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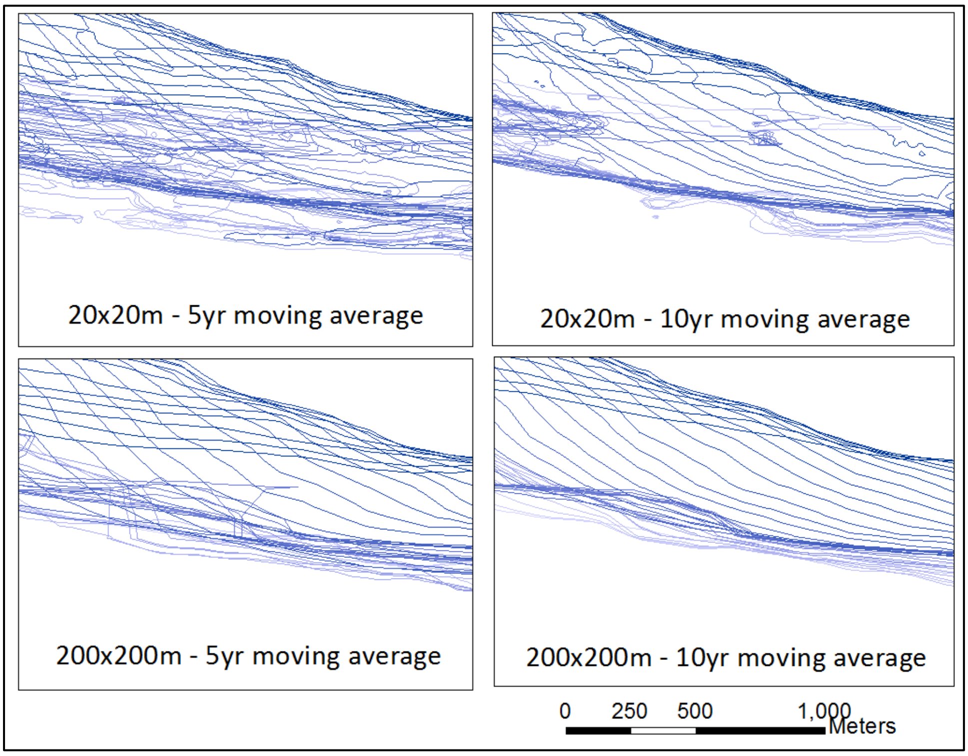
TOWARDS A FRAMEOWRK TO CHARACTERISE SHOREFACE BEHAVIOUR

A study of a barrier island's shoreface slope dynamics

Samantha Krawczyk

06 June 2017



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Towards a Framework to Characterise Shoreface Behaviour

A study of a barrier island's shoreface slope dynamics

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List of Abbreviations

DBM	Digital Bathymetry Model
DTM	Digital Terrain Model
EDA	Exploratory Data Analysis
JARKUS	JAaRlijkse KUStlodingen
TIN	Triangulated Irregular Network

Summary

The shoreface is a part of the coastal zone which, from a hazard mitigation point of view, plays a critical role in protecting the mainland. The run-up along the shoreface helps buffer the power of the waves, reducing their height and energy (Cowell 2000, Masselink, Hughes et al. 2011). However, the shoreface is subject to change in response to external forces such as changes in sea levels, changes in sediment availability (both natural and anthropogenic, e.g. sand nourishments or extraction), and storm events. Studying the shoreface behaviour is important to understand its response to these forces to improve our ability to model and predict them, and, ultimately, better protect the mainland.

To study the behaviour of the shoreface spatially, GIS analysis can be employed. Although coastal dynamics on small spatial (i.e. cm to m) and time (seconds to months) scales are relatively well studied, due to the difficulties in obtaining data, as well as the difficulties in upscaling coastal processes, shoreface behaviour at larger spatial and temporal scales is less understood. Currently, studies on these scales are based on sparse measured bathymetric data usually supplemented with data obtained through remote sensing or sediment analysis, or on models. However, whatever the data source, when designing a GIS analysis of the shoreface, concepts in the field of coastal morphodynamics, GIS, and time series analysis, have to be considered as they will shape and affect the results of the analysis as well as their interpretation. A framework for the design of such studies would help structure the analysis at different scales and provide a frame of reference for issues likely affecting the analysis.

Developing such a framework is beyond the scope of this study, since this would require detailed research into the sensitivity of the various methods and parameters for different scenarios. The objective of this study was to provide a first step towards developing such a framework, by developing a method to analyse the long-term (decadal) behaviour of the shoreface slope of a Dutch barrier island (Ameland) using the JARKUS data (bathymetry measurements collected along cross-shore transects since 1963). The method was developed based on an initial discussion of key morphodynamics, GIS and time series analysis concepts applicable to the focus of this case study. The case study area, and the focus on the long-term behaviour of the shoreface slope, was chosen to continue a series of studies on the impact of coastal management on natural coastal development carried out at Wageningen University & Research.

The study addressed the following research questions:

> *What are the main concepts from a coastal morphodynamics perspective, GIS and time series analysis perspective that should be considered when preparing an analysis of the shoreface slope?*
>
> *How can these concepts be used to devise a methodology for studying the shoreface slope of Ameland using the JARKUS data?*
>
> *What can be learned from the implementation of the methodology about the original concepts?*

The processes affecting the shoreface are complex and act at different spatial and temporal scales. As they are hard to upscale, the scale of the data used must reflect the scale of the process being

investigated. Methods for generalizing data in both the spatial and temporal dimensions are investigated (for raster representations of the terrain). Additionally, when looking at devising a GIS method for the analysis, consideration should be given to the different interpretations of change in GIS and statistics, as well as the impact of different methods for deriving Digital Bathymetry Models (DBMs) and DBM derivatives.

Based on the discussion above, two methods were developed for identifying shoreface dynamics that take into account the coastal morphodynamics, GIS concepts and time series analysis. They differ in their approach to the analysis of the shoreface slope. The first focuses on the analysis of the change in geometry of contour lines to detect changes in the slope gradient, while the second one focuses on the change of the slope gradient attribute to study the variety and magnitude of change at given locations.

The methods were applied to a study of the shoreface of Ameland using the JARKUS data. The implementation of the methods showed the limitations introduced by the data and the study area. The data is collected on an annual basis and thus better suited to studies of decadal (or longer) processes, while the seaward extent of the data mainly covered the part of the shoreface which is affected by processes acting on shorter timescales. However, the results of both methods clearly indicated the known patterns of slope behaviour (a dynamic shoreface around the island's inlets, and more stable shoreface towards the centre of the island).

The concepts in the areas of coastal morphodynamics, GIS and time series analysis were useful in the design of the methods, and enable a methodical comparison of the results. However, to facilitate future research into the shoreface and interpretation of the results, the concepts have to be further examined and their interaction analysed, before a valid framework will become available. Specifically, further research is needed into the issue of dealing with missing data both in the spatial and temporal domain. In the spatial domain research could be conducted into deriving bathymetry data from sources such as photos and satellite images, and combining these with existing point measurements. Additionally, the current research focused only on the analysis of the shoreface slope, however research is needed into other slope characteristics such as gradient and aspect and how they can provide an insight into the shoreface behaviour. Finally, the current discussion of concepts could be expanded to include a more in depth discussion of time series analysis to facilitate the discovery of patterns in the temporal domain.

1.Introduction

The shoreface is a part of the coastal zone which corresponds to the upper part of the continental shelf that is affected by contemporary wave processes (Figure 1). From a hazard mitigation point of view, it plays a critical role in protecting the mainland from waves. Due to friction, the shoreface buffers the power of the waves which reduce their height and energy (Cowell 2000, Masselink, Hughes et al. 2011). The slope of the shoreface affects the amount of friction generated, but the shoreface morphology is also important (Backstrom, Jackson et al. 2015). Additionally, the shoreface is involved in the cross-shore sediment transport and distribution between the inner shelf and beach (Hinton 2000, Backstrom, Jackson et al. 2009), which affect shoreline erosion. However the shoreface itself is not stationary. Changes are an expression of variation in the forcing signal as well as processes inherent in the system (Eleveld 1999). Multi-scale processes and events, such as sea-level rise, changes in currents, storms, coastal engineering projects or sand nourishments all affect the shoreface, often in ways that are not clearly understood (Backstrom, Jackson et al. 2015).

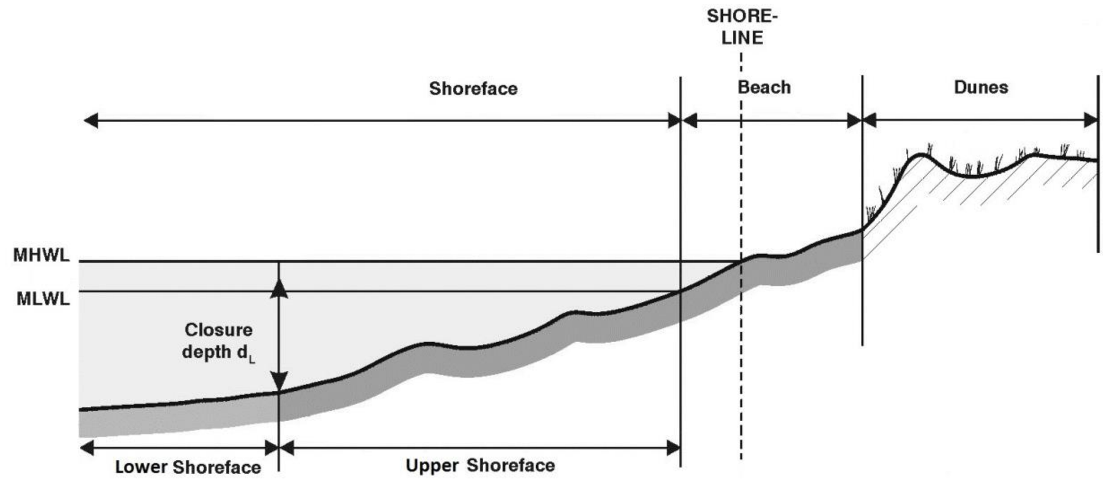

Figure 1. Schematic representation of a cross-section of the coast showing the location of the shoreface (image adapted from Mangor 2008)

The choice of appropriate coastal management techniques depends on our ability to predict coastal changes. These changes can be rather variable on different temporal and/or spatial scales (Stive 2003) necessitating the use of models. However, the models themselves rely on our understanding of the underlying data and processes at different scales. Given the important role of the shoreface in protecting the mainland from waves, as well as increasing sea levels, research aimed at understanding shoreface behaviour is important to improve our ability to fully benefit from its protective role and inform coastal management practices.

The following section presents in more detail the motivation for this research and the questions it addresses.

1.1. Problem definition

As was highlighted in the previous section, knowledge of the behaviour of the shoreface across a range of scales is necessary to inform costal behaviour models which, in turn, inform management practices. With increasing population in coastal areas coupled with sea-level rise and increased severe weather frequency due to climate change (Small and Nicholls 2003, McGranahan, Balk et al. 2007, Coumou and Rahmstorf 2012), the need for informed management practices cannot be ignored.

Time series data of coastal morphology are an important source of information in the process of understanding coastal behaviour. However, acquiring such datasets with a high frequency over long periods of time is challenging, with difficulties increasing the further away from shore the measurements are taken. Due to this, research into coastal physical processes has focused on short temporal and spatial scales (i.e. cm to m and seconds to months). It has also predominantly focused on beach and surf zone dynamics (closer to shore) rather than on the shoreface behaviour (further out to sea) (Backstrom, Jackson et al. 2015).

The studies that do focus on the larger scales (i.e. temporal scales longer than years, and spatial scales larger than 1 km) are based on sparse measured bathymetric data usually supplemented with bathymetric data obtained through remote sensing or sediment analysis, or on models. Patterson and Nielsen (2016) studied sand transport on the lower shoreface over 46 years in Australia based on three bathymetry studies using additional information about e.g. wave direction and height. Aouiche, Daoudi et al (2016) analyse the anthropogenic impact on the shoreface of a bay in Morocco based on two bathymetric surveys. Thomas, Phillips et al. (2011) assess nearshore morphological variability of a headland bay beach at Tenby, West Wales between 1748 – 2007 using historic bathymetry maps. Kroon, Larson et al. (2008) conduct an analysis of coastal morphological data sets over seasonal to decadal time series focusing on sedimentary features such as the nearshore bars and shoreline undulations for a range of sites in Europe, including the Netherlands.

In the Netherlands, given the importance of protecting the low-lying mainland from flooding, regular bathymetry measurements have been carried out for a relatively long time. The annual bathymetry data has been collected by the Dutch Department of Public Works since 1963 and is contained in the JARKUS data base ('JAaRlijkse KUStlodingen' – annual soundings). It is composed of cross-shore bathymetric profiles covering the entire Dutch coast. Because of the availability of the JARKUS dataset, Dutch coastal change has been studied more thoroughly. The research predominantly looks at sediment volume changes given the focus of Dutch coastal management policy on preserving the shoreline and its implementation through sand nourishments. Nevertheless, the JARKUS data has also been used to determine the spatial and temporal variability of the Holland shoreface over the large scale (10 km; decades) by looking at the depth of closure Hinton (Hinton 2000). Wijnberg and Terwindt (1995) developed a method to quantify large-scale morphological changes from long-term bathymetric surveys to define large-scale coastal behaviour regions using empirical orthogonal function (EOF) analysis. They find such regions with sharp borders, but cannot see general long-term trends. Larson, Capobianco et al. (2003) have also applied an EOF analysis to the coast of Terschelling (although the analysis was conducted as a demonstration of the method, rather than a study of the shoreface). Finally, Verbesselt et al. (Lammeren, Verbesselt et al. article in prep) studied the Ameland shoreface by deriving Digital Bathymetry Models (DBMs) from the JARKUS data set and performing an elevation trend-analysis using BFAST (Verbesselt, Zeileis et al. 2012, de Jong, Verbesselt et al. 2013).

Although the study by Lammeren, Verbesselt et al. (article in prep) uses DBMs as the basis for its analysis, the majority of studies using data collected over many points in time (like the JARKUS data) base their analysis on shoreface profiles using data collected along transects. At the same time, studies performed on bathymetry data collected over fewer points in time are more likely to base their analysis on DBMs, although they too employ volumetric analysis along transects (Thomas, Phillips et al. 2011, Aouiche, Daoudi et al. 2016). The difference in approaches is likely linked to the volume of data to be analysed and available methods for presenting the results of the analysis and visualising changes between measurements. Basing the analysis on transect data, although allows for the use of various statistical time series analysis methods (Larson, Capobianco et al. 2003, Southgate, Wijnberg et al. 2003) limits the analysis of other shoreface properties such as slope, aspect, and curvature, which could be of interest to determine shoreface behaviour.

For an analysis based on DBMs, however, irrespective of the scale of the processes being studied, the use of a Geographical Information System (GIS) is required. At the same time, when designing a GIS analysis of the shoreface, coastal morphodynamics, GIS and time series analysis concepts have to be considered, as they will shape and affect the results of the analysis, as well as their interpretation. A framework for the design of such studies would help structure the analysis at different scales and provide a frame of reference for issues likely affecting the analysis..

1.2. Research objectives and questions

The objective of the current study was to provide a first step towards developing a framework for DBM-based analysis of shoreface behaviour at various spatial and temporal scales to facilitate future research into the shoreface and interpretation of the results, by developing a method to analyse the long-term (decadal) behaviour of the shoreface slope of a Dutch barrier island (Ameland) using the JARKUS data. The case study area, and the focus on the long-term shoreface slope, was chosen to continue a series of studies on the impact of coastal management on natural coastal development carried out at Wageningen University & Research. The focus was placed on an introductory analysis of the concepts that should be considered when analysing shoreface slope, as developing a complete discussion is beyond the scope of this study.

The study addressed the following research questions:

1. What are the main concepts from a coastal morphodynamics, GIS and time series analysis perspective that should be considered when preparing an analysis of the shoreface behaviour?

2. How can these concepts be used to devise a methodology for studying the shoreface slope of Ameland using the JARKUS data?

3. What can be learned from the implementation of the methodology about the original concepts?

2. Concepts in the Fields of Coastal Morphodynamics, GIS, and Time Series Analysis

This chapter provides an initial discussion of some of the key concepts from the fields of coastal morphodynamics, GIS, and time series analysis that should be considered when preparing an analysis of shoreface behaviour. The choice of the concepts, as well as their discussion is based on the given case study of developing a methodology for analysing shoreface slope dynamics for a Dutch barrier island. Although the objective of this chapter is to form an initial outline of items that should be included in a framework for shoreface behaviour analysis based on DBMs, the discussions focus on raster representations of terrain since the data used in the case study was provided in the raster format.

2.1. Concepts in coastal morphodynamics

2.1.1. Spatio-temporal resolution of shoreface processes

Coastal environments belong to some of the most dynamic environments on the earth's surface and are characterised by an interaction of interdependent processes and entities acting in a multi-dimensional space (x, y, z) and time domain (Hoekstra 1995 in Eleveld 1999). It follows that, as was stated in section 0, coastal change occurs at every spatial and temporal scale.

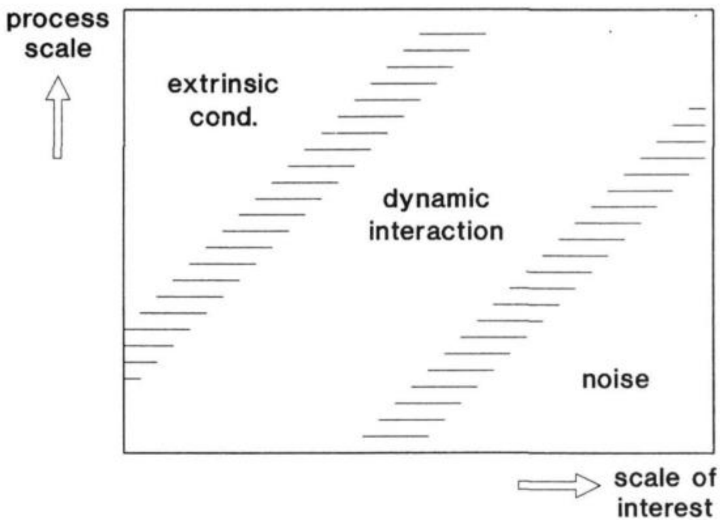

Figure 2. Primary scale relationship. Depending on the scale of interest, the same phenomenon (e.g. storms, tides, sea-level rise) can be noise, a component in the morphodynamics process, or just an extrinsic condition (De Vriend 1991)

In coastal morphodynamics, a relationship between time scales and spatial scales and between process scales and scales of coastal behaviour is presumed (Eleveld 1999). For example, short-term coastal processes such as water and sediment motion, over time influence large-scale coastal behaviour. However, the relationship between the processes and coastal behaviour is not straightforward or clear. This is partly due to the strong variability of the short-term processes, such that the effect of interest is only a weak residual of a very “noisy” signal (De Vriend 1991). De Vriend (1991) further argues that not every process should be relevant to every morphological scale of interest, since, depending on the scale, the same phenomenon (e.g. storms, tides, sea-level rise) can be noise, a component in the morphodynamics process, or just an extrinsic condition. He illustrates this using tidal water level variation. Tides are an extrinsic condition to e.g. dune erosion events, but part of the morphodynamics interaction leading to bar formation on the shoreface. At the same time, at time scales of centuries or more, tide information can be considered as noise (Figure 2).

