Beach nourishment effects at Ystad Sandskogen

Project in practice
At The Department of Geoscience and Natural Resource Management, Copenhagen University and The Danish Coastal Authority (DCA)

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The north-eastern end of Ystad Sandskogen. Photo by Nikolai Sørensen, 2020.
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Abstract
Certain parts of Ystad Sandskogen Beach are subject to erosion and shoreline retreat, especially at the southwestern part, which is the most visited part, where the SPA hotel Ystad Saltsjöbad and the easiest access to the beach are located. The coastline has retreated by an average of 1-1.5 m/yr over the past 150 years (Halldén, 2017). Almström, B & Hanson, H, 2013 estimate a sediment loss of 147,000 m$^3$ from 1997 to 2010, 90 % of which has been eroded from below the water surface. This study, however, finds a less significant volume loss. The construction of Ystad harbour and several groynes influence the sediment budget at Ystad Sandskogen. Sediment is trapped upstream of these structures, resulting in beach erosion of the downstream beaches as the sediment outflow becomes much greater than the sediment input. This study finds a retreat of the coastline up until the 2011 beach nourishment, especially at the most visited parts of the beach, which indicates a sediment redistribution or loss. The 2011 nourishment is found to have had positive effects on the beach volume and beach width for up to at least three years after the nourishment. Some areas, however, have not benefitted from the nourishment at all, while others only showed advantage from the nourishment in the first five months.
1. Introduction and background

Ystad Sandskogen is a beach of high recreational value and therefore of socioeconomic importance to the municipality of Ystad. The value of the beach is estimated to be 42 million euros per year (Halldén, 2017). The hinterland located behind the relatively small dunes are at risk of flooding if the beach is not assisted to sustain a certain resilience level to flooding and sea level rise. Beach nourishment is a coastal management action that is applied to increase the resilience of the beach to flooding and erosion and furthermore maintain a firm beach width and volume (see Figure 1 for nourishment effects on the shoreline extent). Beach nourishment has a lifetime of 1 to 5 years in general, depending on wave climate and the magnitude of nourishment (Giardino et al., 2019).

224,000 m$^3$ of sand has been applied to Ystad Sandskogen over three intervals, 80,000 m$^3$ in May 2011, 64,000 m$^3$ in March 2014 and 80,000 in April 2017. The last nourishment of the total of four nourishments is planned to be carried out in April 2020 (Bontje et al., 2018).

The purpose of this study is to assist parts of the EU, Interreg Building with Nature (BwN) project. BwN is a concept which researches the opportunities of accommodating climate change challenges, such as sea level rise and increased storm frequency, by applying nature’s own dynamics. Through the examination of seven, so-called, living laboratories along the coast of the North Sea region (Ystad Sandskogen is one of these living laboratories), the project aims to quantify nourishment effects for future policy making (Interreg, 2015).

1.1 Objectives

The aim of this study is to analyse the effects of two beach nourishments carried out at Ystad Sandskogen. By examining the cross and longshore distribution of the 80,000 m$^3$ applied sediment in 2011 and 64,000 m$^3$ in 2014 and relating this to physical and hydrodynamic processes, the desired outcome is to estimate volume distributions, the lifetime of nourishment, the impact on morphology and the impact on the beach width.

Research questions:
- How does the total volume evolve post and prior beach nourishments?
- How does the nourished volume distribute?
- How does the momentary coastline (MCL) fluctuate prior and post nourishments?
- How does seabed morphological features (SMF), if present, behave prior and post nourishments?
2. Theory

2.1 Sediment transport
Near-shore currents can lead to sediment transport in a longshore and cross-shore direction. Sediment transport is dependent on the current velocities, grain sizes and sediment concentrations (Aagaard et al., 1999).

**Longshore** currents are present when waves approach the shore at an oblique angle, generating a longshore radiation stress gradient towards the shore. The longshore currents generate a longshore sediment transport (Q) given by Equation 1 (Aagaard and Hughes (2013)):

\[
Q = \frac{KE \cdot C_g \cdot \sin x_b \cdot \cos x_b}{(\rho_s - \rho)g(1-p)}
\]

[Eq. 1]

where K is a constant of proportionality, E is the wave-energy density, \(C_g\) is the wave group velocity, \(x_b\) is the wave incidence wave angle at the breakpoint, \(\rho_s\) is the sediment density, \(\rho\) is the fluid density, and \(p\) is the correction factor for pore space. An angle of 45° between waves and shoreline generates the greatest longshore current (Aagaard et al., 2008). As the wave releases its momentum when breaking, a bed shear stress is generated as compensation for the longshore current in the momentum flux balance. The longshore current has the ability to transport sediment as either bed load or suspended load.

**Cross-shore** currents are generated as shoreward moving water must return back to sea somehow. The seaward flowing current is known as undertow, rip current or cell circulation. The undertow is induced by the pressure gradient generated by wave set-up. Wave set-up is present when waves are breaking. Momentum is released as waves break, which generates a wave set-up, evident by the momentum flux balance (Aagaard et al., 1999):

\[
0 = \frac{\delta S_{xx}}{\delta x} + \rho \cdot g \cdot h \cdot \frac{\delta \eta}{\delta x}
\]

[Eq. 2]

Where \(S_{xx}\) is the radiation stress in a cross-shore direction, \(\rho\) is water density, \(g\) is acceleration due to gravity, \(h\) is mean water depth and \(\eta\) is changes in water level relative to still water level. Equation 2 demonstrates that wave breaking generate an offshore direction flow of water.

2.2 Bedforms and bars
**Bedforms** are vertical morphologic features on the seabed consisting of non-cohesive sediments. The flow and sediment transport influence the bedforms, and bedforms influence the flow via friction (Masselink et al., 2014). Ripples and dunes are generated by orbital motions under waves. Ripples have a length of 0.1-0.2 m and a height of < 0.06 m whereas dunes have a length of 0.6-30 m and height of 0.06-1.5 m.

