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Coastal erosion in Ängelholm: A case study tracking recent and historical changes to Vejbystrand

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Bachelor’s thesis, 15 credits, in *Physical Geography and Ecosystem Analysis*

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Abstract

As global warming continues to change the global climate, extreme weather events become more common. The effects of such events vary regionally due to both natural and anthropogenic influences. This study identifies the main mechanisms causing coastal erosion in Ängelholm and evaluates the adaptation measures implemented by the municipality. A case study of Vejbystrand, a sandy beach in the municipality, is conducted in order to address the issue of coastal erosion due to recurring storms. This study presents methodology for evaluating changes to the coastal topography on different time scales and performs a change detection analysis over Vejbystrand to test the hypothesis that variations in the coastal topography of Vejbystrand have increased during the last decade, and that this increase is related to more frequent storm events.

It was found that erosion in the municipality is influenced by both natural and anthropogenic factors, and that less invasive erosion adaptation measures have fewer consequences. A suitable method for delineating coastal properties using Digital Shoreline Analysis System (DSAS) and digital elevation model (DEM) data is presented and applied to Vejbystrand. By comparing data collected from a recent period of frequent storm events (2010-2017) to a calmer period (1960-1973), the hypothesis that recent changes to Vejbystrand are due to frequent storms can be accepted.

Key words: Coastal erosion, Ängelholm, coastal topography, DSAS, change detection, frequent storms, climate change

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1 Introduction

1.1 Coastal erosion and a changing climate

As climate continues to change due to global warming, sea levels rise, and extreme weather events become more common. A warmer atmosphere contains more water and provides energy for extreme weather events such as intensive storms. At a more regional scale, the south of Sweden can be expected to experience higher levels of precipitation, and more tropical nights near the coast (SMHI 2009). During the fall and winter, winds move toward the low-pressure center on Sweden's west coast causing the winter storm season (Gyllenram et al. 2017). It is largely because of pressure changes and the corresponding winds that sea levels rise during storms. High wind speeds and sea levels cause waves that undermine the coastal dunes on sandy beaches, forcing the top of the dunes to collapse onto the beach face and nearby coastal system. This is known as acute erosion. So long the sand remains in the nearby coastal system, it can eventually return to the shore via perpendicular sand transport towards the shoreline. On the other hand, chronic erosion is when the system is unable to recover the sand because it is permanently removed from the system via parallel sand transport (Ising et al. 2016). Sandy beaches are dynamic ecosystems that can be expected to see fluctuations over short periods of time when the recovery process is still underway. When in balance, they can be expected to remain relatively stable in the long-term (Birgander et al. 2018).

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1.2 Aim

This study is conducted in coalition with Ängelholm municipality. Contact with the municipality was made through the organization Miljöbron, and the project topic was agreed upon between the author and Ängelholm municipality. Much of the data for this study as well as an additional supervisor were provided by the municipality. The primary aims of this study are to:

1. Conduct a literature review to identify the main mechanisms that cause coastal erosion in Ängelholm and evaluate implemented adaption measures in the municipality aiming to limit further erosion.
2. Estimate past, recent and future changes to coastal topography caused by erosion by performing a change detection analysis of the coastal land area of Vejbystrand from 1947 to 2017.
3. Test the hypothesis that variations in the coastal topography of Vejbystrand have increased during the last decade, and that this increase is related to more frequent storm events.

Erosion is consensually seen as an issue in the municipality, and common threads in the research include analyzing the effectiveness of beach nourishment projects and other soft solutions such as sand fences, jetties, and vegetation planting (Sweco 2011; Fredriksson et al. 2017; Lindell 2017; Lindell et al. 2017). Much of the local research has focused on Ängelholm beach, a ten kilometer stretch south of Vejbystrand subject to erosion. As climate changes, however, it is important to compile data of the entire coast in order to fill the gap in knowledge and prepare for future climate.

2 Methods and Scientific Background

2.1 Study area

2.1.1 Ängelholm municipality and the west coast

Ängelholm is a municipality on the northwestern coast of Scania. The Scanian west coast is susceptible to erosion because of its low-lying position and fine sandy beaches which are subject to parallel sand transport from the currents in Skälderviken. Westerly winds and waves increase in intensity during storms, causing erosion of the beaches. The intensity and direction of the wind and waves, as well as the size of the sand grain and water depth, determine where the sand is transported to (Ising et al. 2016; Birgander et al. 2018). The sandy beaches on the west coast are defined by dunes made up of fine-grain sand. Dunes, especially those over 3.5 meters in height, play an extremely important function in protecting the coast by acting as a barrier to flooding and as a hindrance to high winds (Hanley et al. 2014; Thiere 2017). As storm frequency increases, there is little time to recover the beach, leading to continued degradation of the dunes (Ising et al. 2016). Together with parallel sand transport, such an increase could drastically impact the ecosystem and put more coastal areas at risk.

2.1.2 Vejbystrand

Vejbystrand is a small stretch of sandy beach in the northern part of Ängelholm municipality (see Figure 1). A harbor and restaurant sit at the north end of the beach and a parking lot to the south. The beach has three prevalent rock depositions along the shoreline, a drainage pipe jutting out of the center of the beach, and low-lying protective dunes covered in vegetation. Sand grain size on the northern part of Vejbystrand is coarse to medium sand (0.41 mm) while the southern part of the beach has fine to medium sand (0.22 mm; (Sweco 2011). Vejbystrand is considered to have a relatively high recovery rate from erosion (SGU 2018), however, as storm frequency increases this durability will be put to the test. Intense westerly winds and increased sea levels during storms put the area at risk for flooding and erosion (Ising et al. 2016). When strong winds occur frequently, the natural beach recovery process of accumulating sand is severely hindered. Homes along the beach are thus vulnerable to these naturally occurring phenomena which have been anthropogenically enhanced. Additionally, municipalities in Sweden are responsible for coastal safety and erosion issues (Bontje et al. 2016), which further confirms the relevance and importance of this study.

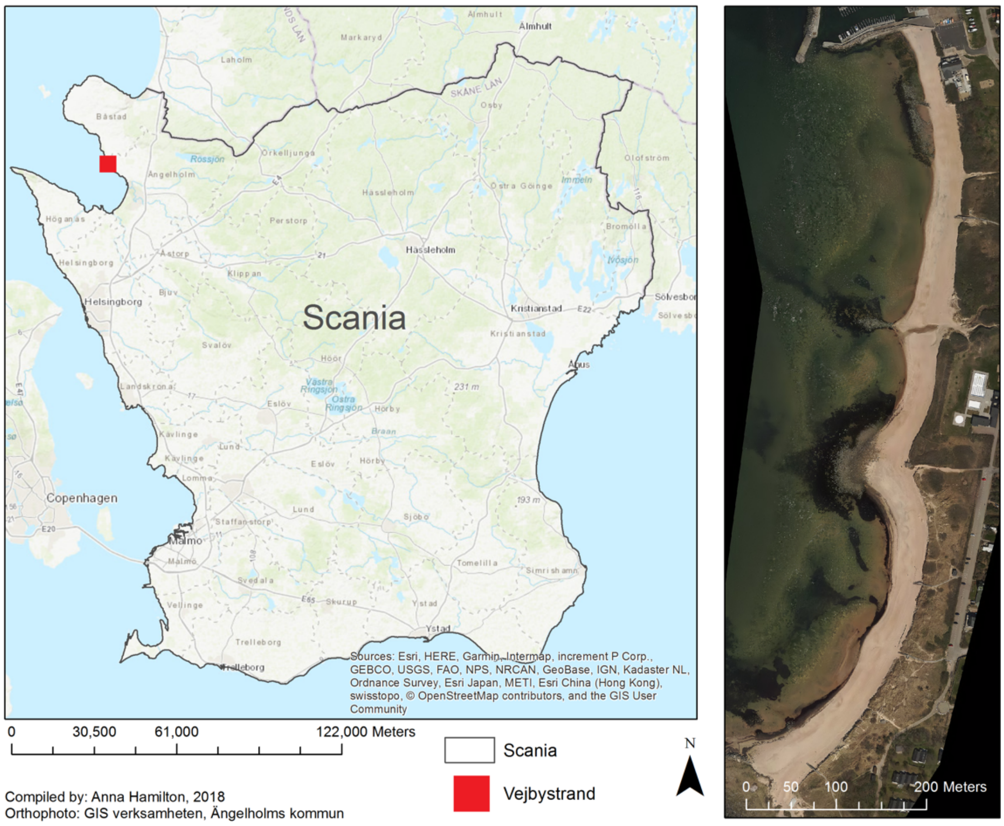

Figure 1 Location and overview of Vejbystrand

2.2 Previous research

The Geological Survey of Sweden (SGU) recently issued the Skånestrand Projekt (Scanian Beach Project), mapping areas of accumulation and erosion on the Scanian coast between the 1930's and 2017. To compensate for uncertainty in the mapping of historical data due to issues in positioning of historic images and the unaccounted-for tides, SGU used a buffer class between -15 and +15 meters. SGU also classified the coast based on its vulnerability to erosion by considering important coastal characteristics such as the soil type, seabed sediment, topography, bathymetry, exposure, as well as sediment dynamics (Ising et al. 2016; SGU 2018).

Areas of accumulation (ackumulation) and erosion on Ängelholm's coast are seen in Figure 2 below. As seen in Figure 2 below, no noteworthy difference (±15 meters) is seen on Vejbystrand during this period. Vejbystrand is, however, considered to have moderate vulnerability to erosion, and SGU predicts that as climate changes in the next 100 years there is a likelihood for increased erosion.

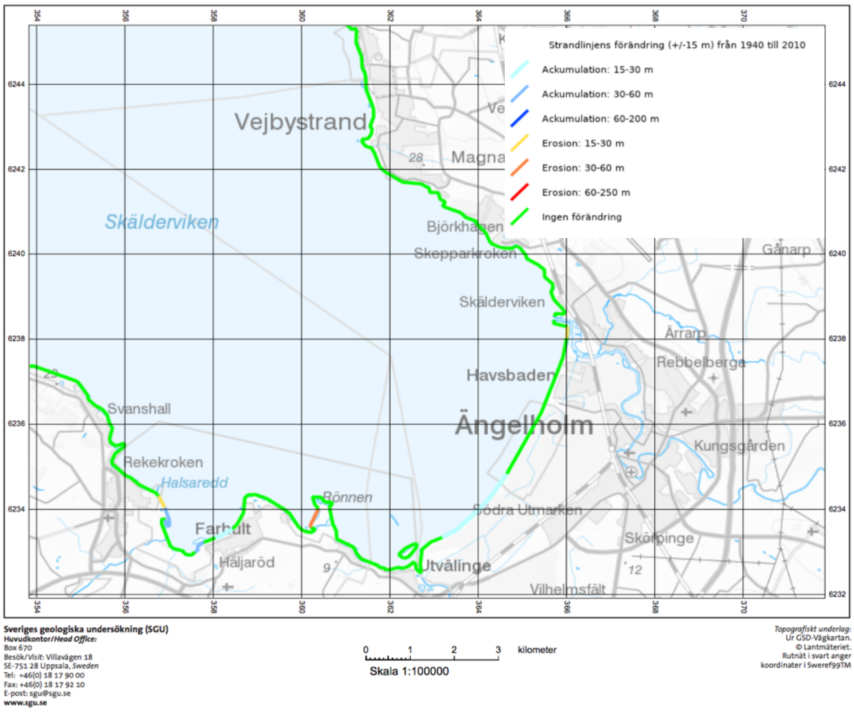

Figure 2 Swedish Geological Survey Coastline Change for the Municipality of Ängelholm. From (SGU 2018)

Determining areas of coastal erosion on sandy beaches can be difficult as these beaches are expected to see short term fluctuations due to the mobility of the fine sediment that can easily erode away or accumulate in the coastal system (Birgander et al. 2018). Therefore, it is best to look at multiple topographic indicators of erosion such as both the vegetation and shore lines. Shorelines vary due to changes in tide and sea level, while the vegetation line is a more stable feature of the coast that both accumulates and recedes sand in response to weather and climate events (Hågeryd et al. 2005). Using both of these features together provides a better indication as to where the sand is coming from and going to.

Research focusing on coastal erosion in Bjärred, also on the west coast of Scania, modeled how an increase in storm frequency due to climate change may impact the coast (de Mas de Mas and Södergren 2011). The authors compared erosion of the beach between 1963 and

2002 to erosion between 2002 and 2010 by manually digitizing the vegetation lines and using Digital Shoreline Analysis System (DSAS), a popular shoreline analysis tool used by the United States Geological Survey (USGS) to determine erosion rates. This information was then input into a model to predict how climate may impact the coast. Additionally, this study looked both at the shore and vegetation lines to compare these periods

Consulting firm, WSP, assessed the vulnerability of the Ängelholm's coast in 2013 after storm Sven by using field measurements and comparing these measurements to a 2010 orthophoto. Some of the most notable damage on the municipality's coast was seen in the southern part of Vejbystrand, and it was recommended that the northernmost and southernmost areas of this beach be prioritized when implementing protective measures, while the middle section of the beach should come as a second priority (WSP 2013).

Fredriksson and Larsson (Fredriksson and Larson 2015) modelled the erosion and accumulation of the sand dunes on Ängelholm beach in order to investigate the impact of parallel sand transport due to northwesterly winds and intense waves that can occur during storms. The study used the weighted linear regression (WLR) statistic in DSAS to analyze erosion on Ängelholm beach using a range of orthophotos between 1940 and 2014. The shorelines were delineated with an uncertainty index of 10 meters for 1940-1963 and 5 meters for 2000-2014. They found that the northern part of the beach had eroded sand while the southern part accumulated sand, and that this was likely due to parallel sand transport along the coast. The authors recommended to continue with sand fencing and to request funding to continue beach nourishment projects that replenish the sand lost to erosion.

In an article by (Fredriksson et al. 2017), the authors estimated the amount of sand volume required to maintain the coastal morphology Scania's southern coast between 2017 and 2100 as coastal erosion and sea levels rise due to climate change. The study used DSAS to determine the end point rate (EPR) of the vegetation line between 1960 and 2012. This data was then input into a model used for estimating the amount of sand required. It was found that the south coast of Scania needs a minimum of 44 million m^3 of sand to be able to preserve the sandy beaches against future sea level rise.

A Master's thesis by Janna Lindell (Lindell 2017) analyzed the impact of dune vegetation removal on Ängelholm beach using LiDAR (Light Detection and Ranging) data. As part of the methodology, the raster calculator spatial analyst tool in ArcMap was used to create a new raster with the change in elevation of the dunes following large amounts of vegetation removal from the Sand Life project on Ängelholm beach. The study area was then divided into seven rectangular sections for which the total change in elevation was summed and then divided by the length of the respective section to find the volume difference. It was found that vegetation removal has increased the impacts of wave and wind erosion, and as dune height decreases, vulnerability to flooding increases.

2.3 Materials

The GIS program ArcMap 10.5 was used to analyze the orthophotos as well as delineate the shore, vegetation and dune toe lines of the beach. The ArcMap extension, DSAS, was used to calculate the statistical changes in these features. Aerial photos from 1947 and 1973 are from the GIS center at Lund and georeferenced by the GIS division of Ängelholm municipality. An orthophoto from 1960 was extracted from Lantmäteriet, while all other orthophotos (2004, 2007, 2010, 2012, 2014, 2016, and 2017) and digital elevation models (DEM) were provided and georeferenced by Ängelholm municipality. Appendix A provides additional metadata, and Figure 3 provides a timeline overview of the data availability and regional storms. The years seen are those involved in this study, blue dots represent storm years, and red dots are years with both an orthophoto and LiDAR (DEM) data.

