




# Beach nourishment effects

Hald beach - Denmark 1984

July 2020



<b>Project</b>	<b>Building with Nature (EU-InterReg)</b>
Start date	01.11.2016
End date	01.04.2020
Project manager (PM)	Ane Højberg Nielsen
Project leader (PL)	Per Sørensen
Project staff (PS)	Henrik Vinge Karlsson
Time registering	402412
Approved date	27.01.2020
Signature	

<b>Report</b>	<b>Analysis of the effect of a beach nourishment, Hald beach, Denmark</b>
Author	Henrik Vinge Karlsson, Per Sørensen
Keyword	Beach nourishment, Coastal protection, Building with nature, Hald beach
Distribution	<a href="http://www.kyst.dk">www.kyst.dk</a> , <a href="http://www.buildingwithnature.com">www.buildingwithnature.com</a>
Referred to as	Kystdirektoratet (2020), Beach nourishment effects - Hald Beach, Kystdirektoratet, Lemvig.

---

# Contents

<b>1</b>	<b>Introduction .....</b>	<b>5</b>
1.1	Objective.....	6
1.2	Criteria's for the nourishment stretch .....	7
1.3	Decision on nourishment stretch .....	7
1.4	Financing of the beach nourishment.....	8
1.5	Definitions and term diagram .....	8
1.6	Nourishment description.....	9
1.7	Data .....	11
1.7.1	Data limitation.....	14
<b>2</b>	<b>Baseline study.....</b>	<b>15</b>
2.1	Hald Beach.....	15
2.2	Morphology before nourishment.....	18
2.2.1	Coastal protection before nourishment.....	18
2.2.2	Sediment budget at Hald beach.....	20
<b>3</b>	<b>Analysis of nourishment 1984 - 1986 .....</b>	<b>21</b>
3.1	Weather conditions during the monitoring period.....	21
3.1.1	Wind conditions.....	21
3.1.2	Water level conditions before and during the study period .....	22
3.1.3	Wave conditions before and during the study period.....	22
3.1.4	Current.....	23
3.1.5	Storm events 1985.....	23
3.2	Nourishment planform and profile development .....	26
3.2.1	Shoreface.....	29
3.2.1	Summary.....	29
3.3	Volume development.....	30
3.3.1	Nourishment diffusion.....	34
3.4	Nourishment impact in neighboring stretches.....	36
<b>4</b>	<b>Discussion.....</b>	<b>40</b>
4.1	When and where did changes occur in the nourished sand volume.....	40
4.2	How quickly did the nourishment diffuse? .....	40
4.3	How does the erosion- and deposition rates vary, in and around the nourishment site? .....	40
4.4	What is the impact seawards the nourishment area and at the neighboring stretches? .....	41

<b>5 Conclusion.....</b>	<b>42</b>
<b>References.....</b>	<b>43</b>
<b>Appendix A - Monitoring program .....</b>	<b>44</b>
<b>Appendix B - Monitoring stations.....</b>	<b>45</b>

# 1 Introduction

This report is one of several publications presented under the European interreg project, Building with Nature (BwN). This report is focusing on reanalyzing the beach nourishment undertaken at Hald beach in Denmark in 1984, Figure 1.1. The analysis is based on the original report published 1986 in Danish.

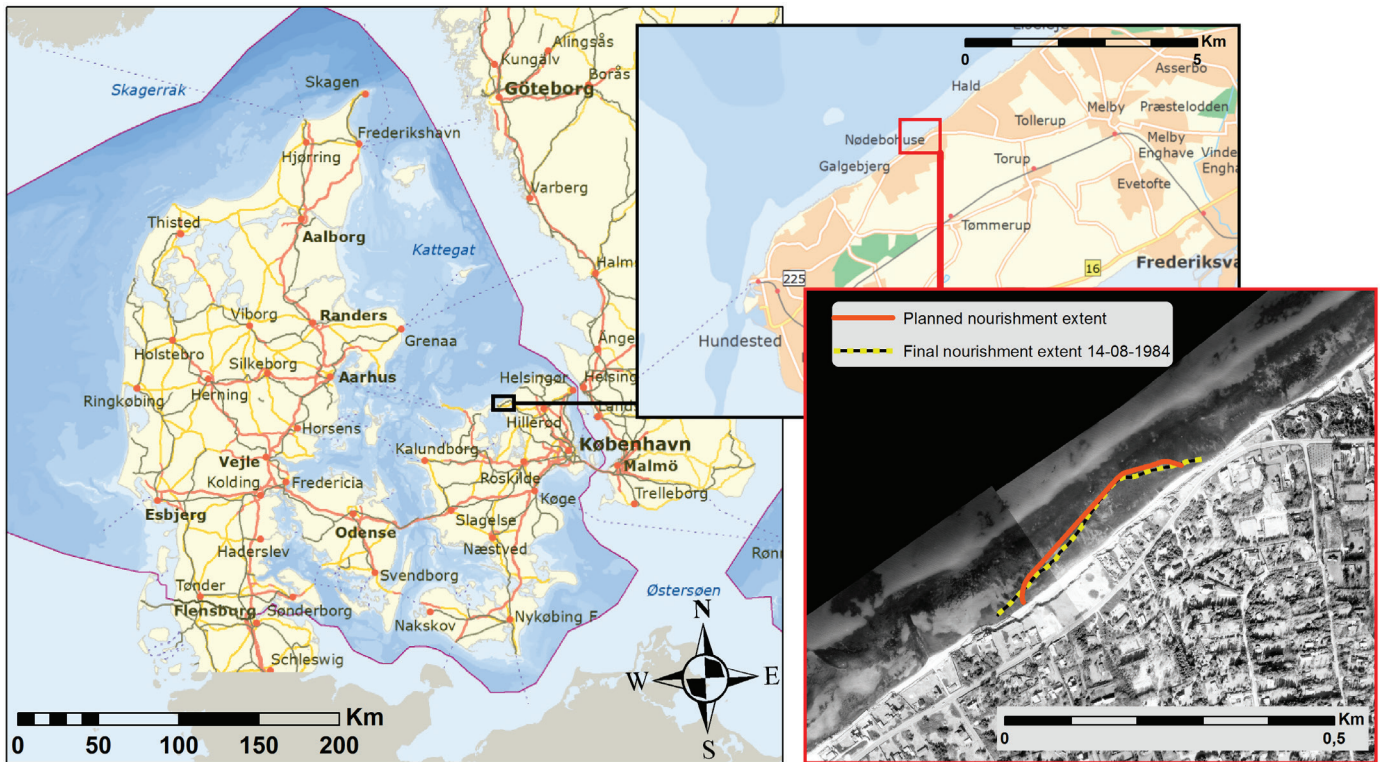


Figure 1.1: Location of Hald beach

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 1.2.

In WP3 the coastal challenges and effects of implementing building with nature methods, in this case beach and shoreface nourishments, is represented by seven ‘living laboratories’ located along the North Sea Coasts and the Wadden Sea. The analysis of the local laboratories will improve the evidence-base needed to incorporate BwN methods into the national investment and policy programs of the North Sea Region countries.

The main focus of the full scale beach nourishment at Hald beach between 1984 and 1986 was to gain insight into the performance and possibilities of beach nourishments as coastal protection, as it presented a more natural and possibly less costly method than traditional protection. Besides the protection, it could also add recreational value to the beach stretches in the nourished area. This re-analysis is based on the publication of the original report from 1987 (Fællesudvalget, 1987) published in Danish at the time. The data availability is limited. Not all the original material has been available. In this report, new additions

are made while parts of the original report have been left out. Despite being more than 30 years old, the original report on the beach nourishment in Hald is still relevant, as it was carried out in such great detail.

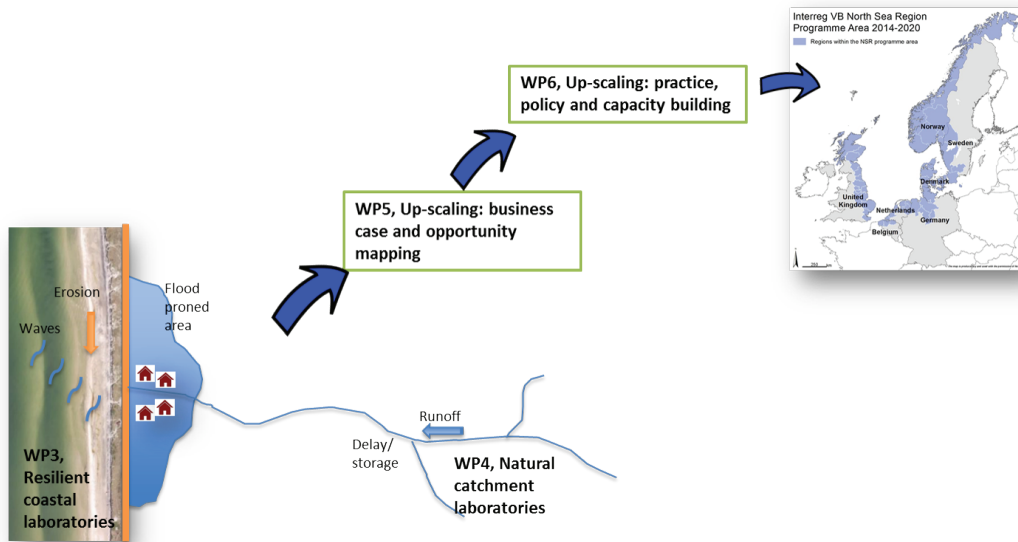


Figure 1.2: The 6 work packages in the Building with Nature project. WP1 - Project Management, and WP2 - Communication is not included as these WP are in-office activities.

## 1.1 Objective

The objective of this re-analysis is to gain insight into the effect of the beach nourishment and its morphological performance and re-publish the original results alongside new findings. The primary objective is to analyze performance of the nourishment, with respect to nourishment changes and morphological responses to the nourishment in the monitoring period. This analysis will therefore mainly rely on the available material from the original report.

The original report also focuses on future planning. In recognition of beach nourishments as an attractive alternative to conventional “hard” coastal protection (such as groynes, revetments and breakwaters), a full-scale beach nourishment was planned on the North coast of Zealand to test the method on inner Danish coastlines in 1984 by “The joint committee for coastal protection and care of the north coast”. At the time, nourishments had already been implemented on some parts of the west coast of Jutland and had gained international recognition.

The main objective of the original report from 1987 was to analyze and demonstrate the protective effects of beach nourishments. An indirect interest in the project was to explore the potential of added recreational values to the beaches.

The overall result from the experiment was expected to establish a foundation for future:

- Rebuilding of retreating coastlines.
- Planning and construction of new beaches for coastal protection and recreational use.
- Cost of projects and long-term effects of beach nourishments.

The morphology response to the nourishment was followed along with the above mentioned planning interest. In order to structure the research and monitoring program, four research questions were formulated:

- I. When and where did changes occur in the nourished sand volume?
- II. How quickly did the nourishment diffuse?

- III. How does the erosion- and deposition rates vary, in and around the nourishment site?
- IV. What is the impact seawards of the nourishment area and on the neighboring stretches?

## 1.2 Criteria's for the nourishment stretch

Using Hald beach as location for the nourishment was based on six criteria that had to be fulfilled:

1. The location should be representative of the general stretch
2. The net-sediment transport (direction) should be clear so interpretation was easy.
3. The stretch, as well as neighboring stretches, should be free from constructions that could hinder the sediment transport. The bottom contours should also be parallel and regular.
4. Accessibility from both sea and land had to be good.
5. Protection of the coastal cliff and improvements of beach quality needed to be relevant.
6. The nourishment area should not be located west of harbors with deepened navigational channels.

Another necessity was to have acceptance from all nearby neighbors.

## 1.3 Decision on nourishment stretch

The stretch referred to as Hald beach was selected for the nourishment campaign as it represented the general North coast of Zealand well. At the time of the beach nourishment the stretch was already affected by different types of coastal protection. The stretch was included, anyway, as it presented other advantages and the six criteria set for the nourishment stretch were almost fulfilled at Hald beach at the time:

1. The coastal profile was characterized by an active moraine cliff, with between 4m and 7 m elevation and a narrow beach with modest sand cover and gravel. The shoreface consisted of abrasion grounds that were characterized by firm bottom layers of clay or stone paving. The moraine cliffs had been receding at least since the 50's and erosion by onshore waves and longshore currents have transported eroded cliff material along and across shore. The eroded cliff materials can be regarded as a part of the sedimentary budget of the stretch.
2. It was shown in earlier reports from the north coast of Zealand that the zero-point for net longshore sediment transport on the stretch was 4 km SW from Hald beach at Kik harbor. The stretch is slightly more easterly orientated, and the primary sediment transport was estimated to be NE-bound.
3. Initially, some coastal protection was found on the neighboring stretches, meaning that the third criteria could not be completely satisfied. Approximately 150 - 200 meters SW of the nourishment, an old pier (made from stones and 70 meters long), with top level a few centimeters above the daily water DNN (1984). This pier might have affected the longshore current, but the permeability of the old pier was expected to allow sediment to travel along. Several other installations existed both up and downstream of the nourishment stretch. The nourishment stretch itself also had hard constructions and the NE-end of the nourishment stretch included existing revetments of different types.
4. Accessibility to the stretch was considered good, as a water depth to 2.5 m was found only 200 meters from the coast. The coastal road was (and still is) located just above the cliff ridge, ensuring easy access with a staircase and parking nearby.
5. All of the stretch, with exception of the municipality grounds, was protected by revetments of varying design, size and condition. The full stretch was found to gain a more harmonic protection and higher degree of effect from the nourishment, likewise, the recreational values were expected to increase, not least due to the parking possibilities nearby. Hald beach was therefore chosen despite the existing coastal protection.

6. No harbors or navigational channels were present in the nearby area.

A more detailed description of the stretch morphology will be presented in the baseline study.

## 1.4 Financing of the beach nourishment

In Denmark it is the landowner's responsibility to pay for coastal protection. This normally leads to coastal protection schemes that focusses on the needs of each individual landowner. This was also the case at Hald beach for a long time. But the "Joint committee for coastal protection and care of the north coast" decided to spend 2 million DKK on the project, raised as follows:

- 50 % from the capital city council
- Frederiksborgs County contributed 25 %
- Each of the north coast municipalities contributed 5 %.
- Additionally a fund of 500,000 DKK was added in 1985 from the ministry of public works, which made it possible to extend the measuring program with wave and current measurements for calibrations of numerical models, as well as for a more extensive coastal mapping
- Danish Hydraulic Institute (DHI) used a research fund of 600,000 DKK and extended the program with additionally 300,000 DKK from their funds. In total 3.4 million DKK was spent on the project.

## 1.5 Definitions and term diagram

As this re-analysis relies on the original report, it is important to note that terms in this document reflect the definitions and terms on morphological zones and elements that are used in the original report. A conceptual presentation of the nourishment and coastal terms are presented in term diagrams 1 and 2 in Figure 1.3, while a characteristic profile at Hald is presented in Figure 1.4. These models rely on the original report with English translations.

Abrasion ground - Shallow area formed by wave erosion. In front of moraine cliffs it is often characterizes by large, sporadically distributed stones and blocks.

Upper beach - The beach part, which is affected by the sea in storm situations and/or during extreme high-water events. Often, there is marine activity in this section of the beach, and no dense vegetation cover is found.

Foreshore - Defined as the zone between the step and the maximum extent for the wave swash. It refers to that part of the beach, which is affected by momentary wave action and therefore shifts position dependent on hydrodynamic forcing.

Beach bar - Low, asymmetric bar form in the upper shoreface.

Trough - Runnels parallel to the shoreline found between breaker bars and beach bars.

Upper shoreface - The zone from the outermost breaker bar to the foreshore.

Lower shoreface - The zone from where waves first affect the seabed to the outer breaker bar.