**Bars** usually form at the convergence zone of the outflowing undertow and the onshore directed flow, encouraged by asymmetric waves. Bars are relatively dynamic morphologic features, determined by wave energy, bar size and water depth. Bars migrate offshore during high-energy scenarios and onshore at low energy periods (Masselink et al., 2014).

**Seabed morphological features (SMFs)** refers to both bars and bedforms in contexts where these two terms are not distinguished.
2.3 Seasonal Profile variability
High energy events are most frequent in the winter months, whereas the summer months provide a calmer wave climate, in general. High-energy waves generate a powerful undertow, surpassing the onshore flow velocity from asymmetric waves. A consequence of high-energy events are berm erosion and offshore bar migration. In calm conditions, bars move onshore as the undertow gets weak, and bars merge towards the beach and form a beach berm. Elevated water level, as a consequence of high energy events, can potentially cause flooding and dune erosion. The shoreline position and beach volume change with the seasons, or more precisely they change with the wave energy intensity (Masselink et al., 2014).

2.4 Beach nourishment
Beach nourishment is the action of transferring sediment to the subaerial part of the beach. Grain sizes equal to or greater than the present grains are usually applied. The larger the grainsize in the nourishment, the wider the beach will become (Dean, 1991).

After beach nourishment events, waves transport the applied sediment from the beach to the shoreface, striving towards a more natural cross-shore profile. This results in a transverse movement of the shoreline after the beach nourishment, which does not necessarily mean sediment loss from the system, but rather a seaward redistribution. Beach nourishment enhances the beach’s resilience to erosion, but does not change the fact that the sediment budget is out of balance (at erosive beaches), as more sediment leaves the system than sediment entering, meaning that nourishment has to be carried out regularly (Masselink et al., 2014).

Figure 2 illustrates the 2011 nourishment at Ystad Sandskogen. The tube is spraying sediment rich water on to the beach, where a sand dyke is constructed to trap the sediment rich water (the dyke is breached in this scenario). The sediment rich water is pumped in from a ship, which has transported sand from deeper waters.

![Figure 2: 2011 beach nourishment, Ystad Sandskogen. Photo by Peter Sørensen (DCA), 2011.](image-url)
2.5 Coastal management structures
Ystad Sandskogen is home to several types of so-called “hard” coastal managements actions such as breakwaters, revetments and groynes. Furthermore, Ystad harbor is impacting the study area’s physical processes. **Breakwaters** are built to dissipate the energy from waves before they reach the shore, to avoid coastal and shoreface erosion. Breakwaters are hard, shore-parallel structures placed in front of the shoreline. **Revetments** reflect the erosive wave energy back to sea. **Groynes** are structures perpendicular to the coast, usually built to protect sand from being eroded or to trap incoming sand on certain areas of a beach. Groynes catch the longshore transported sediment, but starve the areas downstream, leaving these areas with a negative sediment budget (Masselink et al., 2014). The same effect and consequences follow the construction of a harbour. This dynamic is evident when observing the first groyne in Figure 1 (right), where an upstream accumulation side and a downstream lee/erosion side are noticeable.

2.6 Momentary coastline (MCL)
The momentary coastline model is applied to calculate a distance from a reference point to the estimated position of the coastline. The MCL model calculates the location of the shoreline by defining the area on the cross-shore profile between an upper and a lower boundary. The upper and lower boundaries are elevation levels. The MCL is defined as the area between the upper and lower boundaries divided by the elevation difference between the upper and lower boundaries (Lodder et al., 2012).
3. Study site

Ystad Sandskogen is located on the coast of Scania in southern Sweden (Figure 3). The southern part of Sweden has a higher potential of coastal erosion compared to the rest of Sweden because of its sandy coastline. The southern part of Sweden is subsiding (0.5 mm/y) due to isostatic adjustments, which increase the coast’s vulnerability, especially when considering the increasing occurrence of storms with climate change (Hanson, 2002). The micro-tidal environment of the Baltic Sea is a few centimeters, and is considered to be insignificant (SMHI, 2018). Waves in the area are often generated by local winds, and often approach from SSW followed by SE. The wave height is limited by the fetch from all directions. Ystad Sandskogen is subject to chronic erosion as the area is starved of sediment at Ystad Harbour. The areas downstream of the groynes and breakwaters at Ystad Sandskogen are undergoing crucial erosion, as the historic shorelines in Figure 4 indicate.

Figure 3: Top left: Ystad Sandskog Beach location (red arrow) in Scania. Bottom: The Bay of Ystad, the blue box is the river mouth of Nybroån and the red box is the area from Ystad Harbor to Sandskogen presented in the top right figure.
The area referred to as Ystad Sandskogen is the area seen to the left in Figure 4. This figure also shows where the nourishments have been carried out and the historic coastlines. Ystad Sandskogen is influenced by hard structures - to the west there is rock revetment, then five groynes are evident, followed by more rock revetment, and finally five breakwaters (see Figure 6). The bathymetry of Ystad Sandskogen in May 2016 is presented in Figure 4 (right), indicating a relatively uniform and smooth cross-shore profile to the east, and a few SMFs to the west.

Acute erosion has the ability to cause great sediment loss in a relatively small period of time. The prominent erosion line at Ystad Sandskogen as of 2nd of March 2020 (Figure 5, right) is a product of chronic erosion and a month of strong winds (120 % stronger winds than normal), and even winds of storm power (SMHI, 2020). The picture to the left in Figure 5 illustrates Ystad Sandskogen just days after the 2014 nourishment and the differences in the two pictures are noticeable.
Figure 6: Photo illustrating the low-lying hinterland, rock revetment and breakwaters. Photo by Nikolai Sørensen on the 2nd of March 2020.
4. Physical processes

4.1 Waves

Long-term wave climates are presented in two wave roses (Figure 7), both generated from hindcast models. The wave roses reveal the average wave directions and heights over a certain period of time. The wave rose in the bottom right corner of Figure 7 (2005-2015) and the annual wave roses in Figure 8 are divided into 36 potential wave directions, each consisting of 10°, and six categories of significant wave height (Hs) each of 1 m except for the >2.5 m group. For the 2005-2015 wave rose, Hs between 0 and 1.5 m are the most frequent and the highest waves approach from S and SSW. The wave direction is predominantly from SSW followed by E/ESE.

