06-01-2006	100410	-84270	100410	-84270
06-07-2006	173930	73520	173930	73520
25-01-2007	88900	-85030	88900	-85030
09-02-2007	-118090	-206990	-118090	-206990
20-08-2007	-137120	-19030	-137120	-19030
04-01-2008	-569550	-432430	-569550	-432430
09-12-2008	-319030	250520	-319030	250520
30-01-2009	-403910	-84880	-403910	-84880
17-03-2010	-554820	-150910	-554820	-150910
08-09-2010	-273010	281810	-558010	-3190
17-02-2011	-124310	148700	-409310	148700
09-11-2011	314720	439030	-280396	128914
21-05-2012	269960	-44760	-325156	-44760
07-05-2013	470260	200300	-124856	200300
27-03-2014	134440	-335820	-460676	-335820

Appendix E:

Total volumes per section

The table show the cumulative volume and volume changes between surveys for each section.

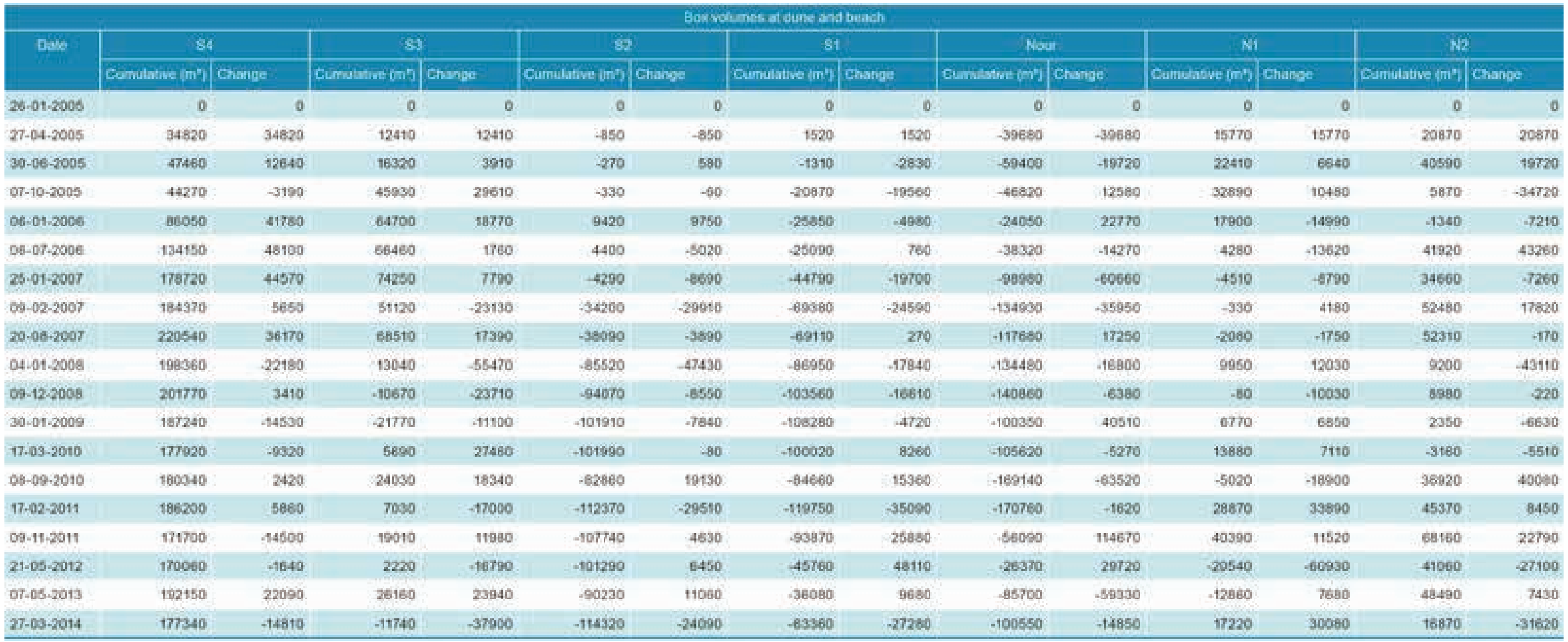


	Coastal sections volumes													
Date	S4		S3		S2		S1		Nour		N1		N2	
	Cumulative (m^3)	Change	Cumulative (m^3)	Change	Cumulative (m^3)	Change	Cumulative (m^3)	Change	Cumulative (m^3)	Change	Cumulative (m^3)	Change	Cumulative (m^3)	Change
26-01-2005	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27-04-2005	49650	49650	9200	9200	19340	19340	16030	16030	-47390	-47390	-970	-970	55780	55780
30-06-2005	74150	24500	30830	21630	15560	-3780	13040	-2990	37120	84510	-59940	-58970	75790	20010
07-10-2005	74830	680	122820	91990	740	-14820	-69900	-82940	36990	-130	-36500	23440	55700	-20090
06-01-2006	138480	63650	95520	-27300	-49030	-49770	-59770	10130	-5530	-42520	-86820	-50320	67560	11860
06-07-2006	210960	72480	67460	-28060	-105630	-56600	-13230	46540	22900	28430	-78340	8480	69810	2250
