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Coastal Authority

Beach Nourishment Effects

Østerstrand Fredericia - Denmark 2017

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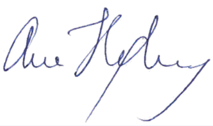
Signature	

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Contents

1. Introduction

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

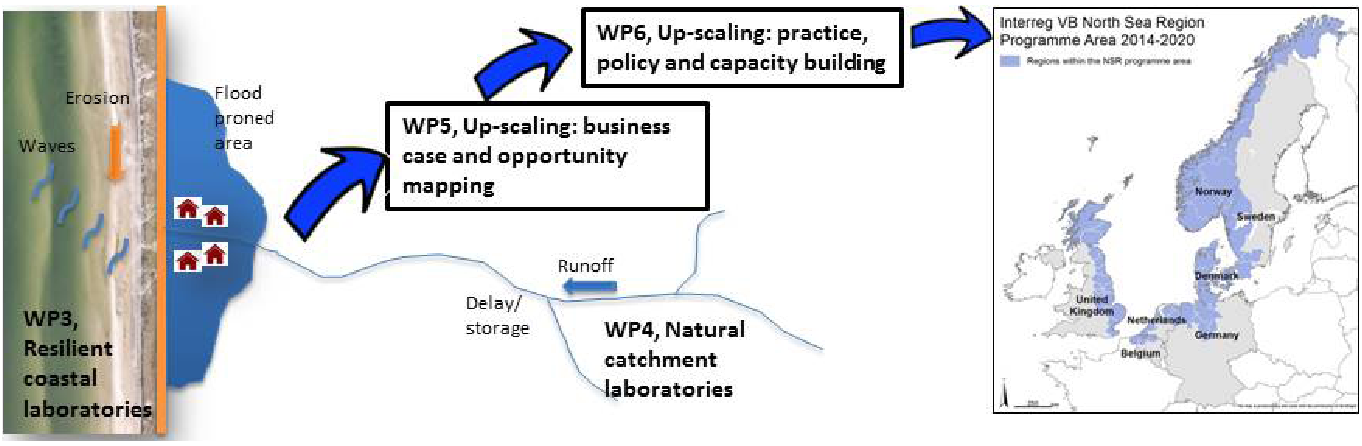

Figure 1.1: The 6 work packages in the Building with Nature project. WP1 - Project Management, and WP2 – Communication is not included as these WP are in-office activities.

The BWN-project is a combination of six different work packages, (Figure 1.1) and this report on Østerstrand in Fredericia (Denmark) belongs under Work Package 3 (WP3): Resilient Coastal Laboratories. However, the coastal stretch in this report is not a laboratory site.

Work Package 3 (WP3) focuses on coastal challenges and effects of implementing BwN-methods to handle these challenges, which in this case centers around a beach nourishment.

This report focuses on a small-scale beach nourishment at a low energy coast at the town of Fredericia. The aim of this report is to analyze the performance of the nourishment and describe the changes in the coast, and effects from the nourishment performed in 2017. The beach nourishment volume was approx. 18000 m³, placed partly by dumpers but mainly by ship along a stretch of 800 m. The main goal was to re-establish a beach and extend the shoreline to the same position it had in 1954, thereby increasing the protection of the coastline and the recreational values of the beach. Multiple revetment and groynes existed before the nourishment, but only some have been changed. Two older concrete piers were demolished and a new circular jetty was built instead, together with 3 new wooden jetties along the 800 m coastal stretch. The results from this analysis will be included in future guidelines for beach nourishments.

1.1 Description of Study site

The town of Fredericia is located in the SE-part of Jutland and is neighbor to the strait "Lillebælt". As seen in Figure 1.2, the nourishment stretch lies adjacent to the main town center of Fredericia. The combination of location, presence of lifeguards in summer, sandy beach pockets and continuous water quality checks, makes the beach very popular among locals and tourists.

Figure 1.2: The town of Fredericia is located in the SE-part of Jutland. The nourishment stretch is found in the orthophoto, and drone imagery in picture 1, 2 and 3 show the nourishment from three different angles. Picture 1, 2 and 3 are taken more than a year after completion of nourishment. View from the drone images are as follows: Picture 1 is from N to S, Picture 2 is from E to W and picture 3 is from S to N.

The nourishment stretch is orientated close to 0° and consist of a sandy beach, with a grass flat between the beach and a steep inland ridge. The ridge is part of a rampart defense line that encircles the entire old town of Fredericia. The structured and close to linear slope of the rampart facing the sea is the result of stabilizing interventions with grass turfs on the ridge face and was performed on the entire rampart at Østerstrand. The ridge top was also stabilized and the top was elevated several meters. (Dal, et al., 2004) The ridge face is not threatened by erosion from the sea, as there are more than 20m between the seaward vegetation line and the toe of the ridge.

The nourishment stretch lies in extension of the headland referred to as “Trelde Næs” (a ness). The geological layers in the cliff at Trelde Næs bears witness to several geological time series, but is most famous for the expanding clay formation known as Lillebælt clay (Sand-Jensen, et al., 2012). Undercutting and continues erosion in the northern coastal cliffs of Trelde Næs, cause exposure of the sedimentary layers, which occasionally causes mudslides. The sandy sediment at Østerstrand stems partly from this northern stretch, which is evident from the fact that fossils from different geological periods found in the Trelde Næs formations also often can be found on the beach at Østerstrand, as a result of long- and cross-shore transport. The beach at Østerstrand should therefore be considered in relation to a larger system in which a main sediment source for input stems from the longshore transport.

During the recent decades, increasing amounts of revetments and groyne of various designs and sizes were built on the two km upstream stretch. This has reduced the sediment input at Østerstrand, where groynes and revetments have also been built over the past decades. Before the nourishment, in general, the beach was controlled by the existing groynes, piers and revetments. As most structures are still present or have been renovated after the nourishment, the hard coastal protection will largely control the nourishment and beach sections.

1.2 Division of study stretch

The study stretch has been divided into four sections alongshore, which is exemplified in Figure 1.3. The division is made to ease the overview of the changes in the nourishment and in the downstream stretch. The division is based on both physical marks and considerations regarding the stretch morphology, based on preliminary analysis from drone imagery and orthophotos.

Section 1: The northern boundary of section 1 is demarcated by the headland construction seaward of the Norwegian Bastion, as this is where the nourishment has its northern boundary. The southern boundary is set where the former bathing piers was and where the new circle jetty is now located. Parts of the wooden deck on the new circle jetty was destroyed during the first couple of storms, which can be seen in Figure 1.3.

Section 2: The northern boundary is at the south side of the new circle jetty, while the southernmost boundary is set at the first of the new jetties. Section 2 is relatively short in comparison with the other boxes, but the new circle jetty is expected to affect the immediate downstream stretch because the inner half of the circle jetty is constructed with sheet piles.

Section 3: The southernmost boundary is set at the new jetty closest to the circle bridge (from the south and later referred to as jetty no. 2), and the northern boundary is set at the terminal groyne. This stretch shows a slightly different coastal orientation compared to the other section, and several groynes in various conditions control the stretch. The primary element is the southernmost groyne, the terminal groyne, as it controls the sediment bypass.

Section 4: The northern boundary is set at the terminal groyne and the southern boundary is at the tip of the artificial spit at the oil terminal. Just south of the terminal groyne the rowing club and the kayak club are located. Both have a floating bridge but neither of these are expected to have significant influence on the coastal dynamics.

1.3 Description of Nourishment

The purpose of the nourishment campaign at Østerstrand, Fredericia, was to increase the planimetric beach width with 10 m along a stretch of 800 m, thereby re-establishing the shoreline at the same position as in 1954. The beach width is often defined as the distance from the shoreline (0 datum) to where vegetation starts, but in the nourishment plans, the beach width definition is not clear. On naturally evolving coasts the beach width is determined by the sediment composition and the hydrodynamic forcing, primarily wave run-up. After nourishment, under normal conditions, vegetation will migrate from the hinterland to the point of maximum wave run-up.

On average, the coastline retreat since 1954 has been more than 10 m (Ramboll, 2016). The increase in width should increase protection of the inland rampart and enhance the recreational values of the beach. (Ramboll, 2016). The designed lifetime of the beach nourishment was not explicitly stated, but based on the estimated erosion on the stretch and nourishment volume, the lifetime is approximately three years.

Cross-shore profiles from north of the swimming facilities (Cross section B-B) and south of it (A-A) are presented in Appendix B, modified from Danish into English from the original application for the construction.

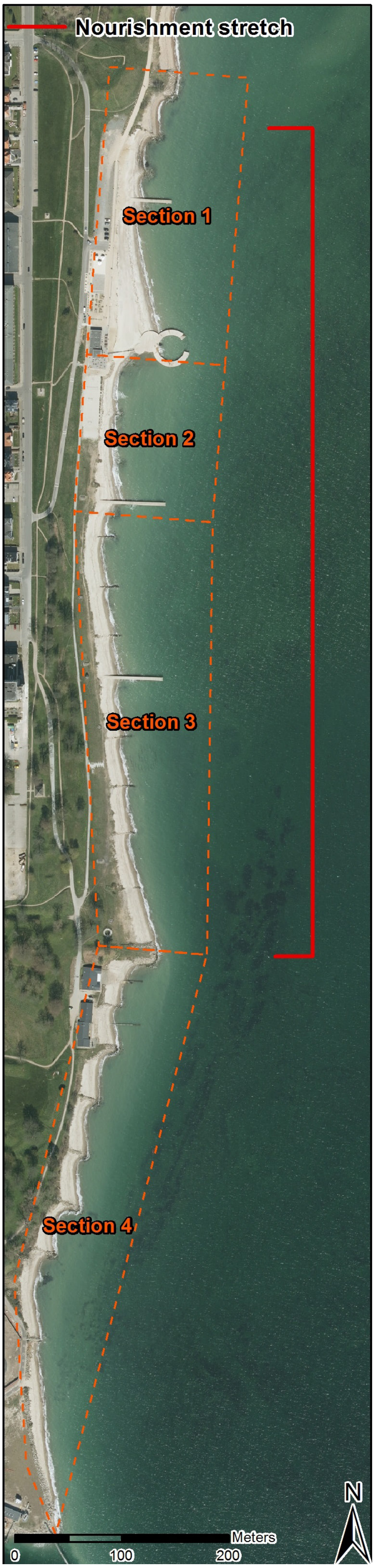

Figure 1.3: Sectional division of the study stretch. Orthophoto from 2017 after Nourishment.

The main part of the nourishment volume, 14,000 m³, was pumped onto the beach via pipeline by ship. The sediment placed by ship was dredged in Lillebælt and sediment sampling showed slightly coarser sediment than the one native to the stretch. (Fyens-Stiftidende, et al., 2017) There has not (to the authors' knowledge) been used any alongshore nourishment dikes. The nourishment can be viewed on YouTube by following the hyperlink: Nourishment at Østerstrand, Fredericia.

Additional to the nourishment by ship, 4,000 m³ was placed by dumper trucks and came from a development area in the city. This sediment was primarily used to establish a nourishment buffer in the upper beach in section 1. The 4,000 m³/m sand came from the area "Kanalbyen". The sediment was originally placed on top of a geotechnical fill in an old dry dock in order for the fill to settle. Therefore, the sand needed to be removed before new structures could be built on the now consolidated layers in the dry dock, and the sediment could therefore be placed at Østerstrand. (Fredericia-Avisen, 2017)

The total nourishment volume has been estimated to be 18,000 m³ by the local municipality.

Note that from appendix b the beach extension is placed from +0.5 m DVR90 and seaward, meaning that the planned extension of the shoreline has been slightly wider than the 10 m. The transect drawings show that it is planned to place 16-20 m³/m in the shoreline, but with the 18,000 m³ the actual nourishment is 22,5 m³/m, as the stretch is 800 m long.

Additional to the nourishment, establishment of three new perpendicular jetties (here numbered 1, 2 and 3, from north to south), a new circle jetty and a "swimming snail" made with steel piles were constructed. The former bathing piers was demolished and some of the existing groynes were removed or reduced in size.

No surveys were conducted before, during, nor after the nourishment. The designed lifetime for the nourishment are not described in any of the available literature. In the original design plan, the natural shoreface slope was estimated to 1:50 based on the length between 0.0 and -2.0 m contours on navigational maps, and the native d50 for the grain size was estimated conservatively to be 0.2 mm. The net sediment transport was estimated at ~ 5,500 m³/y to the south. (Ramboll, 2016). This indicates a lifetime of the nourishment of approximately three years.

1.4 Research design

The scope of this report is to describe the visible morphological changes and the development of the nourishment over time. These changes will be evaluated in relation to the main wave energy components. Quantifications of the nourishment dispersion are not directly possible as, to the DCAs knowledge, there are no detailed surveys available from the study site, but the volume development between the National DTM measurement from 2015 and 2018 will be included to evaluate the actual dispersion of the nourishment volume. Aerial images from drones and orthophotos will be used to analyze the morphological changes.

The structure of the report will rely on hypothesis on the stretch dynamic and nourishment development. These are the foundation for the research questions formulated.

Hypothesis on natural dynamics:

The stretch at Østerstrand has a predominant longshore wave energy component towards S. The natural sediment input has decreased because of increase in hard passive coastal protection measures such as revetments, groynes, etc. along the upstream stretch. The decrease in width and height of the beach on some parts of the stretch indicates a chronical sediment deficit on the stretch, and the impact of a shore parallel revetment. Slight acute erosion of the grass flats (beach meadows) laying inland of the beaches are rare, but will, in general, contribute to the overall retreat of the profile.

Hypothesis on nourishment development:
The nourishment sediment is expected to redistribute across- and alongshore over time. The main cross-shore redistributions are expected to happen during the first storm because the coastal profile is out of equilibrium. The planform is expected to be reduced from rectangular to triangular between the individual groynes with accumulation on the northern upstream side of the groynes and leeside erosion in the southern sides of the groynes. The reduction of beach width by wave energy is expected to be rapid in the first couple of months as the planform equilibrates to the dynamics of the natural system and nourishment sediment diffuses across and alongshore. The diffusion of nourishment volume will then become more stable. Re-nourishment will be necessary, as there is a chronic sediment deficit on the stretch.

The new circular jetty is expected to continue to work in the same way as a groyne, which will lead to increase in reduction of the leeward beach width. The three new straight jetties have all been constructed with boulders underneath, and will likely function as groynes. The terminal groyne in the southern end of section 3 will eventually fill and reach its detaining capacity. Longshore transport will pass the groyne and eventually increase the volume of sediment on the downstream stretch, which potentially will lead to an increase in beach width.

1.4.1 Research questions

The research questions are based on the general hypothesis on the stretch and nourishment behavior and dynamics:

- What is the general direction of longshore transport and the dominant energy component?
- How did the nourishment planform change over time?
- How has the nourishment sediment been distributed in the profile?
- Did the nourishment achieve the intended goals?

To analyze the defined research questions, it is necessary to establish a baseline study for the stretch, in other words, the autonomous behavior of the stretch must be understood. The success criteria or purposes of the nourishment must be evaluated with regard to the actual design and finished enterprise before an analysis of the nourishment development can be performed.

2. Data

The following chapter presents the data included in the analysis.

2.1 Drone imagery

Drone filming has been done in 4K resolution on 14 occasion with a DJI Phantom 4 Pro. First time was 5th of May 2017, which was just after some of the inland sand had been placed and before the nourishment by ship began. The remaining drone flights were done to follow the development of the nourishment. It has been sought to film the stretch in a comparable way each time so that drone film and imagery can be used to describe the changes over time. Dates are provided on the timeline in Figure 2.1.

As the drone imagery and films are the primary data resource for analysis of temporal changes, the individual dates from which data is available is used to split the study period into sub-periods. This leads to 13 periods in total, with period 1 being the first and period 13 being the last as seen in Table 2.1.

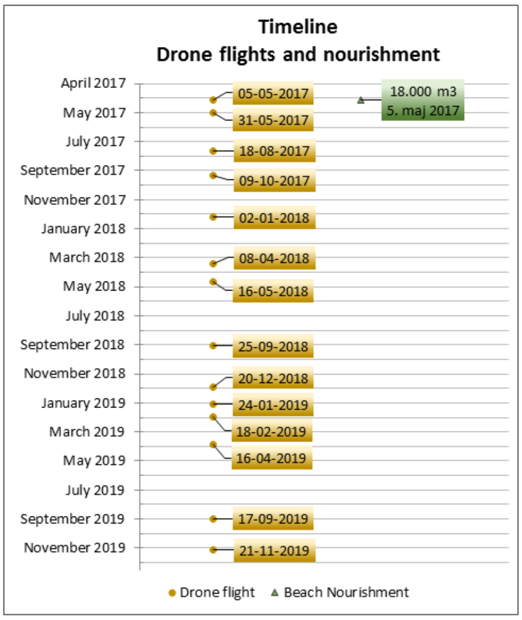

Figure 2.1: Timeline showing the date for the drone flights and the establishment of the nourishment

2.2 Wave and water level data

Modelled hydrodynamic data have been obtained from DMIs (Danish Metrological Institute) model, and have been extracted from the nearest model cell to the defined point in Figure 1.2.

Wave and water level data were delivered in UTC and the timestamps of the drone flights have therefor been converted to UTC from Danish summer time (UTC +1 hour) and standard time (UTC + 2 hours) in Table 2.1.