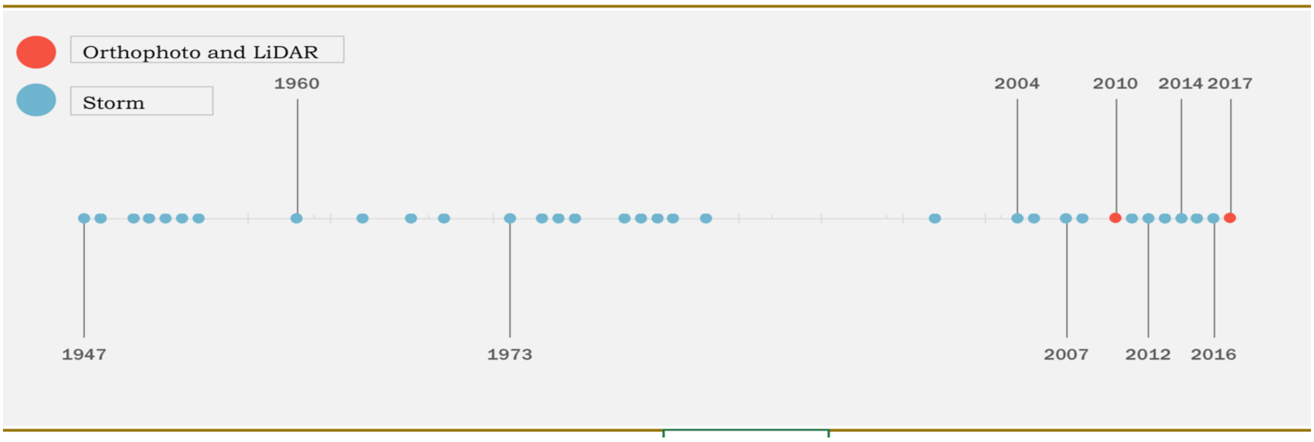

Figure 3 Swedish west coast storm timeline and available remote sensing data

2.4 Literature review

Anthropogenic and natural parameters of coastal erosion impacting the municipality, relevant values for the region, solutions implemented by the municipality, and potential solutions for the future were compiled into a literature review seen in Appendix B and C. To do so, I studied existing literature on the subject which include government documents, journal articles, and environmental consulting reports. I then compiled the data into a table for which the municipality can refer to for future adaptation measures (Appendix B and C).

2.5 Delineation of coastal features

2.5.1 Vegetation and shoreline

A field visit to the area was made prior to delineation of the coastal features in order to further define the shore and vegetation lines. The vegetation line excludes shadows from vegetation and other disturbances and keeps a continuous straight line when buildings or paths obstruct the natural line. The shoreline is defined as where the sea and sand meet. Rock depositions along the beach are not included in the shoreline in order to keep the analysis specific to sand movement, as these depositions are not considered to be a part of the sandy beach (Toxicon 2015).

To accurately delineate the vegetation and shorelines for each orthophoto, the image analysis tool in ArcMap was used to increase image contrast. I have increased image contrast by 20% for all pre-2000 images, and for all images, I have implemented the stretch function (standard deviation = 3), which enhances certain image properties. These alterations make the shore and vegetation lines clearer for delineation. This tool is further expanded upon and described on the ESRI homepage (ESRI 2017). For years with DEM data (2010 and 2017), the sea level (0 m) line was extracted and used as a reference. Delineation of all vegetation and shorelines were otherwise done manually at a mapping scale based on image resolution (see Appendix A for uncertainty value).

2.5.2 Dune toe line

The dune toe line is defined as a sudden increase in slope between the beach and the dune face which is usually depicted as a relatively high value (Gao 2009; Hardin et al. 2014). Slope and curvature were extracted using from the 2010 and 2017 DEM data in order to delineate the respective dune toe lines. This was done using the corresponding ArcMap spatial analyst tools. The slope function provides a picture of where there is a sudden increase in slope, while the profile curvature function determines whether the slope is concave or convex. Profile curvature is useful in portraying the formation of the dune and the dynamics of slope (Hardin et al. 2014), however, in this study it is used to strengthen and confirm the slope data. Figure 4 shows the different profile curvature possibilities and the value they are assigned in ArcMap. The dune toe lines were then manually digitized following this break in slope and curvature for both 2010 and 2017.

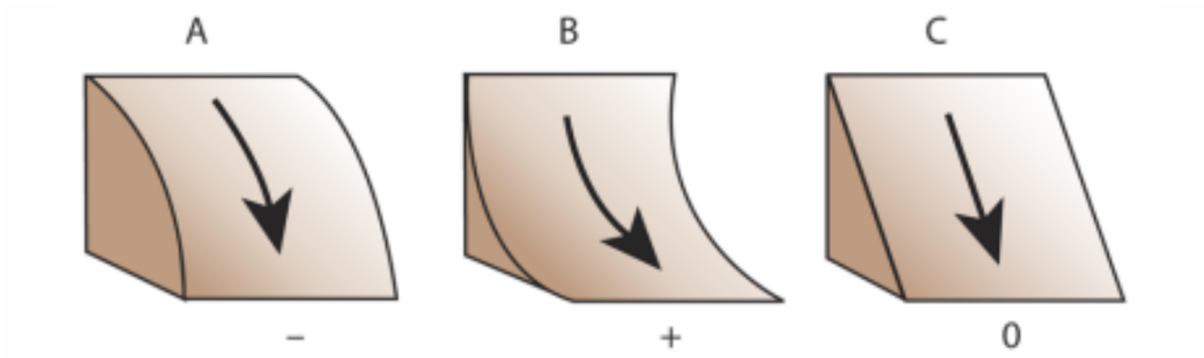

Figure 4 Profile curvature. From (ESRI 2016b)
Shows the sign for which ArcMap depicts convex (A) slope, concave slope (B value) and a linear surface (C) in the profile curvature function.

2.6 Change detection analysis of the coast

2.6.1 Storm data collection

Storm data was collected from the Swedish Meteorological and Hydrological Institute (SMHI) in order to consider the differences between different meteorological stations as well as examine the frequency and intensity of storms during the study period. SMHI defines a storm as wind speeds above 24.5 m/s, and high winds to be anywhere between 13.9 and 24.4 m/s (SMHI 2012). Historic storm dates were collected from a study by Olsson (Olsson 2002) that compiled and assessed storm data between 1919 – 2000 for the west coast of Sweden. All of these storms landed in close proximity to Ängelholm and Vejbystrand, potentially damaging the coast.

Wind speed and direction of the known storm events between 1947 and 2017 were compiled from two SMHI wind stations, Barkåkra and Hallands Vädero. Barkåkra is a land-based station about six kilometers southeast of Vejbystrand. This data dates back to 1946, covering the entire study period. The differences between land and coastal wind data are stark because wind measured at land-based stations are affected by the topography (SMHI 2013b). For this reason, data from Hallands Vädero was also taken. The data from Hallands Väderö do not cover the entire study period as the station was only in place from 1961-1965 and then re-established in 1995. Since 1995, both stations have used an automatic wind speed measurement device placed ten meters above the ground that take the ten-minute average wind speed and direction every hour. For each known storm date, the highest value and corresponding wind direction was taken. Additionally, sea level data from Viken was compiled for the available years. This station was established in 1976 and takes the average sea level every hour. The highest value was also taken for each storm date.

2.6.2 Digital shoreline analysis

Using the DSAS extension, statistics for the historic change of the vegetation and shorelines were made. Essentially, DSAS allows users to take dated polyline features, and from a user-determined baseline, it casts transects at a user-determined interval to then calculate statistics for the changes.

For this analysis, an onshore baseline was made by creating a buffer around all shoreline data and extracting only the onshore side of the buffer. This method, and others, are expanded upon in the DSAS handbook (Thieler et al. 2017). Transects are spaced one meter apart from each other to be as precise as possible for local use. The extension also allows the user to add an uncertainty value to the dataset. The uncertainty value is entirely up to the user and can either be a single value applied to all features, or individually assigned in cases for which uncertainty in the data varies. This ultimately allows the program to create statistics that give weight to the more accurate data.

The uncertainty values used in this study can be found in the metadata in Appendix A and were chosen based on the scale at which the feature was mapped. The mapping scale varied depending on resolution of the images, so it is considered to be a representative value of the mapping uncertainty for this study.

The chosen statistical analyses for detecting historic changes along the coast include end point rate (EPR) and weighted linear regression (WLR). EPR is a statistic that uses only the oldest and most recent year, in this case, 1947 and 2017. It then calculates the average movement of the specified feature along each transect per year by dividing the net shoreline movement (NSM) by the years passed. WLR is used when more than two years are being compared. It compares the individual linear features to the baseline to determine the linear regression equation, or the approximate rate of change, between all years at each transect. It also considers the uncertainty value for each feature, giving greater weight to features with higher certainty (Thieler et al. 2017).

2.6.3 Classifying the changes

The SGU classification of the Scanian coast described above uses a buffer of ±15 meters to make up for any uncertainty in the historical data. The same classification system is used in this study both to provide consistency in the classification of the DSAS results as well as to compare the results of this localized study to SGU’s regional study. This classification is seen both in Figure 1, and the table below.

Table 1 Swedish Geological Survey erosion and accumulation classification

Class	Change	Net movement
1	Accumulation (growth)	+ 15–30 meters
2	Accumulation (growth)	+ 30–60 meters
3	Accumulation (growth)	+ 60–250 meters
4	Erosion (recession)	-15 – -30 meters
5	Erosion (recession)	-30 – -60 meters
6	Erosion (recession)	-60 – -250 meters
7	No change	-15m − +15 meters

(SGU 2018)

Additionally, transect values were categorized as positive or negative in order to determine the percentage of transects experiencing accumulation or erosion during the period. The change in area, that is the total area loss or gain in land cover, was calculated for the area in between the shore and vegetation lines respectively between 1947 and 2017. This was done by creating a new polygon feature class from the shore and vegetation lines respectively. Using the calculate geometry function, area was calculated for each feature, and then adjusted to the correct sign based on direction of movement during the period. These values were then summed to determine the total area loss or gain.

2.6.4 Shoreline comparison

A comparison of the changes between the 1960-1973 and 2010-2017 vegetation line and shoreline EPR was made in order to estimate the difference in rate of change between a period with recurring storms (2010-2017) to a period with less frequent storms (1960-1973). A linear regression rate-of-change (LRR) was conducted for 2010-2017 to further assess the shoreline change during this period. LRR is similar to the WLR but does not take into account uncertainty in the data so it is used when mapping certainty is the same across the data. One limiting factor to the linear regression method is that it is susceptible to outlier effects and may underestimate the rate of change compared to EPR (Dolan, and others, 1991; Genz and others, 2007 in Thieler et al. 2017). The change in shore and vegetation area between 1960 and 1973, as well as 2010-2017 was calculated using the same method as described above.

2.7 Estimating coastal changes due to frequent storms

2.7.1 Preparing the raster data

DEM data was used to estimate the changes on Vejbystrand during a period of frequent storms between 2010 and 2017. DEM data from both 2010 and 2017 were used. Though the DEM data used had the same grid cell size (0.25m by 0.25m) and coordinate system (Sweref 99 13 30), these grids were not perfectly aligned. In order to accurately compare these rasters, the grids needed to be aligned. This was done by clipping the 2010 raster to the same processing extent as the 2017 raster. In order to limit the potential errors in the DEM, a polygon feature from the 2017 shoreline to ten meters inland of the 2017 vegetation line was created using the buffer tool. This polygon was then used to extract the desired extent of the raster.

2.7.2 Change in elevation and protective dune height

The 2017 DEM was subtracted from the 2010 DEM to determine difference in ground elevation between the years. This difference raster was divided into two classes, one of accumulation values (less than 0 m), and one of erosion values (greater than 0 m). To examine changes in the protective dune height, elevation data greater than or equal to 3.5 meters was extracted for both years using the Select by Attributes spatial analyst function. A difference raster was also created using the raster calculator to determine the change is protective dune height.

2.7.3 Estimating change in volume

Volume analysis of this data was first attempted using Cut fill, a function in the spatial analyst tool for ArcMap recommended in a tutorial by the National Oceanic and Atmospheric Administration (NOAA 2012). This function determines net volume loss, gain, and areas of no change. However, as this function did not describe the percentage of volume change, the Zonal Statistics Table function in ArcMap was used. The individual heights from the 2010 and 2017 DEMs were summed, for which the resulting value was multiplied by the area of each grid (0.25m x 0.25m) to calculate the total difference in volume. The same was done for protective dune height. Percent change was then calculated in order to provide perspective to the changes.

3 Results

3.1 Parameters impacting erosion in Ängelholm and municipal efforts

Appendix B shows that there are both natural and anthropogenic parameters affecting erosion along the municipality's coast. The main factors affecting coastal erosion on sandy beaches include sand grain size, sea levels, ocean currents, waves and wind exposure, terrain conditions, and human constructions. Anthropogenic factors influencing erosion include: low-lying, lacking, or damaged vegetation; built-up areas; tourism; movement of deposited sand; seaweed and beach vegetation clearing; as well as protective barriers. These factors can be seen as short-term, climate change adaptation issues that may be more immediately addressed. Natural factors include: aeolian sand transport; temporary elevated sea levels; high waves during storms; and parallel sand transport. From the perspective of the municipality, these issues may be considered long-term climate change mitigation issues that need to be dealt with at a larger scale than just the municipal level. This issue of adaptation vs mitigation, or short vs long term, will be a critical consideration as the municipality continues to address coastal erosion. As these parameters influence one another, it is recommended that they be addressed collectively. The erosion taking place on the coast is part of a regional system of factors, so any changes or alterations made to the natural systems in place may impact another part of the system, though it is uncertain how much of an effect they have on one another. As to not place the municipality in a compromised situation in the future, it is important to gain a systemic understanding of this changing ecosystem and continue to use and expand upon GIS and remote sensing data to be able to understand and estimate the changes taking place. Appendix C lists potential erosion protection measures and evaluates the pros and cons. These measures are also expanded upon in the discussion section below.

3.2 Delineation of coastal features

3.2.1 Vegetation and Shorelines

Figure 5 shows the difference that enhancing image properties can make using the 1947 orthophoto as an example. The beach face becomes clearer and the transition between vegetation and sand, as well as between sand and sea is slightly sharper.

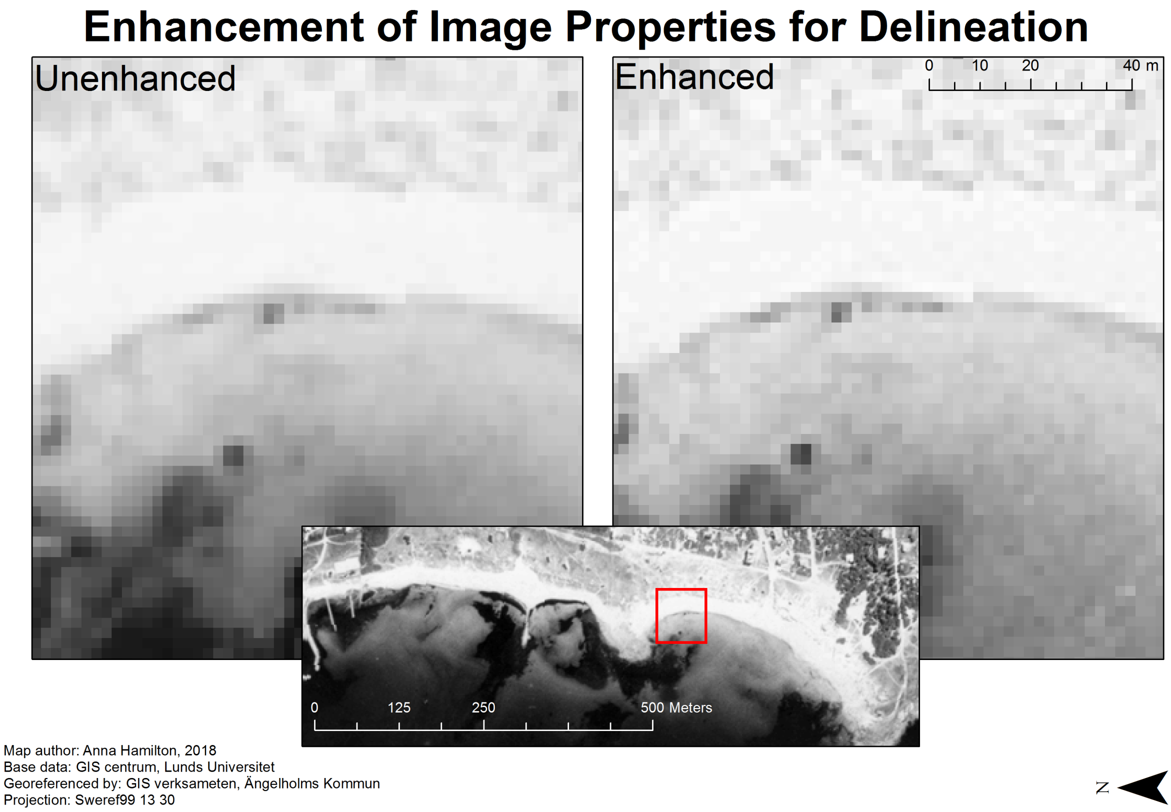

Figure 5 Enhancement of image properties for delineation of historic orthophoto

A zoomed in image of all vegetation and shorelines overlain the 1943 orthophoto is seen below in Figure 6 to give an overview of the delineation process.