25-01-2007	208090	-2870	10970	-56490	-169060	-63430	-56650	-43420	-46520	-69420	-49050	29290	191120	121310
09-02-2007	246230	38140	-94360	-105330	-226080	-57020	-91330	-34680	-94010	-47490	-67000	-17950	208460	17340
20-08-2007	285370	39140	-59930	34430	-273300	-47220	-96810	-5480	-113040	-19030	-16840	50160	137430	-71030
04-01-2008	218390	-66980	-116220	-56290	-314870	-41570	-130790	-33980	-175460	-62420	-47050	-30210	-3550	-140980
09-12-2008	298650	80260	-163790	-47570	-224220	90650	-123400	7390	-82760	92700	-44200	2850	20690	24240
30-01-2009	262830	-35820	-145460	18330	-215800	8420	-171450	-48050	-16170	66590	-79440	-35240	-38420	-59110
17-03-2010	213260	-49570	-131720	13740	-245990	-30190	-173450	-2000	-77350	-61180	-111730	-32290	-27840	10580
08-09-2010	279070	65810	-149670	-17950	-195920	50070	-65490	107960	-90050	-12700	-106950	4780	56000	83840
17-02-2011	257520	-21550	-93330	56340	-212230	-16310	-68130	-2640	-96680	-6630	-17790	89160	106330	50330
09-11-2011	190140	-67380	61320	154650	-236820	-24590	-3470	64660	278860	375540	-103840	-86050	128530	22200
21-05-2012	260110	69970	-125130	-186450	-54370	182450	138590	142060	73240	-205620	-209590	-105750	187110	58580
07-05-2013	175900	-84210	65490	190620	-130030	-75660	169450	30860	59560	-13680	-35320	174270	165210	-21900
27-03-2014	191920	16020	-53450	-118940	-183380	-53350	44970	-124480	21860	-37700	25470	60790	87050	-78160

Appendix F:

Beach and dune volume per section

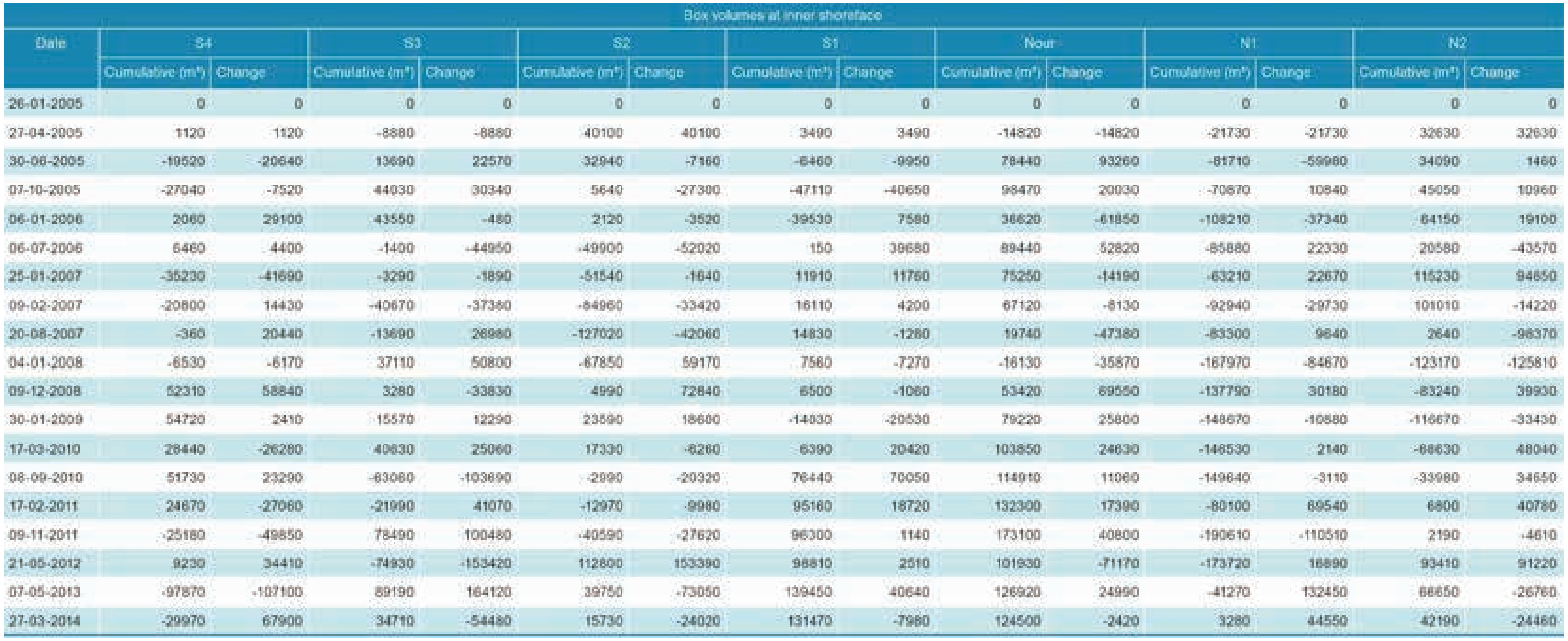
The table show the cumulative volume of the beach and dune and the change between surveys per section.