Given the relation between time and spatial scales, and process and behaviour scales, as well as the fact that many of the coastal changes are circulatory in space or periodic in time (e.g. sandbar creation and migration seaward), Eleveld (1999) argues that when studying coastal processes, variables (slope 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. The problem was also expressed by Niedoroda et al. (in Cowell, Hanslow et al. 1999) as the need for "matching dynamic length and time scales to the morphological scales" (Figure 3). In this context Eleveld (1999) lists the following aspects to consider:

- *"Observations over short time scales (with high frequency) might show that the variable seems inert when change takes significantly longer than the provoking process; reaction and relaxation time are in excess of the time scale of the forcing agent. However, there may be a cumulative effect, especially if the forcing agent itself is undergoing change.*
- *Measuring at the same time intervals as the period of the process might only indicate slow change, while sampling at random time intervals is likely to introduce far greater variation into the results.*
- *Observations over long time scales (at low frequency) might show that the change is significant, but muted or hidden by more dynamic high frequency variations".*

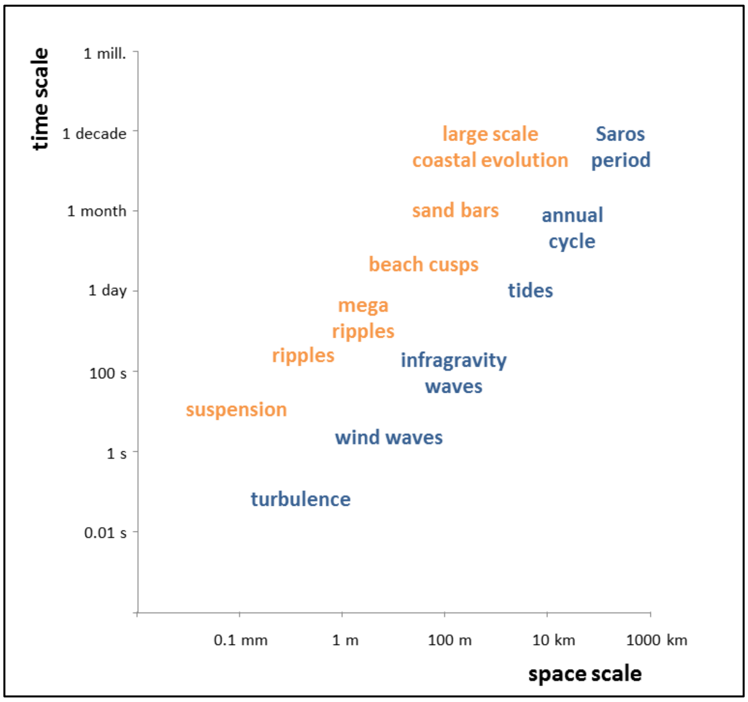

Figure 3.Time and space scales of fluid motions and bed responses in the coastal zone (Stive, De Vriend et al. 1995)

The issue of spatio-temporal scale is intrinsic in establishing the borders of the shoreface itself (Figure 1). An early use of the term shoreface (coined by J. Barrell in 1912) by D. W. Johnson in 1919 referred to the nearshore seabed extending from the low-tide shoreline offshore to a supposed break in slope, seaward of which the gradient was thought to be distinctly less steep (Cowell, Hanslow et al.

1999). Since then, the term has become broader referring to a larger area, typically divided into an upper and lower shoreface. In general, in the upper shoreface, erosion and accretion result in measureable bed elevation changes during a year, while in the lower shoreface, although some sediment transport does take place, significant morphological changes only occur during extreme storm events. The exact limits of the shoreface components, however, are not strictly defined. Davidson-Arnott (2011) describes the landward upper shoreface limit as the low tide line, while Masselink, Hughes et al. (2011) describe it as the limit of wave runup. The border between the upper and lower shoreface, and the seaward limit of the lower shoreface, depend on the time scale of interest.

The border between the upper and lower shoreface is frequently approximated through the concept of the annual depth of closure (Hallemeyer 1981). According to this concept, the changes in bed elevation are largest near the beach face, and decrease progressively offshore. Eventually, the changes diminish to a level which is less than the resolution of standard survey techniques. Hallemeyer (1981) defined this as corresponding to less than 0.3m of vertical change during a typical year (a year without unusually severe storms). However, over longer periods, or with the occurrence of severe storms the depth of closure will increase. Similarly, the definition of the seaward limit of the lower shoreface also depends on the time scale of interest. In general it can be defined as the limit to sediment transport by waves, however, once again, the longer the time-scale, the greater the potential for extreme wave events to occur and therefore the farther seaward the lower shoreface extends (Masselink, Hughes et al. 2011).

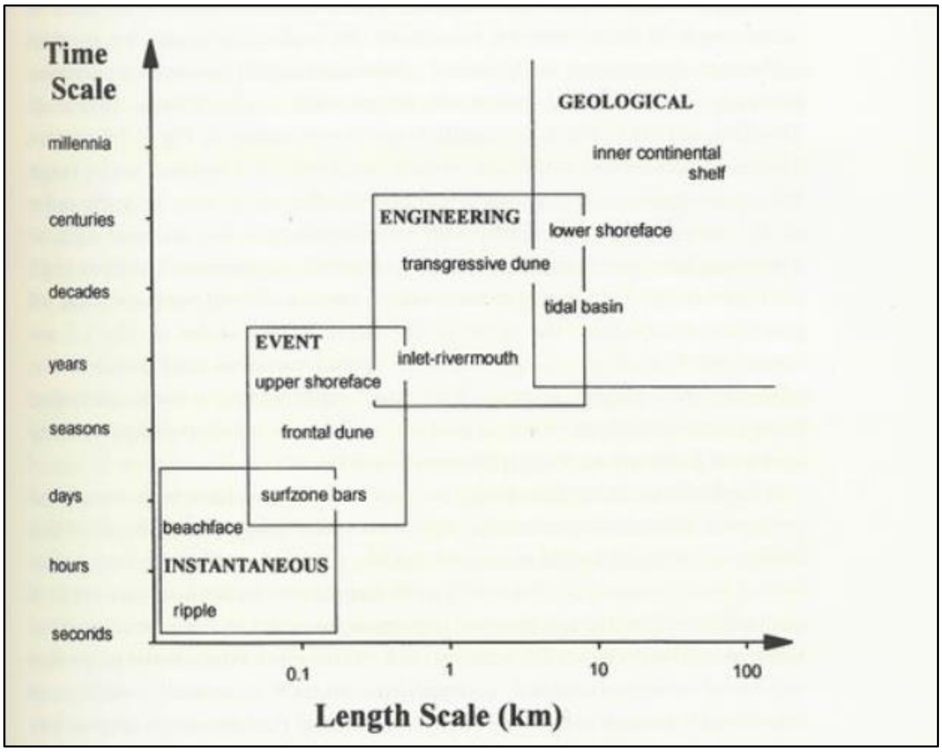

Figure 4. Spatial and temporal scales involved in coastal evolution. Typical sedimentary features are grouped into 4 classes based on the temporal and spatial scale leading to their evolution (Cowell and Thom 1997)

From this section it should be clear that any analysis of the shoreface should ensure that the spatial and temporal scales of the data match the scale of the processes being studied. An indication of these can be drawn from examining the processes affecting the shoreface on temporal scales within the limits of the dataset. For example, if samples in a dataset are collected during on a daily basis during 1 month, the relevant spatial resolution would be in the order of 1m (Figure 3). However it is equally important to consider the location of the samples on the shoreface, and the processes taking place in that location. One may expect less variation, even on a daily basis if the samples are located over the lower shoreface (which is not affected by waves on a daily basis) than if they are located on the upper shoreface (Figure 4).

Finally, in order to ensure consistency, Table 1 sets out the definition of spatial and temporal scales of morphological change used throughout the rest of this 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

2.1.2. Slope properties relevant for shoreface analysis

In mathematics, the slope of a line is a number that describes both the direction and the steepness of the line. It is calculated by finding the ratio of the "vertical change" (rise) to the "horizontal change" (run) between (any) two distinct points on a line.

Given two points (x_1,y_1) and (x_2,y_2) slope can be described with equation 1:

$$m = \frac{\Delta y}{\Delta x} = \frac{vertical\ change}{horizontal\ change} = \frac{rise}{run} = \frac{y_2 - y_1}{x_2 - x_1} \qquad (1)$$

When applied to physical features, slope is the measure of steepness or the degree of inclination of a feature relative to the horizontal plane. Gradient, grade, incline and pitch are used interchangeably with slope. It is typically expressed as a percentage, angle or ratio. In the context of physical features, the slope can be additionally characterized by its aspect (compass direction that the slope faces) and concavity. A convex slope rolls from less steep to steeper terrain with movement downslope, while a concave slope rolls from steeper to gentler terrain. Henceforth, gradient will be used to denote the steepness of the feature, while slope will be used to refer to an inclined surface characterised by gradient, aspect and curvature.

For terrestrial applications, information regarding slope characteristics such as gradient, aspect and concavity, provide information about exposure to the sun, erosion potential, suitability for different habitats, etc. For marine applications, Lecours, Dolan et al. (2016), provide a useful overview of the most commonly used terrain-attributes (gradient, orientation, curvature and terrain variability) and their relevance to geomorphological and ecological applications. Table 2 is adapted from their study to focus on slope derivatives and their geomorphological relevance.

The table focuses on slope characteristics from the perspective of geomorphological analysis. However, the three slope derivatives also apply to a coastal protection perspective. As was previously mentioned, the shoreface buffers the power of waves, reducing their height and energy due to friction (Cowell 2000, Masselink, Hughes et al. 2011). As Cowell (2000) explains:

“the bottom friction depends on the [gradient] of the shoreface and on the seabed grain size and morphology. A gentle [gradient] of the shoreface means that the distance over which waves ‘feel’ the influence of the bottom is larger and thus that the reduction of wave height due to friction at the seafloor is large. On a steep [gradient] the distance over which the influence of the bottom is felt is much smaller and hence, the reduction of the wave height is more limited.”

Table 2. Slope derivatives and their geomorphological relevance (adapted from Lecours, Dolan et al. 2016)

	Gradient	Orientation/Aspect	Curvature
Geomorphological relevance	• Stability of sediments (grain size); • Local acceleration of currents (erosion, movement of sediments, creation of bedforms)	• Relation to direction of dominant geomorphic processes	• Flow, channelling of sediments/currents, hydrological, and glacial processes; • Useful in the classification of landforms
Commonly computed terrain attribute	• Slope	• Aspect; • Northness/ northerness • Eastness/ easterness	• Mean curvature, profile curvature, plain/planimetric curvature; • Bathymetric Position Index (BPI)

On longer time-scales, coastal protection is also dependent on the sediment budget. Numerical modelling investigations demonstrated that steep shorefaces (with gradients > 0.80) are more likely to have offshore-directed sediment transport than dissipative and shallow shorefaces, which have a tendency towards nearshore accretion (Roy et al. in Backstrom, Jackson et al. (2015)). Furthermore, variation in the gradient and curvature of the slope of the shoreface in widely separate regions has been qualitatively attributed to differential sorting of sand deposits through the action of wave-induced currents and to differences in the amount and type of sediment available to local shoreface processes (Niedoroda, Swift et al. 1984). Changes in the gradient or curvature could then provide information about changes to these two parameters. Similarly, information about the aspect of the shoreface could potentially provide information about changes to the direction of dominant geomorphic processes.

To distinguish between changes in the gradient, aspect and curvature due to the shifting of shoreface landforms such as sand bars, and changes due to the long-term shoreface behaviour, it is necessary to consider the spatio-temporal scale of the corresponding processes, described in the previous section.

2.2. Concepts in GIS and time series analysis

2.2.1. Deriving a DTM and slope characteristics

In GIS a surface is represented by a digital terrain model (DTM). However when this surface is located below the water surface it is referred to as a DBM. In this study the term DBM will be used when referring to surface models containing only bathymetry data, and DTM when referring to surface models including above water-level data. This section uses the term DTM as it is a more general discussion of issues arising when deriving surface models.

A DTM can be represented as a raster (gridded array of elevations), or a vector-based Triangulated Irregular Network (TIN, set of contiguous, non-overlapping triangles). Both can be generated through interpolating point data with various interpolation methods. The advantages and disadvantages of using a raster or a TIN terrain representation, as well as the different interpolation methods has been extensively studied (Kumler 1994, Defourny, Hecquet et al. 1999, Theobald 2005). The choice of interpolation method is significant as it will introduce errors into the DTM which will propagate throughout the rest of the analysis (see section on errors in spatial analysis and their propagation).

In addition to various methods of deriving a DTM, there are also many different ways to derive slope properties for each representation model. Gradient is calculated for each triangle in TINs and for each cell in rasters. For a triangulated irregular network (TIN), this is the maximum rate of change in elevation across each triangle. For rasters, the gradient is calculated for each cell with various algorithms developed for this purpose. Evaluations of the different algorithms show that they may produce significantly different slope values. Skidmore (1989) compared six methods that were commonly used to generate aspect and gradient from gridded DTMs, and found that general linear regression models and the third-order finite difference methods were the most accurate. Warren, Hohmann et al. (2004) confirmed this finding based on evaluation of ten methods of computing slope utilizing capabilities inherent in five different GIS. Their analysis showed that methods utilizing differential geometry to compute percent slope from gridded DTMs outperformed methods utilizing trigonometric functions. Additionally, Dolan and Lucieer (2014), who review slope calculations specifically for bathymetry data, demonstrate that further variation in the slope values can be introduced due to the resolution of the data or analysis scale.

As was mentioned at the beginning of this chapter, the rest of this section will focus on the raster terrain representation.

2.2.2. Considering the spatio-temporal resolution of the analysis

An important aspect of shoreface analysis is ensuring that the spatial and temporal scales of the data match the scale of the processes being studied (see section 2.1). Within GIS and time series analysis, various methods exist to change the spatial and temporal scale of data; although they must be used with caution as they alter the original data and can introduce errors (see section 2.2.5). Given the limitations of this study, only methods that decrease the resolution of the data (in order to study processes occurring on a larger scale, over longer periods of time) are discussed.

In the temporal dimension, smoothing of time series data is a common way to detect trends or periodic cycles in the data. Through the application of some form of local averaging, smoothing ensures that outliers and local fluctuations cancel each other out, i.e. noise from processes happening on shorter scales is reduced. There are two most common techniques to achieve this: non-overlapping and overlapping temporal aggregation. Non-overlapping aggregation involves the aggregation of the data to a specified interval – the analysis interval (e.g. a week, month, year, etc.). The drawback of this method is that it assumes that the data are not related to each other and can be segmented into separate blocks. With bathymetry data, depth measurements are a product of the processes affecting the seafloor, but also its state in the past. The most common overlapping temporal aggregation technique is a *simple moving average* smoothing. This technique calculates the averages of subsequent subsets of *n* elements of the original data, where *n* corresponds to the size of the smoothing "window". The calculated subset averages replace each original element of the series. Various other forms of moving average smoothing exist, e.g. weighted, cumulative, or exponential.

In the spatial dimension, smoothing (i.e. generalising) single DTMs can help to ensure that noise from smaller features is reduced. Paddenburg and Wachowicz (2001) studied the use of spatial generalisation to reduce error noise in raster surfaces and found that it did indeed filter the noise. They concluded that the observed spatio-temporal variation, after the generalisation process, was probably more representative of the true spatio-temporal change in the real world (Paddenburg and Wachowicz 2001). Although they were concerned with error noise, variations (or noise) introduced by features that are smaller than the analysis scale can be filtered out in a similar way with the results more representative of the spatio-temporal change at the analysis scale.

In GIS a smoothing effect can be obtained by changing the cell size through interpolating or aggregating the data, or by simply recalculating the value in each cell based on a given number of surrounding cells (focal statistics). Interpolation uses a value derived from the original raster to fill in the output raster with larger cell sizes. The values are most commonly derived using one of the following methods: nearest neighbour, bilinear interpolation or cubic convolution. Aggregation assigns to each output cell, the mean, median, sum, minimum or maximum of the input cells falling within the new output cell. Focal statistics applies similar statistics to the aggregation method, however, as the cell size does not change, the new value is calculated based on a moving window. Additionally, when smoothing a derivative of the terrain (such as gradient), the order in which the smoothing and derivative calculation is carried out can be changed. For example, Dolan and Lucieer (2014) summarize 5 main approaches to obtaining terrain indices for raster terrain representations (including slope derivatives) at different scales (Table 3).

Table 3. Five main approaches to obtaining terrain indices at different spatial scales for gridded DTMs (adapted from Dolan and Lucieer 2014)

Approach	Description
1	Change resolution (resampling) then calculate terrain variable
2	Average depth over n × n windows then calculate terrain variable
3	Calculate terrain variable then average result over n × n window
4	Calculate terrain variable at multiple scales* using selected n × n analysis windows
5	Multiscale analysis** of terrain variable

* 'Multiple scales' refers to an analysis at successive analysis windows

** 'Multiscale analysis' refers to an analysis which runs concurrently at multiple scales and reports the mean value and standard deviation over all analysis scales considered.

The benefit of smoothing in both the temporal and spatial dimension can be seen in Figure 5. The blue lines represent the -4 m contour based on data collected annually over 50 years (lighter – earlier measurements, to darker – later measurements). The original data is a raster with a 20x20 m cell size. This is temporally smoothed using a 5 and 10 year moving window (a) and b)), and then also spatially smoothed by increasing the cell size to 200x200 m (c) and d)). The long-term pattern (shifting of the contour with the sand erosion and deposition cycle affecting this area) of the movement of the contour is most clearly visible in image d) although, clearly, the details of the exact position of the contour are lost.