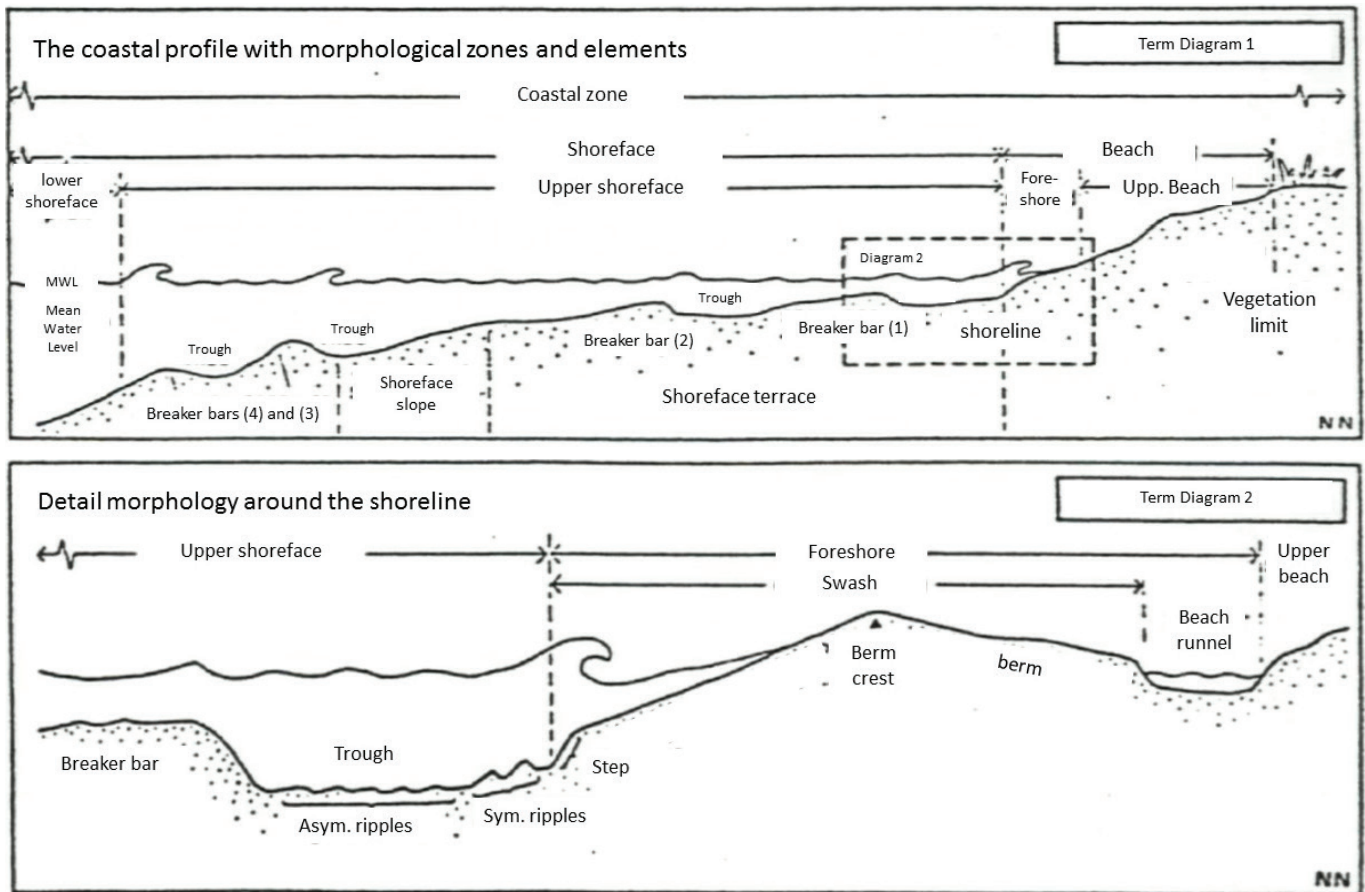


Figure 1.3: Showing an idealized coastal profile and its characteristics. Modified from (Nielsen and Nielsen, 1978)

## 1.6 Nourishment description

The nourishment volume was based on the estimated annual sediment transport along the stretch, which was between 20,000 and 25,000 m<sup>3</sup>/year. The nourishment sediment was required to be slightly coarser than native sediment. Sediment for the nourishment was dredged from the area known as "Grønne revle", WNW of the Hald area. Sediment was dredged below the -8m depth contour. Grain size distribution was tested for every 3,000m<sup>3</sup> and the plant residue content was tested for every 6,000m<sup>3</sup>. Most tests showed that the nourishment sediment was within the desired grain size and the averaged d50 for the nourishment sediment were 0.4mm while the native had a d50 of 0.15mm.

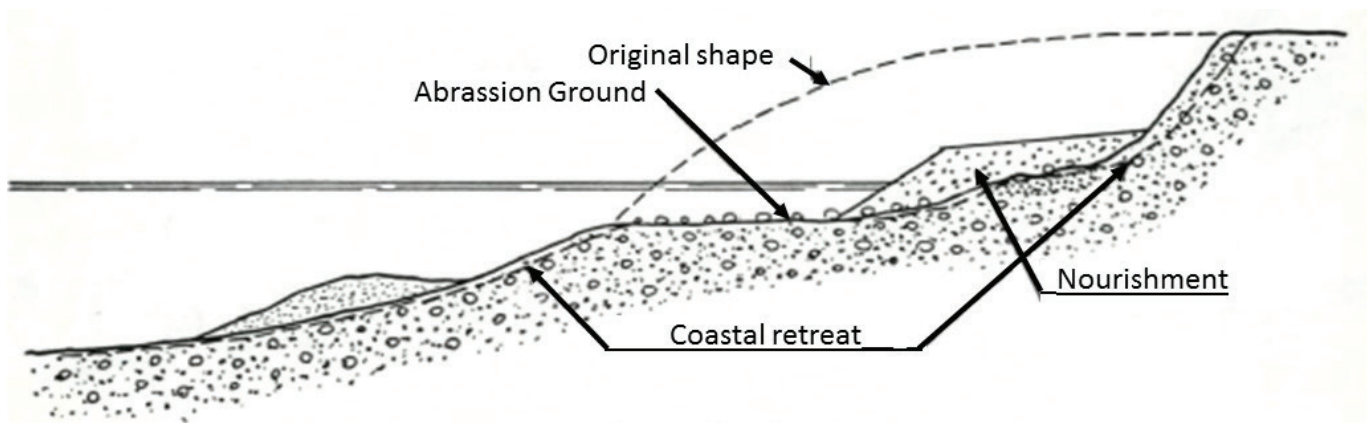


Figure 14: Conceptual figure of the coastal retreat and the nourishment placement. The abrasion grounds are formed as the moraine cliff retreats. The bottom layers consists of hard bottom layers of clays, till and stones, which are left from the moraine deterioration as they are too large for waves and water to move. Other elements exist in the shoreface but are more temporary in nature.

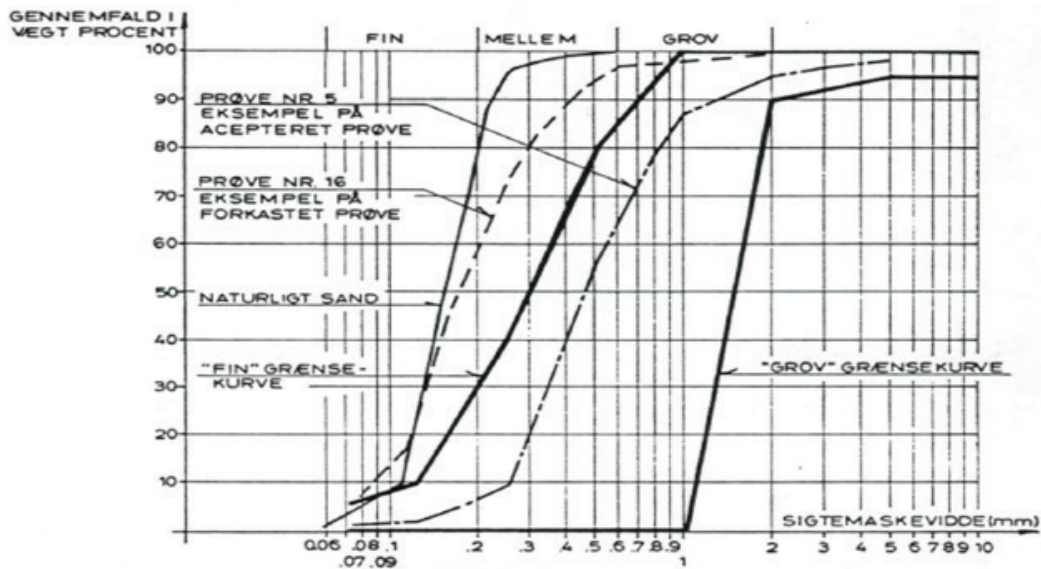


Figure 15: Grain analysis of the natural sediment of Hald beach, and examples on grain analysis from the dredger. A "fine grain" and "coarse grain" limit have been set, to ensure sediment was between the desired values. The limits are shown with bold curves. The solid curve furthest to the left is the native sand.

The planimetric shape was planned so that the orientation of the new shoreline would be perpendicular to the predominant wind and wave directions. This planform requirement was based on the assumption that a perpendicular setting to the oncoming waves would reduce diffusion time and possibly only result in slight leeside erosion of the NE-end. The full extent can be seen in Figure 1.7 while the planned and final planimetric extent of the nourishment is shown in Figure 1.6.

The nourishment was planned to be finished 21st of June 1984 but as problems occurred with the pipeline from the dredger to shore, the nourishment was postponed until a new one could be established. After nourishment was completed, the accumulated sediment formed sand bulges on the beach. Sediment began to redistribute alongshore before dozers could level the sediment into the desired shape. This resulted in nourishment sediment going further to the SW and NE than planned.

The nourishment was finished on August 5<sup>th</sup> 1984 while the final delivery of the project was on 30<sup>th</sup> of August 1984, after dumpers had bulldozed the bulges. The contractor reported that the total nourishment volume was 23,100 m<sup>3</sup>. The volume analysis will later show that the volumetric addition between pre- and post-nourishment was 25,740 m<sup>3</sup>. This was 2,640 m<sup>3</sup> more than reported. Underestimation of volume by the contractor, longshore deposition and/or measuring errors are likely explanations of this difference.

In order to control aeolian sediment transport, wooden windbreaks were erected and marram grass was planted, as well. The windbreak fences were shortened during the monitoring period as the shoreline receded. Photographs before and after the nourishment are shown in Figure 1.7.

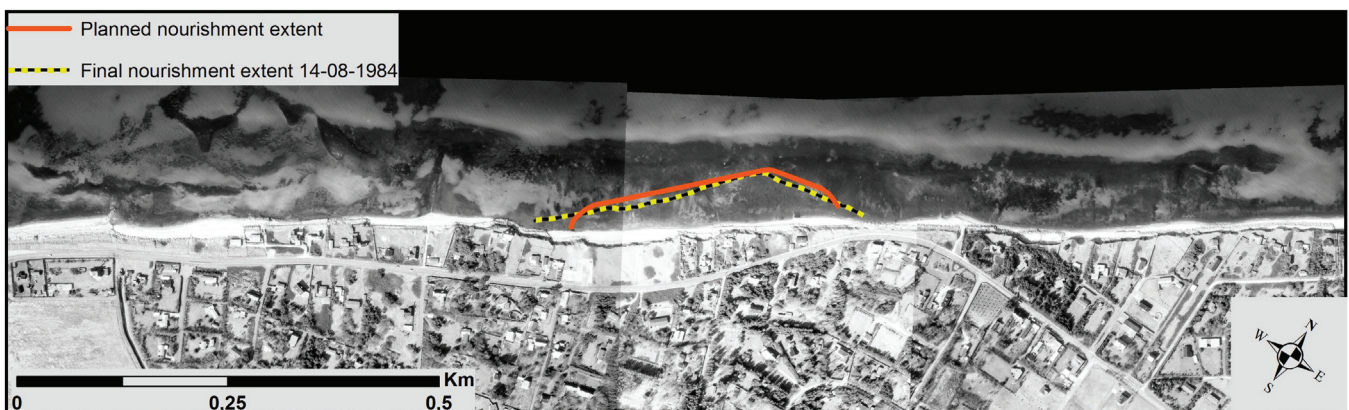


Figure 1.6: The position and extent of the planned nourishment and the actual nourishment extent.

## 1.7 Data

A monitoring program was initiated between August 1984 and October 1986, to track the morphological changes in both nourishment and native areas. The basis of the monitoring campaign was simple: Collect as much information and gain as much knowledge from the beach nourishment as possible, this aim contributed to make the monitoring program extensive.

The data collection and monitoring approach changed during the monitoring period as knowledge and financing increased. To visualize the original monitoring program, including gaps, and terminated data, a timeline with all data collections from the original report has been included in appendix A. Measurement positions have been included on a map from the original report in appendix B. Not all elements have been included in this resumé of the final report, but the following presents the data collection methods used in the original report.

**Wind data:** A self-recording wind gauge was placed at the nourishment stretch. It was set 3 meters inland from the cliff edge and 3.5 meters above terrain, measuring wind in m/s for a full hour every 3<sup>rd</sup> hour. Directions was given in 1/16 parts of a circle. These data are not complete, but the measurement ran uninterrupted for 90 % of the period, and missing data were supplied from the lighthouse wind measurements.

The lighthouse measurements were collected from Spodsbjerg, and compared to those of Nakkehoed. This data series was complete. Wind speeds at the lighthouses were measured as beaufort and in angles ranging in 10 degree spacings, reported three times a day.

**Water levels** were recorded at Hundested harbor, Figure 1.1, and was supplemented with measurements from the local water level board. All water levels are in DNN (Danish Normal Null). Reference level for all topographical mapping in Denmark (at the time). DNN was the average of averaged water level variations in multiple Danish harbors in the inner Danish waters.

**Wave Data:** Significant wave height and mean wave period were measured with DHI's wave buoys. The measurement programs are not complete. The original wave data has not been available for this re-analysis, and will therefore only be presented by the existing figures in the original report.

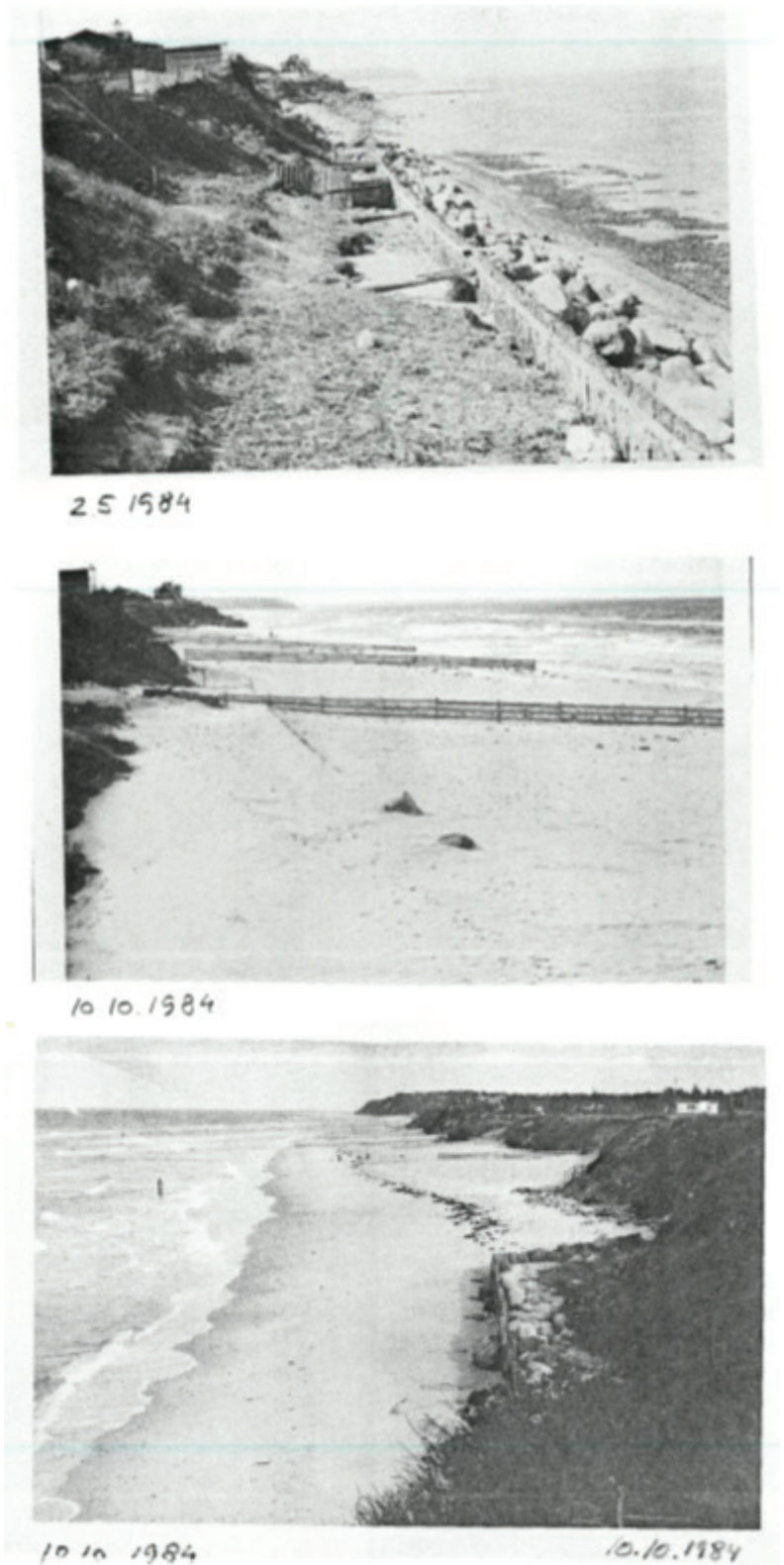


Figure 1.7: Photos before and after the nourishment. The two top photos are from NE of the nourishment facing SW - The house in the upper left corner (Nøddebovej 166) can be used as reference point between photos

Bottom photo is from Nøddebovej 166 facing towards the NE and shows the extent of the nourishment.

**Currents** were measured during several shorter periods by DHI. Sensors monitoring orbital speed in waves, wave period, wave direction, mean current speed and direction were used. The test setup was installed at two depths, 2.5 m and 4.5 m with the sensors set 0.45 m and 1.5 m above the seabed.

**Observations** - Daily coastal observations were conducted manually by an observer between mid-august 1984 and august 1985. The observations were collected in a predefined scheme and contained:

- Wind speed measurement with handheld anemometer at the beach (approx. 2 m above sea)
- The wind direction was estimated
- Estimation of current direction
- Evaluation of distance from beach to wave breaking position, wave approach at the outer buoys and in the inner profile, wave period/height at the outer buoys and wave height in the breaker zone.

Daily observations were terminated as funds for wave and current data was achieved.

**Flight photographs.** Between 1945 and 1980, planview flight photographs had been made 11 times for the nourishment stretch. These were used to establish a baseline study on the natural development on the stretch, making it possible to see the changes from the nourishment in respect to the general patterns.

From 1983, the stretch was photographed nine times (see appendix A for periods) from Hundested to Tisvildeleje. This was in order to follow the evolution of the nourishment, and follow the changes on the coast in general.

It has been possible to retrieve some of the Nadir imagery from before and during the monitoring period from the Royal Danish Library website. This has been compiled into georeferenced mosaics used as background maps in this following report. References are made in accordance with the rules of the Royal Danish libraries regarding references to the original owner and the library itself.

### **Coastal mappings**

Coastal mappings were conducted seven times - these mappings are not necessarily to scale as they are hand drawn based on visual inspection, additional information found from the available arial photographs were added later. Their general purpose was to describe, and not to quantify changes.

**Shoreface surveying** was conducted in two ways:

1. The inner shoreface (shoreline to 0.7 m under daily water) was measured tachymetrically using three established fix points on the cliff front. All measurements were referenced in DNN.
2. Surveys were conducted from boat using sonar for depth measurement and a distance wire from the beach to the boat. In this way a depth and distance to a beach fix point served as profile measurements at depths below -0.7m under daily waters. This was done to a distance of approx. 500 m from the shoreline.