	Box volumes at dune and beach													
Date	S4		S3		S2		S1		Nour		N1		N2	
	Cumulative (m^3)	Change	Cumulative (m^3)	Change	Cumulative (m^3)	Change	Cumulative (m^3)	Change	Cumulative (m^3)	Change	Cumulative (m^3)	Change	Cumulative (m^3)	Change
26-01-2005	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27-04-2005	34820	34820	12410	12410	-850	-850	1520	1520	-39680	-39680	15770	15770	20870	20870
30-06-2005	47460	12640	16320	3910	-270	580	-1310	-2830	-59400	-19720	22410	6640	40590	19720
07-10-2005	44270	-3190	45930	29610	-330	-60	-20870	-19560	-46820	12580	32890	10480	5870	-34720
06-01-2006	86050	41780	64700	18770	9420	9750	-25850	-4980	-24050	22770	17900	-14990	-1340	-7210
06-07-2006	134150	48100	66460	1760	4400	-5020	-25090	760	-38320	-14270	4280	-13620	41920	43260
25-01-2007	178720	44570	74250	7790	-4290	-8690	-44790	-19700	-98980	-60660	-4510	-8790	34660	-7260
09-02-2007	184370	5650	51120	-23130	-34200	-29910	-69380	-24590	-134930	-35950	-330	4180	52480	17820
20-08-2007	220540	36170	68510	17390	-38090	-3890	-69110	270	-117680	17250	-2080	-1750	52310	-170
04-01-2008	198360	-22180	13040	-55470	-85520	-47430	-86950	-17840	-134480	-16800	9950	12030	9200	-43110
09-12-2008	201770	3410	-10670	-23710	-94070	-8550	-103560	-16610	-140860	-6380	-80	-10030	8980	-220
30-01-2009	187240	-14530	-21770	-11100	-101910	-7840	-108280	-4720	-100350	40510	6770	6850	2350	-6630
17-03-2010	177920	-9320	5690	27460	-101990	-80	-100020	8260	-105620	-5270	13880	7110	-3160	-5510
08-09-2010	180340	2420	24030	18340	-82860	19130	-84660	15360	-169140	-63520	-5020	-18900	36920	40080
17-02-2011	186200	5860	7030	-17000	-112370	-29510	-119750	-35090	-170760	-1620	28870	33890	45370	8450
09-11-2011	171700	-14500	19010	11980	-107740	4630	-93870	25880	-56090	114670	40390	11520	68160	22790
21-05-2012	170060	-1640	2220	-16790	-101290	6450	-45760	48110	-26370	29720	-20540	-60930	41060	-27100
07-05-2013	192150	22090	26160	23940	-90230	11060	-36080	9680	-85700	-59330	-12860	7680	48490	7430
27-03-2014	177340	-14810	-11740	-37900	-114320	-24090	-63360	-27280	-100550	-14850	17220	30080	16870	-31620