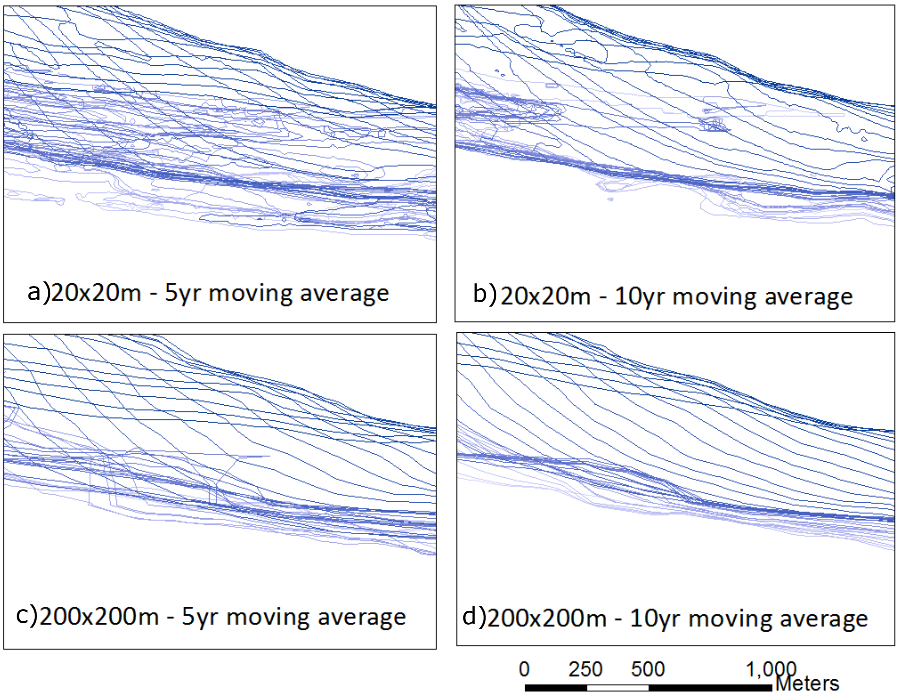

Figure 5. Movement of the -4 m contour over 50 years based on different spatio-temporal smoothing.

2.2.3. Dynamics in the spatial domain

Identifying the dynamics of a physical process using GIS, is closely linked to detecting change, as dynamics refer to "a pattern or process of change" (Merriam-Webster.com). As change happens in space and time, to study change, but also the patterns it generates and the processes influencing it, it is necessary to include time in the analysis (Peuquet 1994). However, the representation of both space and time in digital databases, as well as its visualisation has proved a challenge (Peuquet 2001). According to Paddenburg and Wachowicz (2001), this is because research in temporal and spatial database models has predominantly developed independently.

Al-Taha and Barrera (1990) identified two methods for reasoning about time: a time-based approach which considers time as a separate dimension, and a change-based approach which concentrates on recording changes or facts valid at a certain point in time, without considering explicitly the temporal domain. As Paddenburg and Wachowicz (2001) point out, most spatiotemporal analyses are based on the change-based approach where the time dimension is simply added to the spatial dimension. Change is recorded as a series of 'snapshot' images. This 'snapshot' approach employs a grid or vector data model, and each image represents a 'world state' at a known point in time (Peuquet 2001). However, the changes that occur between 'true states' are not explicitly stored.

Comparing the 'snapshots' it is possible to determine change in place, i.e. change in an aspatial attribute (e.g. elevation) at a specific location, but also a change in space, i.e. change in the geometry of an object (size, shape, position). Indeed, Blok (2005) proposes several concepts within the spatial and temporal domains which describe the characteristics of change of dynamic geospatial phenomena in the physical environment. Within the spatial domain, she distinguishes between mutation (transformations affecting the thematic attribute component of an existing phenomenon) and movement (change in the spatial position and/or geometry of a phenomenon). Thus, patterns created by change can also relate to patterns in the spatial distribution of all attribute values or patterns in the movement of an object with a specific attribute value.

However, when considering a change in the attribute assigned to a specific location over time (i.e. in a time series), there are several ways to define change. Zhou, Shekhar et al. (2014), suggest four ways including change in a statistical parameter, change in actual value, change in models fitted to data, and change in derived attributes (Table 4, Figure 6).

Table 4. Four definitions of change in data (based on Zhou, Shekhar et al. 2014)

Change in Statistical Parameter	Data in some applications are assumed to be random samples drawn from an underlying process. A change is thus defined as a shift in the statistical distribution of the data. For example, in statistical quality control, sensor readings are expected to follow a certain statistical distribution (e.g., Gaussian). If a fault occurs, the mean or variance of data will change.
Change in Actual Value	This definition is based on the actual values of the data. The definition of change is initially modelled (mathematically) in calculus, where a difference between a data value and its neighbourhoods in location or time is viewed as a change. In a one-dimensional continuous function, the magnitude of change is usually characterized by the derivative function, while on two-dimensional surfaces, a change is usually characterized by the magnitude of the gradient. For a discrete function (e.g., time series), the change between two data points can be characterized by the slope of the line connecting the two.
Change in Models Fitted to Data	This definition focuses on the change in the trend/behaviour of the data. A number of function models are fitted to the data where a change in one or more of the models is defined as an instance of change. For example, climate scientists studying the trend of global precipitation want to be able to detect a turning point where the rainfall changes from increasing to decreasing. In such scenarios, a time series can be fitted using a certain number of straight lines by minimizing the error (e.g., least square error). Hence, a change in the data is defined as a discontinuity between two consecutive linear functions. The models can also be nonlinear (e.g., polynomial).
Change in Derived Attributes	Some applications define change patterns indirectly. First, they establish a classification or prediction model of the data. Then they run the model and derive new attributes, such as predicted value or a categorical class label of the data. For example, in time series change detection, a predictive model can be learnt based on a training dataset. The future values are then predicted and compared with actual values. A difference between the prediction and actual value is considered a change.

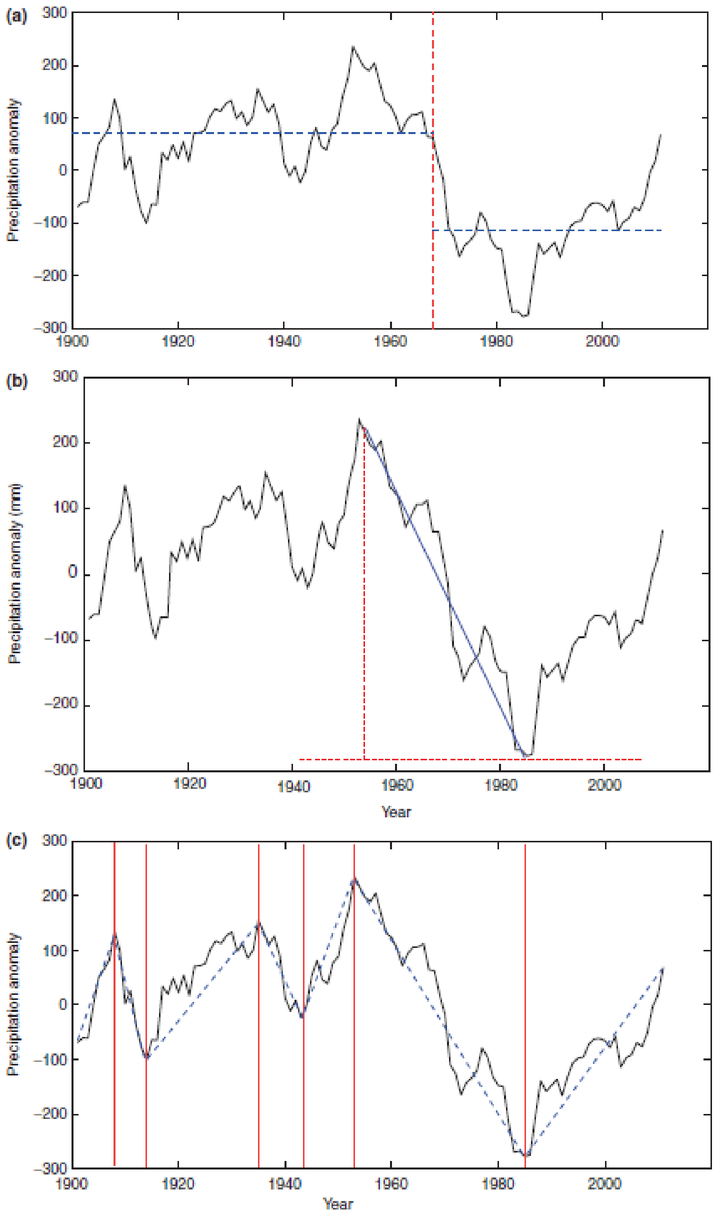

Figure 6. Three sets of results for one time series dataset using three different definitions of change. (a) Statistical parameter change in a time series, (b) Value change in a time series, (c) Change in model fitted on a time series (from Zhou, Shekhar et al. 2014)

2.2.4. Dynamics in the temporal domain

In the 'snapshot' approach, change and patterns can also be described in the temporal domain. (Peuquet 1999) identifies four types of change based on their temporal pattern:

- Continuous: going on throughout some interval of time
- Majorative: going on most of the time
- Sporadic: occurring some of the time
- Unique: occurring only once.

This means that duration and frequency become important characteristics in describing the temporal pattern. In fact Blok (2005), in addition to the frequency and duration, identifies moment in time, sequence and pace, as elements describing change in the temporal domain (Table 5, Figure 7).

Table 5. Concepts of change in the temporal domain (adapted from Blok 2005)

Moment in time	Refers to the date (the location in time) of a change in the spatial domain.
Sequence	Refers to the order of phases in a series of changes in the spatial domain.
Duration	Refers to the length of time involved in a change and/or the time between changes in the spatial domain.
Pace	Refers to the rate of change over time.
Frequency	Refers to the number of times that a particular phase is repeated in a series of changes in the spatial domain.

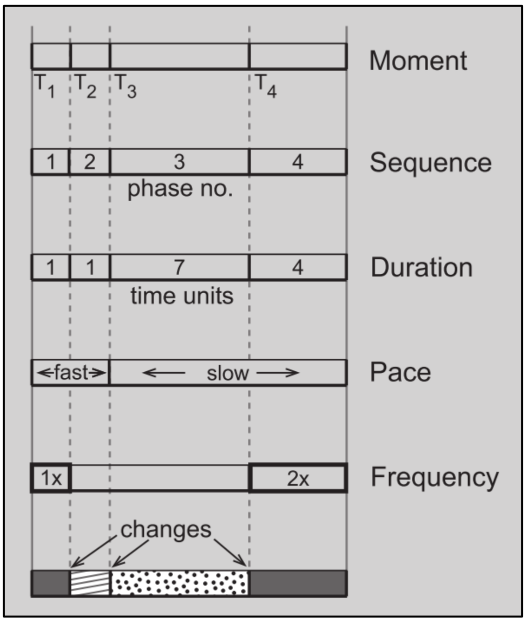

Figure 7. Characteristics of change in the temporal domain; changes are marked by orthogonal lines into the time bar (Blok 2005)

2.2.5. Errors in spatial analysis and their propagation

A DTM is a continuous representation of a complex spatially distributed phenomenon (i.e. depth). As it is not feasible to have information about depth at every location, a DBM is an approximation of the seafloor based on a finite number of samples. However, as this surface is approximated, errors are unavoidable; from both vertical and horizontal errors introduced when measuring the depth at sample locations, to errors introduced when interpolating these sample measurements. According to Yao and Murray (2013), all techniques used to construct a surface representing continuous phenomena are subject to assumptions that are usually not satisfied in practice. Additionally, any errors generated at this stage propagate throughout the remainder of the analysis and can cumulate with errors generated during operations such as deriving slope attributes from a DBM, or spatial and temporal smoothing. Therefore, it is important to choose the most appropriate techniques for a given terrain. However, as Theobald (2005) points out, what dictates the acceptability of a terrain model is the research objective (and so the landforms being studied) and the precision required.

2.2.6. Hypothesis-based data analysis vs. Exploratory Data Analysis (EDA)

Time series data of coastal morphology are an important source of information in the process of understanding coastal behaviour. However, the techniques used to analyse data of coastal morphological evolution can take what Southgate, Wijnberg et al. (2003) call a 'physical scientist's approach' or a 'statistician's approach'. The 'physical scientist's approach' starts with a hypothesis, and then looks for evidence to support or contradict it. The data requirements for this approach are more relaxed – they are determined by the nature of the hypothesis and not the full range of alternative hypotheses, but it requires some knowledge of the physical processes of coastal morphology to begin with. The 'statistician's approach' deduces general properties of a natural system by data analysis alone, and thus does not require any initial knowledge of the system (Southgate, Wijnberg et al. 2003). The "statistician's approach" follows the ideas behind exploratory data analysis (EDA).

The purpose of Exploratory Data Analysis (EDA) is to "get acquainted with the data". This sets it apart from traditional statistical analysis which aims to answer questions; the goal of EDA is to generate hypothesis rather than test hypothesis (Andrienko and Andrienko 2006). In itself, EDA is a philosophy defined by Tukey (1977) of how the analysis should be carried out. According to Tukey, the purpose of EDA is to detect and describe patterns, trends and relationships in data. In their book on EDA of spatial and temporal data, Andrienko and Andrienko (2006) take the following view on EDA:

> *"The analyst has a certain purpose of investigation, which motivates the analysis. The purpose is specified as a general question or a set of general questions. The analyst starts the analysis with looking at what is interesting in the data, where interestingness" is understood as relevance to the purpose of investigation. When something interesting is detected, new, more specific questions appear, which motivate the analyst to look for details. These questions affect what details will be viewed and in what ways" (Andrienko and Andrienko 2006).*

Any analysis of the shoreface will, thus, likely fall into either the 'physical scientist's' approach or employ EDA.

The following chapter describes a methodology for the analysis of the shoreface slope that was developed based on the concepts discussed in this chapter. Chapter 5 contains an in depth discussion of how these concepts were applied, their utility, as well as problems encountered in their application.

3. Methodology

To demonstrate the use of the coastal morphodynamics, GIS and time series analysis concepts discussed in the previous chapter, two methods were developed for identifying shoreface slope dynamics and applied to a case study of Ameland. The methods attempt to answer the following questions: how can the shoreface slope dynamics be identified, and, specifically, how can areas with different slope dynamics be identified?

The decision to focus this study on the shoreface of Ameland comes as a consequence of a series of studies on the impact of coastal management on natural coastal development (Eysink, Dijkema et al. 2000, Jong, Slim et al. 2011, De Jong, Keijsers et al. 2014, Poortinga, Keijsers et al. 2015). These studies began on land, and have progressively moved towards incorporating the seabed. As such the current study is a natural continuation and extension of this research.

The study uses gridded DTM data, to which some initial pre-processing along with spatio-temporal smoothing was applied. The change-based approach to the spatio-temporal analysis was adopted given the data structure and the database model in the GIS software used (ArcMap 10.4.1). Based on the notion of change in this 'snapshot' approach, two different methods to analyse the slope were applied to compare their performance and the information they provide (Figure 8).

In the following sections more information is provided about the case study (study area and data), before discussing in more detail each of the steps in the flowchart.

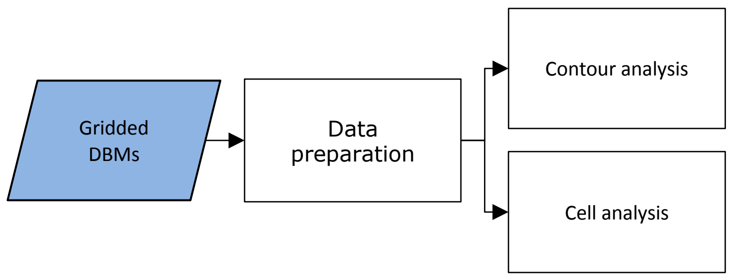

Figure 8. General study workflow

3.1. Case study

The study is developed for a Dutch barrier island – Ameland. This section will first discuss in more detail barrier islands before describing the study area and the data used for the study.

3.1.1. Barrier systems and islands

Barrier islands are a form of barrier - emergent depositional landforms which are separated from the mainland coast by a lagoon, bay or marsh. They are built on a subaqueous platform or base, which itself is built alongshore and offshore by littoral processes and by sediments washed over the barrier by storm waves. Barrier Islands are most commonly found on trailing edge coasts in areas where there is an abundant supply of sand such as the east coast of North America, Western Europe between Holland and the Jutland Peninsula, and on the south-east coast of Africa from South Africa to

Mozambique. These islands are rarely found where they formed, as they migrate relatively rapidly in response to changing sea level, sediment supply, and large storm events.

The presence of barrier islands plays a crucial role in protecting the low-lying hinterland from extreme surges; they act as a barrier between the mainland and processes operating on the open coast (Davidson-Arnott 2011, Masselink, Hughes et al. 2011). They are also highly valued for their biodiversity and wetland habitat, even as many of them (e.g. along the Gulf of Mexico coast of the USA) are heavily urbanised. For all these reasons, various coastal management practices are deployed to prevent barrier island erosion, or to reduce their morphodynamic variability.

3.1.2. Study area

This study will be carried out for the area of a Dutch barrier island - Ameland. The island forms part of an archipelago of islands stretching for 450 km from the northwest of the Netherlands through Germany to the west of Denmark. They are collectively known as the Frisian or Wadden Sea islands, as they are separated from the mainland by the Wadden Sea. The islands evolved as a response to sea-level rise during the Holocene and are 10-30km long, with sand beaches and dunes on their North Sea side. They are separated by tidal inlets with active inlet dynamics (Beets, Valk et al. 1992, Oost, Hoekstra et al. 2012), and exhibit highly dynamic behaviour, which results in an ever-changing morphology (topography/bathymetry) of the islands.