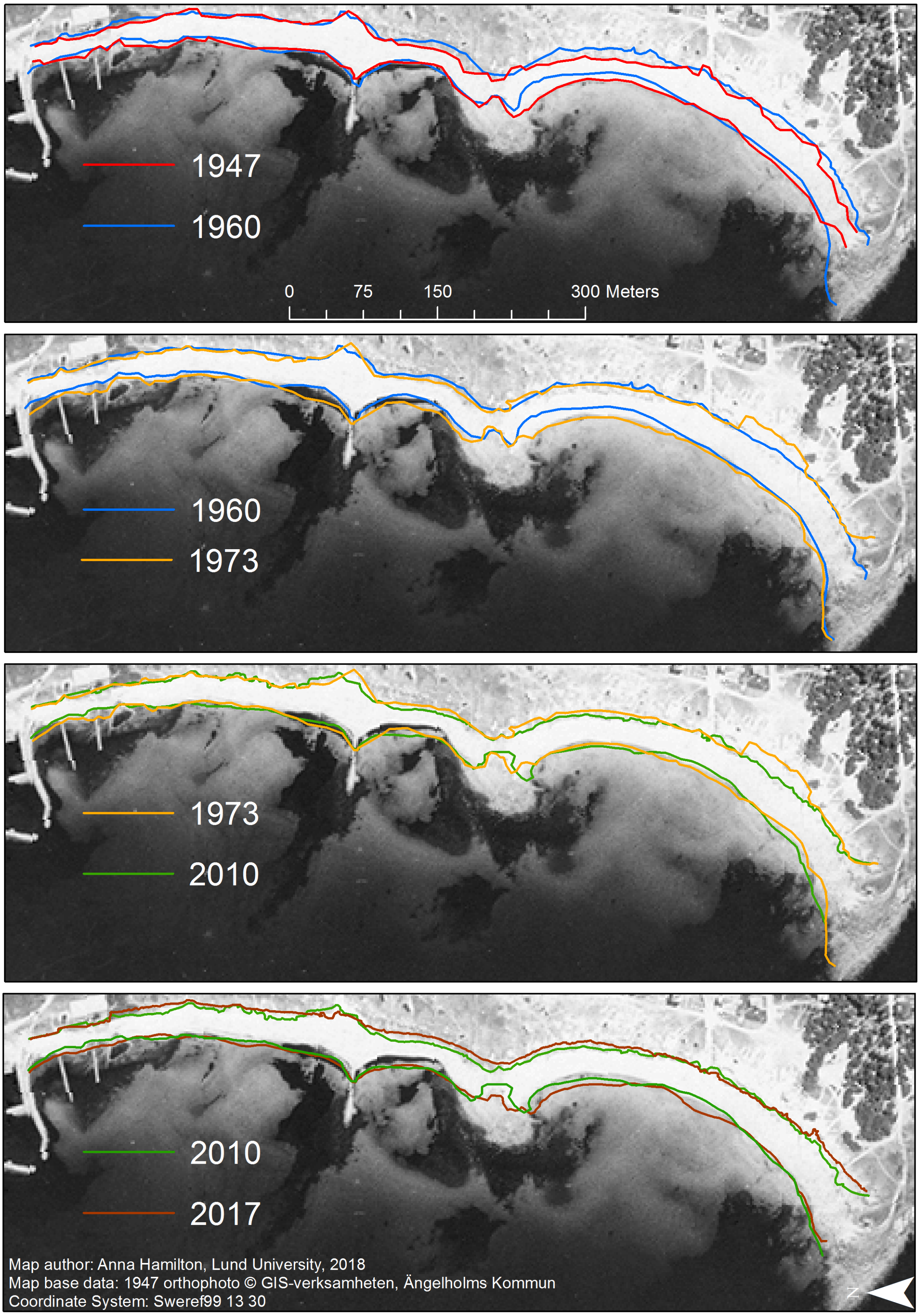

Figure 6 The coastal delineation process on Vejbystrand from 1947-2017

Difficulties in the process were largely avoided by the field visit. Nonetheless, certain features were difficult to differentiate in the older orthophotos. An example of a difficulty in determining the vegetation line for 1973 is seen in Figure 7 below. The delineation was confirmed by examining other historic photos (provided through personal contact with Vejbystrand local, Eva Thulin on May 9, 2018) of the beach which showed that the vegetation line did in fact move back during this period and was later restored with vegetation planting.

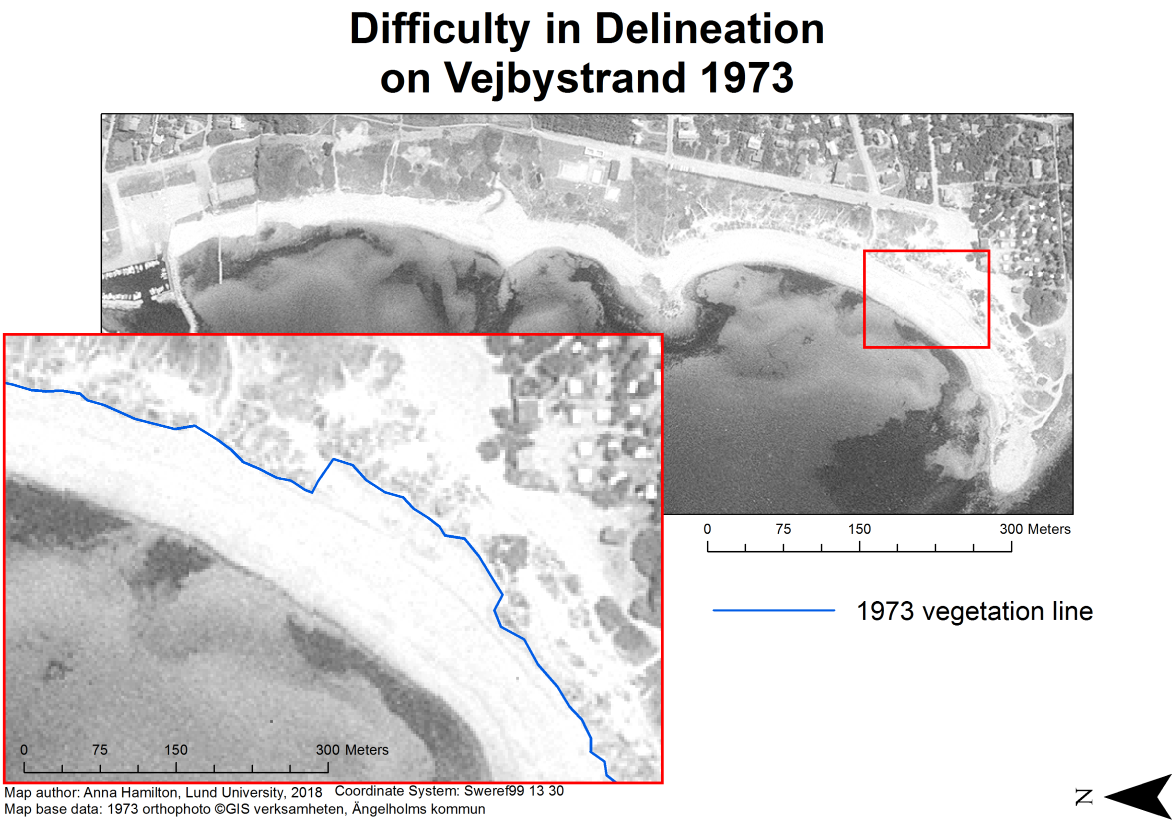

Figure 7 Difficulty in the process of delineating coastal features for 1973

3.2.2 Dune toe line

The slope and profile curvature were extracted from the 2010 and 2017 DEM and used to delineate the dune toe line. A comparison of slope and profile curvature for 2017 is seen in Figure 8. More detailed results in Appendix D show that slopes have become steeper since 2010, indicating a degradation of the dune face due to erosion.

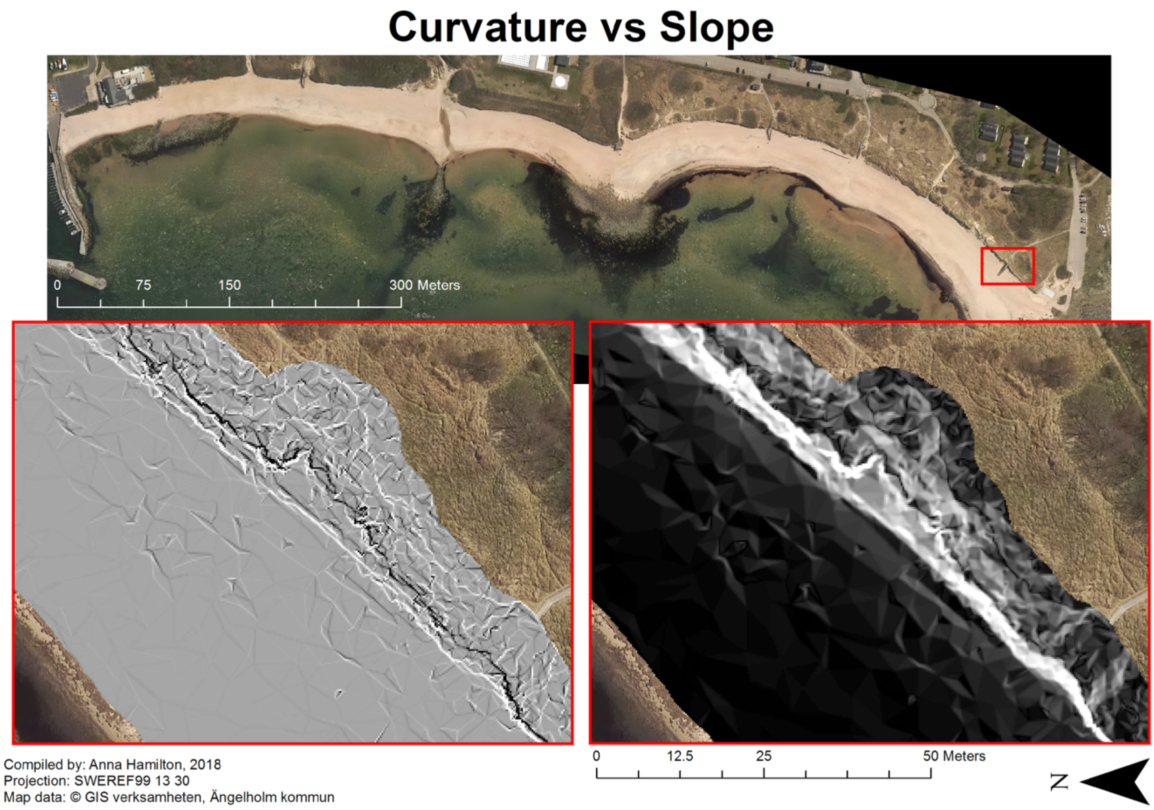

Figure 8 Profile curvature and slope comparison on Vejbystrand for 2017

3.3 Detecting past and recent changes to the coast

3.3.1 Storm data

Wind data from the known storms during between 1947 and 2017 were extracted from two SMHI stations in order to highlight the geographical differences in wind data, but also to show the prevalence of storms in recent years. Storm date, as well as wind speed and direction at one or both weather stations is provided below depending on available data. Additionally, sea level from a third station, Viken, was compiled for available years.

There were three storms between 1960 and 1973. Between 2010 and 2017, there were six storm events. The average wind speed varies between the land-based station (17.1 m/s) and coastal station (24.3 m/s). The Barkåkra station experienced winds predominantly from the WNW while Hallands Väderö experienced winds predominantly from both WSW and WNW, averaging to a westerly wind. The average sea level at Viken during the storms was just over 110 cm, which is considered class one according to the SMHI scale where class two includes sea levels above 120 cm.

Table 2 Storm wind speed and direction at weather stations close to Vejbystrand between 1947 and 2017

Proximate storm dates	**Wind speed (m/s) & Direction Hallands Väderö**	**Wind speed (m/s) & Direction Barkåkra**	**Sea Level (cm) Viken (RH 2000)**
April 26, 1947	No data available	18.5, WSW	No data available
September 18, 1948	No data available	18.5, WNW	No data available
October 22, 1948	No data available	18.5, WNW	No data available
November 9-10, 1948	No data available	15, WNW	No data available
September 16, 1950	No data available	11.5, WNW	No data available
November 25, 1951	No data available	14, W	No data available
December 1, 1951	No data available	15, W	No data available
Januari 15, 1952	No data available	13.5, WSW	No data available
February 21, 1953	No data available	19, WNW	No data available
November 12, 1954	No data available	12.5, WSW	No data available
December 13, 1964	19, WSW	17.5, WSW	No data available
October 17-18, 1967	No data available	24, WNW	No data available
September 22, 1969	No data available	21, WNW	No data available
November 231973	No data available	18, WNW	No data available
Januari 5-6, 1975	No data available	16, WNW	No data available
January 5, 1976	No data available	21, NNW	No data available
September 6, 1977	No data available	10, SSW	42.2
April 18-19, 1980	No data available	22, NNW	95.2
October 8, 1981	No data available	14, W	66.2
December 19, 1982	No data available	11, SSE	33.2
October 19, 1983	No data available	14, WSW	45.2
November 6, 1985	No data available	18, W	167.2
December 3-4, 1999	23.6, SSW	24, WNW	106.2
January 8, 2005	28.1, WSW	No data available	128.8
January 14, 2007	24.7, WNW	No data available	98.8
August 4, 2008	24.3, WNW	24, WNW	81.3
November 27, 2011	18.9, WSW	21, WNW	165.5
October 28, 2013	28.3, WSW	22, WNW	105.1
December 5-7, 2013	27.1, WNW	24, WNW	174.9
January 10-11, 2015	24, WSW	18, WNW	146.5
November 29, 2015	27.9, WNW	22, WNW	150.5
December 27-28, 2016	21.8, WNW	19, WSW	159.4
AVERAGE	**24.3, W**	**17.1, WNW**	**110.4**

(SMHI 2018b, a, d)

3.3.2 Vegetation and shoreline evolution

Below are the results from the EPR statistical analysis for the 1947 to 2017 vegetation and shorelines. The net shoreline movement is depicted by the length of the transect (also seen as the value next to the EPR legend in parenthesis) while the rate of change, or EPR, is depicted by the color differences. There has been an accumulation at the vegetation line since 1947, and 83% of total transects have negative values (inland movement). The highest area of erosion is seen at the south end of the beach near the parking lot. Total area loss for the vegetation line during this period is -4483 m^2.

An opposite trend is seen with the shoreline. The majority of transects (87%) were positive, indicating a seaward movement of the shoreline. Total area gain is 5783 m^2.

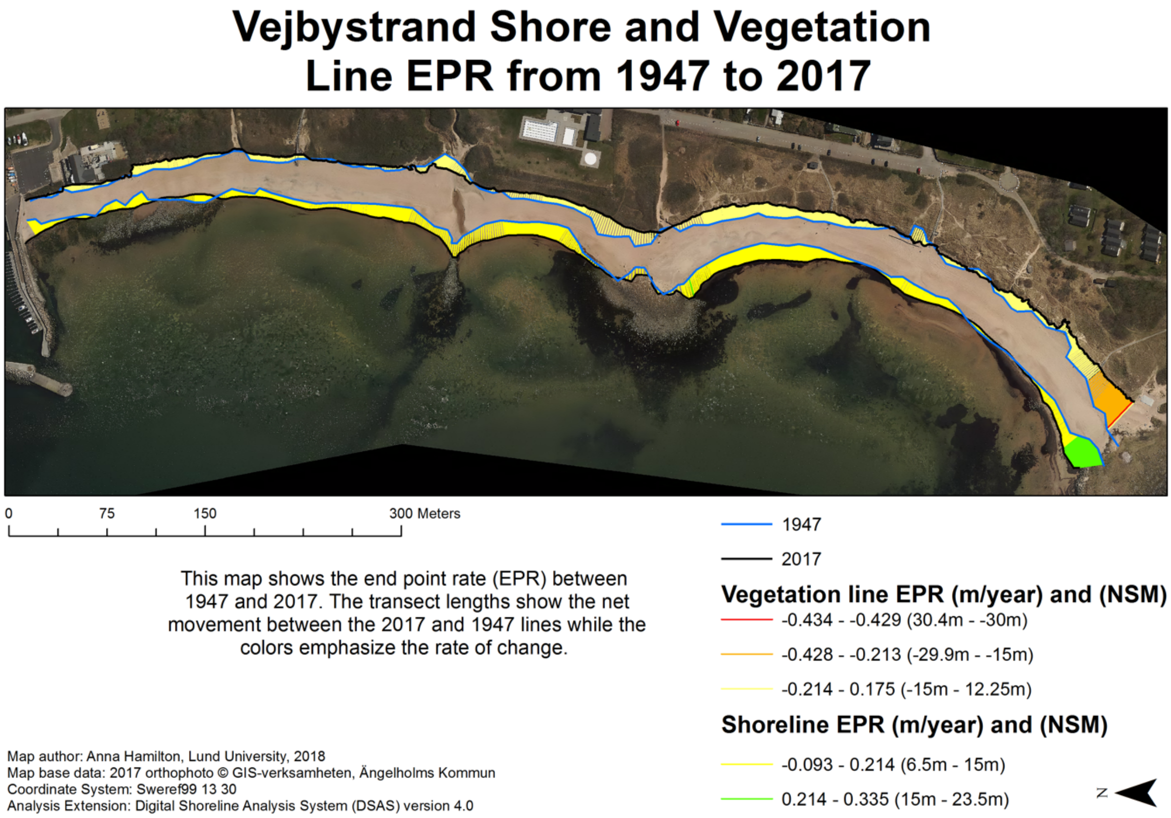

Figure 9 Vegetation and shoreline end point rate 1947-2017

To further confirm these results, a weighted linear regression (WLR) of the data was made. Figure 10 shows the WLR results for all shore and vegetation lines. The color represents the calculated rate of change and the length of the transect represents the greatest fluctuation between the features during the time span. Results differed slightly from the EPR, as 64% of the transect values were negative, indicating only a slight inland movement of the vegetation line. 95% of the total shoreline transects were positive, giving greater emphasis to accumulation of the shoreline than the EPR.

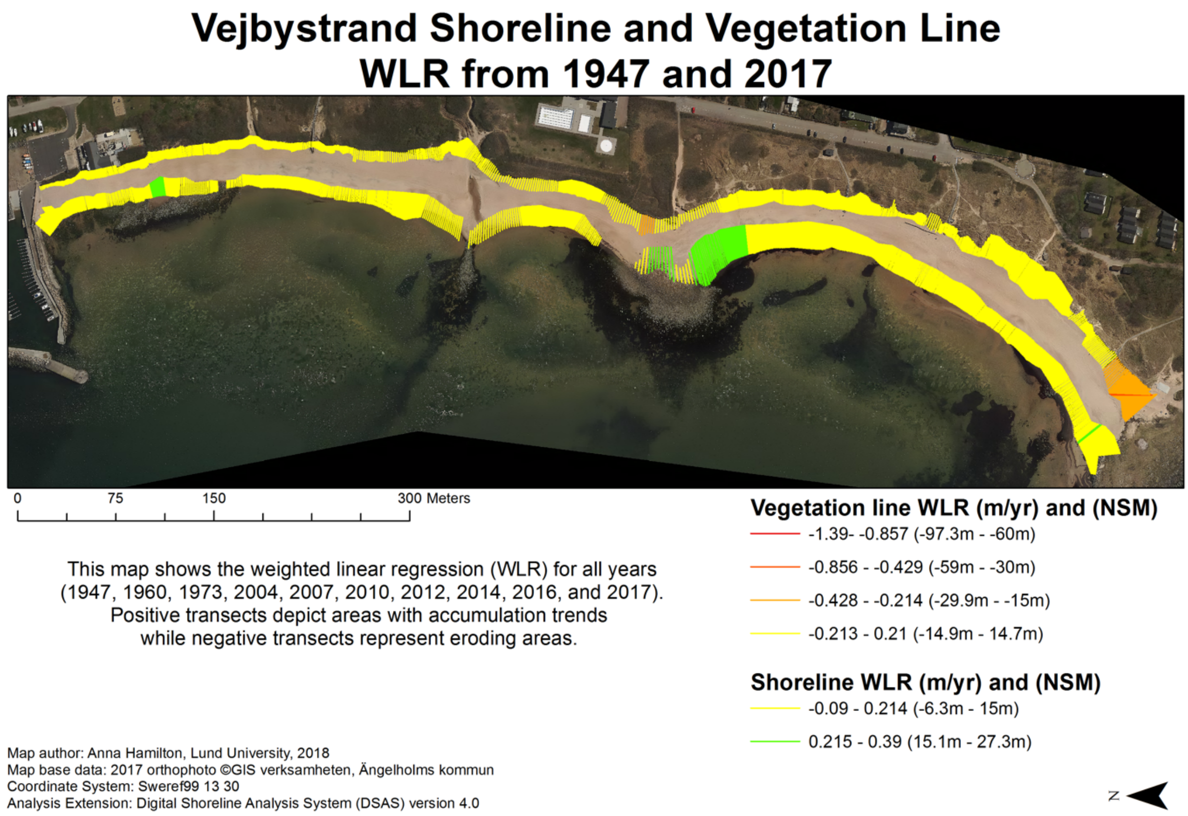

Figure 10 Shore and vegetation line weighted linear regression for 1947-2017

3.3.3 Shoreline Comparison

The EPR statistic was used to compare the movement of the vegetation and shoreline for the periods between 1960 to 1973 and 2010 to 2017 seen in Figure 11a and 11b. In some cases, the period between 2010 and 2017 experienced three times as much accumulation as between 1960-1973. Between 1960 and 1973, 96% of total shoreline transects have a positive value while 61% of vegetation values are negative, indicating an expansion of the beach mainly due to accumulation at the shoreline. Between 2010 and 2017, 66% of shoreline transects experienced accumulation and 72% of vegetation line transects eroded, indicating an expansion of the beach mainly due to erosion of the dunes. All area changes for the vegetation, shore, and dune toe (when applicable) lines for these periods, as well as the entire study period, can be found in Table 3.

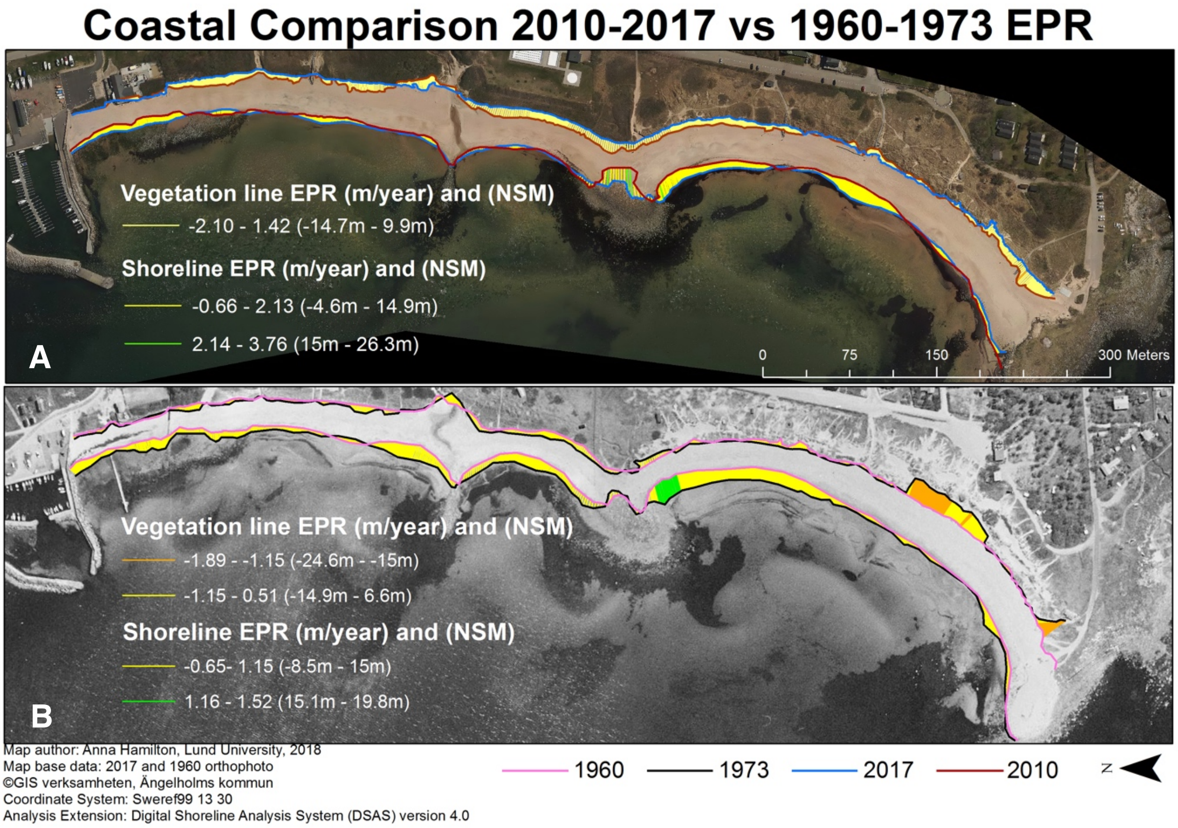

Figure 11 a: Vegetation and Shoreline end point rate for 2010-2017 and b: 1960-1973

Using the DSAS tool, a linear regression rate-of-change was calculated for the storm period years including 2010, 2012, 2014, 2016, and 2017 seen in Figure 12. Results were similar to that of the EPR, with 69% of vegetation line transects eroding and 68% of shoreline transects accumulating sand.

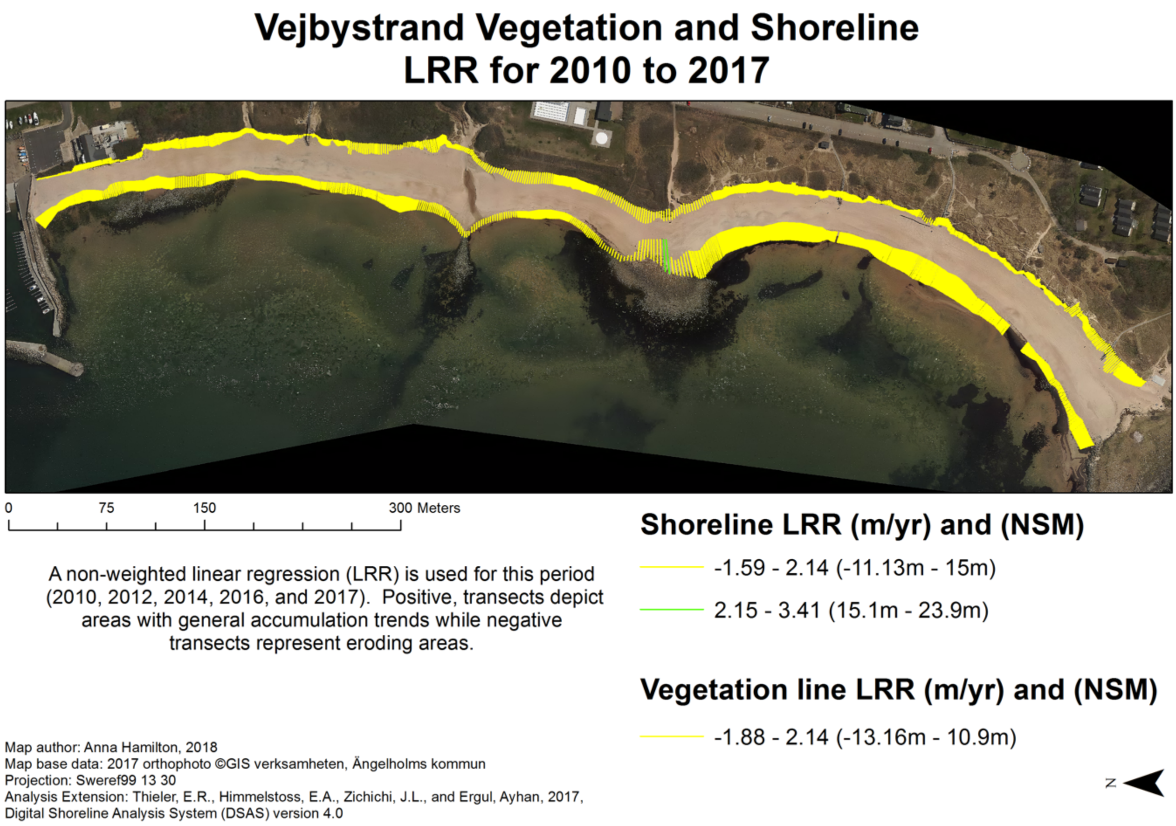

Figure 12 Vegetation and Shoreline linear regression rate of change for 2010-2017

Table 3 Area change of Vejbystrand coastal features during different time periods

Period	Vegetation area change (m^2)	Shore area change (m^2)	Dune toe area change (m^2)
1947-2017	-4483	5783	x
1960-1973	-396	5413	x
2010-2017	-3086	2373	-4110

3.3.4 Dune toe line evolution

The dune toe line EPR is seen in Figure 13. A similar range of movement is seen in the corresponding vegetation line movement from Figure 11a. The dune toe line does, however, extend into a classification for notable levels of erosion according to the SGU classification system which the corresponding vegetation line does not.

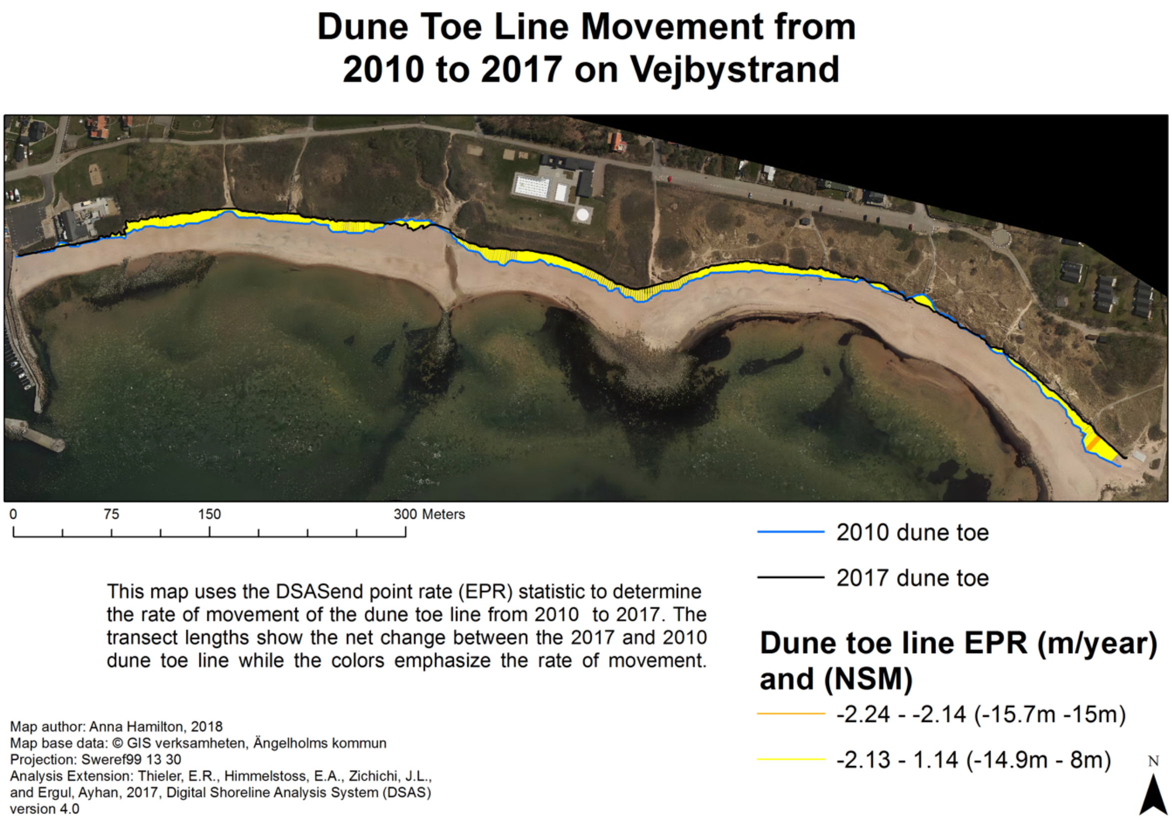

Figure 13 Dune toe line end point rate for 2010 to 2017

3.4 Estimating coastal changes due to frequent storms

3.4.1 Change in elevation

Figure 14 shows the difference in elevation and protective dune height between 2010 and 2017. Positive values therefore indicate erosion while negative values indicate accumulation. It is apparent that areas of high loss (red) are along the dune toe and vegetation line and that areas of high gain (dark green) are more spread out along the beach face and along the vegetation line. The change in the protective dune height is also seen and correlates directly with the change in height. Orange and red areas are where the protective dune height has decreased while green areas are where it has increased. Much of the protective dunes remain unchanged, though the most prominent areas of accumulation and erosion are in the south end of the beach.

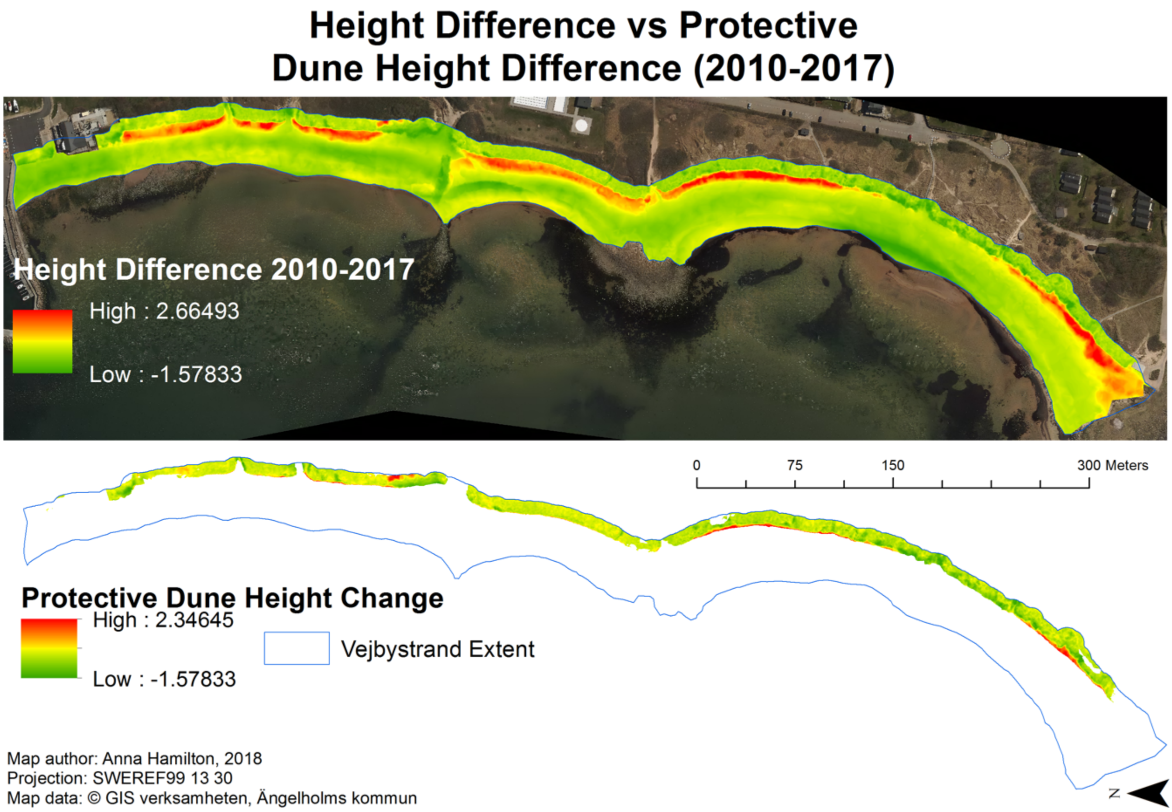

Figure 14 Vejbystrand elevation and protective dune elevation difference between 2010 and 2017

3.4.2 Change in volume

Change in volume was initially calculated using the spatial analyst Cut fill tool in ArcMap, and these results are found in Figure 15. This method only provides a classified, rather than graduated, overview of net gain and loss. Additionally, this method gives no indication of the percent change in volume between years.

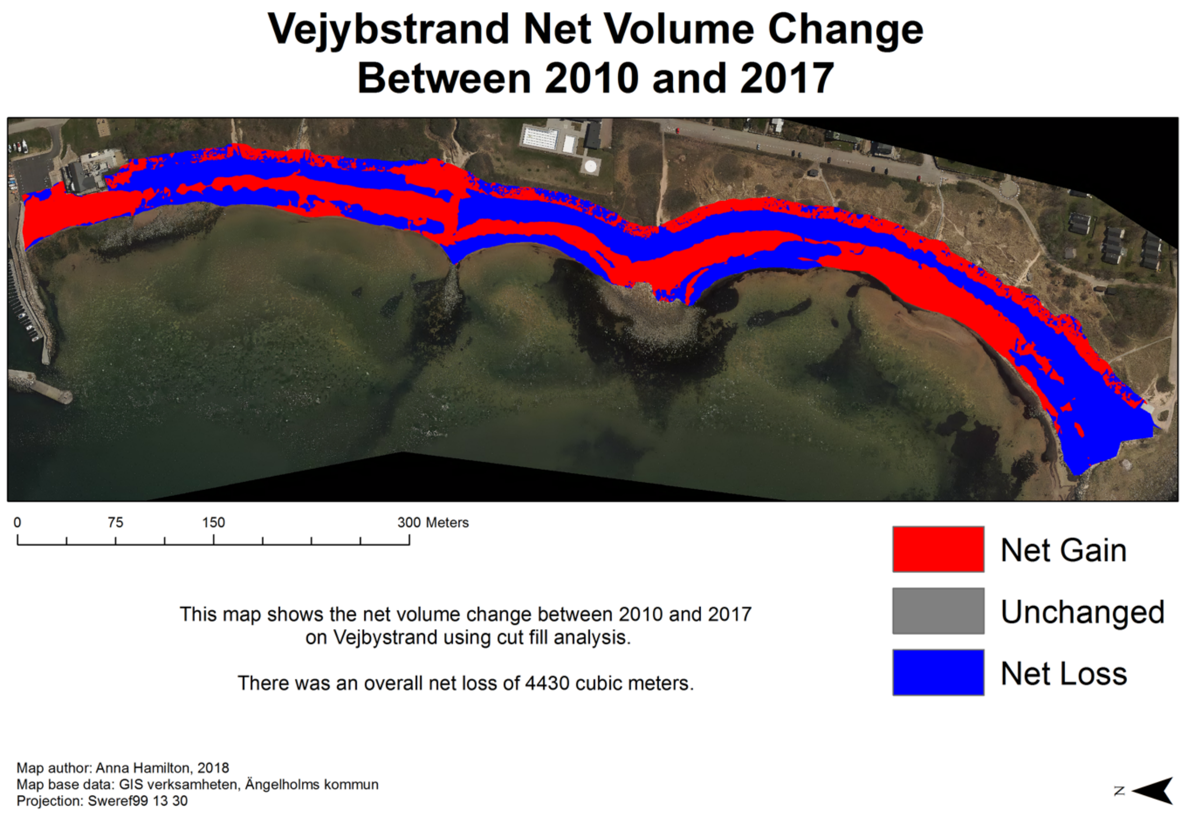

Figure 15 Net volume change between 2010 and 2017 on Vejbystrand

The total volume change of Vejbystrand, as well at the protective dune volume between 2010 and 2017 calculated using the Zonal Statistics Tool are seen in the table below:

Table 4 Vejbystrand volume change between 2010 and 2017

	2010	2017	Difference	% change
Total beach volume (m^3)	94254	89835	-4419	-4.9%
Total protective dune volume (m^3)	48618	39683	-8935	-18.4%

4 Discussion

4.1 Assessment of implemented erosion protection measures

Appendix B and C provide short descriptions of each of the parameters along with an analysis of their prominence, recommendations for update cycle, potential and attempted solutions, as well as relevant literature references. Some of the interesting findings include that jetties, which have been implemented as a protection measure against erosion, may lead to erosion along other parts of the beach and even decrease water quality by the build-up up sediment. Beach nourishment projects which have also been largely implemented along the coast should not only consider practical issues such as sand grain size and vegetation planting to bind the new sand, but also the potential impacts on local flora and fauna. A species historically planted along the Scanian coast was the *Rosa rugosa*, a non-native beach rose, which can decrease biodiversity as it is an invasive species to the area. Conversely, this plant is extremely efficient in binding the sand on dunes.

4.2 Delineation of coastal features

Difficulties in the process of delineation arose in the historic orthophotos from 1947, 1960, and 1973. These are notably lower quality; so, mapping scale must be smaller in order to accommodate the difference in resolution. These images are also in black and white while the post-2000 images are all in color. Enhancing image properties helped in the delineation process, as seen in Figure 5, but there is nonetheless a greater uncertainty in the mapping of the historic coastal features.

Further limitations exist in the mapping of the coastal features. The shoreline, for instance, is something that varies with the tide. Tide is not accounted for in this study as the normal tidal variation along Sweden's west coast is usually below twenty-five centimeters (SMHI 2013a). Other studies have utilized the mean high-water line (MHWL) in order to delineate the coastline. To calculate this, high-quality imagery is required which is not the case for older orthophotos used in this study, and even so, some tidal error will still persist (Fisher and Overton 1994). Lack of near infrared (NIR) data limits the delineation of both the shoreline and vegetation line. NIR data could be used to even better distinguish vegetation from sand, and sand from water along the coast (Masria et al. 2015). Investing in NIR data is of interest for future studies that may use it to identify and distinguish between different species along the coast. The *Rosa rugosa,* for instance, could be better managed along the coast by tracking its development.

Slope and profile curvature were primarily used to delineate the dune toe line, however, comparing the two slope profiles it is apparent that the 2017 profile is defined by more steep slopes than in 2010 (see Appendix D1 and D2). Erosion has likely blunted the dune face during this period, leading to steeper slopes. Looking into slope as well as profile curvature of the coastal dunes in the future could provide data as to where the dunes are most impacted during storms and flooding by providing information on relative speed and direction of water flow on the beach.

4.3 Past and recent changes to the coast

4.3.1 Storm Data

The differences between the station data are mostly due to the differences between coastal and land-based stations which is due to the impact of the landscape on wind speed and direction. Differences may also be due to the spatial distance between the stations. Wind data and sea level data had to be taken from three different stations (Barkåkra, Hallands Väderö, and Viken) which limits the accuracy of the data, but at the same time highlights the differences between different stations. Data is missing from the Barkåkra station between 2003 and 2007 when the station blew down. This means that some storm data, for instance during storms Per and Gudrun, is not taken into account. Hallands Väderö and Viken do not cover the entire study period and are also further away from the study area.

From this data it is evident that there were more frequent storms than normal, however, it is not evident that this period is abnormal in comparison to similar periods of recurring storms, for instance between the late 1940's and early 1960's. Today, the highest sea level experienced at Viken is around 175 cm, whereas by 2100 the highest sea levels may hover just under 300 cm based on climate scenario RCP8.5 (SMHI 2018c). Such a change can be expected to drastically affect the coast. Exploring how the coast reacts to periods of recurring storms is crucial for understanding how the coast may change as climate changes and storm frequency increases.

4.3.2 Long-term vegetation and shoreline trends

There has been a slow inland movement of the vegetation line and seaward movement of the shoreline, indicating a widening of the beach between 1947 and 2017. This is seen in both the vegetation and shoreline EPR and WLR statistics (Figures 9 and 10). The number of transects showing accumulation of the shoreline and erosion of the vegetation line are almost equal, however, 1,300 m^2 more sand area has accumulated at the shoreline than has eroded away at the vegetation line. This poses the question as to where this sand came from. It is likely that the collapse of the sand forming the dune underneath the vegetation line during high winds has spread out across the beach face and shoreline. Other factors that may influence this difference include mapping errors as well as the possibility that the beach is accumulating sand from the nearby coastal system.

Erosion of the vegetation line and accumulation of the shoreline are both concentrated at the south end of the beach, indicating that in the long-term, the southern region of Vejbystrand is most susceptible to coastal erosion. This is unlike the long-term trend on Ängelholm beach which is most susceptible in the north due to parallel sand transport of fine grain sand from the north to the south. Vejbystrand also has finer sand grain particles in the south but did not experience this same trend. This may be due to the geomorphology of the shoreline which has two prominent rock depositions in the middle of the beach. These may act as barriers, preventing sand from eroding from the northern part of the beach. In this case, accumulation would be expected in the north, however, accumulation in the north is minimal. It is possible that these rock depositions just balance the effects of parallel sand transport that would otherwise erode the northern end of the beach.

A parking lot established in the south end of Vejbystrand sometime in between when the 1960 and 1975 aerial images were taken may also be a contributing factor. Increased traffic may have contributed to degradation of both the dunes and the vegetation as people trampled over them. The water drainage pipe in the middle of the beach implemented after the 1947 aerial photo does not seem to further contribute to erosion of this part of the beach.

There are clearly long-term erosion trends not indicated by the SGU study that were found in this study using the same classification. This is likely due to the larger mapping scale used which allows for finer detail in this analysis. Recent storms may skew these results, and it is recommended that future studies consider the degree to which recent storms skew the long-term trend. From this analysis, it is difficult to say whether the long-term erosion on Vejbystrand is acute or chronic. To accurately study this, an analysis of the nearby seabed and bathymetry is needed.

4.3.3 Shoreline Comparison

It is apparent by simply looking at the base data in Figure 11b that the south end of the 1960 shoreline extends further westward than today's shoreline in Figure 11a. The vegetation line between 1960 and 1973 was seen to accumulate, which is opposite both the long-term trend (1947-2017), and the recent trend between 2010 and 2017 seen in Figure 11a. The small area towards the south of the beach for which the 1973 vegetation line is a notably further inland than the rest of the vegetation line (seen in Figure 7). The difference between total shoreline accumulation and vegetation line erosion is +5017 m^2. The loss of vegetation area is most concentrated in this patch of lost vegetation described above, so the main difference is due to movement of the shoreline. This seaward movement indicates that the beach was able to recover from the three notable storms that took place during this period.

Similar to the period between 1960 and 1973, between 2010 and 2017 there is also an expansion of the beach. As seen in both the EPR (Figure 11a) and LRR (Figure 12), the expansion during the most recent period is due to both accumulation at the shoreline and erosion of the vegetation line. This is unlike between 1960 and 1973 for which shoreline accumulation was the major source of expansion. Erosion of the vegetation line and accumulation of the shoreline between 2010-2017 is also most prominent at the south end of the shoreline, with some sections accumulating as much as 26 meters. Total area difference between shoreline accumulation and vegetation line erosion is -713 m^2. This is the only period studied that experienced such a trend. Reason for this is best explained by the dunes being constantly undermined during the recurring storms. Though it cannot be said whether sand has permanently left the coastal system, it can be said that acute erosion for which the beach has not yet recovered from has taken place.

4.3.4 Dune toe line vs vegetation line as erosion measures

The vegetation line and dune toe line experienced similar trends in both the EPR analysis as and total area difference, showing that they are potentially interchangeable when studying erosion of the dune-side of the beach in historic images that do not have available LiDAR data. The vegetation line provides a good indication of where the top of the dune begins, and therefore follows a similar trend to the dune toe line. Mapping the vegetation line is also simpler than mapping the dune toe line as it requires less data extraction. The data used to delineate the dune toe line, specifically the profile curvature, is interesting for future studies which could assess the dispersal of water on the beach during, for example, floods (ESRI 2016a).

4.4 Coastal changes due to frequent storms

4.4.1 Preparing the raster data

Preparing the initial data required additional processing in order to align the rasters. Reason for the grids not matching is likely due to the different number of data points in the initial LiDAR data. According to the metadata provided by the municipality (also seen in Appendix A) there were 0-1 data points per grid and 1-3 per square meter in 2010. In 2017, there was at least one data point per grid and sixteen per square meter. This may have influenced the output interpolated DEM grid, causing the mismatch. Such errors in DEM data are important to consider prior to calculating changes between two or more rasters.

4.4.2 Evaluating the change in elevation and protective dune height

During the recurring storm period between 2010 and 2017, the difference in elevation shows there have been more areas of acute erosion of the dunes than intense accumulation. As seen in Figure 14, a stretch along the dunes has eroded. Exceptions to this include the accumulation of sand north of the restaurant, by the drainage system, as well as a stretch in the south. The eroded areas may be vulnerable due to heavy traffic and walkways that have not only degraded the natural protective barrier, but also hindered the recovery process after storms. The type of vegetation along the dunes may also be playing a role. *Rosa rugosa* which is known both for stabilizing the sand and being an invasive species to the area (CABI 2018), may be protecting areas that have accumulated sand. This is supported by the Master's thesis discussed above by Janna Lindell (2017) who found that removal of the *Rosa rugosa* on Ängelholm beach negatively impacted the dune morphology. On Vejbystrand, however, this would need to be further explored in a study distinguishing between vegetation species along the beach. The heavy impact on the southernmost region of the beach may be due to the prevailing wind direction during the recurring storms. Areas of accumulation along the shoreline could indicate that sand remaining in the system has begun to recover itself onto the beach face. A study of the seabed would have to be made in order to confirm this.

4.4.3 Evaluating the change in volume

The Cut fill analysis in Figure 15 clearly shows where areas of loss and gain have occurred but does not provide a graduated symbology which would visualize the most and least affected regions of the beach. It also does not provide the percentage change. Therefore, the Zonal Statistics function in ArcMap was used determine the before and after volumes, as well as percentage of sand lost. This, however, still does not indicate the most and least vulnerable areas of the beach. These two methods produced a similar difference in volume between 2010 and 2017, with only 10 m^3 difference which can be attributed to a slight difference in rounding indicating that both methods are viable for determining volume difference. The Zonal Statistics method better contextualizes the data while the cut fill analysis provides some visualization.

The -5% loss of sand volume during the storm period indicates that the sand has not yet recovered but does not indicate whether the sand has left the system or not. Figures 14 and 15 shows that loss of sand volume is spread across the dunes. If recurring storms persist, the substantial loss in volume of the protective dunes (-18%) will likely have significant implications for the ability of the beach to defend the coast from flooding and high winds speeds.

4.5 Further limitations

Some limitations were discussed in the preceding section, but still some persist. Besides the issue with difference in image quality, it is difficult to define the class system for visualizing the EPR, LRR, and WLR. Using the SGU system is reliable for the historical period between 1947 and 2017 because there is variation in the data quality and the coast can be expected to be in relative balance over longer time spans. However, for classifying shorter time spans, it is a less reliable classification system as fluctuations are expected to occur in the short term. In Figure 12 for instance, the vegetation line is shown to not have changed when using this classification because the net movement did not fluctuate more than ±15 meters. The SGU system is used in this study regardless of timespan in order to directly compare the long-term changes to those in the short term.

The orthophotos used only provide a snapshot of the coastal features on Vejbystrand. It is important to note that coastal features are dynamic in nature and this is not able to be accounted for in the measurements. To test the hypothesis and compare the most recent period to a period with less storms, 1960-1973 was chosen. Ideally a more similar timespan with few storms would be compared (i.e. in the 1990's). Limitations also exist with the available wind and sea level data discussed above.

4.6 Future studies

Future studies may expand upon this study and implement the suggested and applied methods to longer stretches of the municipality's coast. Further comparisons between each year would be interesting for an even more in-depth comparison. The recent storm period could also be compared to a similar period of recurring storms, such as during the late 1940's to early 1960's. NIR data could be used to more accurately discern between coastal features such as sand and vegetation, as well as classify the different species. Slope and curvature data extracted from the DEM may be further analyzed to determine the flow of water on the beach. To better distinguish the movement of sand and determine whether the beach is experiencing acute or chronic erosion, future studies may utilize bathymetric data. To better indicate where sand volumes are moving on the beach, it would be useful to section off the beach and calculate volume differences for each section as done in a study by Lindell (Lindell 2017).

Based on the literature review in Appendix B and C, the municipality could further examine the effects of implemented measures against erosion. For instance, the municipality installed sand fences along the south of Vejbystrand in 2017. Only one fence is seen in the 2017 aerial photo, the others were implemented later in the year. Future studies may look into the effectiveness of sand fences in the southern region of Vejbystrand. Another suggestion for studying the implemented measures against erosion is to study the impact of beach nourishment projects on the local flora and fauna.

As climate continues to change, so might the effectiveness of these measures, so it is important to study the efficiency of implemented solutions. In general, the municipality should strive to maintain up-to-date data along the coastline in order to study and prepare for the impacts of climate change by collecting both LiDAR and aerial imagery at least every other year.

5 Conclusion

Coastal erosion parameters impacting the municipality are both natural and anthropogenic in nature. Adaptation measures such as beach nourishment, sand fences, and vegetation planting are favorable methods as they are less intrusive. These measures, however, often have a slower, less intense effect than harder implementation measures such as stone piers and jetties. This may be either positive or negative depending on the level of erosion present and severity of any unintended consequences of the implementation measure.

The hypothesis that recent changes to Vejbystrand are related to frequent storms can be accepted, and unlike the results from the SGU study (SGU 2018) which deemed Vejbystrand as in balance, this study shows it to be expanding due to erosion at the vegetation line. Recent changes to the coast were found to be more intense than a period with fewer storms (1960 to 1973), and comparable to the long-term changes of beach expansion between 1947 and 2017. Manual digitization of the coastal features and use of DSAS is a suitable method for estimating changes of coastal properties over time. DEM data is extremely useful in estimating the degree of changes, as well as delineating features such as the dune toe line. Changes in the past decade include a notable decrease in protective dune height, erosion at the dune toe and vegetation line, accumulation of sand at the shoreline, steeper slopes leading into the dunes, and overall decrease in sand volume. Erosion is especially present in the southern region of the beach where the sand is finer.

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Appendices

Appendix A: Metadata

YEAR/DATA	RESOLUTION	UNCERTAINTY*	SOURCE
1947 orthophoto	1m	8m	© GIS-center, Lunds University; Gereferencing: GIS-Division, Ängelholm municipality
1960 orthophoto	50cm	5m	©Lantmäteriet. Distribution: GIS-centrum, Lunds universitet
1973 orthophoto	50cm	5m	© GIS-center, Lunds University; Georeferencing: GIS-Division, Ängelholm municipality
2004 orthophoto (summer)	50cm	3m	© Lantmäteriet; Georeferencing: GIS-Division, Ängelholm municipality
2007 orthophoto (summer)	50cm	3m	©Lantmäteriet; Georeferencing: GIS-Division, Ängelholm municipality
2010 orthophoto (spring)	10cm	1m	© GIS- Division, Ängelholm municipality
2010 LiDar (spring)	25cm grid (0-1 data points per grid, 1-3 per m2)	1m	© GIS- Division, Ängelholms municipality
2012 orthophoto (summer)	25cm	1m	© Lantmäteriet; Georeferencing: GIS-Division, Ängelholm municipality
2014 orthophoto (summer)	10cm	1m	© GIS- Division, Ängelholms municipality
2016 orthophoto (summer)	25cm	1m	© Lantmäteriet; Georeferencing: GIS-Division, Ängelholm municipality
2017 orthophoto (spring)	8cm	1m	© GIS- Division, Ängelholm municipality
2017 LiDar (spring)	25cm grid (at least one data point per grid, 16 per m2)	1m	© GIS- Division, Ängelholms municipality
*Uncertainty is a precision value. It is the value of possible error (meters) in mapping due to the mapping reference scale. This value is used in DSAS analysis to conduct a weighted linear regression (WLR).			

Appendix B: Primary parameters causing coastal erosion in Ängelholm

Anthropogenic Parameters	Description	Prominence and recommended update cycle	Potential and Attempted Solutions	Literature
Low-lying, lacking, or damaged vegetation	Low-lying or non-existent vegetation due to tourism, erosion, and beach clearing on the sand dunes along the coast is detrimental to the dune system. Without a root system to hold sediment in place, sand is easily eroded (Sweco, 2012a). For an in-depth description of natural vegetation which can be useful for future planning, Lännstyrelssen in Skåne (2010) presents this in their findings.	As the area has experienced recurring severe storms in recent years, this issue has more prominence because any existing vegetation has had little time to recover (Almström, 2012; Schönström, 2013; and Ängelholms Kommun, 2012). SWECO presented a visualization of the 40 meter recession of the vegetation line during the past 70 years in Almström (2013). Thiere (2017) also presents a comparison of the vegetation line over this 70 year period. **Recommended update cycle** is yearly, preferably in early fall after summer season.	a. Planting of natural vegetation can aid the recovery process of dunes and prevent future erosion by reestablishing an underground root system that can keep sand in place (Sweco, 2012a). An example of utilizing vegetation to prevent erosion from Rönne Å is described by Sweco (2010). b. Avoid seaweed clearing when possible. Though clearing provides aesthetic benefit, the morphological benefit of keeping sand in place outweighs this (Fredriksson, et al., 2017; Sweco, 2012a). c. Sweco recommends a control plan to keep track, as well as information campaigns, planting vegetation, and building lifted walking paths rather than stairs (Sweco, 2011b). An example of this may include the plan from Ystad's municipality, (Fredriksson, et al., 2014).	Almström, et al. (2017); Fredriksson, et al. (2014); Fredriksson, et al. (2017); Lilja & Lindgren (2011); Länsstyrelsen Skåne (2010); Schönström, (2013); Sweco (2010); Sweco (2011a); Sweco (2012a); Sweco (2012c); Sweco (2013b); Sweco (2016); Thiere (2017), Ängelholms Kommun (2012)
Built-up areas	Built-up areas contribute both to erosion as well harm the natural coastal system in place. Building too close to the beaches have been shown	**Recommended update cycle**: After compiling information on vulnerable areas, it will be important to update after major	a. Create a buffer zone between buildings and the beach, avoid construction when possible, focus on sustainability, communal education about the issues (Sweco, 2012a).	Fredriksson, et al. (2014); Fredriksson (2017); Fredriksson, et al. (2017); Länsstyrelsen

	worldwide to contribute to erosion and put owners at risk. (Fredriksson, 2017; Fredriksson, et al., 2017; and Sweco 2012a) Ängelholm is especially prone to this as many houses exist very close to the beaches and coast line (Sweco, 2012a)	storms and upon completing construction.	b. Do not allow for buildings to be built closer than 100m from the vegetation line. This will allow some freedom of movement of the shoreline without impacting owners (Sweco, 2012a). Länsstyrelsen i Skåne Län (2013) does not allow for buildings to be built in nature protected environments; expanding upon these areas could be useful. c. Study buildings to be built at or less than 5m above sea level to be studied on a case-by-case basis (Sweco, 2012a). This has been somewhat applied by WSP in a 2013 report by Joachim Schönström where at risk areas are marked and graded on vulnerability. d. Beach buildings should be seasonal (summer) and removed after the season and any construction (ie. spas and piers) being built out over the sea should be under special supervision and consideration as they can seriously impact the natural processes (Sweco, 2012a). e. Ystad's municipality was recommended to build more buildings in front of existing ones along the coast. This solution is controversial and recreationally focused. It should be seriously considered along with its consequences before implementation (Fredriksson, et al., 2014). f. Beach nourishment in vulnerable areas i.e. where there are already buildings close to the sea (Fredriksson, et al., 2014)	Skåne (2010); Schönström (2013); Sweco (2012a); Sweco (2016); Thiere (2017)
Tourism	Tourists, in the northern beaches especially, cause damage to beach vegetation and	Recommended update cycle: Yearly, early fall	a. Built beach for recreation	Almström (2012); Almström & Fredriksson (2011);

	dunes, thus contributing to the overall erosion (Sweco, 2012a). Tourism is nonetheless an economic contributor to Ängelholm and thus this worth should be taken into account (Sweco, 2011b; Sweco, 2012a; Sweco, 2016; and Thiere, 2017) Increasing tourism has also led to construction along the beaches for attractions such as the Klitterhus spa and hotel. These buildings, though attractive, also pose a threat to the coast by contributing to erosion (Sweco, 2012a).	Priority of tourism issues is in the summer when tourism is up. People walking along and between the dunes is the second most prominent reason for erosion after storms (Sweco, 2012c)	b. Sand pit for catching sand, walkways over the dunes, and strategically placed fences to prevent visitors from trampling the dunes (Sweco, 2012a).	Almström & Fredriksson (2012); Almström & Persson (2016); Sweco (2012a); Sweco (2012c); Sweco (2016); Thiere (2017)
Movement of deposited sand	Sand is often deposited in order to nourish the beaches from erosion as well as allow for some natural reconstruction. This method, however, has also been seen to be destructive as the deposited sand continues to erode and move itself to an unintended part of the coast	Though this process takes some time, the prominence is quite high as this is the most common method chosen by Ängelholm to address erosion problems, it is also the most economical (Sweco, 2013a).	Keep beach nourishment projects south of the piers and jetties in order to prevent build-up of the deposited sand. (Sweco, 2013a). Using too fine of a sand grain can induce the transport, so it is important to use a coarser grain of sand (Sweco, 2016)	Fredriksson (2013); Sweco (2013a); Sweco (2016)

Seaweed and beach vegetation clearing	In order to keep the beaches fresh and attractive, the municipality clears much of the seaweed from its beaches. This is problematic because seaweed plays a large role in the morphology and biodiversity of the environment and also prevents erosion of the beaches (Sweco, 2012a) The municipality also, in attempt to increase beach biodiversity, have periodically cleared dune vegetation which in turn puts the dune at risk for erosion (Fredriksson, et al., 2017)	The municipality is aware of this issue and has been recommended by SWECO to keep clearing to a minimum with the knowledge that clearing is also important for keeping the beaches recreational (Sweco, 2012a). Prominence of erosion is estimated to be 4x the amount on dunes without vegetation than those with (Fredriksson, et al., 2017)	Avoid seaweed clearing when possible as though clearing provides aesthetic benefit, the morphological benefit of keeping sand in place outweighs this (Sweco, 2012a).	Fredriksson (2017); Fredriksson, et al. (2017); Sweco (2012a)
Protective barriers	Protective barriers may include jetties that act as wind breakers as well as sea walls, beach accessibility mechanisms, or sand deposition/beach nourishment. Many of these have been built in response to natural storms, erosion, and other natural processes. Though seemingly solutions to the problem at hand, the solutions are often temporary and end up causing more harm to the environment. A more comprehensive analysis of		a. An analysis of all protective barriers should be conducted. b. To prepare for the next 100 years, a 3.5-meter increase in the protective wall was recommended by Sweco (Lilja & Lindgren, 2011)	Lilja & Lindgren (2011)

	these “solutions” is provided in Table 2.			
Natural Parameters	**Description**	**Prominence and recommended update cycle**	**Potential and Attempted Solutions**	**Literature**
Rising global temperatures and severe storms	Increasing temperatures help lead to the increasing sea level which in turn causes erosion and a threat to Ängelholm’s coast (Sweco, 2012b) (Sweco, 2011b). Increasing temperatures also help induce the storms that not only damage the west coast, but cause erosion via sea level rise, high waves, and aeolian transport. Storms have been re-curring more frequently in re-cent years (SMHI, 2017a).	**Recommended update cycle:** after severe storms	Potential solutions are difficult to address as increasing temperatures and recurring storms are problems that are seen on a global scale. Thus, it is more realistic to address the consequences which follow.	Bontje, et al. (2016); Fredriksson, et al. (2017); SMHI (2017a); SMHI (2017b); Sweco (2011b); Sweco (2012b); Sweco (2016)

Temporary/elevated sea levels	The dune system has been unable to rehabilitate itself after the nearly annually recurring storms between 2010 and 2017. These dunes are important for many reasons, including keeping a natural barrier between the sea and the built-up areas (Almström, 2017; Thiere, 2017) Increasing water levels means that extreme increases will be even more extreme than they are today leads to flooding. Elevated sea levels may also be due to climate change and greenhouse effect. Most municipalities in Sweden are preparing for a 1m increase in sea level by 2100 (Sweco, 2012a). A recent report by SMHI (2017a; 2017b) present data on sea level rise estimates, putting the west coast at highest risk.	This issue is most prominent during severe winter storm periods. It has been especially prominent since 2010. Keeping up-to-date on the impacts of temporary sea level rise is crucial for emergency preparedness (Thiere, 2017). Additionally, if the Mediterranean Sea were to rise the predicted 1m by 2100, the coast of Ängelholm is expected to recede by at least 100m. **Recommended update cycle** is yearly, in the early spring, and always after a severe storm.	a. Man-made barrier (this is very expensive, up to 140 million SEK for 1.5 km**)** (Thiere, 2017) (Almström, 2017) b. Moving sand from shallow waters to the damaged dune areas along the beach (also expensive and currently the municipality is seeking funding beyond the 10-year budget accounted for (Sweco, 2017) c. Ängelholm has for the past 8 years kept up-to-date with erosion of the beaches. They have also come up with a management plan presented by SWECO (Almström, 2017). This should be continued as to keep current information at hand as well as define parameters that are most important.	Almström (2017); Almström & Persson (2016), SMHI (2017a); SMHI (2017b); Sweco (2012a); Thiere (2017)
Aeolian transport	Wind can be useful in building the dunes, however, it will naturally erode the ones in place if there is no vegetation holding the sediment down (Sweco, 2012a). Westerly winds dominate Ängelholm's coast, which especially impacts Skälderviken where westerly	**Recommended update cycle**: yearly after storm season, and always after severe storm takes place	a. Planting of natural vegetation can aid the recovery process of dunes and prevent future erosion by reestablishing an underground root system that can keep sand in place (Sweco, 2012a). b. Avoid seaweed clearing when possible as though clearing provides aesthetic benefit, the morphological benefit of keeping sand in place outweighs this	Fredriksson, et al. (2017); SMHI (2017a); SMHI (2017b); Sweco (2012a); Sweco (2012b)

	winds push waves towards the coast and thus lead to increased sea levels and erosion (SMHI, 2017a; Sweco, 2012b).			
High waves during storms	High waves generally lead to erosion while smaller waves bring back sediment to the beaches. When storms occur more regularly, as Ängelholm has experienced for the past 8 years, natural recovery is hindered, erosion becomes more prominent, and the overall sand volume is reduced in effected areas (Almström, 2017). High waves also put the municipality at risk for flooding.	**Recommended update cycle**: Always after a severe storm, it is important to inventory damage after a storm (Sweco, 2012a) Preferably future analysis would be made in order to predict the impact of incoming storms so that emergency preparedness can take place. Most prominent during severe winter storm periods. It has been especially prominent since 2010 (Almström, 2017) Priority is on the "red zones" described by SWECO as the zones most prone to damage (Sweco, 2011a)	a. Freestanding jetty parallel to the coast. Though this option may reduce the impact of waves in the future, there are many biological, hydraulic, and morphological impacts. Furthermore, it does not bring more sand to the system, which is the actual problem at hand. The purpose would be to reduce wave height incoming to the shore. This alternative is expensive and has many potential risk factors explained in (Almström, 2017)**.** Additionally, the jetty will not be enough because it does not prevent erosion. A complimentary beach nourishment would need to take place. Analysis of existing jetties was done by SWECO in 2012 (Sweco, 2012b)**.** b. Levee. Overall this would be better at preventing erosion and flood but is very expensive and has many risk factors (Almström, 2017). c. Beach nourishment – best option according to LTH because it spreads the cost over longer period, is more flexible, and has the least environmental consequences (Almström, 2017). Consequences of this alternative are found in (Almström & Persson, 2016). SWECO recommends 6000 m^3 sand be placed in the areas marked in red from their report by Fredriksson (2011).	Almström (2017)**;** Almström & Persson (2016); Fredriksson, et al. (2017); SMHI (2017a); SMHI (2017b); Sweco (2011a); Sweco (2012b)

			d. Maintain a record of damage inventory after severe storms to be able to refer back to when analyzing storm influence and damge (Sweco, 2012a)	
Parallel Sand Transport	Longitudinal sand transport from North to South is primary erosion process (Sweco, 2012a). This is largely due to the natural ocean currents in Skälderviken (Birgander et al. 2018)	**Recommendation** by SWECO is to update the proposed municipal control program (point d in 'Potential and attempted solutions') documents every fourth year (Sweco, 2012a).	a. Gabions have previously been implemented (Sweco, 2012a) b. Vegetation planting (Sweco, 2012a) c. Dune reconstruction and beach nourishment (Sweco, 2012a) (Fredriksson, et al., 2017) d. Municipal control program in order to keep an eye out and inventory sediment movement. Suggestions by SWECO include: coastal profile measurement, sea level height measurement, bathing water quality, tourism income, mapping of shore exploitation, (Sweco, 2012a) An example from Ystad's municipality may provide a starting point (Fredriksson, et al., 2014).	Fredriksson, et al. (2017)**;** Sweco (2012a)**;** Sweco (2012b); (Birgander et al. 2018)

Appendix C: Analysis of potential erosion protection implementations

Solution	Pro	Con	Literature
Jetty (free floating)	1.Flexibility – can be taken up during winter months, moved etc 2. Favorable cost – not dependent on water depth (1.5-2 million kronor) 3. Environmental – doesn't touch the ocean bottom, nor does it interfere too much with streams and sediment movement 4.Widens the beach 5.The dunes are protected from high waves	1. Only effective against shorter waves (~ 5m wide) 2. Can be difficult to dock, so when waves are strong they can penetrate the sides 3. Requires sand transport and beach nourishment 4. Does not protect against flooding due to high sea levels 5. May cause erosion problems downstream 6. Can be technically complicated and therefore expensive to construct compared to facilities on the beach	(Sweco, 2012b) (Sweco, 2011a)
Jetty (set)	1.Very effective in weakening most waves	1. Cost is dependent on water depth, thus more expensive (3-3.5 million kronor) 2. Accumulates sand on the leeward side 3. Can pose danger to sailboats and other water sports	(Sweco, 2012b)
Jetty (altering existing)	1. Would likely reduce wave impact	1.Not recommended by Sweco as the cost benefit is low 2.Extremely expensive (1-7 million kronor) 3.Poses a threat to sailors and recreation in the water	(Sweco, 2012b)
Sand fence along beach and vegetation lines	1.Gives vegetation time to grow without being trampled 2.Blends into natural environment 3.Environmentally friendly 4.Prevents visitors from trampling the recovering dunes	1. Can be overtaken by moving sand	(Sweco, 2012c)

Walkways over the dunes	1.Rather than impeding the dunes as stairs do, walkways over the dunes allow the dunes to recover more naturally 2.Hanidicap and family accessible	1.Regular inspections and repairs need to be made do to the harsh climate	(Sweco, 2012c; Sweco, 2012a) (Ängelholms Kommun, 2012)
Sea wall	1.Secures the area from flooding 2.Aesthetically appealing	1.May cause erosion close to the construction as well as downstream 2.Costly and maintenance intensive 3.Impairs beach accessibility	(Sweco, 2011a)
Stone pier	1.Doesnt impact beach access and can also be used for bathing access 2. Builds up the beach plane	1. Requires sand transport and beach nourishment 2.Only works for erosion parallel to the coast 3.Contributes to downstream erosion 4.Outgoing currents may result in loss of sand further out to sea 5.Protects neither underlying areas nor dunes	(Sweco, 2011a)
Beach nourishment	1.Beach environment is not negatively impacted, so it is positive both for coastal species and tourists 2.Building up the dunes gives flood protection and works as a sand buffer against waves 3. Economical 4. No increase in erosion elsewhere along the coast	1.Sewage systems may fill with sand quicker than normal 2. Though success has been widely acknowledged, longer term consequences have not been studied in-depth 3. Finding sand with proper grain size can be difficult	(Bontje, et al., 2016) (Sweco, 2011a) (Fredriksson, et al., 2014) (Sweco, 2012a) (Länsstyrelsen Skåne, 2013) (Almström, 2017) (Sweco, 2017)
Planting vegetation	1.Effective in preventing erosion	1.Tendency to be trampled by tourists 2.The vegetation line has receded in recent years, as much as 8 meters in the northern part of the coast, and thus is less effective along the beach (Sweco, 2011b).	(Sweco, 2011b)

Appendix D: Slope and curvature data

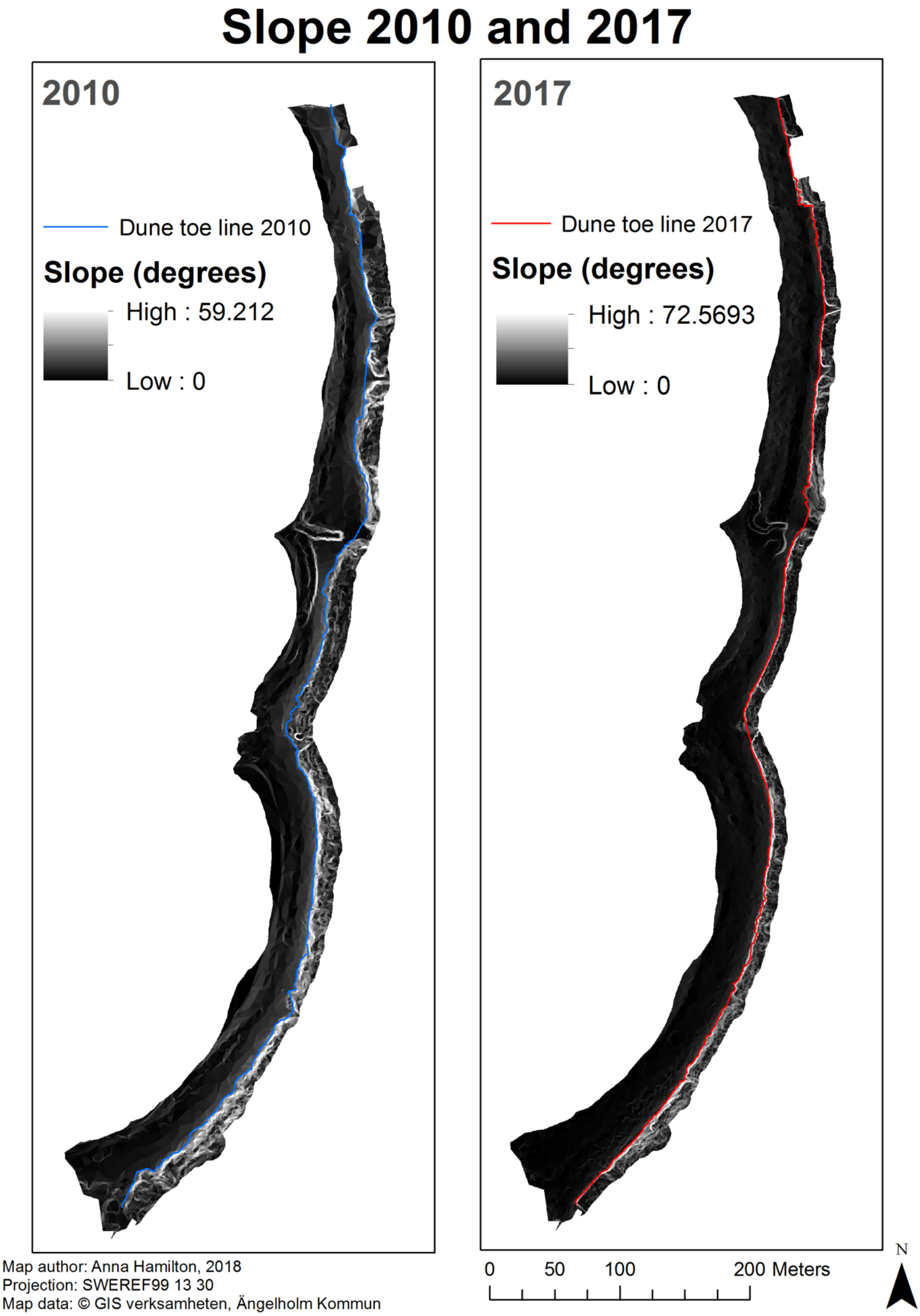

Figure D1 Vejbystrand slope values for 2010 and 2017

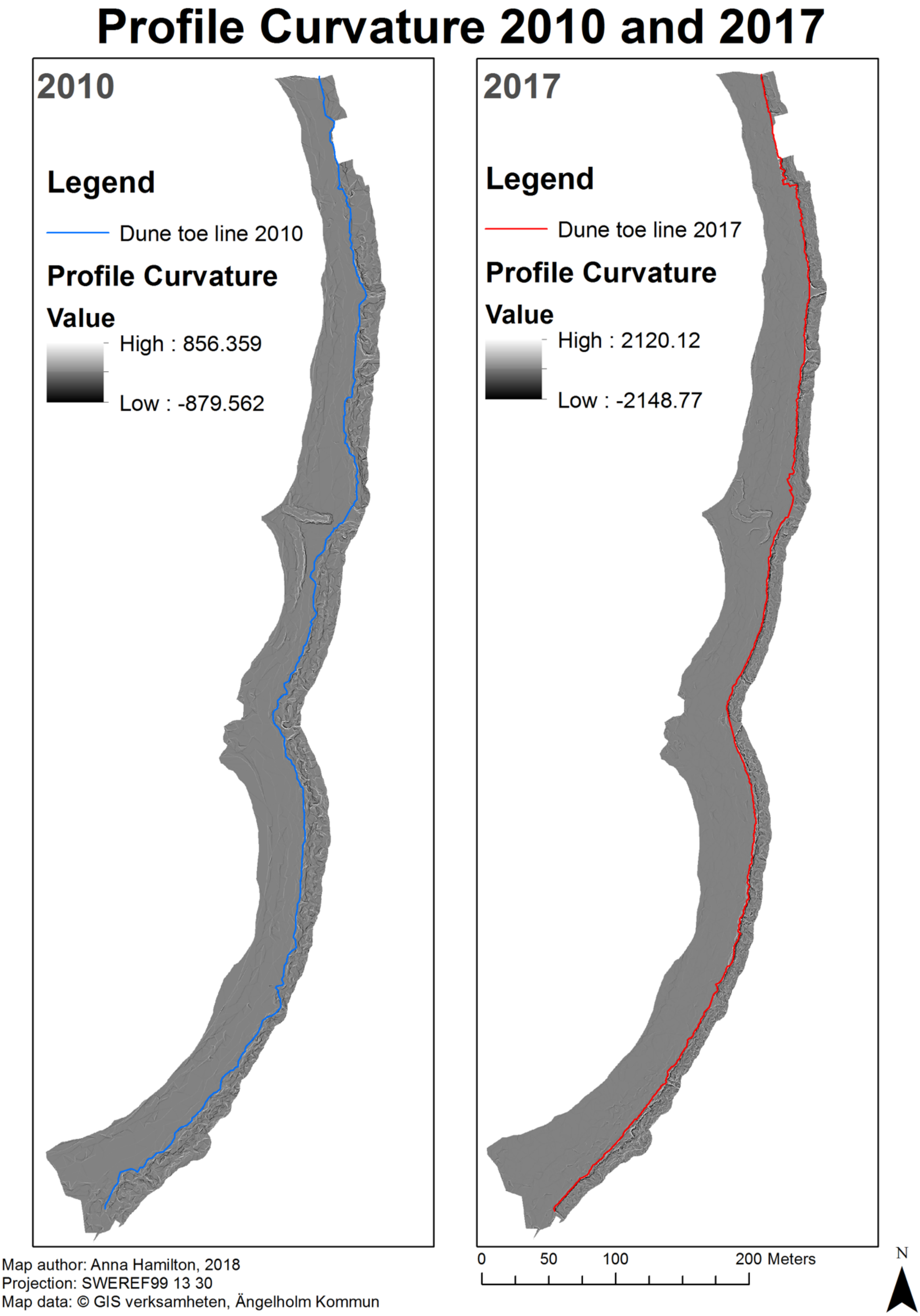

Figure D2 Vejbystrand profile curvature values for 2010 and 2017

Appendix E: Supplementary data for shore, vegetation, and dune toe line movement

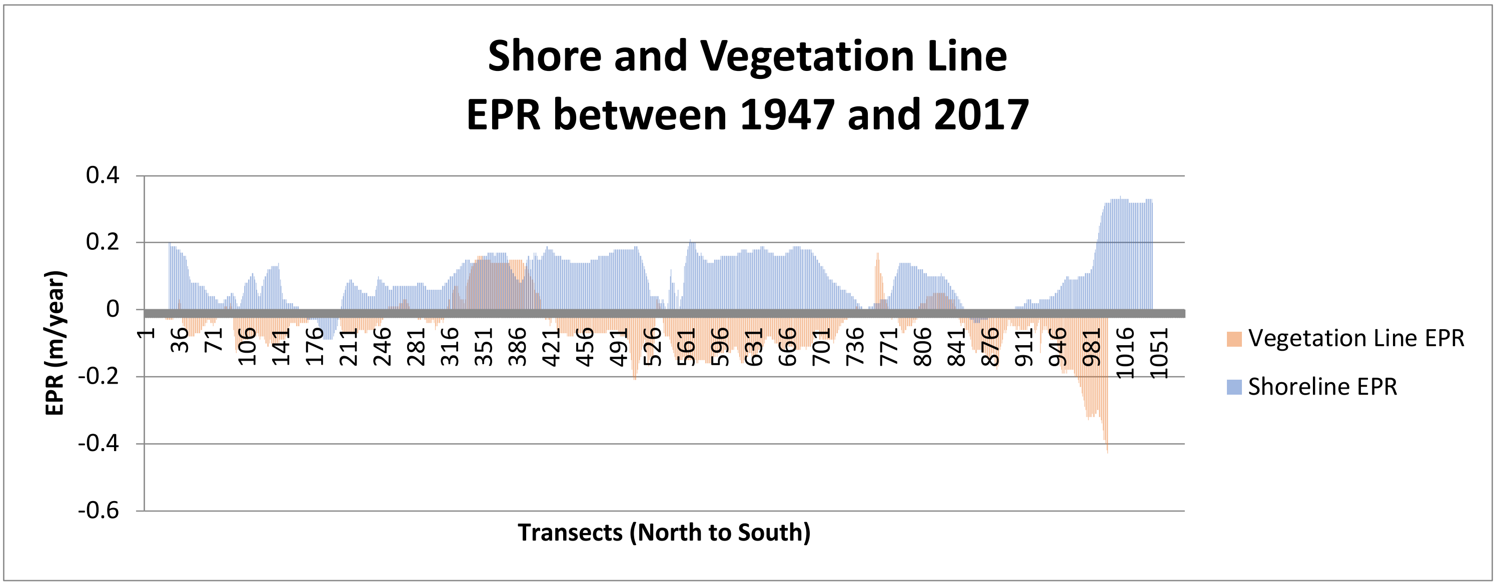

Figure E1 Shore and vegetation line EPR between 1947 and 2017

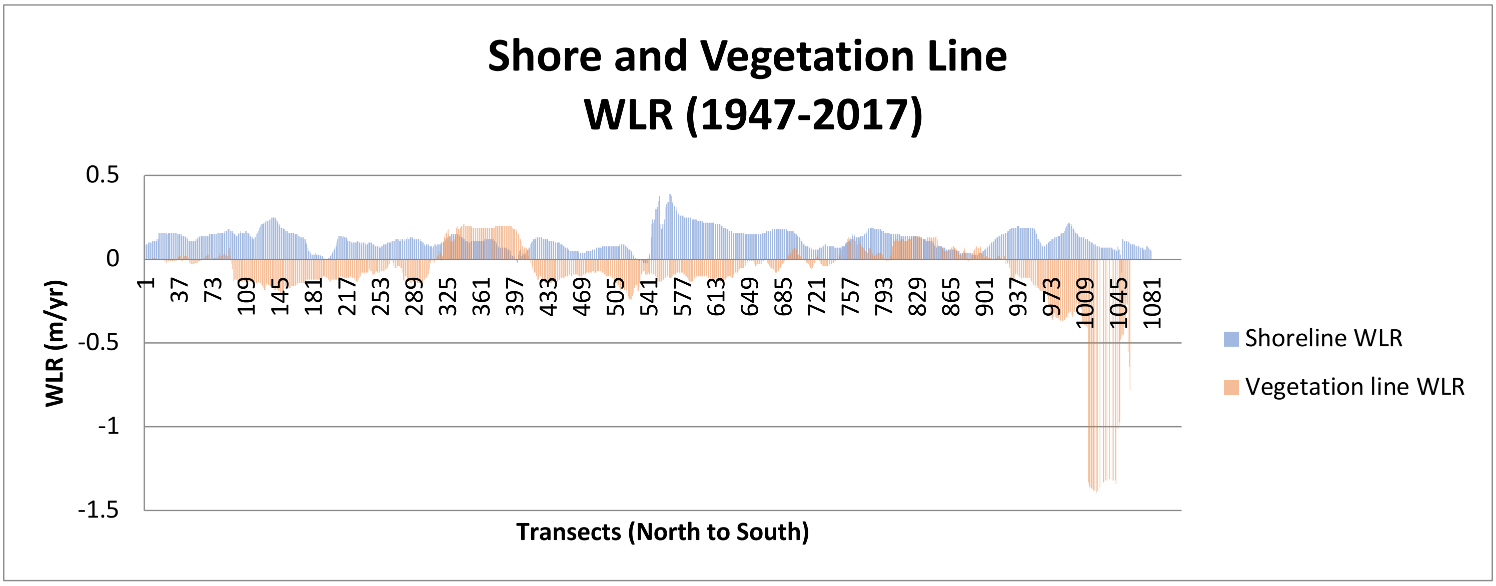

Figure E2 Shore and vegetation line WLR for all orthophoto years between 1947 and 2017

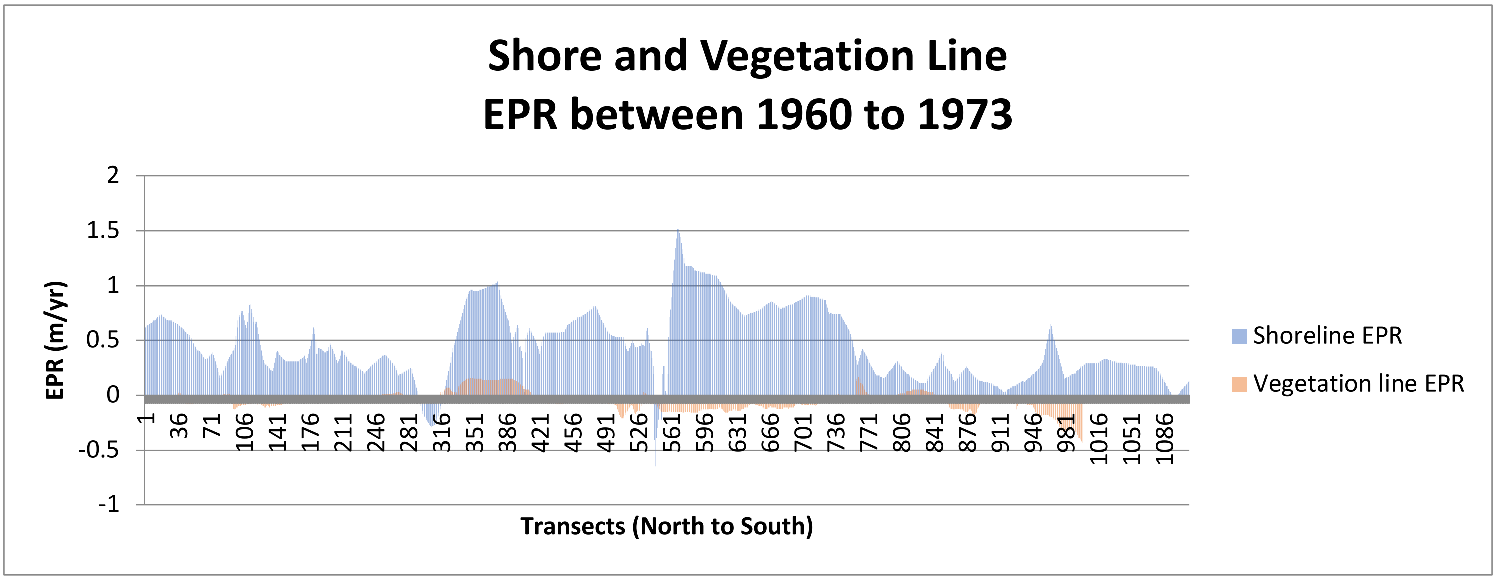

Figure E3 Shore and vegtation line EPR between 1960 and 1973

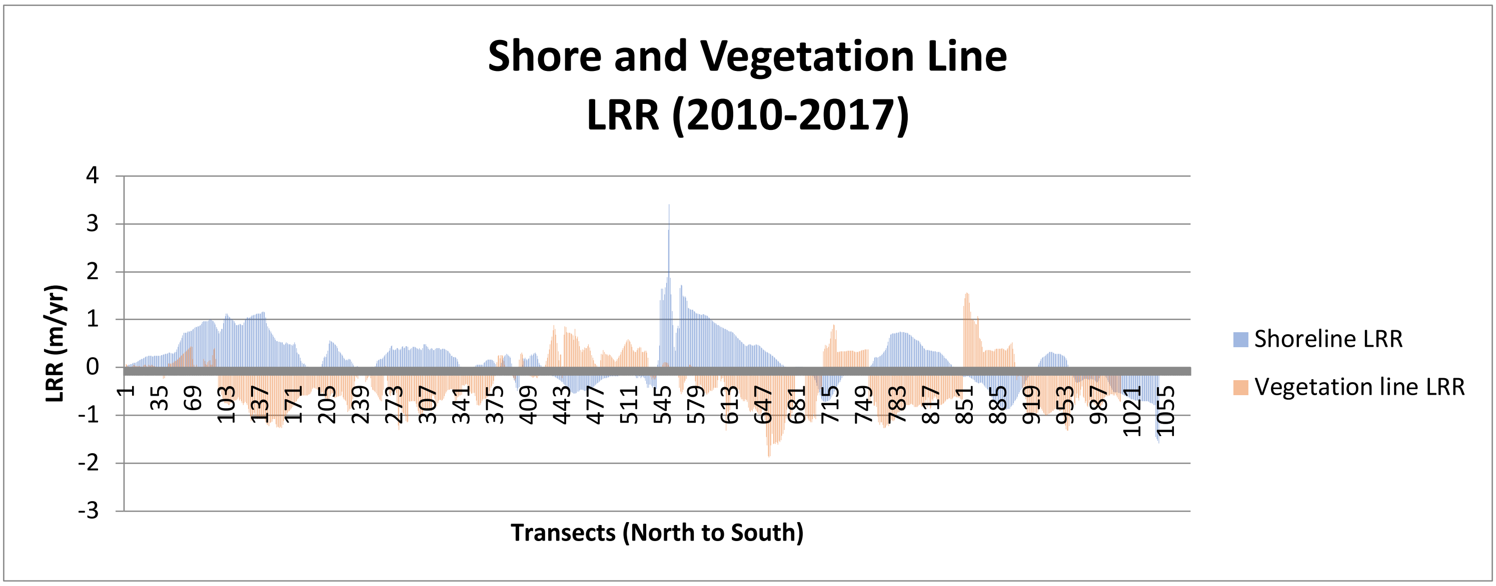

Figure E4 Shore and vegetation line LRR for all orthophoto years between 2010 and 2017

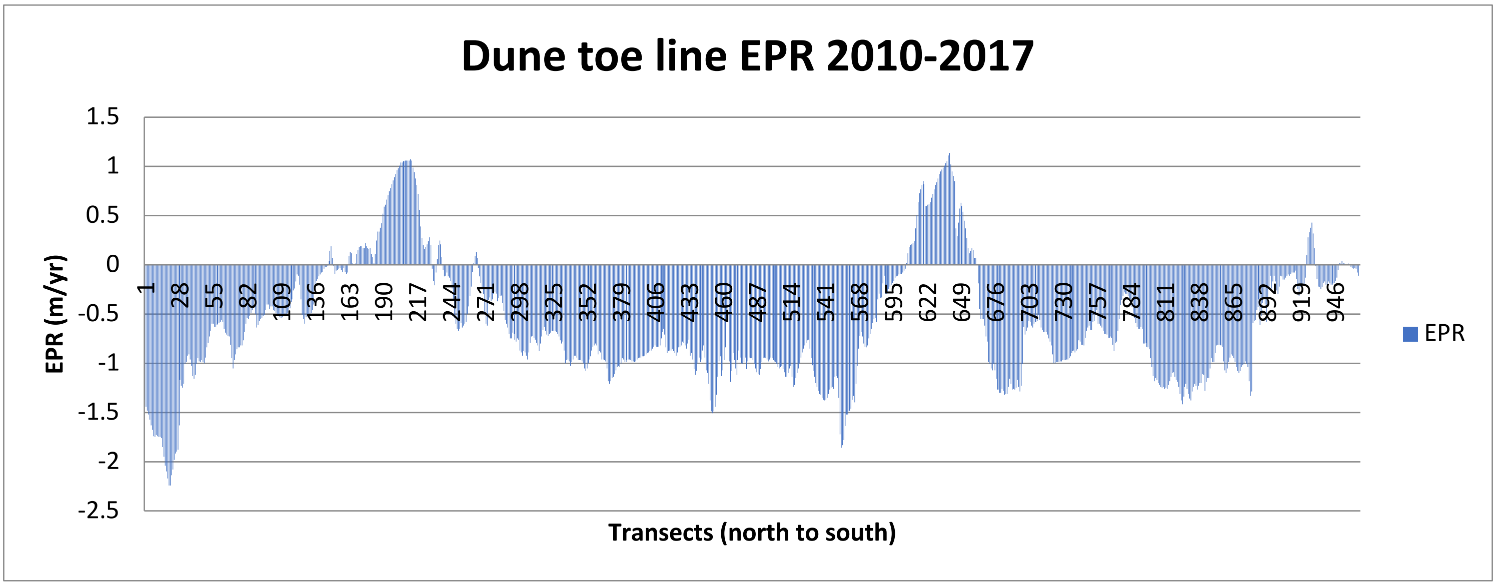

Figure E5 Dune toe line EPR between 2010 and 2017