Appendix G:
Inner shoreface volume per section

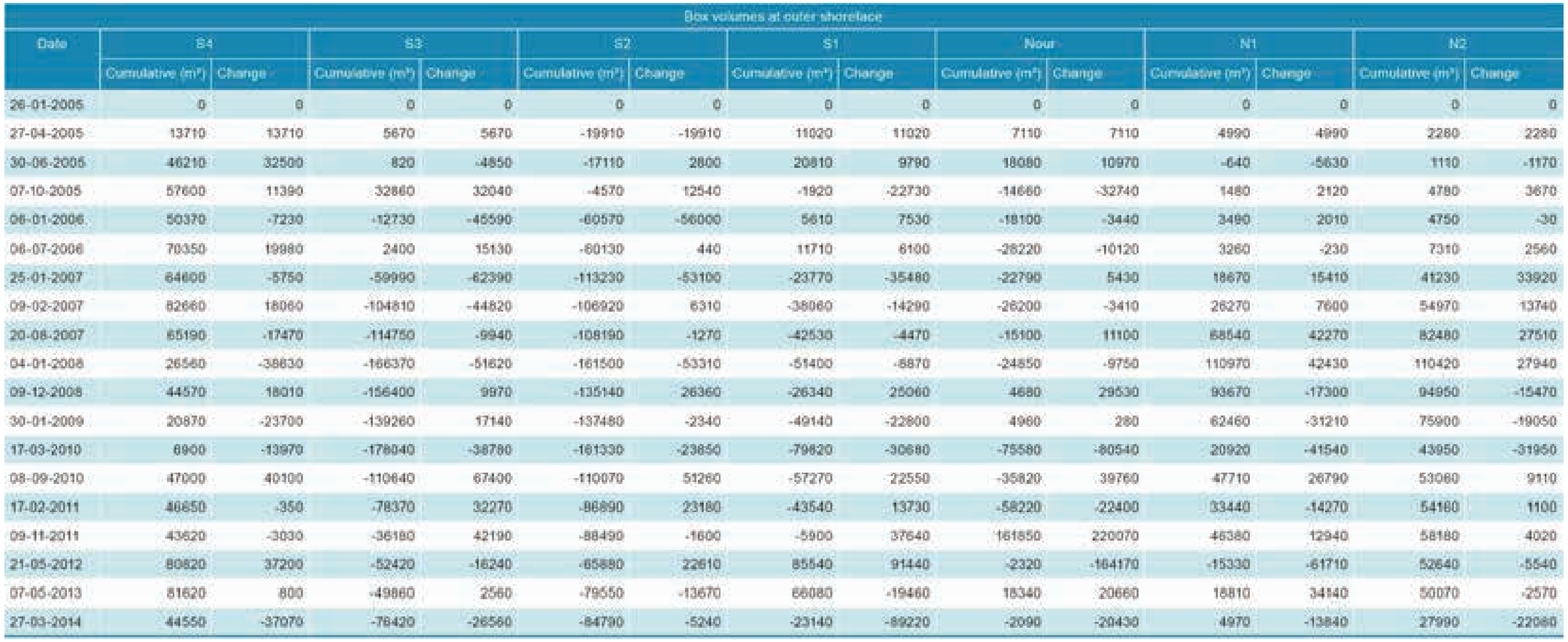
The table show the cumulative volume of the inner shoreface and the change between surveys per section



Date	Box volumes at inner shoreface													
	S4		S3		S2		S1		Nour		N1		N2	
	Cumulative (m^3)	Change	Cumulative (m^3)	Change	Cumulative (m^3)	Change	Cumulative (m^3)	Change	Cumulative (m^3)	Change	Cumulative (m^3)	Change	Cumulative (m^3)	Change
26-01-2005	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27-04-2005	1120	1120	-8880	-8880	40100	40100	3490	3490	-14820	-14820	-21730	-21730	32630	32630
30-06-2005	-19520	-20640	13690	22570	32940	-7160	-6460	-9950	78440	93260	-81710	-59980	34090	1460
07-10-2005	-27040	-7520	44030	30340	5640	-27300	-47110	-40650	98470	20030	-70870	10840	45050	10960
06-01-2006	2060	29100	43550	-480	2120	-3520	-39530	7580	36620	-61850	-108210	-37340	64150	19100
06-07-2006	6460	4400	-1400	-44950	-49900	-52020	150	39680	89440	52820	-85880	22330	20580	-43570
25-01-2007	-35230	-41690	-3290	-1890	-51540	-1640	11910	11760	75250	-14190	-63210	22670	115230	94650
09-02-2007	-20800	14430	-40670	-37380	-84960	-33420	16110	4200	67120	-8130	-92940	-29730	101010	-14220
20-08-2007	-360	20440	-13690	26980	-127020	-42060	14830	-1280	19740	-47380	-83300	9640	2640	-98370
04-01-2008	-6530	-6170	37110	50800	-67850	59170	7560	-7270	-16130	-35870	-167970	-84670	-123170	-125810
09-12-2008	52310	58840	3280	-33830	4990	72840	6500	-1060	53420	69550	-137790	30180	-83240	39930
30-01-2009	54720	2410	15570	12290	23590	18600	-14030	-20530	79220	25800	-148670	-10880	-116670	-33430
17-03-2010	28440	-26280	40630	25060	17330	-6260	6390	20420	103850	24630	-146530	2140	-68630	48040
08-09-2010	51730	23290	-63060	-103690	-2990	-20320	76440	70050	114910	11060	-149640	-3110	-33980	34650
17-02-2011	24670	-27060	-21990	41070	-12970	-9980	95160	18720	132300	17390	-80100	69540	6800	40780
09-11-2011	-25180	-49850	78490	100480	-40590	-27620	96300	1140	173100	40800	-190610	-110510	2190	-4610
21-05-2012	9230	34410	-74930	-153420	112800	153390	98810	2510	101930	-71170	-173720	16890	93410	91220
07-05-2013	-97870	-107100	89190	164120	39750	-73050	139450	40640	126920	24990	-41270	132450	66650	-26760
27-03-2014	-29970	67900	34710	-54480	15730	-24020	131470	-7980	124500	-2420	3280	44550	42190	-24460