The ABPmer wave rose in the top left corner of Figure 7 uses data from 1979 to 2009. The wave rose is only divided into eight categories of direction, making this wave rose less detailed compared to the other. Wave heights are divided into nine groups, each representing 0.25 m except for the +2 m section. The ABPmer wave rose indicates a dominating southwestern wave direction followed by a southeastern wave direction and finally a smaller number of waves from the south.

When calculating the actual longshore transport, small changes in wave direction and wave heights can lead to significantly different results. However when examining the wave roses to estimate the direction or directions of the longshore transport, the two wave roses both indicate a dominating transport from SW to NE. The wave roses also indicate a certain number of waves approaching from SE, leading to a longshore transport from NE to SW. The wave climate can vary considerably between years, and can therefore influence the sediment volume distribution patterns from year to year. Figure 8 illustrates the annual wave climate in wave roses.

Figure 7: Wave rose plots for Ystad Sandskogen on an orthophoto. Top left: ABPmer hindcast modelled rose plot (1979-2009) (Data Explorer, 2018). Bottom right: Rose plot (2005-2015) made in MATLAB 2019, with data provided by DMI, 2020, the outer ring of the plot represents a 20% frequency.
The annual wave climate shows a more detailed picture of the wave climate at Ystad Sandskogen. The roses represent the time between measurements rather than calendar years, thus some of the wave roses contain data from more months than others. The SSE wave direction is still the dominating wave direction in most years, however some years (2006, 2009, 2010, 2011, 2013 and 2014) experience relatively high frequencies of waves approaching from SE and ESE. This confirms that the longshore transport can be directed both NE and SW.

*Figure 8: Wave roses from 2005 to January 2015 (data from DMI, 2020). The outer circle represents a 20 % frequency.*
4.2 Sediment transport convergence zone

The sediment transport at Ystad Sandskogen is predominantly NE directed, and SE directed in the rest of the Bay of Ystad, as illustrated in Figure 9. The convergence zone of the two sediment transport directions varies over time and can result in sediment deposition on both sides of groynes as seen in Figure 1. The wave rose plots indicate a dominating longshore sediment transport from SW to NE, but also a longshore transport in the opposite direction.

The displacement of the river Nybroån outflow (Figure 10) indicates that there is a dominating westward sediment transport at this specific location, east of Ystad Sandskogen. However, an eastward sediment transport is also observed, when examining the relative outflow placement. The Nybroån outflow to the Baltic Sea is an indicator of shifting directions of longshore sediment transport.

Figure 9: Sediment transport patterns. Blue arrows represent sediment transport, and red arrows are the anthropogenic redistribution of sediment (Hanson, H., & Almström, B., 2013).

Figure 10: The Nybroån River’s outflow into the Baltic Sea in April 2015 (top) and July 2015 (bottom) (Google Earth, 2020).
4.3 Storms
As described in Chapter 2, high-energy events, like storms, are important climatic actors to take into account when analyzing beach profiles. The storms presented in Table 1 have all affected Ystad. The storms are applied to the results presented in Chapter 6, to understand the volume evolution in the context of high-energy events.

Table 1: Timeline of storms affecting the Ystad area (SMHI, 2019).

<table>
<thead>
<tr>
<th>Time of storm</th>
<th>Name of storm</th>
</tr>
</thead>
<tbody>
<tr>
<td>29-11-1999</td>
<td>Hösten</td>
</tr>
<tr>
<td>07-01-2005</td>
<td>Gudrun</td>
</tr>
<tr>
<td>14-01-2007</td>
<td>Per</td>
</tr>
<tr>
<td>04-08-2008</td>
<td>Sommerovädret</td>
</tr>
<tr>
<td>27-11-2011</td>
<td>Förste adventsstormen</td>
</tr>
<tr>
<td>28-10-2013</td>
<td>Simone</td>
</tr>
<tr>
<td>05-12-2013</td>
<td>Sven</td>
</tr>
</tbody>
</table>
5. Methods and data
This chapter describes the methods and clarifies how the data is transformed into the results presented in the Chapter 6. The methods are important to consider when interpreting the results and are therefore described in detail in order to make the results as transparent as possible. The methods will be discussed in relation to the results in Chapter 7.

5.1. Data processing
The primary data for this study are transect point measurements from 1997 to 2015 (no measurements in 2003 and 2014), carried out and provided by Lund University. Profile points are measured with a Trimble GPS attached to a rod. In deeper waters, the measurements are made with an echosounder on a boat. Some profiles have measurements for all the years while others only represent a few years. The point profiles are processed in ArcMap 10.4.1 in the “SWEREF99 15” coordinate system. Reference points are manually generated 50 m to 100 m inland from the first measurement point. Point profiles are aligned to a straight line for each year, representing approximate average locations of the points, ranging from the reference point to the outermost point measurement. An example of point alignment lines is presented in Figure 11. X and Y coordinates are generated for the new locations of the data points, and the respective Z values are extracted to Microsoft Excel 2016. X, Y and Z values for each profile are compressed into a Jarkus file, with MATLAB R2019b, which can be opened in MorphAn 1.5.

Besides point profiles, orthophotos and historical coastline data are used for visualizing the evolution of the coastline. The orthophotos are found in Google Earth Pro’s historic photos tool and the historical coastlines are handled in ArcMap 10.4.1 via a Web Map Service (WMS), provided by the The Geological Survey of Sweden (SGU).

The wave rose plots are processed in MATLAB R2019b, with data (Hs and wave direction) provided by DMI, 2020. The DMI wave data comes from a hindcast model, applying observed pressure gradients. The data is from a cell approximately 1 km off shore from profile 5 (P5) from 2005 to 2015. In any future study, wave data for the entire examined period would be preferable. There is no wave gauge in the area, and the wave data available is from DMI’s model. Defining high-energy events and calculating the potential longshore transport would also have been appropriate, especially if data was available for the entire period.