Periods	From (UTC)	To (UTC)
Period 1	05-05-17 06:00	31-05-17 11:00
Period 2	31-05-17 11:00	18-08-17 13:00
Period 3	18-08-17 13:00	09-10-17 14:00
Period 4	09-10-17 14:00	02-01-18 08:00
Period 5	02-01-18 08:00	08-04-18 13:00
Period 6	08-04-18 13:00	16-05-18 08:00
Period 7	16-05-18 08:00	25-09-18 18:00
Period 8	25-09-18 18:00	20-12-18 06:00
Period 9	20-12-18 06:00	24-01-19 07:00
Period 10	24-01-19 07:00	18-02-19 09:00
Period 11	18-02-19 09:00	16-04-19 11:00
Period 12	16-04-19 11:00	17-09-19 07:00
Period 13	17-09-19 07:00	21-11-19 07:00

Table 2.1: Periodical division of the full study period.

Modelled data are available between 01-01-2016 and 25-11-2019 in hourly averaged time steps.
Measured water level data are available between 01-01-2017 and 01-01-2020 in 10-min intervals.

2.2.1 Modelled wave data

Wave data are extracted from the DMI wave model “WAM cycle 4.5.1” with grid resolution of ½ nautical mile. Available wave data are presented in Table 2.2. Data extraction in the model was made at 55.570 N and 9.800 E, so slightly different from what is shown in Figure 1.2.

Lower boundary cut-off for modelled wave height is 0.08 m until June 2017, and 0.12 m from July 2017, meaning everything below has been filtered out. The timestamps of the data are in UCT and available every hour.

Available hydrodynamic model data		
swh	Significant wave height	m
mdir	mean wave direction	from deg.T
pp1d	dominating wave period	s
mwp	mean wave period	s
shww	height of wind waves	m
mdww	direction of wind waves	from deg.T
mpww	mean period of wind waves	s
shts	height of swell	m
mdts	direction of swell,	from deg.T
mpts	mean period of swell	s

Table 2.2: The available data from the DMI model. Extracted data extends from 01-01-2016 and 25-11-2019.

To test the time series for gaps or “NoData” the series was tested against a constructed time series with 1 hour time steps. By comparing the amount of time steps between modelled and constructed test series, a potential gap could be found. Additionally, the last time step between the series was the same. The time series is complete. No missing values are detected in the time series either.

2.2.2 Modelled water level data

Water level is measured in meters, and extracted from the DMI storm flood model DKSS2013, which has a resolution of 0.5 nautical mile. Data extraction point in model is: 55.562 N and 9.798 E.

The timestamps of the data are in UCT and available every hour. To test the time series for gaps or “NoData” the series was tested against a constructed time series with 1 hour time steps. By comparing the amount of time steps between modelled and constructed test series, a potential gap could be found. Additionally, the last time step between the series was the same. The time series are complete and no missing values are detected in the time series either.

2.2.3 Measured water level data

The measured water levels are derived from DMIs measurement station 23293/23289 in the port of Fredericia. The position of the station is given at lat: 55,559494 and long: 9,753045. Measurements are conducted with both radar and pressure. (Kystdirektoratet, et al., 2017). Measurements are in UTC time and measured every 10th minute.

Corrections of erroneous data are conducted by DMI. Missing data have been replaced with the value “999”. By counting the amount of “999”-values and dividing by the total amount of time steps, it was found that missing data accounted for 1.5 % of the entire dataset.

2.2.4 Test of water level data

During initial analysis of the drone imagery, it was found that there were significant deviation between the modelled water levels data and the water levels visible at the given time stamps. The modelled water levels are used for wave modelling and since no actual wave measurements exist, we cannot qualify wave data. Instead, descriptive statistical treatment between measured and modelled water levels are applied together with an analysis of the errors found between all time steps.

The difference in mean between modelled and measured data was reported by DMI to be equivalent to: "Modelled WL = Measured WL + 0.05cm". This can be confirmed from Table 2.3.

	Count	Min	Max	Range	Median	μ (Mean)	σ (Standard deviation)	σ^2 (Variance)
Modelled	23251	-0.98	1.48	2.46	0.10	0.10	0.22	0.5
Measured	22899	-0.98	1.34	2.32	0.06	0.05	0.19	0.4

Table 2.3: Standard statistical parameter for the modelled and measured water level data.

To evaluate the modelled data to the measured, common statistical parameters for the two datasets are presented in Table 2.3. Since modelled data are available at hourly time steps and measured are available every 10th minute a resampling of the measured data into hourly bins was performed. This was simply done by only including measured water levels for every whole hourly time step and by narrowing the datasets to comparable lengths within the study period. The sample period was set to be between 1-04-2017 and 25-11-2019. The count in Table 2.3 shows the amount of time steps in the sorted datasets. The measured count is slightly lower due to additional filtering out of error data with the value "999".

The probability distribution for modelled and measured water levels are presented in Figure 2.2. This shows that both datasets are close to normal distribution but with the upper tail slightly longer than the lower. The modelled water levels are slightly higher than the measured water levels and has a slightly wider range. The modelled mean is 0.05 m higher than the measured water level.

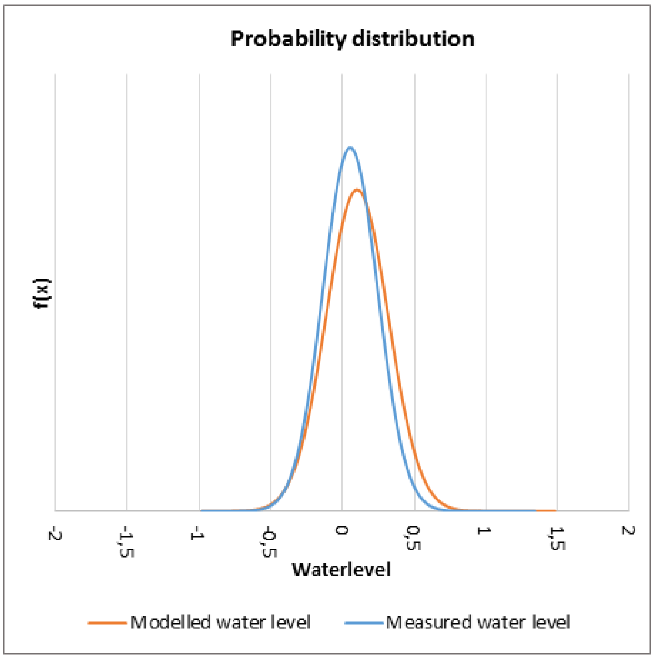

Fig. 2.2: Probability density distribution for modelled and measured water levels.

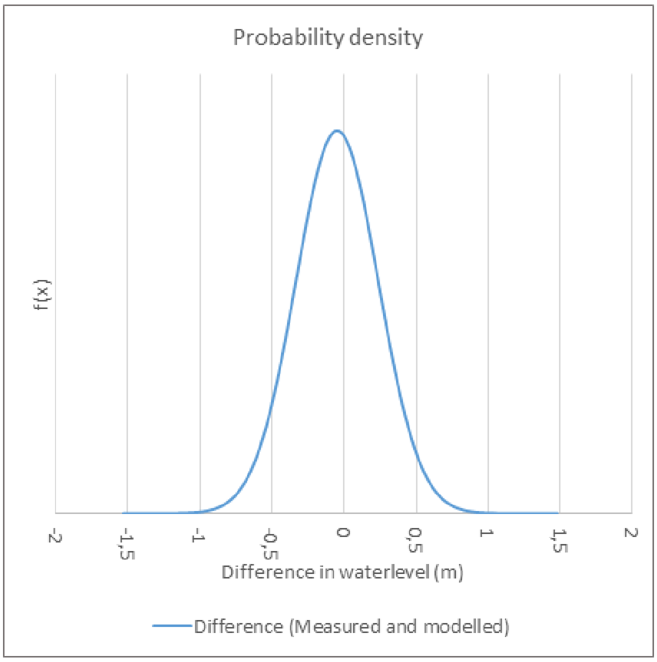

Fig. 2.3: Probability density distribution for modelled and measured water levels.

Count	Min	Max	Range	Median	*m* (Sample mean)	*s* (Sample Standard deviation)	s^2 (Variance)
22899	-1.53	1.48	3.01	-0.05	-0.05	0.29	0.08

Table 2.4: Sample statistics for the difference between modelled and measured data.

As the time steps are comparable, the difference between modelled and measured data can be determined for every time step. The sample statistics for the calculated difference between modelled and measured data is presented in Table 2.4. The differences are close to evenly distributed around the mean as also seen in the probability density distribution of the difference in Figure 2.3. The spread of the differences ranges between +1.48 m and -1.53 m. The standard deviation of 0.29 m indicates that there is a high degree of difference. The 95 % confidence interval has been determined from:

$$x \in \left[m - t_{\frac{a}{2}} * s * \left(1 + \frac{1}{n}\right)^{0.5} ; m + t_{\frac{a}{2}} * s * \left(1 + \frac{1}{n}\right)^{0.5} \right]$$

and has been calculated to -0.61 m and 0.51 m.

In short, based on the differences between modelled and measured water levels, there is 95 % chances that the differences in modelled and measured water levels fall within -0.61m and 0.51m. Despite the slight difference in means of 0.05 m, there are significant differences throughout the data series. It must be stressed that the port measurements are conducted inside the harbor, south of the "Skanse spit" at the study area, while the modelled data are constructed further offshore. Differences can therefore also be a result of the difference in locations.

2.3 National digital elevation models

The national elevation model for Denmark is available from three periods at Østerstrand, Fredericia. The first model is from 2004-2005 with a spatial resolution of 1.6 m. The second model is from 2014-2015 and has a spatial resolution of 0.4 m while the newest model is from 02-05-2018 with resolution comparable to that of 2015. Point cloud data is available for both 2014-2015 and 2018 measurements.

The 2004-2005 model have not been included in the analysis due to the difference in resolution.

2.4 Orthophotos

Orthophotos with varying resolution is available for multiple years. The orthophotos included in this research design are presented in Table 2.5.

Year	Resolution
1954	25 cm
1995	80 cm
1999	40 cm
2006	25 cm
2012	12.5 cm
2016	12.5 cm
2017	10 cm
2018	10 cm
2019	10 cm

Table 2.5: Orthophotos included in the report and their spatial resolution.

3. Methods

The methods applied to analyze the available data will be presented in this chapter.

3.1 Drone imagery

Individual frames from the drone videos have been exported from five different positions along the stretch. These images are stacked in Appendix A. The five positions are presented in Figure 3.1.

Imagery is taken from N towards S and the five positions (A to E) are presented in appendix A with images from left (S-end) to right (N-end). The imagery from the same positions are then stacked over each other in time making visual analysis of the development more manageable.

When analyzing these data it is necessary to underline that quantifications are not possible directly. The individual descriptions are supported by additional imagery when relevant, and references to measured water levels from the port and permanent structures are used to describe the changes.

3.2 Energy component

Establishing the primary energy components based on wave data is included to estimate the cross- and alongshore energy. This simple calculation will be used to describe the energy components and thereby indicate the dominant redistribution of nourishment sediment across and along the profile.

The following method for determination of the energy component is utilized in an earlier BwN report (Kystdirektoratet, et al., 2018). From linear wave theory, the total wave energy *E* of the singular wave can be determined from:

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

Where ρ is water density, g is gravitational acceleration and H_{m0} is significant wave height. *E* Describes the amount of energy per area and is expressed as Kg s².

The wave energy can be divided into a parallel and a perpendicular component relative to the coast. The coastal parallel component. Ey, is defined as:

$Ey = E \cdot \sin \alpha$

In the same manner, the coastal perpendicular component. Ex, is defined as:

$Ex = E \cdot \cos \alpha$

The angle α is defined between incident wave and the coast normal.

The energy components are averaged every hour as the wave parameters are given as 1-hour averages.

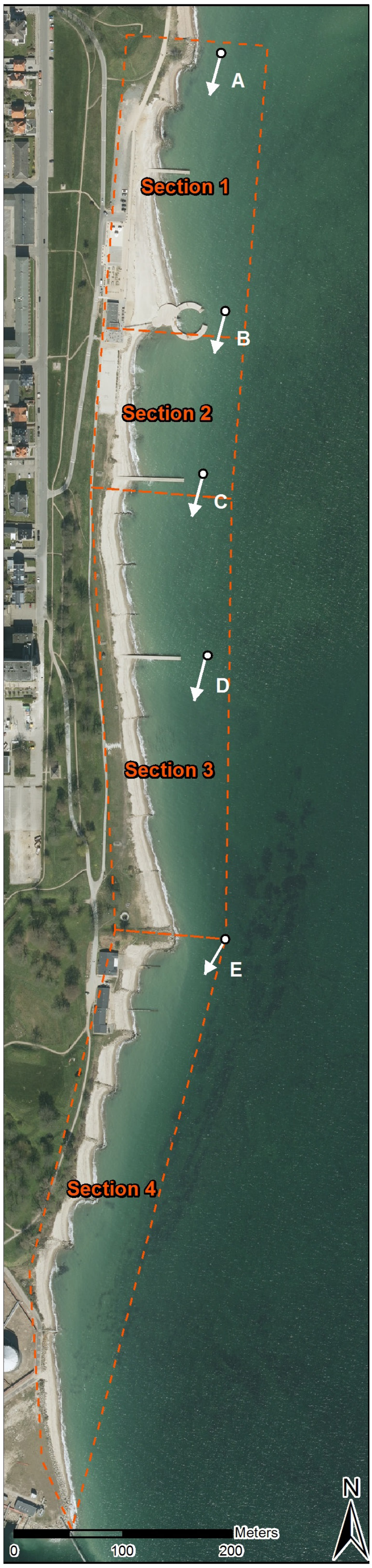

Figure 3.1: White arrows indicate from where and in which direction drone imagery is recorded.

Energy components are calculated for every time step and summed up for each period. As we are interested in analyzing the onshore and alongshore (north and south) energy components, the dataset has been restricted to wave direction between 0° to 180°.

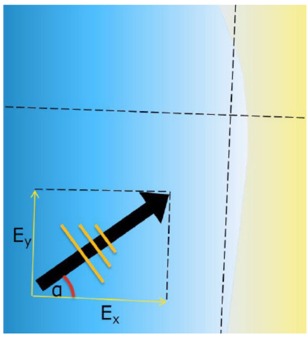

Figure 3.2: Energy decomposition of oblique waves in cross-shore and alongshore directions (Kystdirektoratet, et al., 2018)

3.3 Shoreline analysis from orthophotos

As multiple orthophotos of the stretch of Østerstrand are available, these are utilized for both visualizing differences between years, but also for estimation of the shoreline position. As the separation between water and beach is detectable in orthophotos, manual drawing in ArcMap is used to depict shorelines in time. These manual drawings will have errors, which can range from centimeters to meters, as the exact position can be difficult to detect. There is a slight distortion in older orthophotos and their respective resolution range between 10cm to 80cm, which can result in offsets when determining the shoreline. Furthermore, there have been no corrections of the shoreline in regards to water level, since it is unknown when individual frames have been captured in the orthophotos.

The shoreline retreat is estimated at 11 transects along the stretch. These are placed perpendicular to an inland station line with reference points at the end of the transect lines (green dots in Figure 3.3). Intersections between transect- and shorelines are found using ArcMaps "Intersect" tool. The distance from intersect point to transect reference point are found using the "generate near table" tool. The referenced distances can then be used to estimate the shoreline retreat as shown in Figure 3.4.

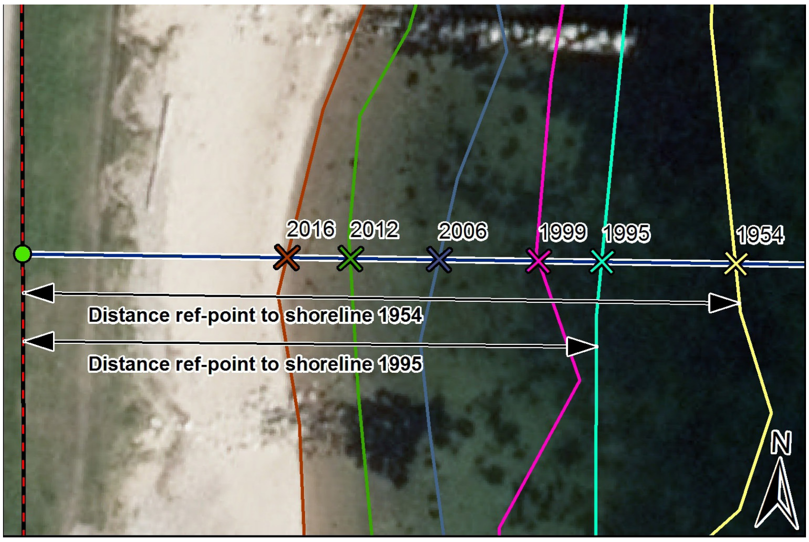

Figure 3.4: The intersections marked with crosses are created as described in the text. Here the shoreline retreat would be found as:
Retreat from 1954 to 1995 = Distance 1954 – Distance 1995.

