Msc. Thesis

Sandbar breakwaters

Analysis of the effects of variations in wave climate on the morphological development of sandbar breakwaters by using the Lekki Sandbar Breakwater case study

N. (Niek) Moesker

TU Delft

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by

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TU Delft

Acknowledgements

This report finalises my graduation to obtain my MSc degree in Hydraulic Engineering at the Delft University of Technology.

During my search for a graduation project combining breakwaters with computational modelling I ended up at Svašek Hydraulics which had just cooperated in building the first Sandbar Breakwater at Lekki in association with CDR International and Boskalis. All three companies are very interested in the possibilities of the sandbar breakwater like structure. Researching the possibilities of the sandbar breakwater perfectly combines my two preferences (breakwaters and modelling) and thus I took the opportunity to research this topic at Svašek.

I would like to thank all the people who have supported me during this project. Firstly, I want to thank my graduation committee for the constructive meetings. In particular I would like to thank Alessandro Antonini with whom I have had several long and helpful sessions on how to tackle the research objectives, Robert-Jan Labeur who provided me with constructive suggestions and remarks on the report, Stefan Aarninkhof for being the chairman of the committee and thinking along with finding the best research method, and Sanne Poortman and Lynyrd de Wit who always were available for discussion at the office.

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N. (Niek) Moesker
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Abstract

Many coastlines feature a sediment transport in a dominant direction, possibly burying a traditional breakwater in sand in several years. The sandbar breakwater concept uses this sediment supply to its benefit to make the use of vast amounts of rocks abundant. During this research the morphological development of the worlds first sandbar breakwater built in Lekki, Nigeria, is analysed: The minimal amount of sand used for construction of the Lekki breakwater is placed such that the combination of the adaptation of the initial profile and the natural supply of sediment results in a smooth coastline at the end of the first year. This development is in turn used to setup a calibrated model to study the influence of the wave climate on the development of the sandbar breakwater concept. The wave climate at Lekki is characterised by a single dominant wave direction (called unidirectional) and has a narrow direction bandwidth (yearly standard deviation of the wave direction is about 5 degrees). This ideal wave climate is altered to research the influence of the mean wave direction, directional variation and the sequence of waves (seasonality). The study showed the sandbar breakwater concept to be mainly influenced by the mean wave direction and to lesser extent by the directional variation and the seasonality. These results can be used to make a first assessment on the possibility of applying a sandbar breakwater for a wave climate somewhere around the world.

Summary

Sand burying traditional breakwaters in a few months time at some coastline raised the question: Why not use the sand as a functional part of the breakwater? This concept has now been applied for the first time near Lekki, Nigeria. The design at this location followed from the ideal wave conditions; unidirectional swell climate with no locally generated storm events. Construction was finished in March 2018. The design features a minimal amount of sand nourished for the coastline (Figure 1 area A). The area is to be adapted and supplied by the natural sediment transport.

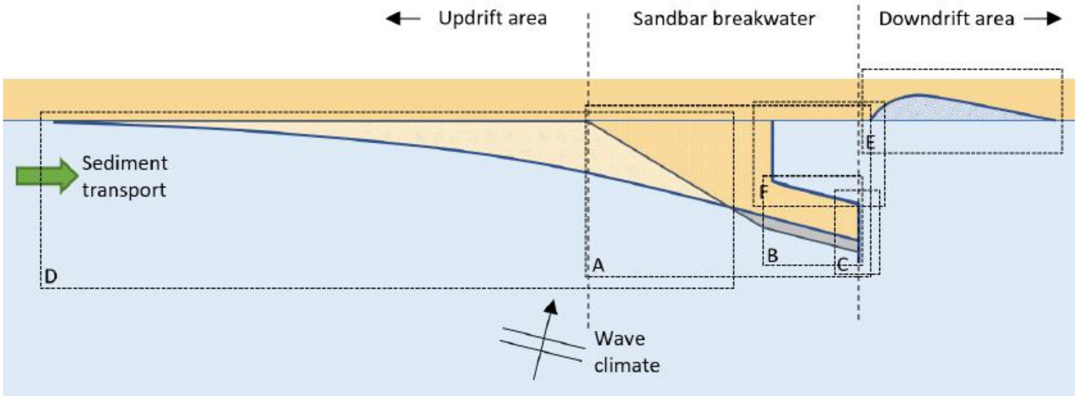


Figure 1: A sketch of the sandbar breakwater showing its initial layout (darker brown) and the resulting layout after adaptation to the wave climate (in lighter shade brown). The area surrounding the sandbar breakwater has been divided in several sections (updrift, breakwater and downdrift) and focus areas: A. Initial breakwater, B. Sandbar, C. Groyne, D. Updrift area, E. Downdrift area and F. Harbour basin. In grey erosion of the initial layout is shown.

As the sandbar breakwater as built in Lekki is built with different coastline orientations, two opposite directed transport directions exist during the start of the breakwater development. One being the supply towards the breakwater, the other one being the sandbar eroding. The waves at Lekki generally coming from the same direction results in the transport directions being generally in the same (favourable) direction. But what if this concept of the sandbar breakwater is to be applied for other wave climates? Most wave climates do not show such a unidirectional character. This is what is researched during this master thesis research.

The sensitivity of the Lekki sandbar breakwater to three types of wave climate alterations is studied by means of a computational one-line model. The model is validated and calibrated by using the data obtained during the analysis of the morphological development of the Lekki sandbar breakwater during its first year after construction. This data analysis showed the sandbar breakwater at Lekki to develop under the influence of the Lekki wave climate as follows: During the period just after construction the sandbar erodes (grey area in area B). The eroded sediment is transported to the intersection between the original coastline and the breakwater (area D). The longshore transport from the updrift direction also supplies sediment to this intersection. The accumulation of sediment at this location results in accretion: the coastline moves seaward. In combination with the coastline of the sandbar retreating, this results in a smooth coastline at the last available measurement in February 2019.

The calibrated model is used to model the effect of three variation types:(i) mean wave direction, (ii) directional variation and (iii) wave climate sequence. Changing the mean direction is chosen to show what is the turning point of the breakwater: When does the breakwater erode completely? The directional variation is chosen to research whether or not it is important to have a wave climate with a narrow bandwidth of wave directions. The wave climate sequence will show the influence of the chronological order of the median wave height and wave direction of events. For each of the alterations longshore transport amounts and coastline developments are analysed. The maximum amount of coastline retreat is then used to quantify the influence of each wave climate alteration on the morphological development.

The mean wave direction proved to have the largest influence on the development of the sandbar breakwater. A change of the mean direction of -2 degrees already led to 40 meters of extra coastline retreat. For a further counter clockwise rotation of the climate the coastline retreat increases even more. For a rotation of the mean wave direction in the opposite direction the amount of erosion decreases. The effects of an increase of directional variation (increase of the standard deviation of the wave direction) of up to a factor 5 (standard deviation of 25.4 degrees) results to a maximum increase of the coastline retreat of 33 meters. This shows that a narrow bandwidth of the wave direction is not really necessary for the breakwater to become stable. It does however increase the amount of erosion. Changing the sequence of wave climate events only results in variations over the year, but at the end of the year the results are equal. There is however one exception: The climate with a decreasing direction (directions are order from high angle to low angle) shows a larger amount of coastline retreat of 10m. For most tested climates the location of maximal coastline retreat was at the location where initially the sandbar and the stretch of coast connecting the coastline to the breakwater intersect. All climates imposing a larger amount of erosion than the original climate have their maximal amount of coastline retreat near the groyne.

The performed study shows how the breakwater would react to situations which are not typical for the Lekki breakwater. Although the breakwater being designed for the conditions at Lekki, it still proved to be able to 'survive' many of the altered wave climates. Based on the results of the analysis the following can be said about the sensitivity of the model of the sandbar breakwater at Lekki and can also be true for similar structures under the influence of different wave climates: Small variations (order of degrees) in the mean wave direction could lead to a significant increase of coastline retreat (order of tens to hundreds of meters). Variations of the directional variation (standard deviation of the wave direction) lead to a maximum of several dozens of meters of coastline retreat. And lastly, when considering the seasonality of a wave climate, an increase of the amount of coastline retreat can be expected when the wave direction turns from the favourable directions to the unfavourable directions over time.

The following recommendation is made on what to consider when one wants to design a sandbar breakwater at some location without directly making use of a hydrodynamic model: 1) The coastline type: an abundance of sand should be available, now and in the future. 2) The wave climate should be such that a sufficiently large amount of net LST is present. This can be checked by either comparing the considered wave climate to the climate at Lekki or by calculating LST rates by for example using CERC.

Contents

1

Introduction

The Cambridge dictionary defines a breakwater as “a very large wall that is built from the coast out into the sea to protect a beach or harbour from big waves”. This is how breakwaters have been protecting harbours against waves ever since the ancient times. The oldest known breakwater, the Wadi el-Jarf breakwater in the Gulf of Suez, dates back to ca. 2570 BC (de Graauw, 2017). Masonry, but foremost loose elements like gravel, quarry rock, and/or concrete blocks are used to build strategically placed elongated structures to prevent waves from penetrating into a harbour basin. The layout of a breakwater is designed keeping in mind that ships should be able to enter the harbour while ensuring minimal wave penetration into the harbour basin. Figure 1.1 shows the rubble mound breakwaters of the harbour of IJmuiden in the Netherlands. One can clearly see the elongated structures breaking the waves while the layout allows for the passage of ships.

Figure 1.1: The breakwater at the harbour of IJmuiden, The Netherlands. One can clearly see the influence of the breakwater on the wave propagation. (CIRIA et al., 2007)

The coastal zone is under the influence of several natural processes. Incoming waves in combination with wind driven and tidal currents can create a transport of sediment along the coastline, or in short; longshore sediment transport (LST). Some coastlines are prone to environmental conditions resulting in LST in one dominant direction. The breakwater, being built in this coastal zone, can have a large influence on the LST as the longshore current is interrupted. A breakwater built at such a location can result in an accretion and erosion pattern as shown in figure 1.2 (van Rijn, 2013). The shore-perpendicular structure forms an obstacle for the LST. The sediment is trapped at the updrift side of the breakwater. On the other side of the breakwater, the downdrift side, the sediment transport is restarted. Due to the absence of sediment supply, as all sediment is trapped on the updrift side, this area will start eroding.

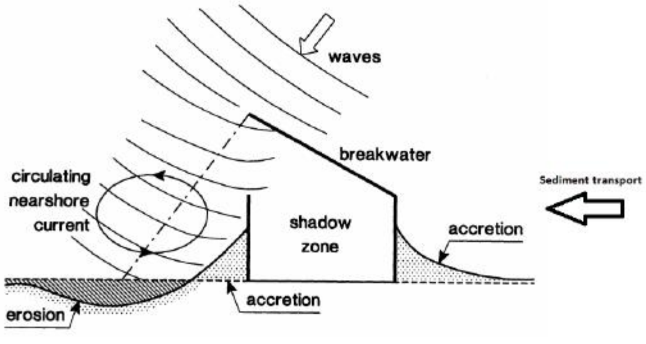


Figure 1.2: Overview of the accretion and erosion processes around a conventional breakwater. (van Rijn, 2013)

The accretion of sediment on the updrift side can, depending on the LST rate, bury a traditional breakwater in sand only a few years after construction (Van Rijn, 2005). This will result in the breaking of waves before reaching the originally constructed rubble mound breakwater. As a result the wave attack on the breakwater is significantly reduced or even absent. As this breakwater is designed to be able to resist much larger waves the structure becomes overdimensioned or even unnecessary. This led to the question: can (the accretion of) sand be used as a functional part of a breakwater? If sand is present from the start, the amount and size of rocks needed can significantly be reduced. Depending on the availability of sand and rock in the vicinity this can lead to a more economical solution.

Not only can the breakwater be a more economical solution, it is also a great example of a structure which uses the dynamics of nature rather than only fighting it; A Building with Nature solution (Ecoshape). The natural longshore sediment supply helps creating and maintaining a stable breakwater. Sand is abundantly available and less rocks need to be supplied to the construction site, hence transport movements and thus emissions are reduced. And lastly, as the solution provides new land , opportunities are created for nature development.

1.0.1. First sandbar breakwater: Lekki, Nigeria

The first and, at the moment of writing, only breakwater using this concept is built at the coast near Lekki, Nigeria, to protect a harbour from wave penetration (Figure 1.3). The wave climate, in combination with the coastline orientation and abundant availability of sand, made this the perfect location for the first application of the concept.

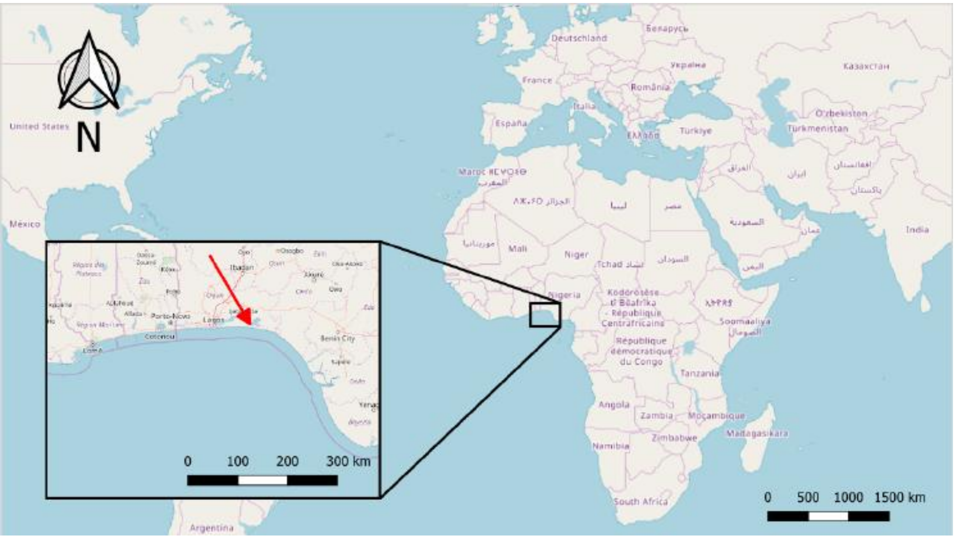


Figure 1.3: Location of the sandbar breakwater at Lekki, Nigeria (red arrow).

The wave climate at Lekki can be characterised as a unidirectional swell wave climate with relatively low waves, as can be seen in the wave rose in figure 1.4. Not only is the wave climate unidirectional it also shows a small standard deviation around this one direction, a narrow bandwidth of directions. The climate can thus be called a unidirectional narrow bandwidth swell wave climate.

The combination of the coastline orientation and the wave climate results in a net longshore sediment transport of 650.000 to 900.000 m3/year in eastern direction (Poortman and van der Spek, 2017). In combination with a poor availability of good quality rock required for the construction of a conventional rubble mound breakwater, this led to the first realisation of this new concept: A so called "Sandbar Breakwater" was designed and constructed. The design is based on a minimal initial nourishment which is reshaped by nearshore morphological processes. The final result can be seen on the cover of this report.

In figure 1.5 a schematic of the Lekki sandbar breakwater is shown. The initial design contains three key areas as indicated in the figure: Area A indicates the initial layout of the breakwater containing area B and C. Area B is the narrow sandbar and area C contains the rubble mount groyne. The lighter shaded area D is the area which is expected to be filled in by the natural morphological processes. While the grey coloured area, part

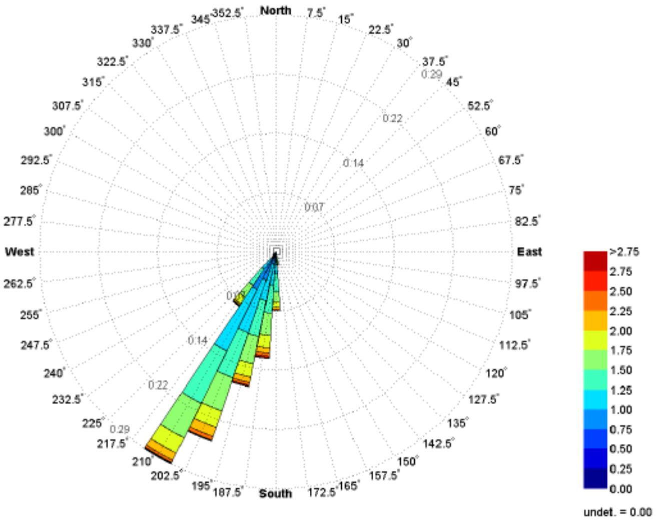


Figure 1.4: Wave rose of the Lekki wave climate from 2005 to 2016 showing the distribution of the wave height per wave direction. *source (Poortman and van der Spek, 2017)*

of the initial sandbar, inside area B indicates the expected erosion of the sandbar. The areas E and F indicate the downdrift erosion and the harbour basin respectively.