A drone equipped with a camera was sent to fly over the study site when it was visited on the 2nd of March 2020. The drone images were handled in the DroneDeploy software where a TIF file was generated and handled in ArcMap 10.4. The drone data is used for observing the area from above in a high spatial resolution.
5.2 Data accuracy
Profile lines were made for each year for each profile to ensure that measured points were aligned to a close by line and hence more likely representing the depth at the new location. The fact that the points are not aligned to the same line, however, results in an uncertainty in distance when comparing morphological features. Figure 12 is a theoretical sketch of the situation where the maximum distance (28.7 m) between two profile lines for different years in the same profile is observed (red and blue line). The blue line is 0.84 m longer than red line and the maximum cross-shore distance uncertainty is thus 0.84 m.

The point measurements, measured by GPS and echosounder, are carried out with an uncertainty of minimum 2 cm in elevation (Z) (Rivero et al., 2018). When 2 cm is multiplied by the area on which the volumes are calculated, the total maximum uncertainty is approximately 4,000 m$^3$ which is 5 % of the 2011 nourishment of 80,000 m$^3$. As the X, Y, Z values are gathered from a GPS on a rod, in a sandy environment, the elevation inaccuracy might increase due to sinking of the rod into the sand. As the data was provided, it is assumed that the measurements are registered when the rod is completely straight and not penetrating the surface. Data uncertainties are important to consider when examining the results.

5.3 Sediment volume calculations
5.3.1 MorphAn volumes
MorphAn 1.5 is able to read Jarkus files and model volumes and momentary coastlines (MCL). Certain boundary conditions are applied before running the model, most importantly, the horizontal and vertical extent on which the volumes are calculated. To clarify the challenge of restricting an area on which the volumes are calculated, an example is presented in Figure 13. There are multiple ways of limiting the areas of volume calculations and Figure 13 presents three different ways in 2011 for P3. P3 consists of 17 profiles, one for each year between 1997 and 2015 (except for 2003 and 2014). The top model in Figure 13 represents the volume (blue) when the boundary conditions are set to -5 m for the lower boundary and the upper, landward and seaward boundaries are set to default values. The default value for the landward boundary is the most seaward location of the start measurement within the 17 profiles representing P3. The seaward boundary is the most landward of the end measurements of the profiles. These are the boundary conditions applied to the calculated volumes in this study.
The applied boundary conditions are considered to be the most appropriate when comparing volumes, as the volumes represent the same distances. A downside of this method is that some data is “wasted” like the brown parts in Figure 13, which can be reduced by taking out exceptionally short profiles. Another downside of this method is that morphologic features, especially bars, can be cut out, as Figure 13 indicates. When examining the beach volume changes, it is important to consider redistribution patterns as well as sediment losses. As described in Chapter 2, the profile’s different states carry sediment in and out of the profile and if the bar volumes are not included, a misleading picture of sediment loss becomes present, rather than a picture of sediment redistribution. P1 and P3 are the only profiles where bars are excluded in some of the years from sediment volume calculations. It is possible to include bars by diminishing the seaward boundary as in the bottom model of Figure 13. This method is, however, not appropriate to apply as it does not relevant to compare volumes calculated on different lengths. The middle model in Figure 13 represents the same boundary conditions as the ones applied in the top model, except for the lower boundary, which is set to -3.4 m. The volume is obviously different between the two, but this becomes irrelevant, as relative volumes are studied rather than absolute volumes. Contour -5 m is chosen as the lower boundary to include all measured depths as -4.94 m is the deepest measurement.
5.3.2. Sediment volume sections

To calculate sediment volumes, the output from MorphAn in the unit m$^3$/m is multiplied by a distance perpendicular to the profiles, which is estimated to represent a certain part of the coast. Profiles that are not enclosed by two groynes represent half the distances to their neighbouring profiles. Profiles between two groynes are assumed to represent the area between the constructions rather than half distances to the surrounding two profiles. The distances which each profile represents are presented in Table 2. Sediment volumes are calculated for the profile lengths defined in MorphAn multiplied by the cross-shore distance (Figure 14, left) and for the landward and seaward boxes (Figure 14, right), which are divided by contour -1 m. Contour -1 m is qualitatively estimated to be the depth impacted immediately by the beach nourishment, based on the profiles of Appendix B. The white boxes give rise to the results examining the total sediment volume evolution of the area. The volumes of the coloured boxes (six sections in total) provide information of the cross- and longshore sediment distribution over time. The light coloured boxes represent the three landward sections (L1, 2 & 3) and the dark coloured boxes show the area of the three seaward sections (S1, 2 & 3).

![Figure 14: Area of which each profile represents referred to by boxes. Left: White boxes represent area of calculated volumes. Right: volume calculation boxes, approximate locations of landward boxes (L) and seaward boxes (S).](image)

Since the coastline is concave, the sediment volume boxes overlap and diverge from each another. This is mostly evident in the two most eastward boxes. The fact that these boxes have different orientations, gives rise to the problem of whether or not to include the entire area, or to include the same area twice. This is however considered to be the most appropriate way of dividing the coast into volume boxes, and is the same method Hans Hanson (2013) applies when calculating sediment volumes.
Table 2: Distances of the coast, which each profile is set to represent.