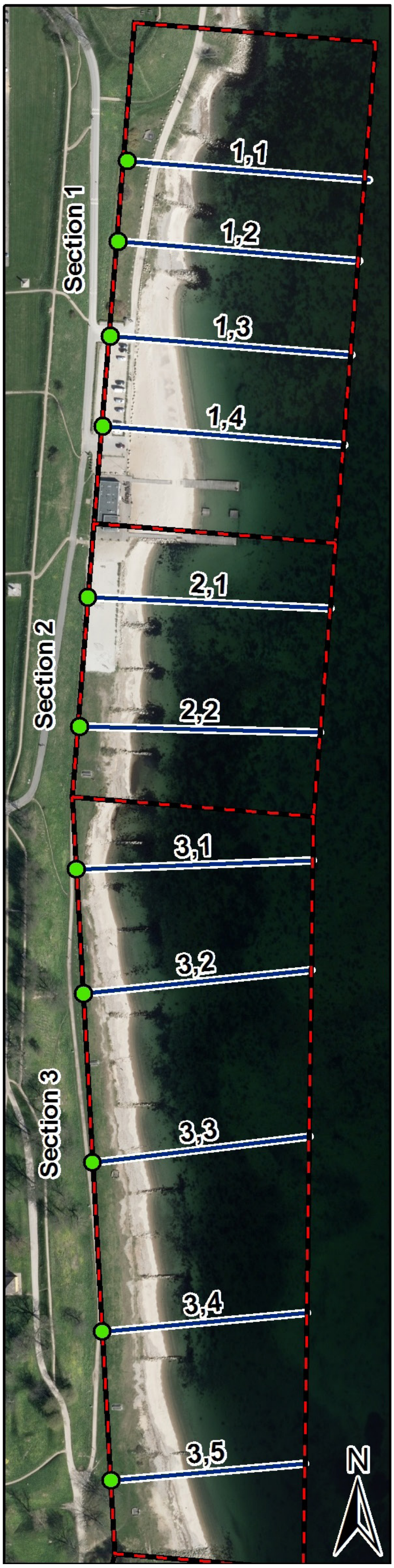

Figure 3.3: Profile lines drawn for estimation of shoreline retreat.

3.4 Difference mapping 2015-2018

As there are both a DTM from 2015 and from 2018 in comparable resolution and acquisition methods, a difference map is constructed to evaluate the changes between the models. Using the "minus" tool in ArcMap the older DTM is subtracted from the newer version and elevation changes are thus found. This difference mapping will be accompanied by the position of 0 m and 1.5 m contours from both 2015 and 2018. The 0 m contour is included to best represent the shoreline and extension/retreat can be identified. The 1.5 m contour is included as it best represent the vegetation line and the elevation of the meadow above the beach, and changes in this position will assist in identifying possible acute erosion.

3.5 Beach volume 2015-2018

The DTMs makes it possible not only to visualize changes, but also quantify them. The beach volume is analyzed between the maximum seaward extent of the 0 m contour (2015 and 2018) and the maximum inland extent of the 1.5 m contour (corrected to the nourishment extent in section 1 and 2) in each section. The process is depicted in Figure 3.5, and the method for creating the volume boxes is described below.

The polygon layer used for volume analysis is constructed on the basis of the 0 and 1.5 m contours from 2015DTM and 2018DTM, as well as the sectional division. These are input features in the tool "feature to polygon", which creates multiple polygons based on the input feature. Besides the main polygons on the beach, the method also results in a high number of smaller polygons. e.g. in intersections between contours. Based on locality, all features representing the individual sections are merged into one polygon, so the maximum seaward extent of the 0 m contour is represented as the seaward boundary and the max inland extent of the 1.5 m contour as the landward boundary. However, the landward boundary has been manually corrected to the extent of the nourishment in sections 1 and 2, since the 1.5 m contour is stretching further seaward in these two sections.

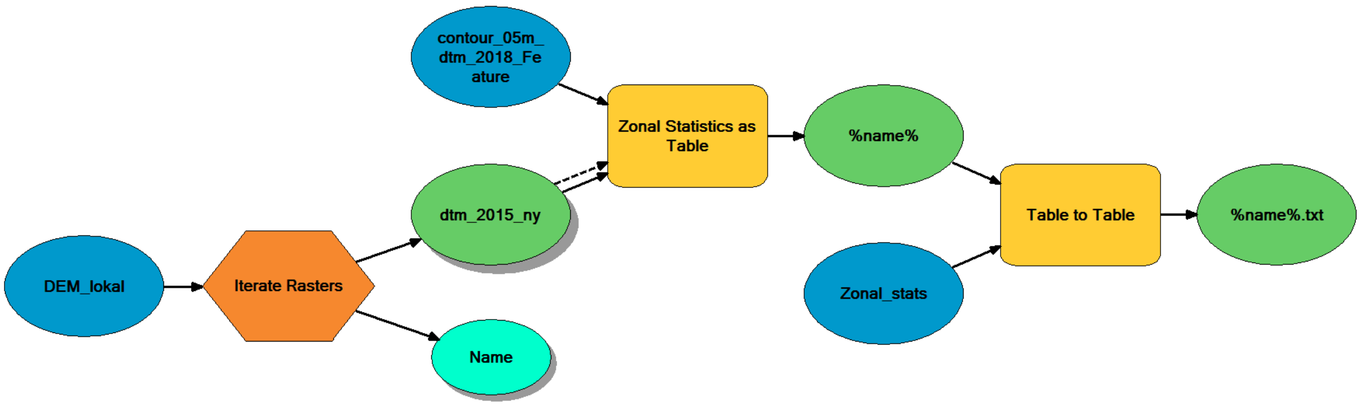

Figure 3.5: The beach volume in each section has been determined using the Model builder shown in this figure. The method is relatively simple, but it is, however, important to set input raster as snap raster to avoid unwanted resampling and set zone to the section number in the input for zonal layer.

4. Autonomous development

The beach width has decreased on the nourishment stretch between 1954 and 2017. There is only a slight increase in width on the N-side of the two old swimming piers, which is a result of the upstream side accumulation. The construction of these swimming piers increased the beach reduction on the leeside and the construction an the groyne fields was intensified in the 1980's. Between 1999 and 2004 the Southern terminal groyne was prolonged using stones from some of the older inactive groynes (also seen in Figure 4.1), and there was a reduction in the amount of revetments.

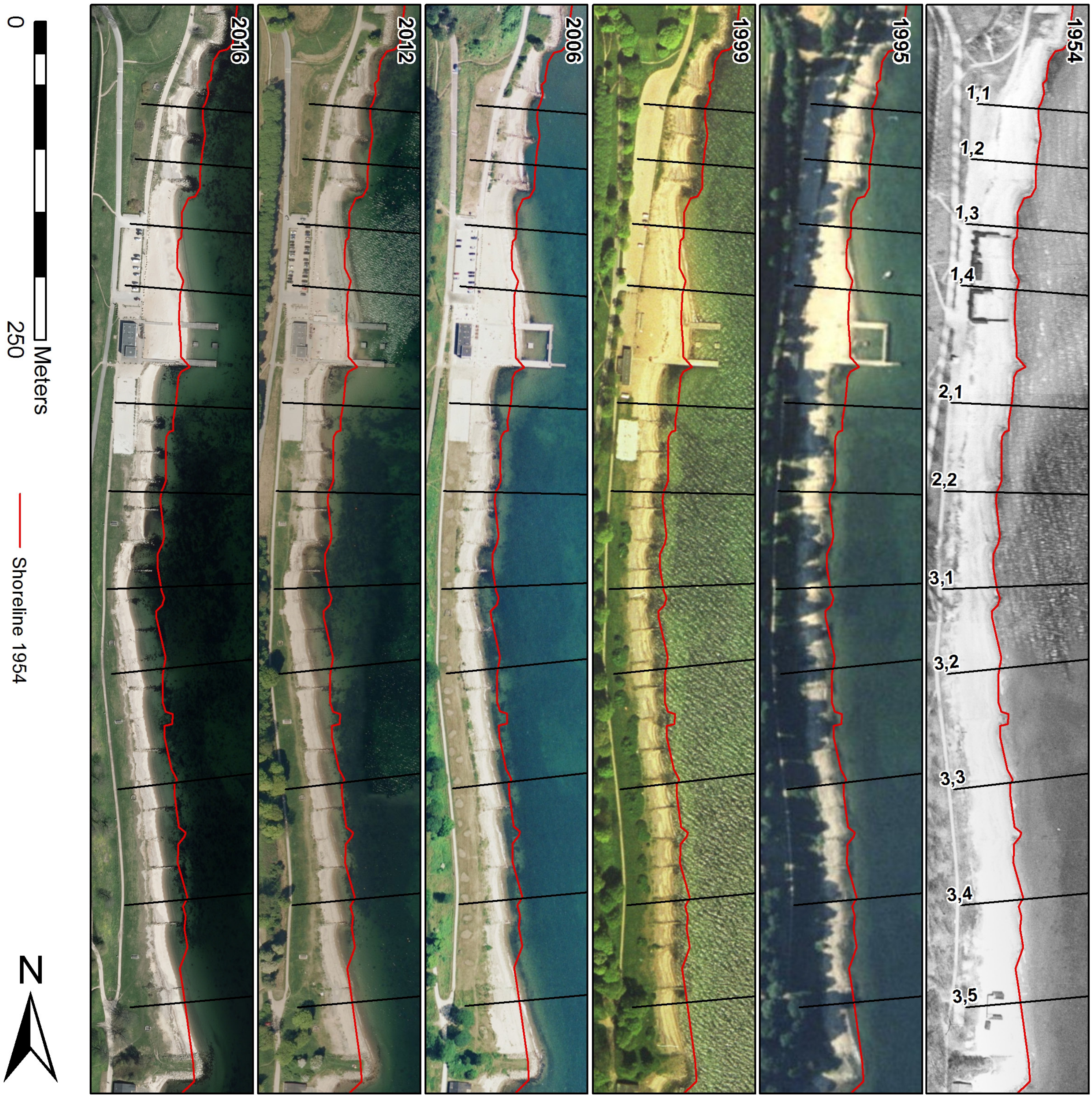

Figure 4.1: Time stack of Orthophotos at Østerstrand, Fredericia. The Shoreline polyline in red are drawn by hand as the approximate boundary between sand and water on the 1954 imagery.

As sediment input at Østerstrand diminished due to upstream increase in coastal protection (N to Trelde Næs), several groynes have been installed at Østerstrand. Although the groynes have detained sediment in smaller cells, acute erosion has not been hindered, which is seen as retreat in the vegetation line of the grass flats above the beach. Chronic erosion has been ongoing as the reduction of sandy sediment was seen in the beach stretches, while larger areas of black spots have emerged in orthophotos over the last 20 years. These black spots are difficult to interpret since they could both resemble seaweed and/or rocks and there are neither visible nor physical confirmation on the actual spots. Interpretation of these spots is therefore not undertaken. Despite the groynes´ ability to detain some longshore sediment, the shoreface deficit has continued.

4.1 Shoreline analysis

As data availability is limited, the changes in shoreline position is analyzed to evaluate retreat and advance of the coast. Although the analysis does not represent the general profile evolution it can indicate a trend. The shoreline analysis is performed according to the method described in chapter 3.3. The following sub-chapters divides the analysis according to the sectional division, presenting the results together with a description.

4.1.1 Section 1 - Change in waterline position

The position of the waterline has been determined from the defined lines in Figure 3.3. Figure 4.2 presents the waterline position relative to 1954 for the lines 1.1 to 1.4 in section 1 and the movement has been quantified in Table 4.1 for three different periods. The three northern lines show to have been retreating for the whole period with the exception of the period between 1999 and 2006. There is a small decrease in the retreat rate between 1995 and 2016 compared to the period from 1954 to 1995 – this is likely due to intensification of groyne fields in the period, which has detained sediment for some of the period but the deficit has thus increased in the wet part of the profile because of chronic erosion. The general pattern is that the waterline retreats. The only line in the entire stretch, which have migrated seaward compared to 1954 is line 1.4. This is the result of sediment accumulation on the upstream side of the swimming piers, which have functioned as one large groyne.

Linear regression of waterline movement				
Line	**1.1**	**1.2**	**1.3**	**1.4**
Change in m/y (1954 to 2016)	-0.18	-0.24	-0.08	0.08
Change in m/y (1954 to 1995)	-0.20	-0.24	-0.10	0.10
Change in m/y (1995 to 2016)	-0.15	-0.25	-0.05	0.01

Table 4.1: The trend for each line in section 1 is presented as linear regression between both

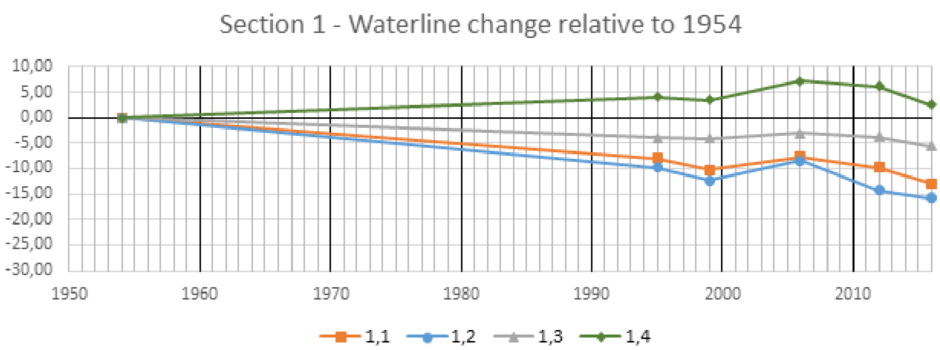

Figure 4.2: Showing the measured shoreline position for the included years, relative to the 1954 position.

4.1.2 Section 2 - Change in waterline position

The position of the waterline has been determined from the defined lines in Figure 3.3. Figure 4.3 presents the waterline position relative to 1954 for the lines 2.1 and 2.2 in section 2 while the movement has been quantified in Table 4.2 for three different periods. Line 2.1 shows a rapid reduction in beach width between 1995 and 2016 compared to line 2.2.

Linear regression of waterline movement		
Line	2.1	2.2
Change in m/y (1954 to 2016)	-0.30	-0.19
Change in m/y (1954 to 1995)	-0.34	-0.13
Change in m/y (1995 to 2016)	-0.13	-0.31

Table 4.2: The trend for each line in section 2 is presented as linear regression between both

The beach width reduction at line 2.2 shows increase between 1995 and 2016. On the contrary, line 2.1 showed decrease in shoreline retreat between 1995 and 2016. The four groynes in section 2 seem to control the stretch and the sediment pockets at the beach.

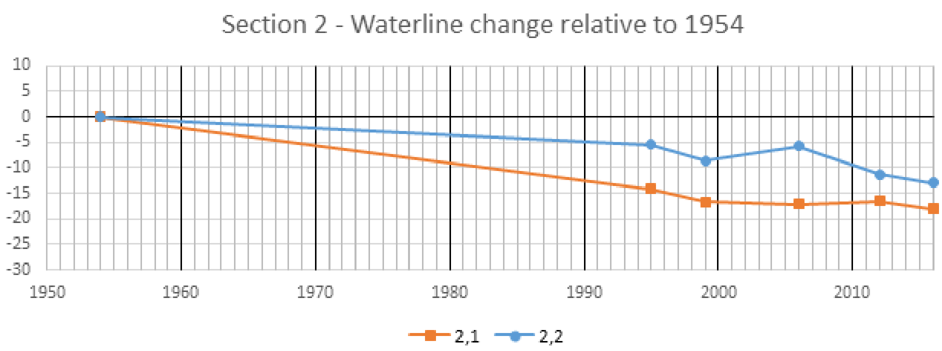

Figure 4.3: Showing the measured shoreline position for the included years, relative to the 1954 position.

4.1.3 Section 3 - Change in waterline position

The position of the waterline has been determined from the defined lines in Figure 3.3. The highest rates of retreat in the shoreline is found to be at line 3.1 and noticing the changes in vegetation line at line 3.1 from orthophotos in Figure 4.1, this retreat is coupled with the most pronounced acute erosion for the stretch. The retreat rate decreases slightly from 3.1 to 3.5 and 3.5 even shows seaward migration. The seaward migration at line 3.5 is likely a response to the prolonging of the terminal groyne, which has detained slightly more sediment. Nevertheless, there has still been a general intensification in retreat between 1995 and 2016, compared to the period between 1954 and 1995.

Linear regression of waterline movement					
Line	3.1	3.2	3.3	3.4	3.5
Change in m/y (1954 to 2016)	-0.40	-0.27	-0.27	-0.27	-0.01
Change in m/y (1954 to 1995)	-0.19	-0.10	-0.20	-0.20	-0.13
Change in m/y (1995 to 2016)	-0.88	-0.58	-0.49	-0.37	0.32

Table 4.3: The trend for each line in section 3 is presented as linear regression between both

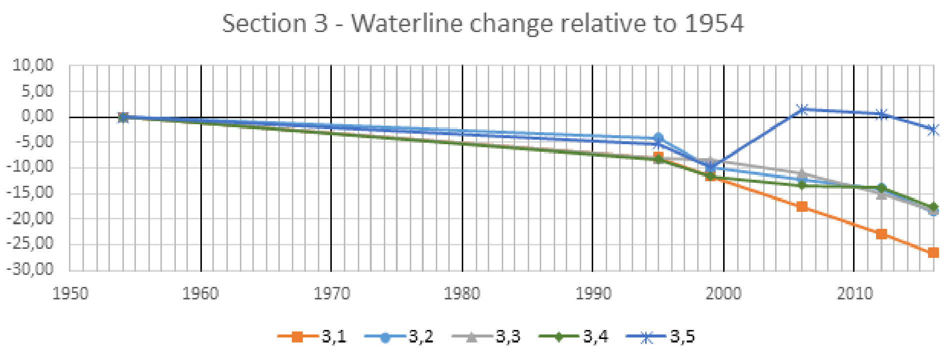

Figure 4.4: Showing the measured shoreline position for the included years, relative to the 1954 position.