Appendix H:
Inner shoreface volume per section

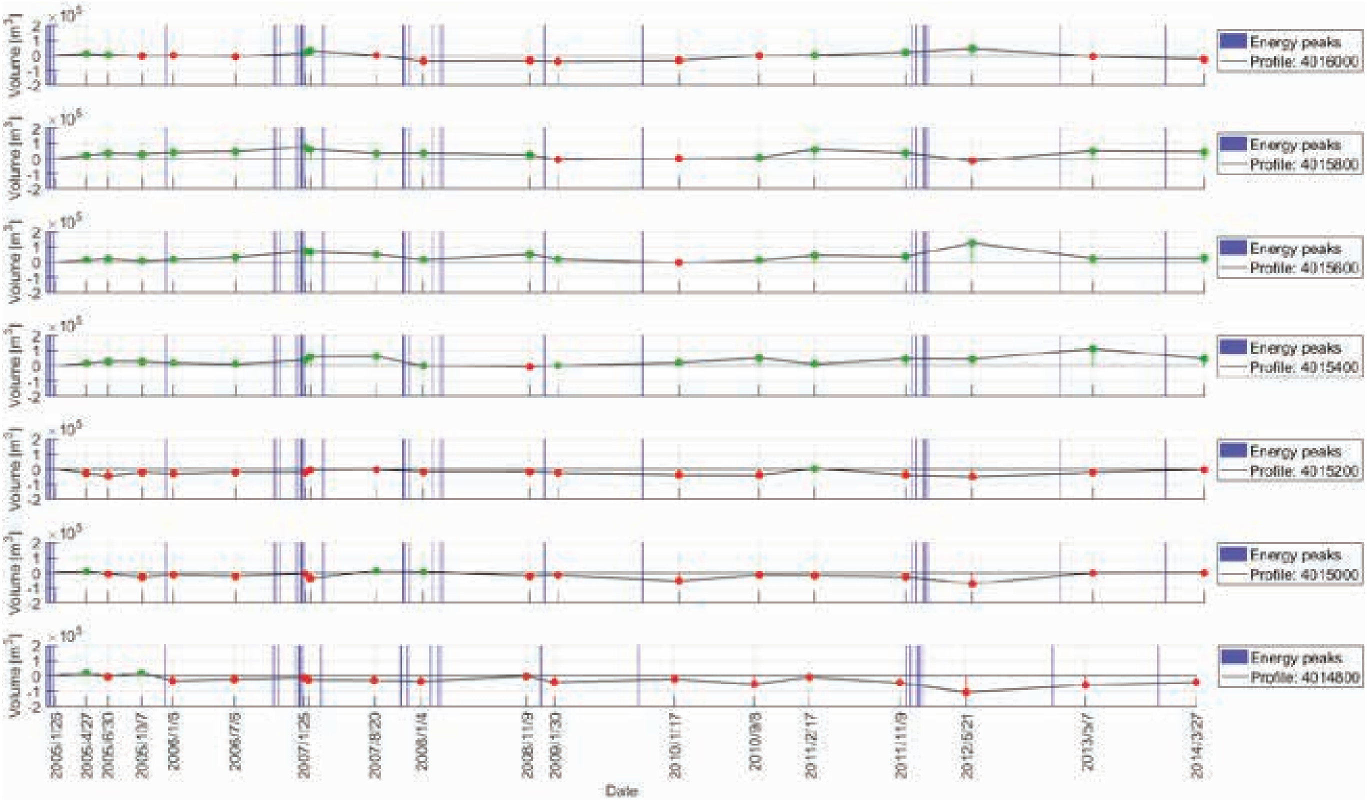
The table show the cumulative volume of the outer shoreface and the change between surveys per section.