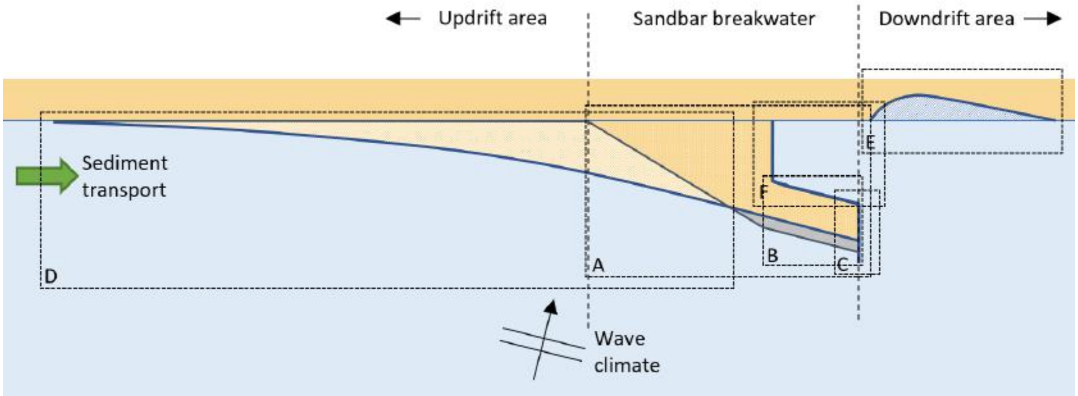


Figure 1.5: The area surrounding the sandbar breakwater has been divided in several sections (updrift, breakwater and downdrift) and focus areas: A. Initial breakwater, B. Sandbar, C. Groyne, D. Updrift area, E. Downdrift area and F. Harbour basin. In grey erosion of the initial layout is shown.

In relation to a traditional rubble mound breakwater the sandbar breakwater imposes one very important new failure mode: breaching of the sandbar. When the sandy body (figure 1.5, area A) erodes that much that waves can penetrate directly into the basin, this can be considered a breach and thus a failure. Of course other failure modes like overtopping and failure of the groyne are also important, however these are not the failure modes which distinguish the sandbar breakwater from a traditional breakwater. During the period in which the initial layout adapts to the wave climate, by means of morphological processes, local retreat of the coastline is expected on the sandbar. As the sand buffer is minimal here, this location is expected to be the area which has the highest probability of failing due this failure mode.

The wave climate at Lekki is perfect for preventing large amounts of erosion at this location. The constant direction of waves imposes a unidirectional longshore transport in the most favourable (eastern) direction. The absence of short term local wind driven storm events or events which impose longshore transport in the opposite direction, creates an environment in which erosion of the sandbar is expected to be minimal. The logical question follows; What if a sandbar breakwater is designed for a location with a more varying wave climate?

This research will focus on answering this question by analysing the morphological development of the Lekki breakwater during its first year after construction has finished. It will result in the understanding of the morphological behaviour of the sandbar breakwater concept for a wave climate as present in Lekki. This knowledge is then used to set up a model to research the sensitivity of the sandbar breakwater for variations in the wave climate. The results of this study can in turn be used to (I) assess the applicability of a sandbar breakwater for a certain wave climate and (II) improve future sandbar breakwater designs.

1.1. Problem definition

The minimal initial nourishment used to create the sandbar breakwater is supposed to be supplemented by a natural supply of sediment to adapt to a smooth coastline. Waves do not only create an LST supply towards the breakwater, but also cause erosion of the initial breakwater layout. The relation between the wave climate and the erosion of the initial layout makes the sandbar breakwater an interesting structure. The supply of sediment towards the breakwater and the amount of erosion of the initially placed nourishment should be well balanced. This is important in order to keep the nourishment as small as possible, but also to prevent a breach of the breakwater.

The favourable wave climate at Lekki causes a unidirectional LST in the direction of the breakwater, supplying the breakwater with a large amount of sediment. However, despite this large supply, erosion of the sandbar is still expected (Poortman and van der Spek, 2017).

This phenomenon can be explained by taking a closer look at the morphological development of the initial layout of the sandbar breakwater in the present wave climate. Furthermore, it is unknown how a sandbar breakwater will behave under a less favourable climate with more variations in wave direction. Therefore, it is desirable to further investigate how the morphological development of the nourishment is affected while being approached by waves from for example a wider range of directions.

The current knowledge gaps can be bundled into a main research question:

How is the coastline evolution of the sandbar breakwater concept affected by directional variations in the wave climate?

This question is answered with the support of the following sub questions:

1. How did the sandbar breakwater at Lekki develop during its first year under the influence of the (ideal) wave climate?
    (a) What morphological developments of the sandbar breakwater are observed?
    (b) What influence did the wave climate have on the morphological development?
    (c) Based on these observations, what is expected to be the future development?
2. How sensitive is the sandbar breakwater concept in general to variations in the wave climate?
    (a) Which direction related wave climate variations are of significant influence on the Lekki sandbar breakwater development?
        i. What is the effect of the mean wave direction?
        ii. What is the effect of the directional variation?
        iii. What is the effect of the event sequence?
    (b) Is a unidirectional narrow bandwidth wave climate necessary for the Lekki sandbar breakwater to become stable?
    (c) To what extent can the sensitivity of the Lekki breakwater to wave climate variations be translated to the sensitivity of the sandbar breakwater concept in general?

Answering the first set of research questions gives us insight into how the sandbar breakwater concept currently behaves under the influence of the wave climate present at Lekki. Answering the second set of research questions allows us to predict the influence of the wave climate directional variations on the sandbar breakwater concept in general. The Lekki case study can contribute to the understanding of the sandbar breakwater concept development under wave climate deviations.

1.2. Method

The research is split up into two phases: Firstly a data analysis in which the morphological development of the Lekki breakwater is analysed and used to setup a validated morphological model. And secondly a sensitivity study of the morphological development for the wave climate by using the validated model. The methodology of both phases will be discussed briefly below and in full detail at the start of chapter 3 Data analysis and chapter 4 sensitivity study.

1.2.1. Phase 1: Data analysis: Lekki case study

The available measurements concerning the morphological development and wave climate of the sandbar breakwater at Lekki are analysed to map the real life morphological development as a result of the wave conditions of the first year after construction. Bathymetrical surveys and aerial images are used to assess overall morphological and coastline development. Wave climate and tidal information is coupled to the morphological development to show the influence of the unidirectional narrow bandwidth wave climate on the sandbar breakwater concept. The coastline evolution of the breakwater is then used to create a schematic representation of the morphological development, which is characteristic for the sandbar breakwater. The findings are then used to validate a morphological model for the sensitivity study.

1.2.2. Phase 2: Wave climate sensitivity

The sensitivity of the sandbar breakwater concept to variations in the wave climate is studied by means of the one-line coastline evolution model Unibest. The knowledge gained about the morphological development during the data analysis, in combination with the original wave climate, is used to create a calibrated model of the Lekki sandbar breakwater. Variations of the original wave climate are made and the model is used to calculate the coastline response of the sandbar breakwater to such variations. The sensitivity of the wave climate is then determined based on the analysis and comparison of the coastline development under the influence of these alterations.

To finalise the research, the results of sensitivity of the wave climate on the Lekki sandbar breakwater are used to discuss the importance of the wave climate on the sandbar breakwater concept in general.

2

Literature study

This section gives the background information needed to understand why the Lekki coastline is the ideal location for this breakwater concept and to understand why it is of much value to understand how the concept will react to more variation in the wave climate. First the considerations of the design process of the sandbar breakwater at Lekki are discussed. secondly, a conceptual model of the breakwater is discussed, for the purpose of identifying the coastal processes imposing the development of the breakwater. Followed by the discussion of the most important coastal processes. Then a definition for the stability of a sandbar breakwater is discussed to be able to determine when a breakwater is applied successfully or when not. Lastly the research of fellow student Jochem Peters on the feasibility of a sandy breakwater at Badagry (also Nigeria) is discussed briefly.

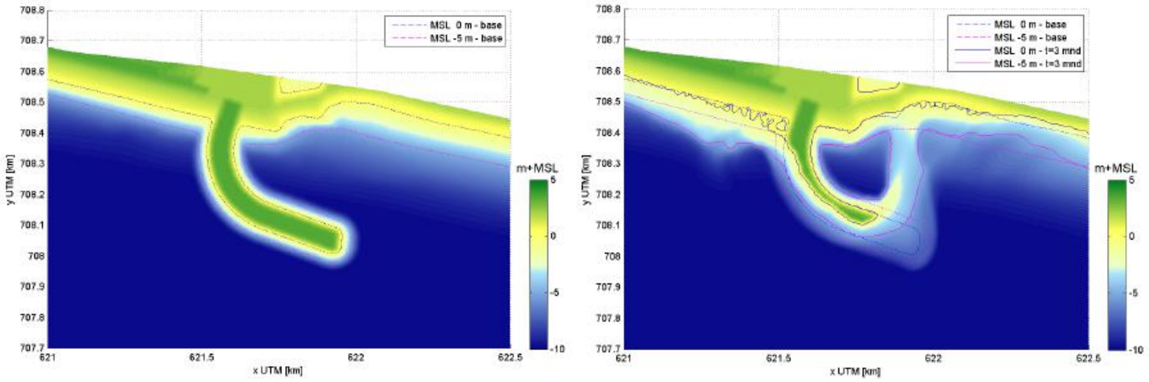
2.1. Lekki sandbar breakwater

Lekki is a city in Lagos State, in South West Nigeria (Figure 1.3). The city is located at the coast of the Gulf of Guinea. A breakwater was needed to protect a harbour basin from wave penetration about 50 kilometres West of Lekki. The sandbar breakwater was proposed as an alternative for a traditional rubble mound breakwater and later chosen by the client to be built. There were several factors contributing to the sandbar breakwater concept being considered. The first one being the bad availability of good quality rock. For creating a traditional rubble mound breakwater vast amounts of rock would need to brought in from far resulting in high costs. Secondly, the Lekki wave climate. The wave climate being a unidirectional swell wave climate imposes a yearly net transport rate of 600.000 to 900.000 m3/year (Poortman and van der Spek, 2017). This amount of transport in one direction is expected to have a positive effect on the morphological development of the breakwater.

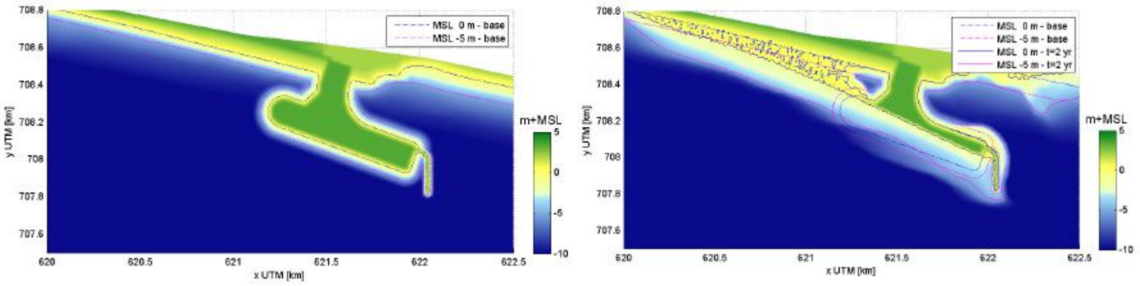
As the Lekki sandbar breakwater is the first breakwater of its kind, the concept had to be developed from scratch. Several designs were made and tested using a morphological computational model. The equilibrium coastline orientation was the starting point for the design, because for this orientation the net longshore sediment transport is (close to) zero (Bosboom and Stive, 2015). This equilibrium orientation depends on the wave climate and mainly on the wave direction as will also be discussed in detail in section 2.3. For the Lekki wave climate the direction is unidirectional, indicating that the equilibrium coastline orientation is within a small range of possible orientations and thus relatively easy to predict and not that variable over time. With this equilibrium orientation in mind, the initial layout of the breakwater was designed such that a minimal initial nourishment volume was required during construction.

Poortman and van der Spek (2017) modelled several designs for the sandbar breakwater. Starting at the bare minimum and finishing with the final design. The morphodynamic model FINEL2D was used to model the designs to give insight into the morphological development over time. The designs and the corresponding morphological change after a certain period of running the model are shown in figure 2.1. The 'after' figure shown for each design is chosen to be after different periods as the time it takes for the breakwater to 'fail' is different. For the first design the layout of a conventional breakwater was created fully out of sand. This design gave insight in the behaviour of a sandy body at this coastline. The results of the modelling (after three months) show that this sandy body erodes fast and the tip on the right side of the breakwater is flushed away completely (Figure 2.1a). Therefore an alteration had to be made. For the second design, as shown in figure 2.1b (results after 2 years of modelling), the breakwater was extended in the updrift, western, direction and at

(a) Design A



(b) Design B



(c) Design C: Final design

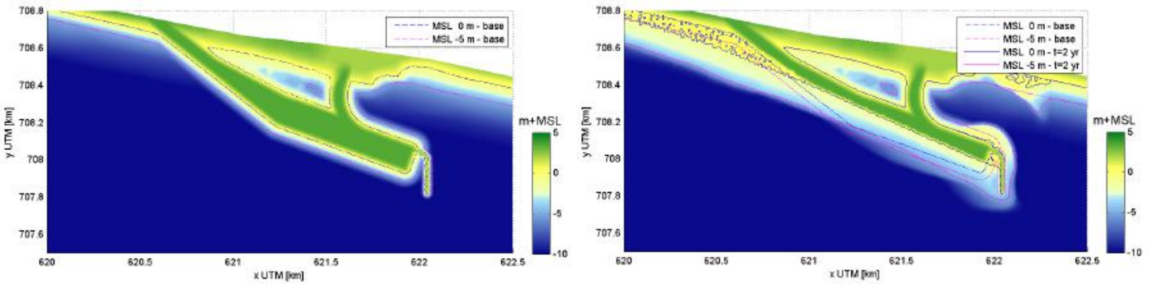


Figure 2.1: The designs of the Lekki breakwater

the tip of the breakwater a traditional rubble mound groyne is added to trap the sediment. The results were already more promising, but the large amounts of erosion were considered to be to high to use this design as a final design. For the final design (figure 2.1c, showing the results after two years of modelling) the breakwater dimensions have been increased even more. This design was considered to be stable as in the period between two to four years after construction the width of the sandbar did not decrease. Therefore this design was used to create the plans for final construction. The design was done by CDR International in collaboration with Svašek Hydraulics. Boskalis did the construction of the breakwater. The last nourishment was performed on March 16th 2018, indicating the start of the development of the breakwater. The rest of the project (shore protections) was finished a few months later.

2.2. Conceptual model

The sandbar breakwater concept distinguishes from a traditional breakwater by the fact that it is very dynamic. Where a traditional breakwater is designed to allow for little movement of the rocks and to remain on the exact same location for its entire lifetime, the sandbar breakwater is designed to be highly dynamic. This highly dynamic character is the result of coastal processes. In this section these processes are identified by means of a conceptual model. In this case a conceptual model describes how the characteristics of the sandbar breakwater (e.g. dimensions) are influenced by coastal processes and vice versa.

In figure 2.2 one can see the conceptual model for the sandbar breakwater. The model has been split up in several colors, each color indicating a category of processes or characteristics: Green for the environmental conditions, blue for sediment transport, purple for the sandbar breakwater characteristics, red for damages and failures and yellow for human interferences.

The conceptual model starts at the lower left with the initial breakwater layout. This is the situation just after construction is finished. It is assumed that there has been no morphological development during construction and the start situation is the situation as the breakwater is designed. In bright blue the bathymetry around the breakwater is included. This is the bathymetry around the breakwater, untouched during construction. In green the environmental conditions are summarised. Then in yellow diffraction is named as an example of a phenomenon which could occur as a result of the wave conditions and the sandbar design. The sediment transport and with that the possible morphological change (blue) follows from the environmental conditions (green) and the breakwater layout (purple). The morphological change then again influences the sandbar breakwater layout (purple) and the circle is round. In red the failure modes of the breakwater are shown. The result of damage or (near) failure is that human interference is needed (yellow). This can be in the form of nourishments of the sandbar or repair of the groyne.

This model shows the complexity of the sandbar breakwater, the many influences between phenomena and the vast number of variables that need to be considered when designing such a structure. As figure 2.2 is rather complicated, figure 2.3 is made as a brief summary showing only the categories.

In the conceptual model only the dimensions (or layout) of the breakwater can be influenced by man. The other processes are the result of natural phenomena. The environmental conditions are the main driver of these processes. One can imagine that large variations of the environmental conditions will make it harder to predict the development of the breakwater than for little variations.

2.3. Coastal dynamics around the sandbar breakwater

In the conceptual model many coastal processes are named. But how do these processes influence the development of a sandbar breakwater. In this section the phenomena and their influence on the sandbar breakwater are discussed. Longshore transport of sediment due to waves and the resulting morphological change will have a key role.

Longshore transport of sediment is the result of waves and currents. A distinction is made between waves generated nearby and wave generated far away. Locally generated waves are generally shorter and the duration of events is shorter. These waves are called wind waves or just ‘sea’. Waves generated far away have travelled far before reaching the coastline this results in two phenomena: (i) Wave periods are longer than the wind waves and (ii) different travel speeds of waves with different length results in faster longer waves arriving ahead of shorter and thus slower waves. As wave speed (in deep water) is defined by: $c = gT/2\pi$. In which g is the gravitational constant and T the wave period. The separation of the waves based on their length is called ‘dispersion’ and it is this effect the wave climate in Lekki to have a typical pattern for the wave period. Over time first the long waves arrive after which the period decreases until a new long wave arrives.

While approaching the shore the wave can start moving sediment in the cross shore and or longshore direction, depending on the direction of the waves relative to the coastline orientation; the angle of incidence. Sediment transport in cross shore direction usually is the result of for example high energy events like locally generated storms. The Lekki wave climate is not prone to this kind of storms and thus the longshore sediment transport (LST) is expected to be dominant for the development of the breakwater.