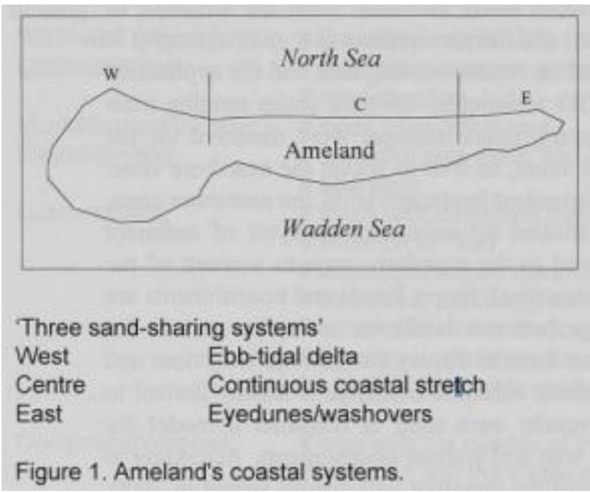

Figure 9. Three sand-sharing systems of Ameland (Eleveld 1999)

In the case of Ameland, based on the main processes affecting the island morphology, Eleveld (1999) distinguishes three sand-sharing systems: the ebb-tidal delta, a continuous coastal stretch, and an eyedunes/washover area (Figure 9). In the ebb-tidal delta, the channel pattern shows a cyclic behaviour in time (Figure 10), in which the channel migrates generally from west to east decreasing in importance before a new channel develops in the west. The cyclic behaviour of the ebb-tidal delta is closely related to the transport of sand along the coast, which under the influence of tide-, wind- and wave-driven alongshore currents is moved in the eastwards direction along the islands, initially has a horizontal sand wave before it loses its coherence. This cyclical pattern results in a highly fluctuating coastline on a scale of years and decades (Wang, Hoekstra et al. 2012). In the central part of the island a coastal retreat of one to a few metres per year takes place, however this has been compensated for by coastal nourishment since 1990 (Wang, Hoekstra et al. 2012). In the East of Ameland the deposition of the eroded sand leads to a shift to the east.

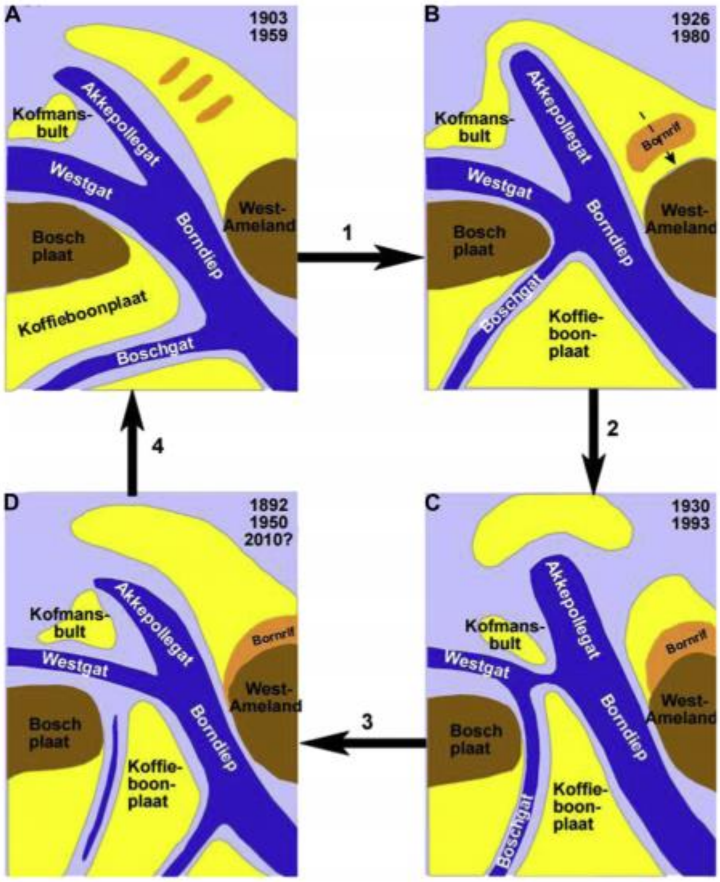

Figure 10. Cyclic behaviour of the tidal inlet to the West of Ameland (Dutch terms are names of shoals and channels (Israël and Dunsbergen 1999 in Wang, Hoekstra et al. 2012)

3.1.3. JARKUS data

The JARKUS data are a collection of cross-shore bathymetric profiles covering the entire coast of the Netherlands, initially intended for coastal zone management. Measurements have been made since 1963 on an annual basis, generally outside of the stormy season.

The JARKUS profiles consist of point measurements (X, Y and Z) along transects perpendicular to the shore line. The cross-shore resolution of the transects varies from the waterline (5 m) to the seaward boundary (40 m) of the transect, while the longshore spacing of the cross-shore transects is 200 m marked by a permanent base of beach poles known as the RSP ('Rijks Strand Palen lijn') reference line. The length of the transects in not consistent over time due to changes in policy, measuring techniques, and simply changes to the island morphology. Up until 1990, they follow more or less the pattern of running for 1000 m from the top of the first dunes towards the sea. Additional, longer transects were also measured. These corresponded to every fifth shorter transect, and were around 3500 m in length. They are measured every 3-5 years. However, over time both the short and long transects have got longer (up to around 5,7 km in 1993), and after 1993 a clear distinction between them is not visible in the data.

The transects are the result of both wet and dry measurements. The former covers the active zone and shoreface and is collected through ship-based echo-sounding. The latter covers the dune and beach and was originally collected through levelling (until 1977), photogrammetry, and most recently – laser altimetry (LIDAR). The wet and dry data are combined and interpolated for the intertidal area (Hinton 2000, Veenstra 2016).

According to Hinton (2000), the data's vertical accuracy has been documented to be 0.25m. The sounding accuracy of depth values is approximately 0.15m, but increases to 0.25m when ship-dependant errors are taken into account. More up-to-date information can be obtained from the Rijkswaterstaat (data form 2002 and 2003 for wet and dry measurement accuracy respectively), however it is only available in Dutch.

The JARKUS data are available for the whole coast of the Netherlands and 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).

Raw data from the measurements are available from the Rijkswaterstaat as *.jrk files (plain text) on the Open Earth Raw Data repository. The raw data do, however, contain duplicate measurements due to the overlapping of the wet and dry measurements. A version of the data without these duplicates or missing values is available as a large NetCDF file at the Deltares OPeNDAP server (Veenstra 2016).

JARKUS Grids from Deltares for Ameland

This study is based on raster DTM (including both below and above sea-level areas) interpolated from the JARKUS data and transformed to the ESRI native ADF format. These rasters were made available by Tommer Vermaas at Deltares, and cover the years 1963 to 2014. The decision to use this dataset was based on the premise that the current study is a demonstration of an approach to detecting shoreface dynamics rather than a study of these dynamics in itself. As such the need for accurate and verified interpolation methods was unnecessary.

The grids are projected to the Amersfoort / RD New spatial reference system and have a resolution of 20 x 20 m. Until 1993, the DTMs are based on an interpolation of the measurements conducted along the shorter transects; the bathymetry data of the longer transects is excluded. Although measurements within the JARKUS dataset started in 1963, measurements for Ameland only started in 1964. Even so, in 1964 the measurements do not extend further than to a depth of -2m. For this study only the JARKUS Grids for the years 1965 to 2014 will be used (i.e. covering 50 years).

As was mentioned above, the extent of the JARKUS transects, and therefore also the extent of coverage of the DTM, varies over time. Additionally, for several years for Ameland, data is missing within the extent of the transects measured that year, i.e. there are areas of NoData within the Grids. Finally, in 1972 only a small segment of the shoreface was measured around the western inlet, while in 1973 no measurements at all were taken along the transects originating on Ameland. Consequently, for the majority of the study area there is a 2-year gap in the data.

As the extent of the measurements varies from year to year, it was important to obtain an overview of areas which are well covered during the 50 years, and areas where only a few measurements were made, to ensure that data availability is correctly accounted for when interpreting the results of the analysis. In Figure 11 below, a well-covered stretch of shoreface close to the shoreline (corresponding the average length of the short transects) is clearly identifiable, while the further seaward, the fewer the years with measurements in that area become.

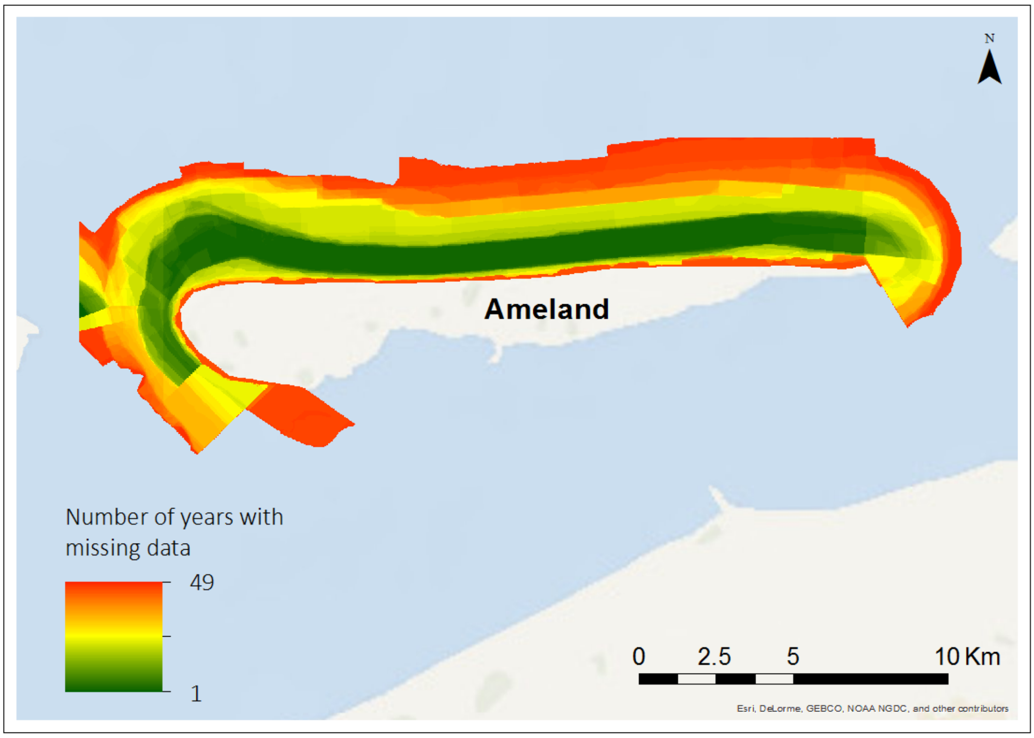

Figure 11. JARKUS Grids coverage for Ameland, 1965 - 2014

Furthermore, within the JARKUS Grids area, the average elevation ranges from -25m in the area of the western inlet, to + 20 m on the dunes. The lowest areas other than the inlet can be found towards the northern edge of the Grids and reach -12m.

3.2. Data Analysis

The section will first describe the steps taken to prepare the data for analysis including cropping to the study area, and performing temporal and spatial smoothing to enable the analysis of trends on a decadal scale, before discussing the two methods for the analysis of shoreface slope – a geometry-based approach (contour analysis) and an attribute-based approach (cell analysis).

The two methods were developed to offer different insights into the dynamics of the shoreface slope. They both take an EDA approach, but they differ in terms of their approach to identifying change. The first method focuses on the analysis of the change in geometry of contour lines to detect changes in the slope gradient, while the second one focuses on the change of the slope gradient attribute to study the variety of values and magnitude of change at given locations. A comparison of the results obtained through the application of both methods will allow for a discussion of their performance and insights they provide.

Finally, in this study the term DTM will be used to refer to the grids which include both underwater and above water elevation data, while the term DBM will be used when the data contains only elevation data of the seabed.

3.2.1. Data preparation

This section will discuss in detail the workflow presented in Figure 12.

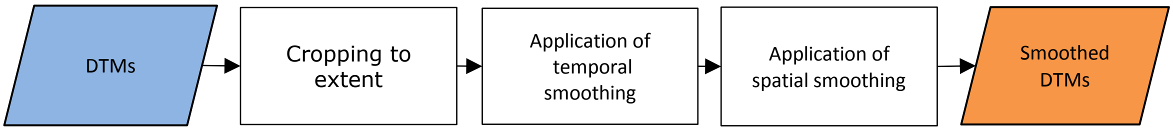

Figure 12. Data preparation workflow

Cropping the data to the study area extent

The JARKUS Grids data cover the whole Dutch coastline. As a first step each raster had to be cropped to an extent encompassing only the data generated from transects originating on Ameland. The chosen extent is provided in Table 6.

Table 6. Extent of case study area in Amersfoort / RD New projected coordinate system

Top:	612900	Left:	167280
Bottom:	601520	Right:	195800

Considering the spatio-temporal resolution of the analysis

The JARKUS data are collected at a much higher spatial and temporal resolution than the processes affecting the shoreface in the long-term. Following the discussion in section 2.1 on process scales, the high resolution data may thus contain information about processes operating on a shorter time-scale and smaller spatial scale, which can be considered to be noise at the medium-scale. In the spatial dimension these can be seen as smaller features such as sandbars on the shoreface, while in the temporal dimensions these can be seen as short-term fluctuations around the trend.

To extract the information pertaining to the scale of analysis, both a spatial and temporal smoothing was applied to the data.

Temporal smoothing

In this study an overlapping simple moving average was used to smooth the data. An overlapping temporal aggregation was chosen given that the bathymetry values are dependent on their past values, and so a non-overlapping technique could reduce the visibility of any patterns in the data. A simple moving average was chosen since all years have the same significance to the study.

A procedure was developed which implemented the following algorithm:

1. List all the original DTMs for the years 1965 to 2014;
2. Given a window size *n*, take a subset corresponding to the first *n* DTMs;
3. Create an empty raster with the same extent as the original DTMs;
4. For every cell in the DTM, calculate the average for that cell from the subset;
5. Take the next subset (i.e. shift the first DTM in the subset by 1 compared to the previous subset);

6. Repeat steps 3-5 until it is not possible to create an *n*-sized subset anymore (the remaining DBMs are not used for further analysis).

The limitation in step 6 was created to ensure that averages weren't calculated based on data from fewer than *n* years in a bid to make them comparable. Additionally, the average was calculated only based on the number of years with data within any given *n* years, i.e. years without any data were ignored.

The new values generated by every iteration of steps 3-5 represent an average of *n* years. The consecutive n years will from now on be referred to as a smoothing period. To enable a fast understanding of the years corresponding to each new value, this value is assigned the number of the first year in the smoothing period. For example, if the subset corresponds to the years 1965 to 1969 (using a 5 year window), then the average of this subset will be assigned to 1965.

To establish the size of the window used for further analysis, an initial sensitivity analysis was conducted. Given the study's focus on the long-term, the 3 window sizes were chosen that take into account the time-scales of the processes studied, as well as the length of the dataset, i.e. 5, 10 and 15 years. Three sets of temporally smoothed DTMs were generated – one for each window size. To compare the effect of the different window sizes on the data, 6 points were selected on the shoreface (Appendix 2: Selecting a moving window size for temporal smoothing). They were spread over the sub-merged extent of the data to reflect areas were different processes affect the seabed, but also were different amount of data are available. The time series of bathymetry data was plotted for each point for the three window sizes. These were then compared against each other and the original bathymetry time series for those points (Appendix 2: Selecting a moving window size for temporal smoothing). Based on this visual assessment, a single window size was chosen to be used in the next steps.

Spatial smoothing

In addition to a temporal smoothing of the time series of the bathymetry data per cell, a spatial smoothing was also applied to each smoothing period. This step helped to ensure that noise from smaller features in a single smoothing period was reduced. For this study a simple aggregation based on the mean was used. Several output cell sizes were tested (40, 80, 200 meters) to establish a new resolution at which features on the shoreface (such as sandbars) that were not of interest to this study were not visible (Appendix 3: Effect of cell size on spatial smoothing).

3.2.2. Contour analysis for shoreface slope dynamics

The first method to analyse the shoreface slope dynamics is a geometry-based one. In section 2.1.2, a gradient is described as the ratio of the "vertical change" (rise) to the "horizontal change" (run) between (any) two distinct points on a line. In cartography, points with the same Z value can be joined by a line (contour) to represent areas with equal elevation. On such contour maps, the gradient is then calculated by choosing a transect and finding the points where the transect intersects the contour lines before applying the definition above.

In the context of this study, calculating the gradient based only on two contours can allow for a further averaging of the gradient value. The Bruun rule (Bruun 1962) for equilibrium shoreline retreat is based on such an averaging of the shoreface gradient. His proposed equation includes as a variable the gradient of the active zone as measured from the shoreline to the depth of closure. This approach to calculating the shoreface gradient is also applied by Halouani, Fathallah et al. (2011), who use contours at different depths (5 m and 10 m) to calculate average nearshore slopes and characterise their study area.

A single contour-based analysis is a frequent approach for studying changes to shorelines, where the shoreline position is plotted over time (e.g. Hansen and Barnard (2010)), i.e. the analysis is focussed on the change in geometry of the contour. However, as discussed above, two contours at different elevations provide information about slope gradient values. Analysing the distance of these two contours over time (absolute distance) can provide information about the change in the gradient attribute, i.e. the steepening or flattening of the slope, while analysing their position relative to a stable point (relative distance) can provide information about changes to their spatial dimension, i.e. the location and dynamics of a specific contour.

In this study a method for such a contour-based analysis is proposed for assessing the patterns of changes to the shoreface slope gradient and characterising changes (Figure 13).