<table>
<thead>
<tr>
<th>Profiles</th>
<th>Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>157</td>
</tr>
<tr>
<td>P2</td>
<td>201</td>
</tr>
<tr>
<td>P3</td>
<td>61</td>
</tr>
<tr>
<td>P4</td>
<td>225</td>
</tr>
<tr>
<td>P5</td>
<td>305</td>
</tr>
<tr>
<td>P6</td>
<td>288</td>
</tr>
<tr>
<td>P7</td>
<td>294</td>
</tr>
<tr>
<td>P8</td>
<td>338</td>
</tr>
<tr>
<td>P9</td>
<td>79</td>
</tr>
<tr>
<td>P10</td>
<td>67</td>
</tr>
<tr>
<td>P11</td>
<td>38</td>
</tr>
<tr>
<td>P12</td>
<td>51</td>
</tr>
<tr>
<td>P13</td>
<td>184</td>
</tr>
<tr>
<td>P14</td>
<td>148</td>
</tr>
</tbody>
</table>

The profiles are not necessarily representative for the areas defined in Figure 14, particularly the profiles between groynes and breakwaters. As described in Chapter 2, the beach morphology is highly affected by groynes. The sediment is unevenly distributed between groynes and it is a basic and incorrect presumption to assume that one profile volume represents the entire volume between two groynes. P7, particularly, gives rise to a wrong volume estimation - most likely an overestimation - as the profile is located on a groyne accumulation side (Figure 4).

5.4 MorphAn momentary coastline position (MCL)

MorphAn is able to estimate the position of the MCL as a distance from an inland reference point for each profile (Lodder et al., 2012). The MCL is calculated as a position on the profile between MHWL and MLWL, set to 0.1 m and -0.1 m respectively. The MCL results are a product of the reference point, and since the reference points are located 50 to 100 m inland from the first measurements, only relative MCL values can be interpreted between profiles and not absolute MCL positions.

5.5 Morphological evolution (Timestack plot)

The X, Y, Z data is transformed into linear interpolated profiles and stacked in a plot to exhibit SMFs, such as bars, and their movement over time. Bars, ripples and dunes are not quantitatively distinguished in the plots. The plots represent each profile with their respective years of profile measurements. The timestack plot was created by adding 1m to the Z-values per year after the first measurement, in order to shift the profiles vertically in the plot. The Z-values shift by 2 m when profiles overlap with a 1 m shift. The evolution of morphologic features can therefore solely be interpreted by the timestack plot and not by volumes.
6. Results
Chapter 6 presents the results, generated from the methods described in the Chapter 5. The MorphAn volume evolution of all profiles is attached in Appendix B.

6.1 Volumes
Ystad Sandskögen is highly managed and manipulated, and the morphology is a result of this. It is difficult to estimate autonomous dynamics in a complexly managed coast and this study therefore distinguishes between pre and post nourishment, rather than between autonomous and post nourishment behaviour.

6.1.1 Total volume evolution
The total volume change does not indicate erosion from the system from 1997 to 2010 in P1, 2, 3, 4 & 6 (Figure 15, top), as the average annual volume tendency increase is roughly 50 m$^3$. When the nourishments are subtracted from the volume curve, a volume loss of approximately 60,000 m$^3$ at an average tendency of 2,000 m$^3$/y is, however, observed in the period from 1997 to 2015. No signs of overall erosion are found for the profiles with measurements from 2002-2015 (Figure 15, bottom). In fact, an average tendency increase of approximately 1570 m$^3$/y and a total of 40,000 m$^3$ are observed between 2002 and 2010. When subtracting the nourishments, an average tendency increase of 140 m$^3$/y is calculated between 2002 and 2015.

![Volume evolution relative to 1997 in the coastal sections defined by: P1, 2, 3, 4 & 6 (1997-2015)](image1)

![Volume evolution relative to 2002 in the coastal sections defined by: P1, 2, 3, 4, 5, 6, 7, 8, 13 & 14 (2002-2015)](image2)

Figure 15: Beach volumes, relative to the respective first year, for profiles consisting of data from the same years. The vertical grey lines display storm events and red lines represent nourishments. Errors of a 2 cm elevation uncertainty are shown at each measurement.
and a total increase of about 20,000m$^3$. When subtracting the 2014 nourishment, the total volumes of P1, 2, 3, 4 & 6 decrease by roughly 20,000 m$^3$, while the total volume of P1, 2, 3, 4, 5, 6, 7, 8, 13 & 14 increase by roughly 20,000 m$^3$ in the period from 2013 to 2015.

The volumes increase in the first measurement after the two nourishments (red lines in Figure 15) and decrease in the following measurement point after the 2011 nourishment. The volumes decrease after storm events in 2004, 2007 (only for P1, 2, 3, 4, 5, 6, 7, 8, 13 & 14), 2008 and 2012 while the volume increases in 2000, 2007 (only for P1, 2, 3, 4 & 6) and 2015.

There are no indications of a significant volume loss, when considering the entire system, in fact the time span representing the most profiles (Figure 15, bottom) indicates a volume accretion. The distribution of volumes is presented in Chapter 6.1.2 and discussed in Chapter 7.

6.1.2 Profile volumes

The volumes and evolution hereof varies from P1 to P14, as is evident in Figure 16 which demonstrates the evolution of profile volumes and its trends. Profiles with sufficient data include a volume trend prior and post nourishment. Note that the 2011 nourishment is carried out in P2, 3, 4 & 5 and the 2014 nourishment in P4, 5 & 6. P1, 2, 4, 13 & 14 accrete volume up until the 2011 nourishment, whereas P3, 5, 6, 7 & 8 all undergo decreasing profile volume prior to the 2011 nourishment. Noticeable volume accretion post the 2011 nourishment is present in P2, 3, 4, 5, 10, 12 & 13. In the profiles where the nourishment is held out, the volumes have increased in October 2011 (more or less five months after nourishment), whereas the volume increases in the eastern profiles roughly one year after the nourishment. The volumes in P2, 3, 4, 5, 6, 10, 12, 13 & 14 increase after the 2014 nourishment.
Figure 16: Volume evolution of profiles. Black marks indicate annual volumes. Red tendency lines and functions represent volume evolution prior to 2011 nourishment and blue tendency lines and functions display volume evolution post 2011 nourishment.
The area upstream of the first groyne (P1, P2 & P3), experiences a modest increase in volumes overall from 1997 to 2010. P3 however, undergoes slight erosion, which is evident between contour 0 m and 1 m (Figure 17, left). P4, 5, 6 & 7 are located in the area between the groynes, where a general volume loss is observed pre nourishments, as seen especially for the dry part of P6 for example (Figure 17, right). P4 is the only profile between the groynes with a slight gain in volume, which is takes place primarily below contour -0.5 m. Of the profiles downstream of the groynes (P8, 9, 10, 11, 12, 13 & 14), only P8, 13 & 14 indicate evolutions prior to the 2011 nourishment, as these are the only profiles consisting of data ranging back to 2002. P8 (Figure 18, left) shows onshore SMF migration simultaneously with volume loss from 2004 to 2009. P13 (Figure 18, right) & 14 are submitted to accretion and the greatest average annual accretion of sediment in all profiles, prior to 2011 nourishment, is observed in P13 (10.5 m3/m/y).

The 2011 nourishment is easy to detect in P2, 3, 4 & 5, where the nourishments are carried out (Appendix B). In P3 (Figure 17, left) the 2011 nourishment displays as an outer SMF at contour -3 m and from contour -2.4 m to 1.7 m. The 2011 nourishment is not perceptible in P6 and P8, in contrast to P13, where the volume increases after the nourishment, especially in the area from contour -4 m to 1.5 m. The 2014 nourishment is, however, visible in P6 from contour -1.5 to 2 m.
6.1.3 Section volumes
In an attempt to trace the nourished sediment after the 2011 nourishment, the volumes of the six sections, represented by same coloured boxes in Figure 14 (right), are calculated. The volume evolution relative to 2010 indicates which sections have gained or lost volume up until 2015 (Figure 19). The 2011 nourishment (May) is clear in 2011 (October) in L1, as most of the nourishment is carried out in this section. L1, L2, S1 & S2 show a decrease in volume from 2011 until 2012, where L1 is the only section decreasing until 2013, whereas L2, S1 & S2 increase from 2012 to 2013. L3 & S3 gain volume all years between 2010 and 2015. A shift of sediment volume from L1 to S1 is observed between 2012 and 2013. The same tendency is present from section L2 to S2 from 2011 to 2013.

6.2 Morphology
The cross-shore morphological evolution can be examined by a timestack of profiles (Figure 20). The timestack plot gives an overview of the cross-shore evolution of the morphological features such as dunes, ripples and bars. Dunes, bars and ripples are not quantitatively distinguished in this study, as described previously in this analysis, and are therefore referred to as a seabed morphological feature (SMF) throughout this section.

SMFs are present in P1, 2, 3, 5, 7, 8, 13 & 14 prior to the beach nourishments. The rest of the profiles are relatively uniform on the seaward side of the dunes. The 2011 nourishment is carried out in P2, 3, 4 & 5 and in P4, 5 & 6 in 2014. A notable SMF becomes present after the 2011 nourishment in P1, 2, 3, 6, 10, 12, 13 & 14. The SMFs in profile 1 and 2 are only present five months after the 2011 nourishment whereas the SMFs in P3 & 6 are still present the following year. In P10, 12, 13 & 14 the SMF is present until the 2014 nourishment. Following the 2014 nourishment, SMFs are found in January 2015 in P1, 3, 10, 12, 13 & 14.
Figure 20: Timestack plot of profiles.
6.3 Momentary Coastline (MCL)
The position of the coastline is important to consider when examining opportunities in preserving or enhancing beach quality seen from a recreational point of view as well as in relation to beach resilience to flooding and erosion. MCL position at all profiles is presented in Figure 21.

Figure 21: Annual momentary coastline (MCL) position relative to reference point for each profile. Black points represent MCL prior to nourishment and orange; MCL position post nourishment, except in P9, 10 & 12, which is from...
The MCL is retrograding prior to the 2011 nourishment in P2, 3, 4 & 6 whereas a coastline progression is observed in P1, 5, 7, 8, 13 & 14. The 2011 nourishment profiles (P2, 3, 4 & 5) expand 24 m, 70 m, 35 m and 20 m respectively from 2010 to 2011 and post nourishment, after approximately two years, the MCL is respectively 10 m, 10 m, 16 m and 9 m longer, relative to 2010. P2, 3, 4 & 5 MCL positions all extend from 2013 to 2015, after the 2014 nourishment, especially P4 & 5 which expand 26 m and 28 m respectively. The MCL at P6, 7, 8 & 9 does not expand after the 2011 nourishment, nor does the MCL at P7, 8 & 9 after the 2014 nourishment whereas P6 does, as P6 is a nourishment profile in 2014. The MCL of P10, 12 & 13 expands roughly 5 m for P10 & 12 and 9 m for P13 from 2010 to 2011 and 30 m in all three profiles from 2010 to 2013. It remains more or less steady until 2015. The MCL of P14 retreats from 2010 to 2012 and increases from 2012 to 2015.
7. Discussion

7.1 Nourishment impact on the beach volume

The total volume of P1, 2, 3, 4 & 6 has a decreasing tendency of 2,000 m$^3$/y from 1997 to 2015 when subtracting the nourishments (Figure 15, top). This part of the beach is especially valuable as a recreational site and the volume would most likely have undergone rapid loss of volume if the nourishments had not been carried out. When northeastern parts of the beach are considered, then an increase in total volume is observed from 2002 to 2015 although nourishments are subtracted from the volumes (Figure 15, bottom). The observed volume accumulation in the eastern area can explain this. There is an increase of 165,000 m$^3$ from 2002 to 2015, including the nourishments, and a “natural” increase in beach volume of 20,000 m$^3$ when the nourishments are subtracted. It appears that the beach is in a “natural” period of erosion from 2010 to 2012, when examining volumes with subtracted nourishments in Figure 15.

Subtracting nourishments from the volume curves to display “natural” volume evolution is a simple and easy method. Feedback mechanisms, linking the nourishments and profile volumes, are however not considered, and it is questionable whether the subtraction of nourishment gives an exact picture of how the volume evolution would have progressed without nourishments. An example of a feedback mechanism could be the SMFs observed after nourishments, in some profiles (P3 for instance), inducing wave breaking further away from the coastline, dissipating wave energy and reducing erosion. Subtracting the nourishments is nevertheless an indicator of how the volume would evolve had it not been for the nourishments, and whether the beach is in a period of recovery or recession.