4.2 Beach state before nourishment

To describe the initial conditions of the beach before the nourishment, all sections are described from drone imagery taken on the 5th of May 2017, as seen in appendix A (The water level was +0.38 m). Description of coastal protection prior to nourishment is based on the drone imagery and the orthophoto from spring 2017.

4.2.1 Section 1

The fill sediment from the inland deposit was already placed on the 5-5-2017 and some of the sand mass has been dozed onto the beach in section 1. The three groynes in the north end are still intact and construction of the circle jetty has already created an accumulation on the north side of it.

Coastal protection before nourishment – The northern boundary is a headland with rock revetment. Within section 1 there are three groynes, which increase in width from beach to seaward tip. The groynes seem to have been undermined over time and the width is the result of filling with stones during the 2000s and 2010s. Before the nourishment, the swimming facility included two concrete piers perpendicular to the coast with two platforms in-between them. Both were constructed of concrete and with pile sheet frame. They acted as one main groyne blocking the longshore transport.

4.2.2 Section 2

The beach just south of the circle jetty is sandy. The beach in-between the four groynes mainly consists of pebbles. Groynes are intact and no nourishment has yet been conducted.

Coastal protection before nourishment – a revetment was placed alongside the southern part of the southernmost swimming pier, which had not been removed on the 5th of May 2017 and therefore more resembled a groyne. Along the beach volleyball court a revetment is present. On the stretch between the southern boundary of section 2 and the revetment, five groynes of varying conditions and lengths were present.

4.2.3 Section 3

The beach is dominated by pebbles and narrow strips of sandy sediment. The condition of the groynes vary significantly and some are in such poor condition that they are not expected to have a significant effect on the longshore transport. Wave breaking takes place in the swash, and there are no indication that breaker bars exist. The shoreline at the terminal groyne to the south is affected by swash from oncoming waves and it is not possible to determine the extent of the regular shoreline, but swash is present halfway up the beach along the groyne and has not reached its detaining capacity at this point.

Coastal protection before nourishment – In section 3, 14 groynes of varying size, position and width were present before the nourishment, not counting the terminal groyne to the south. In general the groynes vary in length, width, design etc. and they generally seem to be deteriorating. Of the 14 groynes, five of them were only located on the beach, and can be considered piles of rocks rather than groynes. Some of the longer groynes are constructed with wooden pile frames with boulder blocks within. As constructions have been undermined or piles have broken, the groynes have flattened, as they were undermined. Additional fill on various occasions with stones on top of the older ones have been identified from orthophoto inspection.

4.2.4 Section 4

Sand and gravel makes up the beach sections between the individual groynes. The Skanse spit does not show any consistent beach section.

Coastal protection before nourishment – South of the rowing club is a revetment with an additional groyne. South of the kayak club a headland/groyne is build. From the kayak club to the oil terminal four groynes are found. The full stretch along the oil terminal is surrounded by revetments, and the southern spit is a man-made construction.

5. Results

The results chapter present the findings from the analysis performed. Firstly, the wave energy calculations are presented for all periods. These are presented first as they are included during the analysis of the drone imagery under section 5.2. Together with the wave energy calculation, measured water levels and modelled wave heights are also included for interpretation of changes in each period from the drone imagery. To estimate and quantify the changes, difference mapping and volume analysis based on DTMs from 2014/2015 and 2018 will be presented in section 5.3.

5.1 Energy components

The wave energy is calculated as described in chapter 3. Results of the hourly-calculated energy components are presented in Figure 5.1 and Table 5.1. Significant wave height has been presented in graphs whilst the modelled water level is presented for each period under chapter 5.2.

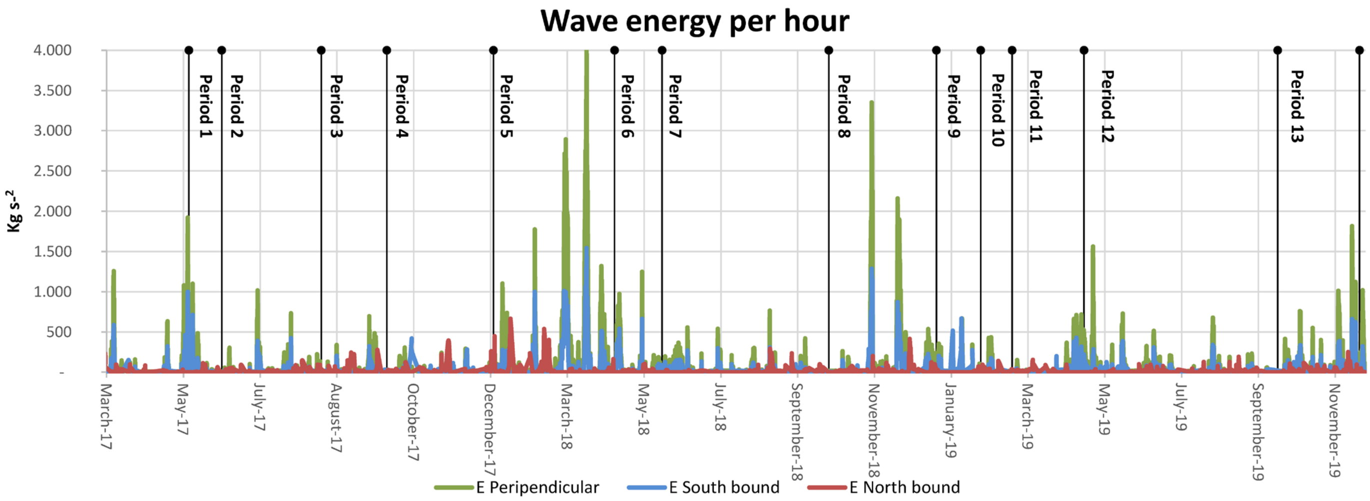

Figure 5.1: The wave energy alongshore (north/south) and perpendicularly is calculated every hour from the method described in Chapter 3. Division into periods is represented as black vertical lines with the respective date attached.

The dominant energy component is cross-shore while the southbound energy component is the 2nd largest. The northbound energy component generally shows to be the smallest for the entire period, and compared to the southbound component, the primary alongshore transport must be from north to south. However, during a few episodes in e.g. periods 3 to 5, the N-component is dominating. This can be seen in Figure 5.1 as small peaks where the north bound energy is larger than the other two.

Periods	Days in period	Hours in period	E kg/m² Perpendicular per Hour (Averaged)	E kg/m² South bound per hour (Averaged)	E kg/m² North bound per hour (Averaged)
Period 1	26.2	629	54.8	26.0	3.7
Period 2	79.1	1898	30.2	11.5	2.5
Period 3	52.0	1249	41.7	12.2	5.5
Period 4	84.7	2034	15.1	6.0	3.3
Period 5	96.2	2309	247.3	89.8	15.2
Period 6	37.8	907	87.5	39.8	3.3
Period 7	132.4	3178	29.9	12.2	1.7
Period 8	85.5	2052	138.7	51.7	11.4
Period 9	35.0	841	35.5	30.0	2.5
Period 10	25.1	602	35.9	9.7	5.5
Period 11	57.1	1370	57.4	26.2	3.3
Period 12	153.8	3692	39.2	14.7	2.2
Period 13	65.0	1560	86.9	33.1	7.4

Table 5.1: The average hourly energy components for each period in the study period are presented for the perpendicular, South and North bound components.

The periods 5 and 8 can be determined as storm periods as they present significantly higher energy than the remaining periods. As seen in Figure 5.1 the high intensity of energy is not general for the periods, but consists of multiple peaks and some longer events with high-energy. Period 5 shows to be the most significant period concerning energy input, as it is close to double of period 8.

5.2 Imagery analysis

As the angles and positions of the imagery differs over time, it is difficult to quantify changes. However, the structures on the beach are stable features, which in this analysis can be used to determine changes in time. Although Fredericia is considered a micro-tidal environment with under 20 cm fluctuation in tides, the general water level at the time of the imagery must be considered in relation to analyzing the photo. The following will describe the state of the nourishment and the development for the individual periods, for every section. The analysis relies on the imagery from appendix A and will be accompanied by measured water level and modelled wave height data for each period.

Period 1

The water level was -0.33 m during image recording on the 31-05-2017 (Period 1 is from 05-05-2017 to 31-05-2017). Figure 5.2 shows the final changes in the passive coastal protections made after the nourihsment was complete.

Section 1: Nourishment is completed and the beach has widened significantly. Some redistribution is seen in the swash but only little natural equalization have begun. The undulating shoreline is the result of redistribution by dumpers. Two out of three groynes are close to covered by nourishment sediment. Beach width in the upstream side of the circle jetty extends to the end of the pile-sheet inserts and detaining capacity is reached.

Coastal protection after nourishment – The swimming piers were demolished and a new circular jetty was built at the same time as the nourishment was completed. The steel framing of the older piers are likely to have been left and still work as groynes in combination with the new circle jetty. Additionally, a jetty is placed in the middle of the stretch, built on steel piles and with a rock groyne build underneath half of the length of it.

Section 2: The nourishment has widened the beach significantly compared to its former state. The four groynes in the middle of section 2 are almost topped with nourishment sediment. The swash is steep and with coarser grains, which indicates that until this point there has only been redistribution of finer sediment in the swash.

Coastal protection after nourishment – The 4th and 5th groynes (southernmost) were removed but the three others remain. A new jetty (no. 2 from north) is under construction, but so far only the steel piles have been placed.

Section 3: Steel piles for the 3rd jetty are placed, but the new jetty is not yet completed. Between the two new planned jetties, some of the lower laying stone groynes are covered with sand. The groynes have not been renovated, but the nourishment has extended the beach beyond the end of the frames. As in section 2, there seems to be a coarser grain distribution in the swash compared to that seen on the beach.

Coastal protection after nourishment –The two planned jetties in section 3 are not finished at this point but it will show that rock revetments are placed underneath half of their lengths once they are completed. Of the former 14 groynes, 10 are left. Whether the four groynes have been removed or simply covered with nourishment sediment in uncertain, but it seems likely that the revetment stones have been utilized underneath the jetties.

In general, the beach has widened along the entire stretch of section 3 to the end of the older groynes. The groynes are close to topped with sediment. Undulations in the shoreline are also evident here and are the likely result of redistribution of sediment by dumpers.

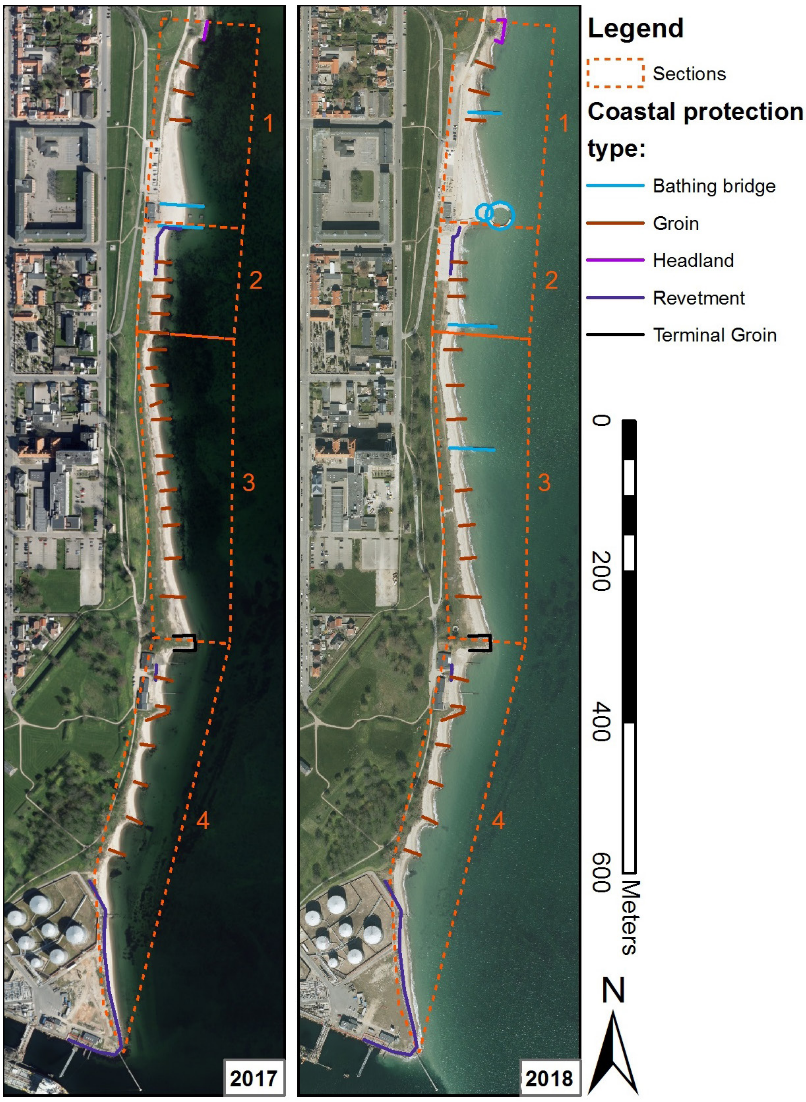

Figure 5.2: Passive hard coastal protection measure before and after the beach nourishment.

Section 4: Unfortunately, there are not a good view of section 4 from 31st of May. Instead, an S to N image from the middle of section 3 toward section 1 is inserted in Appendix A.

Coastal protection after nourishment – No changes are made.

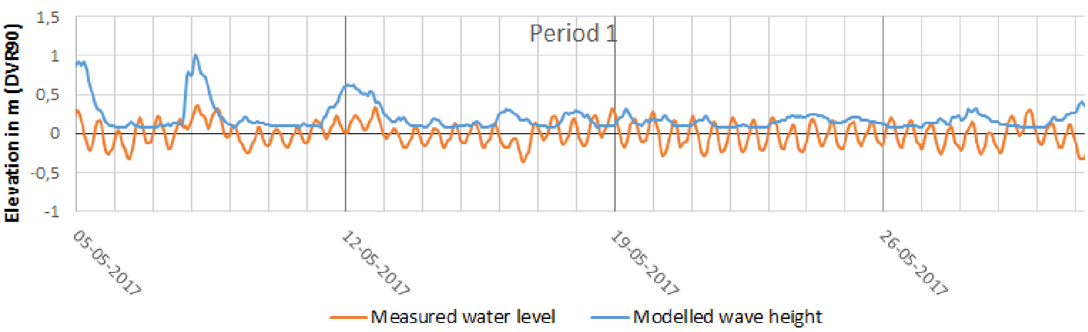

Figure 5.3: Modelled wave height and water level from the DMI dataset for period 1. Note that SWH is short for "significant wave height".

The nourishment criteria of restoring the beach width from 1954 can be considered accomplished this. This is noted as the nourishment width extends further seaward than the existing groynes. As seen in the 2017 orthophoto, the 1954 waterline actually corresponds well with the tips of the groynes (Figure 4.1), and therefore, the shoreline is at the same position as it was in 1954, give or take a couple of meters. During period 1, three occasions with waves above 0.5 are encountered. There are no high water events of significance during period 1, which explains the few changes in the planform of the nourishment. Only the step in the swash has experienced a steepening.

Period 2

The water level was -0.07 m during image recording on the 18-08-2017 (Period 2 is from 31-05-2017 to 18-08-2017).

Section 1: The nourishment planform has been reduced in width, and a characteristic, exponential plan-form between the jetty and the circle jetty has formed. Two of three groynes are now completely covered with sediment.

Section 2: The beach has been reduced slightly in width and undulations in the shoreline have been equilibrated to a more natural state compared to 31st of May. The assumption that the new circle jetty would work as a groyne is confirmed when we look at the shoreline, as the reduction in beach width is most significant on the immediate south side of the construction. Beach width south of section 2 is close to the same as 31st of May. All groynes in section 2 are completely covered with sediment and the new jetty is now finished.

Section 3: The shoreline has retreated inland between the jetties and the shoreline is now landward of the groyne tips. Jetty No. 2 shows accumulation/erosion, as would a groyne, which is due to the boulders placed underneath the jetty. It is not possible to determine cross-shore distribution from these images, but there are indications of increase of sandy sediment in the swash and shallows.

Between the 3rd jetty and the terminal groyne, the planform reduction is not as pronounced as in the N-part of section 3, although the shoreline has retreated slightly inland of the groyne tips with exception of the two groynes nearest to the terminal groyne. The strip of sandy sediment seen in the swash zone is likely to stem from upstream nourishment reduction and some from cross-shore redistribution. The terminal groyne has filled up and no longer accumulates sediment on the upstream side.

Section 4: Increase in beach width between all groynes and a narrow beach section have emerged at the spit in the S-end of section 4. The water level at this particular moment is close to 0.15 m higher than on 5th of May so the increase is not due to a lower water table. It is clear that sediment has been transported around the terminal groyne of section 3 into section 4. This is visible as a sediment strip along all groyne tips in section 4, which is extending from section 3.

There has been some redistribution of the sediment and in general a reduction in planform. Morpho-logical marks from wave or water level on the beach indicate some redistribution by water. There have been two events with waves above 0.5 m in height, one event between 28th and 29th of June and one on 25th of July. The dominant energy direction in both cases have been cross-shore, as seen in Figure 5.1, and the water level at the time has not been enough to reach the upper sections of the beach. Since the water level only reaches +0.5 m, the upper beach sections have not experienced any significant changes.