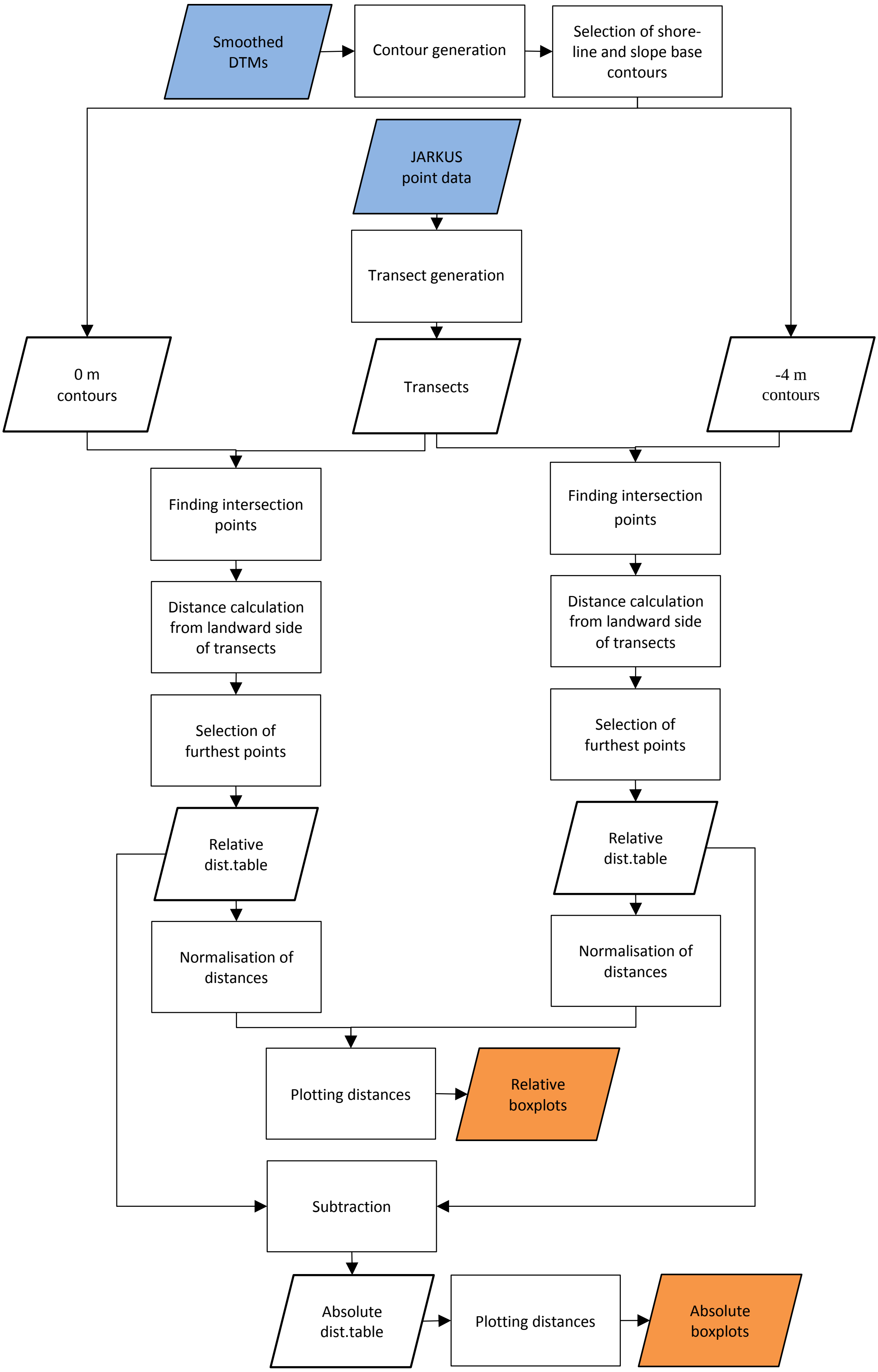

Figure 13. Contour analysis workflow

Deriving transects

To be able to conduct the contour analysis, information about the distance of the contours relative to each other and a fixed point was required. For this purpose, transects were drawn along the North Sea coast of Ameland, parallel to the JARKUS transects (Figure 14). They were spaced out evenly along the length of the shore to provide information about the dynamics affecting each area of the shore. The heads of the island were not fully covered by the transects since the dynamics affecting these areas are different to those affecting the shoreface. The transects were spaced 4km along-shore, resulting in a total of 6 transects. The spacing distance of 4 km was chosen after considering the temporal scale of the processes being investigated (decades), the corresponding spatial scale (10km, Table 1), the extent of the data, the total length of the Ameland shoreface, as well as processes affecting it.

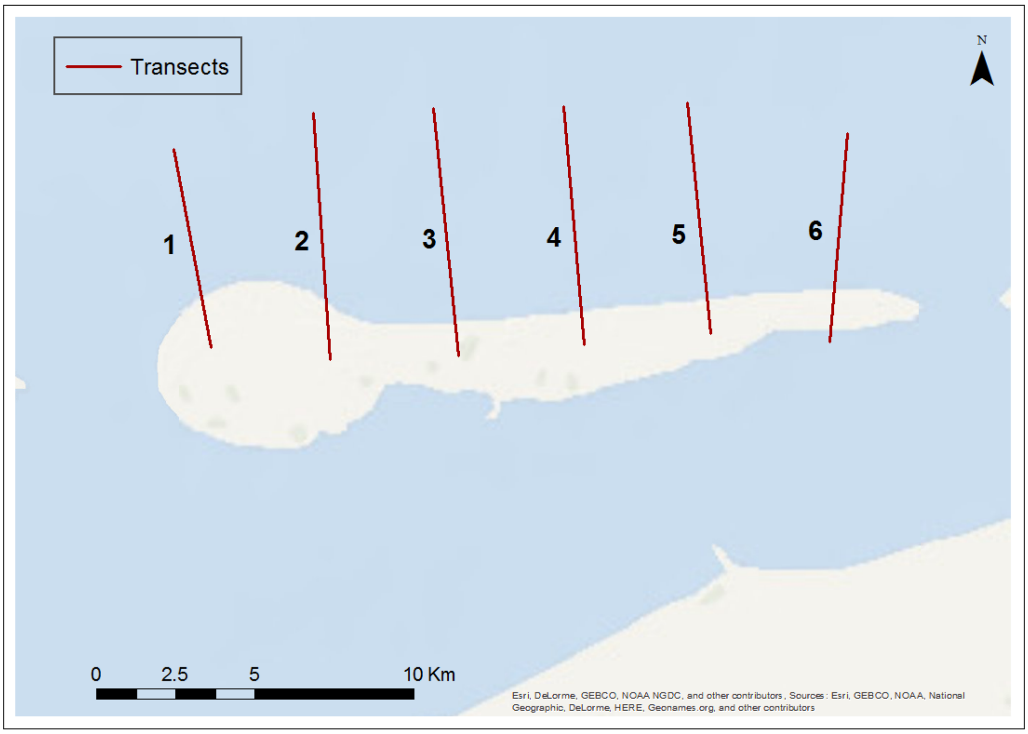

Figure 14. Position of transects for contour analysis on Ameland, and their corresponding number

Calculating contour relative and absolute distances

- *Choosing contour depths for analysis*

To ensure that the subsequent analysis reflected the changes and dynamics of the whole shoreface, the contour depths for analysis should have represented the entire cross-shore length of the shoreface (see section 2.1). Ideally, a depth should have be chosen representing the shoreline (e.g. average low-tide line) on the landward side of the shoreface, and one representing at least the average depth of closure during the study period on the seaward side. However, establishing both the average low-tide line and depth of closure for the 50 years studied and the length of the island was beyond the scope of this study. Additionally, the JARKUS dataset, especially until the 1980s, did not extend sufficiently far out to sea to ensure that the depth of closure would be reached.

Because of this, contours were generated for each period at an interval of 1 m starting at 0 m. The contour at 0 m was selected to represent the shoreline (i.e. the top of the slope). The contour representing the base of the slope was selected based on an assessment of the maximum depth reached in the majority of the periods to ensure that sufficient data was available for the analysis.

- *Deriving relative distances of contours and analysis of the contour dynamics*

The relative distance of the two contours is their distance to a fixed point represented by the landward start of the transect. To calculate this distance points were generated at the intersection of the transects and the two selected contours, per line, per period. Then the distance from the start of the transect to each point was calculated. The analysis required that only one location of the intersection of a given contour with the transect line was provided. As the same contour sometimes crossed a transect several times (e.g. if a sandbar crossed the transect) resulting in several intersection points, an extra step was added. Once the distance of all points along the transect was calculated, only the points with the largest distance from the start of the line were kept for each contour depth, i.e. the furthest point representing the 0 m contour and the furthest point representing the slope base contour. This solution was based on the assumption that any other points lying closer to the start of the transect were a result of small shoreface features, rather than representing the top or base of the shoreface. The result of this step were 6 tables (one per line) listing the relative distance of the 0 m contour and the slope base contour per period.

To enable the analysis of the relative positions of the contours, the tables generated in the previous step were transformed into two tables, each containing information about the distance of either the 0 m contour or the slope base contour. The transformation had to take into account the fact that, especially for the slope base contour, for certain periods there wasn't any information about the contour distance. This happened when the data for that period did not extend sufficiently far out to sea to reach the depth of the slope base contour. Additionally, to enable comparisons between transects, the distances of points along the transects were modified for each transect to begin from the first intersection of a contour with the transect.

Finally, to allow for an assessment and comparison of the contour dynamics along the whole island, boxplots were simultaneously plotted for the two contours and for each line.

- *Deriving absolute distances between contours and analysis of the slope trend*

The absolute distances between the 0 m contour and slope base contour per period and per transect were calculated based on the relative distance tables. For each transect, the range (i.e. absolute distance) between the two contours was calculated per smoothing period with the results stored in a table.

The results were then plotted as boxplots per transect. The boxplots allow for an assessment of the dynamics of the changes to the gradient of the shoreface slope along the length of the island. Additionally, the absolute distances per period were plotted per transect in order to reveal the trend in the distance between the two contours, and consequently to the shoreface gradient, for a specific location along the coast.

3.2.3. Cell analysis for shoreface slope dynamics

The second method to analyse the shoreface slope dynamics is an attribute-based one, looking at the change in the gradient attribute for a specific location, i.e. per cell (Figure 15).

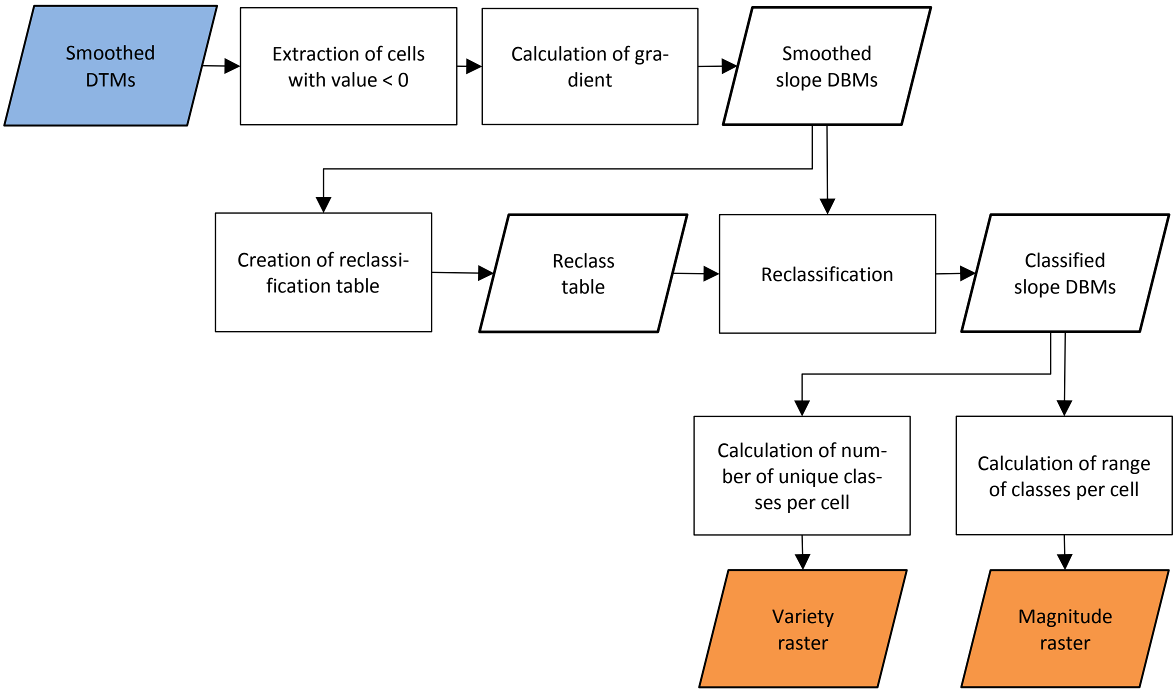

Figure 15. Cell analysis workflow

The contour analysis focused on assessing the overall steepness of the shoreface slope and its change through time, as well as variation in trend along the coast. The cell analysis method will also allow for a spatial comparison of the shoreface gradient dynamics, but it will provide more information about the dynamics of the shoreface slope at each cell.

In this study this attribute-based approach to change detection is used to study the variety of gradient values, as well as the magnitude of change in gradient values at specific locations. However, using an attribute-based approach to change detection is also employed in methods that detect change through analysing the time series data per cell (e.g. BFAST (Verbesselt, Zeileis et al. 2012, de Jong, Verbesselt et al. 2013)).

Calculating the gradient

As the analysis was meant to focus solely on the submerged shoreface, initially only areas with an elevation below or equal to zero were selected from all spatially and temporally smoothed rasters. This step was important as once the gradient was calculated, it would be impossible to distinguish between areas that were above the water or submerged. The gradient was then calculated in degrees using the standard function within the GIS software used. It is third-order finite difference method (Burrough and McDonell 1998).

Assessment of gradient dynamics

To assess the gradient dynamics, gradient values obtained in the previous step were first grouped into 5 classes. The distribution of the gradient values was unimodal but highly skewed with mean values around 0.3 – 0.4 degrees. The maximum values were dependent on the spatial resolution of the data, with the values decreasing at higher levels of aggregation, but reaching 13.6 degrees at a cell size of 40 m. Additionally, the range of values varied for every smoothing period. To create the 5 classes, the mean gradient value per cell was first calculated. The gradient values of the resulting mean gradient raster were classified into 5 classes based on the quantile method. Then, to encompass the whole range of gradient values, the first and last class borders were extended to include both the minimum gradient value (0 degrees), and the maximum gradient value occurring for the given spatial resolution. Using the resultant classification table (Table 7), all the gradient rasters were reclassified into 5 classes.

Table 7. Reclassification table 200 m (based on quantiles)

From	To	Class
0	0.090688	1
0.090688	0.122714	2
0.122714	0.184951	3
0.184951	0.308959	4
0.308959	3.5	5

Per cell statistics were then calculated on the classified rasters. These aimed to establish the number of unique slope zones in a cell and the range of these zones, as this would provide information on how dynamic the slope is at that cell, whether it changes and how dramatically it changes.

3.2.4. Implementation: Software and Scripting Languages

The methodology was implemented using ArcGIS 10.4. To help with the automation of the analysis, several steps were scripted in Python using ArcPy – a Python site package, allowing for the use of ArcGIS tools in Python. Additionally, several steps were carried out in R (raster, zoo, sp and rgdal libraries) or excel to benefit from their superior plotting capabilities.

4. Results

4.1. Results of Spatio-Temporal Sensitivity

The benefits of applying a moving average to the JARKUS Grids are visible even with a moving window size of 5 years (Appendix 2: Selecting a moving window size for temporal smoothing). The noise is reduced while the trends are clearer. However, given the scale of interest, and the fact that the data are collected annually, a 5 year moving window size was deemed insufficient. The results still contained some shorter-term fluctuations. On the other hand, the 15 year moving window size was deemed to large given the length of the data. During a 50 year span, applying the 15 year moving window would result in only 3 completely independent smoothing periods (i.e. based on subsets of years which do not overlap and so do not influence each other). A 10 year moving window size was deemed most appropriate for the analysis, since it smoothed the data more than a 5 year window, but also offered a few more independent smoothing periods than a 15 year moving window.

In contrast to the temporal smoothing, the spatial smoothing through aggregation was less obvious (Appendix 3: Effect of cell size on spatial smoothing). The rasters at the original 20 m cell size, and at 40 and 80 m do not dramatically change in relation to the visibility of features on the shoreface such as sandbars. This is mainly due to the fact that the sandbars are very elongated, and are larger than the new cell sizes. This effect could also be due to the fact that the spatial sensitivity was conducted on the temporally smoothed rasters, so smaller features were already generalised. For the rest of the analysis, a cell size of 200 m was chosen. At this cell size the elongated sandbars are the least visible, although the resulting raster is very pixelated.

4.2. Results of contour analysis

As was mentioned in section 3.2.2, to implement the contour analysis 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, however the variation in the extent of the data limited the ability to choose the base contour at a depth representing the base of the shoreface (i.e. the depth of closure). Not only are the deeper areas of the shoreface reached less frequently, the measurements for the areas are also heavily concentrated the second half of the dataset (after 1980). This means that if a deeper contour was chosen for the analysis, the length of the study time would have to be reduced. After visually analysing the location of different contour depths over the extent of the JARKUS Grids data, a depth of -4 m was chosen to represent the slope base as this depth was frequently reached by the dataset since 1965.

Plotting box plots of the absolute distance between the 0 and -4 m contours for each transect (Figure 16) shows the spatial variation in the dynamics of the gradient of the slope. The absolute distances are significantly more varied around the western inlet (transect 1), dropping off dramatically towards the centre of the island (transect 2 – 5), before again becoming more varied around the eastern inlet (transect 6). This indicates that also the gradient of the shoreface slope changes more dramatically around the western and eastern inlets, and remains more stable at the centre of the island.

The relative distance boxplots (Figure 17) display a similar pattern, although the contribution of the dynamics of the 0 m contour versus the -4 m contour are clear. Again it is possible to see the effect of the western inlet dynamics, especially with the -4 m contour shifting position more than anywhere else along the island. Indeed, for transect 1 to 5, the -4 m contour is more dynamic than the 0 m contour. Surprisingly, for transect 2, both the 0 m and -4 m contour appear dynamic shifting position over more than 500 m. However, looking at Figure 16, the mean absolute distance is similar to that of transects 3-5 where the contours appear less dynamic.

Additionally, by looking at the median values of the absolute distances per transect, it is possible to see the sediment deposition at the inlets, as the median distance between the two contours here is greater than at the centre of the island indicating overall a more gradual gradient. This is also confirmed by plotting the time series of the absolute distances for each transect (Figure 18 and Figure 19).

However, for transect 1, although the time series plot resembles the known cyclical behaviour of sedimentation and erosion around the western inlet, the resulting curve is not smooth with sudden jumps in the distance between the contours after the 1975 and 1995 smoothing periods. These results indicate that the gradient of the shoreface slope in this region is highly dynamic, steepening and flattening rapidly over time. The time series data for transect 2 also exhibit peculiar behaviour with a clear peak around the 1995 smoothing period signifying a brief flattening of the shoreface slope, while the data for transect 6 seem to indicate a peak around 1975. However, data is missing for four smoothing periods in the region of transect 6 making it difficult to assess whether this was indeed the case. The shoreface gradient for the regions around transects 3-5 does not show considerable change. Weak flattening trends can be seen for transect 3 and 5, however this is countered by a weak steepening of the slope for transect 4.