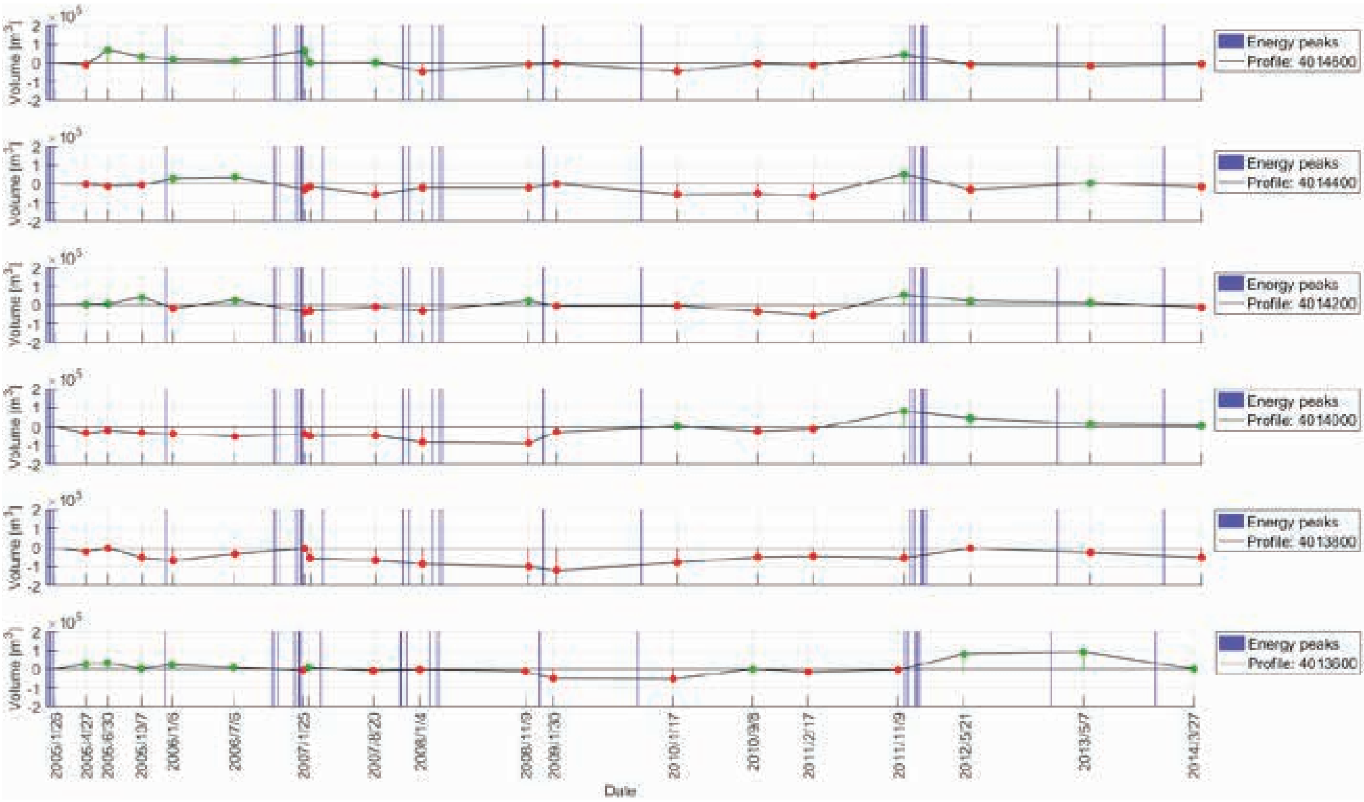


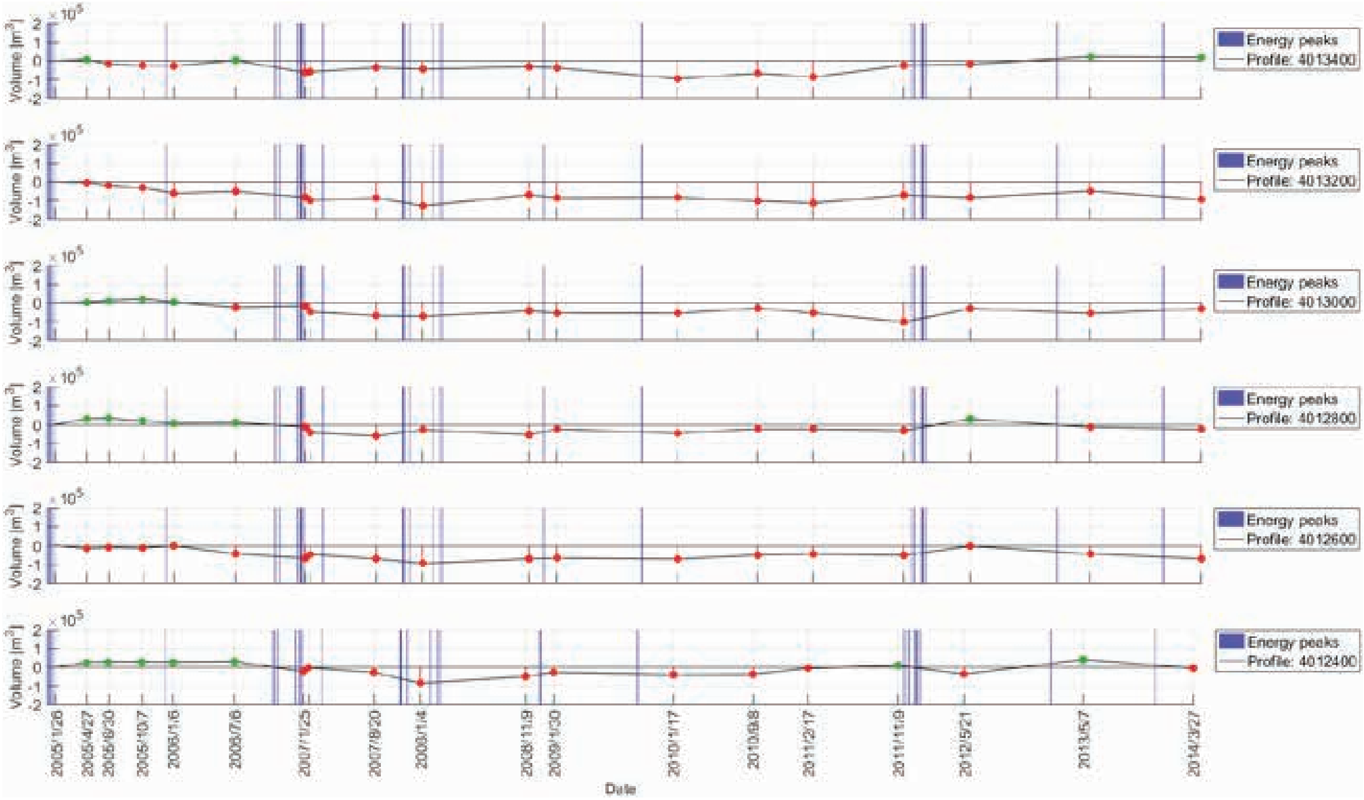
Box volumes at outer shoreface														
Date	S4		S3		S2		S1		Nour		N1		N2	
	Cumulative (m³)	Change	Cumulative (m³)	Change	Cumulative (m³)	Change	Cumulative (m³)	Change	Cumulative (m³)	Change	Cumulative (m³)	Change	Cumulative (m³)	Change
26-01-2005	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27-04-2005	13710	13710	5670	5670	-19910	-19910	11020	11020	7110	7110	4990	4990	2280	2280
30-06-2005	46210	32500	820	-4850	-17110	2800	20810	9790	18080	10970	-640	-5630	1110	-1170
07-10-2005	57600	11390	32860	32040	-4570	12540	-1920	-22730	-14660	-32740	1480	2120	4780	3670
06-01-2006	50370	-7230	-12730	-45590	-60570	-56000	5610	7530	-18100	-3440	3490	2010	4750	-30
06-07-2006	70350	19980	2400	15130	-60130	440	11710	6100	-28220	-10120	3260	-230	7310	2560
25-01-2007	64600	-5750	-59990	-62390	-113230	-53100	-23770	-35480	-22790	5430	18670	15410	41230	33920
09-02-2007	82660	18060	-104810	-44820	-106920	6310	-38060	-14290	-26200	-3410	26270	7600	54970	13740