The total volume of the beach system is positively influenced by the nourishments. It is difficult to calculate how long the effect of the 2011 nourishment lasts because of the “disturbance” from the 2014 nourishment. However the volume decreases roughly 20,000 m$^3$ in P1, 2, 3, 4 & 6 (Figure 15, top) from 2013 to 2015, and increases roughly 20,000 m$^3$ for the total volume in P1, 2, 3, 4, 5, 6, 7, 8, 13 & 14 (Figure 15, bottom) in the same period when subtracting the 2014 nourishment. Based on these numbers it can be argued that the 2011 nourishment had a longer and more positive influence, when calculating the volume for the entire study area, whereas the 2011 nourishment effect is shorter, when only examining the southwestern part of the beach. This tendency indicates that the nourishment is still to be found in Ystad Sandskogen beach years after nourishment, but volumes have been redistributed. Redistribution of sediment volumes will be discussed in the next section.

7.2 Nourishment distribution

The section’s volume distribution (Figure 19) displays the volumes decrease in L1 and S1 and increase in L3 and S3 five months after the 2011 nourishment. Figure 22 illustrates the volume sections and interpreted volume exchange patterns based on the volume evolution of the volume sections in Figure 19. The volume loss from SW and gain in NE and the dominating northeastward longshore transport indicates that some of the nourished sediment is eroded from the nourishment area and accreted at the breakwaters in the northeast. The breakwaters and their tombolo morphologies can function as a sediment trap, similar to the accumulation side of a groyne (Masselink et al., 2014), which could explain the volume accumulation at the easternmost section (L3 & S3). Besides the breakwaters in the northeastern end of the area, another explanation for the volume increase in L3 and S3 could be attributed to the accumulation of sediment delivered from a SW bound longshore transport (described in Chapter 4). The relatively large increase in volume and MCL extent after the 2011
nourishments in P10, 12 & 13 can however not be explained better than by the nourishments and possibly by the construction of two new breakwaters between 2010 and 2012. P10 & 12 are located right where the two new breakwaters are constructed between 2010 and 2012 and are the two profiles increasing most in volume after the 2011 nourishment (Figure 16). When examining the orthophotos in Figure 1 it is evident that more sediment has accumulated on the beach behind the most recent breakwaters.

Since the 2011 nourishment did not indicate any major coherent changes in L2 and S2, most of the nourished sediment must have been transported past L2 and S2, directly to L3 and S3. P5 is a part of L2 and was a nourished in 2011 and 2014 (P6 only in 2014), which could explain parts of the relatively small increase in volume in L2 after the nourishment. The fact that the sediment bypasses the middle section (L2 and S2) is remarkable, but could possibly be explained by limitations due to the relatively small window of time of measurement. Another explanation could be that the distribution of sediment between two groynes potentially varies significantly over space and time, especially in this area, with a shifting longshore sediment transport direction. A calculated volume loss might instead be a volume redistribution within the area of two groynes, especially when a profile right next to the groyne is determined to represent the entire volume between two groynes. On top of this, some of the groynes are not sediment tight and might explain some of the evolution in P7 (located right on the accumulation side of a groyne), where a decrease in volume and length of beach are observed after the 2011 nourishment. This is counterintuitive, when considering previous MCL evolution and might be attributed to changes of the groyne composition and shifted longshore transport direction. It is evident from the wave roses from 2005-2015 and 1979-2010 that the longshore current’s dominating direction is from P1 towards P14. At the same time a longshore transport in the opposite direction, induced by southeastern waves, is apparent but occurs less frequently.

The section’s volume evolution also exhibits a cross-shore movement of the sediment, as the coast strives towards equilibrium after the beach nourishments. This is especially evident in Figure 19, where a shift of volume from L1 to S1 takes place between 2012 and 2013 and from L2 to S2 from 2011 to 2013. The cross- shore transport from land to sea can assemble the sediment to the surf zone undergoing longshore transport. The cross-shore transport is therefore important to consider when examining the potential magnitude of longshore sediment transport.

The shifting longshore transport direction, evident at the Nybroån river mouth, is backed up by groyne accumulation sides on both the SW facing and NE facing sides (Figure 1). It was observed that some of the groynes are not sediment tight when the site was visited in March 2020. The sediment can thus be transported from the accumulation side to the leeside through the groyne. A relative loss is expected on the accumulation side of the groin after opening the way for transport of sediment to the leeside, where a relative volume increase is expected. The
observed double lee/accumulation sides are a product of shifting longshore transport direction, and the porous groynes make the dynamics even more complex to interpret. Visualization of a permeable groyne at Ystad Sandskogen is presented in Figure 23, where the accumulation side gradually transits to the leeside. It was unfortunately not possible to determine when or if the groynes have been reconstructed.

This study does not examine the aeolian processes and, as parts of the nourishments might have been transported to the dunes by wind (see Figure 2 and 5 for dunes), an aeolian analysis would have been beneficial. Unfortunately, no consistent elevation data from the back to the front of the dunes is available for the period from 1997 to 2015. The differences in dune elevation, and dune movement, from year to year, indicating volume evolutions of the dunes and beach volumes would have been appropriate to compare and analyse simultaneously.

7.3 Hydrodynamic and nourishment impacts on morphology, MCL and volumes

The wave direction appears to have an influence on the MCL in some profiles. P1 & 14 seem to have a more seaward MCL in years with a relatively larger portion of waves approaching from southeast, as in 2006, 2009 and 2010. A landward shift of MCL in P1 & 14 is observed in years of dominating waves from SSE such as 2007 and 2008. 2007 and 2008 are the years between 2005 and 2010 with the smallest profile volumes in P14 and 2009 is the year of largest profile volume in P14. It makes sense that erosion will take place under southwestern waves as P1 & 14 are located on the leeside of the harbor and breakwaters respectively, and that the two profiles accrete in opposite longshore transport direction when the profiles are located at the accumulation side of the obstacles.

P7 is located along a groyne on the accumulation side where a gain of volume would be expected when the longshore transport is flowing from P1 to P14 on southeastern waves. This is evident in 2007 and 2008, and the opposite picture is evident in 2009 when southeastern waves become more frequent, however MCL prolongs in 2010 again, counteracting this theory.

If the nourishment welcomes breaker bars, beach erosion might decrease, as energy will dissipate towards the beach. Bar enhancement of nourishments could therefore be a success criteria for the nourishments, if the local hydrodynamics welcomes bar formation. The fact that some of the post 2011 nourishment SMFs observed in the timestack plot (Figure 20) and
profiles in Appendix B is present several years after the 2011 nourishment is positive for the beach volume and width, however some of the SMFs are only present in the measurements five months after the nourishment and most profiles do not achieve an outer SMF. The lifetime of the nourishment induced SMFs varies from a minimum five months at least until the time of nourishment in 2014. Because of the 2014 nourishment, it is difficult to determine the lifetime of the 2011 nourishment SMFs after the 2014 nourishment.

The MCL in P10, 12 & 13 responds to the 2011 nourishment one year after the 2011 nourishment, which indicates that there is a lag in the nourishment effects between the southwestern and northeastern parts of the area when assuming that the volume increase is attributed to nourishment. The sediment can however also originate from longshore transport from the northeast, which the wave roses indicate is a possibility. A one year lag effect could be an expected time lag as the beach nourishment is transported seaward over the winter and can be transported alongshore hereafter and onshore again in the summer after a winter with high wave energy.

The MCL and profile volumes seem to follow the same pattern more or less, when comparing Figure 16 and Figure 21. In other words the profile volume and MCL are related to a certain extent, which especially makes sense post nourishment as the nourishments were carried out on the beach. Masselink et al (2014) in a study of five beaches finds a correlation (R^2 = 0.71-0.96) between shoreline change and beach volume change. P6 only shows signs of shoreline extension after the 2014 nourishment, taking into consideration that P6 is a nourishment profile in 2014 and not in 2011. This indicates that nourished profiles are likely to experience prolongation of the MCL. P13 is subject to seaward displacement of the MCL after the 2011 nourishment, especially after two years, exemplifying that non-nourished profiles downstream of the nourishment might experience positive MCL effects as well, especially when breakwaters are present. Giardino et al. (2019) finds that there is a 77 % chance of the shoreline to move seaward one year after beach nourishment, based on data available from the past 50 years from 604 locations in Holland which can be related to the findings of this study.
8. Conclusion

The nourishments at Ystad Sandskogen have had positive effects on the beach volume, the width of the beach (MCL) in most cases and SMFs in a few cases. The intention of extending the beach width for both beach resilience and recreational purposes has thus been relatively effective. The nourishment effects however deteriorated after a maximum of a year at nourished areas on the beach, as the beach sand was transported seaward and alongshore. Even though the volume and MCL decreased rapidly after the 2011 nourishment, the volumes in the nourished areas were in most cases still larger and the MCL longer than the pre-nourishment situation. The nourishment effects in most of the eastern parts of Ystad Sandskogen also indicated positive effects on volume and MCL, especially after one and two years. The nourishment in 2014 contributed positively to both volumes and MCL in almost all profiles. It is difficult to distinguish whether the volume changes at specific locations are due to nourishments or wave climate and its physical components. Linking the nourishments and the volume distribution to hydrodynamics, physical processes and theory leads however to the following conclusions:

- The total volume increases after the nourishments, and the nourishment effect lasts longer when more of the downstream area is considered.
- Volumes distributed cross-shore, mainly in a seaward direction, after the 2011 nourishment.
- Large portions of the nourished volume are distributed in the direction of the dominating longshore transport path.
- Volumes accrete at breakwaters in the NE however the groynes did not accumulate as much of the nourishment as expected.
- The MCL progresses in areas with increased volumes. The 2011 nourishment solved the pre- nourishment challenges of MCL retreat in most places for the observed time period.

As the nourishments are effective in a relatively short-term perspective, and as the physical sediment transport processes remain, a regular supply of sediment in the future is necessary to ensure a volume surplus and a desired beach width.
9. References


Halldén, T. H. (2017). Measuring coastal erosion along the coast of Ystad municipality using PSInSAR and SBAS.


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Appendix A: Timeline

1952: Construction of several pillar groynes reaching approximately 40 m out in the water (Hanson, H., & Almström, B., 2013).
1960: Orthophoto (available at https://kso.etjanster.lantmateriet.se/#).
1975: Orthophoto (Available at https://kso.etjanster.lantmateriet.se/#).
1990: Groin constructed outside Saltsjöbad, Ystad (Hanson, H., & Almström, B., 2013).
2010 31st of December: Orthophoto (available in Google Earth Pro).
2010: Between 2010 and 2012 two breakwaters are constructed on top of the existing three (Google Earth Pro).
2011 May 23rd: Beach nourishment of 80,000m³ is carried out (Bontje et al., 2018 & https://www.ystad.se/strandfodring).
2011 May: Pictures taken by Peter Sørensen (DCA).
2012 June: Orthophoto (available in Google Earth Pro).
2014 March: Beach nourishment of 64,000 m³ is completed (Bontje et al., 2018 & https://www.ystad.se/strandfodring).
2014 14th of June: Pictures taken by Peter Sørensen (DCA) two weeks after nourishment.
2015 April and July: Orthophotos (available in Google Earth Pro).
2017 April, Beach nourishment 80,000 m³ (Bontje et al., 2018 & https://www.ystad.se/strandfodring).
2018 23rd of September: Pictures taken by Peter Sørensen (DCA).
2019 25th of August: Orthophoto (available at from Google Earth Pro).
2019 22nd of November: Pictures by Peter Sørensen (DCA).
2020 March: Photos available by Nikolai Heath Sørensen, and Drone orthophotos at DCA.
2020 April: Beach nourishment (Bontje et al., 2018 & https://www.ystad.se/strandfodring).
Appendix B: Profile volume evolutions