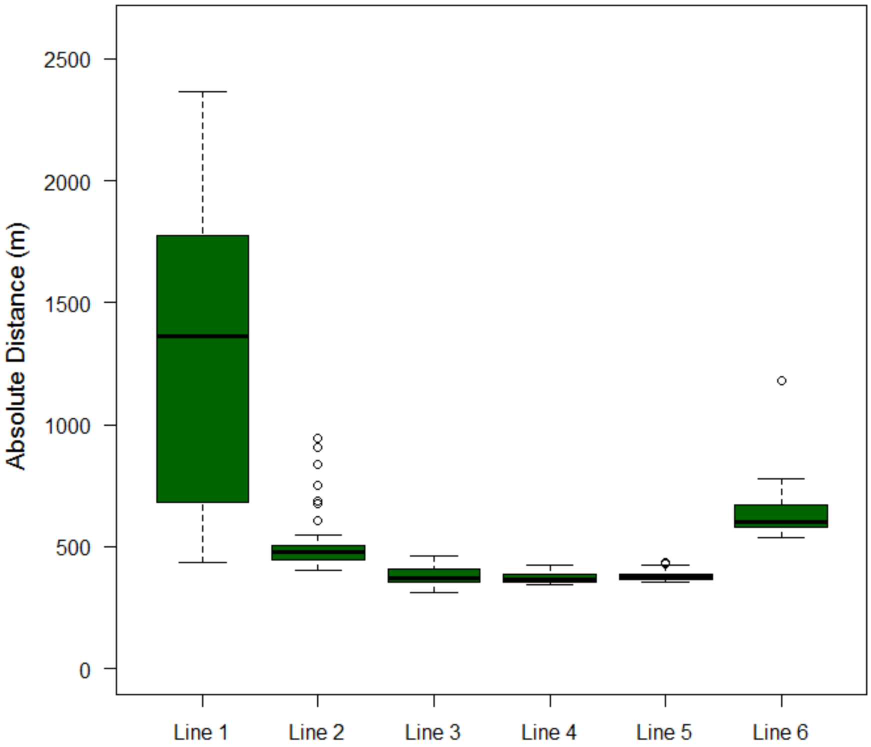

Figure 16. Absolute distances between the 0 and -4 m contour for JARKUS Grids with a 10 year temporal smoothing and 200 m cell size

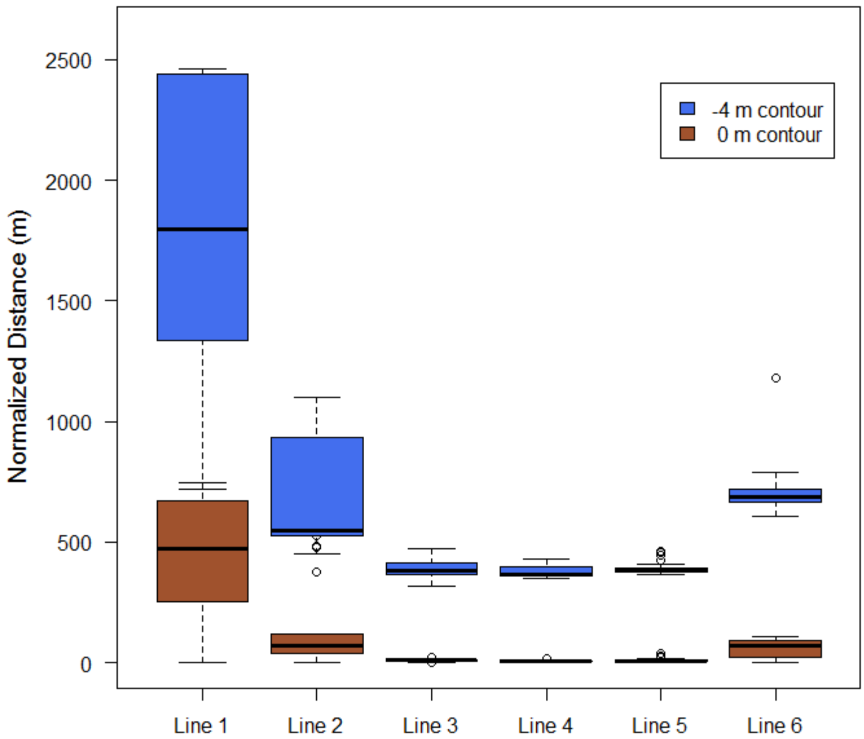

Figure 17. Relative distances of the 0 and -4 m contour from the first intersection of a contour with the transect for JARKUS Grids with a 10 year temporal smoothing and 200 m cell size

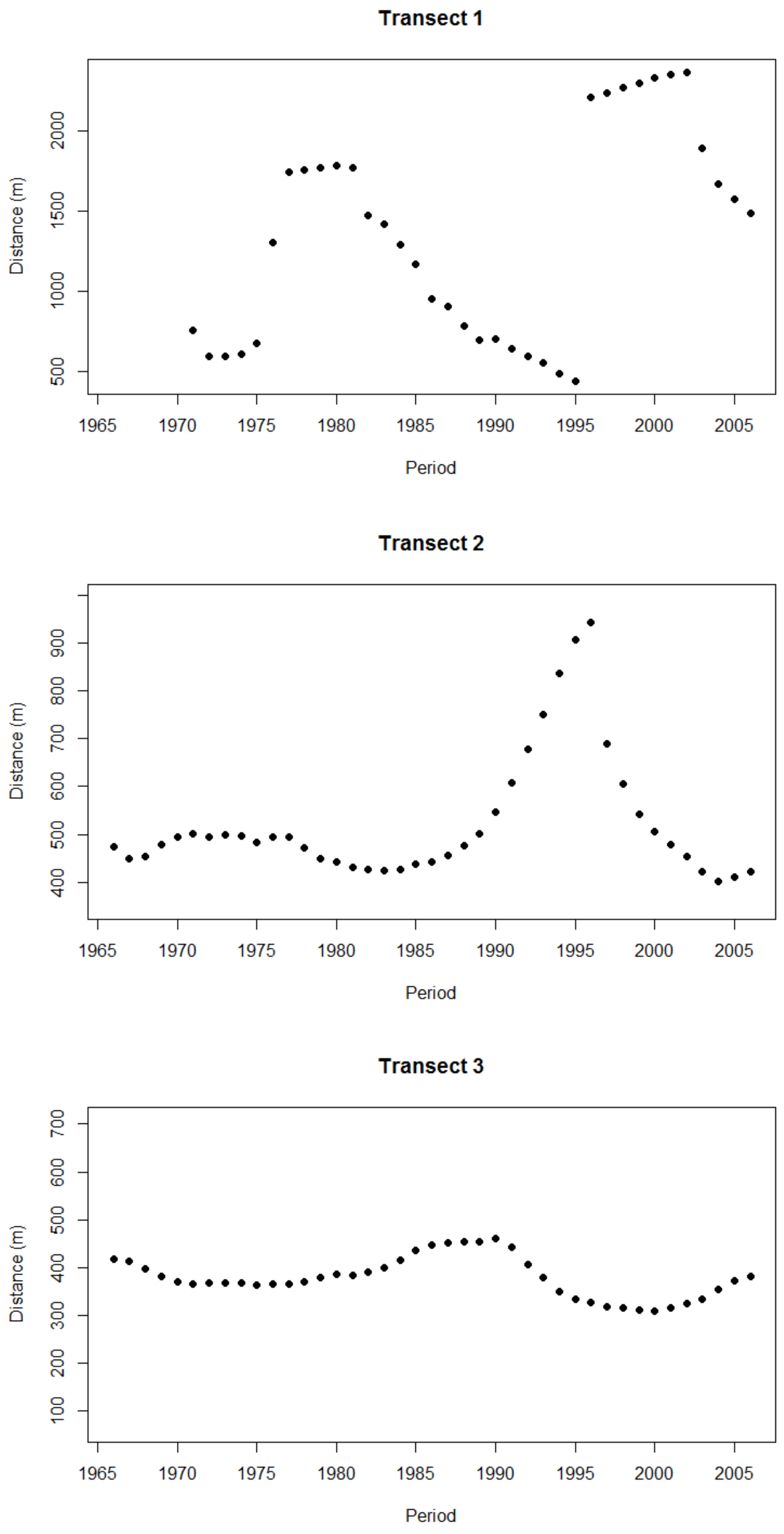

Figure 18. Time series of absolute distances between the 0 and -4 m contour for transects 1-3

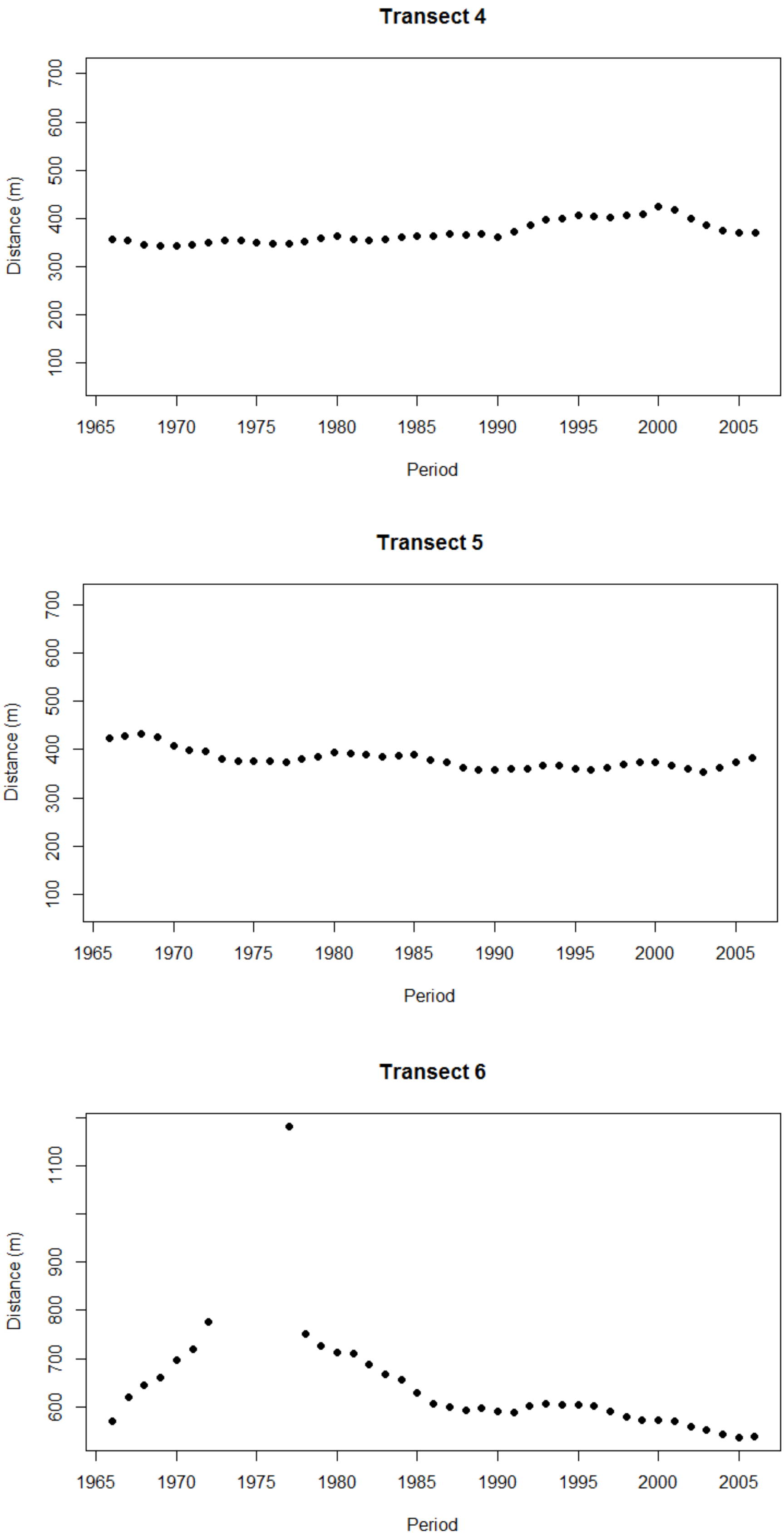

Figure 19. Time series of absolute distances between the 0 and –4 m contour for transects 4-6

4.3. Results of the cell analysis

The results of variety analysis (Figure 20) show that the slope gradient values span 5 different gradient classes near the western inlet, and in the eastern inlet. Additionally, the slope gradient changes between several classes along a strip running parallel to the coast of the island, just north of the mean -4 m contour. In the central part of the island, the number of classes decreases progressively towards the seaward extent of the data, as well as South of the -4 m contour.

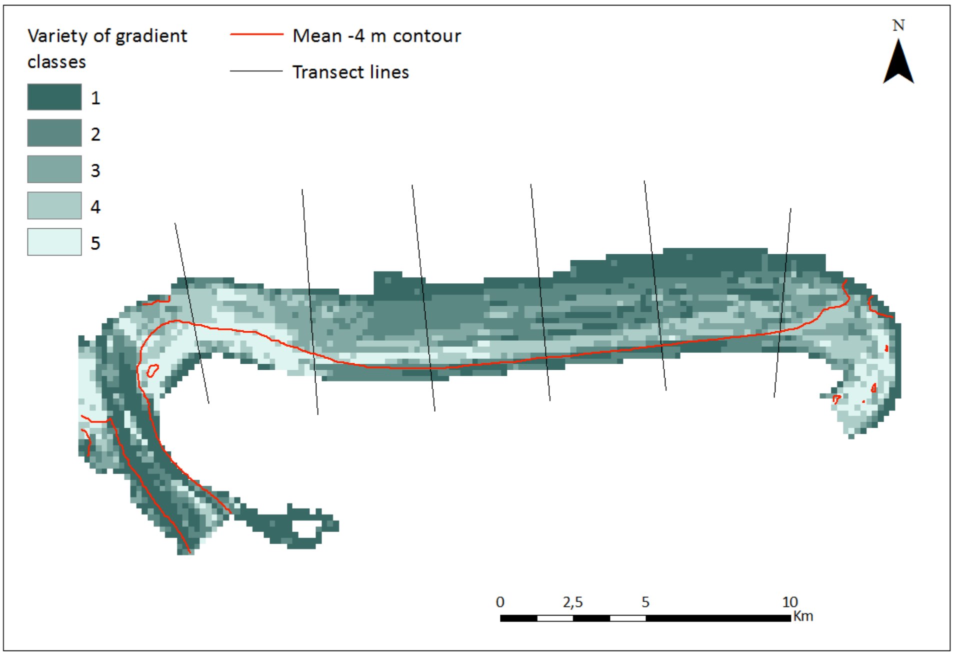

Figure 20. Variety of gradient classes per cell, for JARKUS Grids with 10 year temporal smoothing and 200 m cell size

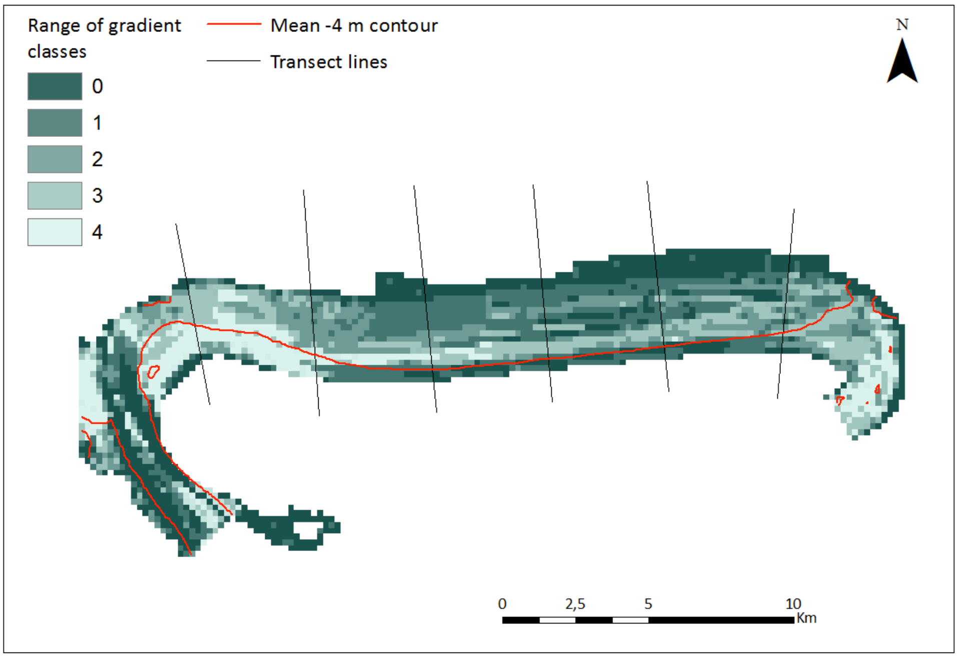

Figure 21. Magnitude of change in gradient classes per cell, for JARKUS Grids with 10 year temporal smoothing and 200 m cell size

The results of the magnitude analysis (Figure 21) closely follow the pattern of the variety analysis results. The area near the western inlet, an along-shore strip North of the mean -4 m contour, the area near the eastern inlet, all show a higher magnitude of change than the central part of the island seaward, and South of the mean -4 m contour.

5. Discussion

This discussion serves mainly to discuss the application of the concepts discussed in Chapter 2. An analysis of the results of applying the developed methods will only be conducted to the extent that it helps understand the utility and/or drawbacks of the method and so reflect on the use of the concepts it is based on, rather than to understand the processes affecting the shoreface slope.

Spatio-temporal resolution of shoreface processes

The choice of studying the shoreface slope of Ameland was driven by interest in its behaviour in the long-term, i.e. over a time scale of decades. As the JARKUS data is collected annually, it was possible to use it for this purpose with some temporal smoothing applied to reduce the noise. However, the corresponding spatial scale for processes affecting the shoreface is in the tens of kilometres. The study area, longshore, is only around 28 km long. Additionally, any processes affecting the shoreface of Ameland, would potentially also interact with the other barrier islands, the inlets, and the Wadden Sea. Thus, the analysis would benefit from an extended study area.

Furthermore, the North Sea shoreface of Ameland has a very gentle slope. The data for the majority of the years do not extend further than the -4 m contour, and the depths reached near the inlets are even shallower. These depths represent only a portion of the upper shoreface. As was shown in Figure 4, this part of the shoreface undergoes changes on a scale of years and 0.1 km. Additionally, Wang, Hoekstra et al. (2012), argue that the development of the upper shoreface on a scale of years to a decade is decoupled from the development of the lower shoreface. “On a time scale of years the shallow foreshore functions as a more or less closed system, while continuous transverse redistribution of sediment takes place under the effect of bar migration” (Wang, Hoekstra et al. 2012, p. 47).

The goal of the study was to assess the behaviour of the shoreface slope in the long-term, and the spatial and temporal smoothing was performed accordingly. However, given the extent of the data in the study area and the process affecting the upper shoreface, perhaps a smaller spatial and temporal smoothing would be more adequate. Nevertheless, as the data do not cover the entire upper shoreface, the understanding of the process shaping the behaviour of the shoreface within the study area would not be complete.

Slope properties relevant for shoreface analysis

The methods developed in this study focused on exploring the dynamics of the gradient of the shoreface slope, with the contour-based method providing information on the trend of the gradient for different areas of the study area, and the cell-based method providing more local information and exploring the characteristics of the gradient (variety and magnitude). The focus on the gradient allowed for the application of these two methods based on the way it is calculated (i.e. derived from elevation) and the notions of change in the spatial domain (change in attribute and change in geometry).

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 and curvature in the same way as the gradient from a change in geometry perspective is not possible, since they cannot be easily derived from contours.