20-08-2007	65190	-17470	-114750	-9940	-108190	-1270	-42530	-4470	-15100	11100	68540	42270	82480	27510
04-01-2008	26560	-38630	-166370	-51620	-161500	-53310	-51400	-8870	-24850	-9750	110970	42430	110420	27940
09-12-2008	44570	18010	-156400	9970	-135140	26360	-26340	25060	4680	29530	93670	-17300	94950	-15470
30-01-2009	20870	-23700	-139260	17140	-137480	-2340	-49140	-22800	4960	280	62460	-31210	75900	-19050
17-03-2010	6900	-13970	-178040	-38780	-161330	-23850	-79820	-30680	-75580	-80540	20920	-41540	43950	-31950
08-09-2010	47000	40100	-110640	67400	-110070	51260	-57270	22550	-35820	39760	47710	26790	53060	9110
17-02-2011	46650	-350	-78370	32270	-86890	23180	-43540	13730	-58220	-22400	33440	-14270	54160	1100
09-11-2011	43620	-3030	-36180	42190	-88490	-1600	-5900	37640	161850	220070	46380	12940	58180	4020
21-05-2012	80820	37200	-52420	-16240	-65880	22610	85540	91440	-2320	-164170	-15330	-61710	52640	-5540
07-05-2013	81620	800	-49860	2560	-79550	-13670	66080	-19460	18340	20660	18810	34140	50070	-2570
27-03-2014	44550	-37070	-76420	-26560	-84790	-5240	-23140	-89220	-2090	-20430	4970	-13840	27990	-22060

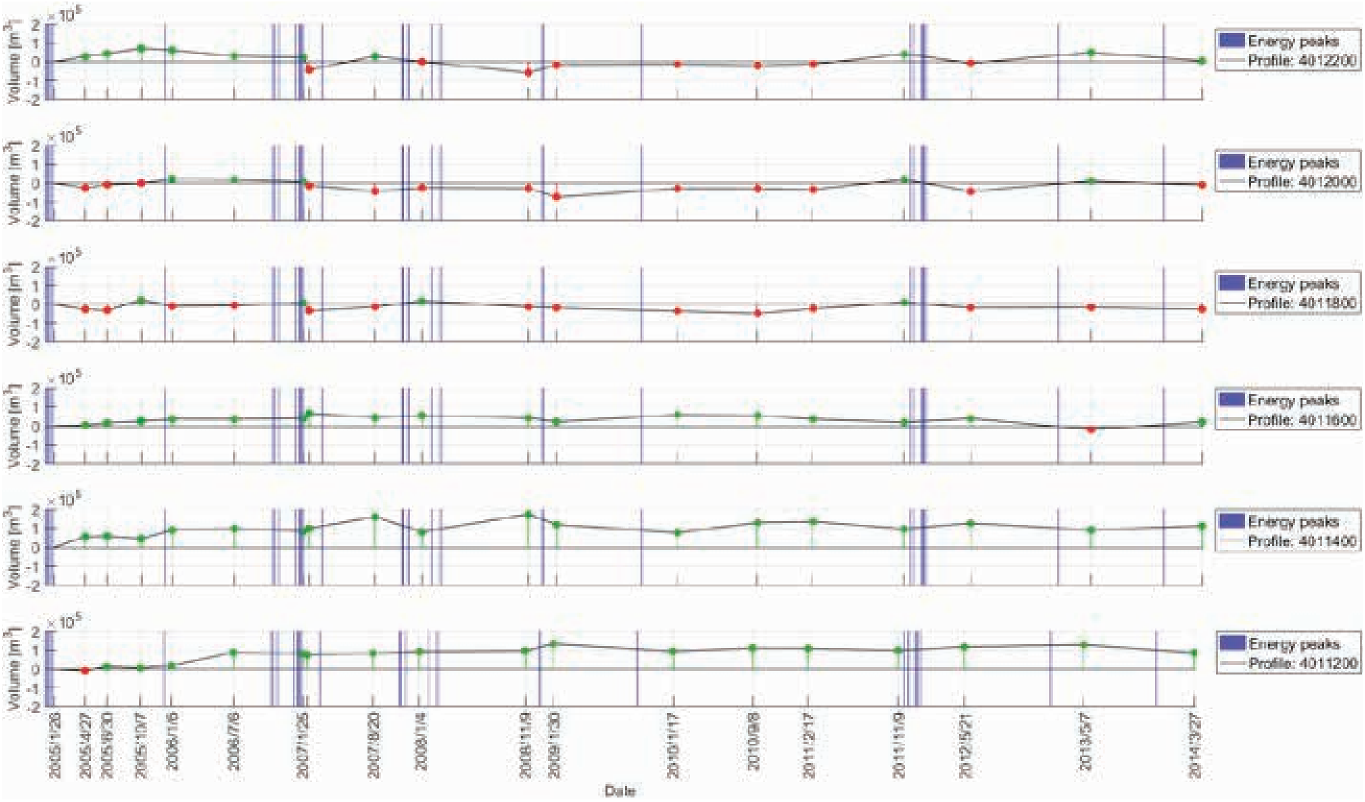
Appendix I:

Local volume development and nourishment response




× 10^5
Volume [m^3]
2
1
0
-1
-2
Energy peaks
Profile: 4014600
Profile: 4014400
Profile: 4014200
Profile: 4014000
Profile: 4013800
Profile: 4013600
2005/1/26
2005/4/27
2005/6/30
2005/10/7
2006/1/6
2006/7/6
2007/1/25
2007/8/20
2008/1/4
2008/11/9
2009/1/30
2010/1/17
2010/9/8
2011/2/17
2011/11/9
2012/5/21
2013/5/7
2014/3/27
Date


× 10^5
Volume [m^3]
2
1
0
-1
-2
Energy peaks
Profile: 4013400
Profile: 4013200
Profile: 4013000
Profile: 4012800
Profile: 4012600
Profile: 4012400
2005/1/26
2005/4/27
2005/6/30
2005/10/7
2006/1/6
2006/7/6
2007/1/25
2007/8/20
2008/1/4
2008/11/9
2009/1/30
2010/1/17
2010/9/8
2011/2/17
2011/11/9
2012/5/21
2013/5/7
2014/3/27
Date



× 10^5
Volume [m^3]
2
1
0
-1
-2
Energy peaks
Profile: 4012200
Profile: 4012000
Profile: 4011800
Profile: 4011600
Profile: 4011400
Profile: 4011200
2005/1/26
2005/4/27
2005/6/30
2005/10/7
2006/1/6
2006/7/6
2007/1/25
2007/8/20
2008/1/4
2008/11/9
2009/1/30
2010/1/17
2010/9/8
2011/2/17
2011/11/9
2012/5/21
2013/5/7
2014/3/27
Date

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