The profile measurements below -0.7 m were conducted in transect lines named after their distance in kilometers from Hundested harbor to Helsingør (No. 0 at Hundested and No. 56 at Helsingør).

The levels of measurements were corrected from locally established fix points, which were in accordance with DNN. Corrections from the watermark were made in respect to the water level board setup in the local stretch.

In order to ensure comparable measurements with the distance wire, an inland baseline was defined each time and distance wires were connected to well-defined constructions. The direction of the survey

was perpendicular to the baseline each time and done with a bearings compass. This gave a  $\pm 1^\circ$  deviation from the line. The depth indication from the sonar were  $\pm 0.1$  m.

### Mapping of the nourishment area

Using tachymetric measurement techniques, 200 to 300 point measurements were conducted for each mapping of the beach. These point measurements were referenced to the three inland fix points in the cliff front and converted to DNN measures<sup>1</sup>. Mappings were conducted within a predefined observation area of 35800 m<sup>2</sup>.

The point measurements were treated in the "COMA" software, which produced a detailed contour map and various difference plans showing volumetric development both in regards to the reference measurement (April 1984), as well as to the most recent measurement. A hypsographic curve model was also produced for absolute, as well as, percentage values for the beach area.

Originally, it was planned to map the nourishment area once a month, but during the winter months January-March 1985 and February 1986 mappings were not possible due to ice covers on the beaches, but successful mapping was made twice in September 1985, before and after a storm.

### Sediment dynamics in the upper shoreface at the nourishment stretch

It was expected that the nourishment sand would redistribute over time, and it was assessed that the main transport would be across the shoreface. Therefore, constructions for underwater measurements of the maximum erosion depths were installed. Steel piles were rammed into the seabed, and a flat plate was placed on top of the piles, making downward movement possible. Maximum erosion depths could hereby be found between surveys, as a downwards movement indicated erosion since last inspection. Of course, the plate could not adjust to accretion, but sediment overlaying the plate could be measured and accumulation was obvious. Originally, three station lines with piles for every 25 meters (300 meters across) were installed. Out of the 36 piles, only two were followed during the monitoring period, as the remaining were damaged by severe weather conditions.

### Mapping of the shoreline changes at the nourishment stretch.

Position of the shoreline was measured on 23 occasions for the nourishment, three times before the nourishment and 20 times after. This was done in two different ways. One method was based on referencing the waterline position between metal piles and coastal mapping by hand, while others relied on true point measurements and determination of the 0 m contours. There are no direct description in the original report on how this determination was performed exactly, but from the original mapping, it is possible to determine that the shoreline position on 12/7/1984, 14/08/1984, 5/8/1985 and 26/9/1986 were referenced as 0 m relative to DNN. The shoreline positions documented in this re-analysis has been drawn on the basis of the original ones and do not serve as quantitative measures, but qualitative measures for description of the planform development.

### Additional profile measurements

In September 1985 five additional transect lines were defined in the stretch NE of the nourishment. These were numbered P1 to P5 - profile measurements were conducted nine times and were measured between the upper beach and seaward to a depth of -1.0 m to -1.5 m, with lengths of between 70-100 m. These profile lines are presented in Figure 3.12.

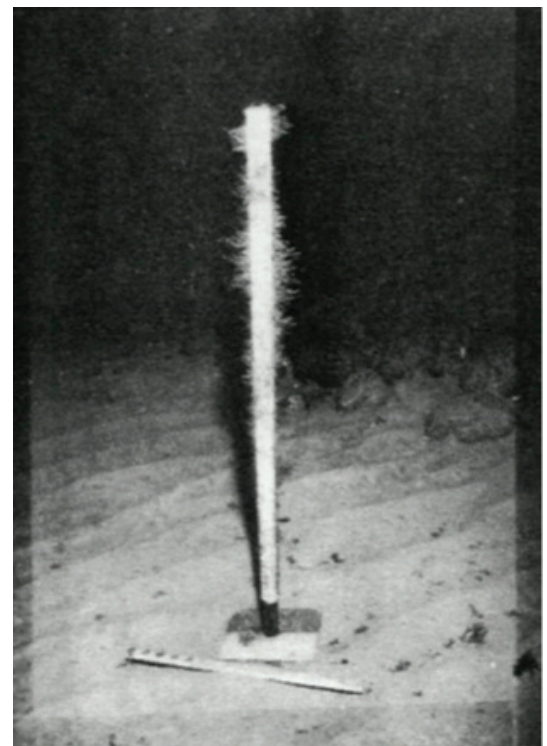


Figure 18: Pile with plate mounted. Found at 3 m depths and as seen, there is a rocky section in the background.

<sup>1</sup> Whether the points were measured sporadically across and along the beach or in defined profiles is uncertain, as description is not included in the original method chapter.

### **1.7.1 Data limitation**

Most of the data from the monitoring program are unavailable and re-analysis will therefore rely on the available material presented in the original report together with plan view imagery retrieved from the royal library, which have been georeferenced and mosaicked in ArcMap. These images stem from the area during the monitoring period.

Some elements from the original report are left out since the data are unavailable or simply not relevant. A numerical modelling of the changes in nourishment planform and volume was performed by the Danish Hydrological Institute, and showed promising results. Since numerical modelling has undergone tremendous development since 1986, the results are not presented in this report.

The original report presents several elements on sediment sampling at the beach and shoreface, which have only been included on a practical level. The sediment analysis were conducted in order to investigate whether the nourishment sediment could be traced among native sediment. Since the nourishment sediment proved to have an overall grainsize diameter, which was double of the native sediments, it was expected to be fairly simple. The results from these analyses are not included in this re-analysis, as they are inconclusive due to the high degree of mobility in the sandy accumulations of the shoreface and beach.

# 2 Baseline study

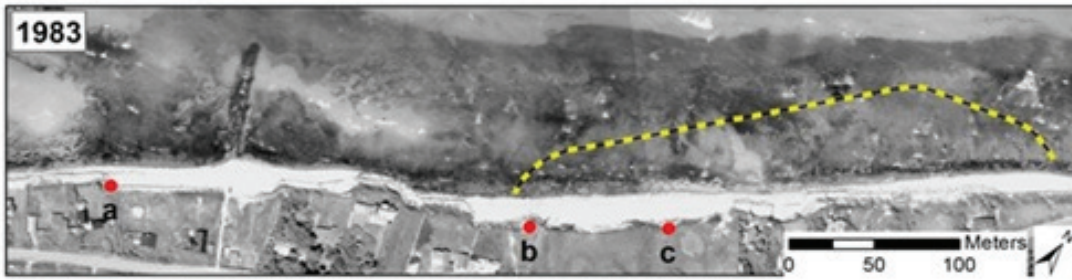
A baseline study of the 30 km stretch between Spodsbjerg (5 km west/upstream of Hald) and Gilleleje (25 km east/downstream of Hald) was conducted in the original report in order to have comparable foundations for the results of the nourishment analysis. This was partly based on a report published in 1984 on the general erosion rates on the north coast of Zealand (between 1897 and 1983, based on coastal cartography). The original analysis included an evaluation of the changes in the beach and shoreface from nadir imagery (1945, 1954, 1959, 1961, 1964, 1967, 1969, 1972, 1974, 1978, 1980, 1983 and 1984). Furthermore, an analysis of the upper and lower shoreface was conducted based on the shoreface surveys described earlier.

The nourishment stretch referred to as Hald beach lies between the small villages “Nøddebohus” and “Hald”, which can be seen in Figure 2.2, and is a part of the overall coastal stretch between Spodsbjerg and Gilleleje. The overall stretch consists of a variety of coastal landscapes from steep moraine cliffs with narrow beach sections and shallow abrasion grounds, to sandy beaches with vegetated dunes in the hinterland and slightly steeper shoreface with quite well developed bars. One overall similarity found in the baseline study of 1984 was that the coast in general was receding along the whole stretch. The coastline changes between 1897 and 1983 was retreat at a rate of between 0.35m/y to 0.75m/y on average.

## 2.1 Hald Beach

At Hald beach the coastal profile consists of 4-7 m high moraine cliffs inland of a narrow beach section of gravel and sand. The shoreface is dominated by abrasion platform, which consists of erosive moraine banks with sporadically distributed clay and stone bottom, occasionally overlaid by sand covers of varying width and depth. The geology is varying along the north coast, but in general the analyzed stretch consists of moraine layers, till/silty layers and additionally a top layer of aeolian sand and marine deposits. Although these different layers consist of different sediment fractions, they all naturally serve as available sediment for the coastal sediment transport processes when erosion is taking place at the cliff toe or material from the cliffs in slumping. It is worth noticing that a layer of Aeolian sand is found in the top of the cliff layers. This must indicate that at some given time, there have been sandy beaches with continuous sediment supply. It was mentioned in the original report that this was confirmed by a local resident, who also mentioned that around 1920 there were sandy beaches and small dune cover in the upper beach, a fact which he could document with photos, see Figure 2.2.

In general, the cliffs at Hald were receding and mean retreat (1945 to 1983) was estimated to be between 0.23 m/y and 0.45 m/y at different points along the nourishment stretch (Figure 2.1) on the basis of coastal cartographic and nadir photography.



- a: West of old lee pier
- b: Public area, at staircase
- c: Public area, central

Planned nourishment extent

Ar	a		b		c	
	1)	2)	1)	2)	1)	2)
1945	0.0		0.0		0.0	
1954	-4.0	-0.4	-1.3	-0.1	-2.0	-0.2
1959	-8.4	-0.9	-0.2	+0.2	-4.5	-0.5
1961	-8.6	-0.1	-0.7	-0.3	-4.8	-0.2
1964	-10.9	-0.8	-0.8	-0.0	-6.0	-1.2
1967	-10.7	+0.1	-3.9	-1.0	-6.2	-0.1
1969	-10.7	0.0	-4.9	-0.5	-10.6	-2.2
1972	-10.8	0.0	-7.0	-0.7	-13.4	-0.9
1974	-15.2	-2.6*)	-8.0	-0.5	-14.1	-0.6
1978	-12.3	+0.7**)	-8.4	-0.1**)	-16.2	-0.5
1980	-12.3	0.0	-8.5	-0.1	-17.5	-0.6
1983	-9.6	+0.2***)	-8.6	-0.0	-17.4	+0.0
1984	-9.4	-0.2	-8.9	-0.3	-17.7	-0.3
1945-84	0.24	m/year	0.23	m/year	0.45	m/year

1: Cliff change relative to 1945 (m)  
 2: m/year since last obs.

\*) Stones installed just west of cliff observation  
 \*\*) Stones installed below cliff observation  
 \*\*\*) Fill of sediment

Figure 21: Cliff edge movement is presented between available imagery (2), accumulated over the years (2) and mean retreat rate between 1945 and 1984. Top map shows nourishment box and where retreat of cliffs were measured (a, b and c). At the position where several coastal protection schemes have been implemented between 1945 and 1984, while c represents an unprotected point. The average erosion is presented in the bottom. Modified from original report.

The retreat is analyzed at three points, and each represents different cliff retreat. Area "c" shows close to double retreat rate compared to "b" and "c," but this is mainly due to coastal protective installations at "a" and "b" between 1945 and 1984 which have temporarily hindered or reduced the cliff erosion, while the beach has been found to narrow while sediment has coarsened.

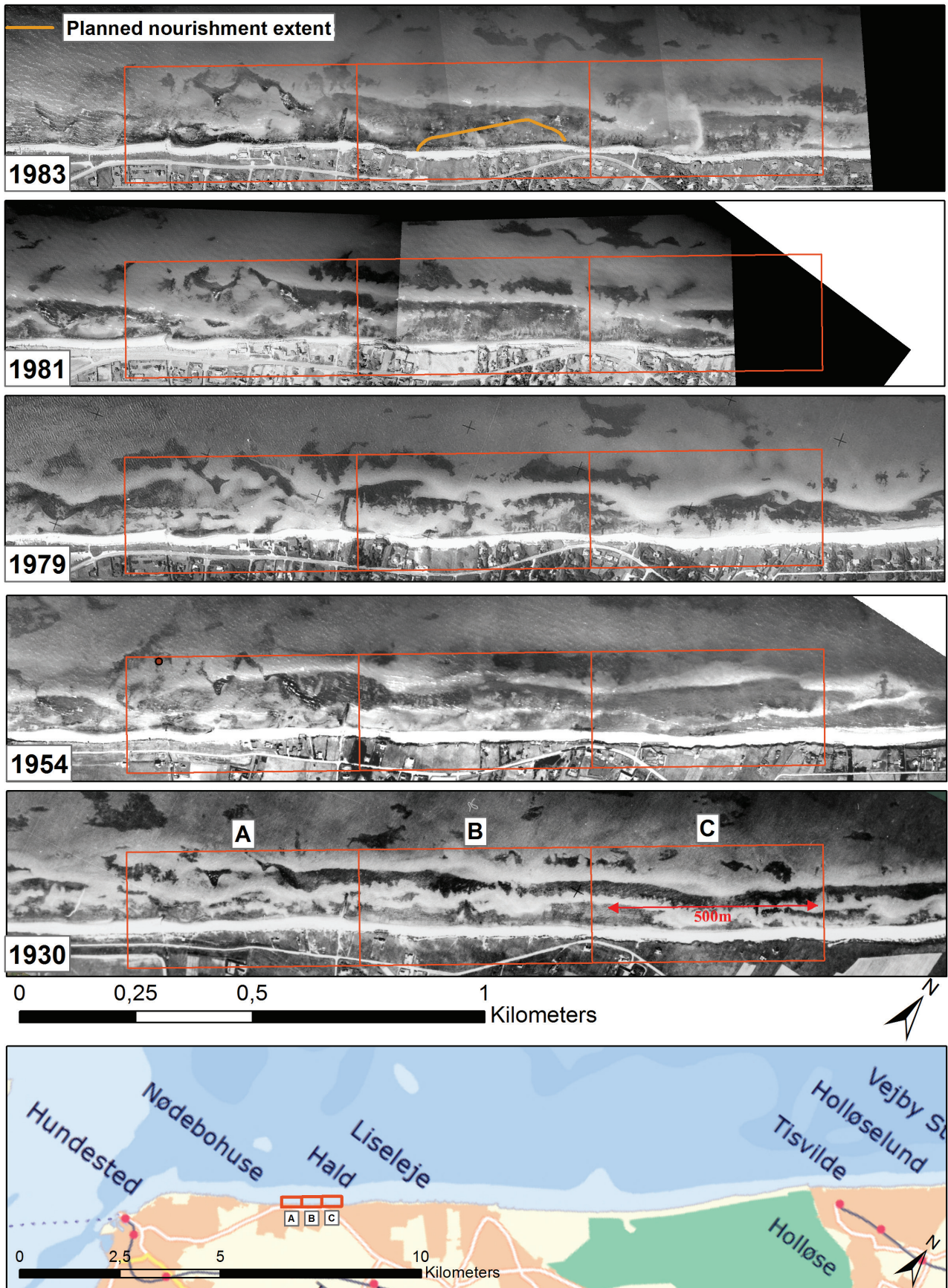


Figure 2.2: Time stack of georeferenced nadir photos from 1930, 1979, 1981 and 1983 together with orthophoto from 1954. Bottom map presents the setting on the overall stretch. The Nadir imagery acquired from (Luftfotosamling & Det Kgl. Bibliotek, 2019) and (Aerokort Luftfoto; Det Kgl. Bibliotek, 2019) has been manually georeferenced and stitched together in arcmap. The precision of the imagery is therefore not guaranteed and inaccuracies could range from cm to m, and not all Nadir tile images were available as seen in 1981. The boxes A, B and C are inserted to divide the stretch. A is referred to as Galgebjerg, B is Nødebohuse

In general, the beach section in the nourishment stretch, as well as the nearby up- and downstream stretches, were observed to narrow during multiple periods in the baseline study, which has also led to a coarsening of the beach material on most of the stretch. Narrowing of beach sections and depletion of sandy sediments in the shoreface were observed in aerial photos from 1954, 1969, 1972 and 1974, it was therefore not considered unusual and a complete sand cover of the shoreface was not observed at any point in the baseline study. Some sandy spots showed to be mobile, but some stayed intact during the years. Underwater observations showed that some spots assumed to be sand were in fact immobile clay layers. A narrowing between 1978 and 1984 was seen in the coastal cartographic and 1984 nadir images indicated the smallest area of sand cover in the shoreface ever discovered from nadir imagery and coastal cartographic.

One of the major changes on the coastline in Northern Zealand was the construction of various forms of coastal protection in a variety of designs. Figure 2.2 shows georeferenced nadir images from 1930, 1979, 1981 and 1983 and an orthophoto from 1954. These reveal details on the differentiated retreat along the stretch. Although not linear, the coast is more symmetric in 1930 compared to other years, but all boxes show a narrower beach in 1983. This is likely to be a result of the impact of various revetments, wave breakers, fences etc. At the beginning of the planned nourishment, the middle of box B shows increased retreat compared to the areas up- and downstream. This increased retreat is the result of leeside erosion from the revetments and the pier to the SW.

## 2.2 Morphology before nourishment

The stretch in box "b" Figure 2.2 is the nourishment stretch known as Hald beach. The stretch is a "steep coast" with a 4-7 m high moraine cliff, a narrow beach section and clay and stone dominated upper shoreface (abrasion platform). The cliff front is actively eroding along most of the stretch where no coastal protection is found. Cliff erosion is also found at some of the stretches protected by fences and revetments. The cliff front is inactive in the NE-stretch due to the walls and fences.

The moraine cliff partly consists of layers of till (mix of sand, silt and clay) with some larger stones. Above the moraine layers, aeolian sand deposits of 2-3 m are found, which testifies to a period with sand surplus. Some of the NE-moraine layers, under the aeolian sand, consist of a thin clay bench with 2-3 m of sand, gravel and pebbles underneath. Generally, the geology represents material, which functions as input for littoral redistribution and profile build up.

The beach width ranged between 0 m and 15 m before the nourishment. Beach material mainly consisted of gravel and pebbles with sporadically distributed larger stones. At the middle section in Box B, where no revetments were found, narrow sand segments were present – see Figure 2.4.