Deriving a Digital Bathymetry Model and slope characteristics

This study was based on pre-existing DTMs, and as such did not focus on analysing the appropriateness of different ways to derive DTMs from point data. Similarly, the study did not perform any sensitivity analysis on different methods to derive gradient values. The method implemented in the software has been shown in review literature to perform well, and was therefore deemed sufficient to demonstrate the developed methods. Additionally, Dolan and Lucieer (2014) find that, although the use of different algorithms affects the gradient at a local level, the same patterns are produced at a general level. They also find that over broader scale features, with lower slope values there is generally better agreement among all algorithms. Thus, the importance of the gradient calculation algorithm is higher for analyses focusing on shoreface features such as sandbars or for study areas with a steep shoreface. The Ameland study area has in general a very gentle shoreface slope, and additionally, given the focus of the study, the data was already smoothed to remove smaller features.

Considering the spatio-temporal resolution of the analysis

The benefits of performing a spatio-temporal smoothing on the data to reduce noise are already visible from Figure 5. However, the performance of the smoothing depends, not only on the method used, but also the availability of data for an area.

The design of the moving average to smooth the data temporally, accounted for the fact that the total number of years of data may not be divisible by n – the size of the moving window, resulting in an insufficient number of data measurements to complete a window at the end of the time series. These additional years of data were discarded from the analysis on the basis that they would introduce errors, as a smoothing period value would in fact not be based on the whole n-years of data. However, this design did not account for similar situations occurring at the beginning or in the middle of the time series (i.e. where there are n data entries, but one or more of them are NoData). As was highlighted in section 3.1.3, areas located further out towards the sea were not only less frequently covered by the JARKUS data, but also the collection of measurements in these areas often did not start until the 1980s. Consequently, these areas have many years (especially up until the 1980s) with missing data. However, as soon as the moving window encounters one year with a valid measurement, that measurement is assigned to the whole smoothing period. The result of this can be seen in the time series plots for 6 points on the shoreface in Appendix 2: Selecting a moving window size for temporal smoothing, as it affects the shape and length of the time series. Looking at the original time series data for points 1, 2, and 3, it can be seen that the measurements here did not begin until the 1980s, or even 1990s. Comparing these time series to the ones generated after applying progressively larger moving average windows, it can be seen that the time series “shifts” to the left. Data points are cut off at the end due to the planed limitation, but also points are added at the beginning due to the effect described above. It is also visible how this introduces distortions in the data, since these time series seem a lot more stable and smooth at the beginning where the values were derived based on only a few measurement points.

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.

In terms of the spatial smoothing, this study used a simple aggregation based on the mean to increase the cell size. Although in principle this method does reduce the appearance of small features, in practice it resulted in a pixelated, rather than smoothed, raster. The method is also based on the assumption of a normal distribution of values in the cells being used to derive the new cell value. In this study, due to the temporal smoothing, any outliers should have already been minimized; however this is another drawback of the method used. Additionally, the spatial smoothing was conducted using a 200 m cell size. At the same time, the results of the contour distance analysis for transects 3-5 show movement of the contours below 200 m. Thus, the movement detected was smaller than the cell size and could be related to the interpolation of values between cells when deriving the contours.

Finally, the spatial smoothing is subject to similar problems as the temporal smoothing in that, in choosing to ignore cells with NoData, new cells based on only a few values can be created leading to misrepresentations of the area (especially on the edges of the data). The results in Figure 20 and Figure 21 indicate a strip North of the mean -4 m contour that is more dynamic than the areas further North or directly South from it. However, when comparing these figures to the map of the JARKUS Grids coverage (Figure 11), it can be see that this strip overlaps with the edge of the dark green, well-covered stretch of shoreface close to the shoreline. Thus the more dynamic strip may just be a result of errors introduced during the spatial smoothing.

Dynamics in the spatial domain

The methods developed in this study applied two interpretations of change in the spatial domain. The first method focused on the analysis of the change in geometry of contour lines to detect changes in the slope gradient, while the second one focused on the change of the slope gradient attribute to study the variety of values at given locations.

The two methods were focused on discovering the patterns and characterising the general dynamics of the shoreface slope, rather than at identifying the temporal pattern of change (see section below about the dynamics in the temporal domain). Consequently, the four definitions of change by Zhou, Shekhar et al. (2014) were not explicitly applied. Nevertheless, both methods use these definitions in support of identifying the patterns and general dynamics. The cell-based method, given its focus on a time series at a single location, is the closest in its understanding of change. It uses the change in gradient category, i.e. change in a modified actual value, to draw conclusions on the gradient dynamics at the cell location. The contour-based method compares the statistical parameters of the contour locations through the use of boxplots. The change in statistical parameter is thus applied across space, rather than across time, to identify dynamics.

The results from both methods show broadly similar patterns, which reflect the known dynamics described in section 3.1.2. Both methods show more dynamic areas around the inlets (especially the western inlet), and a more stable shoreface in the centre of the island. The contour-based method allows for a faster overview of the gradient trends by plotting time series of absolute distances, but also provides information about the dynamics of the individual contours, i.e. whether the shoreline and base of the slope are equally dynamic, or if any changes in the gradient are rather attributed to movement of only one of the contours. Long-shore, this method only provides information at the transects. However, with the transects spaced out according to the scale of the analysis (in this case the large-scale), the results can be seen as representative of the area around the transect. Additionally, this method provides information about an average gradient – the slope between two contours chosen to represent the cross-shore length of the shoreface. Any variation in the gradient between the contours is lost.

The cell-based approach provides more localised information which allows for an overview of variations in slope dynamics in the whole extent of the data. It allows for the assessment of how the gradient changes along-shore and cross-shore. By looking at both the variety of gradient classes and the magnitude of change between them, it allows for an assessment of the scale of variation, i.e. whether the gradient changes slowly, progressing through all the classes, or whether it changes drastically from a low gradient class to a high gradient class.

Both methods are equally dependent on the data coverage. Errors from the lack of data are less pronounced in the results of the contour-based method, since the analysis extent was limited to a part of the upper shoreface (-4 m contour). On the other hand, the extent of analysis was not limited for the cell-based analysis, leading to results which can be assumed to be erroneous in the areas where there is less coverage.

Dynamics in the temporal domain

The methods developed in this study do not specifically address the temporal pattern of change. Nevertheless, the plotted time series of absolute distances between contours offer some information about the temporal pattern and, with additional time series analysis, could provide more information about it, such as the moment, duration of change, etc. Similarly, time series analysis could be applied per cell to obtain more information on the cell-based temporal pattern (e.g. BFAST (Verbesselt, Zeileis et al. 2012, de Jong, Verbesselt et al. 2013)).

Errors in spatial analysis and their propagation

As was discussed in section on errors, any errors generated during the gathering of data, generation of the DTM, or any subsequent analysis steps will cumulate and propagate throughout the analysis. Methods exist to quantify this error (Goodchild and Gopal 1989, Heuvelink 1998, Oksanen and Sarjakoski 2005), however, its assessment was beyond the scope of this study. Additionally, following Theobald (2005), given the study's focus on large-scale dynamics and trend, a high precision of the terrain models was not required. Indeed, the spatial and temporal smoothing intentionally modifies the terrain model, perhaps reducing the impact of the errors.

Hypothesis-based data analysis vs. Exploratory Data Analysis (EDA)

The two proposed methods took an exploratory approach to the data analysis. The aim of the research was to analyse the large-scale dynamics of the shoreface. As the processes acting at these scales are not well known, the exploratory approach was chosen with the expectation that it would provide some initial insight on which to build an understanding of the relevant processes.

5.1. Recommendations

Although this study provided a first step towards developing a framework for DBM-based analysis of shoreface behaviour, to facilitate future research into the shoreface and interpretation of the results, the concepts discussed in Chapter 2 have to be further examined and their interaction analysed.

The implementation of the methods for discovering patterns in the dynamics of Ameland's shoreface slope provided the initial results, but also indicated that more research is needed into the issue of scale and dealing with missing data. Dolan and Lucieer (2014) conducted research into different algorithms to derive slope gradient values, specifically for bathymetry data, and analysed the results of combining these algorithms with different methods for varying the spatial scale. Their analysis should be expanded to include methods for changing the temporal scale, as well as algorithms to derive other slope properties such as aspect and curvature.

Given the problems with the lack of measurements in the JARKUS data (which is already unique in terms of its duration and frequency of data collection), the framework should be expanded by a discussion of other methods for deriving bathymetry data (e.g. from photos and satellites), as well as methods for combining data from different sources.

Furthermore, the study presented two basic methods for analysing the shoreface slope, however further research could address expanding these methods to include time-series analysis, as well as considering how different definitions of change can be included in the analysis of aspect and curvature, and how these slope properties could be combined with a slope gradient analysis to offer comprehensive information about the shoreface behaviour.

Finally, the propagation of error throughout the analysis requires further attention, although this should be done in relation to the aim of studying the shoreface behaviour at different scales; the error should be assessed from the perspective of the research objectives.

6. Conclusion

This research provided a first step towards developing a framework for DBM-based analysis of shoreface behaviour. It examines the key concepts that should be included in such a framework through the results of a study of the shoreface slope of Ameland. The key findings of the main research questions are discussed below.

RQ1) What are the main concepts from a coastal morphodynamics perspective, GIS and time series analysis perspective that should be considered when preparing an analysis of the shoreface behaviour?

Any analysis of the shoreface behaviour must be clearly grounded in the relevant existing knowledge in coastal morphodynamics. Specifically, as the processes affecting the shoreface and its response to these processes take place at different spatial and temporal scales, due consideration must be given to choosing the appropriate scale for the analysis. This choice translates into the spatial and temporal resolution of the data required for the analysis. Similarly, an understanding of the nature of the phenomenon being studied is required. This research focused on the shoreface gradient which is important from a coastal protection and management perspective as it influences the height and power of the waves hitting the shore and plays a role in sediment transportation.

From a GIS perspective, depending on the data being used and the research focus, the first issue in the analysis may be deriving a DTM from point measurements and, subsequently, deriving slope characteristics. For both of these steps a number of methods exist, which can lead to varying results. Depending on the research objective, the precision of the different methods will be more or less important. Nevertheless, the impact of these decisions should be acknowledged. Additionally, if the scale of the data does not match the scale of analysis, various methods for changing the resolution of the data in both the spatial and temporal dimensions are available. This step is important to ensure that noise from processes occurring at different scales is reduced. This research focused on methods to smooth (i.e. generalise) the data. In the spatial dimension this means applying a version of focal or block statistics, while in the temporal dimension a moving average window applied to the time series data per cell was investigated.

Furthermore, the study of the shoreface behaviour is closely linked to the concept of change. The interpretation of change depends on the perspective, with change in geometry and change in attributes commonly identified in the spatial domain, while change in the temporal domain is linked to the analysis of time series. An understanding of the different interpretations of change can help in developing an analysis method, interpreting and comparing the results.

An important issue in spatial analysis is that of error generation and propagation throughout the analysis. Errors can be introduced at different stages (e.g. measurement, interpolation of point data, derivation of terrain characteristics from the DTM, generalisation, etc.). As was mentioned above, the acceptable error will change with the research objective, however understanding its impact and being able to quantify it, can help in the design of the analysis and in the interpretation of the results.

Finally, clarifying the purpose of the research, whether it sets out to test a hypothesis or explore the data will inform the choice of data, as well as the analysis design.

RQ2) How can these concepts be used to devise a methodology for studying the shoreface slope of Ameland?

The application of the above mentioned concepts was tested for an EDA of the large-scale dynamics of the gradient of the shoreface slope of Ameland. As the JARKUS Grids data with an annual temporal resolution, and 20 m spatial resolution was used for this analysis, smoothing in both the temporal and spatial dimension was applied to ensure that noise from smaller-scale features was reduced. The focus of the analysis was on the shoreface slope gradient. Based on the ideas of change in the spatial dimension represented by change in geometry or change in an asaptial attribute, two methods were developed to study the spatial patterns of the gradient dynamics. One focused on the movement of a shoreline and slope base contour, while the other focused on an analysis of the gradient values at the cell level.

Given the limitations of the study, the methodology did not explore in detail the temporal pattern of the dynamics. Additionally, an assessment of the error in the original DTMs, or error generated at the subsequent analysis stages was not conducted.

RQ 3) What can be learned from the implementation of the methodology about the original concepts?

The discussion of the concepts in the area of coastal morphodynamics perspective, GIS and time series analysis, was useful at an introductory level to help structure the methodology and understand its shortcomings. However, after implementing the analysis of the Ameland shoreface slope, a few additional issues became clear.

The benefit of adjusting the spatial and temporal scale of the data to match the analysis scale was discussed, but the importance of the study area was not sufficiently stressed. If an analysis is constrained by the study area, the processes affecting this area influence the scale of analysis. In the Ameland case study, the study area covered only a portion of the shoreface which operates as a closed system on the analysis scale. Furthermore, the application of a spatio-temporal smoothing to the data has to be performed with caution, as, in addition to removing noise, the process can also help hide missing data. This can result in either unnaturally smooth data in the temporal dimension or unnatural values in the spatial dimension. Finally, the notions of change in the spatial and temporal domain did prove useful in setting up the analysis and understanding the differences in the results.

To facilitate future research into the shoreface and interpretation of the results, the concepts discussed in Chapter 2 have to be further examined and their interaction analysed, before a fully formed framework can be developed. Specifically, further research is needed into the issue of dealing with missing data both in the spatial and temporal domain. In the spatial domain research could be conducted into deriving bathymetry data from sources such as photos and satellite images, and combining these with existing point measurements. Additionally, the current research focused only on the analysis of the shoreface slope, however research is needed into other slope characteristics such as gradient and aspect and how they can provide an insight into the shoreface behaviour. Finally, the current discussion of concepts could be expanded to include a more in depth discussion of time series analysis to facilitate the discovery of patterns in the temporal domain.

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Appendices

Appendix 1: Contents of the DVD accompanying the report

The general contents of the DVD are listed below. For a detailed description of the contents, as well as a description of the structure of the folders, please see the README file on the DVD.

- Report (Word, PDF)
- Midterm & Final presentations (PPT)
- Datasets used and created
- Scripts (Python and R)
- Figures
- Maps
- Tables
- Literature (PDFs and Endnote)

Appendix 2: Selecting a moving window size for temporal smoothing

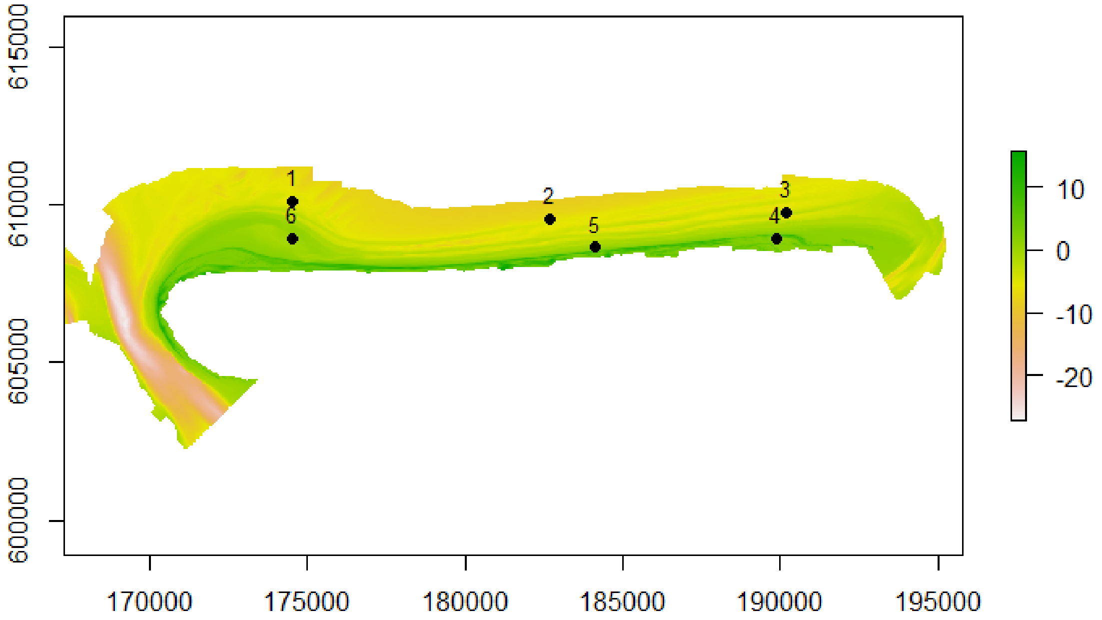


Figure 22. Location of sample pixels (based on a JARKUS Grid from 1999)