Longshore sediment transport rates are proportional to the relation between the wave height (H_s) and the angle of wave incidence (α): $S \propto (H_s)^n sin(2\alpha)$. In which n is 2.5, when using CERC (1984). The amount of sediment transport thus depends on wave height and angle of incidence. As the transport rate is proportional to $sin(2\alpha)$ the sediment transport is maximum at an angle of incidence of 45 degrees and zero at an angle of 0 degree with the shore normal line. It is this phenomenon that is very important for the morphological development of the sandbar breakwater. As different coastlines orientations exist very close together. The orientation of these coastlines will create sediment transports based on the relation between the wave direction and the coastline orientation. In figure 2.4 the LST direction as a result of the different coastline orientations

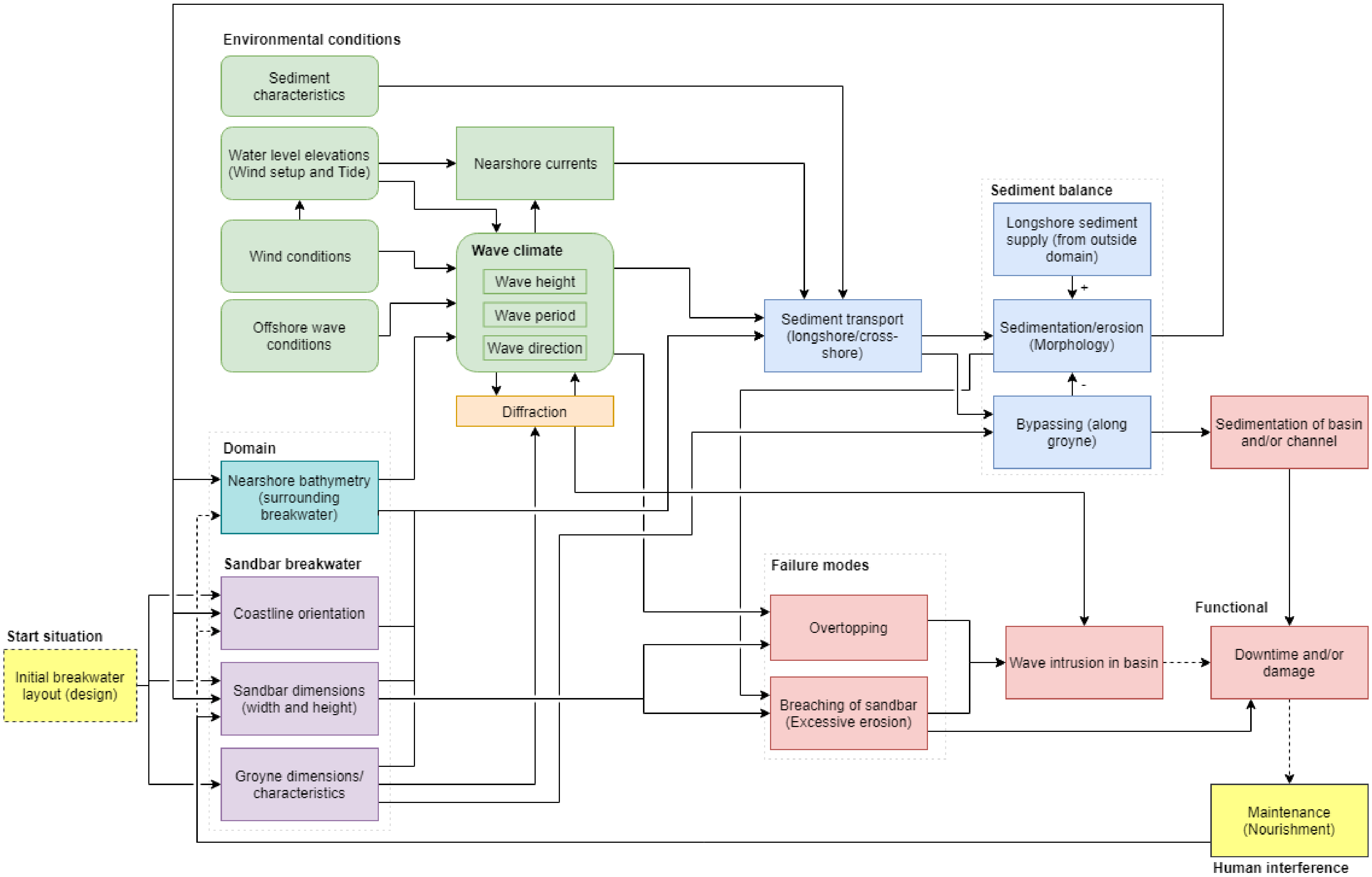


Figure 2.2: Conceptual model of the sandbar breakwater concept.

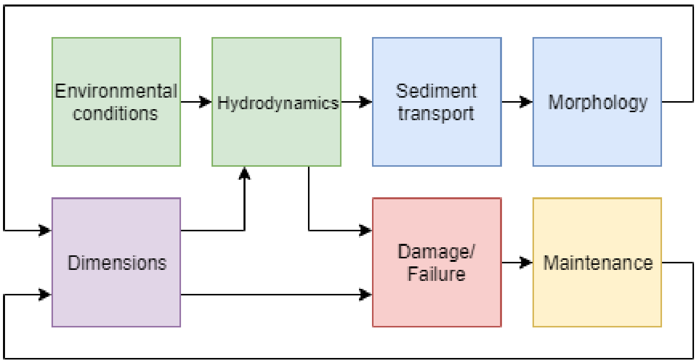


Figure 2.3: Compact version of the conceptual model of the sandbar breakwater concept.

is sketched for the situation just after finishing the breakwater. Two directions of LST will occur. This will continue as long as the coastline has not fully adapted to the (mean) wave direction. This orientation, the coastline orientation being about equal to the wave direction, is called the equilibrium coastline orientation. When the equilibrium coastline is reached by the entire breakwater, gradients in sediment transport over the breakwater length will have disappeared and the sediment transport rates will decrease.

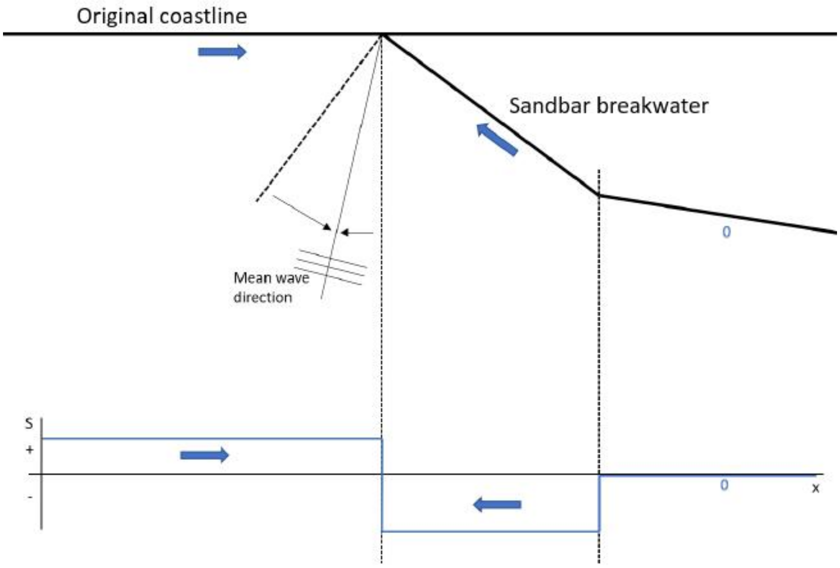


Figure 2.4: The sediment transport directions as a result of the sandbar breakwater having different coastline orientations just after construction of the breakwater has finished. In the upper half of the figure the sandbar breakwater, original coastline and the mean wave direction are indicated. The lower half of the figure shows a sketch of the sediment transport direction, S, over the longshore direction, x.

As the wave climate at Lekki is unidirectional, waves will generally come from the direction indicated in figure 2.4, or have a similar direction. This makes the development of the breakwater relatively easy to predict. But what if the wave climate can not that simply be indicated by one mean wave direction? What if waves come from a larger range of directions? Those are the questions that that are answered by this research.

2.4. Stability and successful application definition

A sandbar breakwater can be, depending on the environmental conditions, a very dynamic construction. One can imagine that as long as the dynamic character of the sandbar breakwater is between certain limits, there is no problem. However, when these limits are exceeded, it can lead to failure and even loss of the structure.

The successful application in terms of the creating a functioning and financially feasible breakwater, depends mainly on two requirement types; 1) functional and 2) stability requirements. The functional requirements are the requirements which need to be met by the breakwater to be useful for fulfilling the function it is intended for. These requirements are equal to the functional requirements of a traditional breakwater and are therefore not discussed in detail. Examples are: a minimal amount of wave penetration minimising off time, and a required depth of the basin and the approach channel. The stability requirements are however very different from those of the traditional breakwater. Where the stability of a rubble mount breakwater is determined by the resistance of the rocks to the forcing of waves, the resistance of the sandbar breakwater is determined by the balance between sedimentation and erosion of the coastline.

This sedimentation and erosion is the result of variations in the environmental conditions. For know it is enough to know that variations in the wave climate will result in variations in the amount and direction of longshore sediment transport. Simply said; A sediment transport in the left to right direction (figure 1.5) will result in a supply of sediment to the domain and with that accretion of land. And vice versa, sediment transport in the opposite direction will result in erosion. One can image that when the environmental conditions are such that a sediment transport from right to left occurs, that the area of the sandbar near the groyne is most vulnerable to erosion. As there is no supply of sediment from the right of the groyne, the sediment just left of the groyne will not be replaced when transported away. Depending on the transport rate and the duration, transport in this direction can result in a total loss of the sandbar (Figure 1.5, B) and thus failure of the breakwater.

The critical phase of the breakwater failing is during the time just after construction; The breakwater is designed such that a minimal nourishment is needed and thus a minimal amount of sand should suffice to create a breakwater which will be able to protect the basin for a long time. Simply said, the application of a sandbar breakwater can be called successful when the sandbar maintains enough width to prevent penetration of waves into the basin protected by the breakwater; No breaching. However whether or not this width is sufficient depends on two factors: 1) The state of the adjustment of the initially constructed profile to the natural profile and 2) the future environmental conditions.

So stability is something that can be reached after a certain amount of time; when the initially constructed profile has adjusted to the natural conditions and when a smooth coastline has formed. **The breakwater can be called *stable* when there is no structural erosion. Short term erosion, by for example an event of sediment transport in an unfavourable direction or a storm, is filled in by a natural (longshore) supply of sediment.** This is the situation that one wants to reach when building the breakwater as it will then maintain itself without interference by men.

Before this stable situation is reached, a lot of morphological development will occur to transform the initial profile to the natural profile. To see whether or not the sandbar breakwater has been applied successfully during this period, it is also important to define the definition of a successfully applied sandbar breakwater just after construction until the stable situation is reached. During this phase it is important that there is enough sediment in the domain to prevent the sandbar from becoming to narrow and breaching and also transform the initial profile to the smoothed stable profile. **The application of the sandbar breakwater can therefore be called *successful* if during the initial phase the width of the breakwater does not decrease below a critical value to prevent breaching and after this phase the breakwater reaches a stable situation in which periodical erosion is counteracted by a natural (longshore) supply of sediment.**

2.5. Related previous research

The topic of sandbar breakwaters has only been researched once before: (Peters, 2018). This master thesis research by J.H.J. Peters has been performed to find the best alternative out of three different breakwater designs containing a sandy body to break the waves. This study mainly focused on the feasibility of the different design in both technical and financial terms at the coastline of Badagry, which is situated 100 km West of Lekki. The wave climate at Badagry is about equal to the Lekki wave climate. The research gave insight in how the three different designs behave under the prevailing wave conditions. All three designs do however not rely on the natural sediment supply, but rather see this supply as a disadvantage, as one of the requirements is no bypassing in the fifty year lifetime of the breakwater. This makes these 'sandy' breakwater designs fundamentally different than the concept applied at Lekki, as the Lekki concept relies on this natural supply of sediment to reach a stable situation. Therefore the results of that thesis are not used for this research.

3

Data analysis: Lekki sandbar breakwater

In this chapter the morphological development during the first year after construction of the sandbar breakwater at Lekki is discussed. A combination of aerial images and bathymetrical surveys is used to asses the morphological development. Hindcast wave and tidal data is used to asses the environmental conditions. This chapter will give an answer to research question 1:

1. *How did the concept of the sandbar breakwater develop during its first year under the influence of the (ideal) wave climate at Lekki?*
   (a) *What morphological developments of the sandbar breakwater are observed?*
   (b) *What influence did the wave climate have on the morphological development?*
   (c) *Based on these observations, what is expected to be the future development?*

3.1. Method

The morphological development of the first year after construction is evaluated by means of a data analysis. The first step is gathering the data from different sources. Several data types can be distinguished: Bathymetry data, environmental conditions and construction logs.

The available bathymetry data is analysed by means of comparing the bathymetry for several moments in time after construction. This analysis is performed by using Matlab. From the bathymetry information like the change of the coastline (orientation), sedimentation/erosion volumes and cross shore profile can be analysed. The bathymetry data and is than coupled to the wave conditions to show the influence of the environmental conditions on the morphological development of the sandbar breakwater at Lekki for the first year after construction. The development of the first year is then used to determine how the breakwater will develop in future years.

3.2. Data

The following data is used to perform this data analysis (the source is presented between brackets and also discussed later):

1. Aerial images (Google Earth)
2. Bathymetrical surveys (Boskalis)
3. Hindcast wave data (BMT ARGOSS)
4. Tidal information (TPXO)
5. Construction logs (Boskalis and CDR International)

3.2.1. Aerial images

Three aerial images are available on Google Earth showing the development of the sandbar breakwater and the area surrounding it (Figure 3.1). The first image is taken before construction (25-12-2017), the second during construction (06-03-2018, which is 10 days before the last nourishment) and the last images several months after construction has finished (24-12-2018).

Figure 3.1: Three states of the construction and development after construction of the Lekki breakwater. The first image is taken before construction on 25-12-2017. The second image is taken during construction on 06-03-2018. The third image is taken some time after finishing the construction at 24-12-2018. The yellow line in the last image shows the coastline profile of 06-03-2018 (second image) (201, 2019)

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3.2.2. Bottom surveys

Three bottom surveys containing elevation data on a 1x1m grid of the sandbar breakwater at Lekki are made available by Royal Boskalis Westminster N.V. (Figure 3.2). These surveys are made on the following dates and contain the area as indicated between brackets:

1. 01-06-2018 (full breakwater)
2. 18-10-2018 (only submerged)
3. 19-02-2019 (only sandbar)

3.2.3. Wave data

Wave data has been acquired from the BMT ARGOSS Wave Climate Database for the period from 1992-2018. For the morphological study (Poortman and van der Spek, 2017) NOAA hindcast wave data was used, however this dataset showed (at the moment of the research) some gaps for the year 2018, which made it unsuitable to use for this research. The WaveClimate data has been compared to quantify any differences between the sets, this comparison can be found in appendix A. The ARGOSS wave height is on average around 0.1m lower than the NOAA wave height, the peak period is around 1.5 seconds lower and the wave directions can vary by a maximum of around 3 degrees. The WaveClimate data has also been validated by means of comparison with wave buoy data. This analysis can also be found in appendix A.

The nearshore wavedata is determined for location 6°24’8.42"N and 4° 5’51.51"E. Which is just offshore of the breakwater. The BMT ARGOSS SWRT model uses the offshore wavedata from points 6N3.5E, 6N4E and 6N4.5E to calculate the nearshore wave data.

3.2.4. Tidal information

Surface level variations at the location of the breakwater (6°24’8.42"N and 4° 5’51.51"E) are calculated by using the TPXO model, which is a fully-global model of ocean tides. TPXO provides the tides as complex amplitudes of earth-relative sea-surface elevation for eight primary ($M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1$), two long period ($M_f, M_m$) and 3 non-linear ($M_4, MS_4, MN_4$) harmonic constituents (Egbert and Erofeeva, 2002). The eight most important tidal constituents for this location can be seen in table 3.1. The minimal and maximal tidal elevation are based on the period of 1900 to 2018 and are listed in table 3.2. A tidal amplitude of 1 meter can be expected. The time series of the waterlevel can be found in appendix B.

Constituent	M_2	S_2	N_2	K_2	K_1	O_1	P_1	Q_1
Return period [hours]	12.42	12.00	12.66	11.97	23.93	25.82	24.07	24.07
Amplitude [m]	0.5070	0.1808	0.1100	0.0491	0.1292	0.0286	0.0386	0.0033
Phase lag [deg]	104.69	132.77	99.87	131.44	353.54	328.64	348.81	91.43

Table 3.1: The tidal constituents contributing to the surface level elevation at Lekki. (Egbert and Erofeeva, 2002)

	Relative to MSL [m]	Relative to LAT [m]
HAT	0.99	2.00
MSL	0	1.01
LAT	-1.01	0

Table 3.2: Maximum, minimum and mean of the tide. Both relative to MSL and LAT.(Based on TPXO)

3.2.5. Construction logs

Between 06-03-2018 (date of the aerial image closest to the end of the construction) and 16-03-2018 2 hoppers added 25.000 to 35.000 m^3/day to the sandbar. Therefore 16-03-2018 can be seen as the final day of construction for the sandy part of the breakwater.