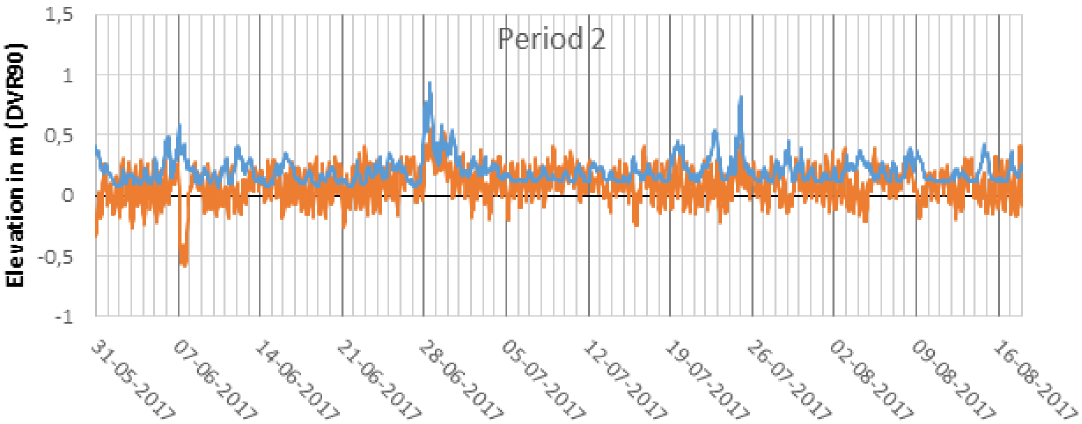

Figure 5.4: Modelled wave height and water level from the DMI dataset for period 2. Note that SWH is short for "significant wave height".

Period 3

The water level was +0.26 m during image recording on the 09-10-2017 (Period 3 is from 18-08-2017 to 09-10-2017)

Section 1: The northern end indicates increase of sandy sediment in the nearshore shoreface and smaller bars or ripples have developed. Based on the beach width at the jetty and the northern most groyne there has been no reduction in beach width. However, indications of higher water levels are seen, as the swash seems to have extended further up the beach.

Section 2: No clear change in beach width can be seen. Groynes are still covered by the nourishment sediment and the swash seems flat.

Section 3: There has been a reduction of beach width between jetties No.2 and 3. Bright sandy sediment is still visible in the swash and nearshore.
Between the jetty No. 3 and the terminal groyne there has been some reduction in planform. The south end of the terminal groyne still shows the same width and is still at its maximum detaining capacity.

Section 4: The imagery clearly shows that sediment bypasses the terminal groyne at section 3. In addition, there is a significant increase in beach width and height at the rowing clubs. The groynes along section 4 have the shoreline at their very tip and this indicates a general increase in sediment.
During period 3, there has been a slight reduction in beach width along parts of the nourishment stretch and the longshore transport is generally toward south. In period 3, there has been several events with wave heights above 0.5m, but the most significant event takes place from 25th of august until 1st of September. However, this was combined with low water levels and again with predominate cross-shore energy.

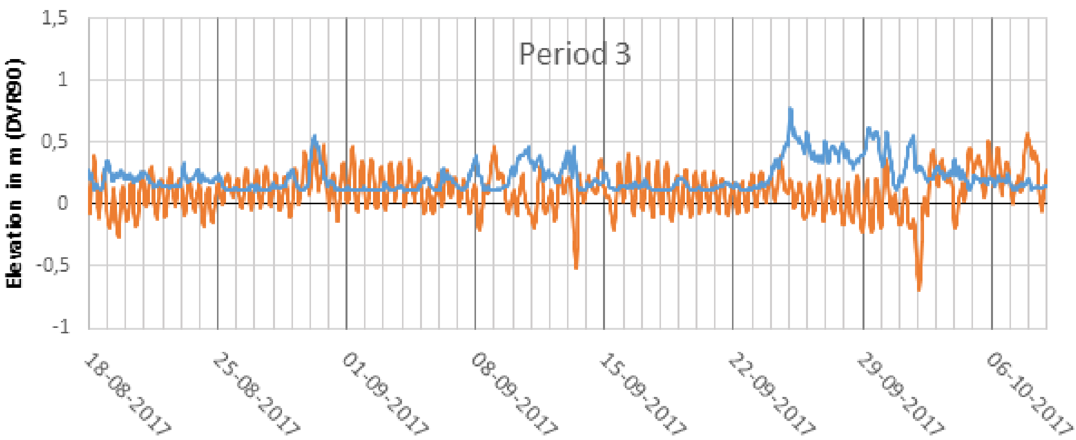

Figure 5.5: Modelled wave height and water level from the DMI dataset for period 3. Note that SWH is short for "significant wave height".

Period 4

The water level was +0.33 m during image recording on the 02-01-2018 – (Period 4 is from 09-10-2017 to 02-01-2018)

Section 1: There seems to be an increase in berm height along the entire stretch. Cusps have developed and a sheet of sediment is still present in the swash and the nearshore shoreface. The shoreline has retreated slightly compared to 9th of October 2017.

Section 2: Slight reduction in beach planform and a retreat of the shoreline. The same pattern as in section 1 with increase in berm height and forming of cusps in section 2.

Section 3: There are only little change on the entire stretch. In general cusps have formed in the swash, the berm height has increased but there is only very little reduction in beach width. There is an indication of a breaker bar along the entire stretch at the groyne tips.

Section 4: Accumulation is taking place in the berm in front of the rowing clubs. Furthermore, the longshore transport around the terminal groyne has become very clear. Figure 5.6 illustrate how a sheet or longshore bar of sandy sediment migrates from north to south around the terminal groyne in section 3. Furthermore, the bottom section of the image indicates that leeside accumulations behind either underwater vegetation or stones are taking place.

Figure 5.6: Frame extracted from the drone film made on the 02-01-2018. The image shows the rowing and kayaking club in the N-end of section 4. The longshore transport is evident in the sediment fan from the terminal groyne of section 3 towards S in section4.

There has been a general increase in berm height despite a reduction in beach width. Additionally, the shoreface shows indications of at least one bar building up. The maximum water level in period 4 has reached 1.5 m at its peak on 29th of October, but as there has generally been little wave energy impact during the period, there has not been any visible decrease in the nourishment width. Instead, it has been observed that the berm has increased in height. As period 4 generally has been dominated by higher water levels and multiple events with low energy waves, this can have led to sediment being transported back to the shoreline after cross-shore dissipation. Period 4 is the period with lowest overall wave energy impact.

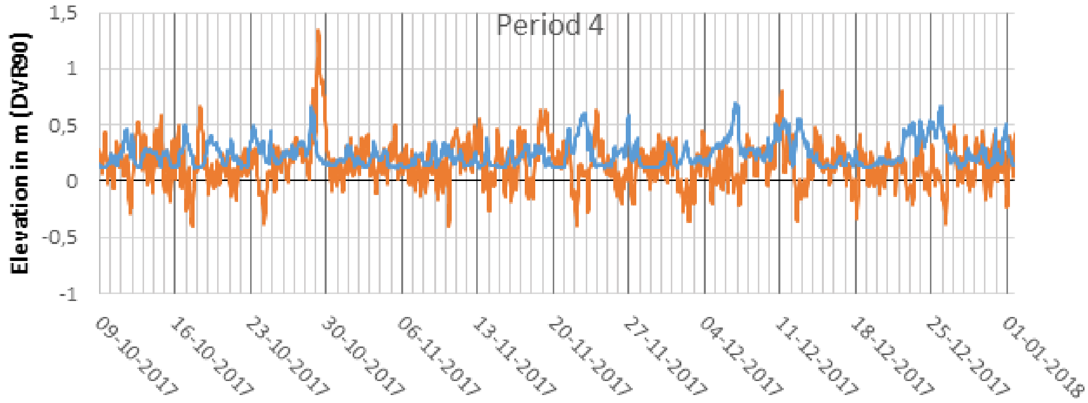

Figure 5.7: Modelled wave height and water level from the DMI dataset for period 4. Note that SWH is short for "significant wave height".

Period 5– After storm

The water level was -0.08 m during image recording on the 08-04-2018 (Period 5 is from 02-01-2018 to 08-04-2018)

Section 1: The northernmost half of section 1 shows that coarser sediment now dominates the beach while the two revetments that were formerly covered by sediment, have emerged again. This indicates that the beach height and volume must have been generally reduced. This is also seen as the beach has been scarped along the entire stretch. Beach width has reduced for most of the stretch but the accumulation on the north side is still clear.

Section 2: The groynes, which were covered by nourishment sediment, are now visible again. Wave run-up have been all the way to the revetment at the beach volley court. Beach width has decreased and the buildup in the berm has dissipated again.

Section 3: Remains of an older groyne have appeared just south of jetty No. 2. The leeside effect of the construction underneath jetty No 2 is seen as an increased reduction of the beach at the immediate leeside. Furthermore, there are clear signs of acute erosion in the grass flat between jetties 2 and 3.

Between jetty no. 3 and the terminal groyne, an older groyne has emerged. The beach elevation has decreased for the entire stretch and acute erosion of the vegetation line is evident in several places. The terminal groyne is still at maximum detaining capacity, which leads to longshore transport bypassing the groyne into section 4. The sheet, or bar, of sandy sediment in shore face is far more consistent and wider than earlier.

Section 4: The increase in the sediment sheet width is visible in this section. Despite a reduction of the beach height, the width is intact and has even increased at some parts of the stretch.

As period 5 can be considered a storm period, it is not unexpected that there has been a significant change in the beach nourishment planform. Multiple high-energy events have impacted the stretch during period 5 but the most significant storms are on 25th of February and on 17th of March. Here wave height reached more than 1m in height for several periods longer than 24 hours and with peaks above 1.5 m. This in combination with water levels above +0.5 m has been the reason for the change and redistribution of sediment. The maximum extent of the swash is seen on the beach, and waves have clearly reached the top of the beach and in some areas even the toe of the grass flats causing acute erosion. As the system in general was out of equilibrium before the nourishment, most of the redistributed sediment is likely to have been transported cross-shore, which corresponds well with the primary cross-shore energy component during the period. The sporadic increases in beach width seen for period 5 needs to be considered, as the water level was more than 40 cm lower than on 8th of April 2018, compared to the previous photos from 2nd of January 2018. Generally, the sediment composition of the beach have coarsened and the beach has flattened.

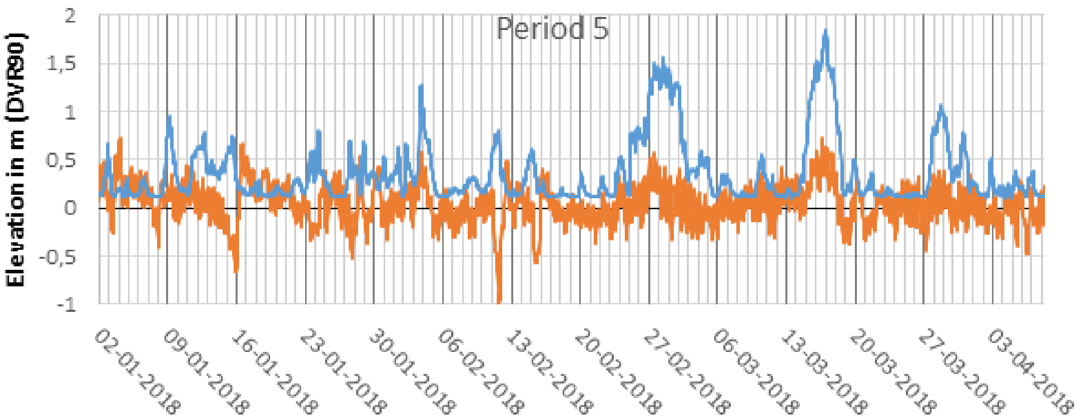

Figure 5.8: Modelled wave height and water level from the DMI dataset for period 5. Note that SWH is short for "significant wave height".

Period 6

The water level was +0.01 m during image recording on the 16-05-2018 (Period 6 is from 08-04-2018 to 16-05-2018)

Section 1: Beach width increases between jetty no. 1 and the circle jetty. Buildup of sediment in the swash indicates re-entering of nourishment sediment. Due to capillary waves and low light, the details of the shoreface are difficult to detect. There still seems to be a coarse sediment composition in the swash.

Section 2: The beach width increases and the pebbles accumulated in the S-end of the revetment at the beach volley court are now covered with finer sandy sediment. One of the groynes, which was uncovered after the storm, has now been overtopped with sediment again.

Section 3: Between the two jetties no. 2 and 3, the groyne, which emerged during period 5, is again partly covered by sand. There seems to be more sandy sediment in the beach pockets compared to the end of period 5. This is also seen in the southern half between jetty No. 3 and the terminal groyne. It is clear that the characteristic exponential planform between the groynes have formed since the storm and is more pronounced now than in any prior periods.

Section 4: There is no changes in planform between the groynes and at the spit. There is the same indication of sediment covering the pebbles as has been seen in the remaining sections.
Period 6 shows two wave energy peaks, which corresponds, with peaking wave height. It is noted that there is no indications of volume reduction in the period despite the peaks in energy. In period 6 the groynes have controlled the planform of the beach on the stretch, which corresponds well with the energy calculations. They show a general predominant cross-shore energy component. This period also shows a significantly higher S-bound energy component compared to the N-bound energy. In fact more than 10 times higher.

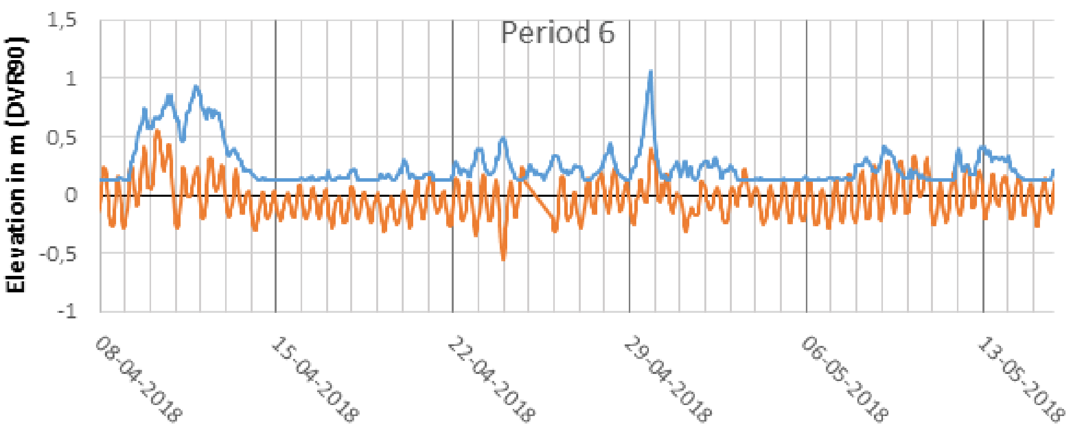

Figure 5.9: Modelled wave height and water level from the DMI dataset for period 6. Note that SWH is short for "significant wave height".

Period 7

The water level was -0.19 m during image recording on the 25-09-2018 (Period 7 is from 16-05-2018 to 25-09-2018)

Section 1: No significant changes occur relative to 16-05-2018 in relation to beach width. The nearshore shoreface indicates sandy sediment between the jetty and circle jetty. The coarser sediment is either covered or replaced by fine sandy sediment in the mid-section of the beach.

Section 2: Generally, a slight reduction in beach width relative to 16-05-2018, and especially in the direct leeside of the circle jetty, where a small groyne has now emerged. The berm has increased in height.

Section 3: Sandy sediment has covered or replaced the pebbles and now dominates the beach sections. The beach width has increased slightly since 16-05-2018 along the stretch, while the berm has increased in height.

Section 4: Beach width is close to the same as in 16-05-2018 and no significant changes are detected.

The water level is found to be 0.2 m lower than in the prior imagery. The beach width might have appeared larger than they actually would be at the same water level. An overall decrease in beach width is therefore assumed for period 7. This period has the second smallest energy component and is dominated by a cross-shore energy component. The impacts and responses during period 7 have high similarity to those in period 4 and the resulting increase in berm height is seen in both periods. The N-bound energy component in period 7 is the smallest measured for all periods and most of the redistribution is likely to have been cross-shore.

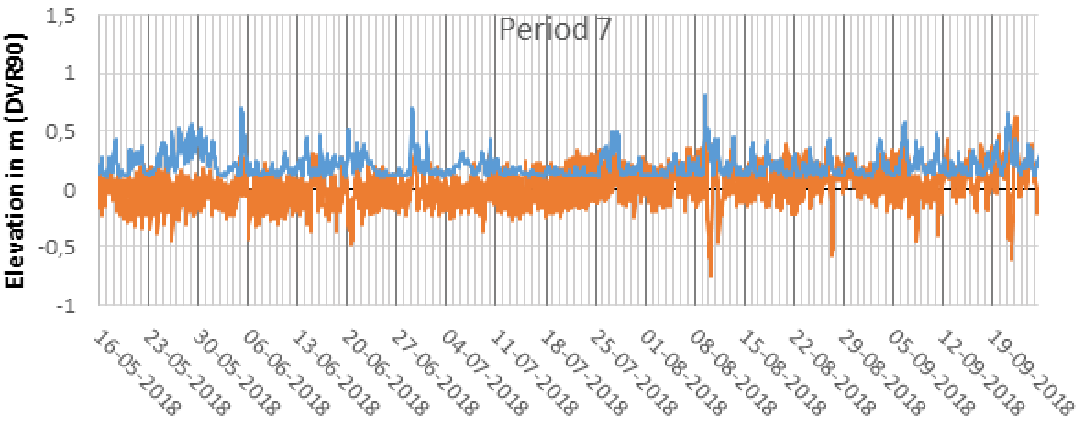

Figure 5.10: Modelled wave height and water level from the DMI dataset for period 7. Note that SWH is short for "significant wave height".