The upper shoreface (shoreline and 100 m seaward) showed unusually low on sandy sediment, as no sand covers were found in the shoreface. These sections were mainly stone paved with sediments ranging from pebbles to blocks, while some bald spots consisted of clay bottoms (can be noticed in Figure 2.3). These bottom types are referred to as "Hard bottom" in the original report and they will be designated in the same way in the following. Beyond the 100 m seaward mark (lower shoreface) sand bars of different width and length were present. They all formed on the hard bottom and consisted of well-sorted sandy quartz sediment. At the time of the nourishment in 1984 the shore and beach had been seen to retreat since 1978, and acute storm recession of the cliffs was therefore expected for the neighboring stretches, as well as in Hald within few storm cycles. Before the nourishment, the upper shoreface was uniform along the stretch though with a few sporadic pockets of sand layers overlaying abrasion grounds and clay/stone paved layers, which were visible between the sand sheets.

### 2.2.1 Coastal protection before nourishment

One of the main considerations when choosing the nourishment stretch was that no coastal protection should be present and it was described in the original report that only few coastal protection installations were influencing the stretch in Hald. However, when all coastal protections are drawn for spring 1984 and presented on a map (Figure 2.3) it is clear that the stretch chosen for nourishment was affected by a variety of coastal protections with different shapes, outlines and proportions.

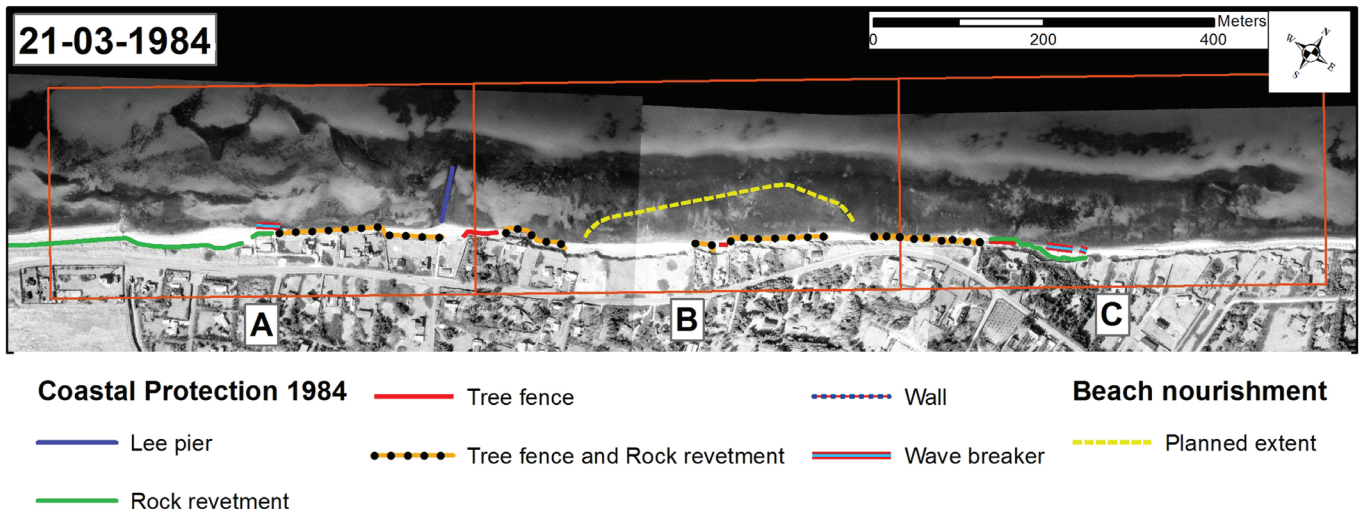


Figure 2.3: The Background photo are georeferenced Nadir imagery from (Aerokort Luftfoto; Det Kgl. Bibliotek, 2019) which is mosaicked. Accuracy is not guaranteed and I likely from cm to m. Coastal protections have been drawn manually on the basis of visual feature, descriptions and other imagery from the period

The old pier, seen in the NE-corner in box A Figure 2.2 and Figure 2.3, lies only 150 m SW of the nourishment stretch. It was described in the original report as consisting of large stones and with a primary height just above daily water (1984). Although in poor condition, the leeside erosion is considered to have had an effect on the nourishment stretch. For an overview of the different types of revetments, wave breakers, fences etc. Figure 2.4 shows the combination between tree and stone revetments - the photo is from the middle of the planned nourishment stretch with view towards SW, showing the stretch before nourishment.



Figure 2.4: Image taken from the original fix imagery point C. Looking from NE towards SW - The old pier can be spotted in the shallow water to the right of the house at Nøddebovejen 166 (May 1984). Photograph is from (Fællesudvalget, 1987)

### **2.2.2 Sediment budget at Hald beach**

Considering a closed system where the sediment volume in a defined box remains the same, despite along- and cross-shore transport, the ideal coastal profile establishes an equilibrium profile in respect to the prevailing hydrodynamic forcing. Theoretically, storm conditions will transport sediment from the cliffs and beach out into the profile, reducing the slope gradient and building up breaker bars. During calmer periods, sediment is transported shoreward and builds up in the beach berm or upper shoreface. For a coast to be stable, sufficient sediment must be available so that profile adjustments are unhindered, at least until an energy level corresponding to average conditions are reached.

In general, the sediment budget for the coastal stretch west of Liseleje was out of balance. Longshore transport was primarily taking place in the shoreface on the sandbars. The transport capacity was above the actual transport due to sediment deficit caused by passive coastal protection structures. This led to incomplete profile adjustments, which again led to increased exposure of the cliff to storm events. Sediment released from acute erosion in the cliff fronts was quickly redistributed alongshore due to the excess transport capacity. The recession is then likely to escalate, as no increase in volume on the immediate stretch is encountered. Continued sediment deficit will allow storm waves to erode the cliffs further, while the instability in sediment budget increases if it is not compensated from upstream. As cliff retreat has been counteracted by "hard" coastal protection in a variety of designs, the release of sediments from the upstream stretch has decreased, which again leads to a further deterioration of the beach and shoreface.

The decrease in available sediment on the stretch between Hundested and Liseleje is complex and a combination of several elements. The main factor was likely the decrease in available sediment (due to passive hard coastal protection).

# 3 Analysis of nourishment 1984 - 1986

The analysis of the nourishment was originally focused on the objectives described in section 1.1 and should establish a foundation for future reconstruction of retreating coastlines, planning and construction of new beaches for coastal protection and recreational use. This would improve economy of projects and long-term effects from beach nourishments.

The primary interest in this project is to analysis the performance of the beach nourishment, with respect to nourishment changes and morphological responses to the nourishment in the monitoring period. The research questions from section 1.1 was:

- When and where did changes occur in the nourished sand volume?
- How quickly did the nourishment diffuse?
- How does the erosion- and deposition rates vary, in and around the nourishment site?
- What consequences are found in the seaward development of nourishment area, as well as in neighboring stretches?

This report has been structured accordingly. As the weather and hydrodynamic forcing influence the nourishment over time, the weather conditions in the monitoring period will be presented in 3.1. This section includes a short summary on three significant storms in 1985. In section 3.2 the changes in the nourishment profiles and planform will be analyzed while a subsection handles the shoreface development separately. Section 3.3 focuses on the volume changes during the monitoring period, and a subsection is devoted to test the fit of two theoretical models on the volume diffusion. Section 3.4 elaborates on the impact seen in the downstream stretches of the nourishment and effects seen in these areas.

## 3.1 Weather conditions during the monitoring period

### 3.1.1 Wind conditions

Wind conditions are presented in Figure 3.1 and Table 3.1. Here, wind measurements from the local wind gauge and Spodsbjerg Lighthouse are presented for the study period between 16/8/1984 and 7/9/1986 and two reference periods (1981 - 1983 and 1981 - 1986) in Table 3.1. Reference periods are included to facilitate comparison with wind conditions during the monitoring period.

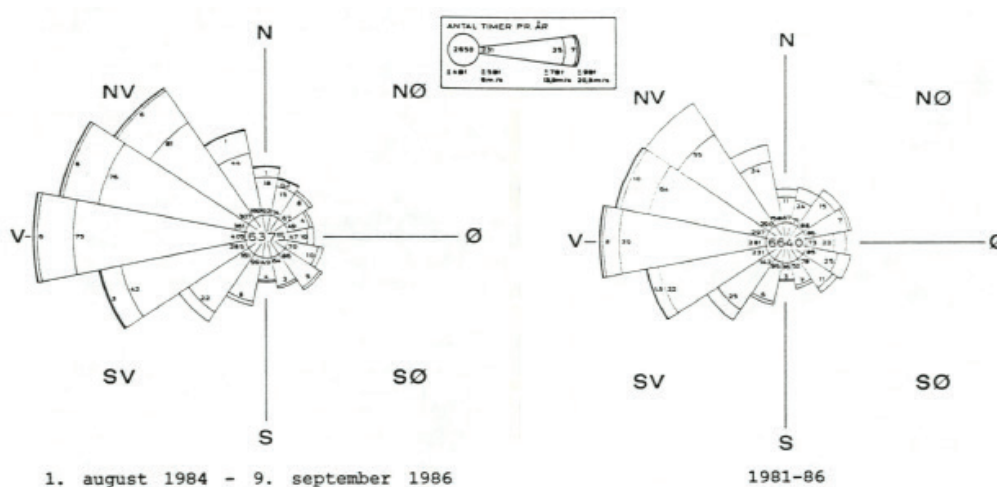


Figure 3.1: Wind roses from Spodsbjerg lighthouse, both from the monitoring period (Left: 1 august 1984 - 9 september 1986) and a 5 year period for comparison (Right: 1981-1986).

Wind speed and direction were observed visually three times a day (08:00, 14: 00 and 21:00) for Spodsbjerg lighthouse, 4 km SW of the nourishment stretch. These measurements were conducted by the metrological institute and the period between 1981 and 1986 was included in the original report. An automatic wind gauge was installed at Hald Beach and it measured from 1/8/1984 to 9/9/1986 and was used as reference to the lighthouse observations.

When looking at Table 3.1 it is clear that the study period was slightly milder than both reference periods. The study period showed that wind speeds above 7Bf were 30 % less frequent than in the reference period between 1981 and 1986. Looking to the wind rose in Figure 3.1 (from the original report) wind from the west was slightly more dominant during the study period than during the reference period between 1981 and 1986.

Wind statistics for wind >5Bf and from WSW,W,WNW,NW,NNW,N,NNE,NE (only onshore winds)									
Wind speed m/s		>8,0	>10,8	>13,9	>17,2	>24,5	>28,5	>32,7	
Wind speed Beaufort ( Bf)		>5	>6	>7	>8	>9	>10	>11	
Locality	Period (incl.)	Years	H/y	H/y	H/y	H/y	H/y	H/y	H/y
Spodsbjerg Lighthouse	1981 - 1983	3	844	710	347	84	17	14	3
Spodsbjerg Lighthouse	1981 - 1986	6	776	625	301	70	14	9	1,4
Spodsbjerg Lighthouse	16/08/84 - 7/9/86	2	674	521	227	51	15	8	
Hald beach	16/08/84 - 7/9/86	2	776	401	161	36	15	3	

Table 3.1: Values are presented as hours/year in the respective periods. Note that the period between 1981 and 1983 shows stronger wind conditions than the remaining periods. Wind measurements are described under the data section in chapter 1.

### 3.1.2 Water level conditions before and during the study period

High water events are of special interest to the coastal development as they may cause waves to break further onshore. The complete dataset on water level is not available. Overall findings described in the original report were that the water level during the study period was not unusual, but did present some differences compared to other years. There was a slightly lower frequency of water levels between 40 and 120 cm (above DNN), while there was a higher frequency of water levels above 120 cm (above DNN) than expected. These high water events can be explained by multiple storms during the study period. Maximum water level in the period was 162 cm above DNN, which at the time was equivalent to a 50-year return event.

### 3.1.3 Wave conditions before and during the study period

Wave conditions in this region depends on the wind, since the wave climate is mainly wind driven. Although the winds have not been as long-lasting or strong as during the period of comparison (1981 to 1983), potentially, there can have been a greater NE-directed longshore transport, as westerly winds were predominant. The incoming wave angle can therefore have slightly more oblique angles to the coast combined with slightly more frequent high and extreme water levels. The largest waves registered by the wave buoy in the study period was  $H_s=2.78\text{m}$ . As the only previous wave measurements was conducted as observations from a lighthouse ship on deeper water (1962-1971), it is difficult to compare wave conditions during the monitoring period with earlier measurements. If measured data from Hald is related to those from the Lighthouse ship data, the maximum wave height would be equivalent to a 1 year return event.

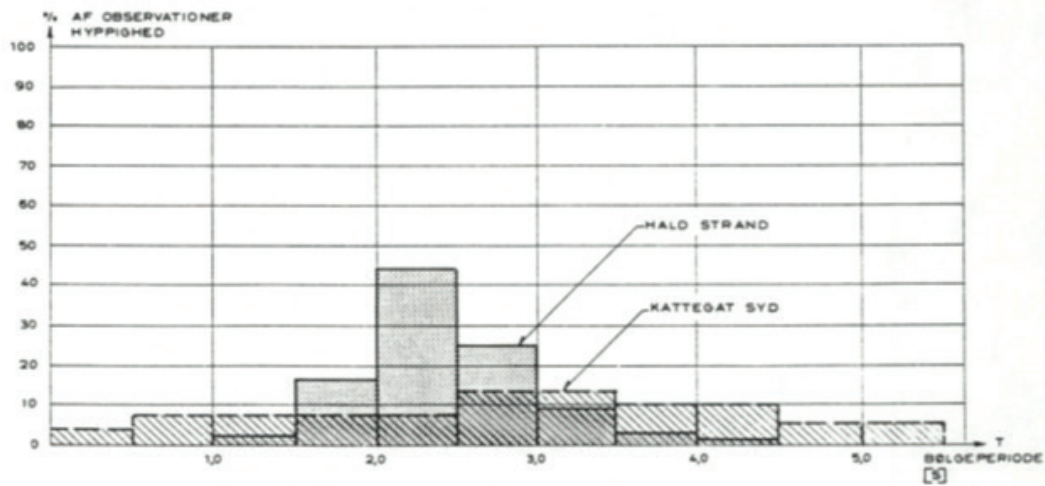


Figure 3.2: Frequency distribution of wave periods, observed at the lighthouse ship Kattegat S (1962-1971) and Hald Beach measurements (1984-1986). The Y-axis shows the % of observations while the X-axis shows the wave period.

The two sets of wave measurements are presented in Figure 3.2. Short period waves (below 3s) are dominating the stretch. This corresponds with the short, but fast waves, often observed, which have developed over short fetches. However, in the original report, it was noted that there could have been larger waves, but they may have been filtered out in observation, as they were overtopped.

### 3.1.4 Current

No previous current data existed so no comparison could be done for these data. A main result from the current data was that there was a short response time between wind and current, and it was identified both from SW and NE. Highest current speed was measured in April 1985 in SW-direction when the outer current measure showed 0.72 m/s while the inner current measure showed 0.6 m/s.

### 3.1.5 Storm events 1985

Only wind strength and direction have been included for the measuring period above, but as the late summer and autumn of 1985 presented a storm cycle with three distinct events, they are presented in greater detail here. The volumetric changes between the events are described in Table 3.2 in chapter 3.3.

First year of the monitoring campaign went without any extraordinary weather events. However, in the autumn of 1985, three low-pressure system passed Denmark and three storm events passed with only a month between each. All three were different in energy and effects, and in the following, each event is presented together with description and characterizations:

### September storm 1985

On the 5<sup>th</sup> of September 1985, a low-pressure system appeared and was slowed by the Norwegian highlands which made it circulate for the following three days. This meant that on the 6<sup>th</sup>, wind strength went from 5 m/s from SE (offshore) to 27 m/s from NE (longshore), creating a wave front almost parallel to the coast. The storm exceeded 20 m/s for 26 hours, which was followed by wind speeds of 10 m/s for more than five days. Wave heights were not recorded during the storm, as the wave buoy was non-functioning, but from visual inspection  $H_{max}$  was estimated to >2.5 m. The loose sediment on the shoreface must therefore have undergone redistribution, but a net transport direction was difficult to distinguish. The highest water level was measured to be +1.2 m above DNN, but this peak did not occur until one day later than the storm peak. If a more northerly or westerly wind had prevailed during the storm, the water level would potentially have been higher.

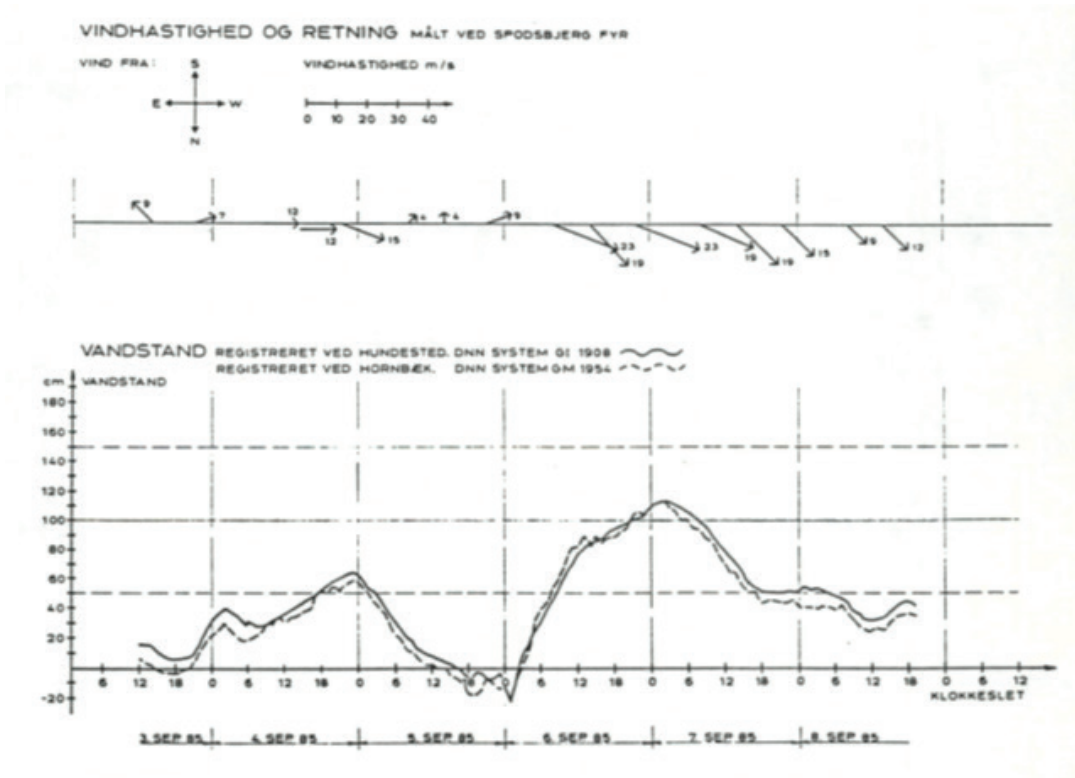


Figure 3.3: Wind speed, Wind direction and water level measurements from 3<sup>rd</sup> of September 1985 to 8<sup>th</sup> of September 1985. The figure is directly depicted from the original report without translation, to avoid loss of information in the graph.

### October Storm 1985

This storm period does not show as high wind speeds nor as long a storm duration as the September storm. Wind direction and speed follow a classic cyclone pattern for the region. Wind speeds increase over a 20 hour period from 5 m/s to 23 m/s. The wind direction changed from SW to NW at the storm climax in a clockwise manner. During the following 24 hours, wind speed decreased and the wind direction changed to NNW and later to N. Wave height in the upper shoreface has possibly been lower than what was registered by the wave buoy (>2.5m) due to wave breaking, and it is estimated that the waves in this October storm were smaller than the once encountered in the September storm.

During the first 24 hours, longshore transport was towards NE, decreasing to almost none, while at the end of the period a smaller energy component and shift in wind direction meant longshore transport towards the SW. High-water level reached 1.06 m and peaked half a day after the storm peaked.

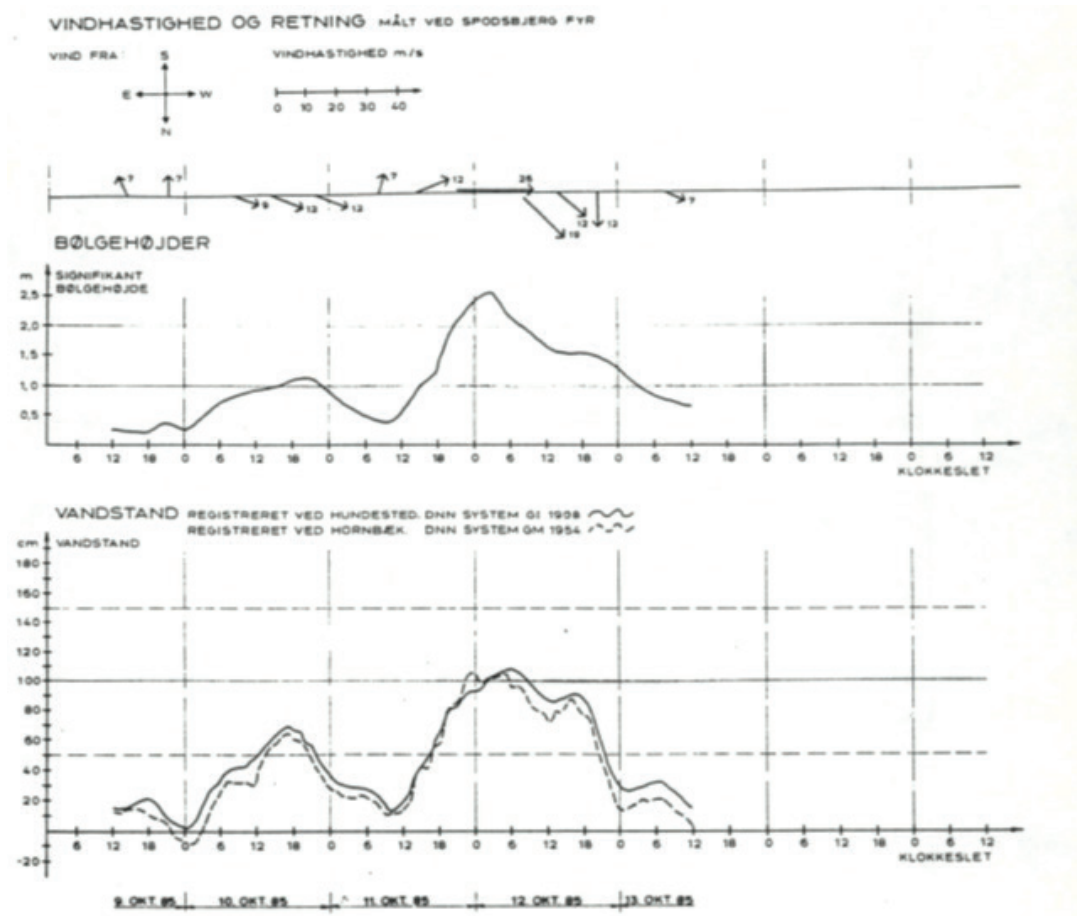


Figure 34: Wind speed, wind direction and water level measurements from 9<sup>th</sup> of October 1985 to 13<sup>th</sup> of October 1985

### November storm 1985

Wind speeds during this event were the lowest of the three incidents and includes multiple peaks at 20 m/s from a westerly direction. During the storm peak, the waves took an oblique angle to the coast normal and would therefore be expected to have refracted in the nearshore at the coast. However, the longshore transport must have been towards the NE. The atypical circumstance for this scenario was the extraordinary high water level at +1.62 m, which was equivalent to a 50-year return event. The high water event is explained by the mass of water being pressed from the North Sea into Kattegat in combination with wave setup at the shores. The high-water peak was found again after the storm peak. As the coastline was still affected by swell waves during the high water peak, this is expected to explain the acute erosion in the cliffs around the nourishment stretch during the storm.

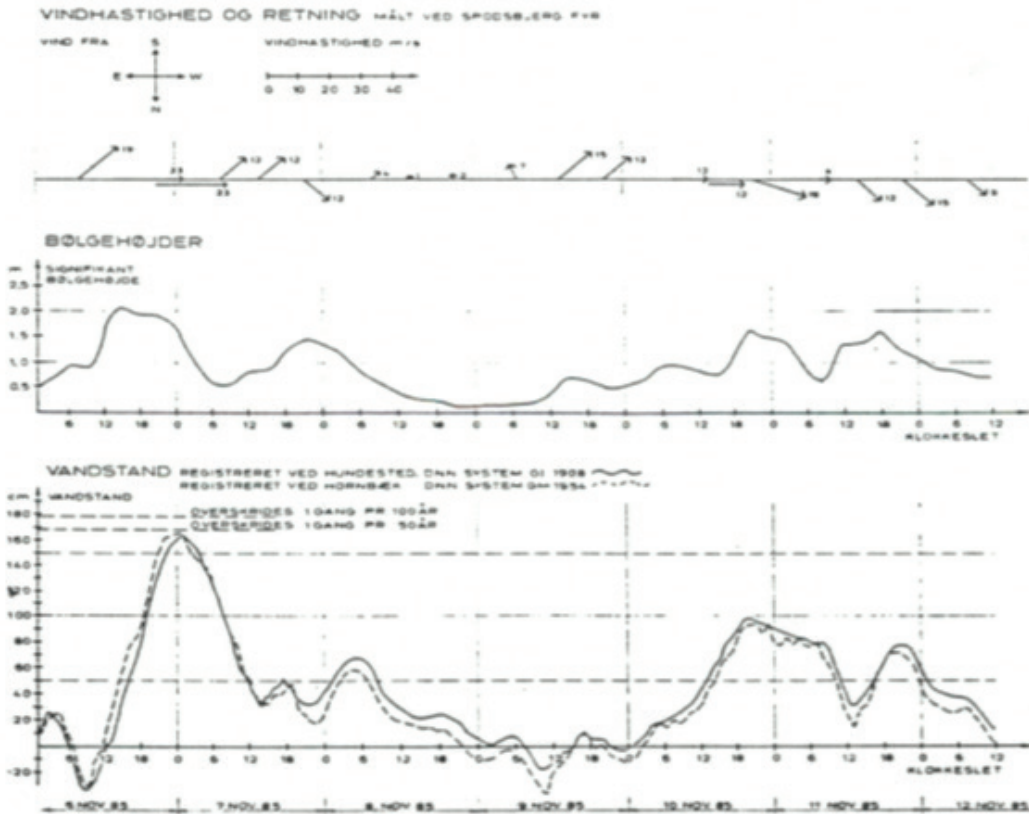


Figure 3.5: Wind speed, wind direction and water level measurements from 6<sup>th</sup> of November 1985 to 12<sup>th</sup> of November 1985

### 3.2 Nourishment planform and profile development

The nourishment was planned to be 23,100m<sup>3</sup> of coarse sand pumped onto the beach from a ship and redistributed by dumpers on the beach into a trapeze shape. The nourishment was finished on the 30<sup>th</sup> of August 1984 and the final shape is seen to be close to the planned from Figure 3.6.

The nourishment planform was registered 23 times during the monitoring period (Appendix A). Not all 23 mappings have been available to this re-analysis and therefore only planforms presented on maps from the original report have been included here, this time in a new map (Figure 3.6). The shoreline has been determined visually in coastal mappings and from tachymetric measurements.

Profile measurements have been carried out for the six transect lines seen in Figure 3.6 and profile measurements are presented for four dates in Figure 3.7. Averaged profiles during the storm period in September to November 1985 are included in Figure 3.8.

The nourishment was completed on the fifth of August 1984. Redistribution by dumpers and final delivery of the project from the contractor was on the 30<sup>th</sup> of August 1984 while the first tacymetric measurement was conducted on 14<sup>th</sup> of August 1984.

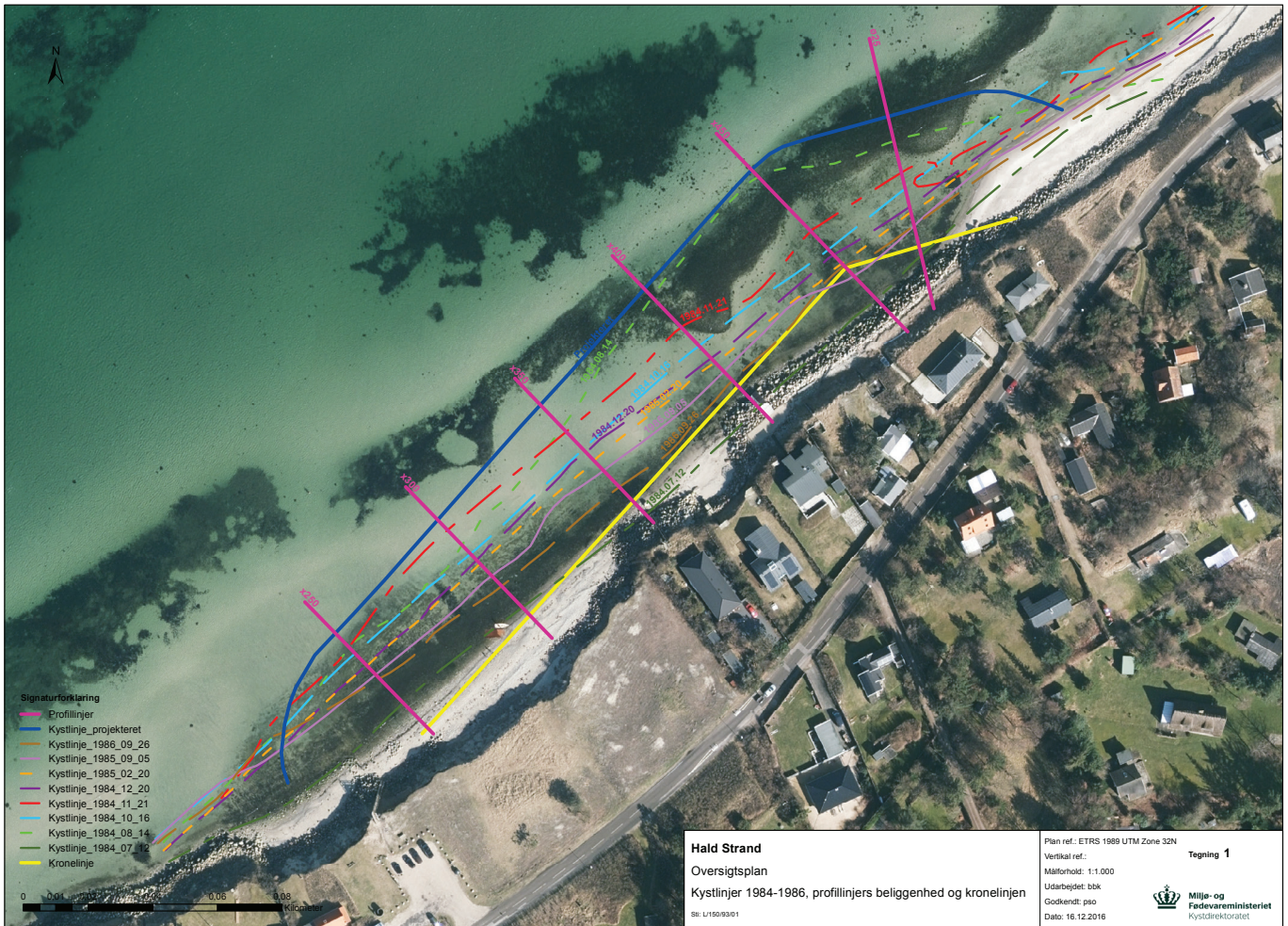


Figure 36: Showing the area distribution and changes in the shoreline over time. Profiles are shown in Figure 3 4

As seen in Figure 3.6, the shape of the nourishment was close to the planned trapeze shape, but did not extend as far seawards as planned. This was partly due to natural equilibrium processes and reshaping of the nourishment planform, which took place immediately after nourishment.

Within 3-4 months, the nourishment area was reduced with 32 % because of redistribution and equilibrium processes. This also meant that the nourishment was reshaped from trapeze to rectangular and parallel to the existing coast. Reduction of nourishment area was a result of longshore transport, both up and downstream, which increased the beach width in the neighboring stretches. The downstream beach did widen between 16-10-1984 and 21-11-1984 but this addition was reduced again on the 20-12-1984 (Figure 3.6). The widening in the NE neighboring stretch corresponded well with the primary transport direction towards NE. Although the nourishment area was reduced by with 32 % during the first four months, the following 21 months showed an overall reduction of 22 % of the remaining nourishment area.

In the period between December 1984 and 20-02-1985, the beach width remained relatively constant and no erosion in the upper beach was found in the coastal mappings nor from observations or measurements. One main factor in the low retreat rate was that a thick ice cover in early 1985 prevented erosion in the beach and upper beach, as the water level raised and waves simply did not reach the sediment. However, this affected the shoreface where retreat increased.

In the period from February 1985 to September 1985 a moderate erosion in the foreshore can be seen both from profile measurements in Figure 3.7 and from the nourishment planform in Figure 3.6. A small widening is noticed in the SW corner, just outside of the nourishment stretch. Despite the erosion at the foreshore, the profiles in Figure 3.7 show a positive buildup in the upper shoreface in the form of small bars, which have developed during the period.

From September 1985 until September 1986, the nourishment planform did not change significantly but larger and more widespread erosion is found in the shoreface, which is also seen from the profiles in Figure 3.7. The beach was affected by ice from December 1985 until February 1986, which resulted in erosion patterns similar to those found in the winter period 1985, when erosion increased in the shoreface. The profile measurements from 5-9-1985 and 26-9-1986 in Figure 3.7 suggest a longshore sediment redistribution in the bars and shoreline during this period. Generally, the profiles show retreat above the 0 m contour during this period. The shoreline position also retreats slightly between 05-09-1985 and 26-09-1986, except at line X450 and in the SW-corner of the nourishment stretch where the shoreline advances, see Figure 3.6.

Some of the changes in the profiles between September 1985 and September 1986 can be attributed to the three storms between September 1985 and December 1985. These three storms (Section 3.1) were different as regards energy, water level, wind direction, etc. but the profile impacts were comparable and resulted in similar morphological changes. The averaged profiles (transect lines seen in Figure 3.7) before and after each storm period are presented in Figure 3.8 and they show a common pattern, since the upper beach levels are eroded, as well as the upper shoreface, while the foreshore experiences a sediment addition, which results in a decrease in slope gradient. The retreat in the upper beach (above 0.8 m contours) can be traced to a redistribution in the foreshore, as well as in the longshore component. However, the upper shoreface does retreat, a fact for which the nourishment sediment does not compensate directly, but instead bars are found to migrate along and across this profile section.

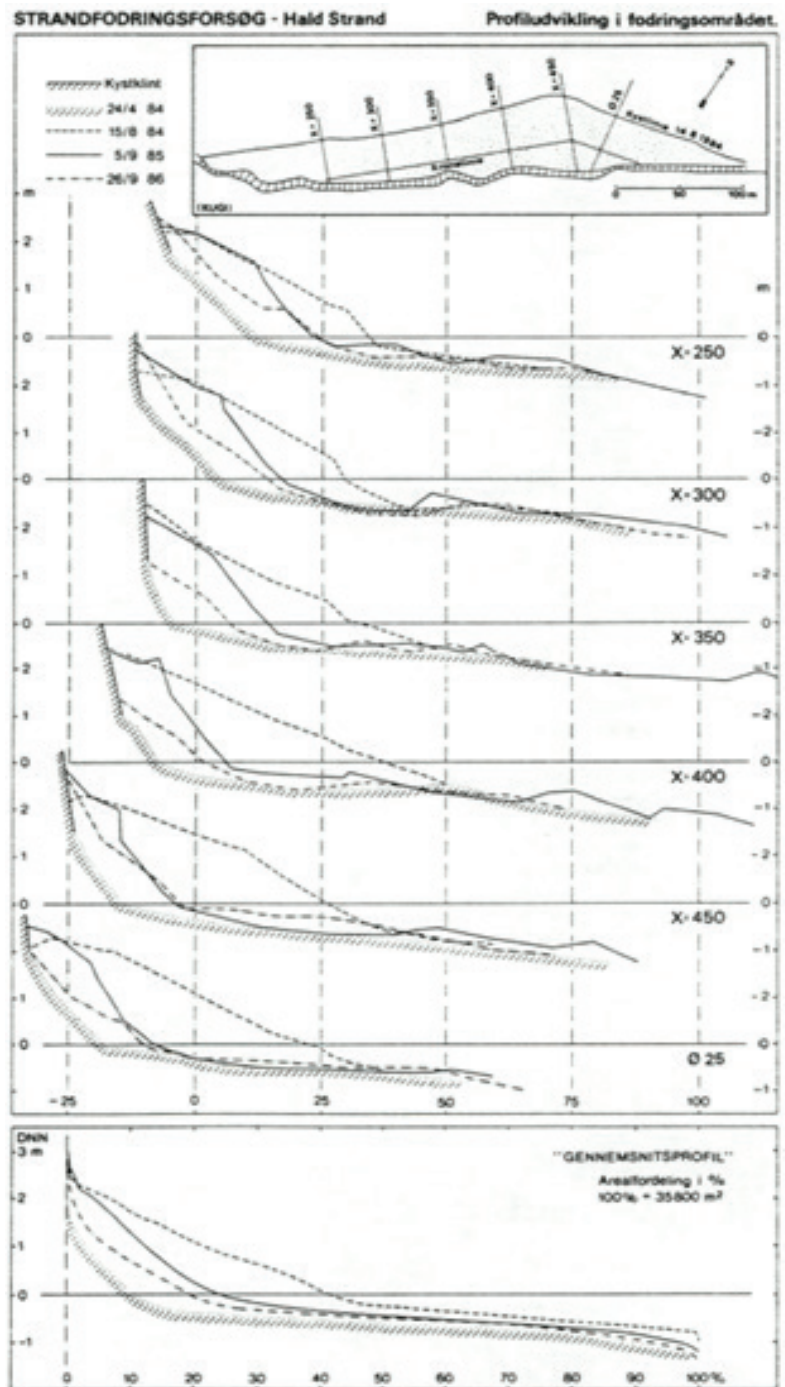


Figure 3.7: Profile measures for the nourishment stretch are presented for all with dates, together with the avg. profile in the bottom graph.

The storm between the November 6<sup>th</sup> and 7<sup>th</sup> did not have the same wave intensity or energy as the September and October storms, but retreat in the upper beach and nourishment was of the same magnitude, as seen in the earlier storms. The explanation could be the unexpected high water level, which reached 1.62 m above DNN (50-year event at the time) during the November storm. If we consider the average profiles of 25-10-1985 and 14-11-1985 in Figure 3.8 we will notice that retreat is only found above  $\approx 0.8$  m contour, while profile height increases and advances slightly below the 0.8 m mark. As the water level was higher during this storm event, than during the other storm events, it may have given way for erosion in a profile above past water levels, which peaked at 1.16 m and 1.06 m in September and October, respectively.

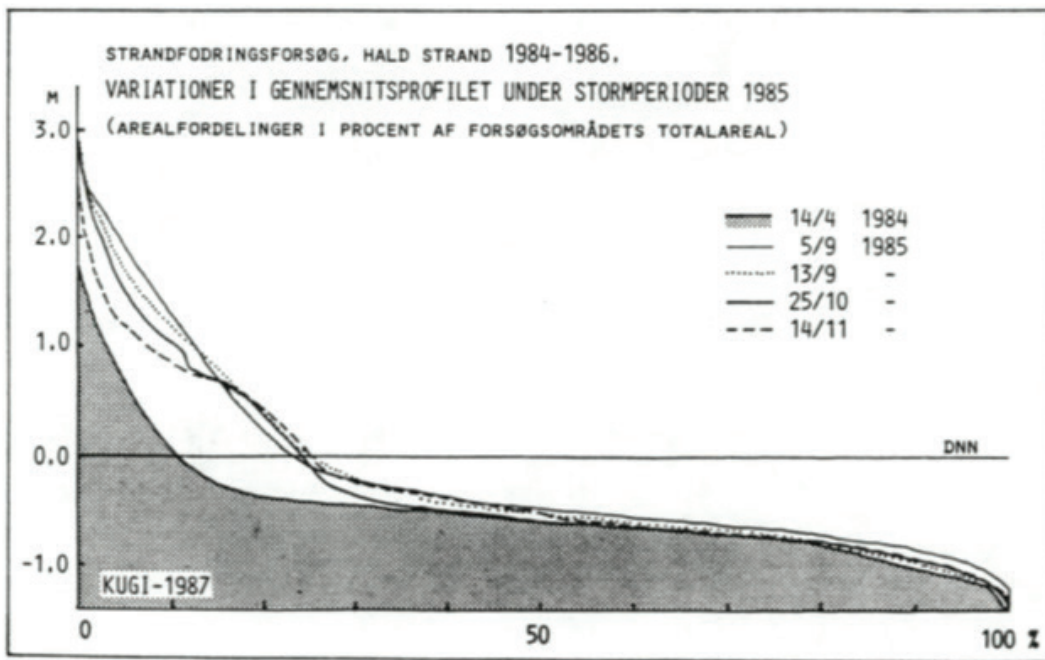


Figure 3.8: Variations in the averaged profiles during storm periods in 1985. Distribution of area in percentage between contours.

### 3.2.1 Shoreface

The hypothesis of sediment exchange between nourishment and breaker bars was not confirmed directly from profile analysis. The shoreface shows different developments depending on depths. Changes between the -0.8 m and -1.0 m contours only take place directly after the nourishment, and in the winter periods, while for remaining periods it is stationary. The sections between -0.2 m, -0.4 m and -0.6 m contours migrate seawards while the slope gradient between each of these contours decreases. Indications of buildup of smaller breaker bars and slight elevations in the upper shoreface between profiles was also found between storm profiles but they show to dissipate over time. These changes correspond well with the mobility of the sand covers of the shoreface, which was inspected in the baseline study, and it is therefore not possible to confirm whether the buildup is a response to cross-shore transport of nourishment sediment or longshore transport from neighboring stretches.

Underwater observations showed that areas containing layers of unconsolidated sandy sediment in the shoreface could be as low as  $0.2 \text{ m}^3/\text{m}$  and almost all of the sediment mass is redistributed even during moderate storms. The mobile sediment was found to be arranged in wide longshore sand covers or in temporal breaker bars. The 2<sup>nd</sup> bar with bar front (landward) 100 m seaward from the shoreline seems to be stable in position despite fluctuations in the total sediment volume in the area.

Another part of the underwater shoreface analysis was tests of grain size distribution cross-shore as the nourishment sediment possibly might be identified among the native sediment. If so, this could have indicated a precise measure for the transport direction, for example if nourishment sediment had been identified in the outer breaker bars. The analysis of the shoreface did unfortunately not provide any evidence of changes in the sediment distribution that could be attributed to the nourishment. Regular and expected seasonal fluctuations were identified, but any nourishment sediment in the samples was blurred by these variations.

### 3.2.1 Summary

The planform and profile measurements showed rapid reshaping and reduction in the dry surface area. The nourishment stretches far into the previous section of the upper shoreface, which increased the exposure of the sediment for redistribution by water and longshore currents. The reduction was a natural response to sediment deficit. Although the trapeze shape was supposed to reduce the shoreline retreat,

the nourishment planform was reshaped into a rectangular form within months, but after that the reshaping rate was reduced.

Both erosion and deposition occur between all measurements for the individual profiles, but the averaged profiles show that the primary retreat of the post-nourishment profiles is taking place in the nourishment sediment. Looking at periods between measurements, the individual profiles show accretion in the foreshore and swash zones while erosion takes place in the upper beach and in the shoreface. The dynamic build-up in foreshore and swash zones is created by sediment transport to the berm during calmer periods but is also found to be redistributed over time in response to the general sediment deficit. High wave conditions happen at high water level events, which results in erosion of the upper beach. This then releases sediment to the foreshore and nearshore bars, but the longshore gradient transports part of the sediment alongshore before it settles in the nourishment stretch. As aeolian transport is limited due to the narrow beach and since combinations of high water and low energy waves are rare, the sediment is rarely transported back to the upper beach section.

Generally, the nourishment has actively protected the cliff-face from further retreat during the monitoring period, and the difference between the reference measurement from 24<sup>th</sup> of April 1984 and the final measurement on 26/9-1986 shows that beach width has doubled and advances are seen in the contours between 0 and -0.8 m. Since the planform decrease and the post-nourishment profile show retreat, the nourishment volume is either redistributed cross-shore outside of the analyzed profile, alongshore, primarily in downstream direction, or both. Indications on increases in beach width for neighboring stretches have already been identified and this will be further elaborated in the following chapter.

### 3.3 Volume development

The volume analysis relies on tacymetrical measurements corrected to DNN and mapped in the software "COMA". These were conducted on 23 different field campaigns. First measurement was made on 24<sup>th</sup> of April 1984. The first measurement is used as reference for the volumetric development over time. Measurements were conducted within a pre-defined area of 35,800m<sup>2</sup>. Whether measurements were conducted sporadically, as profile or from other criteria is not described in the original report. Precision is obviously difficult to estimate at present time, and the data presented in the original report will also be the data included in this report. The quantified volume development is found in Table 3.3 and Table 3.4.

The difference between reference- and post-nourishment measurements showed a deposition of 25,740 m<sup>3</sup> of sand. This was approx. 2,500 m<sup>3</sup> more than designed. The excess sediment can possibly be explained by measurement inaccuracies, additional volume from the dredger or simply due to natural addition of sediment from profile adjustments. The 25,740m<sup>3</sup> will be considered as the actual nourishment volume in the section.

Looking to the full period from 1984 to 1986, it is obvious that the general trend is erosive (Figure 3.9). The best trend fit is a polynomial, and it describes the diffusion of the nourishment volume with a R2 value at 0.94. Smaller accumulations exist between some measurements. Accumulation zones can be determined between all measurements and the erosion/accretion is presented in Table 3.4. The accumulation is mostly due to the dynamic behavior of the profile as deposition of eroded material in berm or breaker bars, while erosion is present within the whole area dependent on time. This was also noted in the profile analysis.

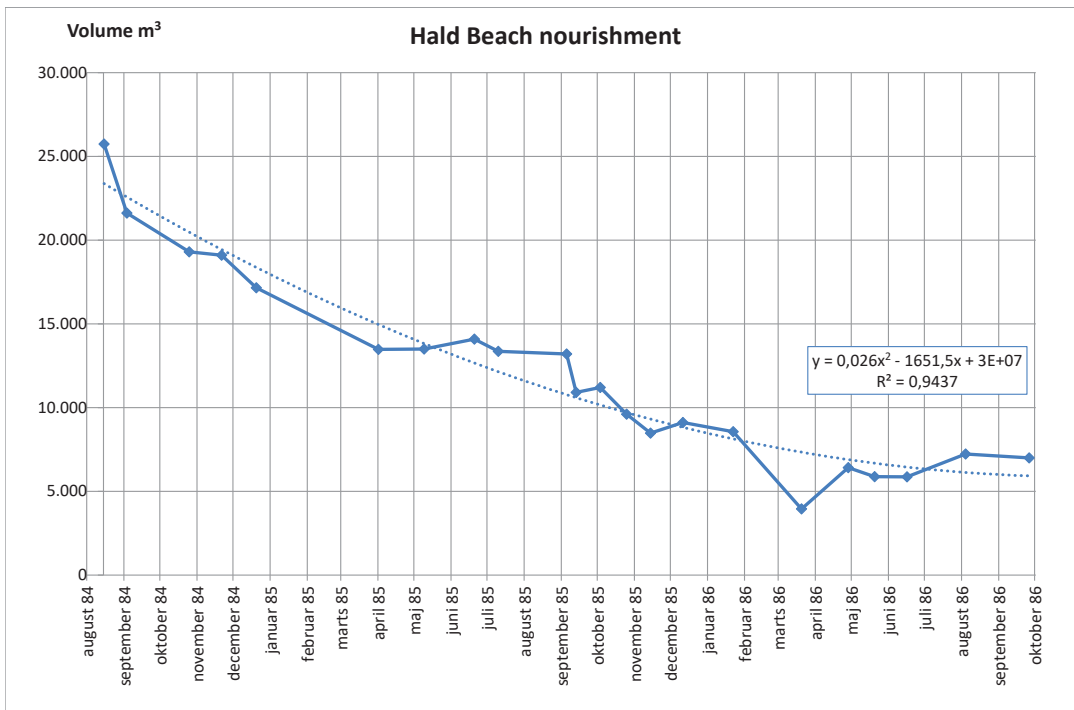


Figure 39: Volume development and polynomial trend line

The first period shows high erosion rates and 20 % of the nourishment volume is redistributed outside of the nourishment area within the first month. This was an expected result, as redistribution of the sediment is faster in an advanced position, as exposure to waves and current is higher. The erosion rate decreases in October and November 1984, but as a high-pressure system was dominating Scandinavia in this period, eastern winds across the area explain the decreasing erosion rates.

Erosion rates increase with 2,000 m³ in Dec. 1984, as the high-pressure system moves east and a low-pressure system with W and NW-winds begin to dominate. Measurements in the area was not possible between 20<sup>th</sup> of December 1984 and 1<sup>st</sup> of April 1985, as the stretch was covered by ice sheets - but between the December 1984 and march 1985 measurements a sediment deficit of 5,000 m³ was seen. The ice was sheltering the beach from erosion, so the primary erosion took place in the shoreface.

Throughout the spring/summer period of 1985, there is a general stability in the nourishment volume, but the measurement on the 05-09-1985 (one year and one months after nourishment) shows close to 50 % decrease compared with the original nourishment volume (25,740 m³ vs. 13,366 m³).

In the autumn 1985, as three storm events passed and the erosion/deposition between before/after storm measurements are presented here:

Measurement period	5 <sup>th</sup> - 13 <sup>th</sup> September	3 <sup>rd</sup> - 25 <sup>th</sup> October	25 <sup>th</sup> Oct - 14 <sup>th</sup> Nov
Storm period	6 <sup>th</sup> - 7 <sup>th</sup> September	11 <sup>th</sup> - 12 <sup>th</sup> October	6 <sup>th</sup> - 7 <sup>th</sup> Nov
Accumulation	1,489	1,101	1,758
Erosion	- 3,783	- 2,695	- 2,895
Net m³	- 2,294	- 1,594	- 1,137

Table 3.2: Showing values of erosion and accumulation between storms. Including date of the storm periods in autumn 1985.

There is proportionality between storm intensity (wind speed and duration) and the volume development. It must be noted that the intervals between measurements vary and only measurements in September can be expected to represent the storm effect directly, while the others are too far apart and include more than just the storm periods.

The storm between the 6<sup>th</sup> and the 9<sup>th</sup> of September 1985 resulted in a net erosion of 2,300 m<sup>3</sup> in the nourishment area (17 % of the remaining volume at the time).

Measurements from 13<sup>th</sup> of September 1985 and 3<sup>rd</sup> of October 1985 represent a period between two storm measurements, and this period resulted in a net-increase in volume of ≈300 m<sup>3</sup>.

Between 3<sup>rd</sup> of October 1985 and 25<sup>th</sup> of October, the storm from 11<sup>th</sup> and 12<sup>th</sup> October passed with wind speeds and wave heights below those of the September storm. Despite lower wave impact and water levels of the same magnitude as in September, the nourishment volume still decreases with close to 1,600 m<sup>3</sup>. This erosion could possibly have been higher if measured right after the storm. The wind direction shifted to NW from SW during the peak of the storm, and remained from N following the peak of the storm. Therefore, some of the eroded material is likely to have been transported back to the nourishment stretch in the period that followed the storm.

The following period between 25<sup>th</sup> of October and 14<sup>th</sup> November resulted in a net-volume decrease of 1,137 m<sup>3</sup>. Despite overall volume decrease, accumulation took place in the shoreface between the two measurements. This indicates that nourishment volume decrease in the upper beach section is transported cross-shore in this period. The higher water level during the storm of 6<sup>th</sup> and 7<sup>th</sup> of November made the upper beach nourishment available for erosion. This sediment has deposited in the upper shoreface as a response to profile equilibration.

Hald Beach - Volume development			
Reference Measurement 24/4/1984			
Measurement date	Volume	Volume development relative to 15/8 1984	
dd-mm-yyyy	m <sup>3</sup>	m <sup>3</sup>	%
15-08-1984	25,740	0	0.0
03-09-1984	21,616	-4,124	16.0
25-10-1984	19,306	-6,434	25.0
21-11-1984	19,099	-6,641	25.8
20-12-1984	17,158	-8,582	33.3
01-04-1985	13,481	-12,259	47.6
09-05-1985	13,502	-12,238	47.5
20-06-1985	14,088	-11,652	45.3
10-07-1985	13,366	-12,374	48.1
05-09-1985	13,207	-12,533	48.7
13-09-1985	10,913	-14,827	57.6
03-10-1985	11,207	-14,533	56.5
25-10-1985	9,613	-16,127	62.7
14-11-1985	8,476	-17,264	67.1
11-12-1985	9,111	-16,629	64.6
22-01-1986	8,558	-17,182	66.8
20-03-1986	3,948	-21,792	84.7
28-04-1986	6,421	-19,319	75.1
20-05-1986	5,878	-19,862	77.2
16-06-1986	5,862	-19,878	77.2
04-08-1986	7,225	-18,515	71.9
26-09-1986	6,996	-18,744	72.8

Table 3.3: Volumetric development of the Nourishment. Reference measurement is the 24/04/1984, which is before nourishment end finished 05-08-1984

The total volume decrease between 3<sup>rd</sup> of September and 14<sup>th</sup> of November 1985 was 4,731m<sup>3</sup>. In the following period between December 1985 and January 1986 an accretion of 635m<sup>3</sup> takes place, which is a response to re-entering of nourishment sediment to the berm.

Between 11<sup>th</sup> of December 1985 and 22<sup>nd</sup> of January 1986 a slight volume decrease of 553m<sup>3</sup> takes place, while between 22<sup>nd</sup> of January and 20<sup>th</sup> of March 1986 there is a substantial volume decrease of 4,695m<sup>3</sup>, leaving 25% of the originally nourishment volume. The significantly higher erosion seen in the March measurement is due to the ice cover in the period. These ice covers creates special morphological dynamics and the development during this ice winter (and 1985), is complex. As frost sets in, the wet beach sections freeze over, while the seawater is still ice-free. This gives way to increased erosion in the berm and lower beach section, as swash over the frozen sections does not percolate. A reflection of water and energy takes place instead. This undercuts the upper beach section over time. After some time with continuous temperatures below freezing point, an ice foot forms in the berm because of instant freezing of swash. This will eventually form a vertical wall in the swash, which limits the erosion of the beach section, as waves are reflected. The resulting effect is that erosion is escalated in the shoreface. Furthermore, a complete freeze-over in both periods gives way for the ice to reach the firm bottom layers, which are then scrubbed and eroded by ice sheets during melt- and break-off. Accumulation was also experienced in this period despite a net-erosion. Sand dunes with a layer structure of sand, ice and snow formed in the proximity of the cliff toe, and reached more than 1m in height.

Following the ice winter, a net-deposition of 2,500m<sup>3</sup> is measured between 20<sup>th</sup> of March and 28<sup>th</sup> of April 1986. This period was dominated by limited wave action and low water levels. The primary volume increase in this period was dominating in upper shoreface.

From March 1986 until final measurement 26<sup>th</sup> of September 1986 the remaining nourishment volume fluctuates between 5,800m<sup>3</sup> and 7,200m<sup>3</sup>, and can be considered more or less stable. Despite several events in July and August with strong onshore winds the volume and nourishment shape seems far more stable than in the past monitoring periods. The water levels during July and August events are not as high as those experienced in the autumn events of 1985, but the stability in the nourishment volume is, however, considered remarkable. The nourishment has stabilized after two years with up to 27 % of the nourishment volume remaining. The stability could be a response to the coarser nourishment sediment and profile adjustment during summer months. The erosional trend will continue as storms, sediment deficit and different types of hard coastal protection still result in net-erosion of the sand mass over time.

Volume development between dates							
Year	Difference between measurements:	Deposition		Erosion		Net sediment flow	
		m <sup>3</sup>	%	m <sup>3</sup>	%	m <sup>3</sup>	%
1984	24-04 to 15-08	25,843	100.4	103	0.4	25,740	100
1984	15-08 to 03-09	1,712	6.7	5,952	23.1	-4,240	-16.5
1984	03-09 to 25-10	2,502	11.6	4,815	22.3	-2,313	-10.7
1984	25-10 to 21-11	1,508	7.8	1,712	8.9	-204	-1.1
1984	21-11 to 20-12	1,252	6.6	3,199	16.7	-1,947	-10.2
1984/1985	20-12 to 01-04	1,137	6.6	4,814	28.1	-3,677	-21.4
1985	01-04 to 09-05	1,698	12.6	1,678	12.4	20	0.1
1985	09-05 to 20-06	2,204	16.3	1,618	12.0	586	4.3
1985	20-06 to 10-07	1,414	10.0	2,136	15.2	-722	-5.1
1985	10-07 to 05-09	2,750	20.6	2,909	21.8	-159	-1.2
1985	05-09 to 13-09	1,489	11.3	3,783	28.6	-2,294	-17.4
1985	13-09 to 03-10	1,958	17.9	1,665	15.3	293	2.7
1985	03-10 to 25-10	1,101	9.8	2,695	24.0	-1,594	-14.2
1985	25-10 to 14-11	1,758	18.3	2,895	30.1	-1,137	-11.8
1985	14-11 to 11-12	2,681	31.6	2,046	24.1	635	7.5
1985/1986	11-12 to 22-01	2,274	25.0	2,512	27.6	-238	-2.6
1986	22-01 to 20-03	1,082	12.6	5,777	67.5	-4,695	-54.9
1986	20-03 to 28-04	3,919	99.3	1,446	36.6	2,473	62.6
1986	28-04 to 20-05	1,254	19.5	1,797	28.0	-543	-8.5
1986	20-05 to 16-06	1,441	24.5	1,457	24.8	-16	-0.3
1986	16-06 to 04-08	2,891	49.3	1,528	26.1	1,363	23.3
1986	04-08 to 26-09	2,130	29.5	2,359	32.7	-229	-3.2

Table 3.4: Volumetric development of the nourishment between measurements. Nourishment was completed on 05-08-1984

### 3.3.1 Nourishment diffusion

As an addition to the resumé of the original report, a test of beach nourishment diffusion is included based on (Dean, 2002). This current analytical approach can be applied for estimation of beach nourishment diffusion on long straight beaches. The equation is based on the assumption that multiple nourishments have been required at a given stretch and can be used when estimating the re-nourishment time. The equation is based on an assumed exponential nourishment decay and multiple nourishments in the same stretch will be self-similar:

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

Equation 1

Where M is the remaining proportion of sediment fill at time t and k is an empirical constant estimated from the decay rate of the first nourishment in the same stretch. As there was no previous nourishment, a theoretical test against its own decay rate would give a misleading result with a close to perfect fit. Instead, k will be implemented as the daily estimated erosion rate based on the long-term background erosion rate set to 0.45m/y, which means k is:

$$k = \frac{0.45m/y}{365d/y} = 0.0012m/d$$

This means that the nourishment diffusion is tested against the expected long-term diffusion. It is noted in the literature that the model has been found to over predict the decay. The model does not include

length, placement or shape of the nourishment but assumes an exponential decrease of nourishment sediment due to equilibration to native profile a longshore distribution and is based on long straight, non-obstructed stretches with rectangular nourishment designs. The model does not reflect hydrodynamic forcing, storm, erosional hotspots or residual bathymetry (Dean, 2002), and it is therefore a simple model.

Another approach focusing on beach width and retreat was presented in by Silvester and Hsu (Silvester & Hsu, 1997). They argue that the averaged beach excursion due to nourishment will retreat faster than native stretches as a response to profile equilibration due to beach widening and longshore diffusion of sediment. The excursion retreat rate is considered exponentially decreasing in the time after nourishment. Silvester and Hsu propose the following approach:

$$Z_t = (0.2 + \frac{0.8^{kt}}{10}) - (t * \tan \alpha) / Y$$

Equation 2

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

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

Y: Set as 28.7m which is average beach width along the nourished stretch on 15<sup>th</sup> of August 1984

Tan a: Set to 0.45m/y.

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

$$t_e = \frac{Y}{\tan \alpha} * 0.2$$

Which in the case of Hald results in:

$$t_e = \frac{28.7m}{0.45m/y} * 0.2 = 12.7y$$

The model is modified from Winston et al. (Winton et. al., Winton, Chou, Powell, & Crane, 1981) and is originally based on field measurements. The value of k is (the decay rate), was based on the excursion of MLW, MSL and MHW contours relative to native. These excursions are plotted semi logarithmically against the time after nourishment - the slope of the best linear fit to contour retreat over time defines the rate of decay and thereby the value of k. Neither contour nor elevation models from the original report are available and therefore the "k" constant found by Silvester and Hsu is used.

The theoretical model described above has been developed on the basis of nourishments placed in the swash, thereby extending the water/land boundary seaward, which precisely describes the actual nourishment in Hald. Unfortunately, the width of the nourishment in time is not available. Instead, the reduction of the nourishment volume in percentage is tested against the theoretical reduction in beach width from the averaged initial nourishment width.

All results are normalized, presented as percentages and plotted in Figure 3.10. Best fit between actual diffusion and model is found for Silverster and Hsu, which assumes an exponential decrease in nourishment width. As the nourishment varies in height from swash to cliff, the exponential decrease might also be connected to the increase in nourishment volume from waterline to cliff toe. On the other hand, profile adjustments were seen on several occasions when nourishment sediment from the upper beach was redistributed in foreshore and upper shoreface. The analysis of the shape showed a reduction of 20 % within few months and then the nourishment shape stabilized with only slight retreat in the last part of the monitoring period. The model fit is close to perfect, but again it must be noted that the test of width reduction is made against the volumetric decrease.

The model presented by Dean shows to underestimate the volume decrease in the case of Hald beach. The under-prediction is around 13 % when comparing the volumes on September 26<sup>th</sup> 1986, but it is explained by the model requirements and the decay rate. The decay described by Dean requires that the stretch has been nourished before and the diffusion is supposed to be based on earlier nourishments. This naturally also indicates that there is a continuous sediment addition in a perfect example. Per definition, this is not the case in Hald as this nourishment was the first to be made on the coast, furthermore, there was a general sediment deficit on the stretch. The diffusion rate is set at 0,45 m/y, but this retreat only describes the cliff recession and not the deficit in the shoreface and beach. The excess decrease in nourishment volume should therefore be considered in relation to the actual profile state, which was generally erosive with decreasing sediment input.

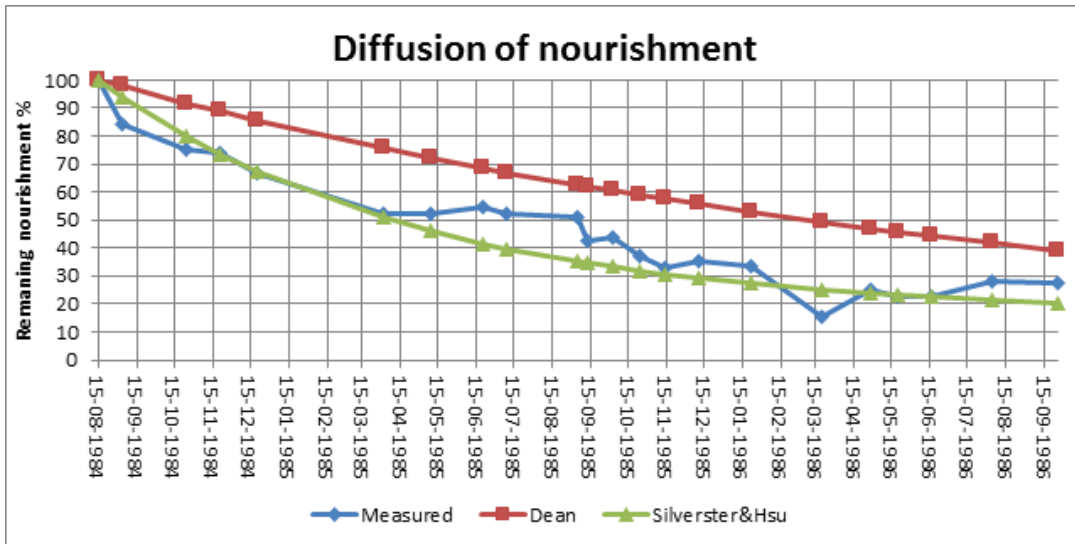


Figure 310: Visualizing the normalized decay projections as well as the true volume decay in percentage of original volume.

The diffusion and volume development of the nourishment is one of the best documented despite shortcomings of the data. The volume and the nourishment area decreases exponentially because of nourishment adjustment to the prevailing forcing and the stretch morphology. Although a good fit between models and measurements was not found in earlier COADAPT reports from Blaavand, Julebæk and Krogen, the fit between the two models in this analysis shows good results. Adjustment of  $k$  in Dean (equation 1) to the actual decay of the nourishment could give a good indication on predictions for future nourishment volumes.

### 3.4 Nourishment impact in neighboring stretches

Flight Photographs
18 <sup>th</sup> April 1984
18 <sup>th</sup> April 1985
26 <sup>th</sup> September 1985
22 <sup>th</sup> October 1985
14 <sup>th</sup> November 1985
05 <sup>th</sup> May 1986
16 <sup>th</sup> June 1986
13 <sup>th</sup> October 1986

Table 3.5: Nadir imagery from neighboring stretches

The original monitoring program did not included the neighboring stretches, but it quickly became clear that sediment redistributed in the longshore direction, especially in a NE direction. The neighboring stretches have been analyzed from coastal mappings, orthophoto analysis and profile analysis. In Figure 3.11 the setup for investigation is presented and the nourishment is found in box E.

In addition, a sediment analysis was conducted in order to trace the moving sand from the nourishment along the stretches. As the sediment analysis was not as robust as first assumed and since the analysis is easily disturbed by natural variations, the results will not be further elaboration upon in this report.

### Coastal mapping:

Coastal mappings were conducted for the stretch from Galgebjerg to Hyllingebjerg for a total of seven times (Jul, Oct and Dec 1984, Apr, Jul and Nov 1985, and again in Jan 1986). Registrations of foreshore, upper shoreface morphology and sedimentary condition were made manually. As these mappings are drawn by hand, there can be severe planimetric and volumetric offsets, especially since no water level correction has been done for the mappings.

In the upstream boxes (A to D), the only impact from the nourishment is seen in April 1985 when a temporary widening of the beach section NE of the old pier in box D (SW of nourishment) takes place. This was a result of a period with predominant winds from the east during the winter months with ice cover. These accumulations of nourishment sediment in the beach are redistributed alongshore within few months. Temporary accumulations take place in the prevailing longshore transport direction. Within a short period of time, they dissipate and redistribute towards NW, which again underlines that the predominant transport direction is NE-bound. Although there can have been longshore inputs from boxes A, B, C and D to box E and the boxes NE of it, this will not be further analyzed, as data are not available and the primary interest is to describe the nourishment impacts.

The only available coastal mappings from the downstream stretch are from boxes G, H, and J, and the downstream effects found from the coastal mappings will therefore be described from these, together with the analysis from the original report. The three stretches showed similar and characteristic developments in the beach during the monitoring period. Beach sections in the three boxes widened and sediment volume increased in the periods between December 1984 and April 1985, as well as between December 1985 and January 1986. Between the winter periods a decrease in beach volume and width are noticed for the downstream boxes, while taking a more undulating form, which was especially noticeable in the period between April 1985 and July 1985. This development is quite the opposite of the expected. The development in the downstream beach sections is a response to the longshore transport of redistributed nourishment sediment. The primary volume reductions in the nourishment took place during the strongest impacts from waves and longshore current, which was during the same months as widening in the downstream beach sections took place. Widening can thereby be attributed to a diffusion of nourishment sediments, which have been transported alongshore to the downstream stretches. This also indicates a short response time between erosion in the nourishment and downstream beach width increase. The decrease in beach volume and width for the downstream boxes during the summer months can thus be explained from the small sediment input from the nourishment, which is stable during this period. Furthermore, the predominant transport direction in summer periods changed from NE-bound to SW-bound.

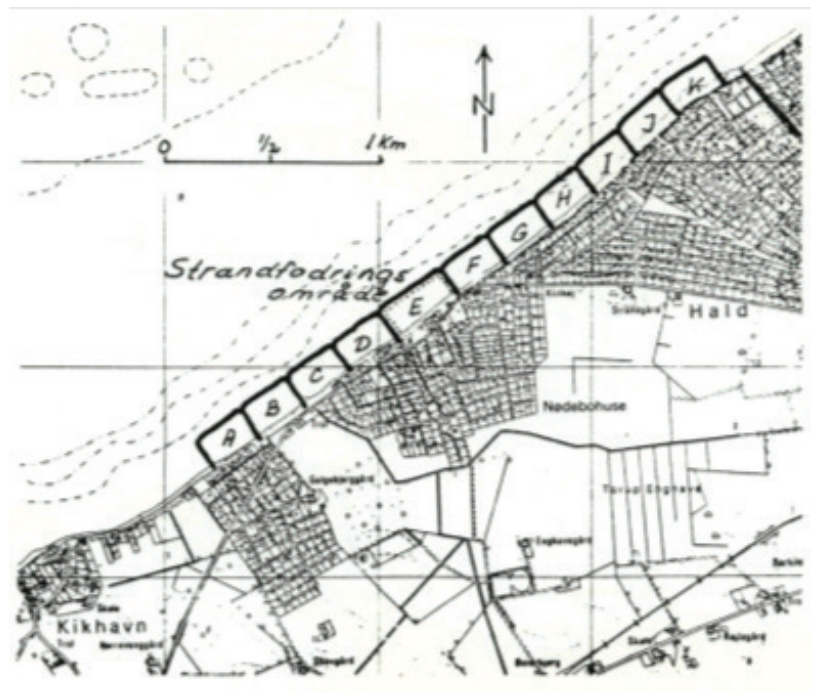


Figure 311: Map of the area of Nøddebohus and Hald, showing the neighboring stretches divided by boxes. Box E contains the nourishment stretch

### **Flight photography analysis**

Several aerial photographs were taken during the monitoring period. When compared with the baseline study from 1945 - 1983 only slight changes were found in the newest (at the time) from 1986. In the photo from 18 April 1984 one finding does stand out, as it showed coherent sand cover in the upper shoreface for the first time since 1961. This sand cover in the shoreface also stretched SW of Hald, which potentially may have increased input of sediment to the beach along the whole stretch. During underwater inspections the thickness of the sediment cover was found to often range between 5 and 10 cm. In addition to the increase in the shoreface sediment volume, this could also be identified in the beach sections of downstream boxes.

### **Downstream profile measurements**

The longshore transport of sediment was only verified by qualitative visual inspections, imprecise coastal mappings and flight photographs, so quantifiable measures in the form of profile measures could improve the observations. Additional profile measurements was therefore implemented in mid-1985 in order to document that nourishment sediment was transported along the coast in a narrow corridor in the swash and nearshore currents. Profile transect lines are represented in Figure 3.12 and numbered P1 to P5 from SW to NE, respectively.

The profile developments for the five transects (Figure 3.13) are far more differentiated than expected, if compared to coastal mappings and flight photo analysis.

Since profiles show differences in length, height and placement of abrasion grounds, the differences are not unexpected. In P2 and P5 the abrasion grounds are flat and generally low-lying at -1.5 m, but they also show to have the greatest sediment volume and sediment redistribution. The abrasion platforms are more irregular in profiles P1 and P3 with the predominant depth being -0.6 m (as in the nourishment stretch). Profiles P1 and P3 do not reveal larger amounts of deposited sandy sediments in any of the measurements, and were often consisting of firm ground with little to no sandy spots or bars present. The last profile, P4, shows an elevated abrasion platform, which is above the other four profiles. All profiles show an increase in the sediment volume during 1986, which is in accordance with the observations from photographs and mappings.

The assessment of the longshore transport of nourishment sediment showed that it took place as undulations of the coastline moving alongshore. These are not identified from the profile measures, but as they are placed far apart, it is likely that a possible trend is blurred by the general dynamic of the profiles. One observation could possibly identify the undulations. P1 has a volume increase for the 30<sup>th</sup> of September 1985, which is right after a storm when 2,300m<sup>3</sup> of sediment is transported from the nourishment stretch. The volume addition in profile 1 dissipates for the next measurement on October 22<sup>nd</sup>, while P2 increases its sediment volume until the November 25<sup>th</sup>. This combined with a slight volume increase in the foreshore of P3 after October 22<sup>th</sup> could indicate some undulating movement, but it is not conclusive, as the same tendencies are not found in profile 4 and 5. An increased erosion in the shoreface could explain the missing tendency in P4 and P5, and the increase could be caused by freeze-over and ice-sheets as seen in the nourishment volume. The hypothesis remains that when larger sediment volumes diffuse from the nourishment, they diffuse alongshore in an undulating movement.

The beach width, sediment volume and the average sediment thickness for the five profiles during the monitoring period are presented in Figure 3.13. Profiles 1, 2 and 3 have a comparable development in width. The shorelines at P1 to P3 advance 10 m seaward, followed by stabilization in the time after the September storm 1985. The shoreline fluctuates around a stable position for profile 4, while profile 5 shows larger fluctuations for the shoreline and the storm in September 1985 resulted in a shoreline retreat of +10 m - despite this retreat, there is a slight advance during the remaining period. Additional sporadic but extensive acute erosion of multiple cliff faces was seen in the September, October and November storm events of 1985. The magnitude of these storms did result in multiple stretches being affected by erosion. This can have caused volume increase in periods following the storm due to swell waves. Beach volume increase, as well as seaward extension cannot be attributed to the nourishment sediment alone.

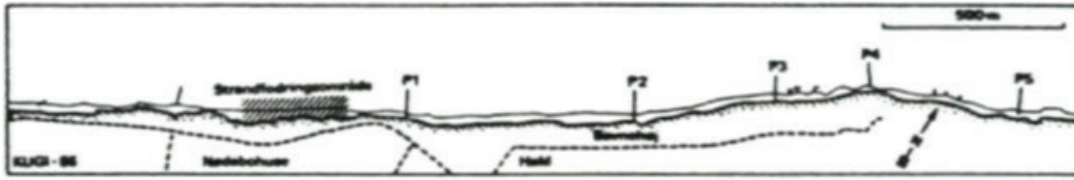


Figure 3.12: The five additional profile measurements are presented here. Notice that the nourishment stretch is shaded to the SW.

The fluctuations of the volume in P1 is probably caused by the diffusion of the nearby nourishment. Autumn periods represent volume increase, while summer periods show stable or slightly stagnating volumes. For the remaining four profiles, a general volume addition is identified, which results in an overall increase between 50-100 % in beach volume.

The value of the nourishment in the neighboring stretches were visible, and the increase in beach width and volume was valued by the general public in the summer period for recreational purposes. The recreational value was not only increased for the nourished stretch, but also for the adjacent stretches due to longshore distribution of the nourishment.

The diffusion of the beach nourishment at Hald is not nearly enough to cover the deficit or depletion in the downstream stretches and despite increase in beach width and volume, the neighboring profiles are generally suffering from sediment shortage. The longshore diffusion of nourishment sediment might increase the beach width occasionally but as sediment depositions is rarely found in the toe of the active cliff or in general, in the upper beach the cliff toe is still exposed during high water and high energy events. However, sediment in the shoreface will increase the profile volume in general.

### Summary

Considering the changes of the coast between Hald and Hyllingebjerg (NE), the nourishment sediment has been found to be transported alongshore towards NE. This, in general, increased the overall recreational quality of the beaches and to some extent the protection level.

The volume of sand found on the downstream beaches is far above the volumes, which until the end of the monitoring has diffused from the nourishment. There has therefore been a temporary increase in the sediment availability either from shoreface or cliff releases.

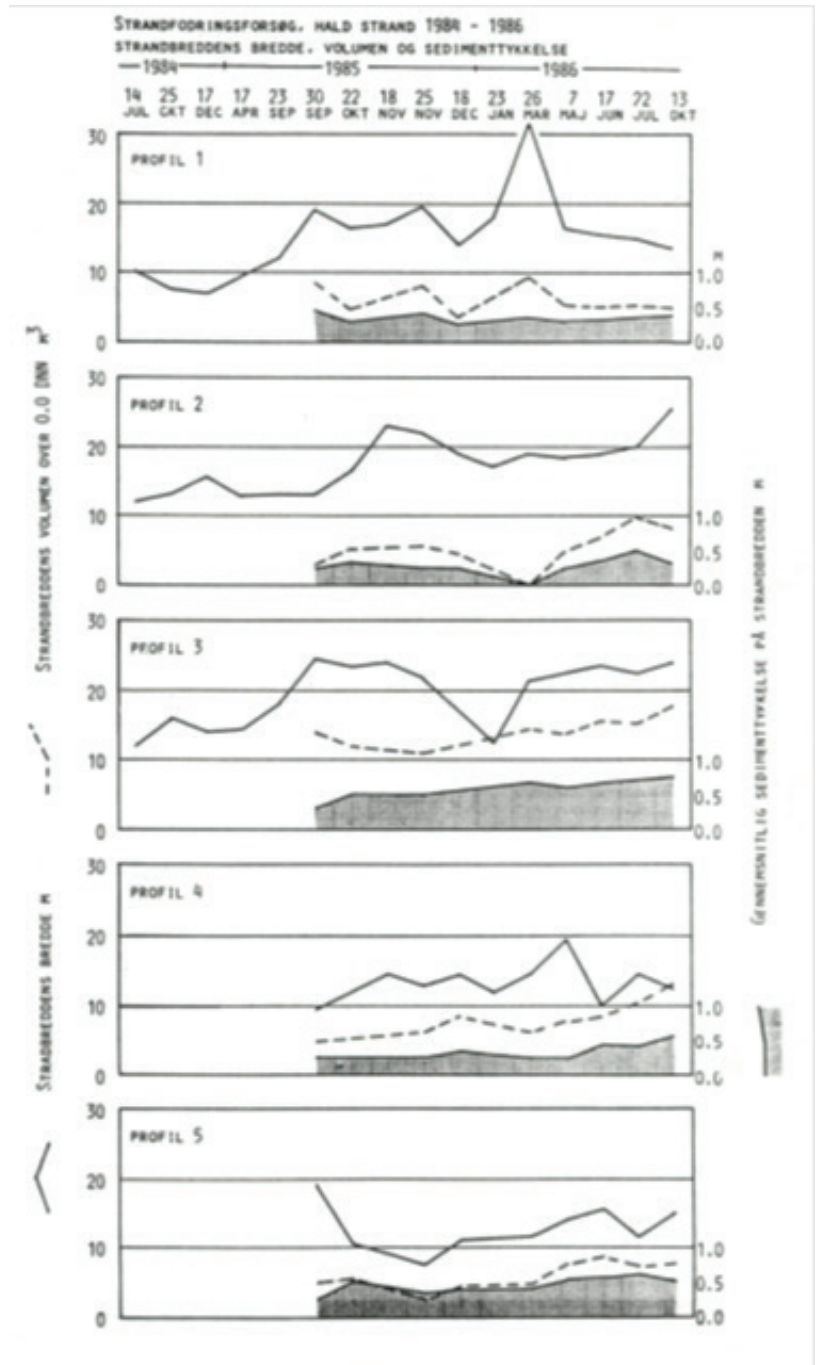


Figure 3.13: On the left y-axis: The Beach width (m) and foreshore volume (m<sup>3</sup>). On the right y-axis: Avg. sediment thickness in the foreshore (m)

# 4 Discussion

The primary objective of this project has been to analyze performance of the beach nourishment, with respect to nourishment diffusion and the coast morphological responses to the nourishment during the monitoring period. This followed the structure of the original report from 1986 and is based on the research questions posed. These are presented individually in the following:

## 4.1 When and where did changes occur in the nourished sand volume

Generally, the hydrodynamic forcing in the measuring period has been found to be slightly calmer than normally, but in the autumn of 1985 there were three storm events including one storm with a 50-year return water level.

The two winter periods showed higher erosion rates than spring and summer periods, while both winter periods resulted in ice armoring of the beach. This caused a larger than expected erosion in the upper shoreface due to reflected waves.

The nourishment volume decreased polynomial and nourishment sediment was found to rapidly redistribute long- and cross-shore during the first couple of months. When high water events passed, the nourishment sediment in the upper beach section functioned as a buffer for the cliff front and erosion took place in nourishment sediment rather than in the cliffs. The nourishment sediment could not be traced in sediment samples after redistribution to shoreface and downstream stretches, but increases were obvious in beach sections in the NE longshore direction and shoreface volume also increased despite rapid sediment changes in the shoreface. The nourishment resembled a trapeze in planimetric shape, as the hypothesis was that angling the nourishment towards the most predominant wave angle could decrease the potential diffusion time. As it was seen, the shape was reduced to rectangular within a few months.

The main factors affecting the nourishment are: Water level, wave height and duration, as well as nearshore currents and direction.

## 4.2 How quickly did the nourishment diffuse?

The nourishment diffuses exponentially and after one year (5<sup>th</sup> of September 1985) 50 % of the nourishment volume is redistributed. On the 20<sup>th</sup> of March 1986, 15 % of the nourishment volume remains in the area. The volume increases to 27 % of the original nourishment on the 26<sup>th</sup> of September 1986, two years after the nourishment.

The nourishment volume fluctuates, dependent on forcing, and the best fit to the diffusion is a polynomial fit with  $R^2 = 0,94$ . If the polynomial fit is used to calculate the lifetime of the beach, it will result in a lifetime of several years, due to the stable volume at the end of the monitoring period. Due to the general sediment deficit for the stretch, the real lifetime will be shorter. The exact lifetime has not been assessed.

## 4.3 How does the erosion- and deposition rates vary, in and around the nourishment site?

In spring and summer periods, profile changes primarily take place around the shoreline. Profile adjustments to low water levels and shoreward transport builds up the beach width and berm. Profile elements in the shoreface, such as sandbars, are often absent during these periods, and this is likely to be a result of the short profile measurements that only reaches water depths less than 1.5 m. The longshore components in spring was mostly orientated towards SW and generally small, but does result in a slight supply of sediment from upstream-stretches resulting in stabilization of the nourishment volume during spring and summer periods. An accumulation of sediment on the NE side of the old pier (SW of nourishment) is expected in these periods and was documented from the flight photography from the 5/5-1986.

The morphological activity in the autumn and winter periods is high and takes place over the entire profile. Onshore storms in combination with high water level, results in erosion of upper beach sections and nourishment sediment, while accumulation takes place in the lower beach creating a flatter storm profile with buildup of longshore breaker bars. The longshore transport is generally towards NE in the autumn and winter periods. The NE directed sediment transport results in general longshore transport of sediment, which is not compensated for from the SW, as it is both sediment depleted and influenced by the old pier. The amount of sediment deposited in the foreshore during the profile adjustment will be eroded by the longshore transport, and is only present for short-term deposition. Slight increase in the upper shoreface could be identified between profile measurements, but diffuses alongshore within months.

As the profile will seek equilibrium continuously in respect to hydrodynamic forcing, a final profile state cannot be defined. Although the volume and area of the nourishment decrease over time, a general volume increase in the shoreface and a widening of the beach are evident from reference measurement to final measurements in 1986. The increase of the beach volume by the nourishment, and the buffering effect from the nourishment against acute erosion, increased the overall profile capability of enduring on-coming storms and high-energy events. This was especially seen during the storm events in the autumn of 1985 when large stretches on the north coast experienced acute erosion of the cliffs, whereas no part of the cliff face in the nourishment stretch eroded.

#### **4.4 What is the impact seawards the nourishment area and at the neighboring stretches?**

The cross-shore studies within the nourishment stretch showed that longshore transport in the shoreface takes place in narrow breakers and adjacent layers of sandy sediment. However, there was no indication of the nourishment sediment reaching the outer breaker at 2 m depth 100 m from shore. If nourishment sediment has been transported cross-shore, this primarily would have taken place in the inner upper most part of the shoreface. This could be identified by the volume increase in the upper shoreface between the profile measurements and from cut/fill mappings in the volume analysis.

The longshore transport showed to be dominant towards the NE. On multiple occasions, this resulted in buildup of the beach sections in the neighboring stretches. The sandy sediment volume above 0 m for the profile p1 to p4 increased with 50 to 100 % during the monitoring period and nourishment sediment was visually confirmed to be transported alongshore in undulating motions. During the autumn of 1985, three storms passed the area. As mentioned, the nourishment stretch at Hald did not experience any acute cliff face erosion, but even at the stretch between Hald and Hyllingebjerg, (end of box k Figure 3.11), only one significant cliff erosion was experienced. The beaches on this stretch did generally widen and sand volumes had increased which is likely to have prevented some acute erosion of the cliff. The increased beach width and volume in the NE-stretch is not only a result of longshore diffusion of nourishment sediment, as this volume is far above the diffusion volume. However, it is evident that nourishment sediment has been transported into neighboring stretches, which has increased the recreational value of the beach and might have increased the profile resilience, as well, as it was seen in the nourishment stretch.

# 5 Conclusion

The following presents the overall findings and conclusions from the Hald beach nourishment report.

Natural retreat rate of the cliffs in the nourishment stretch was about 0.45 m/y between 1945 and 1984. The stretch was experiencing a decrease in sediment input from the upstream coast and chronic and acute erosion were ongoing. The baseline study showed a general deterioration of the sandy sediment cover, beach and coastal quality. This deterioration is explained by a combination of the many passive coastal protection structures (revetments especially) installed upstream in the baseline period. This caused a decrease in the availability of sandy sediment.

The cliffs at Hald were stable between 1980 and 1984, while the beaches were narrowing and the sediment cover in the shoreface decreased. Only one event with high water and galling onshore winds took place in the period between 1980 and 1984, and it did not cause significant erosion in the cliff toe in period.

Shortly after the nourishment was completed, redistribution of nourishment sediment began. The trapeze shaped nourishment was smoothed to a coast parallel beach within few months while the area was reduced with 20 %. The rate of diffusion in the nourishment area and nourishment volume decreased in the remaining period of the monitoring campaign. Nourishment sediment from the upper beach accumulated in the upper shoreface, swash and to some extent in the foreshore sections after erosive events, but most nourishment sediment was transported alongshore into the NE-stretches increasing the beach widths and the recreational quality.

The nourishment volume decreased with a rate that can be described by a polynomial (94 % of the variance). After two years, 27 % of the beach nourishment volume is still present at the nourished stretch. The lifetime of the beach nourishment is several years if the fitted polynomial function is used. The real lifetime was not evaluated, as the monitoring program was too short.

The effect of using coarser nourishment sediment than native on the beach could not be assessed. However, the sediment redistribution across the coastal profile was surprising as no exchange was found between nourishment sediment and the outer bars at depths around -2 m.

The upper shoreface in the neighboring stretches was expected to show increases in volume of temporal features shortly after the nourishment. The positive sediment supply was seen at the foreshore and the inner 10-20 m of the upper shoreface. This was confirmed from the five additional profile measurements (P1 to P5) in the neighboring stretch. When volume increases in profiles P1 to P4 were quantified, a 50-100 % volume increase could be identified. The longshore transport of the sediment took place as undulating motions along the shoreline.

The storms during the autumn of 1985 had an erosive effects along the full coastal stretch of Northern Zealand with retreating cliff fronts, with the exception of the nourishment stretch where the only significant erosion was found NE of it. The beach nourishment served as a buffer for the natural erosion, and acute erosion of the cliff front was prevented while the profile volume increased.

By implementing beach nourishments, in contrast to passive solid structures, a more natural protection was achieved for the coastal stretch of Hald. If placed in accordance with the natural development and behavior of the system, the nourishment sediment will also have a positive impact on the downstream stretches, the higher the volume, the larger the impact. It is a requirement that nourished stretches are re-nourished during the following years to give an optimal effect, as the sediment will be transported across and along the coast over time.

The nourishment at Hald was a success, protecting the erosive cliffs, thus preventing retreat of the cliff edge, while at the same time increasing the overall recreational value of the beaches.

# References

Aerokort Luftfoto; Det Kgl. Bibliotek, D. (September 2019). kb.dk. Hentet fra kb.dk/danmarksetfraluftten: <http://www.kb.dk/danmarksetfraluftten/>

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

Fællesudvalget, k. o. (1987). Sjællands Nordkyst - strandfodringsforsøg 1984 - 1986 slutrapport. Fællesudvalget, kystpleje og kystsikring af nordkysten.

Luftfotosamling, G. I., & Det Kgl. Bibliotek, D. s. (September 2019). kb.dk. Hentet fra kb.dk/danmarksetfraluftten: <http://www.kb.dk/danmarksetfraluftten/>

Nielsen and Nielsen, . (1978). Kystmorfologi. Copenhagen: Geografisk institut.

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

Winton et. al., Winton, T., Chou, I., Powell, G., & Crane, G. (1981). Analysis of Coastal sediment transport processes from wrightsville beach to fisher, North Carolina. Fort Belvoir: U.S. Army, Corps of Engineers.











Kystdirektoratet  
Højbovej 1  
7620 Lemvig  
[www.kyst.dk](http://www.kyst.dk)