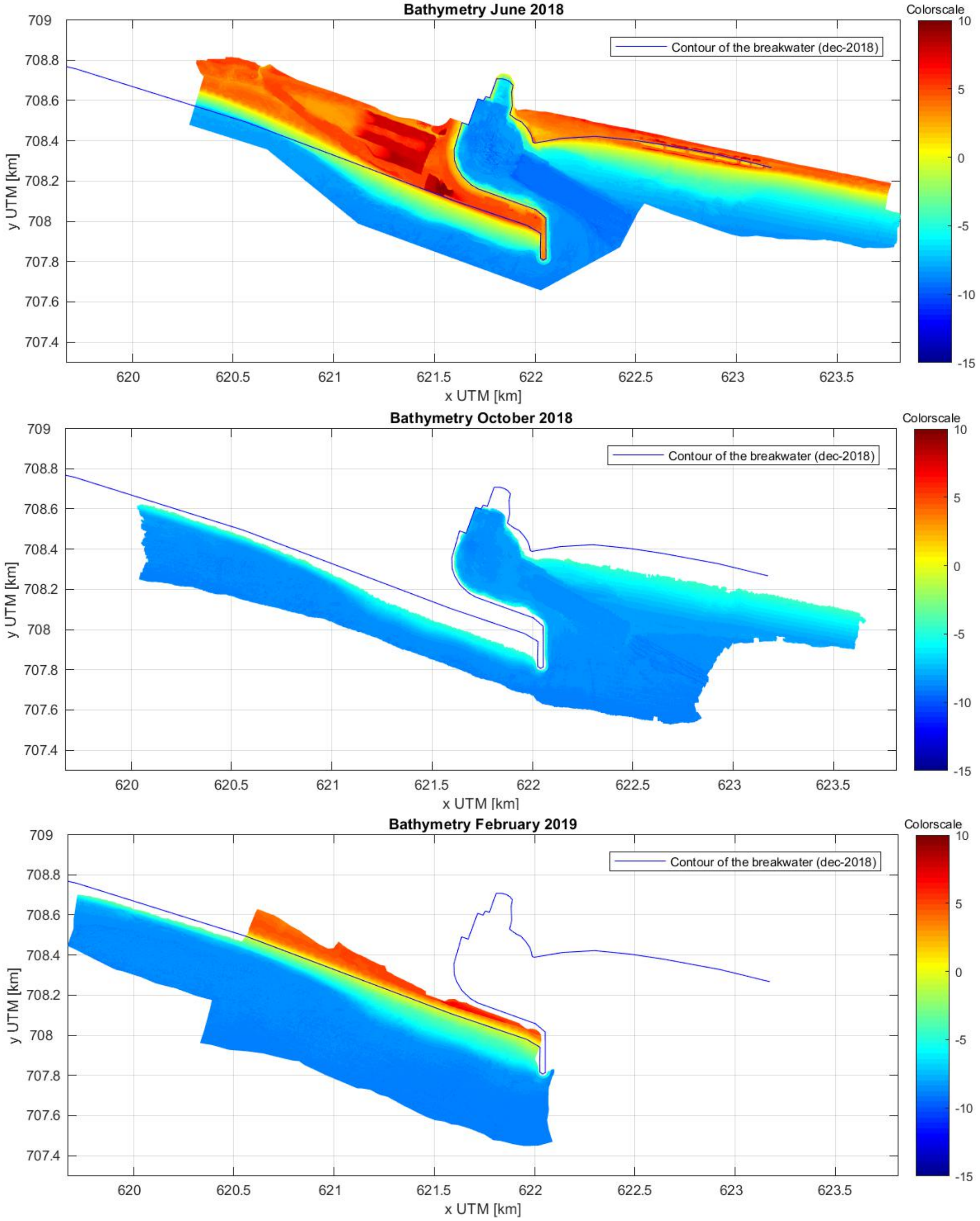


Figure 3.2: The available surveys all on an identical colorscale. The blue contour line shows the 0mCD line in December 2018.

3.3. Analysis

The presented data is used to give an as detailed as possible overview of how the sandy part of the breakwater has developed since construction was finished at 16-03-2018. The bottom surveys and aerial images are used to analyse the morphological development of the breakwater. The change of the bathymetry gives insight in where and how much sedimentation and erosion took place between measurements. This information is valuable as it shows how much of the nourished sediment remains in the domain and how much is lost by for example bypassing. A sediment balance can show whether or not the natural longshore sediment supply of 650.000 to 900.000 m^3/year calculated by (Poortman and van der Spek, 2017) is a good estimate of what has been supplied last year. The coastline development gives insight in whether or not the coastline is adjusting towards an equilibrium orientation. As this is what the design is based on, it is important to verify if this is happening. The evolution of the cross shore profile is investigated to learn how an unnatural profile develops towards a natural profile under the influence of waves. This development can for example influence the coastline location (due to the flattening of the profile). The development is compared to the Dean equilibrium profile to check whether or not an equilibrium situation is reached at this moment. Then the results of the morphological and coastline development are coupled to the environmental conditions. The main goal of this analysis is to research what influence the characteristics of the environmental conditions (e.g. wave height or direction) have on the development of the sandbar breakwater. In the end the conclusions will be combined to show the actual morphological state of the sandbar breakwater in Lekki. To show if the breakwater has been applied successfully, this state will be tested with the definition of a stable/successful sandbar breakwater.

3.3.1. Environmental conditions

The environmental conditions determine how the sandbar breakwater developed over the last year and how it will develop over its lifetime. In this section the characteristics of the environmental conditions are discussed. First the characteristics of the long term wave climate are analysed. Later the wave climate of the last year, which is the year that is important for the development of the breakwater is discussed and compared to the overall wave climate. This to check if 2018 was an average year and it can be expected that the development will continue in this way, or when 2018 was an extreme year, maybe the expectations should be altered. Then the seasonal variability of the wave climate is discussed. Wave energy is a function of the surface level elevation ($E = \rho g \eta^2$), which is of course influenced by waves. The more wave energy the more sediment can be moved. Seasonal variability in the wave climate can result in much morphological development during a high energetic period and no to little development when the energy is low. In this section only the environmental conditions are discussed, later these conditions are coupled to the morphological change to show how both influence each other.

The BMT ARGOS wavedata (see section 3.2.3) is analysed to show the relevant characteristics. These characteristics are the significant wave height, H_s, peak period, T_p, and the wave direction. In table 3.3 the minimum, maximum and mean values of these characteristics are shown for the entire period of the data set and for 2018 only. To show the distribution of the wave height, period and direction figure 3.3 has been made. The lower right image of figure 3.3 shows wave height vs peak period plot. This kind of plot can be used to show the difference between wind waves and swell waves, as wind waves are relatively short and swell waves are longer.

			1992-2018			**2018**		
Characteristic	**Symbol**	**Unit**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
Significant wave height	H_s	m	1.19	0.42	2.78	1.19	0.55	2.30
Peak period	T_p	s	12.0	3.56	21.8	12.2	3.56	19.8
Wave direction	-	degN	201	137	241	202	189	222

Table 3.3: Table showing nearshore mean, maximum and minimum wave data for the period of 1992-2018 en for 2018 only.

Based on the wave characteristics in the table 2018 is an average year; Wave conditions in 2018 do only slightly differ from the wave conditions over the period from 1992-2018. This is confirmed by the graphs in figure 3.3. The upper right figure shows that most of the waves are relatively long waves and only a small peak at the shorter wave periods can be seen. In combination with the direction being fairly constant (lower left figure),

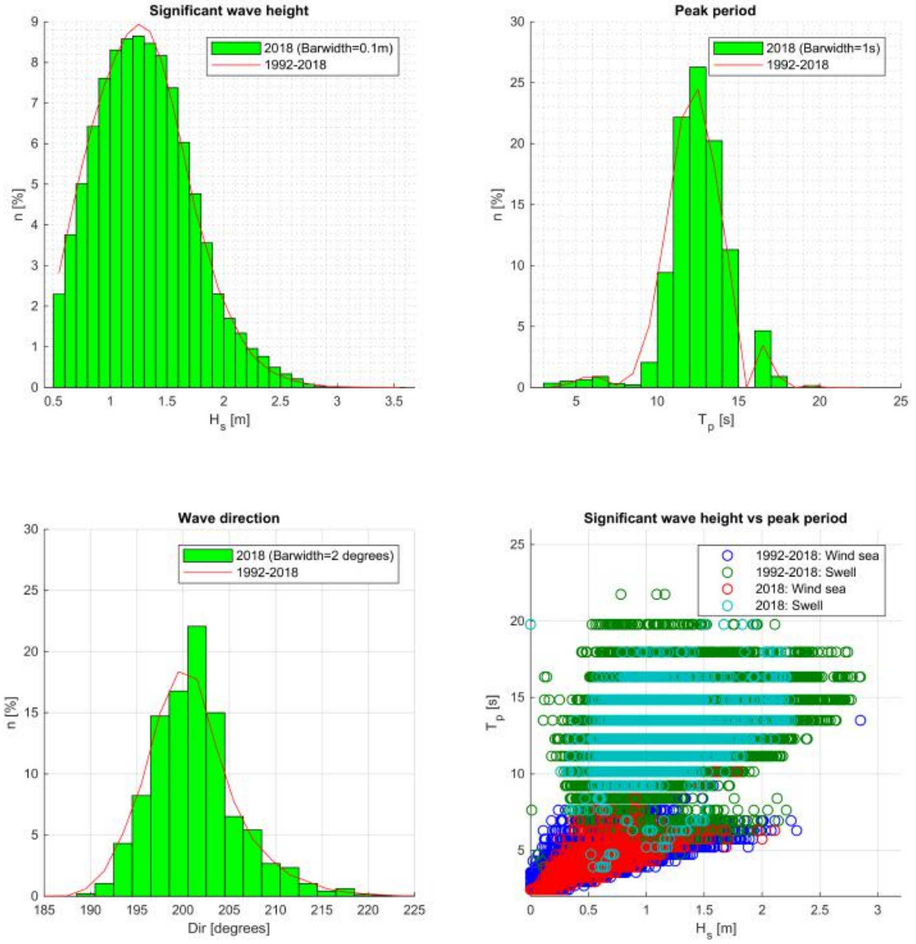


Figure 3.3: Upper left image: Distribution of the number of waves with a certain wave height. Upper right: Distribution of the peak period. Lower left: Distribution of the wave direction. Lower right: Significant wave height vs peak period.

the wave climate at Lekki can be considered a swell wave climate; Swell waves are dominant.

Seasonal variability

The seasonal variability of the wave climate can be shown by means of monthly averages. For each month of the year, the wave characteristics are averaged for the entire period and for 2018 only. The result can be seen in figure 3.4.

The sediment transport being a function of the wave energy shows that most of the sediment transport will occur during periods with high waves in combination with a favourable direction. Figure 3.4 shows that the monthly averaged significant wave height is small in January and than gradually increases until it is largest in July, after which it start decreasing again. The most energetic months are therefore June, July and August. The least energetic months are January and December. The peak period graph shows that the peak period is not longest when the waves are highest. The longer waves are around April to June, but the differences are rather small. In the wave direction some seasonal variability is visible: The direction varies between 198 and 204 degrees, with maximums in February, March, July, August and September and minimums in May and November. For the comparison between the entire data set and 2018 only, it is clear that the wave heights of 2018 are average, however the wave period can differ by about 0.7s, the period of 2018 being longer than the average of the entire set. For the wave direction the 2018 seasonal variability is equal to the average of the entire set, however the values in February and March are higher and the values of July, August and September are lower.

Figure 3.5 shows a rose indicating the direction of the waves with the corresponding peak periods. Figure 1.4 shows the wave rose for the wave direction and the corresponding wave height. As can be seen clearly, most

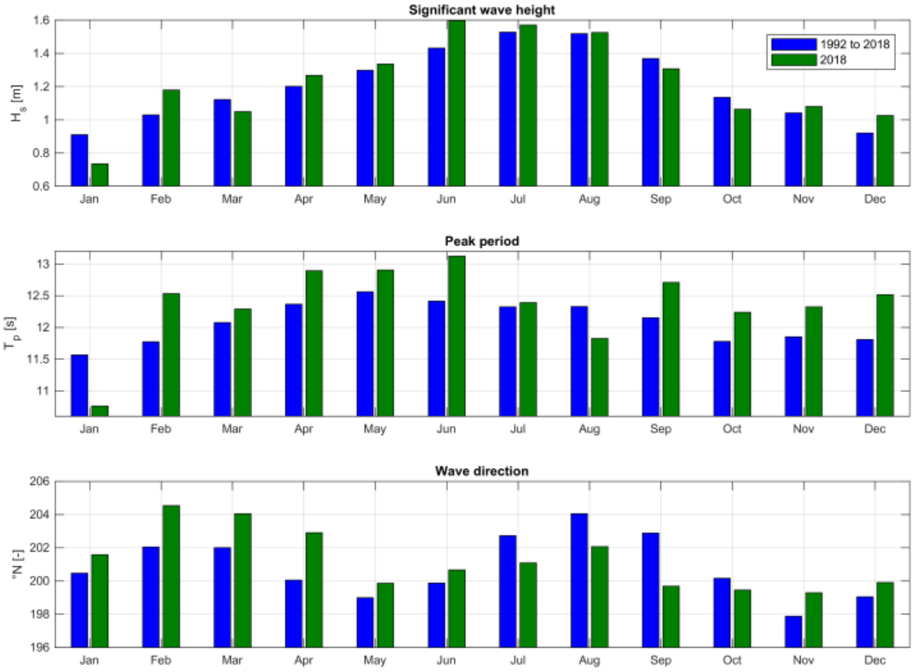


Figure 3.4: Monthly averaged wave characteristics (Wave height, period and direction) for the entire data set and for 2018 only.

of the waves (ca. 56%) come from between 198.8 and 214.0 degrees North. The combination of the relatively long wave length and the wave coming from one direction make that the wave climate can be characterised as a unidirectional swell wave climate.

3.3.2. Morphological development

In this section the morphological development of the breakwater is analysed using the bottom surveys and aerial images. The section has been divided in three sections: bathymetry, coastlines and cross shore profiles. This analysis should answer the question whether or not the breakwater at Lekki is stable and whether or not the breakwater can be considered a success.

Bathymetry

The surveys introduced in section 3.2.2 are used to analyse the morphological development of the sandbar breakwater and its surroundings. This development can be found by subtracting an earlier survey from a later one. When the earlier survey shows for example a value of 6m elevation and the later survey a value of 4m, than 4-6=-2m of erosion has occurred.

The three available surveys are analysed using this method. The result of the difference between the survey of June 2018 and February 2019 can be seen in figure 3.6. Only the difference between these two date is shown in the main text, as the other comparisons do not contain the emerged parts of the breakwater. In appendix C the comparison between June 2018 and October 2018, and October 2018 and February 2019 can be found. For clarity and the understanding of the image to the reader three (coast)lines are plotted: The blue line shows the coastline before construction of the breakwater started, the green line shows the location of the coastline just before construction has finished and the pink line shows the coastline in December 2018. Notice that the pink line not only contains the coastline, but also the contours of the groyne and the harbour basin (how these (coast)lines are obtained is explained in detail later). The boundaries of the coverage of the surveys is shown with grey dashed lines. The colorscales have been set equal for all images. Red is used to show sedimentation and blue for erosion.

The image in figure 3.6 shows the survey of June 2018 and February 2019, which are the first and the last survey. As said before, this image gives the most information as it contains both the emerged and the submerges areas of the breakwater. In this image the large amount of erosion at the eastern part of the breakwater and

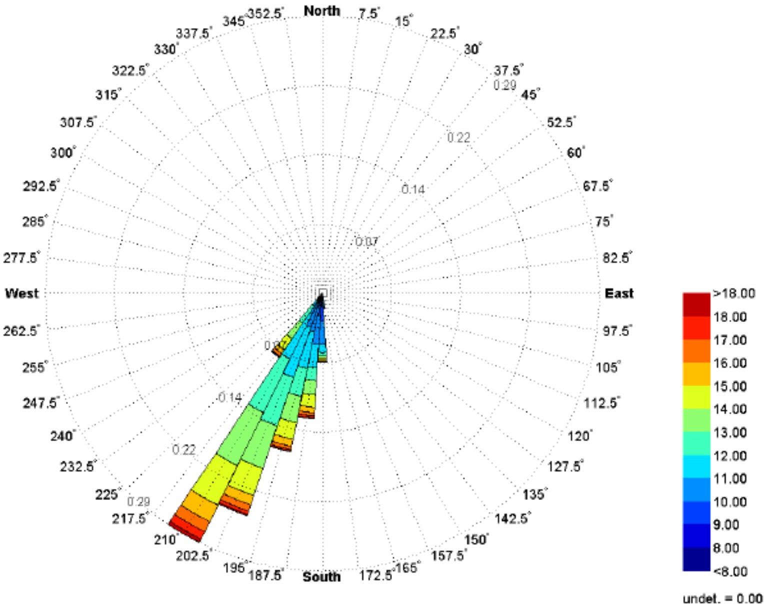


Figure 3.5: Wave rose showing the variation of the wave direction with the corresponding peak period in seconds.

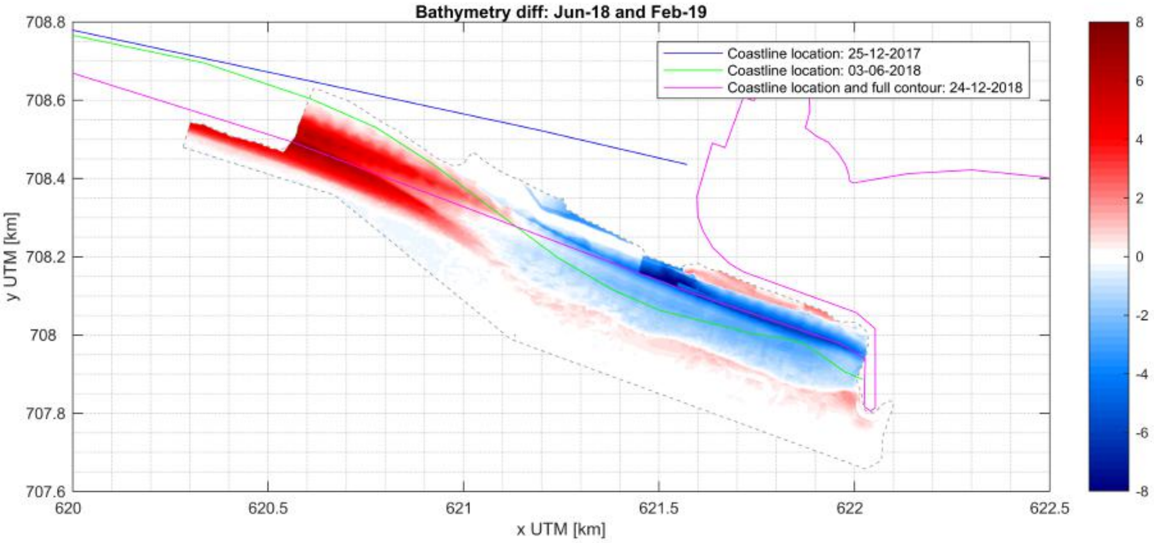


Figure 3.6: The change between the survey of June 2018 and February 2019. The colorscale indicates the amount of accretion or erosion in meters; accretion in red, no change in white and erosion erosion in blue.

the accretion at the western part is clearly visible. Up to 8 meters of sedimentation and erosion in the vertical can be seen. At around xUTM=621.2km the transition between erosion and sedimentation is visible. In this image some strange shapes can be distinguished: The dark blue shape around 621.5km xUTM - 708.2km yUTM is an artificially created elevated area of sand. This area has eroded between the two surveys, hence the amount of erosion for that location is larger than the surrounding area.

Then the two pointy shapes at the right part of the sedimentation area (620.8-621.1km xUTM); Where do they come from? Why does the sedimentation have a shape like that? The answer became clear when analysing the cross-sections shown in figure 3.7. The first four graphs show how the cross shore profile has changed between June 2018 and February 2019 for four different location in the accretion area. The graphs have been

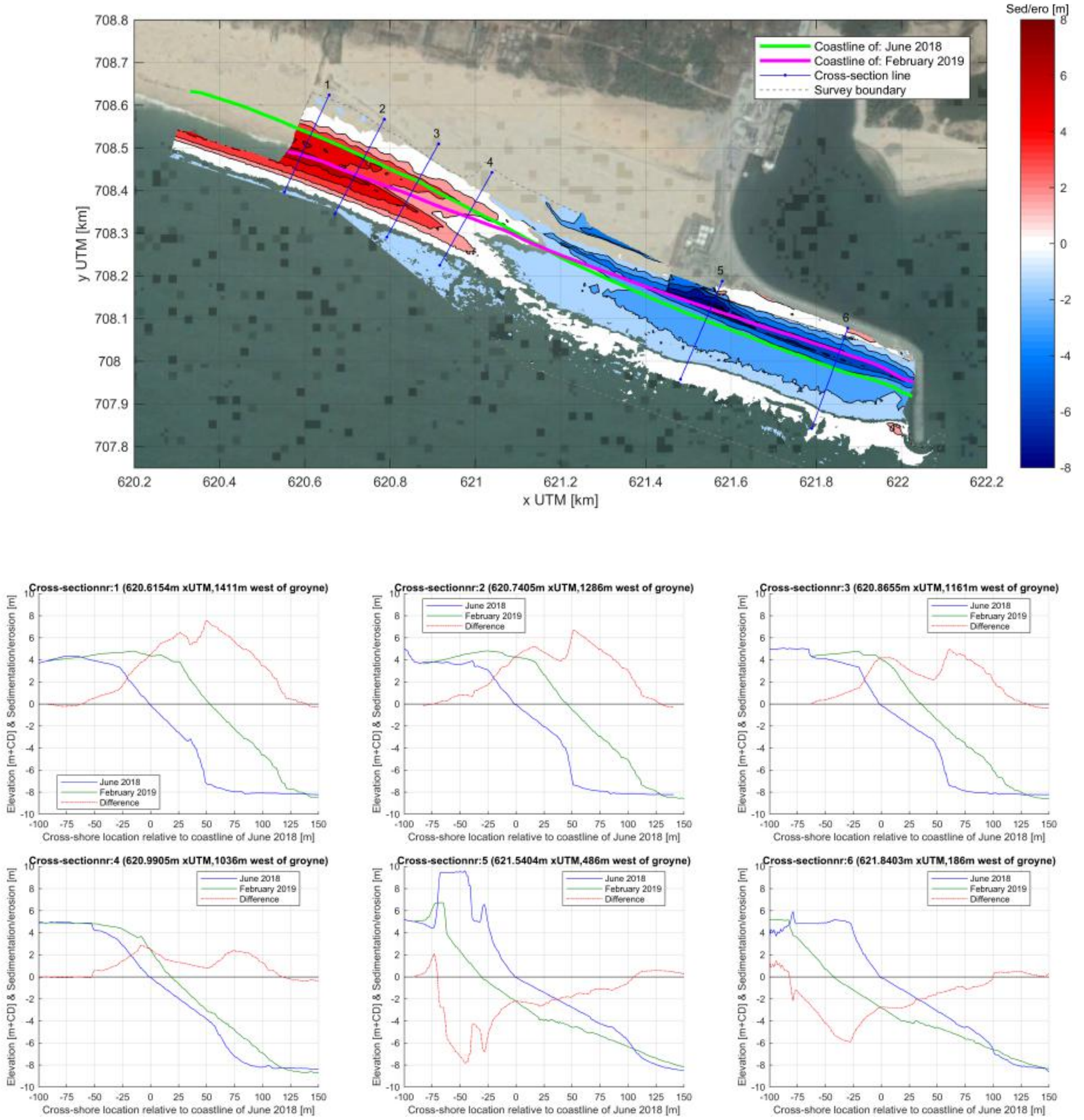


Figure 3.7: Cross-sections on six locations between 1411m and 186m west of the groyne (620.6-621.8km xUTM). 1 to 4 show the the accretion area showing the pointy shapes. 5 and 6 Show the cross sections for the erodes part of the breakwater. The upper image shows the cross-section (1 to 6). In blue the cross shore profile at June 2018 can be seen. In green the profile of February 2019 and in red the difference between those two.

made by extracting lines from the surveys which are perpendicular to the coastline (See blue lines in the upper image of figure 3.7). The lines are 250m long and run from 100m onshore to 150m offshore relative to 0mCD. The pointy shape of the accretion pattern can be seen back in the fact that there are two peaks in the difference plots. These peaks are the result of the change of the slopes of the cross shore profile. In June the slopes were steeper in the lower range of the profile (-8 to -3.5m) than in February. This is due to the fact that these slopes are artificially created, as these are the slopes constructed by the nourishment. In February the slope has been adapted to the wave climate and a more uniform profile is created. The difference in slope between the two surveys creates the distinct shape of the sedimentation.

Coastline development

The coastline development is analysed to give a detailed overview of how the sand of the sandbar breakwater is (re)distributed by the waves during its first year; how the coastline has adapted to the wave conditions. First it is shown how the coastlines are extracted and created from the aerial images and the surveys. Then the coastlines at different time steps are analysed based on the difference with the initial situation just after construction. This will show how the coastline changed over time. Then the cross shore coastline change over the entire breakwater length is compared between several measurements. Lastly the coastline information is used to determine the evolution of the coastline orientation. This will show whether or not using the equilibrium orientation of 200 degN. is a valid choice for the design of the breakwater.

The coastline evolution is analysed by using both aerial images and surveys. The coastlines from the surveys are extracted by selecting the coordinates of locations which have an elevation of 0mCD. The information being on an equidistant grid (1x1m), made this coastline very irregular, which is not realistic. This has been smoothed by using the Matlab Polyfit function, as only a moving average did not smooth the coastline enough and many points at the boundaries were lost when increasing the number of points to average over. The results of the application of the moving average and the polyfit can be found in appendix D. The coastlines from the aerial images have been manually selected by following the coastline in Google Earth. This kind of selection introduces two uncertainties concerning the exact location of the coastline: 1) The time at which the pictures are taken is not known (only the date is known). This can introduce an error between the coastlines as the water levels can be different. With a natural slope of 1:25 for that area, a meter in water level difference could mean 25 meter of 'coastline change'. And 2) The location of the waterline is manually selected on the basis of the waterline. This waterline is influenced by the running up of waves and is therefore difficult to locate exactly. The coastlines can be seen in figure 3.8. While selecting the coastlines in Google Earth a difference of 9 meters in coastline location was seen at a location updrift of the area influenced by the breakwater. The coastline of December 2018 being 9 meters more seaward than the coastline of March 2018. This 9 meter will be taken into account for doing later sediment volume calculations.

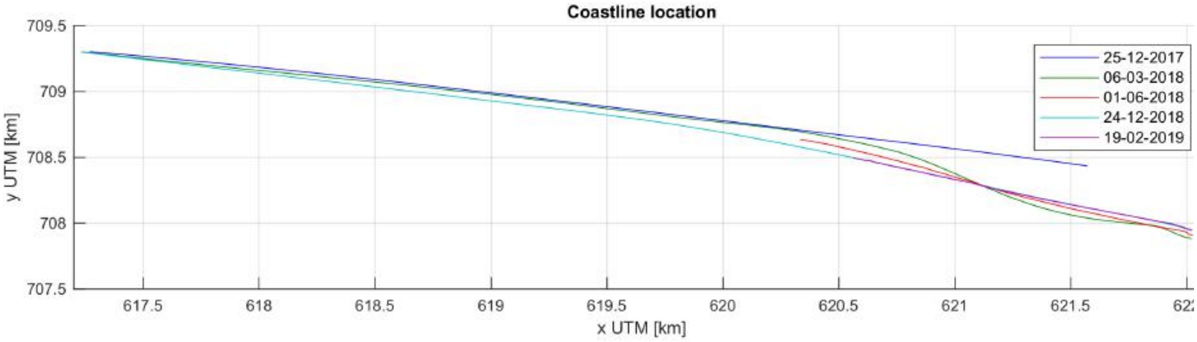


Figure 3.8: Coastlines extracted from the surveys and the aerial images. At 622km xUTM the groyne is located.

When looking at figure 3.8 several phenomena are notables: Firstly, considering the data availability: The coastlines extracted from the surveys show only a relatively small part of the total accreted area, however the aerial images cover the entire area of influence. Then considering the analysis of the available data: The coastline seems to be rotating around one point at 621.1km xUTM, 708.3km yUTM (rotation point). East (to the right) of this rotation point the coastline has retreated. West of the rotation point the coastline has accreted. Between March 2018 and December 2019 a very clear difference in longshore coastline shape is visible: The initial shape, consisting of the sandbar and the connection of the sandbar to the original coastline, has two bends in it. One near the narrow sandbar part (621.2km xUTM) and the other one connecting the breakwater to the existing coastline at 620.7km xUTM. These bends are gone in December and a smooth continuous coastline has formed. How much erosion and sedimentation was needed for changing the shape like that is partly shown in figure 3.9. This figure shows the coastline movement in cross shore yUTM direction between several selected coastlines.

Again it is clearly visible that the coastline has rotated around one point at which the coastline did not move at all during the first year: This graph confirms that there is a rotation point at 621.1km xUTM. This location is about in the middle of the coastline stretch connecting the original coastline with the narrow sandbar part

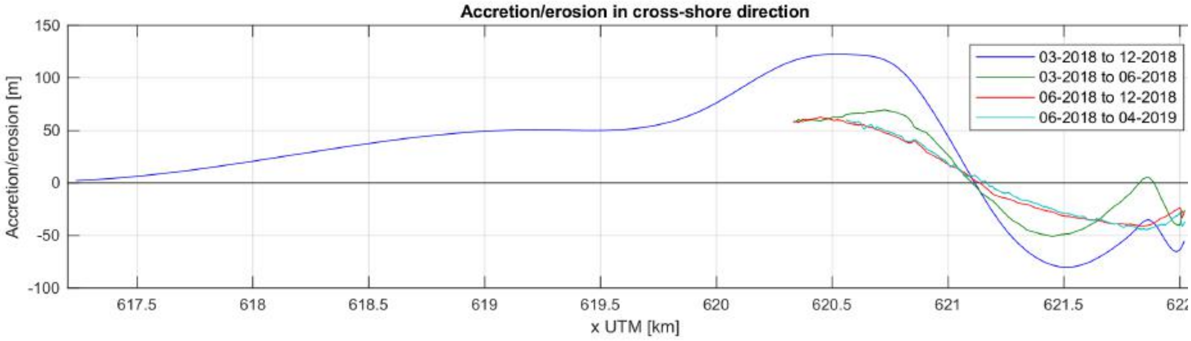


Figure 3.9: The change between several sets of coastlines in horizontal yUTM direction. A positive value indicates accretion (coastline has moved seaward) and erosion is indicated by a negative value.

of the breakwater. Two new phenomena can be learned from this graph: The first one being the amount of accretion and erosion in cross shore direction between March and December: A maximum of 80 meters of coastline retreat is measured at 621.4km xUTM, which is exactly the location where the narrow sandbar part connects to the stretch of coastline connecting it to the original coastline. A maximum amount of 120 meters of accretion in cross shore direction can be seen in the same period further updrift at 620.5km xUTM. Secondly the graph shows that most of the coastline development has occurred from 03-2018 to 12-2018, as the graphs of 06-2018 to 12-2018 is (almost) identical to 06-2018 to 12-2018, little to no change has occurred from December to February. This can be either the result of seasonality of the wave climate, the adaptation of the coastline to the wave climate or a combination of both. One of the most important erosion values is the value of the erosion on the narrow part of the sandbar breakwater. As the width of the breakwater can not be seen clearly on the images shown before, figure 3.10 is created using Google Earth. It is a detail of the aerial image shown in figure 3.1 taken at 24-12-2018. The minimal width of the breakwater, at around 621.9km xUTM, is 90 meters at this time. As almost no change was visible between this image and the survey of February it can be assumed that this value was about equal for February 2019. Although the width is smallest at this location, this is not the location with most erosion. Around 50 meters of erosion happened at this location, which is 70 meters less than at the location of maximum erosion.

Figure 3.10: Detail of the sandbar at 24-12-2018. The red line indicates the narrowest part of the breakwater at around 90 meters from water to water.

Depiction of coastline development

Based on the discussed coastline change a simple representation of the development of the sandbar breakwater during its first period after construction is made. These images show how the coastline develops from the coastline as it has been constructed to the smooth and continuous coastline as it is after adjustment to the wave climate. Note that no seasonal variability is taken into account, just a continuous wave direction. Figure 3.11 shows this representation. The sandbar breakwater is simply depicted as the light brown expansion of darker shaded coast into the sea. The groyne is depicted as a bold blue line. Sediment transport directions and an indication of the rates is shown by means of arrow direction and size respectively. The first image (number 1) shows the situation just after construction has finished. Sediment transport updrift (to the left of the breakwater) is directed in downdrift direction. Due to the angle of the coastline indicated by square A the sediment transport is directed to the left at this location. This transport creates erosion at the intersection of this coastline stretch with the start of the sandbar (indicated by area B). In the image number 2 one can see the development after some time. The right to left transport in area A in combination with the longshore sediment supply from the left make that sediment is starting to build up in the corner between the original coastline and the breakwater (area C). The right to left transport in area A still creates erosion at the corner between area A and the sandbar as can be seen in area B. Then another time step later, image 3 shows the result of the longshore sediment supply and the right to left transport in area A: A smooth coastline is created. Sediment transport rates are now small but in downdrift direction for the entire breakwater, ensuring a slow but steady seaward coastline movement. The fourth image shows the breakwater after some time when the coastline has moved seaward by the constant longshore supply of sediment. For the Lekki situation the follow estimated timestamps can be given to the images: 1. at T=0, 2. at T=4 months, 3. at T=10 months and 4. at T=16+ months.

Coastline orientation

The design of the Lekki sandbar breakwater is based on the an expected equilibrium orientation which should be reached under the influence of the prevailing wave direction. To check whether or not this design criterion is valid, the coastline orientation is analysed. The orientations corresponding to the coastlines of figure 3.8 are calculated using the central difference method. The result is plotted in figure 3.12. The orientations of all aerial images and surveys are plotted in degrees North. The orientation is the direction perpendicular to the coastline; e.g. if the coastline is running from west to east, the coastline orientation is 180 degrees North. The (expected) equilibrium orientation of 200 degN (Poortman and van der Spek, 2017) has been plotted to show as a reference.

The first orientation after construction (06-03-2018) shows large fluctuations; a maximal value of 225 degN and a minimal value of 187 degN. However with time, these fluctuations dampen out. The most recent coastline of 19-02-2019 (Note that this coastline is equal to the coastline of 24-12-2018) has moved to a maximum value of 203 degN and a minimal value of 198 degN at the part of the breakwater which is not influenced by the presence of the groyne at the breakwater tip. Near the groyne, the orientation of the coastline has a maximal value of 210 degN and does not seem to have changed after 01-06-2018. The influence of the groyne is visible to around a distance of 150m west of the groyne, indicated by no to only little change in the coastline location and orientation.

The orientation of the coastline being different near a groyne is something that could be expected due to the effects of refraction and the sheltering of waves. It can therefore be concluded that at this moment, for the part of the breakwater uninfluenced by the groyne, the coastline of the sandbar breakwater is moving towards a coastline profile with a unidirectional orientation. The orientation lies between 198 en 203 degN, which includes the expected equilibrium coastline orientation of 200 degN.

Cross section development

The development of the cross shore profile has been discussed briefly before (figure 3.7). The cross shore profile in June 2018 contained a steep part which was flattened out in the cross shore profile of February 2019. So, the slope seems to have become less steep over the last year. This section will discuss the development of the cross shore profile in more detail. Are the cross shore profiles in February 2019 the equilibrium profiles? Or will the profiles keep on changing?

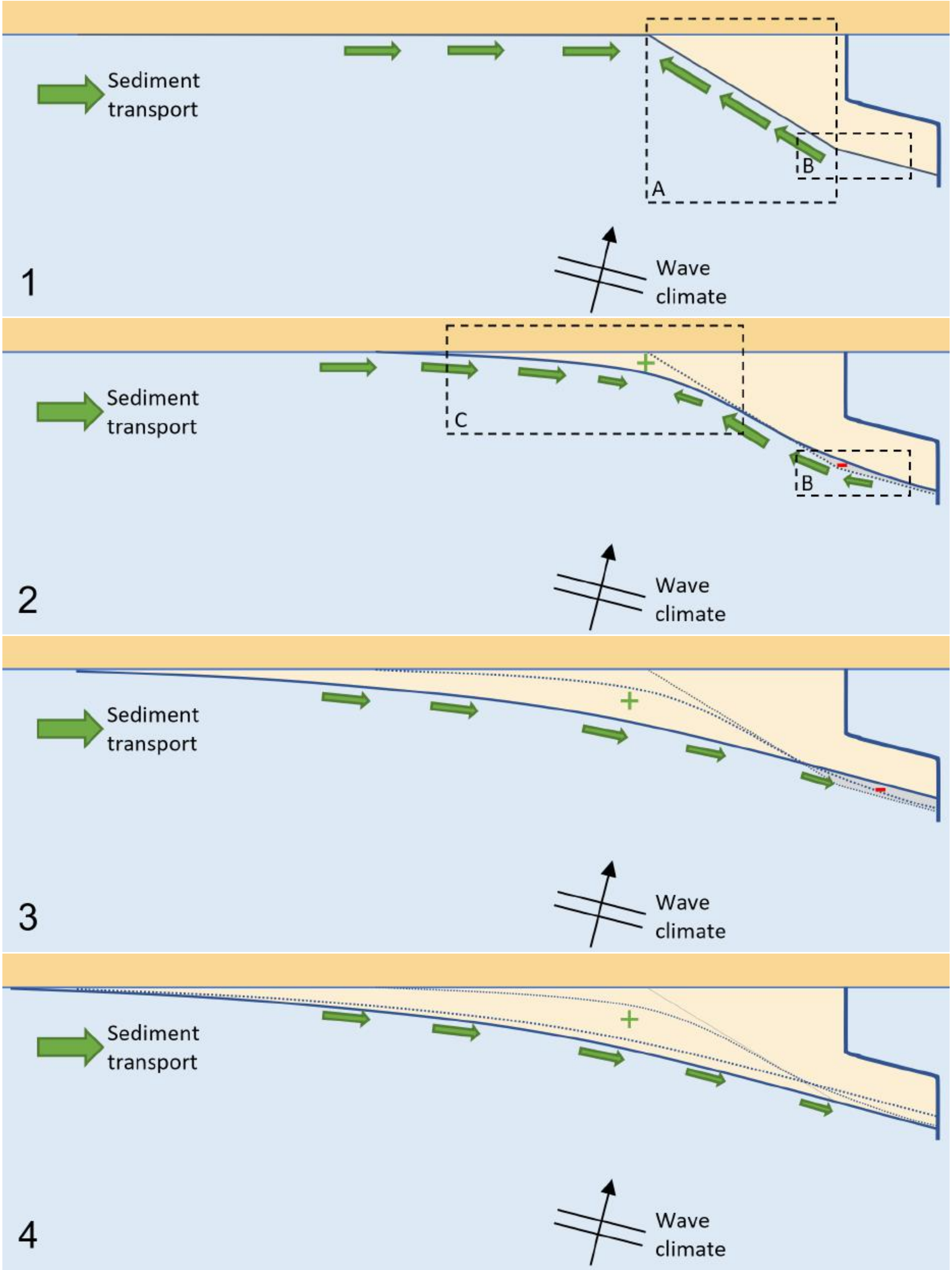


Figure 3.11: Sketches showing the coastline development of the sandbar breakwater at Lekki over time. Longshore sediment transport directions and an indication of the rate is shown by means of the direction and size of the green arrows respectively. The coastline location is indicated by a continuous light blue line and previous coastlines by dotted blue lines. Image 1 shows the initial situation, just after construction is completed. Image 2 shows a step in between the initial situation and a smoothed and continuous coastline profile, as shown in image 3. In image 4 the situation after even more time, when the entire coastline has moved forward due to the longshore sediment supply, can be seen.

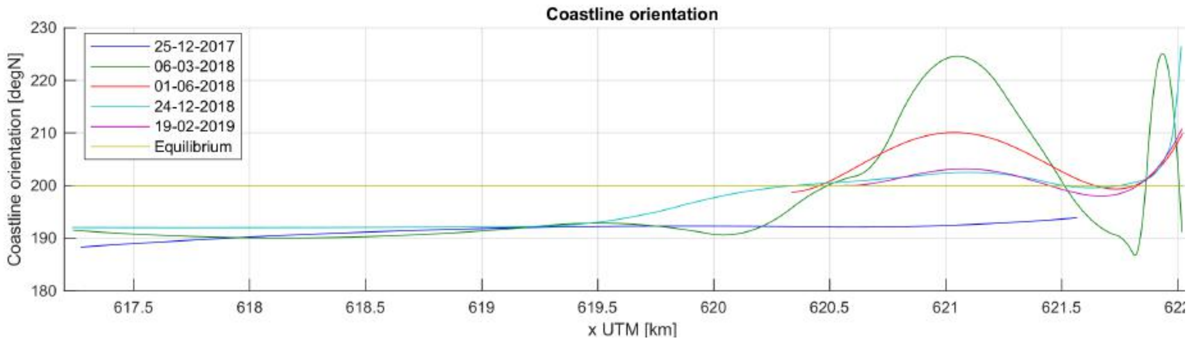


Figure 3.12: The change of the orientation of the coastlines. In yellow the equilibrium orientation has been plotted. Note that the coastline orientation is the direction of the shore normal.

(Bruun, 1954), (Dean, 1991) and (Pilkeyt et al., 1993) proposed a method to determine the dynamic equilibrium cross shore profile for sandy beaches. This method is used to calculate the equilibrium profile for the coastline at Lekki. Pilkeyt et al. (1993) states the method as follows:

$$h = Ay^{\frac{2}{3}}$$

where

$$A = 0.067 w_s^{0.44}$$

and

$$w_s = \frac{(s-1)gD^2}{18\mu}$$

in which h is the water depth at a given location in the cross section; y. A is a scaling parameter determined by the sediment falling velocity. s is the relative density, g the gravitational constant, D the sediment size and μ the dynamic viscosity of water. The following values for the parameters are used: μ=1e-6m^2/s, g=9.81 m/s^2, D=d$_{50}$=600μm, ρ_w=1025kg/m^3, ρ_s=2650kg/m^3 and s=ρ_s/ρ_w. To show the correspondence of the cross shore profile at Lekki to the Dean profile, profiles created for every 100m in longshore direction have been made for the surveys of June 2018 and February 2019. An average profile for both surveys is made to show the difference between these two. All profiles have been shifted such that 0mCD is at the same location. The result can be seen in figure 3.13.

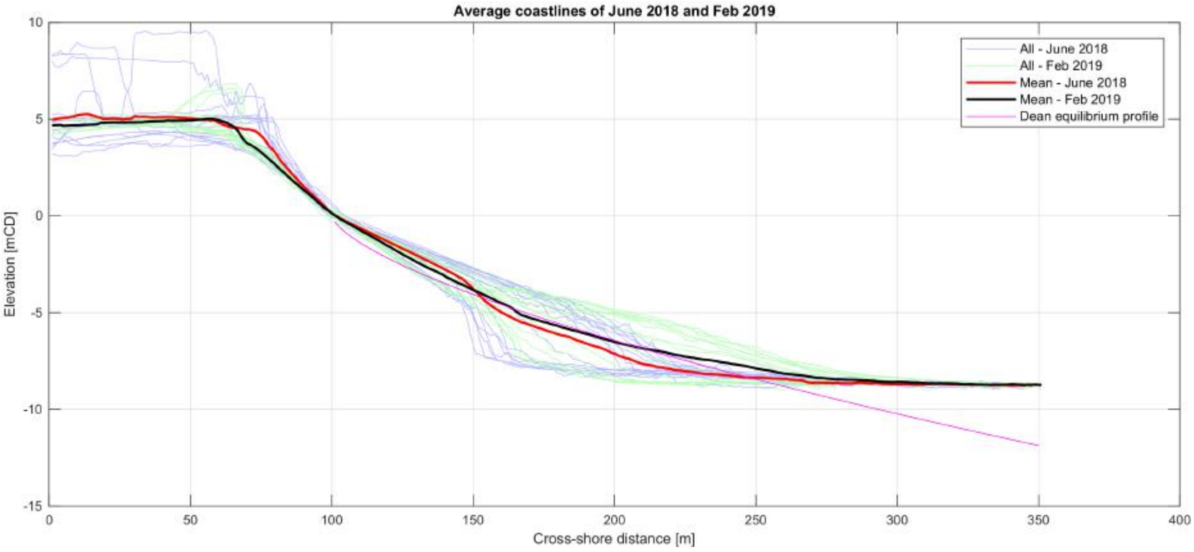


Figure 3.13: Comparison of the cross shore profiles every 100m of coastline of June 2018 and February 2019.

From the figure it becomes clear that on average the cross shore profile has become less steep as many of the green lines of February 2019 are above the blue lines of June 2018. The profile moves from a slope of about

1:10 for the red lines to a slope of about 1:25 for the green lines. The Dean equilibrium profile (Pink line) shows a reasonable similarity to the average profile of 2019. In the region from 100 to 150m in cross shore direction (-3 to 0 mCD) the Dean profile is lower than the actual profile. From 150 to 220m in cross shore direction the Dean profile is equal to the average profile of February 2019 and from 220 seaward the Dean profile starts deviating from the average profile in downward direction. Also the upper green profiles show a slope which is in agreement with the slope of the Dean profile.

Based on figure 3.13 and the Dean profile it can be concluded that the average profile of February 2019 is in reasonable agreement with the Dean profile. However the average profile is a combination of different slopes. Because of a part of the coastlines being significantly flatter in February 2019 than in June 2018, it is expected that the other coastlines, which are still relatively steep in February 2019, will continue to flatten. The upper green lines (which show a uniform slope in cross shore direction) are expected to have reached an equilibrium state and to not change significantly as the slopes are similar to the slope of the Dean profile.

Sedimentation and erosion volumes

The sedimentation and erosion volumes can give insight in the movement of sediment in the domain of the sandbar breakwater and also the interaction with outside the domain. The domain being the area which has been influenced by the morphological development of the breakwater. With this analysis several assumptions about the Lekki breakwater can be checked: Is there really no bypassing? Is the natural supply of sediment 650.000-900.000m^3/year?

Two methods are combined to create an as accurate as possible sediment balance. First the sedimentation and erosion volumes will be determined using the surveys. The surveys showing only a part of the total area of influence, means that more information is required to create a sediment balance for the entire area of interest. Therefore the coastlines from the aerial images are used to estimate a total sedimentation and erosion volume.

When the horizontal area of the erosion and the sedimentation is determined using the aerial images, an average height is needed to calculate a volume. This height is estimated using two methods: The first method being the usage of the closure depth by Hallermeier (1981), which is the largest depth at which waves influence the bottom. For the second method the average height is calculated by using the surveys.

The Hallermeier-equation (Hallermeier, 1981) is used to calculate the closure depth. This equation uses the significant wave height occurring or being exceeded 12 hours in a given year in combination with the corresponding wave period to calculate the closure depth. The 12 hour significant wave height is calculated by sorting the wave heights from the 27 year wave climate data set in descending order. The data-set being 27 years long and containing an entry for every 3 hours, means that the first 27*12/3=108 values are taken to determine the 12 hour per year wave height. The 108 highest values of H_s are averaged resulting in a height of $H_{s,12years}$=2.5m. The corresponding period is T_p=11.6s. This results in a closure depth of h_{cl} ≈5.5m relative to the lowest water level elevation (LAT). LAT being equal to CD means that the closure depth is at -5.5m CD. In figure 3.13 it can be seen that the height of the profile is around +5mCD. This results in a total 'active' height of 5.5+5=10.5m. This value is checked by means of the surveys.

As can be seen in the lower image of figure 3.6 and also mentioned before, the area of influence is only included partly in the survey. The sedimentation area (west of 621.2km xUTM) is therefore disregarded. The erosion area (621.2 to 622.2 xUTM) is fully included and is therefore used to determine an average height of the erosion. The area of the eroded part is calculated by determining the area between the coastlines extracted from the surveys. The volume is determined by calculating the volume of the area east of 621.2km xUTM between the surveys as shown in figure 3.6. The resulting area is 24.411m^2 and the volume is 298.180m^3. This results in an average height of the erosion of 12.2m.

The value for the erosion as calculated by using the surveys and the value calculated using the closure depth differ by 1.7m. Both values seem reasonable when comparing them to cross-sections of 3.13, therefore the average value of 11.4m for the sedimentation height is chosen.

The total sediment balance is now calculated using the average height for the sedimentation and the sedimentation and erosion area between the coastlines of the aerial images (while taking into account the 9 meter offset). Of course also the nourishment should be taken into account: During the 10 days after the aerial image of 06-03-2018 was taken an amount of 250.000-350.000m^3 of sediment was placed on or near the breakwater. The average value of 300.000m^3 is subtracted from the total sediment balance. The results of the calculations can be seen in table 3.4.

Sedimentation height	11.4m	
	Area [m^2]	**Volume [m^3]**
Sedimentation	+190.500	+2.200.000
Erosion	-51.000	-580.000
Total	+140.000	+1.600.000
Nourishment	+25.000	+300.000
Total natural supply	**+115.000**	**+1.300.000**

Table 3.4: Sedimentation and erosion areas and volumes. Volumes are calculated using the sedimentation height.

An approximate amount of +1.3Mm^3 of sediment has been added to the domain. The corresponding accreted area is 115.000m^2. Poortman and van der Spek (2017) concluded that the amount of longshore transport would be in the order of magnitude of 650.000-900.000m^3. The amount of 1.3M m^3 is for the period of 16-03-2018 to 29-12-2018, which is about 9 months. This means that 3 months are missing. These three months however do seem not of significant importance for the morphological change, as can be seen when looking at the almost non existing coastline change between 12-2018 and 02-2019. Which is due to the seasonality of the climate, as discussed in section 3.3.1, and the coastline adaptation to the wave climate. The value of 1.3M m^3 is thus taken as a yearly transport rate. This implies that the calculated value is a factor 1.4-2.0 higher than the value of Poortman and van der Spek (2017). As the amount of longshore transport is hard to measure and therefore to calculate, this difference is relatively small, the values are in the same order of magnitude. The large positive value of the sediment balance in combination with the value being even higher than the value as expected by Poortman and van der Spek (2017), means that it can be said that there has been no bypassing (of a significant amount) during the last year.

Influence of environmental conditions on morphological development

How the sandbar breakwater development is influenced by the environmental conditions is one of the most important aspects to understand. When this development is understood well, one could use it to the benefit of the breakwater design; less sediment could be needed for the initial layout, reducing costs. Or the concept can be applied at locations that first seemed of limits.

The influence of the environmental conditions on morphological development is analysed by comparing the temporal development of the breakwater with the seasonal variability of the environmental conditions. The temporal development can best be illustrated by the coastline change as shown in figures 3.8, 3.12 and 3.9. These graphs show a lot of change for the period from March to December 2018 and no to little change for December 2018 to February 2019. The morphological change being more significant during the months between June and October than between October and February can also be seen in the surveys (figure 3.6),

It is already mentioned that most sediment transport, and thus morphological development, can be expected in the most energetic wave periods, which are the months of June, July and August. No to little development is expected in the periods of low energetic waves; December and January.

The scarcely available temporal data on the morphological development of the breakwater makes it impossible to be 100% sure about the influence of the different wave characteristics on the morphological development. However, when combining the temporal development and the seasonal variability of the environmental conditions, it seems to be so that the wave height influences the morphological development of the breakwater, as the period of high energetic waves overlaps with the period in which most morphological change has occurred. During the remaining period of the lowest wave height no morphological development is visible. Not only the amount of wave energy, but also the coastline already being adapted to the wave climate can be seen as a reason for the lack of morphological development. Which one of the two the main reason is, can not be determined based on the available data.

The variability of the peak period does not coincide with the morphological change, however it can not be concluded whether or not the period influences the morphological development based on the available data.

For the wave direction the same reasoning as for the peak period applies; There is too little temporal data of the morphological development available to proof whether or not the morphological development of the breakwater is influences (significantly) by the wave direction.

3.4. Discussion

Although a lot can be learned from the available data, the amount of data is scarce. When for example a larger area of the breakwater would have been covered during measurement or more temporal data would have been available a better insight into the temporal development as well as a better estimate of the total transport rates could be made.

The long periods between measurements also made it not possible to asses the impact of short term events (e.g. duration of days). Storms, like the storms in the Netherlands, are not present at Lekki; the wave climate is dominated by swell. The morphological development will thus be relatively slow. Secondly, the aerial images and the bathymetrical surveys are snapshots; It could be that the maximum amount of coastline retreat was more that the amount seen in these snapshots. However the wave climate being relatively calm makes it fair to say that the difference could not have been significant.

During the data analysis the cross shore development has been discussed briefly: The unnatural cross shore profile adepts to the wave climate by becoming less steep. This has some effect on the location of the coastline location as sediment moves from the upper part of the cross section to the lower part. The majority of the coastline change is however the result of the LST, as the cross shore profile has already moved towards the equilibrium (Dean) profile in June of 2018. It is assumed that the cross shore displacement of sediment will be smaller when that profile is reached. As the coastline still changes significantly after that period, it can be concluded that LST has a lot more influence on the morphological development than the cross shore transport.

3.5. Conclusions

In this chapter the morphological development and the environmental conditions of the Lekki breakwater are researched to answer the first research questions:

How did the sandbar breakwater at Lekki develop during its first year under the influence of the (ideal) wave climate?

1. What morphological developments of the sandbar breakwater are observed?
2. What influence did the wave climate have on the morphological development?
3. Based on these observations, what is expected to be the future development?

In the first four paragraphs question 1a and 1c are answered by means of the discussion of the overall development of the breakwater, and erosion and accretion quantities in both longshore and cross shore direction (question 1a and 1c). Then the influence of the wave climate on the breakwater is discussed (question 1b).

The sandbar breakwater development is characterised by the coastline of the breakwater adapting to the wave climate. The initially created layout (the layout constructed by Boskalis) starts eroding at the western corner of the sandbar, indicated in figure 3.11 by area B, as the waves impose a sediment in western direction at the stretch of coast connecting the narrow sandbar to the original coastline. At the same time an eastward direction transport updrift of the breakwater supplies sediment towards the breakwater. The combination of these two transport results in (i) accretion at the intersection between the original coastline and initial breakwater coastline and (ii) erosion of the sandbar. This process continues: Sediment is supplied from the West and the sandbar (slowly) erodes. This is the state the sandbar breakwater has reached at February 2019. From this moment on no more erosion of the sandbar is expected due to the process described above. Sediment will continue to be supplied to the intersection of the newly accreted land and the original coastline, this will result in a rotation of the coastline in counter clockwise direction at that location, in turn resulting in sediment transport towards the groyne. This process will continue until the end of the groyne is reached. This development is clarified by means of images in figure 3.11.

The coastline development is characterised by a maximum amount of coastline retreat of 80 meters. This is however not on the narrow sandbar part but just west of the sandbar as indicated by area B in figure 3.11. The minimal width of the breakwater is measured at the last measurement (February 2019) and is around 90 meters at a location 100m West of the groyne (622.0km xUTM). This equals to about 50 meters of coastline retreat for that location. Updrift of the initial layout of the breakwater the coastline has moved seaward by as much as 120 meters. Interesting to note is the rotation of the coastline in the horizontal plane around the point: 621.1km xUTM, 708.3km yUTM.

An analysis of the cross shore profiles shows the profiles to adapt to the wave climate by changing from a steep slope (1:10) to a more natural slope (1:25).

The yearly LST rate is estimated by means of the available data. A value of 1.3Mm^3/year was the result. This value is a factor 1.4 to 2 higher than the value range used for the design of the breakwater by (Poortman and van der Spek, 2017).

The Lekki wave climate is characterised as a unidirectional narrow bandwidth climate; the wave direction only varies little around the mean value. This mean value (202 degrees North for 2018) is such that very little variation in the LST direction is present. This in turn results in a steady adaption of the breakwater to the wave climate. The orientation of the coastline has moved from a range of 187-225 degrees North for the coastline just after construction has finished to a range of 198-203 degrees North. The average wave angle of 2018 lies inside this range, indicating how important this measure is. This value is also very close to the value of the equilibrium profile used by (Poortman and van der Spek, 2017) of 201.5 degrees North.

4

Wave climate sensitivity analysis

In this chapter the sensitivity analysis to research the influence of the wave climate on the morphological conditions of the sandbar breakwater is presented. This analysis is performed to answer research question number 2a and 2b, which are:

2. *How sensitive is the sandbar breakwater concept in general to variations in the wave climate?*
    (a) *Which direction related wave climate variations are of significant influence on the Lekki sandbar breakwater development?*
        i. *What is the effect of the mean wave direction?*
        ii. *What is the effect of the directional variation?*
        iii. *What is the effect of the event sequence?*
    (b) *Is a unidirectional narrow bandwidth wave climate necessary for the Lekki sandbar breakwater to become stable?*

The main question, question 2 and 2c are answered later in the discussion and conclusions chapter.

The main goal of this analysis is to quantify the influence of the wave climate on the morphological development of the sandbar breakwater. The development of the basin and downdrift area exceeds the scope of this research. This study will help to improve the understanding of the development of the sandbar breakwater concept and with that improve future designs. The sensitivity study is performed by using a one-line coastline model which is calibrated using the data gathered during the data analysis. The calibrated model is then run again using slightly altered versions of the original Lekki wave climate. The differences in morphological development are compared to the morphological development belonging to the original wave climate. As differences in the wave climate impose differences in transport different movements of the coastlines are expect. The maximum amount of coastline retreat is used as the main measure to quantify the influence of the wave climate alterations. The maximum coastline retreat in time will indicate what kind of buffer is needed to be able to withstand the initial phase after construction, as this is the moment when maximum coastline retreat will occur.

4.1. Method

In this section it is discussed why a one line coastline model is used and how it is set up. Secondly the three types of alterations made to the wave climate are discussed.

4.1.1. Model choice - Unibest

For predicting and evaluating morphological development in coastal zones usually computational models are used. For this study two model types have been considered; 1) a one line coastline model and 2) a process based 2D-H model. Both models have their advantages and disadvantages. In the following paragraph the two model types are discussed shortly.

The one-line model is a relatively simple model, which, as the name suggests, models the coastline as one line. The coastline is then split in grid cells with a specified longshore length. A bulk transport formula is then used to calculate the sediment transport rate per grid cell based on: the wave conditions, the orientation of the coastline, and, sometimes, the sediment characteristics. Differences in transport rates between the grid cells then determine the morphological change. This process is repeated for pre-defined time steps. The wave conditions are imposed by means of a time series of the wave height, wave period and wave direction. The process based 2D-H model is more complicated. For this model the basis is a 2D grid in the horizontal plane. The bathymetry is included as the elevation of each grid cell, hence the entire coastal area rather than just the coastline is included in the model. Boundary and wave conditions are imposed on the model. Based on these conditions flow velocities are calculated for all grid cells which are 'wet'. By using the flow velocities the sediment transport and in turn the morphological development is calculated. Each of these steps; flow calculation, sediment transport and bottom change is repeated for each grid cell for each step in time. The main advantage of the process based model is that more coastal processes can be included and the model results include the morphological development of the entire coastal area rather than just the coastline. An example of such a process is temporal and spatial building up of longshore transport around structures like groynes inducing a discontinuity in longshore transport. The main disadvantage is its complexity and the computational effort (time) required to perform the calculations.

For this study the focus is put on the morphological development of the unique and characteristic part of the sandbar breakwater only. As can be seen in chapter 3 (data analysis) this development can be summarised well by just looking at the coastline change. Therefore tests have been performed with the one-line model Unibest to assess its applicability and accuracy for this problem. Calibration of the model for the Lekki wave climate indicated that a good representation of the real life situation can be achieved by the model. Therefore the one-line model is chosen rather than the 2D-H model.

4.1.2. Unibest

The one line model used is Unibest (short for Uniform Beach Sediment Transport). Unibest is a software package developed by Deltares for simulating longshore and cross shore process and related morphodynamics of beach profiles and beach planform shaped (coastline evolution) (Kramer, 2005). For this research the Unibest-CL module is used. It consists of two sub-modules: The Longshore Transport (LT) module and the CoastLine module (CL). The LT module first transforms the offshore waves to nearshore by using a linear wave propagation module by including processes like refraction, breaking, friction and shoaling. Then the longshore transport rate is determined. The CL module uses this transport to calculate the coastline evolution for each time step.

The CL module calculates coastline changes due to longshore sediment transport gradients of an alongshore nearly uniform coast, on the basis of the single line theory (One line model) (Kramer, 2005). It is possible to include groynes, breakwaters, sinks and sources, and revetments.

4.1.3. Modelling plan

In short the modelling plan is as follows: First the model is setup and calibrated for the original Lekki case. Then alterations are made to the original wave climate and the model is ran again using the new, altered, wave climates. Setting up and the calibration of the model is discussed in the next section. The wave alterations are discussed in detail later.

4.2. Model setup and calibration

The Unibest model is set up and calibrated for the original Lekki situation. The starting point is the aerial image of 6 March 2018 (first image figure 3.1) and at the end of the run the coastline should follow the coastline as can be seen in the aerial image of 24 December 2018 (second image of figure 3.1).

The model set up and calibration consists of several iterating steps:

1. Setting up the LT module
2. Setting up the CL module
3. Running the model
4. Validating the results
5. Depending on the results go back to step 1 or 2 to change the setup and rerun the model using the new settings.

4.2.1. Longshore transport module

The setup of the longshore transport module consists of four input types: Transport formula, cross shore profile, wave parameters and wave/current information.

Let's first discuss the longshore transport formula. Unibest offers four formulae for calculating the longshore transport rates, all of these functions are so called bulk transport formulae: CERC (1984), Bijker (1967, 1971), van Rijn (1992) and van der Meer/Pilarczyk (which is for coarse material). All three methods for sand are considered and have been tried out. The CERC method has the main advantage over the other two methods that it is simple and fast to use, as it does not depend on as much variables. Only a calibration parameter, a breaker coefficient and the seawater density need to be given. All three methods were tested during calibration and CERC could be calibrated the best to fit the Lekki breakwater development. Also, CERC can only be used when the effect of ambient currents (generated by for example tide or rivers) is negligible, which is the case in Lekki. The calibration is discussed in detail later (section 4.2.3).

Cross shore profile

The wave climate is imposed offshore in deep water. As the CERC formulation requires the wave angle at breaker depth, Unibest has a linear wave propagation module included. It uses the cross shore profile to transform the offshore conditions to nearshore conditions. The cross shore profile is extracted from the survey used in the data analysis and can be seen in figure 4.1.

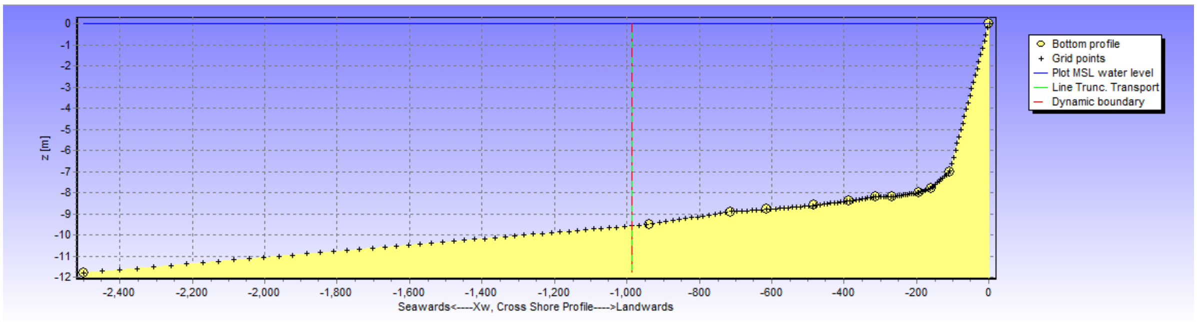


Figure 4.1: Cross shore profile used for the Unibest LT calculations

Wave parameters

Unibest requires several parameters to determine the linear wave propagation; Two coefficients for wave breaking and a value for the bottom friction. The values can be seen in table 4.1. The first coefficient for wave breaking (α_c) is advised to be 1.0 (Kramer, 2005). The second wave breaking parameter (γ) is advised to be 0.5 for a value of H/L close to zero and 0.85 for values of H/L near 0.4. The value has been chosen to be 0.8 during the calibration as this gave the best results. However, for the Lekki wave climate values of H/L close to zero can be expected as waves are long and heights are relatively low, therefore the value of 0.8 found during calibration is on the high side of the spectrum. For the bottom friction f_w and the standard value of 0.01 is used (Kramer, 2005).

Parameter	**Symbol**	**Unit**	**Value**
Coefficient for wave breaking	Gamma	-	0.8
Coefficient for wave breaking	Alfa	-	1.0
Bottom friction	lw	-	0.01

Table 4.1: Wave parameters used for Unibest calculations

Wave/current information

The LT module creates so called 'wave rays' which contain the longshore transport rate belonging to a certain coastline orientation (S/ϕ curves). As the temporal variation of the development of the breakwater over time is expected to be an important parameter, it is chosen to create multiple wave rays from the entire period. A wave ray is created for each week from the start (March 2018) to the end (December 2018), ending up with about 37 rays.

Flow currents are excluded as the tidal elevation is low (see section 3.2.4) and is not expected to have significant influence on the morphological development.

4.2.2. Coastline module

This module simulates the coastline evolution over time using the transport rays from the LT module. The Unibest CL module needs the following input: The initial coastline, definition of the groyne location and boundary conditions at each of the two coastline ends.

Basic model (coastline and groyne)

The basic model consists of the starting situation of the coastline. In this case the aerial image of March 2018 is used as the starting coastline. The model of the coastline is created by following the coastline in the image. In figure 4.2 the result can be seen. The upper figure shows the entire considered area, which is extended 10km updrift and 10km downdrift of the breakwater location. The lower figure shows a detail of the breakwater. Note that the resolution of the grid cells on and near the breakwater, which is the area of interest, are smaller than the grid cells updrift and downdrift of the breakwater.

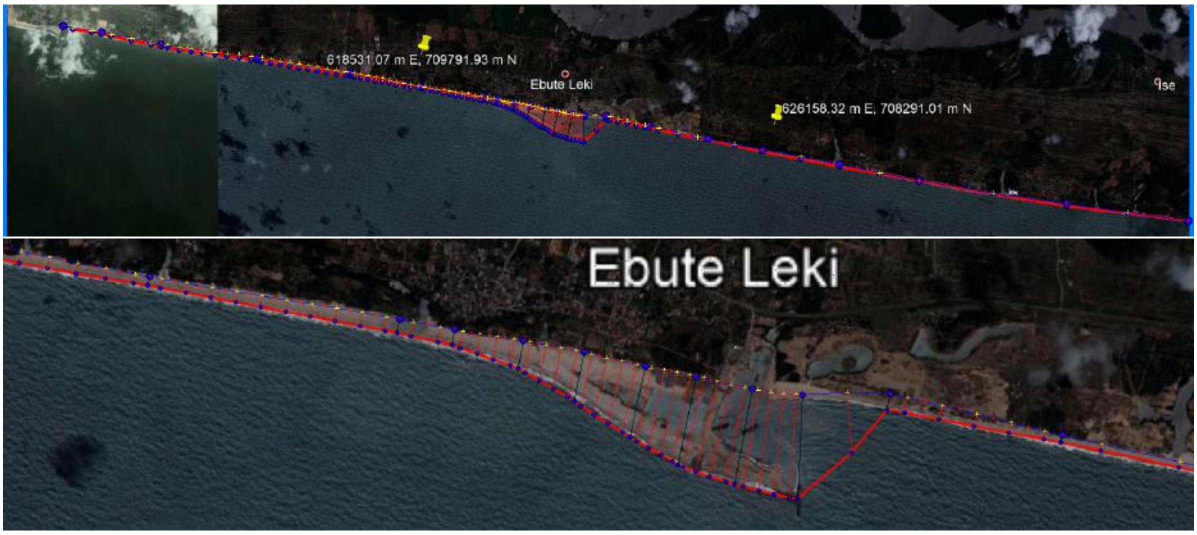


Figure 4.2: Coastline at the start situation as used in Unibest. Lower image is a detail of the breakwater of the upper figure.

Unibest has the option to insert a groyne at one of the cross section in the model, which is inserted at the location of the real life groyne. This groyne can be seen in figure at the breakwater tip. Note that the coastline downdrift of the breakwater (red line) runs from the groyne towards the coast. This is of course not the situation as it is in real life. As Unibest is a one line model, the coast has to continue in one line and it is not possible to include the basin as well. This is however not problematic, as this study only focuses on the development updrift (left) of the groyne. As long as there is no significant accretion on the right side of the groyne, no influence of the downdrift side on the updrift side is expected.

Boundary conditions

At both ends of the coastline a boundary condition needs to be applied. Four options are possible: Constant coastline location, constant coastline angle (imposing constant transport), fixed value of Q, or a value of Q as a function of time. For this study the constant coastline location is chosen rather than the constant angle, as in real life also variations of the transport rate are present.

4.2.3. Model calibration

Calibration of the model is done by finding the model settings for which the coastline evolution calculated by Unibest simulates the real life situation best. The start situation on 6 March 2018 is discussed during the model setup and can be seen in figure 4.2. For the end situation the aerial image of 24 December 2018 is used. This can be seen in figure 4.3. The coastline (red line) in this figure is still at its starting location.

Figure 4.3: The starting situation of the model on March 6th 2018 indicated by the red line on top of the background image showing the desired coastline location at December 24th 2018.

The wave climate used for the calibration and the sensitivity study is the NOAA hindcast wave climate for the corresponding period (6 March 2018 to 24 December 2018). The time series of this climate is shown in figure 4.4. From high to low, the wave height, wave period and wave direction over time are shown. The wave climate is made by transforming the far offshore data from point 6.4N, 4.0E (610592 xUTM,707529 yUTM (zone 31N)) to a point closer to shore (620974 xUTM 707459 yUTM (zone 31N)) by using SWAN. Note that this climate is used rather than the climate used for the data analysis as the WaveClimate database only does yearly hindcasts. The wave date from the start of 2019, which is needed later, is not yet available in that dataset.