Period 8– after storm

The water level was +0.03 m during image recording on the 20-12-2018 – (Period 8 is from 25-09-2018 - 20-12-2018).

Section 1: The beach has decreased in width while the run up extent has reached further than indications showed on 25th of August. The sediment composition again seems to have coarsened. The run up has not yet reached the revetment at the parking area.

Section 2: All groynes in section 2 are now uncovered from the nourishment sediment and the width of the beach has been reduced with at least 1/3. Maximum extent of wave run up has been to the revetment at the beach volley court. The upstream accumulation, seen earlier at jetty No. 2, is reduced, while the groyne setting underneath the jetty is fully submerged at this time.

Section 3: Between the jetties, a leeside effect is now obvious on the S-side of jetty No. 2. Beach width is reduced with several meters and wave run up has reached the middle of the beach section between the groynes.

Between jetty No. 3 and the terminal groyne, there is a more regular beach section. The beach has been reduced in width since 25-09-2018 but no acute erosion is experienced at this point.

Section 4: Due to low light, it is difficult to determine actual changes in the beach morphology, but it looks as if there is a slight reduction in width between all groynes.

There has been a general reduction in beach width along the entire study area stretch, even in the downstream sections. Despite a lower energy impact during period 8 compared to period 5, period 8 showed two significant energy events of the same magnitude as seen in period 5. Between 29th and 30th of September 2018 wave heights reached 1.5 m with water levels above +0.5 m and between 18th and 21st of November wave heights was above 1 m during the entire period, not with the same water levels, but was more consistent and endured for a longer period. The reduction in beach width, and presumably volume, can thus again be linked to storm events. Although morphological marks indicate that waves have been at the top of the beach sections, the storm impacts did not result in acute erosion nor retreat of the vegetation line.

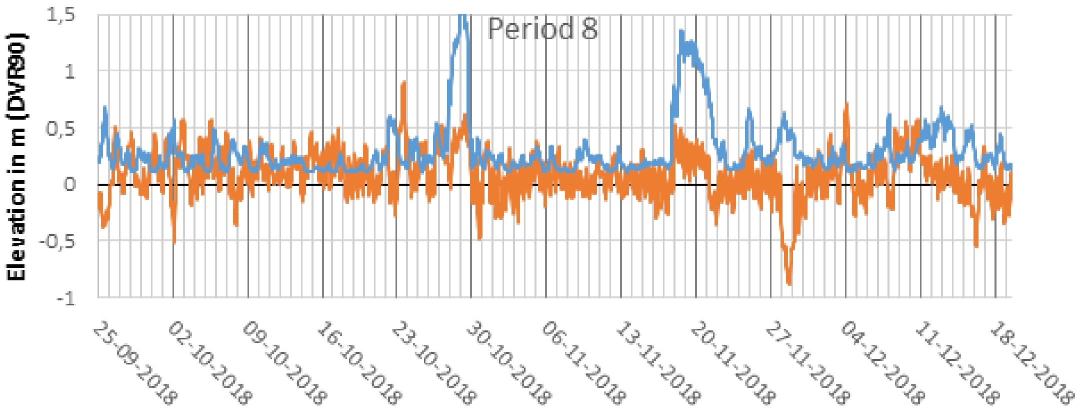

Figure 5.11: Modelled wave height and water level from the DMI dataset for period 8. Note that SWH is short for "significant wave height".

Period 9

The water level was -0.10 m during image recording on the 24-01-2019 (Period 9 is from 20-12-2018 to 24-01-2019).

Section 1: Increase in beach width along the entire stretch but mostly on the upstream side of the circle jetty. The sediment between the groynes and jetty no. 1 seems coarser than between the circle jetty and the groyne.

Section 2: The beach has widened at this point. This increase is likely to result from re-entering of sediment from cross-shore or from longshore transport as the dominant wave energy component in the last days of the period is northbound. All groynes are visible but the parts located on the beach are partly covered again.

Section 3: The beach has increased in width between jetties No. 2 and 3 and the seaweed and coarser grain depositions from the latest storm is now replaced by more sandy sediment. All groynes are visible but the parts located on the beach are partly covered again.

Between jetty 3 and the terminal groyne, the beach section widens. The entire stretch shows a "strip" of coarser sediment in the middle of the beach, which indicates the latest high water mark. The upper beach has accumulated sediment.

Section 4: The strip of sediment bypassing the terminal groynes from section 1, 2 and 3 into section 4 is still evident in the shoreface. Besides a slight increase in beach width, there are no significant changes since 20-12-2018.

There are clear signs of accumulation on the beach – this is especially seen as the groynes are now partly covered with sediment. The increase in beach width could be a result of lower water levels, but it could also be the results of sediment migrating landward after the latest storm period, which would resemble the changes also seen in period 6. The combination of increasing beach width and partial covering of the groyne parts on the beach could be linked to the 3 periods of high water reaching +0.6 m which correlates with low wave energy impacts as seen in Figure 5.12. This period also shows a dominant cross-shore energy component and the southbound energy component is only double that of the northbound, which is only seen in period 4, while the remaining periods show that southbound energy in general exceeds the northbound energy with at least a factor 4.

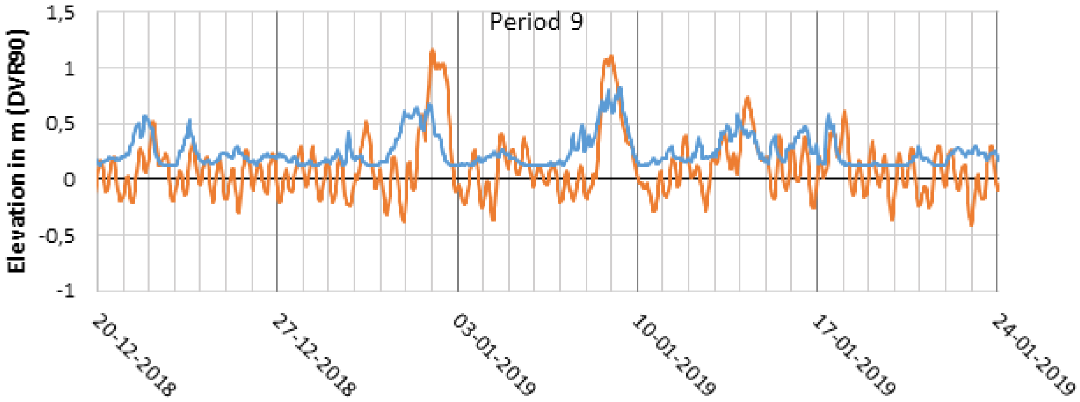

Figure 5.12: Modelled wave height and water level from the DMI dataset for period 9. Note that SWH is short for "significant wave height".

Period 10

The water level was +0.08 m on the 18-02-2019 (Period 10 is from 24-01-2019 to 18-02-2019).

Section 1: There is little change in section 1 since 24-01-2019. From the imagery, the beach seems to have decreased in width, but taking into account the higher water level, the beach is most likely in the same state.

Section 2: The berm was widening the beach on the 24-01-2019 but this is now submerged, as are the groynes and the beach seems to have narrowed while the beach height seems to have increased. Slight accumulation on the s-side of the circle jetty in the inland corner. Otherwise, no significant changes can be detected visually.

Section 3: Same changes as in sections 1 and 2, higher water level and slightly narrower beach section.

Section 4: No changes, only water level.

There are only few changes in this period, but the time between the imagery coincides with a time with no significant energy impacts, nor high-water events. The energy is comparable with that of period 9, but the data show no high water events of the same magnitude as in period 9 and the southbound energy component is far lower, making the cross-shore component the far most significant in this period.

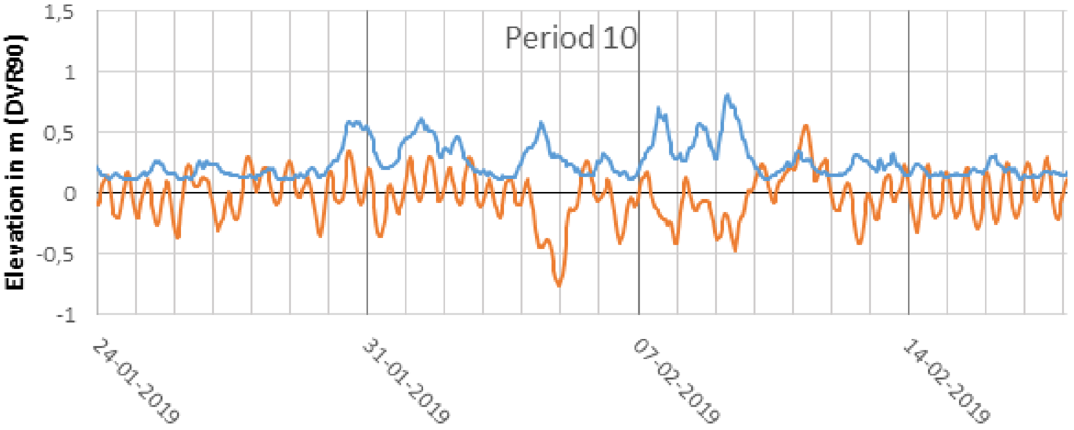

Figure 5.13: Modelled wave height and water level from the DMI dataset for period 10. Note that SWH is short for "significant wave height".

Period 11

The water level was +0.02 m during image recording on the 16-04-2019 (Period 10 is from 18-02-2019 to 16-04-2019)

Section 1: No changes in beach width. The maximum wave run up is marked by the seaweed deposition just above the swash. Wave breaking between the jetty and the circle jetty indicates a shallow bar few meter from the shoreline.

Section 2: The width of the beach has decreased and wave run up is almost at the toe of the revetment between the café and the beach volley court.

Section 3: The maximum wave run up has only reached the middle of the beach sections. Beach width is generally reduced along the entire stretch in section 3. This is indicated by the shoreline position of at groynes compared to earlier imagery. The upstream side of the terminal groyne no longer has the shoreline at the tip. This is likely to be the result of the current wave action and high water level at the time of the filming.

Section 4: No imagery is available of section 4 from this date.

The reduction in beach width in section 3 is linked to the wave energy during the last 9 days of period 11. Multiple occasions with wave height above +0.5 m has occurred while the cross-shore and southbound energy components are dominating. The southbound energy components are also indicated by the groynes, which again have steered the planform of the beach to be exponential between groynes, with accretion on the upstream side and erosion on the downstream side of the individual groynes.

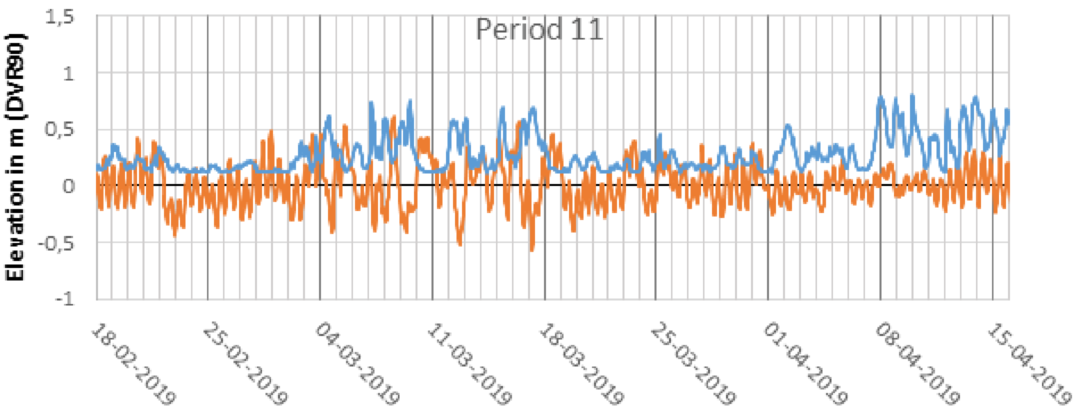

Figure 5.14: Modelled wave height and water level from the DMI dataset for period 11. Note that SWH is short for "significant wave height".

Period 12

The water level was +0.03 m during image recording on the 17-09-2019 (Period 12 is from 16-04-2019 to 17-09-2019)

Section 1: The outer half of the circle jetty has now been removed and only steel piles are left. There is a slight increase in beach width. It is especially noted that a strip of sandy sediment is present in the berm.

Section 2: There is a slight increase in berm height and beach width. The sandy sediment seen in section 1 is also spotted in the swash zone of section 2.

Section 3: The beach width has generally increased and the strips of sandy sediments in the swash zone is also present in section 3. The tip of the terminal groyne is again connected with the shoreline and has reached detaining capacity.

Section 4: Bypassing sediment described in multiple other periods is still evident around the terminal groyne. However, no significant changes are found since 18-02-2019, but the beach section at the spit is still present.

There is a general indication of sediment re-entering to the berm and the swash along the entire nourishment stretch. The sediment is still found to pass by the terminal groyne in a southbound direction, but here it is mainly seen that the sediment is placed along the shore at the tips of the groynes. There is a peak in cross-shore energy on the 23rd of April which is also seen in the wave heights of Figure 5.15, but apart from that event, there are only minor energy peaks, and no events of significant duration with either high-water nor high energy wave impacts. This explains the few changes while the steering of beach planform is not as clear in this period as it was in period 11. This is likely to be the result of dominating cross- and northbound energy during the last month of the period.

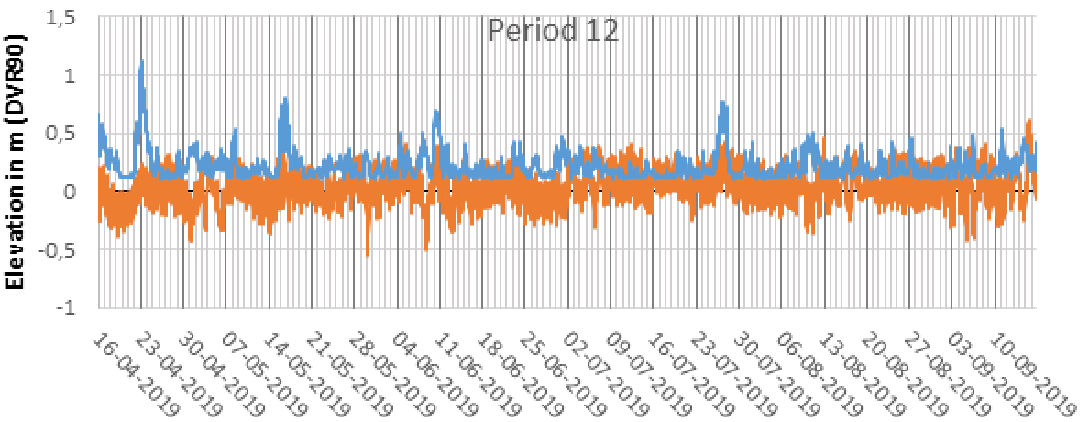

Figure 5.15: Modelled wave height and water level from the DMI dataset for period 12. Note that SWH is short for "significant wave height".

Period 13

The water level was +0.04 m during image recording on the 21-11-2019 (Period 13 is from 17-09-2019 to 21-11-2019)

Section 1: The beach width is comparable to that of 17-09-2019 but the beach indicates that wave run up have reached the middle of the beach section for almost the entire stretch and the height of the berm have decreased.

Section 2: The beach has narrowed significantly and the swash has created coarser grain deposition at the toe of the revetment at the beach volley court. The upstream accumulation seen earlier at jetty No. 2 has decreased.

Section 3: The beach width is close to the same as on 17th of August, but the wave run up has almost reached the toe of the vegetation line as seen from seaweed deposition and the berm has decreased in height.

Section 4: The beach at the spit has narrowed slightly and the swash/berm height between groynes has decreased. Longshore transport of nourishment sediment has definitively increased the beach state along the entire stretch of section 4.

No significant changes are detected regarding beach width. On the other hand, the berm height decreases and there is a flattening of the swash. This corresponds well with three events within the last 21 days of the period when the waves reach more than 1 m in height, but at normal to low water level. In general, the run-up from the waves is likely to have been limited to the mid-section of the beach.

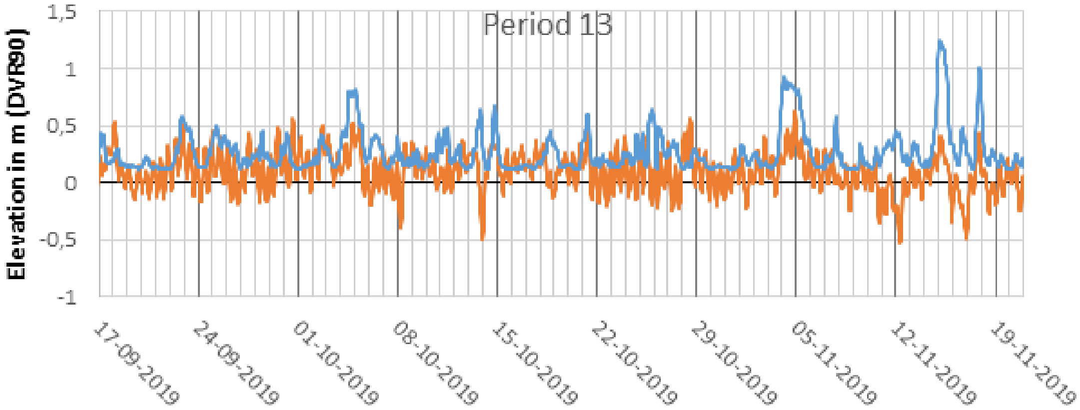

Figure 5.16: Modelled wave height and water level from the DMI dataset for period 13. Note that SWH is short for "significant wave height".

The impact of the nourishment compared to the situation before the nourishment is shown in Figure 5.17. Please note that any erosion that would have taken place without the nourishment is not shown!

The beach nourishment has resulted in a general advance of the coastline, which has generally widened the beach at the nourished stretch. On average, there is still an advanced coastline after 2½ years.

Figure 5.17 Drone images before, just after and 2½ y after beach nourishment

5.3 Difference mapping and volume changes

The overall difference mapping between 2014/2015 and 2018 is presented in Figure 5.18 and the quantifications of the beach volumes and changes between DTMs are presented in Table 5.2.

Section 1: – There is a general increase in beach volume between 2015 and 2018. It is clear that the primary increase in volume is found between the northern jetty and the circle jetty. This is likely to be part of the additional buffer nourishment, which was placed in this stretch, only. The beach has both de- and increased in width along the stretch, but in the northern half the reduction of the groynes meant that the beach could develop more naturally, which could explain the reduction in height. The changes at the south end with the new jetty and changes in construction are responsible for the decrease in beach height here.

Section 2: – As the only section, section 2 demonstrates a negative volume development between 2015 and 2018. A main explanation is the decrease in beach height in the north end. Here the former swimming piers was protected by a cross-shore revetment, which together with the concrete construction has been removed between the 2015 and 2018 elevation models. Furthermore, the central part of the section shows a decrease in beach height, though, with a slight increase in beach width. Generally, the south end of the section has seen an increase in beach height, which can be attributed to the nourishment.

Section 3: – There is an overall increase of 1.700 m³ in beach volume in section 3. Additionally, the beach has widened in the section and the 0 m contour has advanced seaward in 2018 compared to 2015. In general, the north end of the section has experienced an increase in beach height, and this despite this stretch experienced the largest retreat in vegetation line in the natural development analysis. However, this is still in conjunction with an increase in beach volume in the lower beach and an increase in beach width. The south end of section 3 shows both de- and increase in the beach height towards the terminal groyne. However, the capacity of the groynes to detain sediment seems to have been reached as the shoreline is in contact with the most seaward point of the terminal groyne.

Section 4: – There is a general buildup of sediment volume on the beach between the 2015 and 2018. There is a slight increase in beach width along most of the stretch, but most noticeable is the height increase across the beach sections. Especially the increase at the south tip of section 4 where the increase in beach width and sandy sediment is noticeable.

	Area (m²)	Volume 2015 (1,000m³)	Volume 2018 (1,000m³)	Difference (1,000m³)
Section 1	5,828	30.5	32.8	2.3
Section 2	2,181	9.4	8.1	-1.3
Section 3	5,456	23.8	25.5	1.7
Section 4	7,276	29.4	31.6	2.2

Table 5.2: Quantified beach volumes are calculated as described in section 3.5.

5.3.1 Comparison of potential and actual dispersion of nourishment

The total volume for section 1 to 3 is roughly 63.7 x 10³ m³ in 2015. If the theoretical transport capacity were considered true, the volume for section 1 to 3 would have decreased with 11 x 10³ m³ before the nourishment, meaning that the volume before the nourishment was 52.7 x 10³ m³. If we add 18 x 10³ m³ in 2017 and let the transport rate continue in 2018, the total volume would theoretically be 65.2 x 10³ m³. The actual combined volume in section 1 to 3 is 66,400 m³ in 2018, and therefore 1,200m³ higher than what was theoretically expected. This simple example underlines the fact, that the nourishment has increased the beach volume both in theory and in practice and that, in general, the volume development is as expected.

The standard error of the national DEM from 2014/2015 and 2018 is accepted to be 5cm. This means that in section 1 to 3 (total area from Table 5.2 ~ 13.5 x 103 m²) there is a possible bias error of up to ~700m³. This does not change the above results.

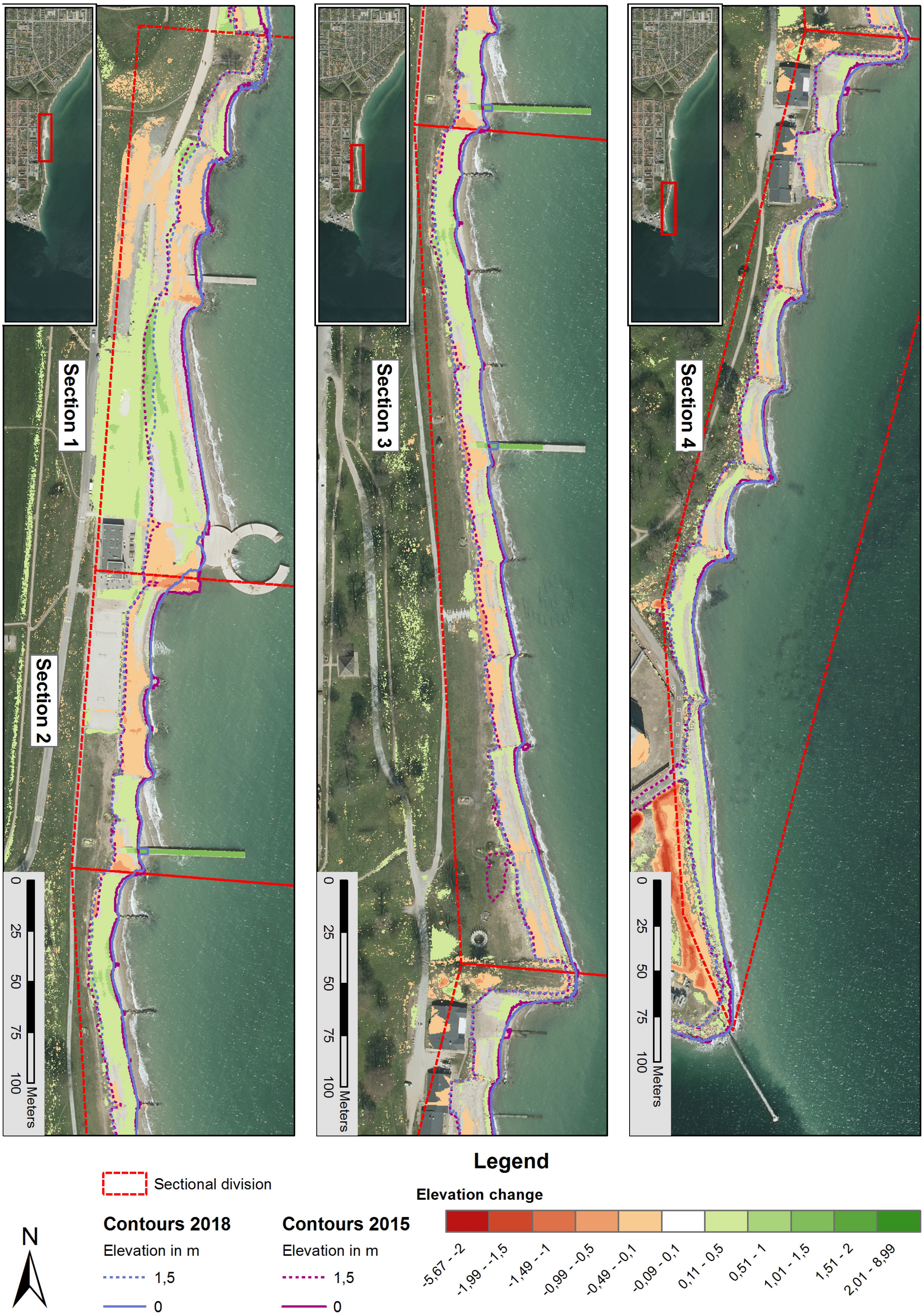

Figure 5.18: Difference mapping between the two national terrain elevation models. The beach volumes are quantified within the total extent of the 1,5m contours and 0m contours in table 3.5.

6 Discussion

To evaluate the results, the methods applied for the analysis and the actual results will be reflected upon in the following chapter.

6.1 Method

Drone Imagery

In this case, the usage of drones in morphological monitoring has provided a high temporal resolution of data. This could not have been achieved with data available nationally nor regionally. The spatial resolution is far from quantifiable as the primary source is recordings from various positions and heights, but the temporal resolution together with a qualitative analysis approach proves to provide an unprecedented information source for this stretch.

The usage of drones in this case requires only one battery and approximately 20 minutes of flying time to document the state of the nourishment stretch. Despite difficulties with differences in recording from comparable locations, it has been possible to follow the morphological development of the stretch at a low cost, both in terms of time and money.

A more strictly planned, or pre-programmed flight route could increase the repeatability of image recording. The method has been flexible with flights having been combined with other travel purposes during the year, but it does require considerable time to cut the individual frames from the recordings, while the analysis must be structured according to the available data and position of imagery. Therefor planning of the recording positions must also be considered with respect to an insight in the natural dynamics of the stretch.

Energy component

The possibility to include the calculation of wave energy has undoubtedly increased the value of the analysis. The calculation on the energy components are rough, very simple and does not directly describe neither transport capabilities nor the direction of the nearshore currents. Nevertheless, in combination with the drone recordings, this indication of the impacting dynamics can be utilized in a combined analysis. The energy calculation related to wave height and water level data in combination with the imagery makes it possible to relate the changes in morphology in relation to the potential forcing. Analyzing the imagery have also supplied information on the quality of the modelled data. It was seen on multiple occasions that the numerical water levels did not correspond with the actual water levels in the imagery.

Shoreline analysis from orthophotos

Analyzing the shoreline from above is an easy-to-use method and the changes in the shoreline over time can be detected over years and decades if the orthophotos are available. These calculations on the shoreline (or vegetation line) development is naturally affected by various degrees of uncertainty. Firstly, the zoom, which is used when drawing the lines, is a factor, as is the resolution of the actual imagery. Secondly, there is the difference in water level over time, and the actual distinction between water and land, which is not always easily pinpointed. The errors regarding the shoreline development must be expected to range within at least the coarsest imagery resolution and the maximum difference in swash extent. This can easily amount to 1m in inaccuracy. This means that the method only provides a coarse measure for the development trend, but it did, however, give clear indications that most of the stretch at Fredericia was retreating with slight decrease/increase in retreat rate within latest decades. Another impractical element is the retreat of the shoreface which is not comparable to that in the shoreline, especially not where the shoreline is as controlled by revetment and groynes as in Fredericia. The chronical erosion in the wet profile is likely far greater than that found in the beach.

Difference mappings and volume changes between DTM 2015 and 2018
The national DEM from 2004-2005 was disregarded as the resolution of the model is far higher than that of 2015, and the data acquisition methods and quality of the models are not directly comparable. Instead, the difference mappings in Figure 5.18 are based on the national elevation models from 2014/2015 and 2018 which indicates some of the before/after nourishment changes that have taken place. This method is not directly showing the actual effects of the beach nourishment from 2017, as there has been a reduction in both beach width and height and consequently volume, between the 2014/2015 DTM and 2017 before the nourishment. However, the mapping does provide a spatial image of what primary changes are seen in elevation and where these are encountered.

The DTMs are used for volume calculation between the 1.5 m contour and the 0.0 m contour. There are some difficulties with dating of the DTM and the decrease in volume up until the nourishment was made. It does however provide a quantifiable measure from which it is clear that an increase in beach volume has taken place. This combined with the difference mappings has also provided insights as to where and what may have caused different changes. The accuracy of the volume estimations should be considered with the accepted 5 cm error in z-values of the DTM. This combined with the extent of the total area gives a 1.000 m³ potential error on the entire stretch, while being around 700 m³ in section 1 to 3. This shows that the actual increase in volume found between the DTMs is within the error margins, and can be accepted as a good estimate for the volume increase. Actual measurements of the stretch before nourishment would though have increased the validity of the approach significantly.

6.2 Research questions

In the following section, the individual research questions will headline a discussion on the results given in the above sections.

What is the general direction of longshore transport and the dominant energy component?
The results from the energy calculations gave the clear result that the dominant energy component was cross-shore, while the southbound was the 2nd largest. This is supported by the observations in the drone imagery. The primary longshore transport direction is undoubtedly toward the south, which is indicated both in the energy calculations and by the drone imagery, showing bypassing sediment migrating from section 3 towards section 4. It would have given better results if measurement of the shoreface had been available. Thereby quantifications of the sedimentary budget and the dominant transport directions could have been verified.

How did the nourishment planform change over time?
The autonomous development of the stretch showed a general sediment deficit, partly due to detainment of upstream sediment and normal wave erosion. This deficit in the natural system explains the rapid reduction of the nourishment planform in the first periods. The re-distribution of sediment is likely to have taken place cross-shore in adjustment to a more natural profile. This equalization to the natural dynamics such as waves and water level was reduced during the study period as a more natural profile state emerged and the natural longshore sediment processes begun to dominate.

The overall changes between nourishment and the latest imagery show a clear reduction in beach width, but if a comparison is made between the before nourishment images and latest imagery the changes are positive. A general increase in both width and height is clearly seen. Fluctuations in width, berm height and beach sediment composition are seen in the individual study periods, but this is to be expected on a dynamic coastal stretch. The increases in berm height during the period is a direct response to sediment transport towards shore and occurs in low energy periods. The berm volume dissipates again after periods with higher water levels and larger energy impact. On multiple occasions increase of sandy sediment in the upper beach sections are visible. Whether this is caused by slight aeolian transport or re-entering of sediment from the shoreface during high tidal events is difficult to determine. Neither can be dismissed. The groynes and the new established jetties showed to control the beach planform on several occasions with accumulation primarily on the northern side of the structures. The stretch also shows that, on some occasions, there is no direct indication in the transport direction seen from the groynes, which corresponds well with the energy component both cross- and longshore.

How has the nourishment sediment been distributed in the profile?
The cross-shore distribution of sediment is difficult to analyze from drone imagery alone and quantifications is naturally not an option. There were visible changes in the extent and amount of black spots in the shoreface, but whether these black spots are eel-grass or stones are unknown and interpretation is therefore difficult. If a confirmation could be obtained and the spots proved to be rocks, this would help interpret the cross-shore re-distribution of nourishment sediment. Furthermore, the increase in the berm height, as discussed above, also indicates some re-entering of sandy sediment from shoreface to beach and berm. The development of a bar system along the stretch also suggested that cross-shore distribution took place. These bar developments also indicate longshore transportation in the shoreface, as sediment in the form of a bar bypassed the terminal groyne in section 3 into section 4. The increase in beach width and height together with lowering of the depths in the shoreface at the rowing clubs could be correlated directly with the time following the nourishment when there was a reduction in width and volume of the nourishment, and with a southbound energy component far greater than the northbound. There is therefore evidence pointing towards a combined cross and longshore transport on the stretch. Furthermore, there is a good indication of an increase in nourishment sediment in the shoreface and the remaning nourishment volume could therefore be greater than indicated in this report.

Did the nourishment achieve the intended goals?
To evaluate whether the intended goal of the nourishment has been achieved, it is necessary to once again underline the premises for the nourishment which was to increase the recreational values of the beach section at Østerstrand by extending the shoreline to the 1954 position, thereby increasing the general beach width. The additional goal is naturally also to reduce or even avoid acute erosion in the hinterland and protect the ramparts.

There is little doubt that the original increase of beach width did, at least, extent the shoreline to the same location as in 1954. However, this was only for a couple of weeks until a reduction in beach width and volume by natural dynamics occurred. There is no specification as to for how long a period the nourishment should provide for a beach with shoreline extending to the 1954 position, so this must at least be said to have been achieved in some form. It can be argued that the beach was unnaturally wide when considering the beach width in historic orthophotos. The recreational values of the beach has clearly increased with an increase in sandy sediments, beach width and height.

The general volume of the beach showed to increase between 2015 and 2018. However, the results from the volume analysis do not reveal the true nature of the nourishment effect. The decrease in beach volume between 2014-2015 DTM and establishment of the nourishment are unknown while the dates of the actual recording of the 2014-2015DTM data all point to a larger margin of error. There is therefore likely to be a far greater volume increase/decrease between before/after nourishment than shown in the volume analysis. It is, however, clearly seen in the difference mappings that in general there is an increase in beach width and height between 2015 and 2018.

7. Conclusion

The development of the nourishment went much like anticipated with a rapid reduction in planform during the first periods followed by a more stable development. The new circular jetty in section 1, the new perpendicular jetties 2 and 3 and the terminal groyne in section 3 were the only structures that truly dominated the planform on the nourishment stretch and lee-side erosion occurred in the planform as a result. The remaining groynes only affected the planform on few occasions.

The nourishment sediment from the initial planform has been re-distributed across and along-shore. It is not possible, with the measures at hand, to definitively quantify the along- and cross-shore redistribution of sediment, but it is clear that the south- and cross-shore energy components are far larger than the northbound, which demonstrates that the dominant transport directions is towards the south. Furthermore, this was confirmed as sediment volume increased in section 4, both in the form of increase in beach width, but also as sediment bypassed the terminal groyne from section 3.

Considering the goals of the nourishment scheme, it can be considered a success, since the goals of the nourishment have been met both as concerns increasing the beach width by extending the shoreline to the 1954 position (although only for some weeks), but also in regards to increasing the profile resilience and the recreational values of the coastal stretch. Re-nourishments will be required, in order to counteract the continued chronic erosion on the stretch to maintain a more natural and resilient coastal profile. It is expected that further re-nourishments will be more stable because the profile has shifted to a more natural profile due to the first nourishment. However, increased erosion on the leeside of the groynes will still take place.

8. Further considerations

The primary goal was to extend the shoreline to the 1954 position. However, there were no goals or objectives defined in relation to beach nourishment lifetime, morphological evolution or to the effects of the groynes and revetments. No monitoring program was implemented in order to be able to assess whether the primary goal was met or not.

The methods used for monitoring and analyzing the development of the beach nourishment in Østerstrand all proved to have potential benefits with very low costs. In general, with a project on this scale it would be interesting to gain insights and knowledge as to the behavior and development of the nourishment. Especially, it is important to be able to assess the cross-shore diffusion. This, in combination with a pre-defined goal for the nourishment would increase its potential gains, while re-nourishments can be planned with greater understanding. Since re-nourishment is required to maintain a resilient profile on a chronically eroding coast, the planners at Fredericia, and in other areas, could benefit from a pre-planned monitoring campaign.

The recording of drone imagery proved to be a method, which increased the temporal resolution of data. It allowed for a flexible data acquisition, which turned out to be valuable when analyzing the development of the nourishment. In this way, the possibilities for evaluation of the project were enhanced. Although it is a low budget method, it can be improved significantly by simple means such a more structured planning of flights, or by acquisition of plan view imagery for orthophotos. However, it is a method, which relies on relatively good weather conditions, but on low exposure coastlines, the potential number of flying days increase.

The fact that the national height model is available for both 2014/2015 and 2018 on the stretch is a mere coincidence. Nevertheless, it provided two open source and high-resolution elevation models, which made it possible to estimate the quantifiable changes made by the nourishment. These results were found from a linear decrease of the beach volume, based on an assumed net-potential-transport per year. This means that the margin of error naturally increases significantly. If a “before” and “after” nourishment measurement had been conducted, the qualitative and quantitative analyzes would have improved significantly. Not necessarily as a full-scale elevation model, transect measurements of the active profile would also increase the possibilities. In general, this is recommendable as a standard part of a general monitoring campaign – again, both to make evaluation of the projects more robust but also to document the development for future planning.

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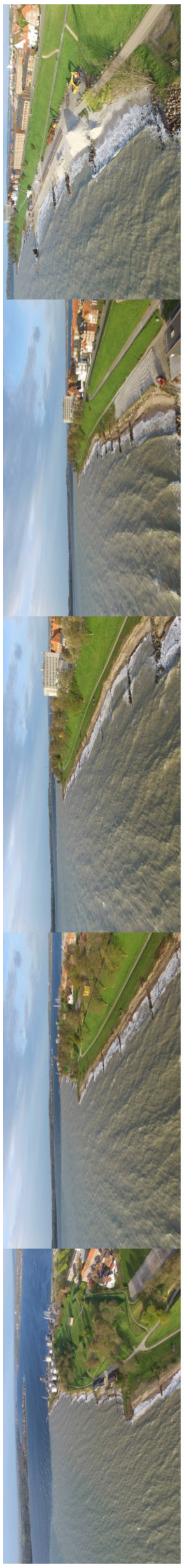
Appendix A

- Drone imagery



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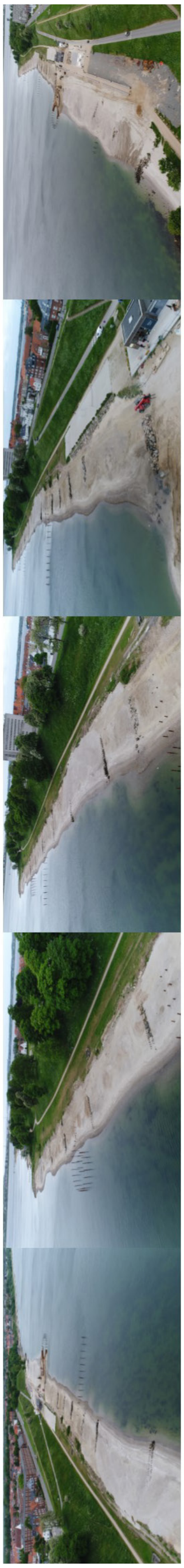

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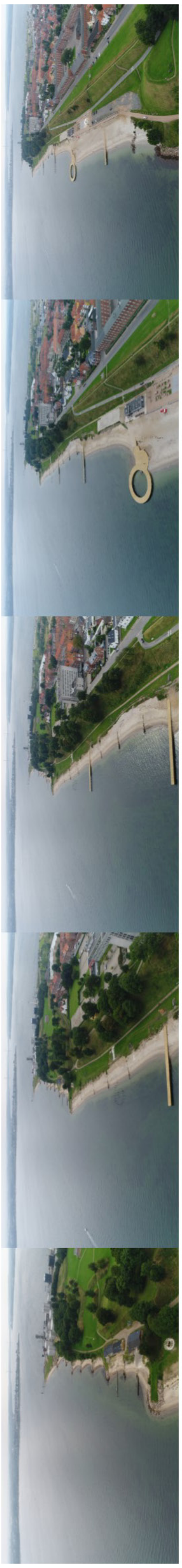

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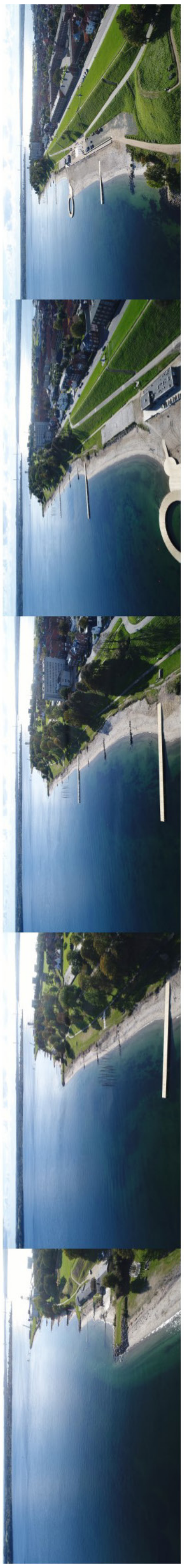

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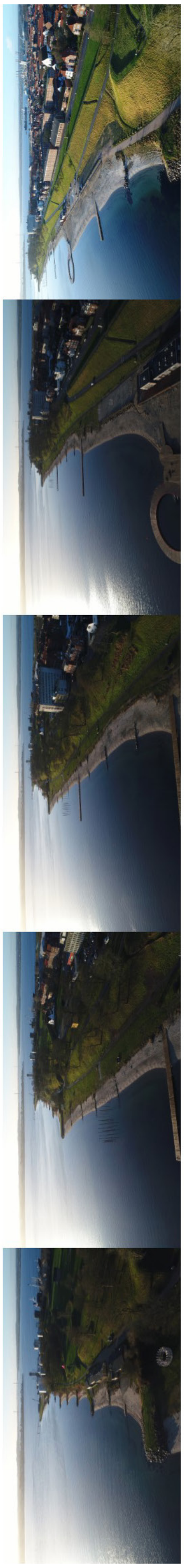

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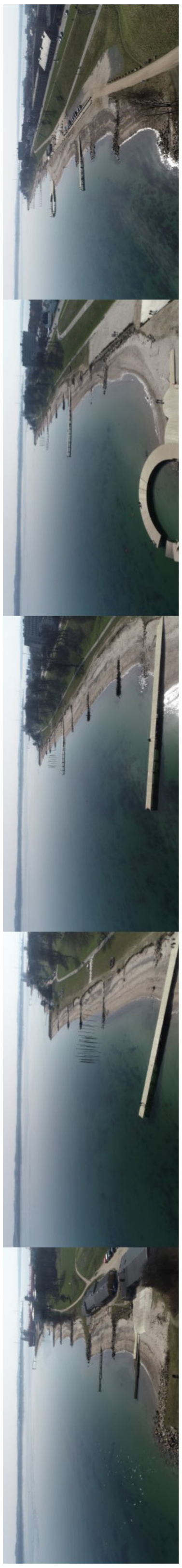

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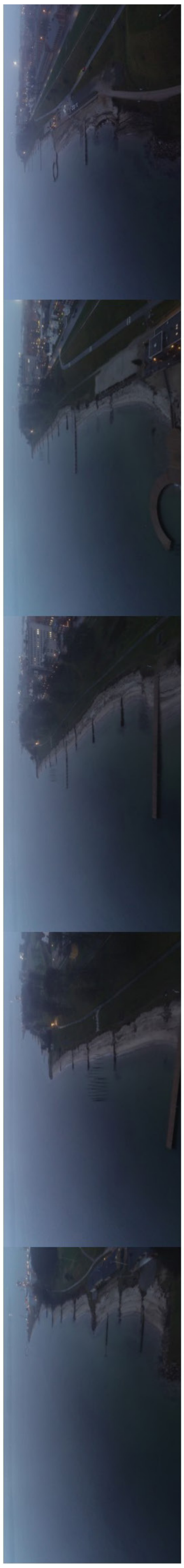
16-05-2018

25-09-2018



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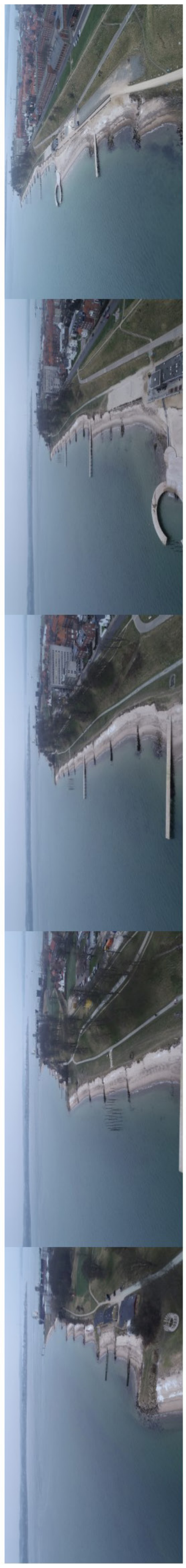

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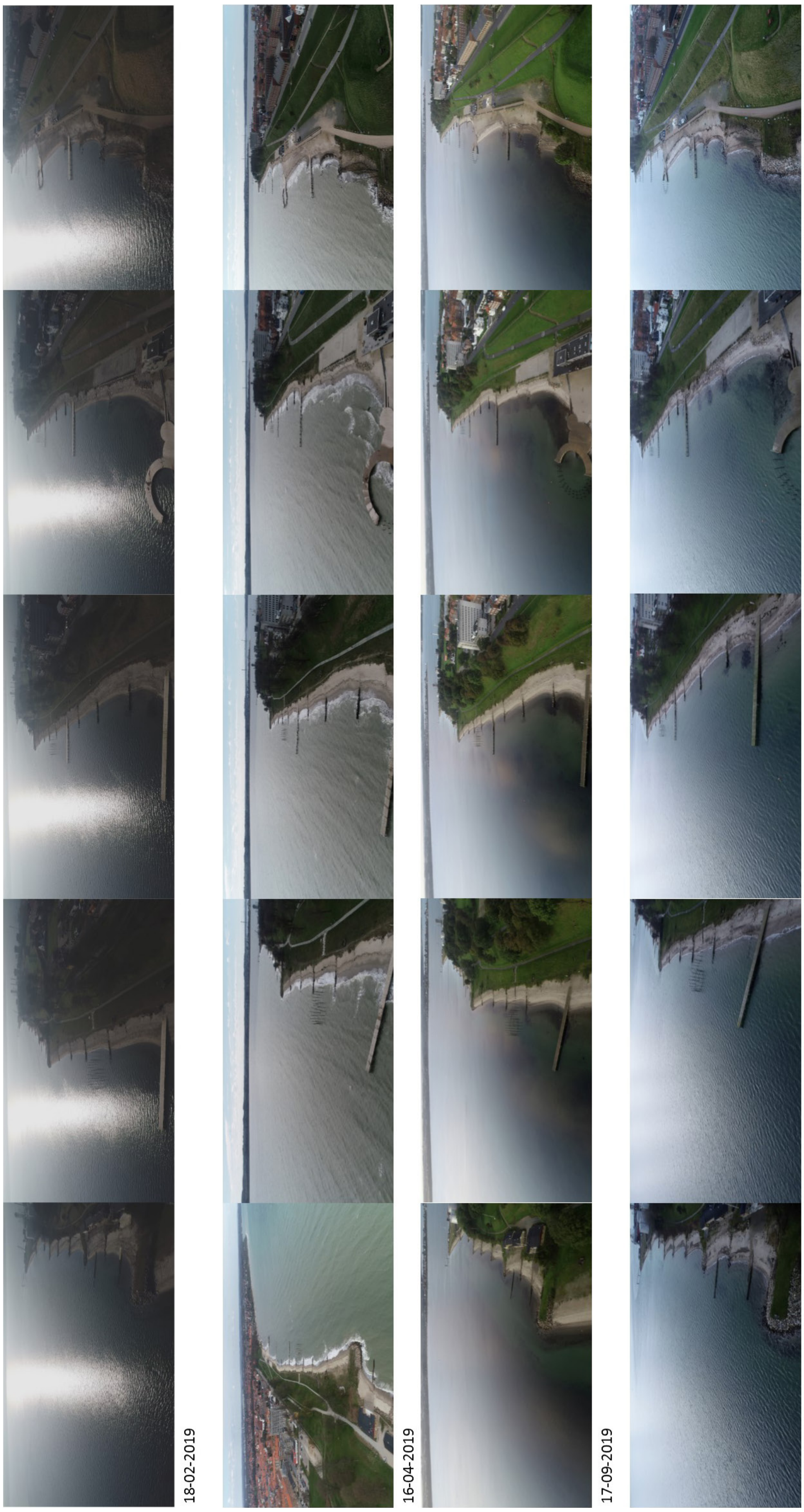

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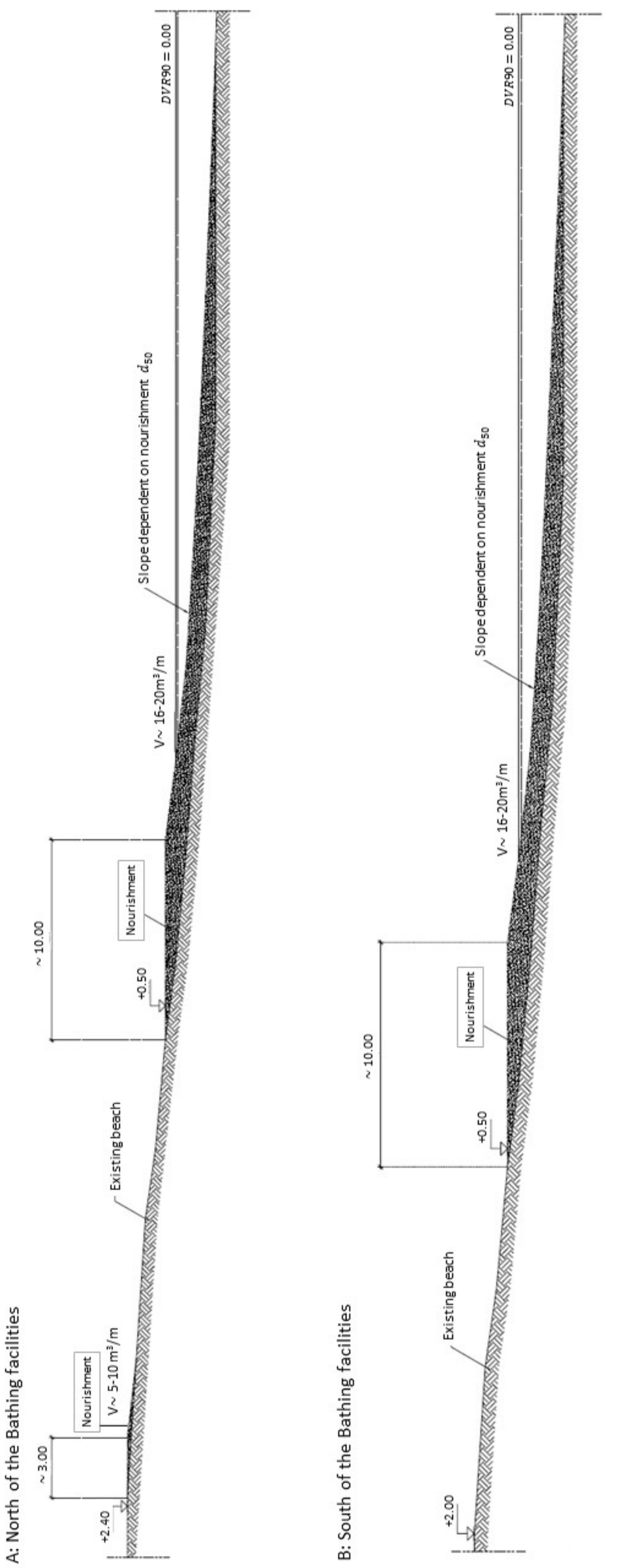
17-09-2019

21-11-2019

Appendix B
– Cross sections of planned nourishment



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