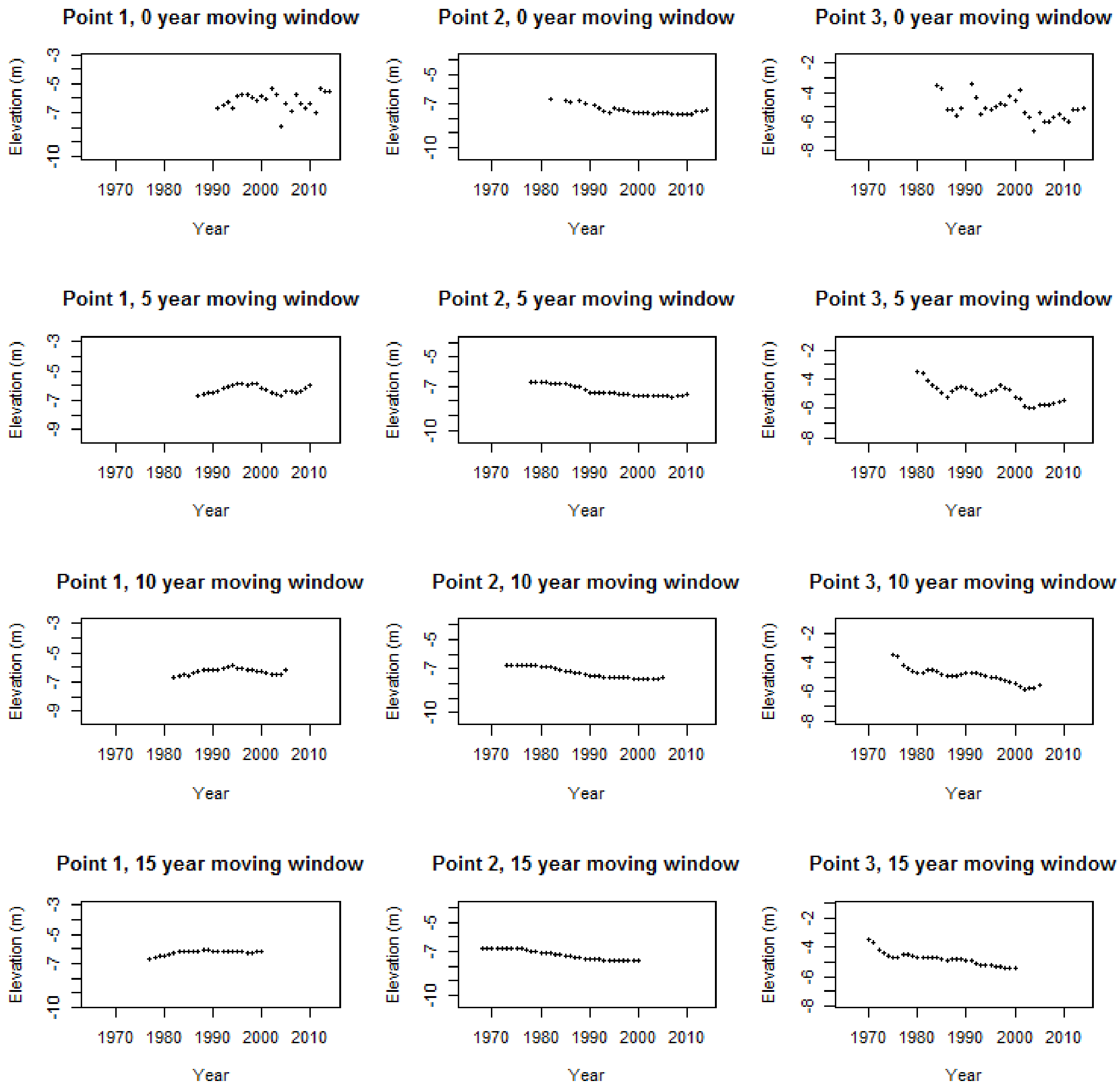


Figure 23. Time series results for points 1-3, for no smoothing (0 year), 5, 20 and 15 year smoothing

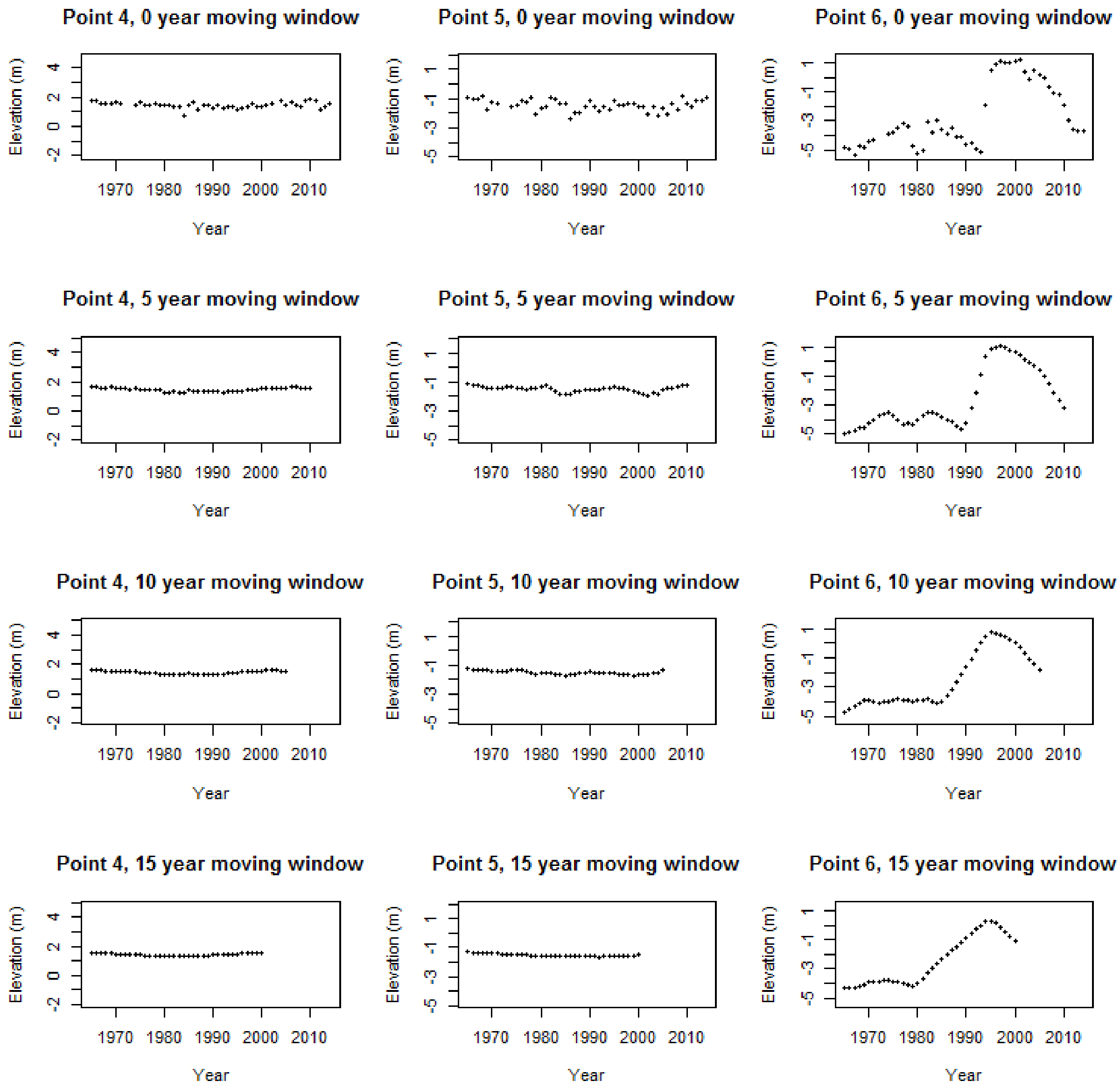
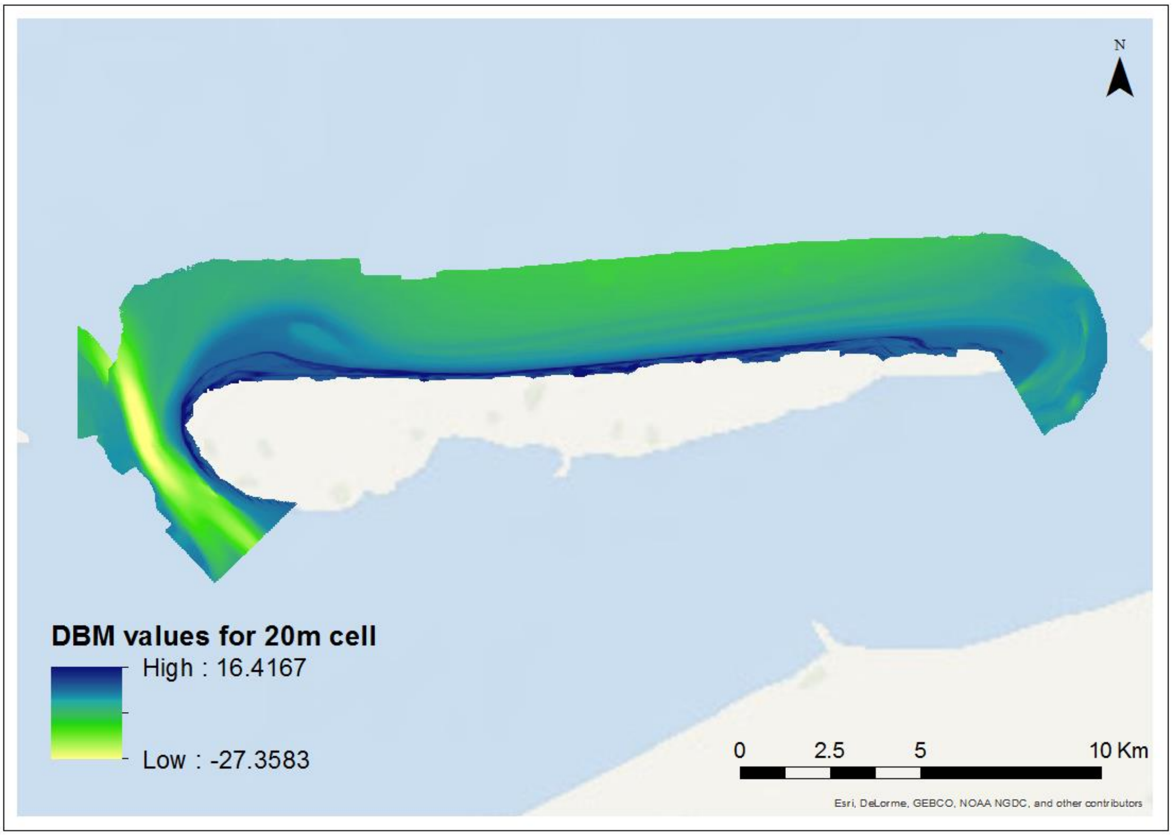
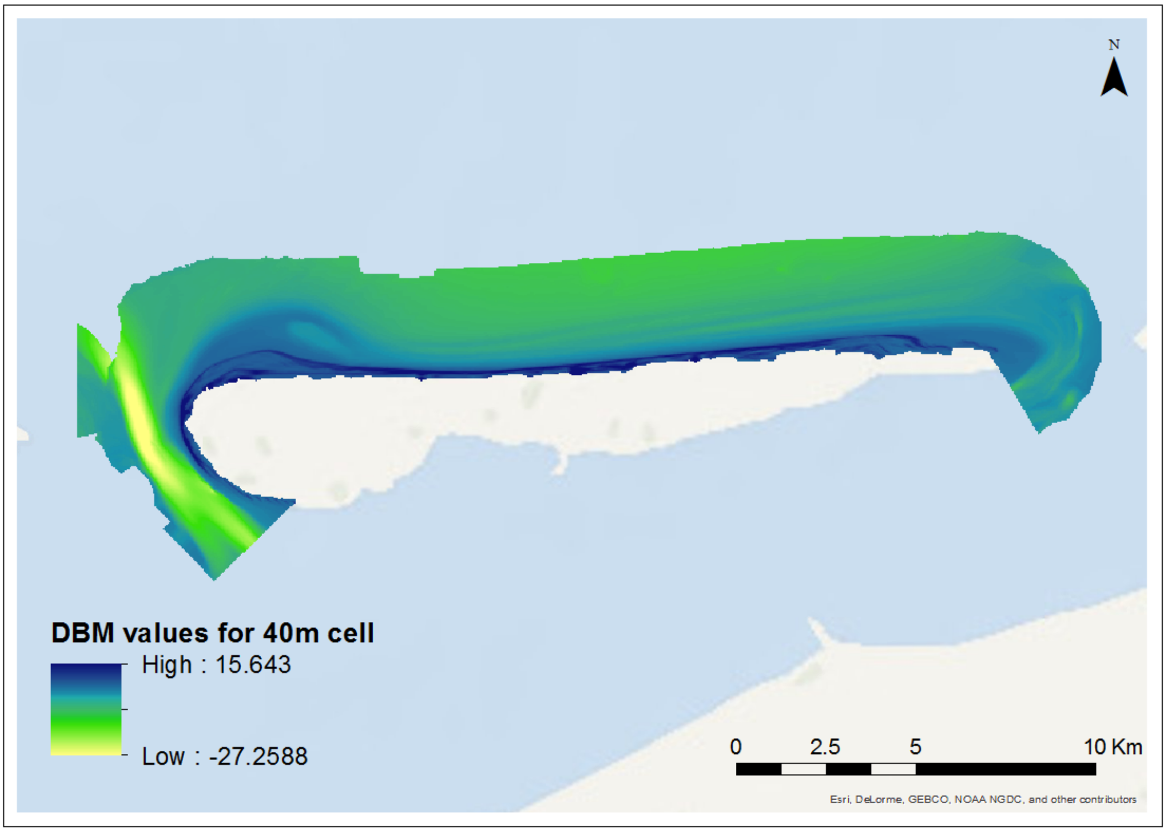


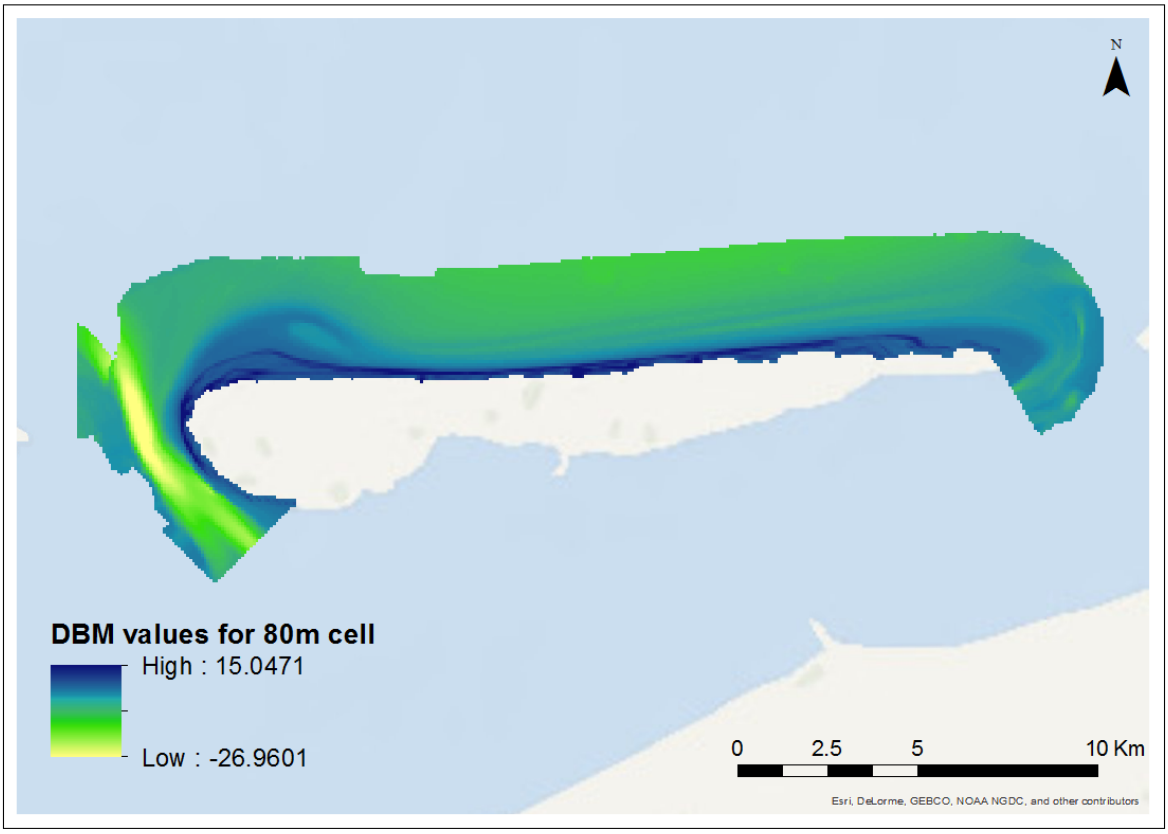
Figure 24. Time series results for points 4-6, for no smoothing (0 year), 5, 20 and 15 year smoothing

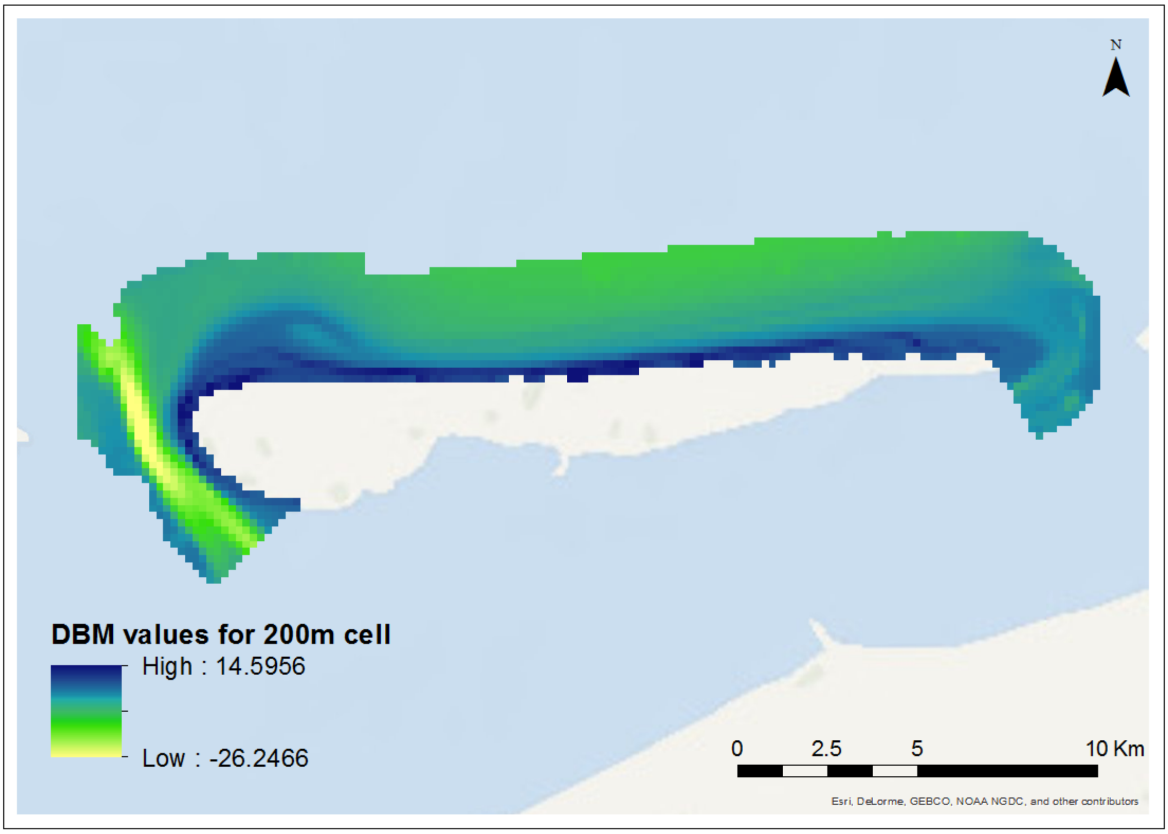
Appendix 3: Effect of cell size on spatial smoothing

The following images represent the DBM for the 10 year smoothing period starting in 1993.






N
DBM values for 80m cell
High : 15.0471
Low : -26.9601
0
2.5
5
10 Km
Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors


N
DBM values for 200m cell
High : 14.5956
Low : -26.2466
0
2.5
5
10 Km
Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors