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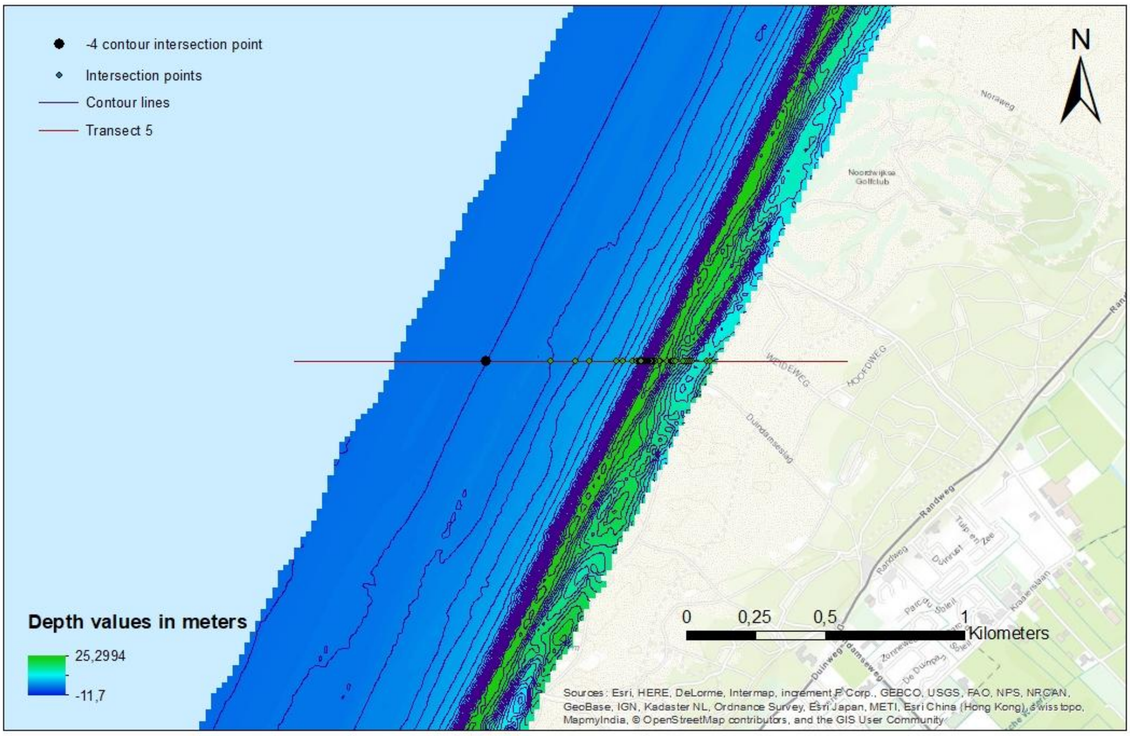
Inge van der Mond

Transect5_1989_90 contour line intersection points



Indicating a critical shoreface contour line along the Central Holland coast

Inge van der Mond

Registration number: 94 06 16 579 110

Supervisor:

Dr. Ir. Ron van Lammeren

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Summary

The Dutch shoreface has a history with threats coming from the North Sea, such as storm events. In combination with an increasing danger from sea level rise it is of great importance to be able to protect the mainland against these threats. Shoreface nourishments have become a dominant type of measure to halt coastal erosion. The coastal area is monitored on an annual bases by using bathymetric data. The Dutch Department of Public Works collects and stores this data known as JARKUS data ('JAaRlijkse KUStlodingen' – annual soundings). Currently the monitoring focuses on the vertical dimension of a virtual coastline. In this research the horizontal dimension of the coastal area is subject of study. Especially the shoreface's capability of protecting the mainland is evaluated by studying the shoreface's morphology. We do so by introducting the term 'critical shoreface contour line'. The study aims to define a critical shoreface contour line by contour analysis and an evaluation of the shoreface morphology before, during and after two major events in the central Holland coast's history for which one can expect changes in morphology. In this study the implementation of the Dynamic Preservation policy and the application of 'the Sand Motor' along the central Holland coast near the Hague (Mulder & Tonnon, 2010) were chosen. The study discussed the following research questions:

1. What is the definition of a critical shoreface contour line?
2. What contour analysis should be used to fit the purpose of this research?
3. What changes in location of the critical shoreface contour line can be detected?
4. In what way does the literature regarding the effects of the Sand Motor support the results derived from this research?

The definition of the critical shoreface contour line is based on the nearshore bars in the shoreface. The critical shoreface contour line is the contour line at which the first nearshore bar (seen towards the shoreline) is located and that is most comparable regarding the gradient and the aspect values with the first nearshore bar in 1990. In this year the Dynamic Preservation policy was implemented to halt structural coast erosion. At that moment in time the Dutch government decided the coastal protection had to be modified in favor of mainland protection.

The analysis to retrieve the critical shoreface contour line from the JARKUS data is based on preprocessed input data with specified spatial (5 x 5 m) and temporal (per 2 years) resolutions of the input data. Additionally, the critical contour line is found by calculating the gradient between two contours, the steepening or flattening of the bar slope. The location and dynamics of specific contour lines have been calculated as well. Also, by deriving the aspect the locations of nearshore sandbars have been analysed.

For the central Holland coast from Wassenaar to Zandvoort the contour analysis and an aspect analysis have been used to evaluate the morphodynamics of the nearshore sandbars and thereby the dynamics of the critical shoreface contour line. For the time period before, during and after the implementation of the Dynamic Preservation policy the critical shoreface contour line has shifted away from the coastline and additional sandbars have appeared, indicating an improvement of the shoreface's protective role compared to the situation of 1990. The years after implementation of the Sand Motor also showed an offshore shift of the critical shoreface contour line and the generation of sandbars. The offshore shift by the latter can be verified by literature indicating accretion on adjacent coastal sections of the location of the Sand Motor. However, there remains a possibility that

the generation phase that naturally occurs in sandbar cycles happens to coincide with the years after implementation of the Sand Motor. This central Holland coast analysis was performed to demonstrate how the designed method should be implemented in order to evaluate the shoreface's capability of protecting the mainland. Reproducible methods should be designed to replace the visual assessments used in this research. The aspect analysis should be extended so that it is able to contribute even more to gaining insight on shoreface's morphodynamics. Finally, more years should be analyzed to create a better overview of the dynamics of the critical shoreface contour line and assure more certainty about conclusions being drawn upon.

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1. Introduction

Two processes are identified as the primary cause of the increase in global mean sea level in the future; ocean thermal expansion in consequence to rising temperatures and freshwater input as a result of melting ice sheets, glaciers and ice caps (Weisse R. , von Storch, Niemeyer, & Knaack, 2012). For the end of the 21st century, the IPCC Fourth Assessment Report (AR4) projects an increase in global mean sea level of 18-59 cm (Meehl, et al., 2007). However, there is variation in the estimated rates of the sea level rise per area, meaning that for the coast of the Netherlands an estimate is provided of about 2.5 mm/year (Katsman, Hazeleger, Drijfhout, van Oldenborgh, & Burgers, 2008) increasing the risk of floods. Also increasing the risk of floods are storm events. One of the two major storm tracks in the Northern Hemisphere is the North Atlantic storm track, influencing the North Sea (Weisse & von Storch, 2009). An increase of about 30% of mean storm track intensity was found by Chang and Fu (2002) when comparing Northern Hemisphere storm track activity during the mid-1990s with the late 1960s.

Rising of the sea level and storm events are both accompanied by increased risk of floods since both processes affect the shoreface. The shoreface of the southern North Sea includes shore-parallel sand banks (Anthony, 2013). These banks evolve in a manner in which they are ‘stretched’ influenced by tide-, wave-, and wind-induced shore-parallel currents nourished by, among other processes, sea level rise and storm events (Anthony, 2013). Eventually this will lead to bank division, leaving the coast without a barrier cushioning (storm) wave energy and thereby more vulnerable to floods. Two of the more recent examples of floods were caused by the storms affecting the coasts on 31 January and 1 February 1953 and on 16-17 February 1962, which were both associated with a wide-spread failure of coastal protection (Gerritsen, 2005; Baxter, 2005; Sönnichsen and Moseberg, 2001).

1.1 Problem definition

As can be derived from the introduction, the Dutch shoreface has a history with threats coming from the North Sea. For the cases in 1953 and 1962 storm events were the cause of major floods. Although storms still form a major risk for the Dutch coast, sea level rise continues to grow as one of the main processes to protect ourselves against. For the Delta area in the south west, the Delta Works have proved to fulfill its protective role against the ocean so far, but the Wadden Sea area and the beach-dune coast of central Holland are, despite protective measurements limiting their effects, still exposed to tides, wind and waves eroding the coast.

The losses of dune area in the nineteen seventies and eighties of about 20 ha per year due to tides, wind and waves (de Ruig, 1998) resulted in a decision made by the Dutch government to halt structural coast erosion. In Hillen and De Haan (1995) one can find that a reference coastline was defined and a yearly test procedure was designed embedded in the Dynamic Preservation policy. The policy stated that coastal erosion should be predominantly compensated with sand nourishments, acting by the motto ‘soft measures where possible, hard structures where necessary’ (van der Spek & Lodder, 2015). Shoreface nourishments have become the dominant type of nourishment along the central coast of the Netherlands (van der Spek, de Kruif, & Spanhoff, 2007).

Because of the fact that tide-, wave-, and wind-induced currents all affect the shoreface in ways that are often not clearly understood (Backstrom, Jackson, Cooper, & Loureiro, 2015), the state of the coast is assessed yearly. This is done by surveying cross-shore profiles at fixed, typically 250 m spaced transects since 1963 (van der Spek & Elias, 2013). This annual bathymetry data has been collected by the Dutch Department of Public Works and is stored in the JARKUS data base ('JAaRlijkse KUStlodingen' – annual soundings). This dataset has been used to study the Dutch coastal change very thoroughly by amongst others Hinton (2000), Wijnberg & Terwindt (1995), Larson et al. (2003) and Lammeren et al. (2017) and will also be used in this study.

In the latter study the Ameland shoreface was studied by deriving Digital Bathymetry Models (DBMs) from the JARKUS data set and by performing an elevation trend-analysis using BFAST (Verbesselt, Zeileis, & Herold, 2012), (de Jong, Keijsers, Riksen, Krol, & Slim, 2014). This is exceptional because of the fact that the majority of studies using data collected over many points in time, base their analysis on the shoreface profiles using data collected along transects. Using DBMs however (Digital Terrain Model of a surface located below the water surface), one can analyze shoreface properties such as slope, aspect and curvature, which could be of interest to determine shoreface behavior. Krawczyk's study provides a first step towards developing a framework for DBM-based analysis of shoreface behavior at various spatial and temporal scales to facilitate future research into the shoreface and interpretation of the results.

This future research on shoreface behavior seems of even greater importance than merely monitoring the coast based on a virtual coastline. When doing research about shoreface systems, one can find that the shoreface's morphology plays a major part in whether the shoreface is able to protect the beach berm and the dunes. Therefore, it is of interest to test the shoreface's capability of protecting the mainland by evaluating the shoreface's morphology. In this research this will be done by means of the term critical shoreface contour line and an improved DBM-based analysis.

1.2 Research objectives and questions

The objective of the current study will be to develop a methodology to test the shoreface's capability of protecting the mainland based on its morphology. A critical shoreface contour line and an improved DBM-based contour analysis will be used as the two main aspects to determine the shoreface's morphology. The aim is to define a critical shoreface contour line, improve DBM-based contour analysis and evaluate the shoreface's morphology before, during and after two major events in the central Holland coast's history for which one can expect changes in morphology. For this study the implementation of the Dynamic Preservation policy and the application of 'the Sand Motor' along the central Holland coast near the Hague (Mulder & Tonnon, 2010) were chosen. The contour lines represent lines of equal elevation along the coast.

To be able to reach the objective, the study addresses the following research questions:

1. What is the definition of a critical shoreface contour line?
2. What contour analysis should be used to fit the purpose of this research?
3. What changes in location of the critical shoreface contour line can be detected?
4. In what way does the literature regarding the effects of the Sand Motor support the results derived from this research?

2. The definition of a critical shoreface contour line

This chapter provides an insight in coastal morphodynamics while deriving the definition of a critical shoreface contour line. Firstly, the shoreface and its morphodynamics are described, where after four aspects (sea level, storm events, beach width and nearshore bars) affecting the shoreface's functioning as protective buffer are presented. Finally, critical values regarding these aspects are evaluated in order to set a definition of a critical shoreface contour line. The main goal of defining a critical shoreface contour line is to be able to determine which characteristics one should be able to derive from the DBM-based contour analysis in order to evaluate the shoreface's capability of protecting the mainland.

2.1 The shoreface

The shoreface is the upper part of the continental shelf that is affected by contemporary wave processes (Fig. 1) and runs from the offshore landward to the low tide line. It can be subdivided into the upper and lower shoreface and may contain nearshore bars in its mostly concave-up profile. These nearshore bars play a critical role in protecting the mainland and can be found in the surf zone within the upper shoreface (Masselink, Hughes, & Knight, 2011). The location of these nearshore bars represents the area of interest, therefore whenever the term shoreface is used, the upper shoreface is meant. Nearshore bars are very dynamic and can migrate onshore or offshore in response to changing wave energy level, tidal range, bar size and water depth over the bar (Ruessink, Pape, & Turner, 2009). Offshore bar migration is often observed during high wave events resulting in a shoreface with less or no bars when these events occur often.

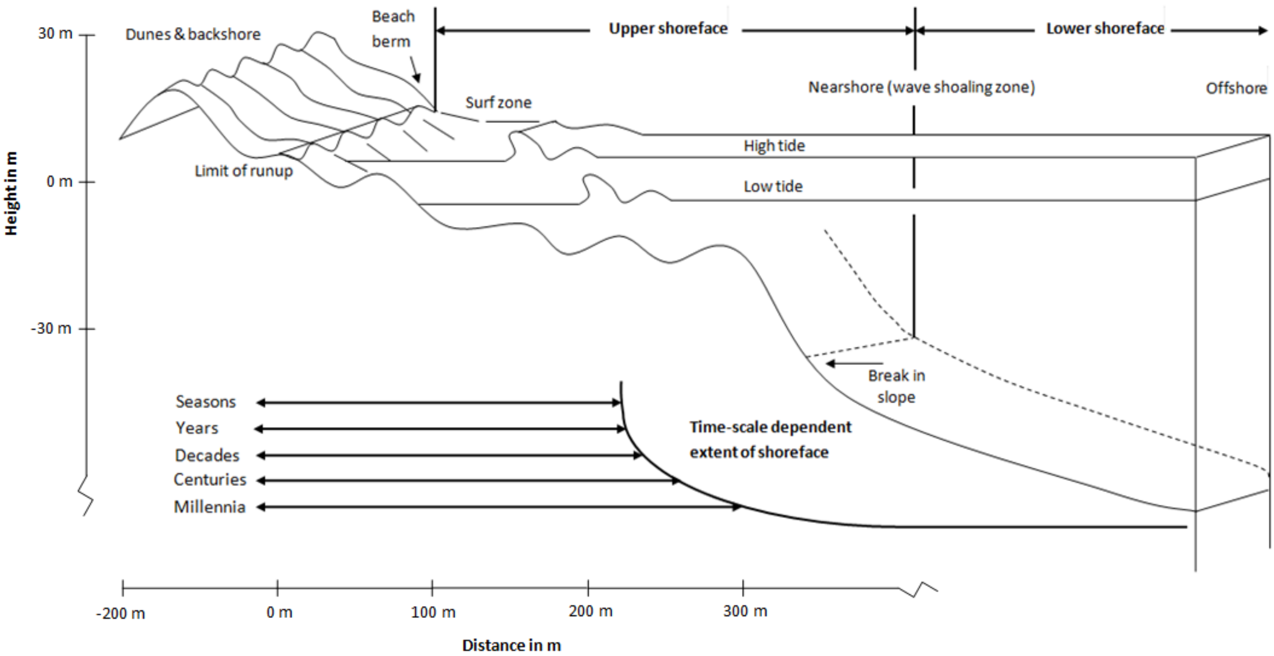


Figure 1: Schematic diagram showing the morphological elements of the shoreface profile (Masselink, Hughes, & Knight, 2011)

One of the more recent images of the geomorphological Dutch coast (Fig. 2) show several bars along the wave-dominated central Holland coast. These ridges are located at a depth of 18 m, and have a height of about 2 m and a cross-bank width of about 5 km in east-west direction (Van de Meene & Van Rijn, 2000). In 1991, this system along the central Holland coast was described as a multi-bar beach system (Short, 1991) meaning that in theory it is a very suitable beach type for protecting the mainland. Moreover, the more bars, the more friction, and due to friction, the shoreface buffers the power of the waves which reduce their height and energy (Cowell, 2000).

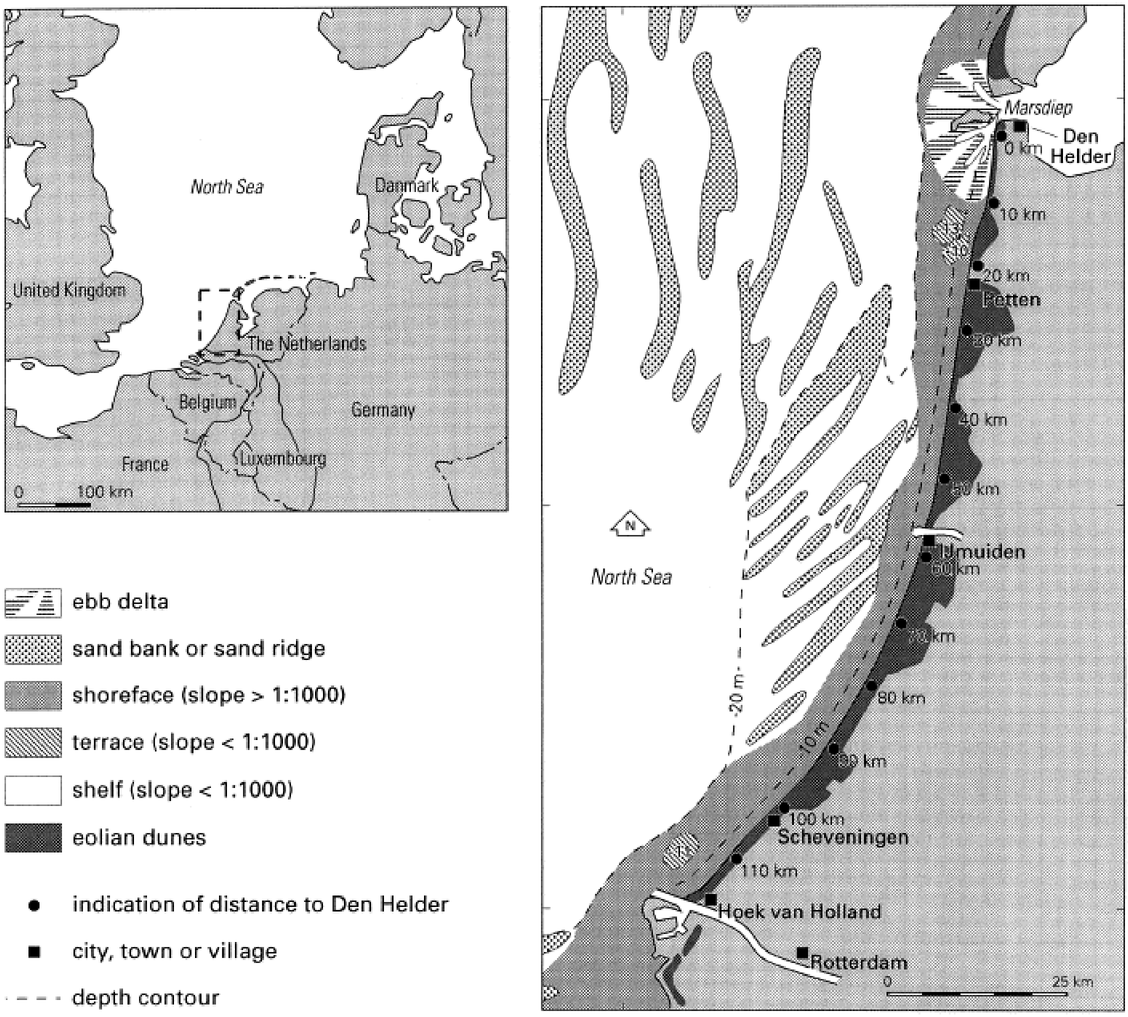


Figure 2: Location and geomorphologic setting of the Dutch coast (Wijnberg, 2002)

2.2 A critical shoreface

After setting the definition of a shoreface, the next step is identifying when the shoreface is in a state at which it can no longer protect the beach berm, dunes and backshore from influences by tides, waves and wind-induced currents. This label of a 'critical shoreface' can, according to this report, be given to any shoreface that has to deal with the following four aspects.

Firstly, the situation concerning a shoreface can become critical due to sea level rise and storm events. Good examples regarding the latter are the storm events that occurred in 1953 and 1962, when the shoreface was inefficient in protecting its mainland. In 1953 waves in front of the southern coast of the Netherlands reached heights of 8 m above NAP (Diephuis, Grijm, Schijf, & Venis, 1991). These waves turned out to be too high to break depending on processes such as soil friction, refraction and other natural processes reducing wave height and strength. Regarding sea level rise, the higher the sea level, the higher the waves during storm events will reach relative to the ground level of the mainland. Furthermore, the movement of water particles in a wave declines from surface to the bottom. When the wavelength is twice the water depth, the undulation at the bottom of the sea is barely noticeable and bottom friction can be neglected (Diephuis, Grijm, Schijf, & Venis, 1991). When this occurs waves will continue their process of erosion at a faster pace. One can say that for this particular aspect the shoreface will, when no measures are taken, gain its label as being in a critical state since sea level will continue to rise (Nicholls & Cazenave, 2010).

Further, the width of the coast (distance between dune crest and shoreline position at high tide) is of great importance when it comes to the shoreface's contribution in protecting the mainland. The narrower the beach, the larger the amount of wave energy reaching the shore (Carter, Monroe, & Guy Jr, 1986), resulting in coastal recession. In its turn this calls for coastal management solutions to hold erosion in check and keep the shore fronted with beaches. For this particular reason a counter measure for the anticipated enhanced coastal recession due to sea level rise has been implemented along the central Holland coast: the Sand Engine (Stive, et al., 2013).

Although these coastal management solutions seem to fulfill its purpose (van der Spek & Lodder, 2006) (Rijkswaterstaat, 2016), the final aspect in the shoreface's natural defence mechanism should not be neglected in this matter. Nearshore bars located in the surfzone of the shoreface have their share in breaking the waves moving towards the beach. As was already stated in the introduction, nearshore bars are very dynamic and change in location and size in response to several factors among which is wave energy. Nearshore bar morphology can include transverse, crescentic, longshore and multiple bars (Masselink, Hughes, & Knight, 2011), all having their own interaction with the waves tempering them and therefore all having a different contribution to breaking waves. However, nearshore bars show cyclic behavior with a generation phase, a net seaward migration phase and a destruction phase (Aagaard, Kroon, Greenwood, & Huges, 2010), meaning that there are moments in which one or multiple nearshore bars fail in contributing to breaking the waves.

Summarized, this means that a shoreface can be labeled as being critical when:
1) sea level rises too high
2) storm events occur that produce waves the shoreface cannot buffer
3) beach width is too narrow
4) nearshore bars are lacking, too small or located ineffectively

2.3 The aspects and their critical values

In order to indicate a shoreface that is critical, each of the aspects that were mentioned in the previous section need to be given a critical value. Of course, for every shoreface these critical values will be different, because every shoreface has its own morphology and therefore an own level of sea level rise it can protect the mainland from. Also different studies may offer different values for this specific aspect. For the remaining three aspects similar arguments can be mentioned. For this reason, the critical values in this research were derived from literature that seemed most reliable and are applicable to the specific shoreface of the central Holland coast.

Starting with sea level rise, the parameter obviously is the height in meters above N.A.P., as far as the critical value of this parameter is concerned, a report by Prof. Dr. Leo van Rijn is used as a reference. In this report several scenarios are given showing the different ways of protecting the mainland against sea level rise. In these scenarios a level of +7 m NAP is used as the water level the coast should be able to resist (Rijn, 2007).

For storm events one should take several aspects into account to be able to find out how high waves are able to reach during the most extreme storm events. In the first chapter of a report written by the Delta Commission these aspects (wind strength and duration, water depth and water surface) are taken into consideration when determining the maximum wave height. After thorough evaluation one can tell that during extreme storm events (e.g. the storm event of 1953) wave heights of 7 meters should be expected in front of the central Holland coast (Diephuis, Grijm, Schijf, & Venis, 1991).

Regarding beach width it has been widely accepted that a wide beach is the best natural form of shore protection (Carter, Monroe, & Guy Jr, 1986), meaning that the wider the beach the better the mainland is protected from the power of the waves. Literature is lacking when it comes to telling where the border is between a safe beach width and a critical beach width. However, the Dynamic Preservation Policy was implemented with the purpose of stopping coastal erosion because a beach width was reached that could not be accepted any longer. Further research provided the information that at that moment the net beach width along the central Holland coast was 117 meters (Short, 1991). Therefore, this value will be accepted as the central Holland coast's critical value for beach width.

The final aspect concerns the presence, height and location of nearshore bars in the shoreface system. From the information already given can be concluded that nearshore bars are very dynamic and their effectiveness in defending the mainland depends on several factors. One of these factors is the water mass on top of the bars determining whether the bars can contribute to the effects of bottom friction. The distance at which the bars are located from the beach determine the moment at which the bars can contribute to breaking the waves coming from the ocean. Finally, the more their aspect is perpendicular to the wave direction, the higher the nearshore bars and the larger the number of bars, the more the power of the waves can be weakened before they reach the beach. Setting a value for the combination of all of these factors can become quite complex and inaccurate. In 1990 the Dynamic Preservation Policy regarding shoreface defence was set up, meaning that the shoreface at that time was considered as no longer sufficient. Therefore this study will use the number, the height, the location and the orientation of the bars at that time as the critical value of these aspects.

Now that the four aspects used to define a critical shoreface have all gained a critical value, the final step in defining the critical shoreface contour line has to be made. As sea level rise and storm events are both capable of causing wave heights against which no shoreface can defend itself, the decision is made to not take these into consideration when setting the critical shoreface contour line. Furthermore, the beach width is an aspect that cannot be measured properly using the JARKUS data that is available and is therefore beyond the scope of this study. The definition of the critical shoreface contour line will therefore be defined in such a way that it can be determined by looking at the nearshore bars in the shoreface system. The critical shoreface contour line is the contour line at which the first nearshore bar (seen from the ocean) is located that is most comparable regarding gradient and aspect with the first nearshore bar in 1990.

3. Concepts in deriving shoreface characteristics

This chapter introduces the concepts that are of interest while deriving the shoreface characteristics necessary to determine the critical shoreface contour line. The concepts mentioned are spatial and temporal resolution, aspect and gradient. These are derived from discussion points addressed in Krawczyk's report and further research. Furthermore, the choices made by Krawczyk regarding these concepts in performing the DBM-based contour analysis are given. By evaluating Krawczyk's choices, improving them where possible and adding aspects that were left out, a methodology can be designed to fit the purpose of this particular research.

3.1 Spatial and temporal resolution

Within coastal environments, for which this and Krawczyk's research was conducted, an interaction of interdependent processes and entities act in a multidimensional space (x, y, z) and time domain (Eleveld, 1999). The coastal change occurring within this highly dynamic environment therefore take place at every spatial and temporal scale. To be able to study specific morphodynamics within such a coastal environment it is necessary to do research at the exact right spatial and temporal scale fitted to the coastal process causing the change in morphology. As (De Vriend, 1991) states, depending on the scale of interest, the same phenomenon (e.g. storms, tides, sea-level rise) can be noise, a component in the morphodynamics process, or just and extrinsic condition. As an example, tides are an extrinsic condition to dune erosion events, part of the morphodynamic interaction leading to bar formation on the shoreface and at the same time noise at time scales of centuries or more. Using (Stive, De Vriend, Cowell, & Niedoroda, 1995), Krawczyk provides an overview of the time and space scales of fluid motions and bed responses in the coastal zone (Fig. 3). From this, one can match dynamic length and time scales to the morphological scales. For this specific research regarding nearshore bars a time scale of a month and a space scale of 100 meters would be appropriate. From Eleveld, 1999 can be derived that when studying coastal processes, variables (slope, aspect, location and height in this study) need to be selected that are both sensitive and reliable enough to indicate change, with the spatial and temporal scale of observations playing a crucial role.

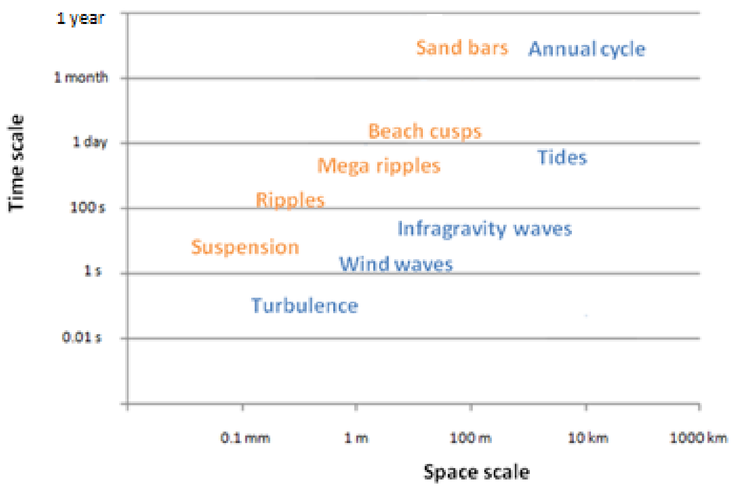


Figure 3: Time and space scales of fluid motions and bed responses in the coastal zone (adjusted from Krawczyk, 2014)

3.1.1 Choices regarding spatial and temporal resolution

For matching the morphological scale to the temporal and spatial scale and thereby ensuring consistency, Krawczyk chose to use Table 1 (Hinton, 2000) as a reference throughout the study.

Table 1: Description of coastal morphological scales (Hinton, 2000)

Scale description	Morphodynamic (longshore) length scale	Time scale
Geological	100 km	Centuries
Large	10 km	Decades
Medium	1 km	Years
Short	100 m	Storms-seasons

Considering the spatio-temporal resolution of the analysis to fit the chosen spatial and temporal scale, Krawczyk mentions methods to change the spatial and temporal scale of data. As Krawczyk's report focuses on processes affecting the shoreface in the long-term and JARKUS data are collected at a much higher spatial and temporal resolution than these processes, the data may contain information that can be considered to be noise for this purpose. Therefore Krawczyk chose to apply a temporal and spatial smoothing to the data, erasing small features such as sandbars spatially and short-term fluctuations temporally.

Regarding the temporal smoothing an overlapping simple moving average was used to smooth the data. An overlapping temporal aggregation considers the fact that data is related to each other. Since depth, as JARKUS data represents, is a product of the processes affecting the seafloor, but also of its state in the past, this technique was chosen. A simple moving average calculates the averages of subsequent subsets of n elements of the original data, where n corresponds to the size of the smoothing "window". In this case an n of 10 years was chosen, based on a performed sensitivity analysis testing 5, 10 and 15 years windows. The calculated subset averages replaces each original element of the series. To perform a spatial smoothing on each smoothing period a simple aggregation based on the mean was used. This is done using the 'Aggregate' tool in ArcGIS, which creates an output raster that has a different cell size than the input. It calculates each output cell value as the mean, median, sum, minimum, or maximum of the input cells that fall within the output cell (Chang K.-t. , 2016). In Figure 4 it uses the mean statistic and a factor of 2 (i.e., a cell in b covers 2-by-2 cells in a). Using factors of 2, 4 and 10 resulted in several new resolutions with output cell sizes of 40, 80 and 200 meters.

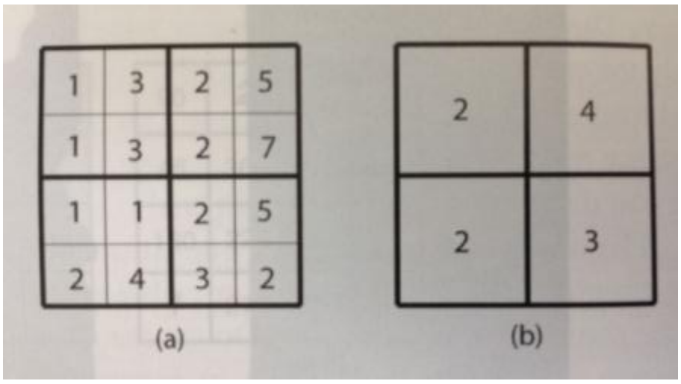


Figure 4: Representation of an aggregate operation (Chang K.-t. , 2016)

3.1.2 Focus points regarding spatial and temporal resolution

Regarding spatial and temporal smoothing this research addressed the following aspects:

- A discard of additional years of data measurements at the end of the time series can occur when the total number of years of data is not divisible by n, the size of the smoothing window during temporal smoothing. Also, one should consider discarding years containing NoData at the beginning or in the middle of the time series. Leaving them in could result in whole smoothing periods that were assigned a value based on only one year containing a valid measurement. (Although this effect, caused by the lack of data at the beginning of the time series, could be corrected through the design of the implementation of the moving window, it would be difficult to correct when there are many years of missing data in the middle of the time series data. In this case, knowledge about the coverage of the study area through time is necessary to mitigate the impact of this effect on the interpretation of the analysis).
- The spatial smoothing in Krawczyk's report was performed using a 200 m cell size. However, the results of the contour distance analysis for transects 3-5 show movement of the contours below 200 m. As was mentioned before, a temporal and spatial smoothing erases small features such as sandbars spatially and short-term fluctuation temporally that could be of interest dependent on the purpose of the research.
- Research results raise curiosity about the order in which the spatial and temporal smoothing should be performed. In Krawczyk's report a temporal smoothing was performed before a spatial smoothing. The use of a simple aggregation based on the mean as a spatial smoothing reduces the appearance of small features in principle. However, in practice it resulted in a pixilated, rather than smoothed, raster. Also the necessity of both smoothing methods can be questioned. Due to a temporal smoothing, any outliers in the data are already minimized, but on top of that a spatial smoothing was performed.

3.2 Gradient and aspect

To be able to grasp the concepts of aspect and gradient that will be addressed within this research, one needs to return to where these concepts are derived from. The slope is the measure of steepness or the degree of inclination of a feature relative to the horizontal plane and is characterized by its gradient, aspect and curvature. The gradient is the ratio of the "vertical change" (rise) to the "horizontal change" (run) between two distinct points on a line. This gradient can be calculated from a contour line, which represents points with the same Z value and thereby possessing equal elevation. The aspect can be defined as the compass direction that the slope faces and is of great importance when it comes to providing information about changes to the direction of dominant geomorphic processes.

3.2.1 Choices made regarding aspect and gradient

In previous studies the contour analysis for shoreface slope dynamics was based on calculating the gradient from a DBM. From such a raster, the gradient is calculated for each cell with various algorithms developed for this purpose, for which general linear regression models and the third-order finite difference methods are the most accurate (Skidmore, 1989). Although the aspect was not generated in Krawczyk's report, the same principal can be used for generating this slope characteristic from gridded DBMs. Krawczyk calculated the gradient based on two contours because it provides information about slope gradient values. By analyzing the distance of two contours over time (absolute distance) information about the change in the gradient attribute, i.e. the steepening or flattening of the slope, was derived. Furthermore, the position of the two contours relative to a stable point (relative distance) generated information about changes to their spatial dimension, i.e. the location and dynamics of a specific contour. To allow for a further averaging of the gradient value the Bruun rule was used (Bruun, 1962).

Transects were drawn along the North Sea coast of Ameland, parallel to the JARKUS transects, to be able to acquire information about the distance of the contours relative to each other and a fixed point necessary to conduct the contour analysis. The chosen spacing distance of 4 km was chosen after considering the spatial (10 km) and temporal (decades) scale, the extent of the data, the total length of the Ameland shoreface and the processes affecting it. Contours were generated for each period at an interval of 1 m, with the a starting point of 0 m, representing the shoreline. This was done using the 'Contour' tool in ArcGIS, which creates a line feature class of contours (isolines) from a raster surface. As the JARKUS Grids contain depth values, the isolines represent lines of equal depth (Contour, 2016)**.**

To calculate the relative distance of the two contours (distance to a fixed point represented by the landward start of the transect), points were generated at the intersection of the transects and the two selected contours, per line, per period. After that, the distance from the start of the transect to each point was calculated. Sometimes a contour crosses a transect several times (e.g. if a sandbar crossed the transect) resulting in several intersection points. Therefore, only the points with the largest distance from the start of the line were kept for each contour depth, meaning the furthest point representing the 0 m contour and the furthest point representing the slope base contour. This information finally resulted in two tables containing information about either the distance of the 0 m contour or the slope base contour. Boxplots were simultaneously plotted for the two contours and for each line to allow for an assessment and comparison of the contour dynamics along the whole island.

To generate the absolute distances between the 0 m contour and slope base contour, for each transect, the range between the two contours was calculated per smoothing period. These results were plotted as boxplots per transect to allow for an assessment of the dynamics of the changes to the gradient of the shoreface slope. Also, the absolute distances per period were plotted to reveal the trend in the distance between the two contours, and consequently to the shoreface gradient, for a specific location along the coast.

3.2.2 Focus points regarding aspect and gradient

Points of improvement regarding the execution of the contour analysis to retrieve the slope characteristic 'gradient' are based on the points of discussion made in Krawczyk's report and several aspects that should be considered according to this research. The aspects that will be addressed within this research are the following:

- Although, the 0 m contour can easily be chosen as the top of the slope, the variation in the extent of the data limits the ability to choose a base contour at a depth representing the base of the shoreface (i.e. the depth of closure). A visual analysis of the location of different contour depths over the extent of the JARKUS Grids data can be performed to choose a depth that is frequently reached by the dataset to represent the slope base.

- The same or similar method based on the change in attribute can be readily applied also to the study of the aspect and curvature of the shoreface slope since these are simply different attributes based on the same raster format. However, studying aspect in the same way as the gradient from a change in geometry perspective is not possible, since they cannot be easily derived from contours.

4. Methodology

To be able to design a contour analysis that fits the purpose of this specific research, a structured methodology is necessary to prevent errors. Firstly, a general workflow (Fig 5.)

is set up after which each element will be described in more detail. By following these exact steps one is assured that no essential steps remain unexecuted, causing faults. Firstly, the study area and the data used will be described. After that the methodology concerning the data preparation, DBM-based contour analysis, aspect analysis and central Holland coast analysis will be provided.

Figure 5: General study workflow

4.1 Case study

This study was developed specifically for the central Holland coast. In this section the study area and the data used for this study will be described.

4.1.1 Study area

The central Holland coast is a wave-dominated coast, has a length of 120 km and is essentially orientated in a North-East to South-West direction (Wijnberg, 2002) (Fig. 2). The central Holland coast is bounded by a tidal inlet (the Marsdiep) in the north and by the Rotterdam Harbour in the south. This is also the location where the river Rhine flows out into the sea. Along the Delfland coast, which is the southern section of the central Holland coast between Hoek van Holland and Scheveningen, the Sand Engine is located. However, the study area is located north of the Sand Engine, ranging from Wassenaar to Zandvoort, as this is the part of the central Holland coast along which the Sand Engine's sediment is distributed (Fig. 6).

Figure 6: Study area from Wassenaar to Zandvoort (Google)

4.1.2 JARKUS data

The JARKUS data ('JAaRlijkse KUStlodingen' – annual soundings) are a collection of cross-shore bathymetric profiles covering the entire coast of the Netherlands. The data has been collected annually by the Dutch Department of Public Works since 1963. This is done by surveying the cross-shore profiles at fixed 250 m spaced transects perpendicular to the shore line (van der Spek & Elias, 2013). The JARKUS profiles consist of point measurements (X, Y and Z) along the transects, the cross-shore resolution varies from 5 to 40 m and the longshore spacing is 200 m marked by beach poles known as the RSP ('Rijks Strand Palen lijn') reference line. The length of the transects is not consistent over time due to changes in policy and measuring techniques (Krawczyk, 2017).

The transects are made up of wet measurements, collected through ship-based echo-sounding, and dry measurements, most recently collected through laser altimetry (LIDAR). The data's vertical accuracy is 0.25 m. The sounding accuracy of depth values is 0.15, but increases to 0.25m when ship dependent errors are taken into account (Hinton, 2000). The JARKUS data are divided into 16 coastal sections (North to South: Schiermonnikoog, Ameland, Terschelling, Vlieland, Texel, Noord-Holland, Rijnland, Delfland, Maasvlakte/slufter, Voorne, Goeree, Schouwen, Oosterschelde/Neeltje Jans, Noord-Beveland, Walcheren, and Zeeuws-Vlaanderen). The raw data is available on the Open Earth Raw Data repository from Rijkswaterstaat as *.jrk files (plain text).

This study uses raster DTMs interpolated from the JARKUS data and transformed to the ESRI native ADF format by Deltares. It covers the entire coast for the years 1963 to 2016 and the grids are projected to the Amersfoort / RD New spatial reference system with a resolution of 20 x 20 m. For this study only the JARKUS grids that fall within the study area will be used. Up until 1985 the data covers a length of about a 1000 m from the top of the first dunes towards the sea. After that the most northern part of the coast, from Zandvoort to the border between Noord- and Zuid-Holland, covers a length of 2500 m. From 2005 onwards the remaining part of the coast within the study area also covers this length. For the years 1963 and 2006 these grids contain NoData. Within the JARKUS grids area, the elevation ranges from -15m to +28 m.

4.2 Data pre-processing

The pre-processing of the JARKUS data as the second element in the general study workflow consists of cropping the data to the study area extent and performing the correct spatial and temporal smoothing that fits the analysis. Both steps are described in the following section.

4.2.1 Cropping the data to the study area extent

At first one has to make sure that only the data relevant for the specified study area will be used within the data analysis. Therefore, it is of great importance that an extent is set to which all data used will be cropped. The chosen extent fits the coastal zone ranging from Wassenaar to Zandvoort (Table 2).

Table 2: Extent of case study area in RD New projected coordinate system

Top:	487490	Left:	80010
Bottom:	462510	Right:	99990

4.2.2 Considering the spatio-temporal resolution of the analysis

After cropping the data to the study area extent the spatio-temporal resolution of the analysis must be considered. In the temporal dimension a smoothing, using an overlapping simple moving average with a window size of 10 years, resulted in erasing short-term fluctuations around the trend. Given the fact that these short-term fluctuations are likely to be of interest when looking at nearshore sandbars, the decision was made to analyze the results of using window sizes smaller than 10 years. For this purpose the tool 'Cell statistics' in ArcGIS is used. By choosing one of the available statistics (majority, maximum, mean, etc.) it calculates a per-cell statistic from multiple rasters (Cell Statistics, 2016). The rasters representing the years of interest are entered and the chosen statistic is the mean, performing a simple moving average for a window size of choice.

While testing, it was made sure that years containing NoData were not used during the assessment to prevent that smoothing periods were assigned a value based on less years containing a valid measurement than the test was performed for. Using smaller window sizes decreases the number of years that might have to be discarded at the end of the time series, reduces the number of years containing NoData within one smoothing period and increases the chance that changes considering nearshore sandbars will be visible. Conclusion is that a temporal smoothing sensitivity analysis was performed following Krawczyk's method, but for window sizes of 2, 4, 6 and 8 years (Fig 7: Step 1).

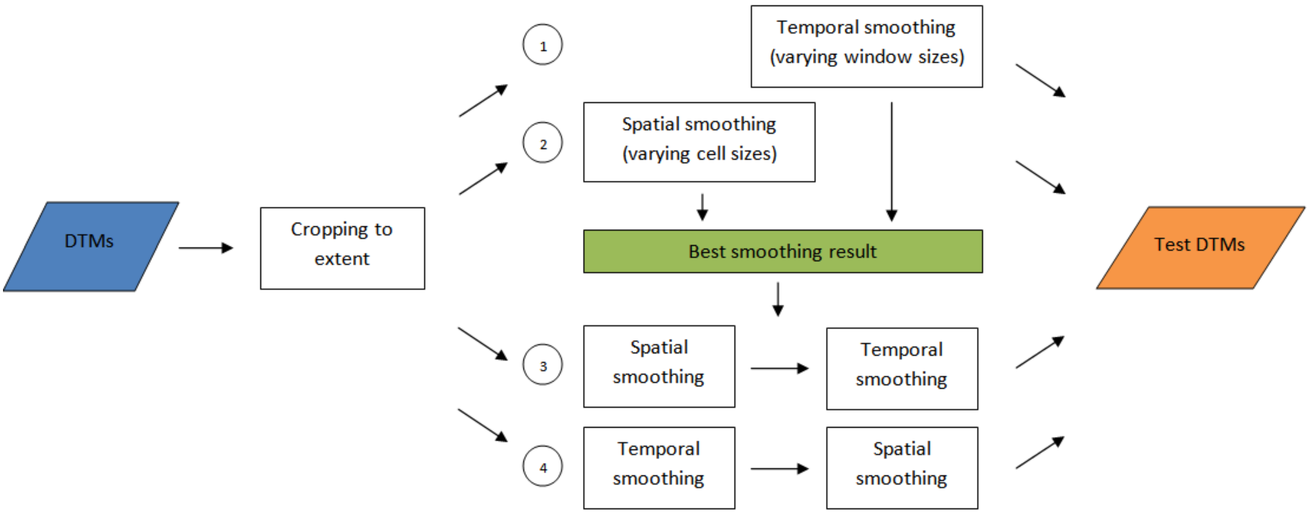


Figure 7: Spatio-temporal resolution workflow

Regarding the spatial smoothing, a simple aggregation based on the mean, resulting in an output cell size of 200 m was performed. This type of smoothing reduces the visibility of small features including sandbars, as was confirmed by Krawczyk's sensitivity analysis showing movement of the contours below 200 m. Another conclusion drawn from Krawczyk's sensitivity analysis was that the rasters at the original 20 m cell size, did not show any dramatic changes in comparison to the tested 40 and 80 m cell sizes. One of the possible explanations for this is that the spatial sensitivity was conducted on the temporally smoothed rasters, so smaller features were already smoothed out. Given these two remarks, the decision was made to add two altered methods within the spatial and temporal resolution workflow. A spatial sensitivity analysis will be performed for cell sizes of 5 and 10 m, which means in this case it concerns a spatial alteration, cell size 20 (no smoothing) and cell size 40 (spatial smoothing) (Fig 7: Step 2). The spatial alterations have been executed using the ‘Resample’ tool in ArcGIS. It alters the raster dataset by changing the cell size using a specified resampling method. In this case the bilinear option was chosen, which performs a bilinear interpolation, meaning that it determines the new value of a cell based on a weighted distance average of the four nearest input cell centers (Resample, 2017). Furthermore, the spatial and temporal smoothing will be performed in the original and reversed order using the window size and cell size that gave the best result in visualizing near shore sandbar changes during the sensitivity analysis (Fig 7: Step 3 + 4).

4.3 DBM-based contour analysis

Krawczyk’s method for deriving the gradient slope characteristic was evaluated and found suitable for this specific research. After all, performing it results in information (absolute distance) about the steepening or flattening of the slope and provides information (relative distance) about the location and dynamics of a specific contour, which is the exact information needed to detect the nearshore bars determining the critical shoreface contour line. Therefore Krawczyk’s contour analysis workflow (Fig. 9) will be followed using parameters fitted to this research.

Transects are drawn along the central Holland coast (Fig. 8) that were spaced out evenly along the length of the shore. These transects are placed in a north-west direction because the orientation is of less of a concern as long as it is long enough to cross the part of the JARKUS data set along the coast where the near shore sandbars are located. They were spaced 4 km from each other, resulting in 7 transects, based on the temporal scale being investigated (years) the corresponding spatial scale (1 km) derived from Table 1, the extent of the data and the total length of the study area (28 km). The parameters regarding the generation of contours remained unchanged, at an interval of 1 m, with the starting point of 0 m, representing the shoreline.

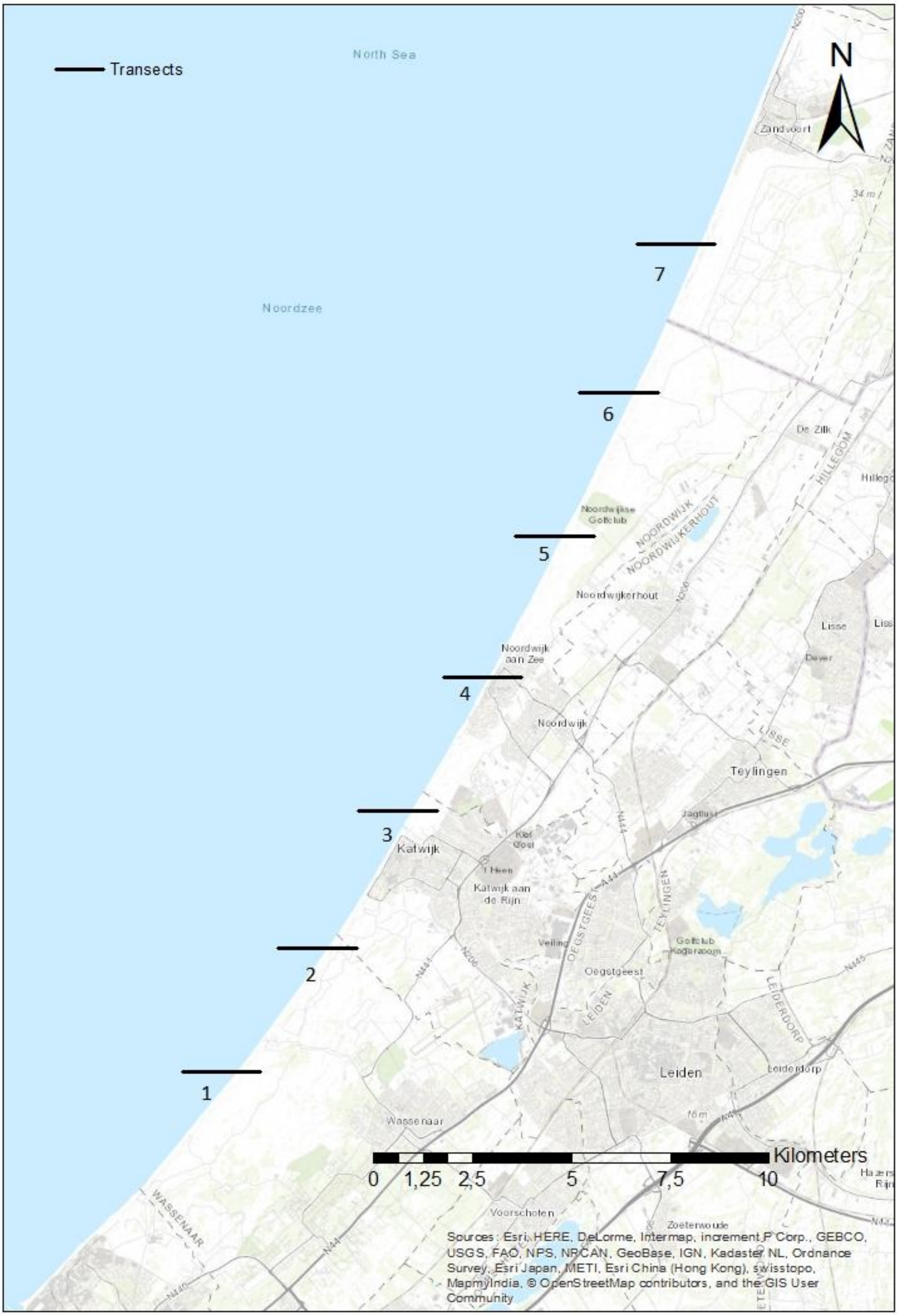


Figure 8: Position of transects for contour analysis along the central Holland coast and their corresponding number

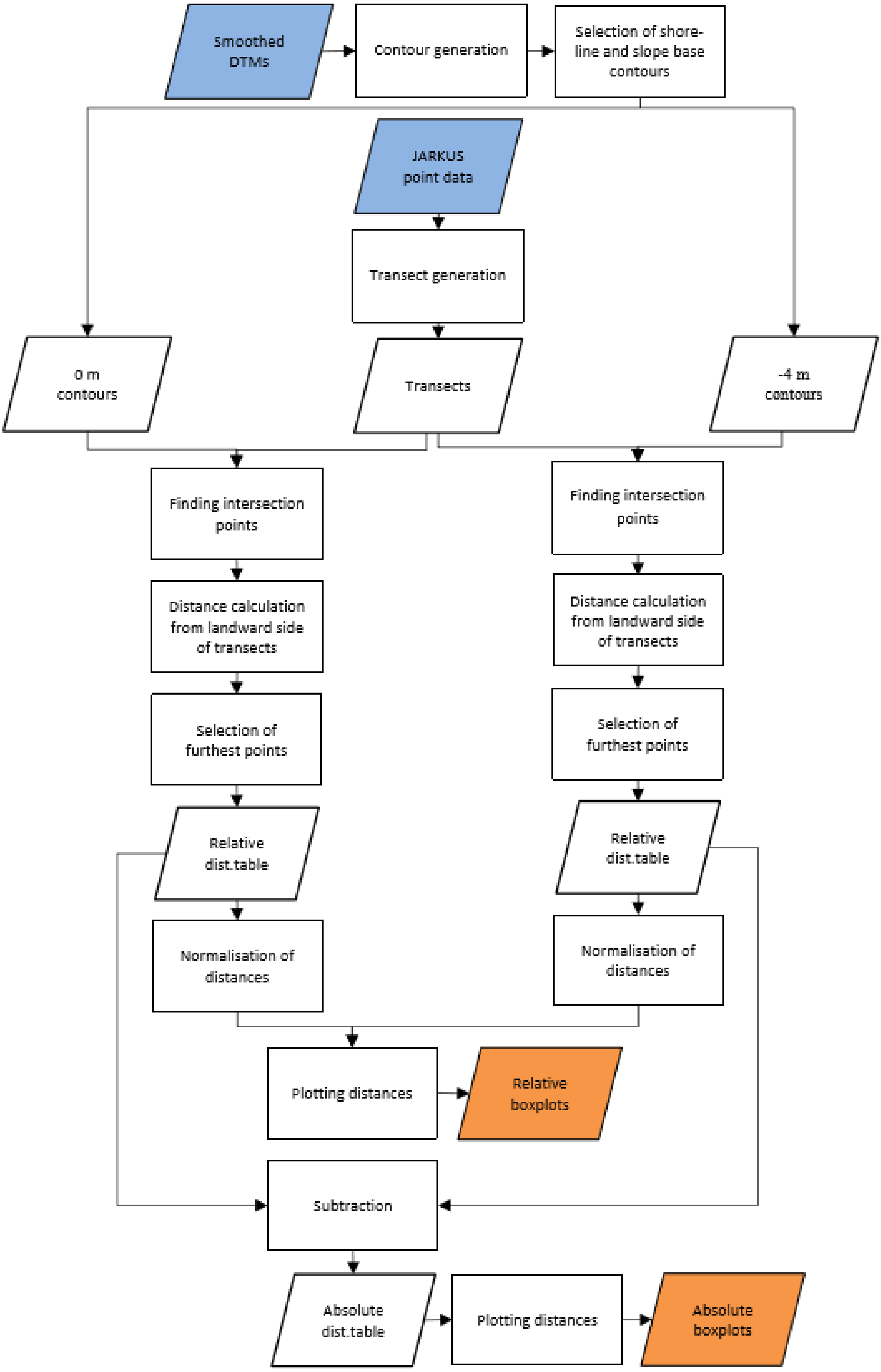


Figure 9: Contour analysis workflow

4.4 Aspect analysis

As soon as the location of the near shore bars has become visible during the contour analysis, their orientation can be derived by calculating the aspect. For this purpose the 'Aspect' tool in ArcGIS will be implemented on the DBMs that were temporally and/or spatially smoothed during the data preparation. A moving 3 x 3 windows visits each cell in the DBM raster and calculates an aspect value for each cell by using an algorithm viewing the values of the cell's eight neighbors. In Figure 10 cells are identified as letters a to i, with e representing the cell for which the aspect is being calculated (Aspect, 2017).

First the rate of change in the x direction for cell e is calculated.

```
[dz/dx] = ((c + 2f + i) - (a + 2d + g)) / 8
```

Additionally, the rate of change in the y direction is calculated.

```
[dz/dy] = ((g + 2h + i) - (a + 2b + c)) / 8
```

Using this rate of change in x and y direction for cell e, the aspect is calculated.

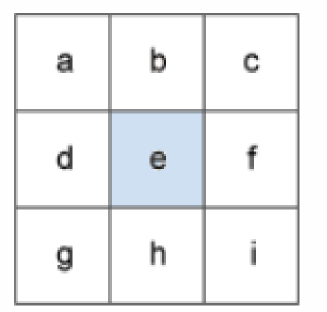


Figure 10: Surface window

```
aspect = 57.29578 * atan2 ([dz/dy], -[dz/dx])
```

Finally, the aspect value is converted to the compass direction values (0-360 degrees) using the following rule:

```
if aspect < 0
    cell = 90.0 - aspect  else if aspect > 90.0
    cell = 360.0 - aspect + 90.0
  else
    cell = 90.0 - aspect
```

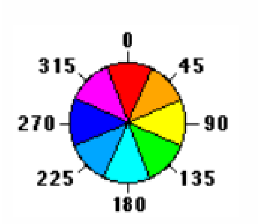


Figure 11: Aspect directions

By performing this calculation the slope direction of each cell is indicated using a compass direction visualized using a color code (Fig. 11) representing the degrees from 0 (north), to 180 (south), back to 360 (north again).

4.5 Central Holland coast analysis

As finalization of the entire analysis, the results of the contour based DBM-analysis and aspect analysis will be used to show how the central Holland shoreface's capability of protecting the mainland can be evaluated. As an example the critical shore face contour line will be determined for the time periods before, during and after 1990 and before, during and after 2011 for the coast of one specific transect. For this purpose a transect will be chosen showing most dynamics based on the aspect analysis. Using literature discussing the effects of the Sand Motor one can evaluate whether the DBM-based contour and aspect analysis can be used as a reliable method for deriving the changes in the morphology of the shoreface.

5. Results

Within this section, the results that were conducted by performing the spatio-temporal sensitivity analysis, the contour analysis, the aspect analysis and the central Holland coast analysis are described. Each of the analysis' contribute to formulating an answer on the research questions asked in this study.

5.1 Results of the Spatio-Temporal sensitivity analysis

The spatio-temporal sensitivity analysis was performed to be able to fit the data to the specific purpose of this study, so that it could be used in the contour, aspect and central Holland analysis. Thereby it contributes to answering the second research question of this study.

Considering the temporal smoothing it has become clear that the less temporal smoothing is applied, the better the nearshore sandbars are visible. This fits with the expected outcome derived from Figure 3, showing that sandbars have an annual cycle, and Table 1, indicating that the most suitable time scale for sandbars is years (features with a morphodynamic length scale of 1 km fitting in the scale description medium). The maps showing the temporal smoothing using a window size of 4, 6 and 8 years show almost no distinction, while the map with a 2 year window size shows a clear distinction in height between sample points 1 and 2 (Fig. 13) that is far less visible in the other maps (Appendix 2: Selecting a suitable moving window size for visualizing sandbars). This is also made clear when the actual depth values of the sample points for all the window sizes are retrieved (Table 3). Sample points 1 and 3 show considerable differentiation in depth values between the 2 year moving window and the others. Since the 2 year moving window gave the best result, this temporal smoothing was applied in the rest of the study.

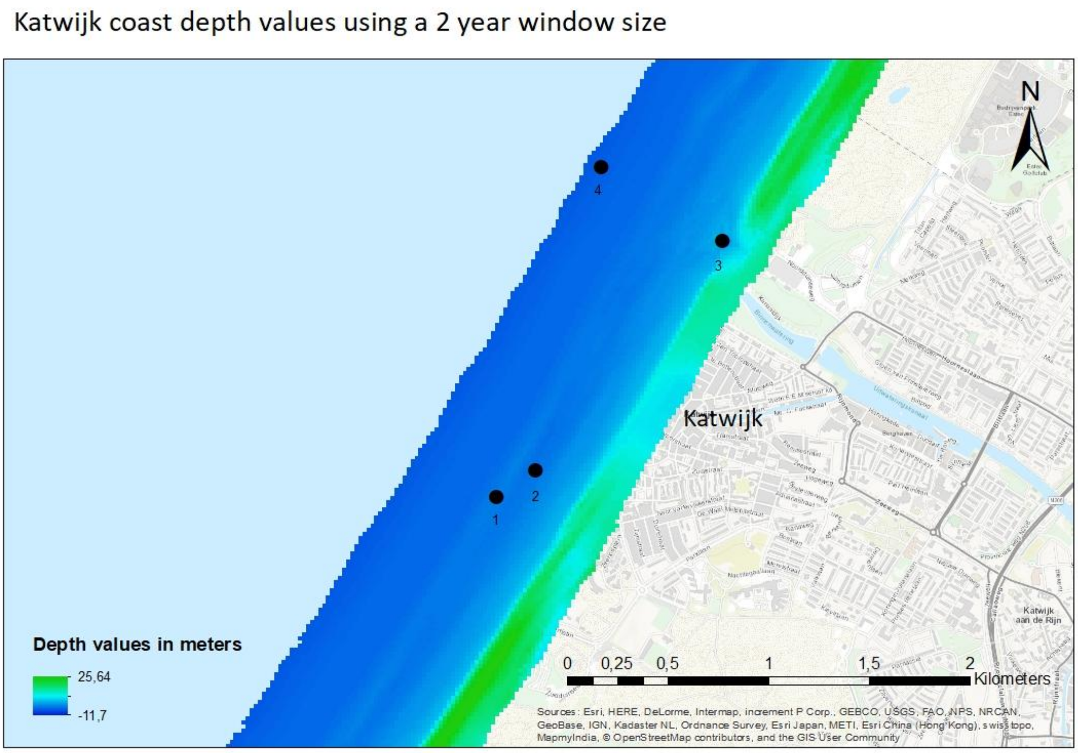


Figure 12: Location of sample pixels (based on JARKUS Grid from 1988)

With regards to altering the cell sizes of the JARKUS Grids using the resampling and aggregation tools from ESRI, one can say that increasing the resolution rather than decreasing show better results (Appendix 1: Selecting a suitable cell size for visualizing sandbars). The grids with a cell size of 20 and 40 m show a blurred image of features on the shoreface such as sandbars. Although both grids with a cell size of 5 and 10 m contain an increased visibility of these features, there is still a small distinction between the two. The grid with a cell size of 5 m portrays a sharper distinction between the values on the shoreface and the beach than the 10 m cell size grid. For the rest of the analysis, the cell size of 5 m was chosen since elongated sandbars are visible and the distinction between the beach and the shoreface is clear.

Table 3: Depth values from sample pixels for window sizes of 2, 4, 6 and 8 years starting from 1988

Sample pixel 1		Sample pixel 2	
Window size in years	Depth value	Window size in years	Depth value
2	-2,6	2	-3,33
4	-3,47	4	-3,59
6	-3,43	6	-3,21
8	-3,77	8	-3,37

Sample pixel 3		Sample pixel 4	
Window size in years	Depth value	Window size in years	Depth value
2	1,42	2	-5,31
4	0,99	4	-5,48
6	0,71	6	-5,42
8	0,88	8	-5,4

Performing a temporal smoothing before a spatial alteration results in no different values or image than performing a spatial alteration before a temporal smoothing (Appendix 3: Considering the order of spatial alteration and temporal smoothing). First the grids representing the years 1988 and 1989 were resampled to a cell size of 5 m. After that the tool Cell Statistics was implemented based on the mean, thereby performing a spatial alteration before a temporal smoothing. Finally, the tool Cell Statistics was used based on the mean after which the smoothed period 1989_99 was resampled to a cell size of 5 m.

5.2 Results of the contour analysis

This contour analysis with its specific methodology was performed to contribute to the answer of the second research question. While performing the contour analysis, conclusions drawn from the spatio-temporal sensitivity analysis were taken into account. A temporal smoothing was performed using a 2 year window, resulting in periods of data ranging from 1987_88 till 1993_94 and 2008_09 till 2014_15. After that the data was spatially altered to a cell size of 5 m. Furthermore, it was necessary to choose two contour lines representing the top and base of the slope to be studied. The 0 m contour was chosen as the top of the slope and the -4 m contour as the base of the slope, following the workflow presented in Figure 10.

The relative distance boxplots (Fig 13 & 14) show the spatial variation in the dynamics of the gradient of the slope. For the 0 m contour it is clear that transect 4 is most dynamic, shifting position with 10 to 90 meters across the years. After that transects 1 and 3 appear most dynamic while transects 2, 5, 6 and 7 appear fairly stable. For the -4 m contour however, results are quite different. As transect 4 was most dynamic in the top of its slope, together with transect 3 it is most stable in its base. Transects 1, 2, 6 and 7 appear most dynamic in this case with maximum of shifting position with almost 150 m, showing that the -4 m contour line is more dynamic than the 0 m contour line in general.

The absolute distance between the 0 and -4 m contours for each transect show little variation except for the fact that the contours at transects 5, 6 and 7 seem to shift slightly more meters than the others (Fig. 15). These small differences in variation between the transects can be explained when looking back at the boxplots presenting the relative distances. Centre transects (3 and 4) showed high dynamics at the top of the slope (0 m) and low dynamics at the base (-4 m), compensating their absolute distance to each other. On the other hand, transects furthest to the north (6 and 7) and south (1 and 2) of the coast showed reversed dynamics being high at the -4 m contour and low the top of the slope, giving the same result concerning their absolute distance.

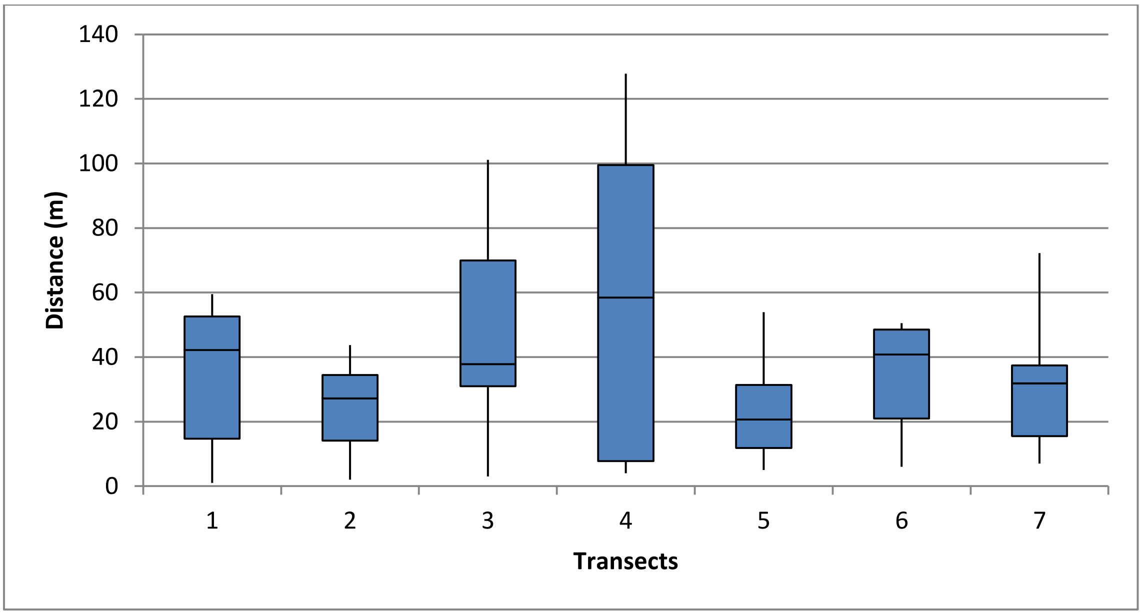


Figure 13: Relative distances of the 0 m contour from the first intersection of a contour with the transect for JARKUS Grids with a 2 year temporal smoothing and 5 m cell size for 8 time periods

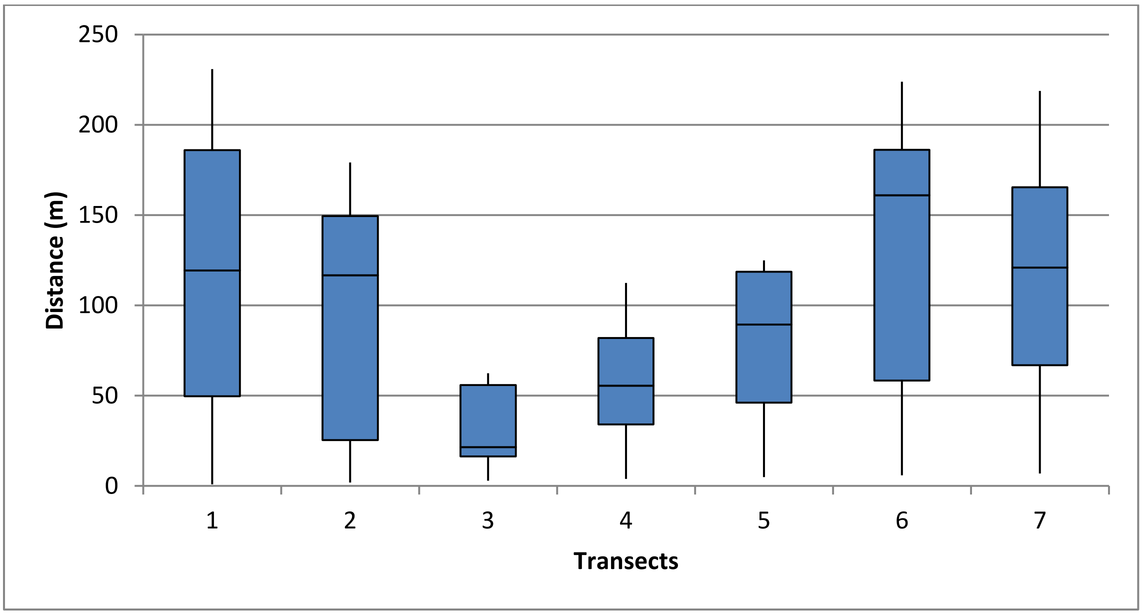


Figure 14: Relative distances of the -4 m contour from the first intersection of a contour with the transect for JARKUS Grids with a 2 year temporal smoothing and 5 m cell size for 8 time periods

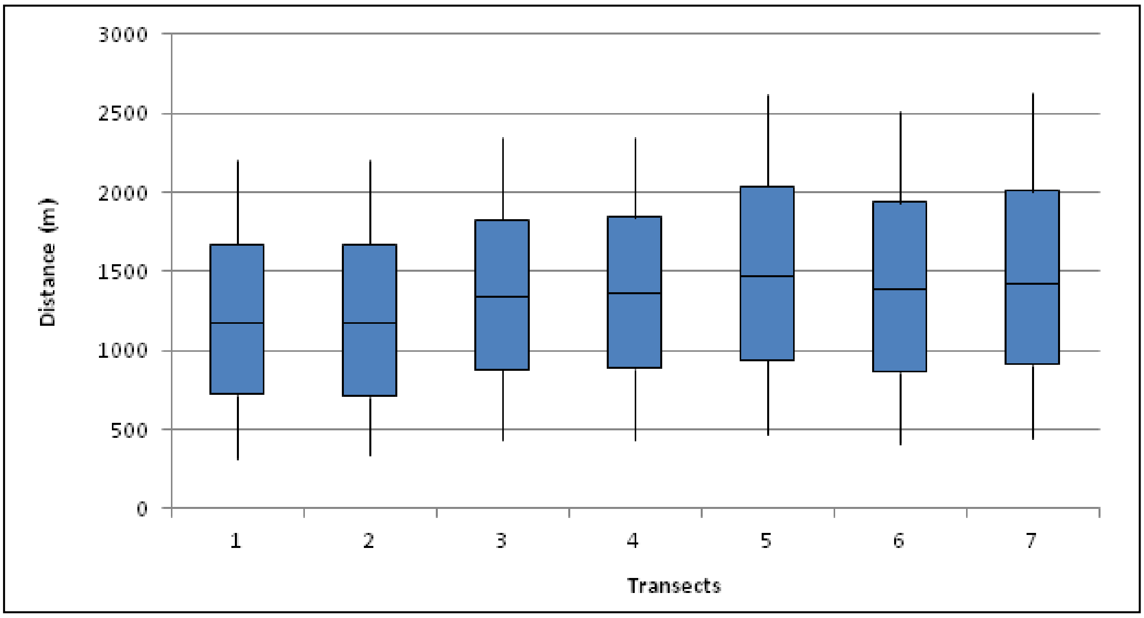


Figure 15: Absolute distances between the 0 and -4 m contour for JARKUS Grids with a 2 year temporal smoothing and 5 m cell size for 8 time periods

5.3 Results of the aspect analysis

This aspect analysis was performed to contribute to the answer of the second research question in combination with the contour analysis that has been performed. The aspect was calculated from 1987 till 1994 (Appendix 4: Aspect analysis 1987 – 1994) and 2008 till 2015 (Appendix 5: Aspect analysis 2008 – 2015) in time periods of two years. The most common orientations along the central Holland coast are southeast, west and northwest. The point at which the orientation shifts from southeast to northwest or west can be seen as the top of a sandbar revealing their exact location.

In 1987_88 the main visible feature is one elongated sandbar stretching out along almost the entire coast with some small interruptions. In 1989_90 this sandbar has thickened along the coast near Katwijk, developing into a mainly southeast orientated sandbar, but has unraveled further north, where also the start of a new sandbar further out into the ocean can be seen. Moving further in time, the thickened sandbar near Katwijk has crumbled and separate parts have shifted toward the coast but also towards the ocean. Further north the second sandbar that was developing has merged with the original sandbar, forming one sandbar with a larger southeast orientated part. Finally, in 1993_94, the structure of the sandbars has almost returned to the state it was in in 1987_88. The crumbled sandbars near Katwijk seem to be merging together and further north, near Noordwijk, the sandbar has thickened resulting in one elongated sandbar with a larger southeast orientated part than in 1987_88.

Although time period 1987 till 1994 already showed quite some shifts in nearshore sandbars location and structure, time period 2008 till 2014 show even more dynamics. In 2008_09 one can clearly distinct two main sandbars along the coast near Katwijk and further north even four rows of sandbars have become visible running parallel to the coast. The years after in 2010_11 the two sandbars along the coast near Katwijk show signs of degradation with several sand deposits further out into the ocean. The rows of sandbars further north however remain in place, indicating that such a larger construction of sandbars is more resistant to the influences of the ongoing currents along the coast. Nevertheless, the natural sandbar cycle of generation, seaward migration and destruction can never be stopped as becomes visible in 2012_13. The sandbars near Katwijk crumble further and even the one remaining sandbar has been divided into two parts. Further north the rows of sandbars are thinning, resulting in less sandbars that additionally have a smaller southeast orientated part. In the northern part of the coast in 2014_15 the destruction phase of the sandbars is continuing with entirely north only two sandbars remaining. However, along the coast near Katwijk and moving north signs of generation are visible with the sandbar furthest into to the ocean thickening and a second sandbar closer to the coast generating.

5.4 Results of the central Holland coast analysis

The central Holland coast analysis was performed to be able to answer the third research question of this study. For the central Holland coast analysis one of the transects was chosen to show how the results of the DBM-based contour analysis and aspect analysis can be used to evaluate the shoreface's capability of protecting the mainland. In this case Transect 5 was chosen, given that it has proven itself to cross a part of the shoreface with multiple sandbars based on the aspect analysis (Appendix 4: Aspect analysis period 1987 – 1994).

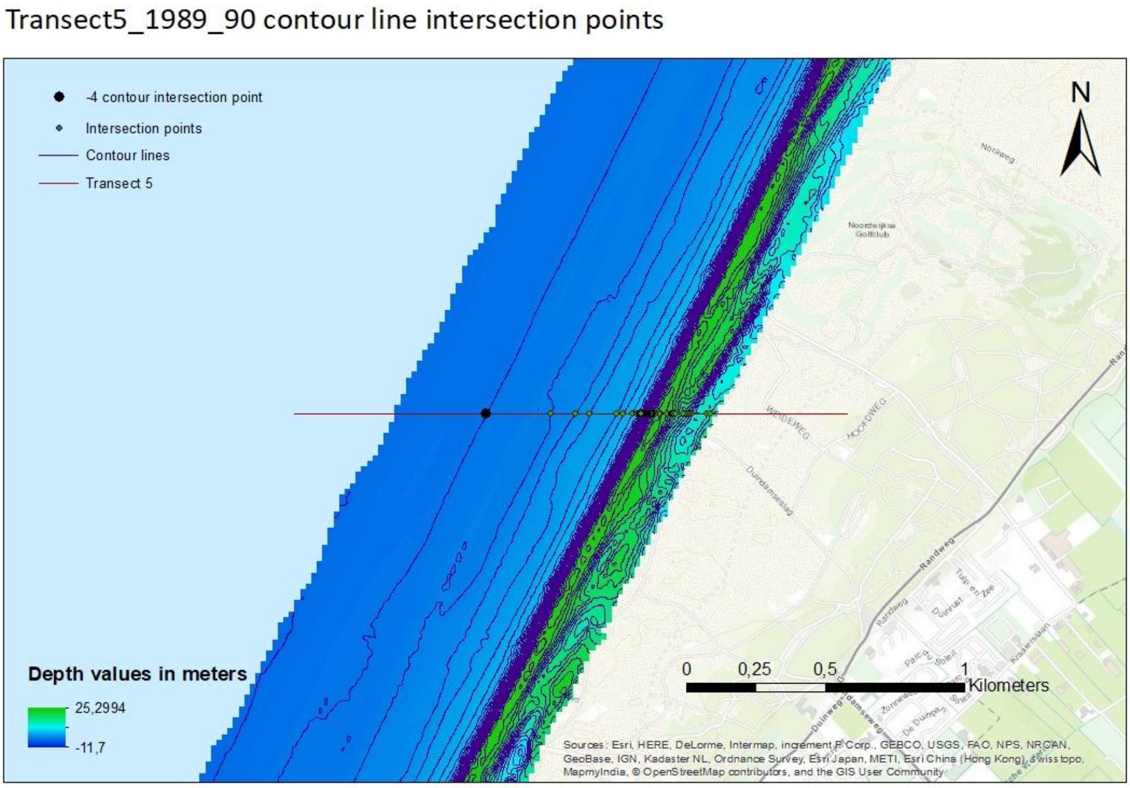


Figure 16: Intersection points of contour lines with Transect 5 in time period 1989_90

Determining the critical shoreface contour line by localizing the nearshore sandbars in 1990 resulted in a contour line of -4 (Fig 16). Focusing on the -4 contour furthest away from the coast (as the critical shoreface contour line is represented by the first nearshore bar seen from the ocean), the critical shoreface contour line in 1987_88 was located at a distance of 1415 m from the beginning (landward side) of the transect (Table 4)(Appendix 6: central Holland coast analysis period 1987 – 1994). According to expectation, based on the fact that the Dynamic Preservation Policy was implemented because of severe erosion of the coast, the -4 contour has shifted towards the coast and located itself at 1298,1 m from the beginning of the transect in 1989_1990. Additionally, other -4 contours have disappeared, indicating that there are no sandbars closer to the coast with bases lying lower than -4 meters. In the periods 1991_92 and 1993_94 other -4 contour lines have reappeared and the critical shoreface contour line has started shifting offshore again and located itself at 1410,6 and 1418,1 m respectively.

Table 4: Distances (m) of the critical shoreface contour line from the beginning (landward side) of the transects for time periods 1987_88 till 1993_94

	1	2	3	4	5	6	7
1987_88	1079,9	1251,1	1216,3	1383,9	1415	1136,3	1049,9
1989_90	1159,1	1365,8	1236,3	1411,7	1298,1	1221,5	864,9
1991_92	1094,8	1399,7	1275,8	1416,7	1410,6	1079,5	993,2
1993_94	1139,8	1323,2	1233,2	1414,7	1418,1	1118,9	854,9

For 2008_09 the critical shoreface contour line has moved towards the coast compared to 1993_1994 and is located at a distance of 1388,1 m and continues this shift by locating itself at 1376,7 m from the beginning of the transect in 2010_11 (Table 5)(Appendix 7: central Holland coast analysis period 2008 – 2015). In 2012_13 the generation of a new sandbar is visible causing the critical shoreface contour line to shift offshore by about 170 meters locating itself at 1540 m along the transect. In 2014_15 this new sandbar seems to have been degraded by currents and the critical shoreface contour line has retaken its position at 1342,3 m comparable to its location in 2010_11.

Table 5: Distances (m) of the critical shoreface contour line from the beginning (landward side) of the transects for time periods 2008_09 till 2014_15

	1	2	3	4	5	6	7
2008_09	1309,8	1351,2	1231,3	1454	1388,1	1247,5	1001,1
2010_11	1289,8	1382,5	1224,7	1458,8	1376,7	1262	1066,7
2012_13	1256,6	1222,5	1268,9	1492,4	1540	1258,9	931,4
2014_15	1237,3	1230,7	1269,8	1470,6	1342,3	1297,4	944,4

6. Conclusion

This research provided a method to indicate the shoreface's capability of protecting the mainland based on its morphology. For this purpose a critical shoreface contour line was defined and a DBM-based contour analysis was developed as part of this method. The key findings of the research questions used to develop the overall method and evaluate its functioning are discussed below.

1. **What is the definition of a critical shoreface contour line?**

The shoreface is the upper part of the continental shelf that is affected by contemporary wave processes and that it runs from the offshore landward to the low tide line. However, it can be subdivided into the upper and lower shoreface. Because of the fact that nearshore bars found in the upper shoreface play a major part in protecting the mainland and is therefore the area of interest, whenever the term shoreface is used, the upper shoreface is meant.

A shoreface becomes critical when sea level rises too high, storm events occur that produce waves the shoreface cannot buffer, beach width is too narrow and nearshore bars are lacking, too small or located ineffectively. These aspects are critical based on the following values found in literature regarding this specific shoreface of the central Holland coast. Sea level rise was found to be too high at +7m NAP. 117 meters is the width of the beach for which the Dutch government found it was no longer acceptable. Finally, in 1990 the Dynamic Preservation Policy was implemented because, amongst other factors, nearshore bars were considered too few in number, too small and not located perfectly. Therefore, this specific moment was chosen as the critical reference for nearshore sandbars.

The contour line in this case is a line connecting all cells in the JARKUS grids that posses equal elevation. Finally, the critical shoreface contour line is the height contour line at which the first nearshore bar (towards the shoreline) is located that is most comparable regarding gradient and aspect with the first nearshore bar in 1990.

2. **What contour analysis should be used to fit the purpose of this research?**

The methodology to analyse contours has paid special attention to several concepts. Especially the fit to the spatial and temporal scale of the phenomenon being studied. After a spatio-temporal sensitivity analysis it became apparent that for the spatial resolution a cell size of 5*5 m is best suitable, since elongated sandbars are most visible and the distinction between the beach and the shoreface is most clear. The second result is that the best temporal resolution for the data is 2 years (averaged). These values are in line with the literature indicating that sandbars have an annual cycle and that features with a morphodynamic length scale of 1 km fit in the description medium (Table 1), which is a time scale of years.

For the purpose of deriving the exact morphology of the shoreface and nearshore bars, the concepts of aspect and gradient are addressed while developing the methodology of the DBM-based contour analysis.

To retrieve the gradient, transects are drawn crossing the central Holland shoreface to acquire the absolute and relative distance of contour lines. The absolute distance provides information about the change in the gradient attribute, i.e. the steepening or flattening of the slope, while the relative distance generates information about the changes to their spatial dimension, i.e. the location and dynamics of a specific contour. The spacing distance needs to be chosen after considering the spatial and temporal scale, which is in this case 1 km and years. After that the contours need to be generated for each period at a specified interval (1 m) and with a starting point representing the shoreline (0 m). The relative distance is calculated by generating points at the intersection of the transect and the two selected contours, per line, per period after which the distance from the start of the transect to each point is calculated. This results in two tables containing information about either the distance of the 0 m contour or the slope base contour from which boxplots are plotted to allow for an assessment and comparison of the contour dynamics along the central Holland coast. After that the absolute distances between the 0 m contour and the slope base contour are generated and plotted as boxplots per transect to allow for an assessment of the dynamics of the changes to the gradient of the shoreface slope.

The aspect is calculated using the ArcGIS tool 'Aspect' after which a first indication can be made about which location along the central Holland coast shows the most sandbars and dynamics in shoreface morphology. For this purpose the border between a Southeast and Northwest or West orientation is seen as the location of a sandbar. The combination of first indicating the location of the sandbar and after that retrieving the gradient provides the base for performing the central Holland coast analysis. Using this information the critical shoreface contour line can be determined for the transect of interest and the shoreface dynamics along this transect can be evaluated.

3. **What changes in location of the critical shoreface contour line can be detected?**

From the results of the central Holland analysis it becomes visible that the critical shoreface contour line shifts through time. In 1987_88 it was located at a distance of 1415 m from the beginning (landward side) of the transect and shifted towards the coast in 1989_1990. This shift towards the coast is reversed in 1991_92 and has become an offshore shift. This offshore shift can also be seen when evaluating the periods of 2010_11 and 2012_13. However, in 2014_15 a shift towards the coast occurs again. Nearshore bars are very dynamic and can migrate onshore or offshore in response to changing wave energy level, tidal range, bar size and water depth over the bar (Ruessink, Pape & Turner, 2009). Shifts towards the ocean indicates that there is a longer pathway for waves to move towards the coast without encountering buffering caused by nearshore sandbars. Alternatively, offshore shifts of the critical shoreface contour line indicate longer pathways across which more buffering by nearshore sandbars can take place. Moreover, the results also show that the farther offshore the critical shoreface contour line is located, the more additional sandbars are presents closer towards the coast (1991_92, 1993_94 and 2012_13). The more bars, the more friction, and due to friction, the shoreface buffers the power of the waves which reduce their height and energy (Cowell, 2000). Based on these results and confirmations of their role in protecting the mainland, one can say that a shift of the critical shoreface contour line towards the virtual coastline indicates a lower capability of the shoreface to protect the mainland and an offshore shift indicates a better capability.

4. **In what way does the literature regarding the effects of the Sand Motor validate the results derived from this research?**

The literature evaluating the effects of applying the Sand Engine show results that verify the offshore shift of the critical shoreface contour line in 2012_13. A paper by de Schipper, et al from 2016 presents the analysis of the morphological evolution of this 17 million m3 nourishment and the adjacent coastal sections during the first 18 months after implementation. It shows that the volumetric loss of the nourishment is about 10% of the added volume. The majority (70%) of these losses were found to be compensated by accretion on adjacent coastal sections. This is supported by a paper by Luijendijk et al. in 2017, also indicating that sand eroded from the Sand Engine is deposited along adjacent north and south coastlines. The cross-shore extent of the Sand Engine decreased by 150 m in this period as the alongshore size increased by 60% (de Schipper, et al., 2014). When merely comparing the results derived from evaluating the critical shoreface contour line's location and the results presented in literature, one can say that literature verifies the offshore shift that became apparent in this study.

7. Discussion and Recommendations

This discussion is set up in such a way that it addresses the main elements of this study. Thereby only analyzing the results of applying the developed methodology regarding spatial and temporal resolution, the contour, aspect and central Holland analysis.

Spatial and temporal resolution

The spatio-temporal sensitivity analysis has been performed to assure that the data used during the contour, aspect and central Holland analysis possessed the right cell size and consisted of periods in which nearshore sandbar shifts are visible. However, the assessment for indicating the right cell size and the most appropriate period of years was done visually. Although the results show clear differences, one should consider constructing a methodology that is more reproducible and independent of human interpretation. The extraction of the exact depth values from sample pixels give some back up to the conclusion drawn from visual assessment, but can still be considered as unsatisfactory.

Contour analysis

Specifically for this contour analysis it was necessary to choose a contour line representing the top of the slope and the base of the slope. As the base of the slope one would ideally use the depth of closure as the base contour. However, the JARKUS dataset does not extend sufficiently far out to sea to ensure that the depth of closure will be reached. Therefore, a visual assessment was necessary to select the maximum depth reached in the majority of the periods.

Additionally, transects had to be drawn along which the contour analysis could be performed. Although the right placement of these transects had been evaluated based on the corresponding spatial and temporal scale of the phenomena being studied, one more aspect could have been considered. The transects were placed in a horizontal position along the coast whereas the sandbars being investigated lie parallel with the coast. A perpendicular placement of the transects could have been more appropriate.

Aspect analysis

For this specific research the aspect analysis is performed as an indication of the location of the different sandbars and to provide an extra insight in the dynamics of the nearshore sandbars along the central Holland coast. Thereafter the contour analysis showed the movement of the first nearshore sandbar seen from the ocean by means of the critical shoreface contour line. However, the aspect analysis indicated more nearshore sandbars, but they are not taken into consideration using the method in this research. This is due to the fact that they did not possess a depth value of -4 m (the base contour). By using additional methods the aspect combined with the contour analysis could provide even more insight in the contribution of nearshore sandbars to the shoreface's protective role. For example, Dolan and Lucieer (2014) conducted research into different algorithms to derive slope gradient values, specifically for bathymetry data, and analyzed the results of combining these algorithms with different methods for varying the spatial scale. By expanding their analysis algorithms to derive other slope properties such as the aspect could be included.

Central Holland coast analysis

This central Holland coast analysis was performed to demonstrate how the developed methodology should be implemented in order to evaluate the shoreface's capability of protecting the mainland. However, to be able to draw conclusions about this with confidence, more research is necessary.

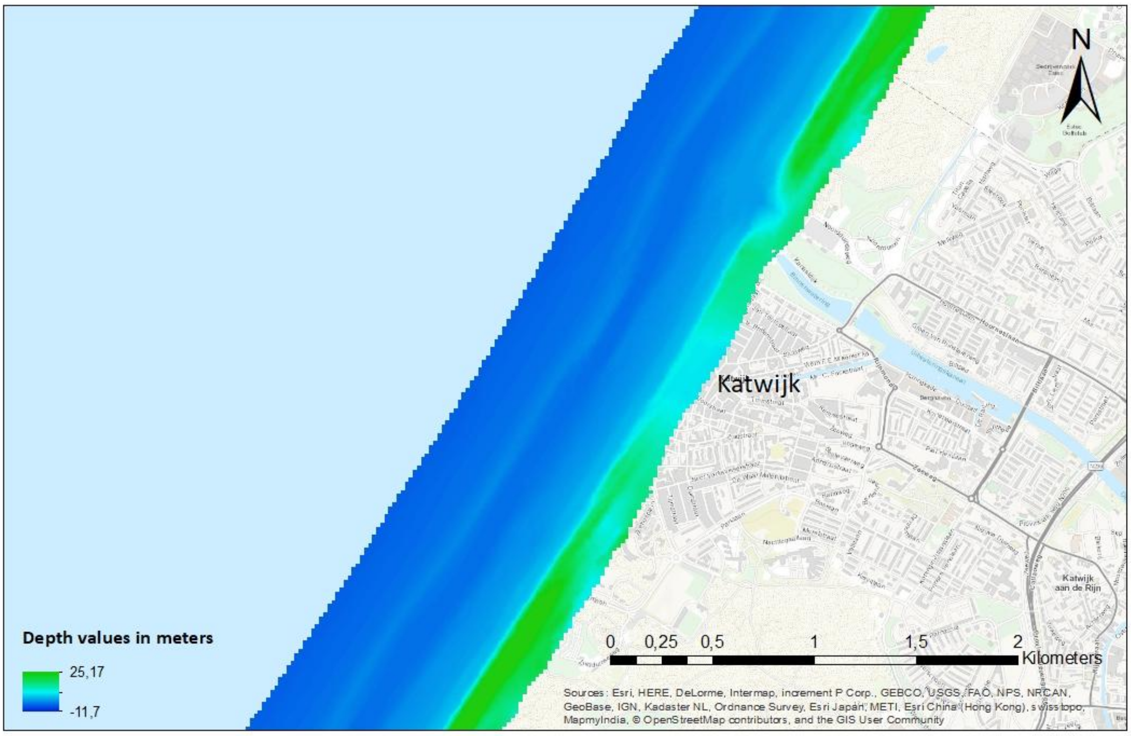
Only one transect has been evaluated on shifts of the critical shoreface contour line, while it is far more interesting to be able to visualize the shifts along the entire central Holland coast. Also the time period for which the shifts were presented is relatively short compared to the amount of data available. The years evaluated were deliberately chosen to gain insight of the shoreface's morphology in relation to the implementation of the Dynamic Preservation Policy and the Sand Motor. However, it covered only a time span of eight years around both events, hereby suggesting that more years should be evaluated to draw more solid conclusions about the shoreface's dynamics.

Additionally, literature indicates accretion of sediment on adjacent coastal sections that seem to fit with the generation of new nearshore sandbars and offshore shifts of the critical shoreface contour line in the years after 2011 (implementation of the Sand Motor). However, there is no solid prove that the latter is an effect of the implementation of the Sand Motor. It could well be possible that the generation phase that naturally occurs in sandbar cycles happens to coincide with the years after 2011.

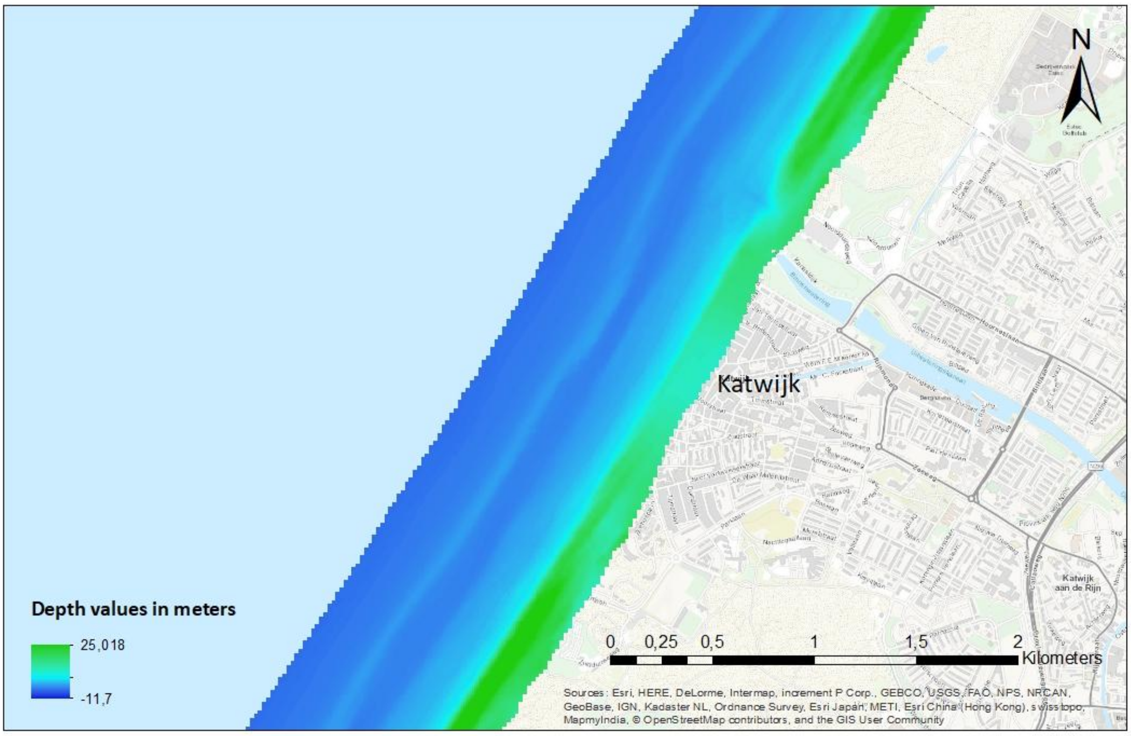
Finally, in Chapter 2 an explanation has been presented as to why the critical shoreface contour line has been based on nearshore bars present within the shoreface. However, the remaining aspects that were presented regarding whether a shoreface can be labeled as being in a critical state, are still an interesting source of inspiration to evaluate the shoreface's capability of protecting the shoreface even further. This can be done by doing additional research using methods specifically designed to evaluate shoreface characteristics and its contributions to protecting the coast against sea level rise and storm events.

Appendix 1: Selecting a suitable cell size for visualizing sandbars

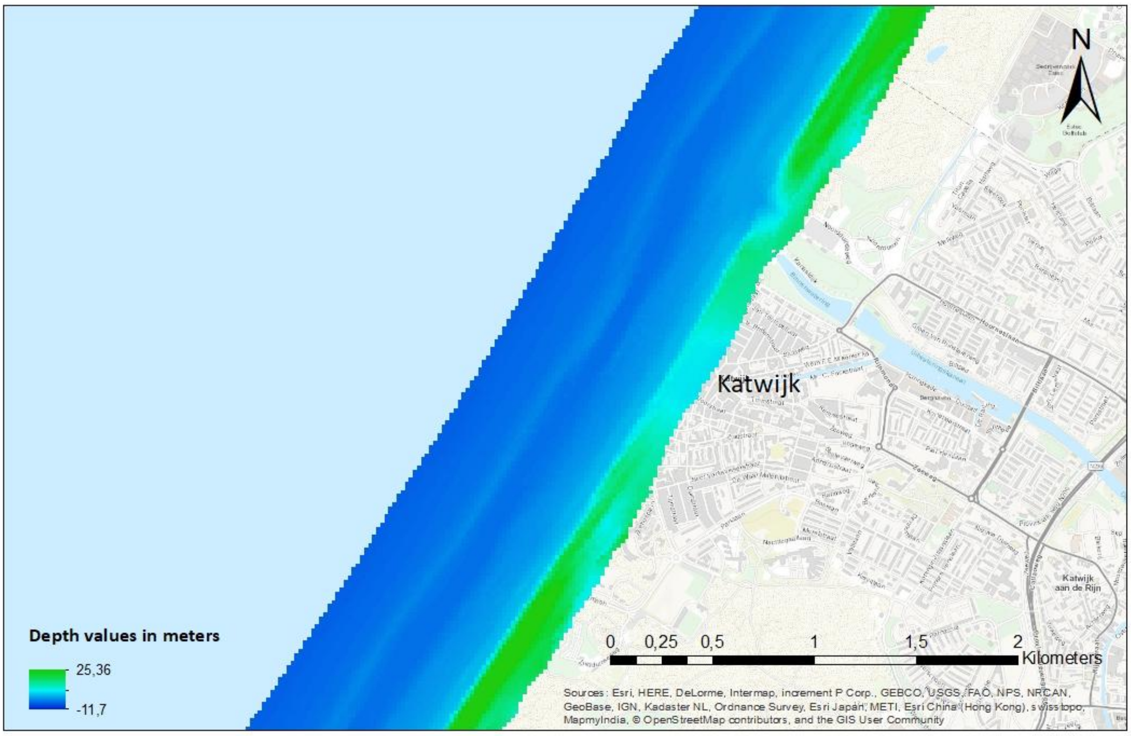
Katwijk coast depth values using a 5 x 5 m cell size



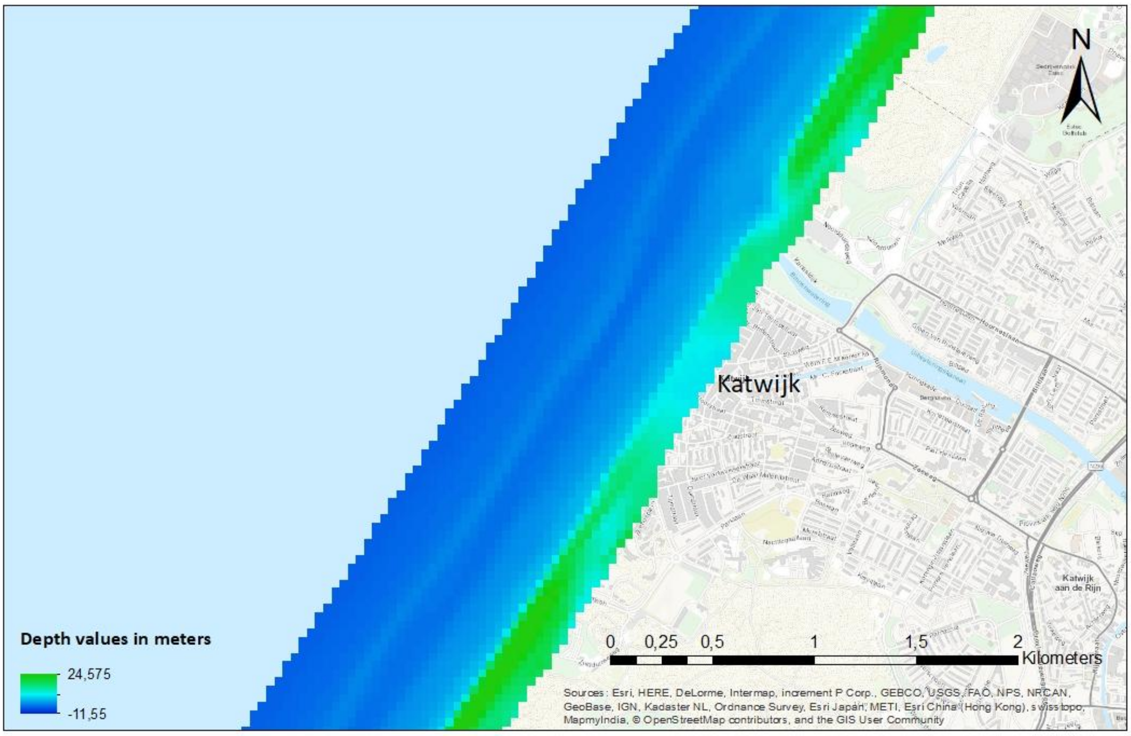
Katwijk coast depth values using a 10 x 10 m cell size



Katwijk coast depth values using a 20 x 20 m cell size

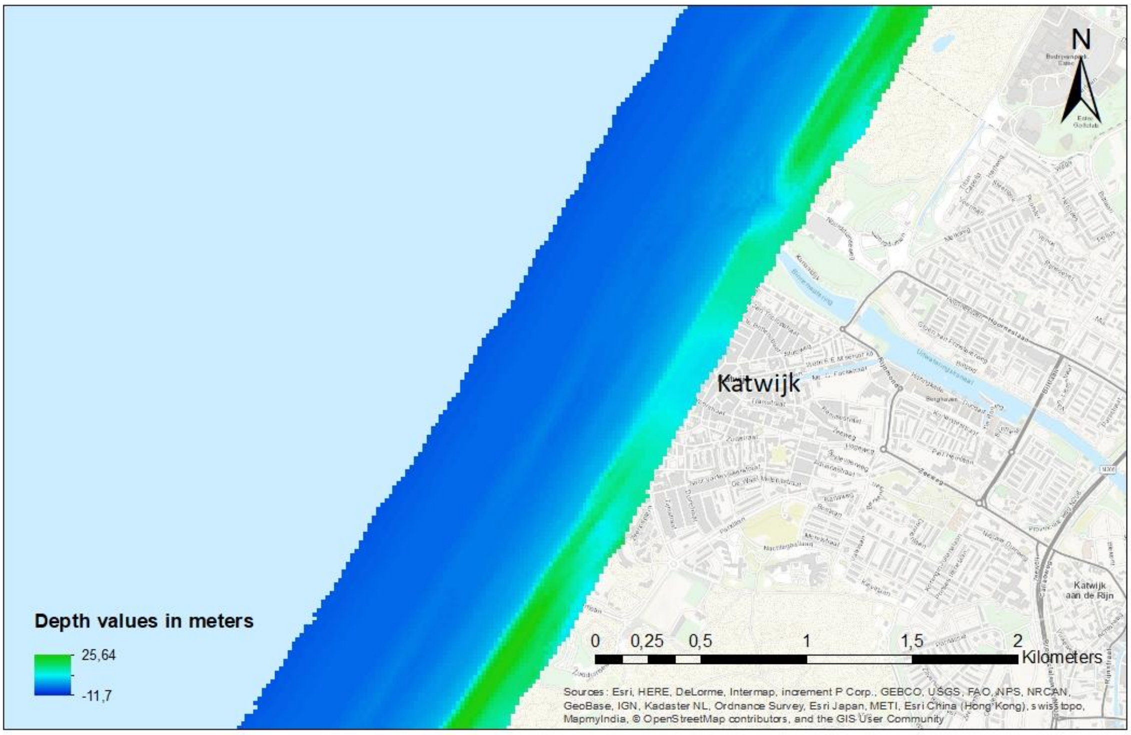


Katwijk coast depth values using a 40 x 40 m cell size

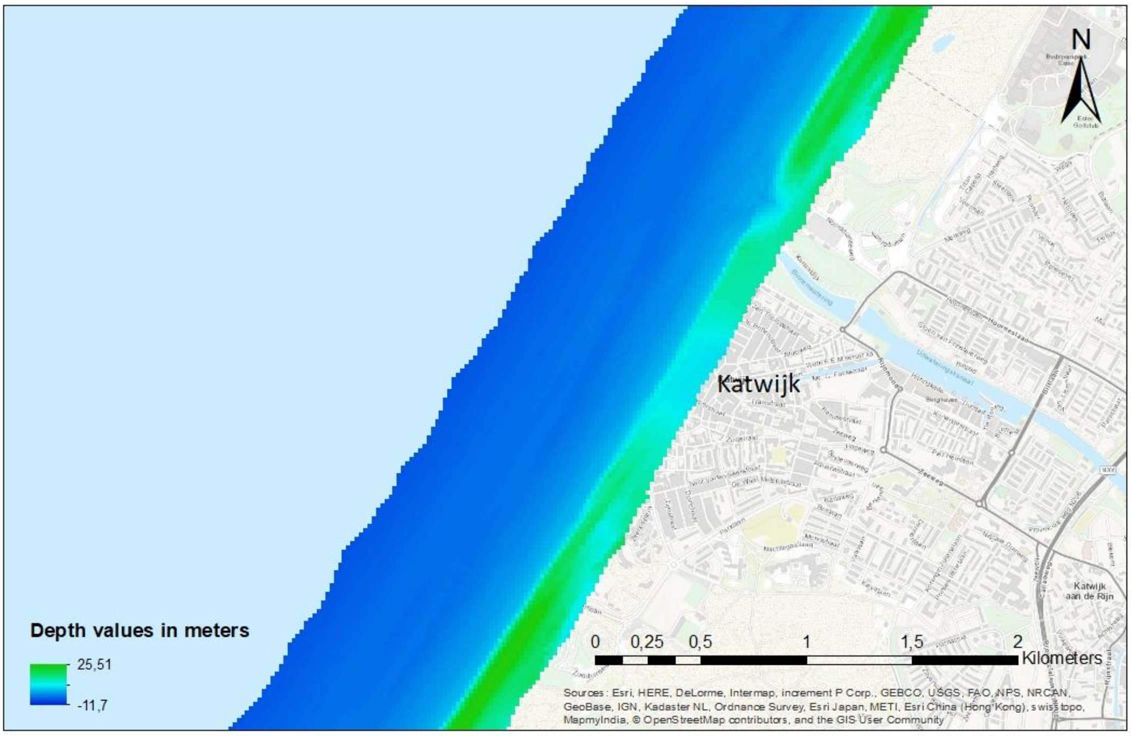


Appendix 2: Selecting a suitable moving window size for visualizing sandbars

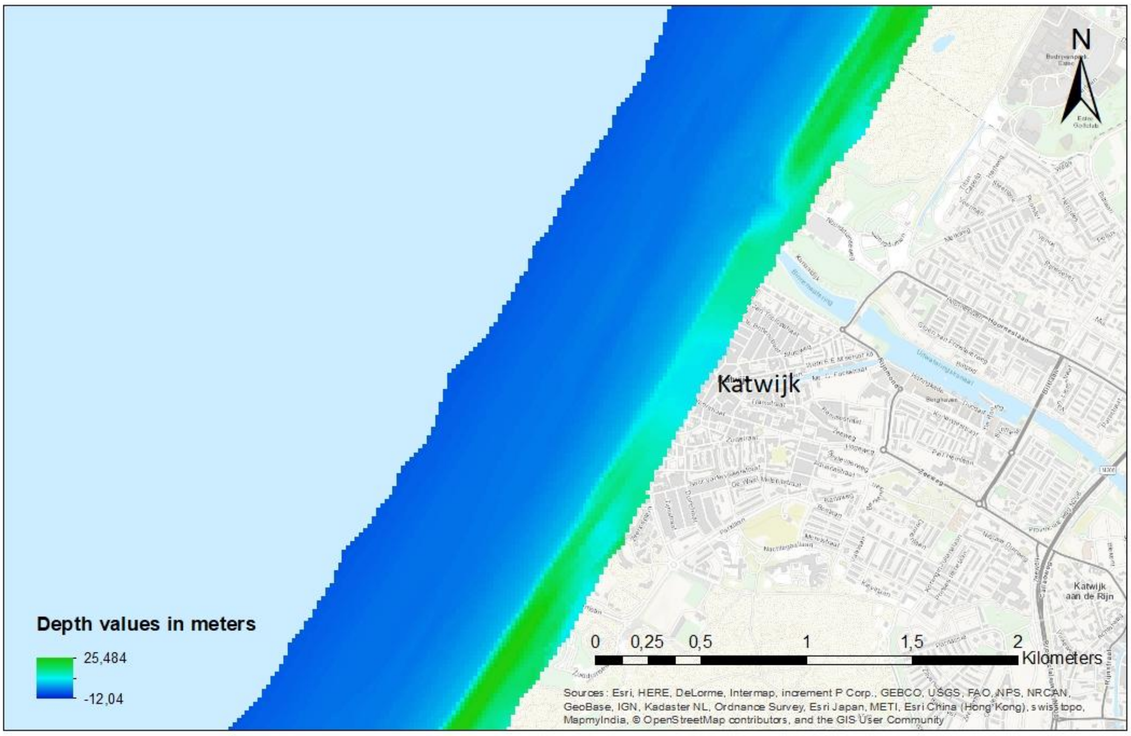
Katwijk coast depth values using a 2 year window size



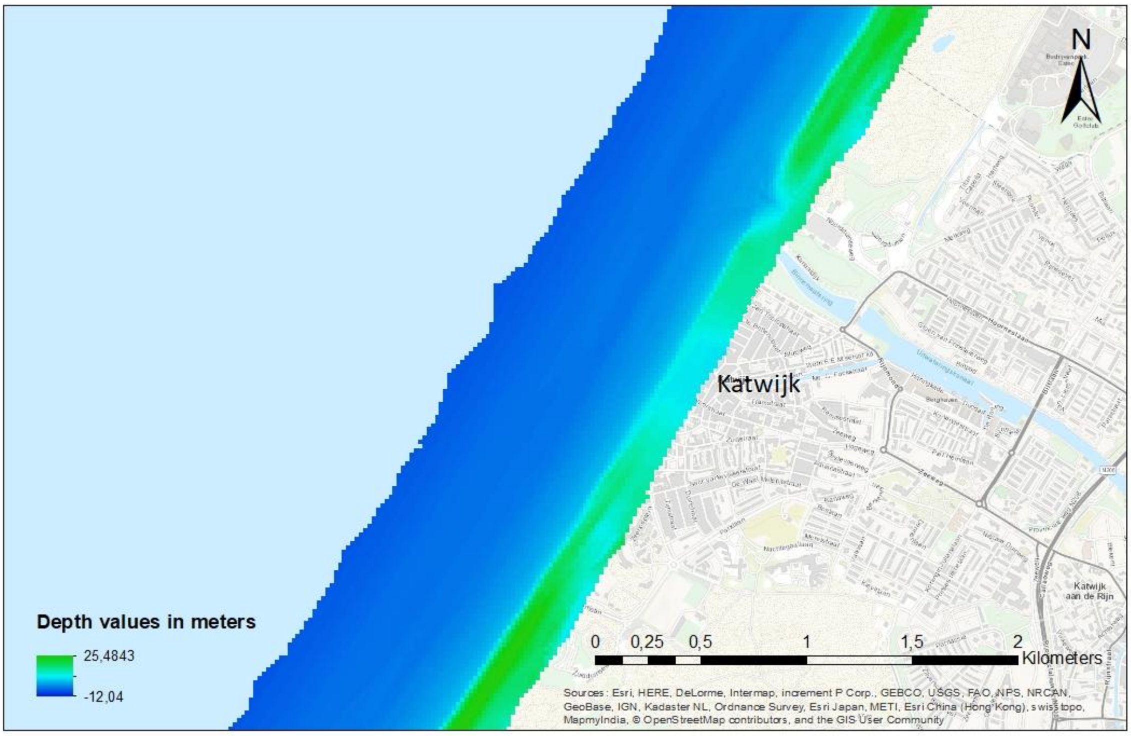
Katwijk coast depth values using a 4 year window size



Katwijk coast depth values using a 6 year window size

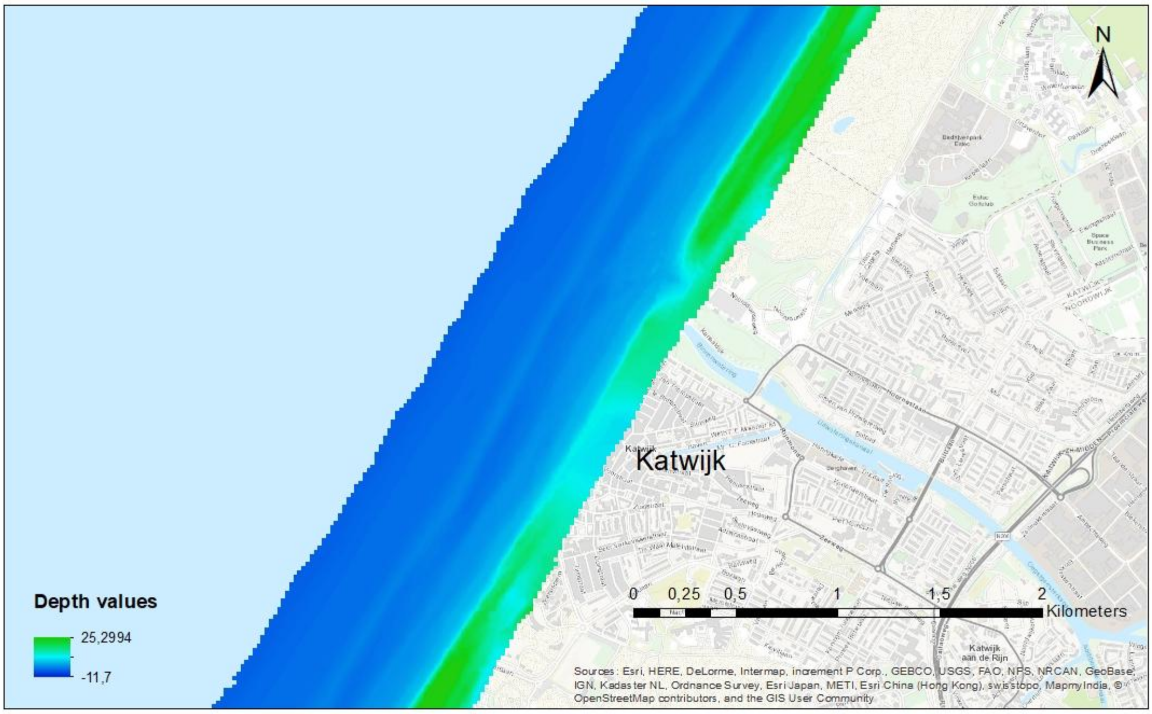


Katwijk coast depth values using an 8 year window size

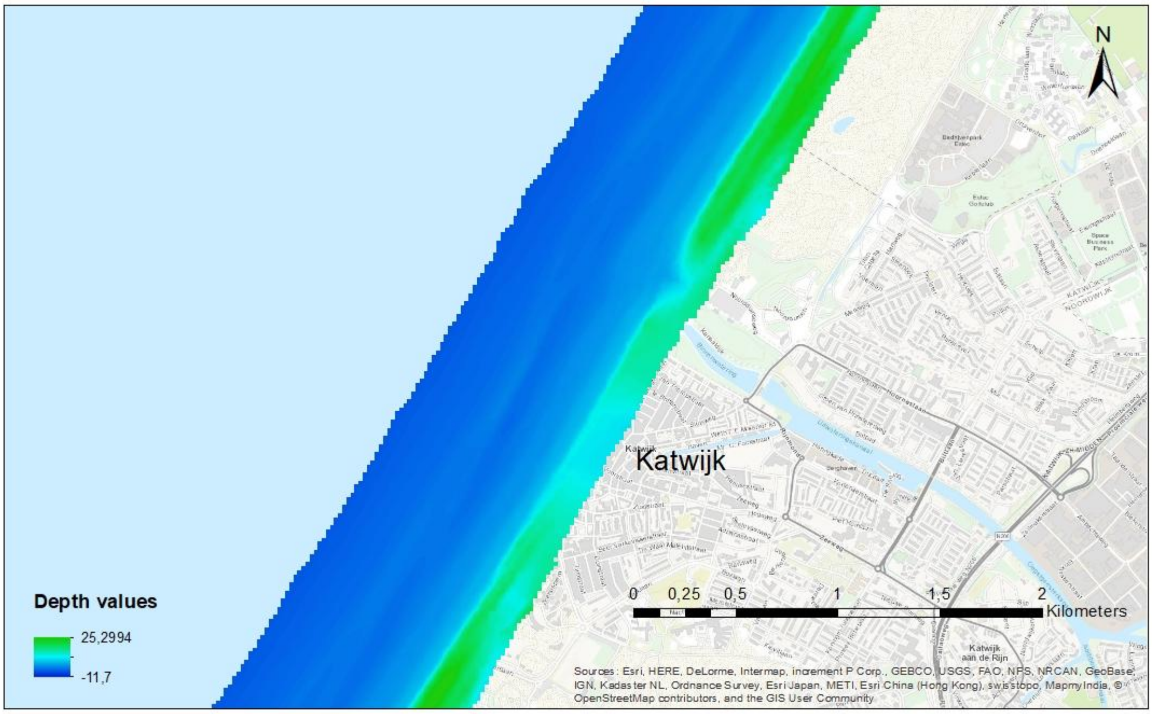


Appendix 3: Considering the order of spatial alteration and temporal smoothing

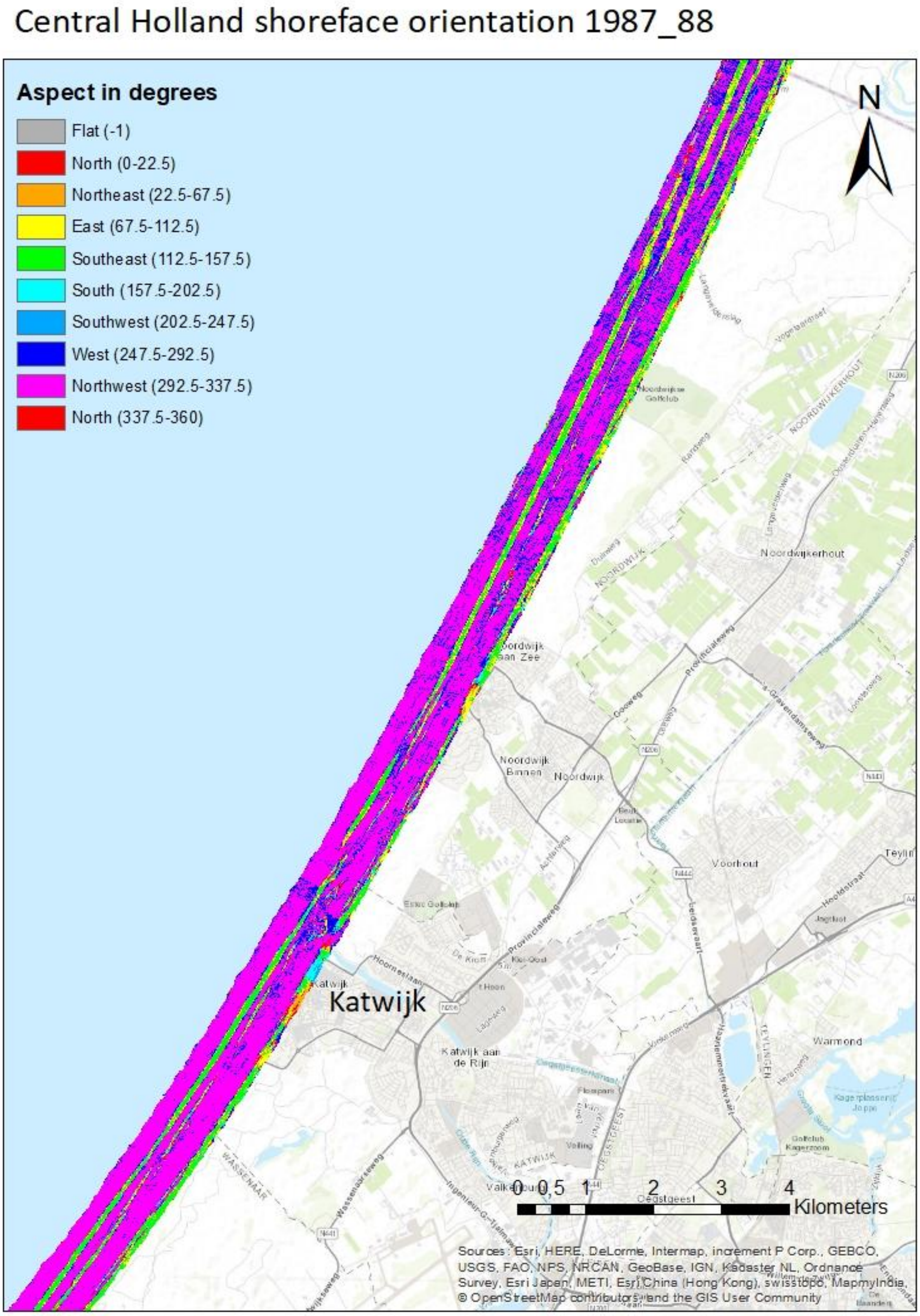
Katwijk coast depth values temporal smoothing before spatial alteration



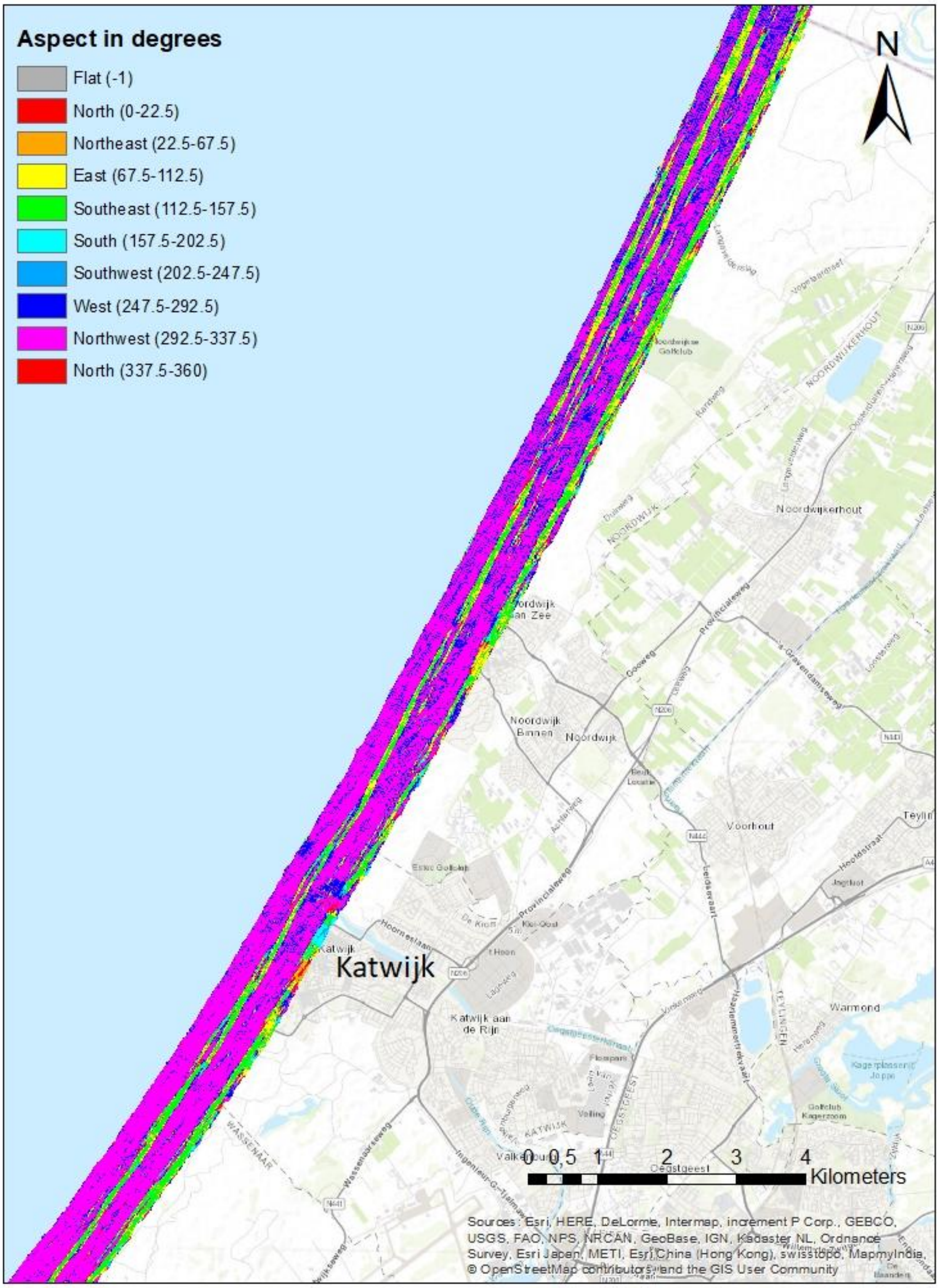
Katwijk coast depth values spatial alteration before temporal smoothing



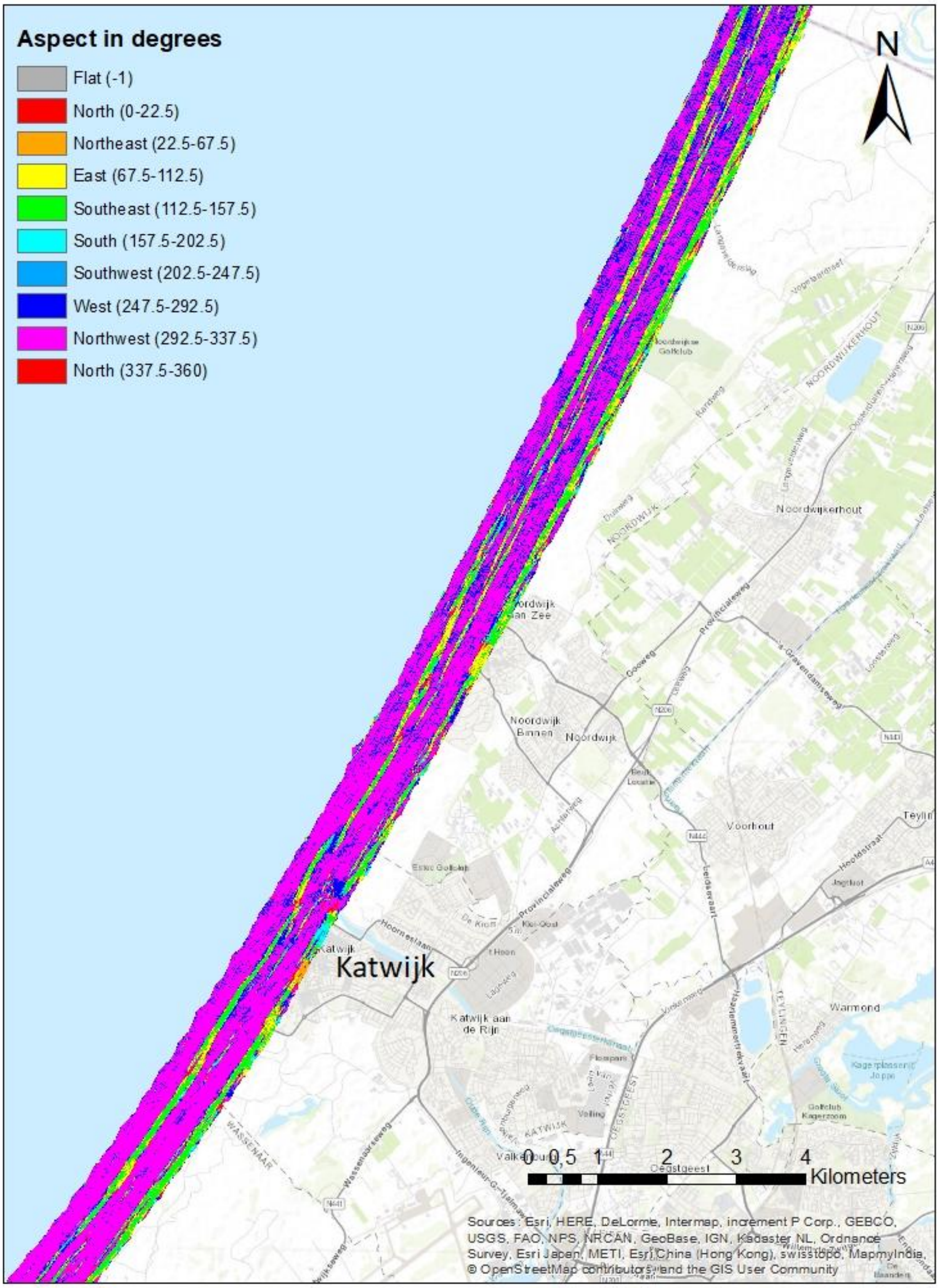
Appendix 4: Aspect analysis period 1987 – 1994



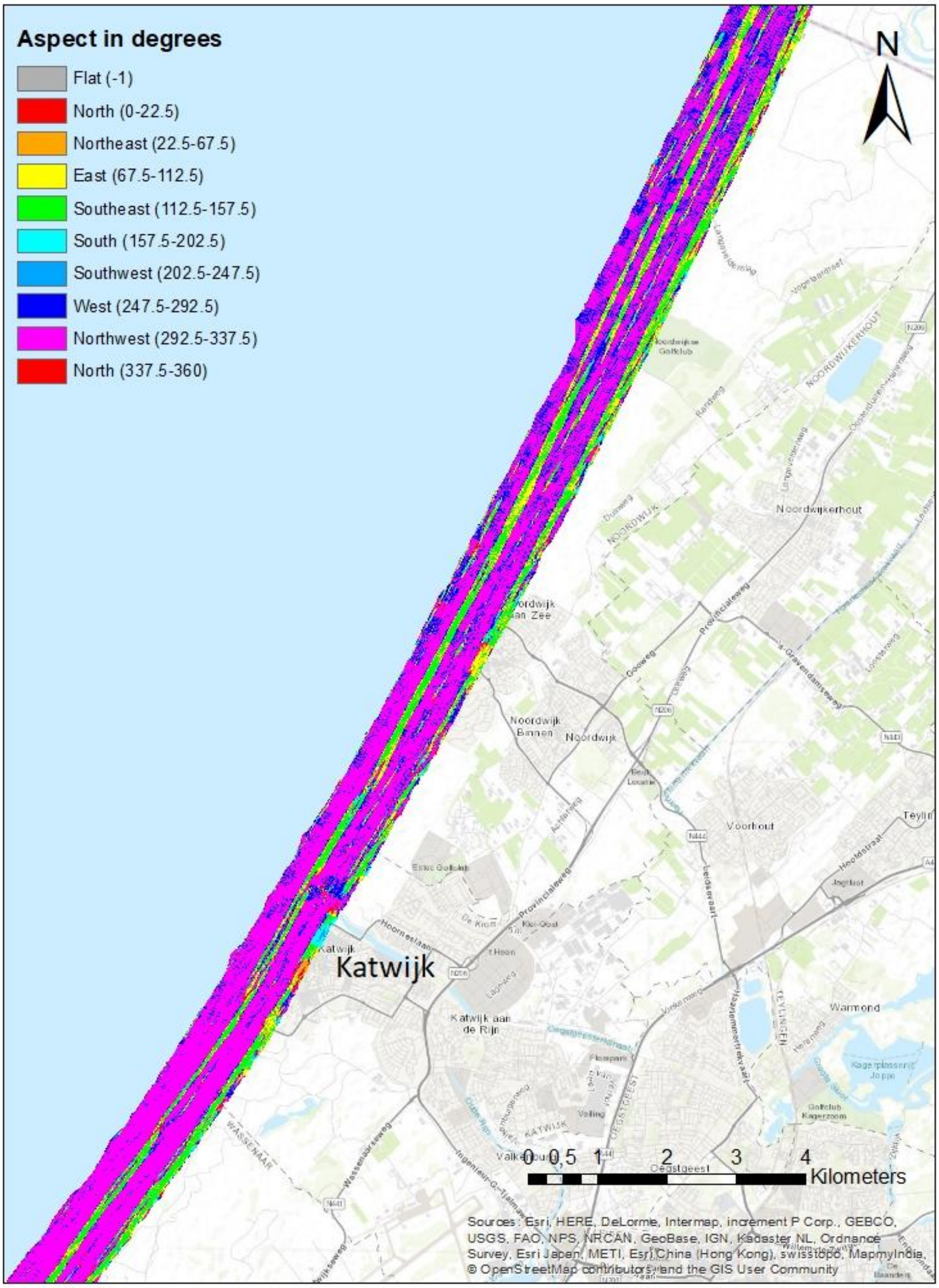
Central Holland shoreface orientation 1989_90



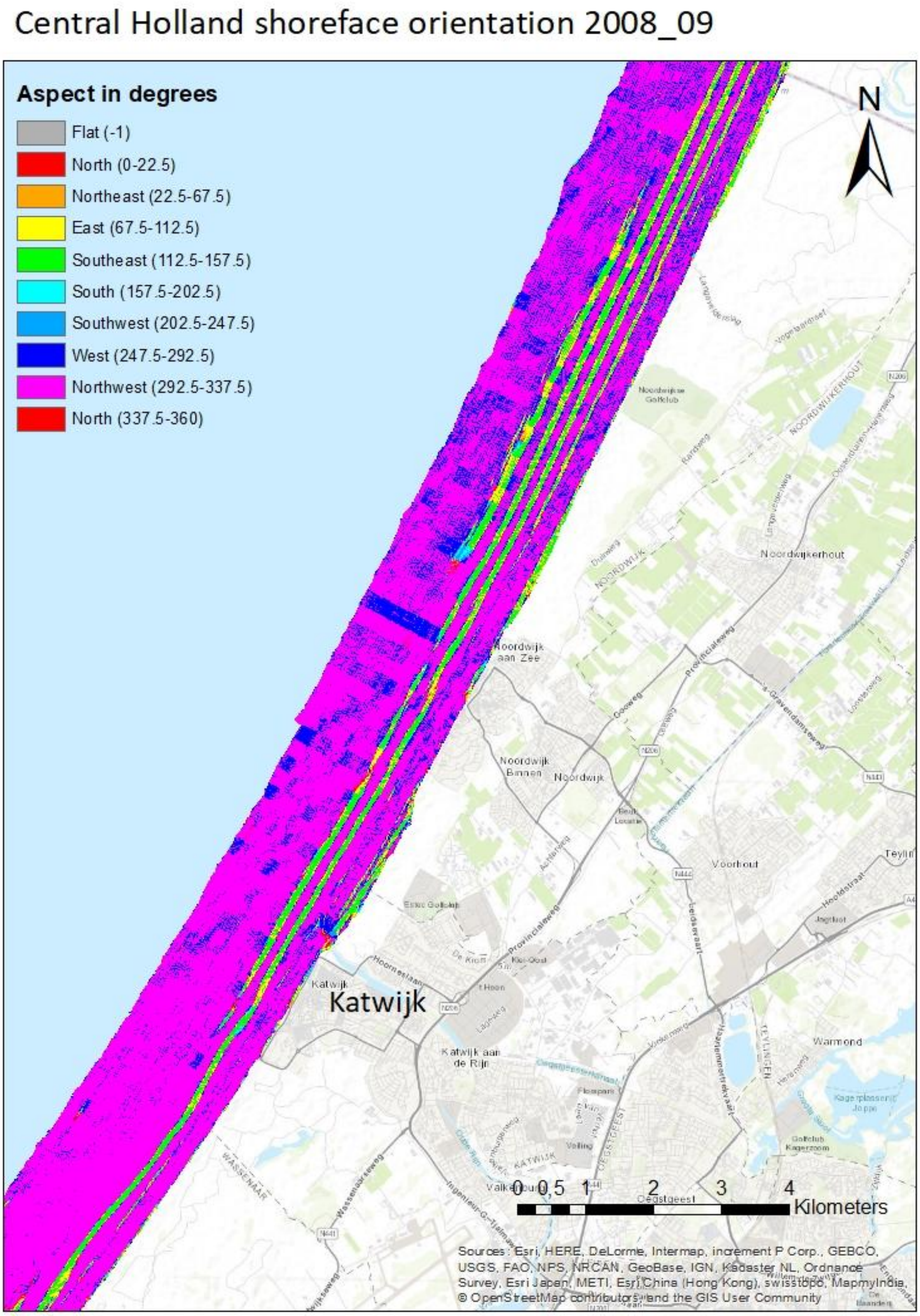
Central Holland shoreface orientation 1991_92



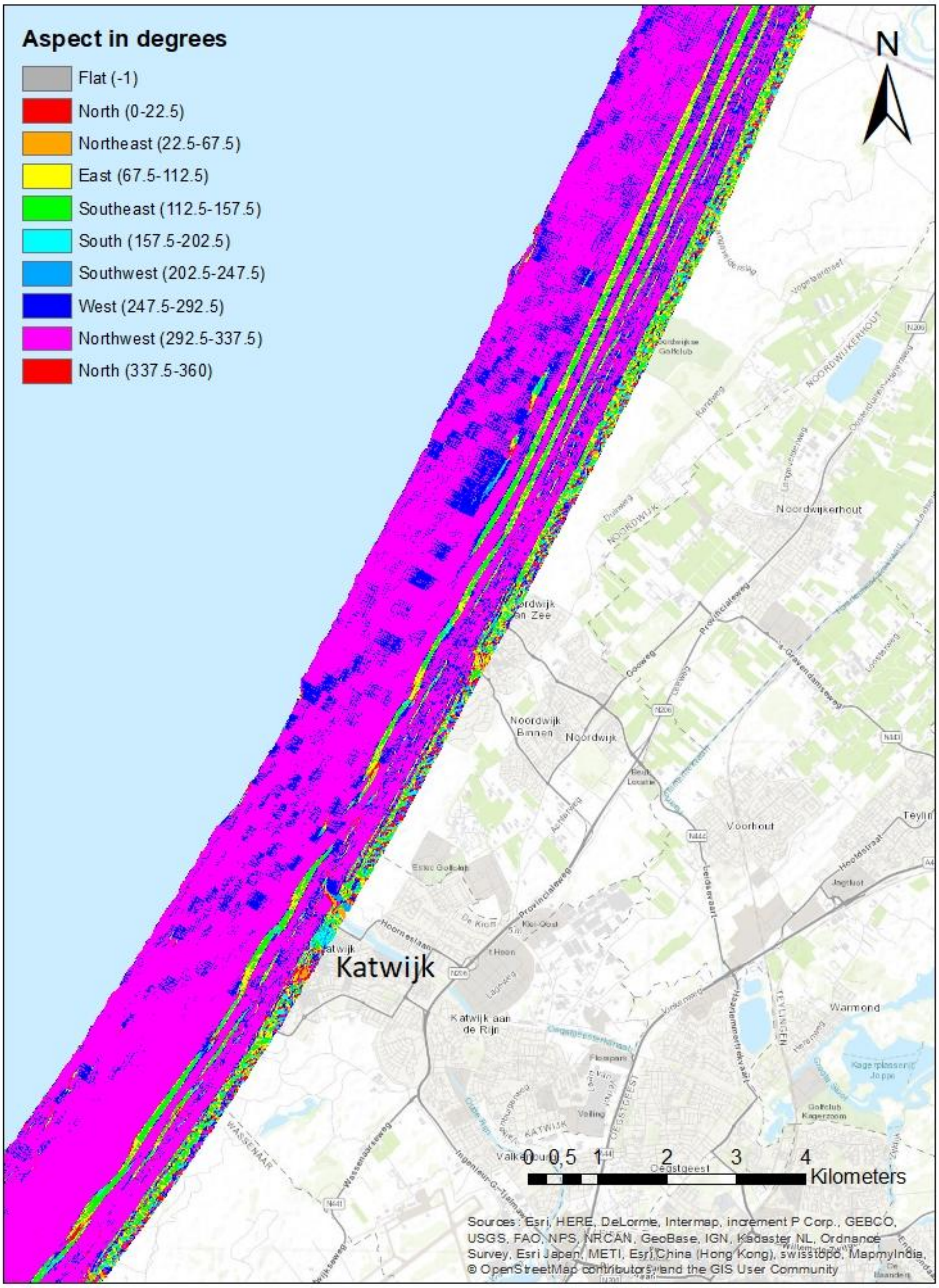
Central Holland shoreface orientation 1993_94



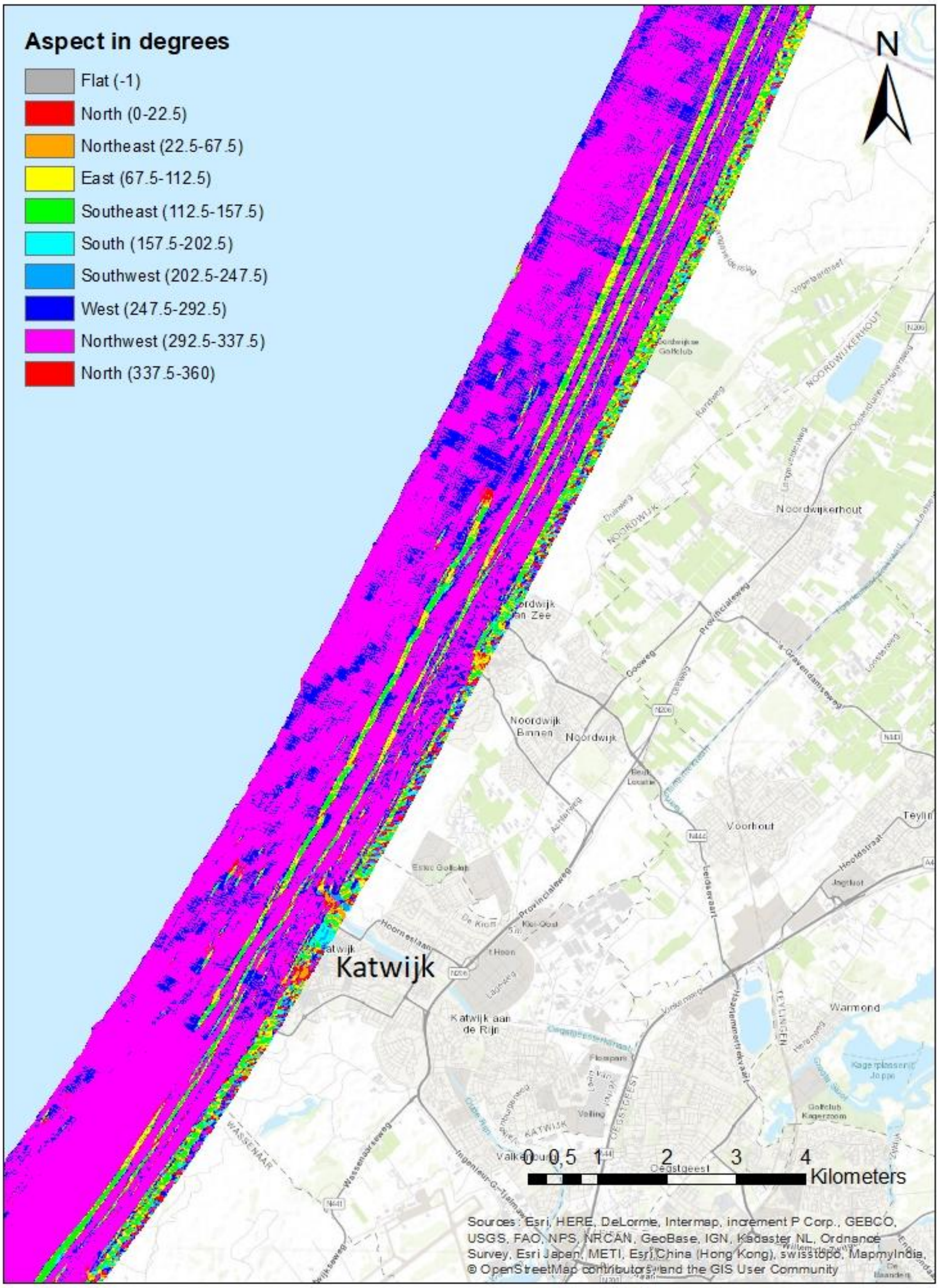
Appendix 5: Aspect analysis period 2008 - 2015



Central Holland shoreface orientation 2012_13

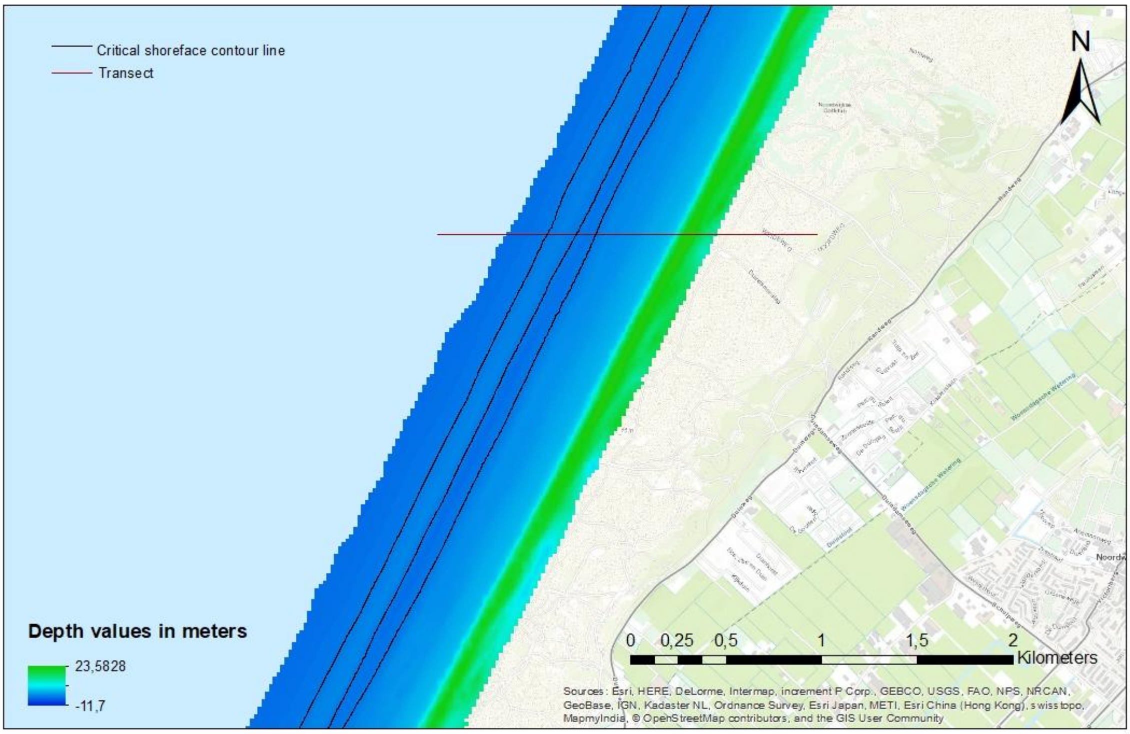


Central Holland shoreface orientation 2014_15

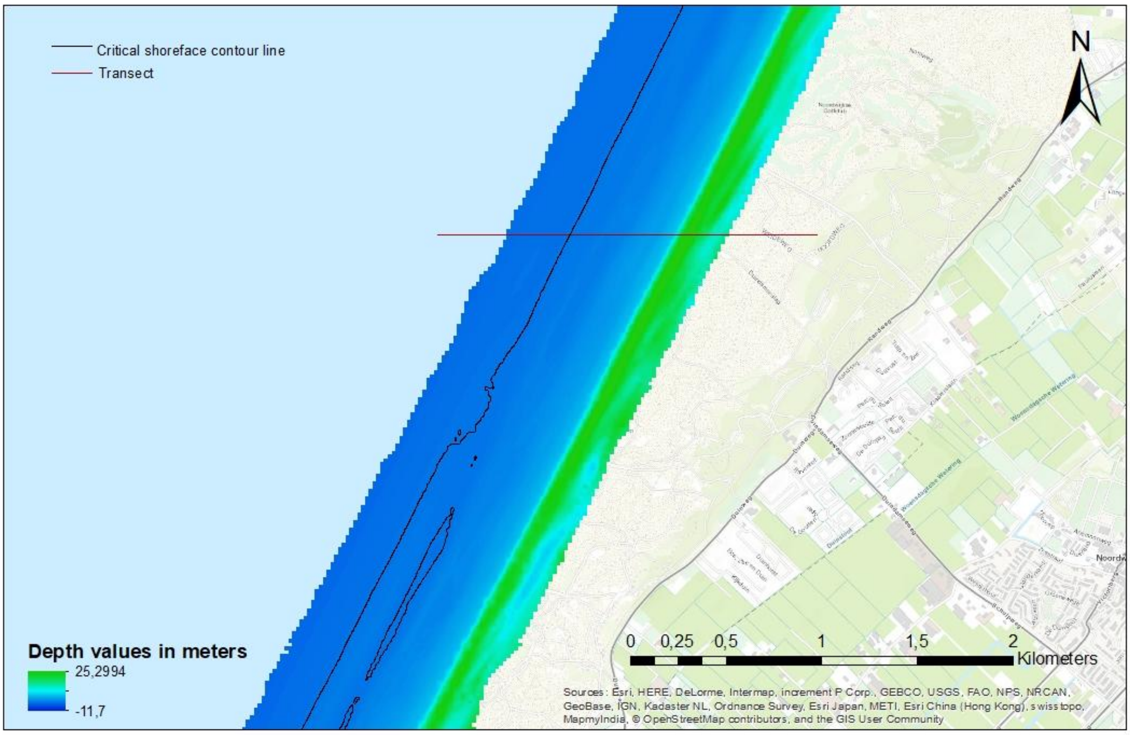


Appendix 6: Central Holland analysis period 1987 – 1994

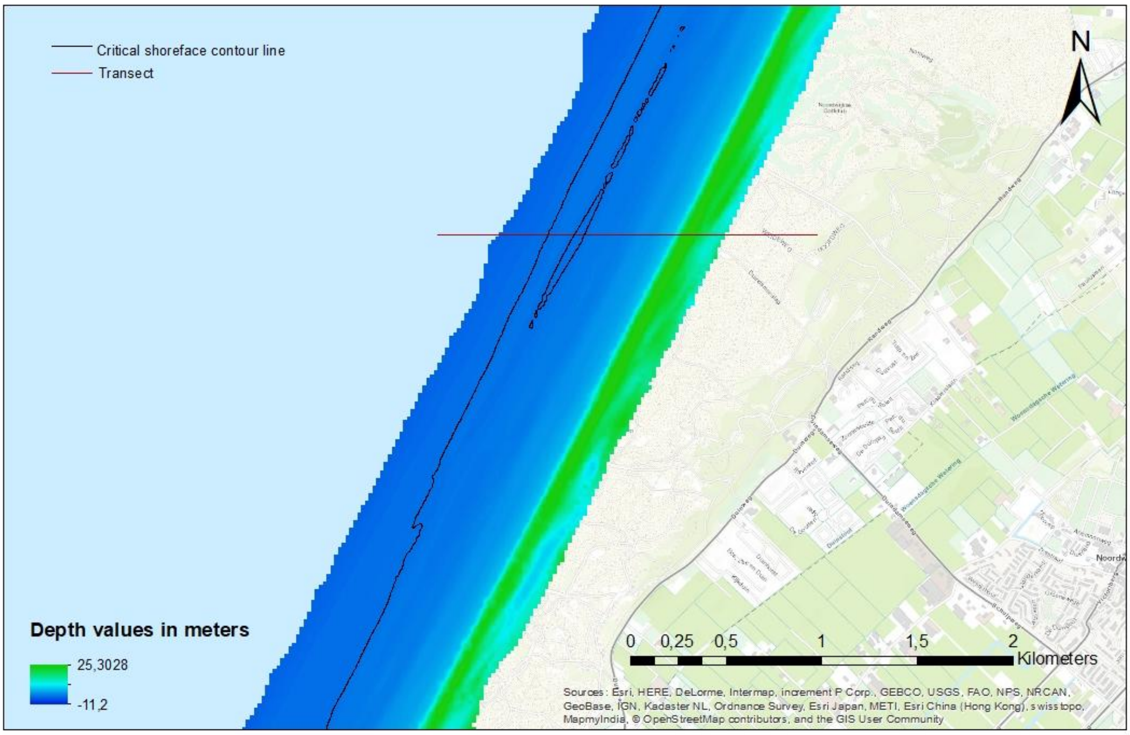
Critical shoreface contour line along Transect 5 in 1987_88



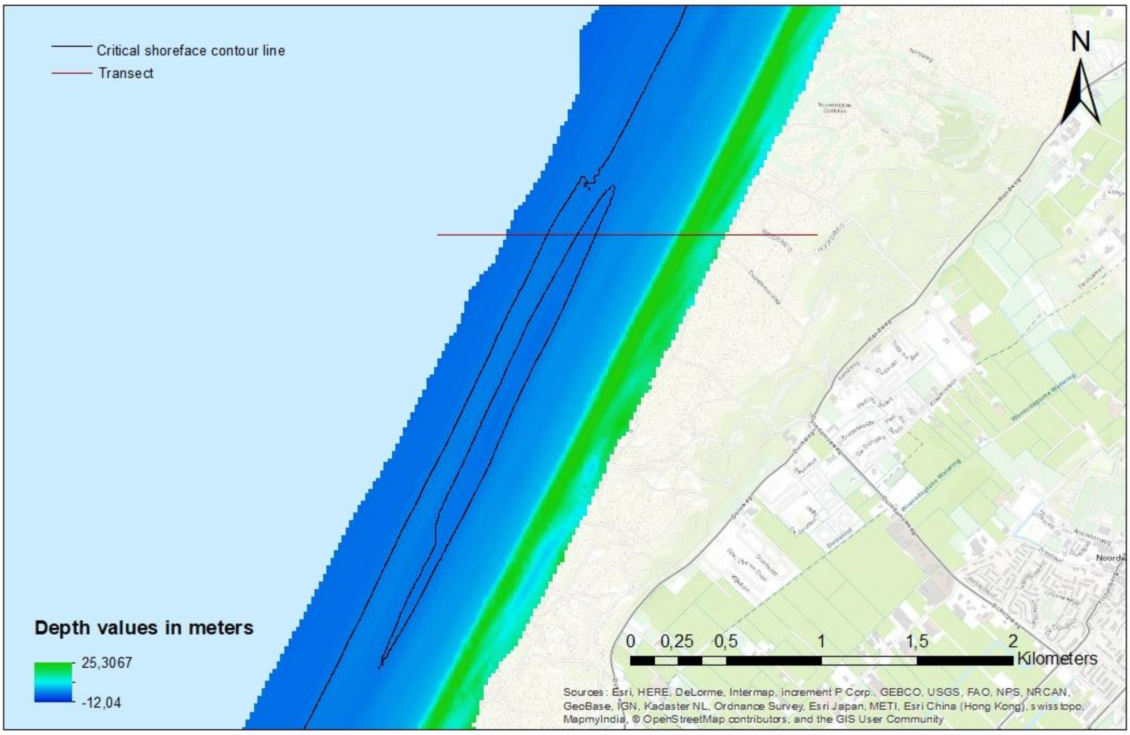
Critical shoreface contour line along Transect 5 in 1989_90



Critical shoreface contour line along Transect 5 in 1991_92

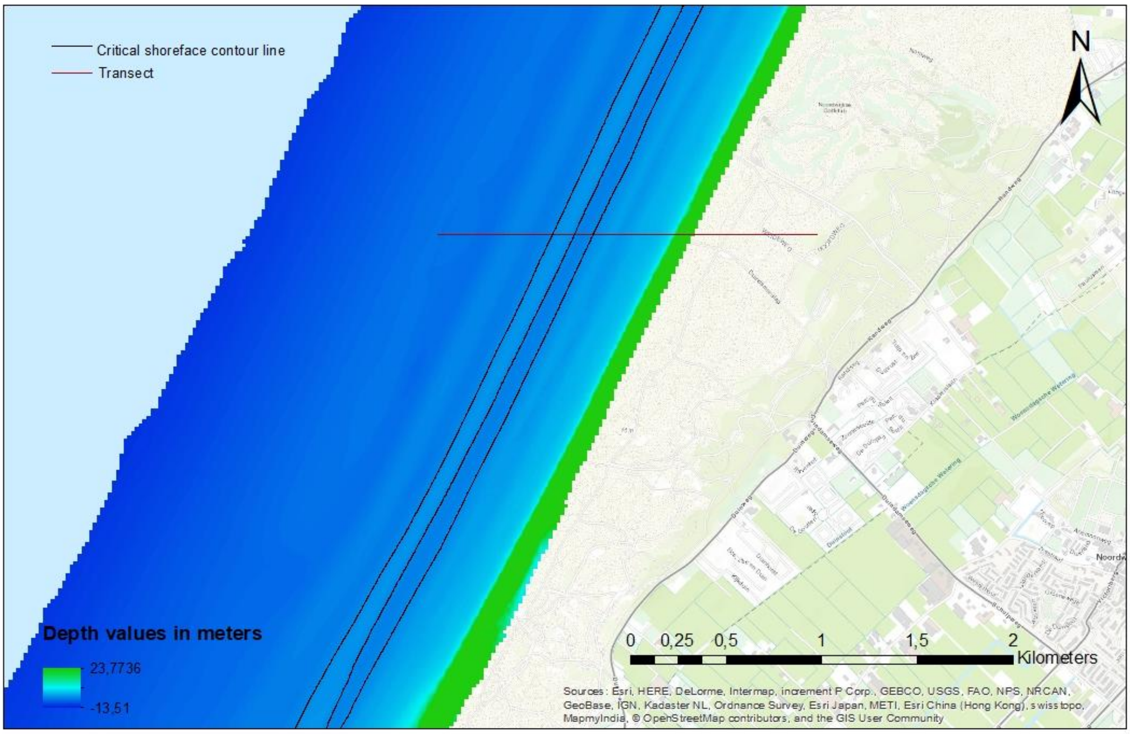


Critical shoreface contour line along Transect 5 in 1993_94

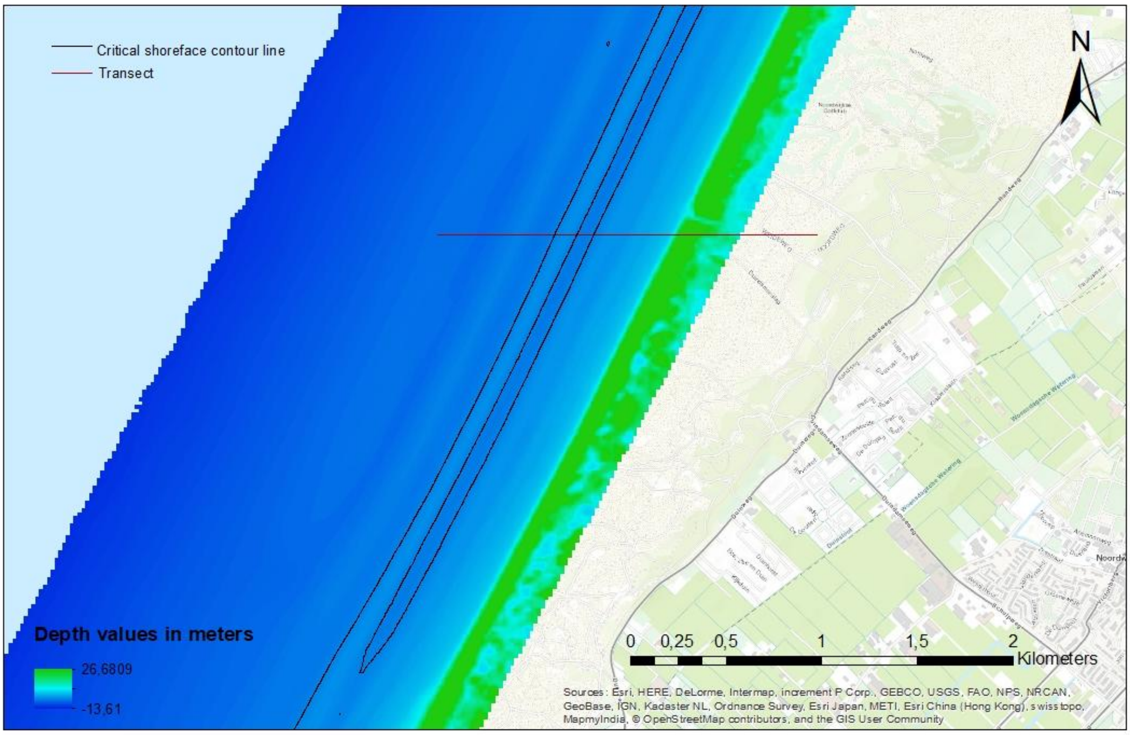


Appendix 7: Central Holland analysis period 2008 – 2015

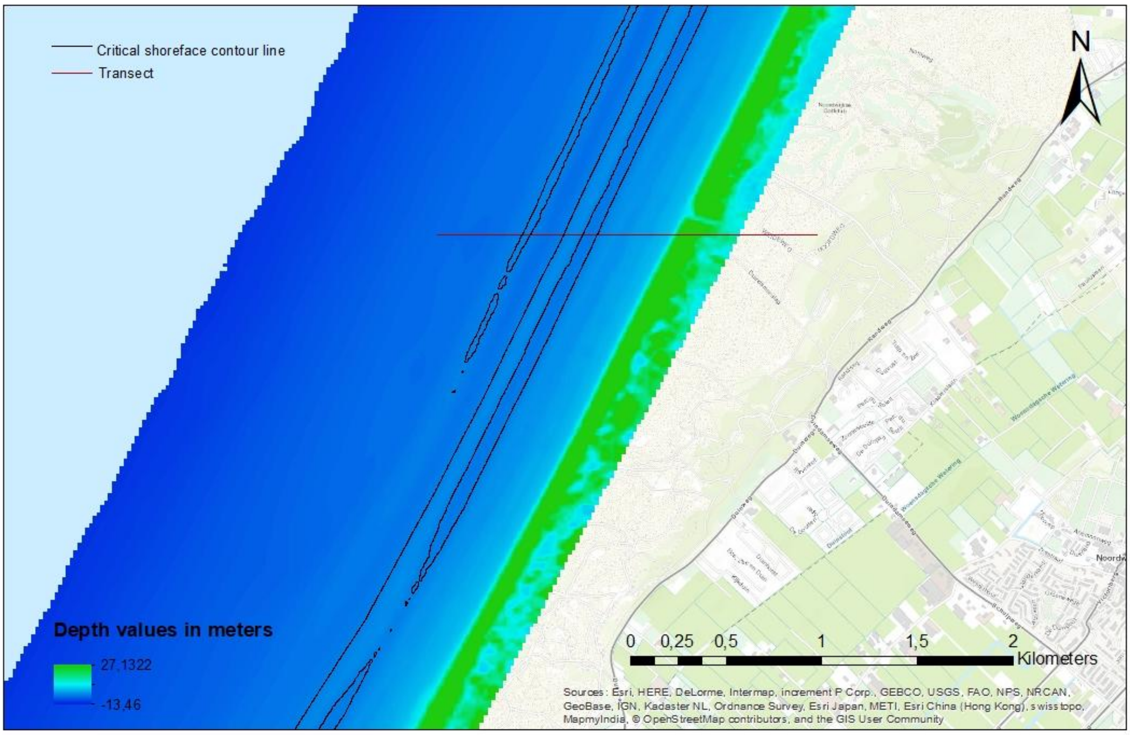
Critical shoreface contour line along Transect 5 in 2008_09



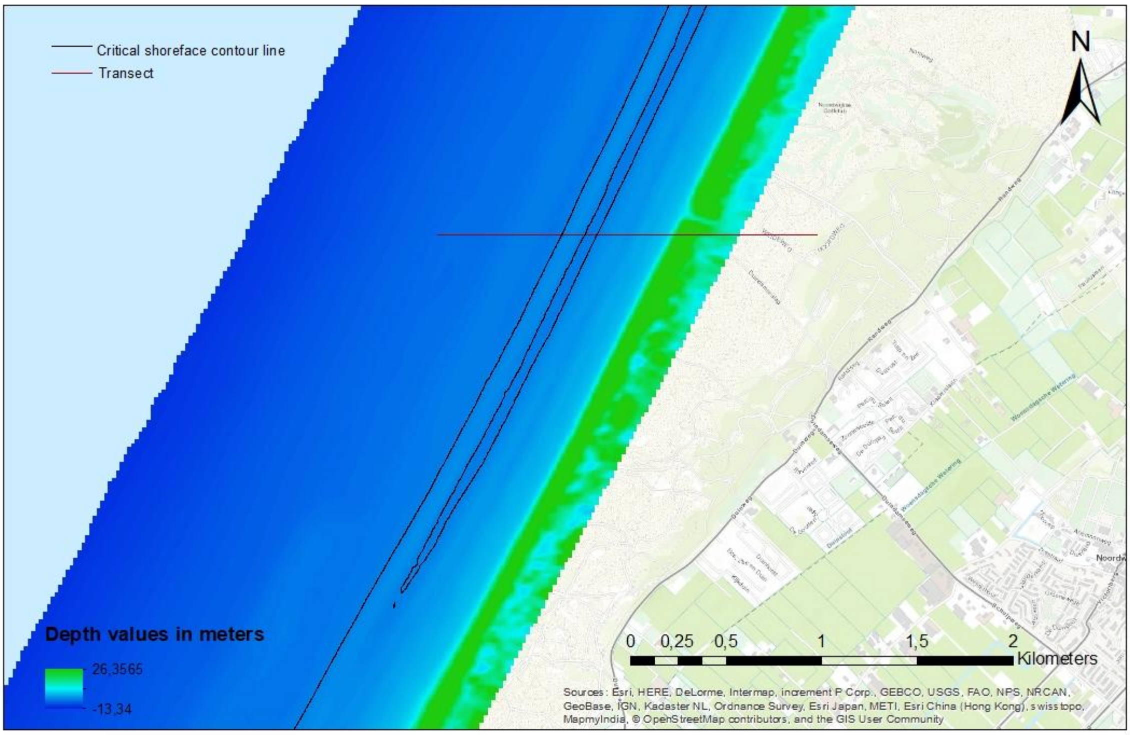
Critical shoreface contour line along Transect 5 in 2010_11



Critical shoreface contour line along Transect 5 in 2012_13



Critical shoreface contour line along Transect 5 in 2014_15



Appendix 8: Table of Contents of the ZIP file/DVD accompanying this report

- Analysis toolboxes and datasets
- Literature
- Midterm & Final presentation
- Raw data
- Results
- Report

References

Aagaard, T., Kroon, A., Greenwood, B., & Huges, M. (2010). Observations of offshore bar decay: Sediment budgets and the role of lower shoreface processes. *Continental Shelf Research* , 1497-1510.

Anthony, E. J. (2013). Storms, shoreface morphodynamics, sand supply, and the accretion and erosion of coastal dune barriers in the southern North Sea. *Geomorphology* , 8-21.

Backstrom, J., Jackson, D., Cooper, A., & Loureiro, C. (2015). Contrasting geomorphological storm response from two adjacent shorefaces. *Earth Surface Processes and Landforms* , 2112-2120.

Bruun, P. (1962). Sea-level rise as a cause of coastal erosion. *Journal of the Waterways and Harbors Division* , 117-130.

Carter, C. H., Monroe, C. B., & Guy Jr, D. E. (1986). Lake Erie Shore Erosion: The Effect of Beach Width and Shore Protection Structures. *Journal of Coastal Research* , 17-23.

Chang, E., & Fu, Y. (2002). Interdecadal variations in Northern Hemisphere winter storm track intensity. *Climate Change 15* , 642-658.

Chang, K.-t. (2016). *Introduction to Geographich Information Systems.* New York: McGraw-Hill Education.

Cowell, P. (2000). Modelling the decrease in wave height over the shoreface due to slope-induced changes in bottom friction. *Reconstruction and modelling of Holocene coastal evolution of the western Netherlands* , 133-144.

de Boer, G., & den Heijer, K. (2016, November 24). *Dataset documentation JarKus*. Opgeroepen op September 26, 2017, van Deltares: https://publicwiki.deltares.nl/display/OET/Dataset+documentation+JarKus

de Jong, B., Keijsers, J., Riksen, M., Krol, J., & Slim, P. (2014). Soft Engineering vs. a Dynamic Approach in Coastal Dune Management: A Case Study on the North Sea Barrier Island of Ameland, the Netherlands. *Journal of Coastal Research* , 670-684.

de Ruig, J. (1998). Coastline management in The Netherlands: human use versus natural dynamics. *Journal of Coastal Conservation* , 127-134.

de Schipper, M., de Vries, S., Ruessink, G., de Zeeuw, R., Rutten, J., van Gelder-Maas, C., et al. (2016). Initial spreaing of a mega feeder nourishment: Observations of the Sand Engine pilot project. *Coastal Engineering* , 23-38.

de Schipper, M., de Vries, S., Stive, M., de Zeeuw, R., Rutten, J., Ruessink, G., et al. (2014). Morphological development of a mega-nourishment; first observations at the sand engine. *Coastal Engineering Proceedings* .

De Vriend, H. (1991). Mathematical modelling and large - scale coastal behaviour: Part 1: Physical processes. *Journal of Hydraulic Research* , 727 - 740.

Diephuis, J., Grijm, W., Schijf, J., & Venis, W. (1991). *Rapport Deltacommissie - Bijdrage V.1 - Golven en golfoploop.* 's-Gravenhage: Deltacommissie.

Eleveld, M. (1999). *Exploring coastal morphodynamics of Ameland (the Netherlands) with remote sensing monitoring techniques and dynamic modelling in GIS.* Amsterdam: University of Amsterdam.

ESRI. (2017). *Aspect*. Opgeroepen op April 11, 2018, van ArcGIS Desktop: http://desktop.arcgis.com/en/arcmap/10.5/tools/spatial-analyst-toolbox/aspect.htm

ESRI. (2016). *Cell Statistics*. Opgeroepen op April 3, 2018, van ArcGIS for Desktop: http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/cell-statistics.htm

ESRI. (2016). *Contour*. Opgeroepen op April 3, 2018, van ArcGIS for Desktop: http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/contour.htm

ESRI. (2017). *Resample*. Opgeroepen op April 11, 2018, van ArcGIS Desktop: http://desktop.arcgis.com/en/arcmap/10.5/tools/data-management-toolbox/resample.htm

Google. (sd). *Google Maps*. Opgeroepen op Maart 12, 2018, van https://www.google.nl/maps/@52.2314823,4.448639,10z

Hinton, C. (2000). *Decadal morphodynamic behaviour of the Holland shoreface.* Middlesex: Middlesex University.

Katsman, C., Hazeleger, W., Drijfhout, S., van Oldenborgh, G., & Burgers, G. (2008). Climate scenarios of sea level rise for the northeast atlantic ocean: a study including the effects of ocean dynamics and gravity changes induced by ice melt. *Climate Change 91* , 351-374.

Krawczyk, S. (2017). *Towards a Framework to Characterise Shoreface Behaviour; A study of a barrier island's shoreface slope dynamics.* Wageningen: Wageningen University and Research Centre.

Luijendijk, A., Ranasinghe, R., de Schipper, M., Huisman, B., Swinkels, C., Walstra, D., et al. (2017). The initial morphological response of the Sand Engine: A process-based modelling study. *Coastal Engineering* , 1-14.

Masselink, G., Hughes, M. G., & Knight, J. (2011). *Introduction to coastal processes & geomorphology.* London: Hodder Education, An Hachette UK Company.

Meehl, G., Stocker, T., Collins, W., Friedlingstein, P., Gaye, A., Gregory, J., et al. (2007). *Global climate projections.* Cambridge, United Kingdom and New York: Cambridge University Press.

Mulder, J., & Tonnon, P. (2010). "Sand Engine" Background and design of a mega nourishment pilot in the Netherlands. *Proceedings of International Coastal Engineering Conference.* Shanghai.

Nicholls, R. J., & Cazenave, A. (2010). Sea-Level Rise and Its Impact on Coastal Zones. *Science* , 1517-1520.

Rijkswaterstaat. (2016). *De Zandmotor: Aanjager van innovatief kustonderhoud.* Rijkswaterstaat.

Rijn, L. v. (2007). *Zeespiegelstijging / Stijgend water: kan de Nederlandse delta stand houden?*

Ruessink, B., Pape, L., & Turner, I. (2009). Daily to interannual cross-shore sandbar migration: observations from a multiple sandbar system. *Continental Shelf Research, 29* , 1663-1677.

Short, A. D. (1991, November 13). Beach systems of the central Netherlands coast: Processes, morphology and structural impacts in a storm driven multi-bar system. *Marine Geology* , pp. 103-137.

Stive, M. J., de Schipper, M., Luijendijk, A., Aarninkhof, S., van Gelder-Maas, C., van Thiel de Vries, J., et al. (2013). A New Alternative to Saving Our Beaches from Sea-Level Rise: The Sand Engine. *Journal of Coastal Research* , 1001-1008.

Stive, M., De Vriend, H., Cowell, P., & Niedoroda, A. (1995). Behaviour-oriented models of shoreface evolution. *Coastal Dynamics* .

Van de Meene, J., & Van Rijn, L. (2000, February 28). The shoreface-connected ridges along the central Dutch coast. Part 1, Field observations. *Continental Shelf Research 20* , pp. 2295-2323.

van der Spek, A., & Elias, E. (2013). The effects of nourishments on autonomous coastal behaviour. *Coastal dynamics* .

van der Spek, A., & Lodder, Q. J. (2006). *A new sediment budget for the netherlands; the effects of 15 years of nourishing (1991-2005).* Delft: Deltares & Rijkswaterstaat.

van der Spek, A., de Kruif, A., & Spanhoff, R. (2007). *Guidelines Shoreface Nourishments.* The Hague: National Institute for Coastal and Marine Management.

Verbesselt, J., Zeileis, A., & Herold, M. (2012). Near real-time disturbance detection using satellite image time series. *Remote Sensing of Environment* , 98-108.

Weisse, R., & von Storch, H. (2009). *Marine Climate and Climate Change: Storms, Wind Waves and Storm Surges.* Berlin Heidelberg New York: Springer-Verlag.

Weisse, R., von Storch, H., Niemeyer, H. D., & Knaack, H. (2012). Changing North Sea storm surge climate: An increasing hazard? *Ocean & Coastal Management* , 58-68.

Wijnberg, K. M. (2002, September 30). Environmental controls on decadal morphologic behaviour of the Holland coast. *Marine Geology* , pp. 227-247.