In figure 4.5 the final result of the calibration can be seen. The coastline (red line) follows the coastline in the aerial image nicely. This result is reached by running the model again and again while adjusting the parameters until a satisfactory situation is reached. The CERC parameters that belong to this calibration are shown in table 4.2. The value for A and γ are both very acceptable as for A a value between 0.014 and 0.025 is advised and for gamma a value between 0.4 and 0.6 is advised by (Kramer, 2005).

Parameter	**Symbol**	**Value**
Calibration parameter [-]	A	0.016
Breaker coefficient [-]	γ	0.5
Seawater density [kg/m^3]	ρ	1025

Table 4.2: CERC parameters after calibration Unibest

4.2.4. Wave climate alterations

For determining the influence of the wave climate on the morphological development of the breakwater two kinds of climates can be tested: Either climates from different locations around the world, or changes can be made to the Lekki wave climate. Using wave climates from different locations around the world will give

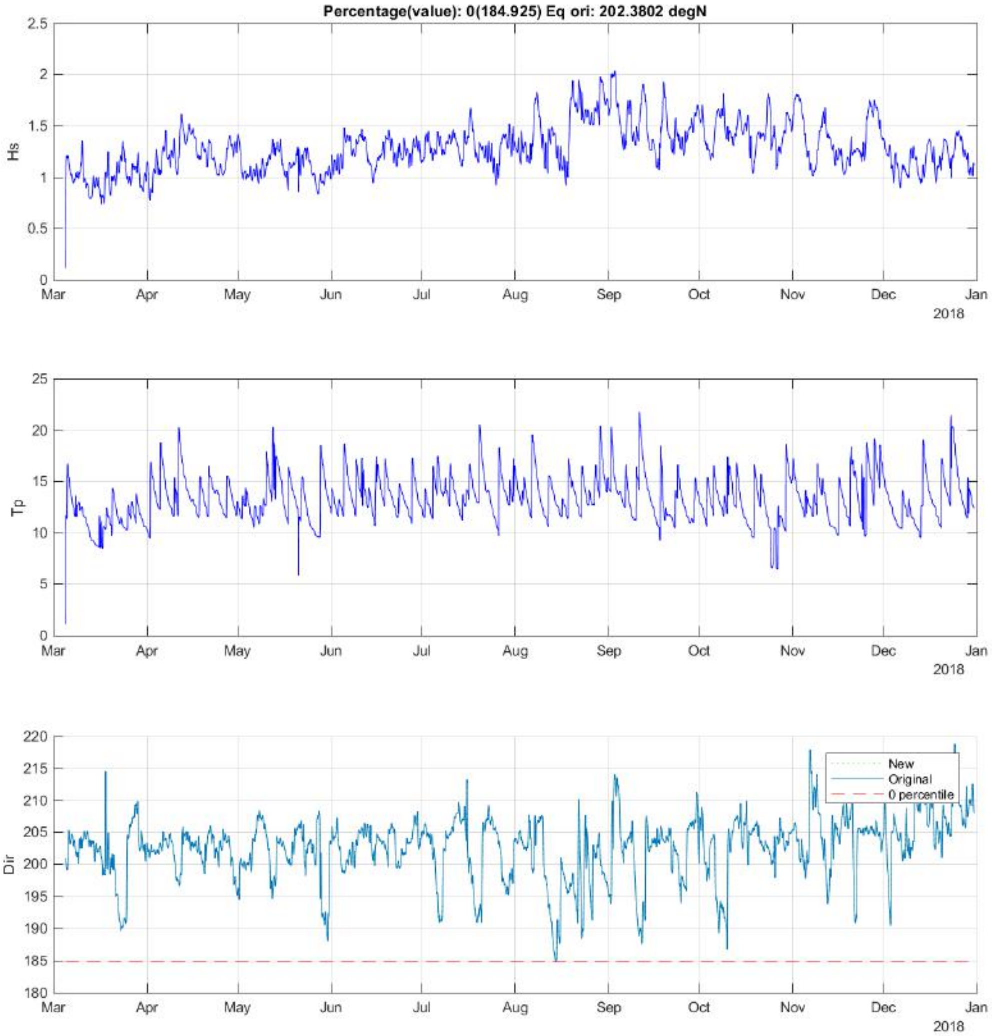


Figure 4.4: Time series of the Lekkki wave data. From up to down the wave height, wave period and wave direction are shown.

insight in how the breakwater will behave for different wave climates, it is however hard to systematically quantify the effects as the climates cannot be easily compared. Secondly, using a completely different wave climate on the breakwater designed for the Lekki wave climate is not logical. Therefore it is decided to use the Lekki wave climate, but slightly alter the climate step by step and rerun the model for each step. The reaction of the morphological development to the alterations then can be quantified and compared to the other slightly different climates. Three types of alterations are made: Change of the mean wave direction, increase of the directional variation, and a change in the chronological order (sequence) of events.

Why these alterations? The wave climate consists of three parameters; wave height, period and direction. Sediment transport is a function of all three of those parameters. But what wave parameter has the most influence on the morphological development of the sandbar breakwater? Altering the wave height by some factor would only influence the transport rate and thus the speed with which the breakwater will develop rather than the spatial development. The same applies for the wave period. Only the wave direction remains. During the data analysis (chapter 3) it was concluded that the wave direction has a large influence on the coastline orientation and thus the development: It is the relation between the wave direction and the coastline orientation which determines how the sandbar breakwater develops both spatially and temporal.

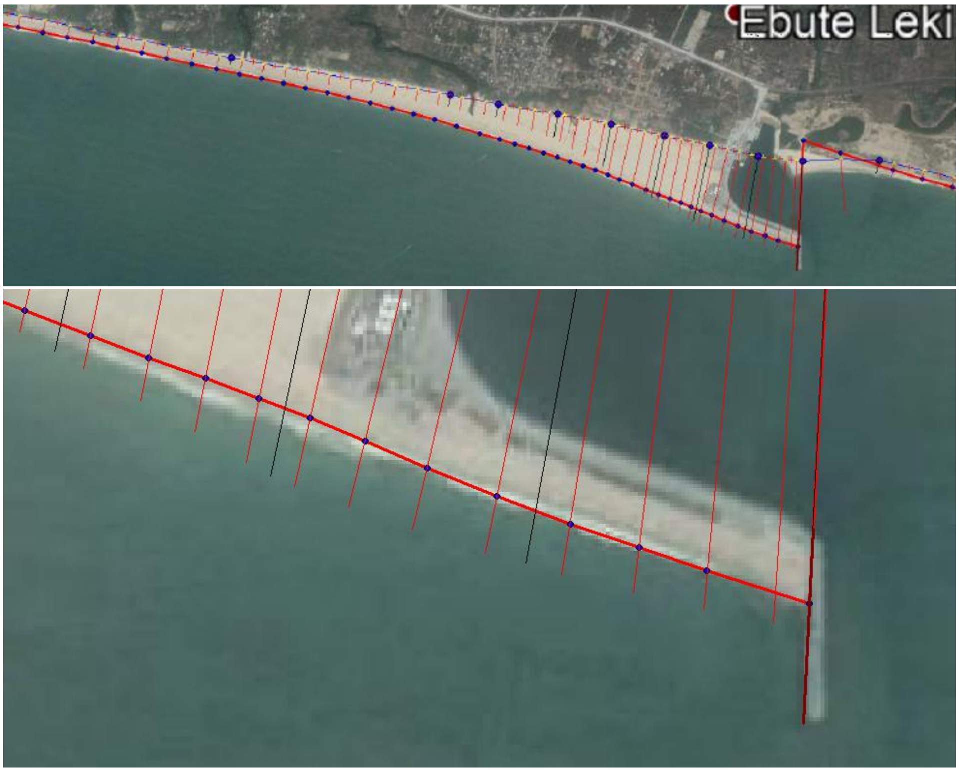


Figure 4.5: The situation after running Unibest for the period from March to December using the optimal settings. The upper figure shows the entire breakwater and the lower figure a detail of the sandbar only. The background shows the desired coastline used to validate the outcome.

Therefore the wave direction is determined to be the parameter to be of most influence of the morphological development of the sandbar breakwater.

The Lekki wave climate is unidirectional with a narrow bandwidth of the wave direction, has a favourable mean direction and the energetic period was several months after construction was finished. But what if the wave direction bandwidth was not as narrow? Or the mean wave direction was different? Or the breakwater was subjected to high energy waves just after finishing construction? These uncertainties will be evaluated by means of altering the original Lekki wave climates step by step: Changes to the mean wave direction, the variation of the wave direction and sequence of the wave climate are made one by one.

During the data analysis it was concluded that two opposite directed longshore sediment transports exist during the initial phase (see figure 3.11). This is the result of the relation between the wave direction and the variation in coastline orientation in longshore direction. Changing the mean wave direction is not only expected to change total transport rate, but also the ratio between these two transport directions. This in turn is expected to influence the morphological development of the sandbar breakwater significantly. The mean wave direction is altered by adding or subtracting a certain angle from the entire wave direction time series. A range of -10 to +10 degrees with steps of 2 degrees in between is determined to be sufficient as the outer limits of +-10 degrees proved to have a sufficiently large influence on the development.

The directional variation can be defined as the standard deviation, or variance, of the wave direction time series. For the narrow bandwidth of the wave direction of the Lekki wave climate the standard deviation is only 5.1 degrees. This characteristic of the wave climate is deemed to be very important for the sandbar breakwater to be applied successfully. It is expected that more directional variation will result in more variation of the morphological development in both time and space. The influence is studied by increasing the directional variation of the time series, or in other words. The standard deviation is increased by increasing the distance of all wave direction entries by up to a factor 5 in steps of 0.5; increasing the standard deviations to a maximum value of 25.5 degrees.

The Lekki wave climate shows higher waves between August and October (figure 4.4). How would the breakwater have reacted when these waves would have occurred earlier in the year? Or what is the influence of the fluctuation of the wave direction over time; the seasonality? What would have happened when during the initial period the waves came from the unfavourable eastern direction? One could imagine that if during the first few months after construction all waves are coming from eastern direction, this results in a large amount of erosion at the sandbar, possibly resulting in a breach. These are questions which will be answered by studying the effect of the chronological order of the wave climate. For the chronological ordering the wave climate is split up in wave events. The wave events are then ordered by wave direction, but also by wave height in both ascending and descending order.

The morphological development of the breakwater for the following wave alterations is researched:

1. **Mean wave direction**: Ten new climates with a new mean direction have been made. The mean direction is changed by adding up -10 to 10 degrees to the direction in steps of 2 degrees.
2. **Directional variation**: 8 climates are made by subtracting the mean direction from all directions in the time series and then multiplying the difference with a factor ranging from 1.5 to 5. The output is then added to the mean.
3. **Wave event sequence**: The chronological order of wave events is changed. Four climates are made to test the influence of the wave sequence on the sandbar breakwater development. One ascending and one descending climate for both the wave height and the direction.

In the next three section, the method of creating the wave climates, the results of the model runs using the wave climates, and the conclusions are discussed separately for the three alterations types. For all alterations types the calibrated Unibest model is run again with the altered wave climates using the exact same settings. The duration of the wave climate used for these runs is increased with 3 months to be one full year; from March 2018 to March 2019. These three months were already available in the wave data from the hindcast model. The model is then run for each of the wave climates for the duration of 10 years, as the morphological development of the sandbar breakwater has not yet reached a stable situation after one year. As the wave climate duration is only one year, the wave climate is repeated 10 times to reach this. This duration is chosen to be 10 years as for (most climates) the interesting part of the development is not yet finished after one year. The 10 year period captures this moment perfectly.

4.3. Mean wave direction

In this section the influence of the mean wave direction on the development of the sandbar breakwater is discussed. First the method on how to change the mean wave direction of the wave climate is discussed. Then the results of the model runs are discussed and the conclusions are presented. In this section the following research question is answered:

How is the Lekki sandbar breakwater development affected by variations in the mean wave direction?

4.3.1. Method

The mean wave direction of the time series of the original Lekki wave climate is altered by adding or subtracting a certain amount of degrees to all individual entries. The wave height and period remain untouched. The range that is chosen is -10 to +10 degrees with a step size of 2 degrees, resulting in a total of 11 climates (the 0 degrees original situation included). As can be seen in the results, a 10 degree change of the mean wave direction results in very large differences and it is therefore not necessary to increase this number. In figure 4.6 an example of the wave direction with a changed mean direction of 10 degrees can be seen (green line). The wave direction time series belonging to the other climates are generated likewise.

4.3.2. Results

The results of the model runs with the wave climates with varying wave climates are presented as follows: First the influence of the wave climate alteration on the longshore transport rate is shown. This will illustrate the influence of the angle between the mean wave direction and the coastline orientation. Then the influence of the mean wave direction on the maximum amount of erosion in cross shore direction over time is

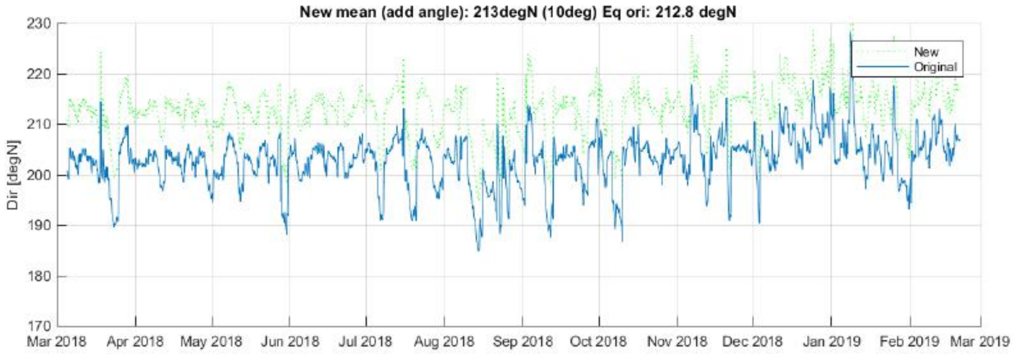


Figure 4.6: The original time series of the wave direction shown in blue and the altered wave direction (+10 degrees) shown in green.

discussed. As stated before, this maximum amount of erosion is chosen as the value to indicate what is the critical amount of erosion over time and place.

First the longshore transport rates are discussed for the different mean wave direction by means of the S/ϕ curve (S=transport rate, ϕ=wave direction or in this case: mean wave direction change). This curve indicates the sediment transport rate per degree of wave direction change. In figure 4.7 the S/ϕ curve showing the influence of the mean wave direction on the total transport on a cross section with little influence of the breakwater, just updrift of the breakwater at 617.5km xUTM (just left of the image shown in figure 4.9). This graph indicates a very clear increase in yearly transport rate with increasing mean wave direction. The yearly transport rate doubles when the mean wave climate is increased by 10 degrees (which is a clockwise rotation) and goes to zero for a decrease of 10 degrees. The increasing and decreasing rate is the result of the angle between the wave direction and the shore normal increasing and decreasing respectively. The decrease of the transport rate over time is the result of the adaptation of the coastline over time at the location at which the longshore transport transport rates are calculated. The decrease of the transport rate over time indicates that the coastline orientation moves slightly towards the mean wave direction at that location. As the S/ϕ curve in figure 4.7 only shows a range of 20 degrees the larger part of the total S/ϕ, as schematised in figure 4.8, curve is not included.

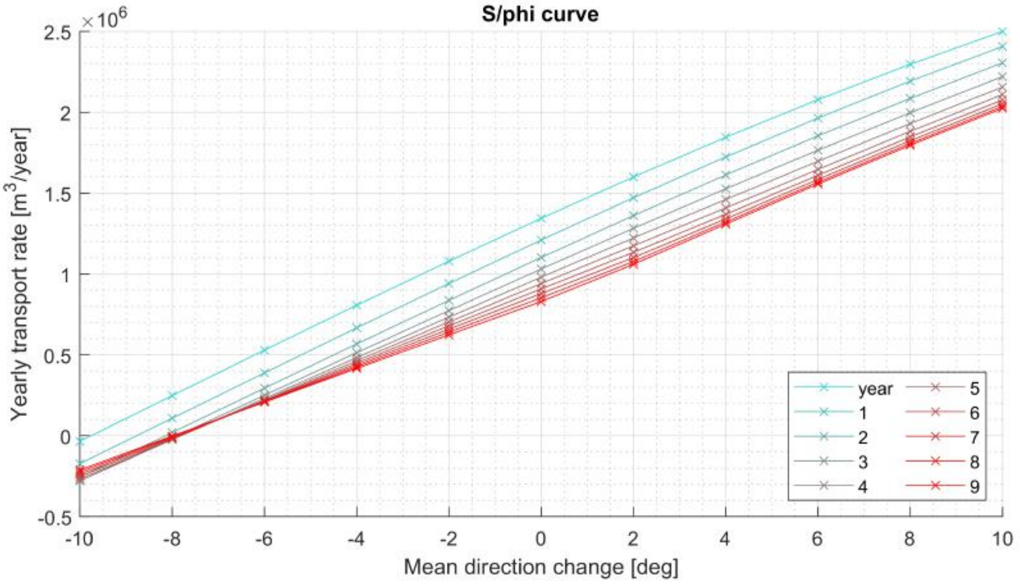


Figure 4.7: S/phi curve of the sediment transport at the cross section at 617.5km xUTM. The x axes show the change of the mean direction ranging from -10 to +10 and the y axes the yearly transport rate corresponding to each climate. A line is shown for each of the years 1 to 10.

The differences in transport rates between the different mean directions results in significant differences in the sandbar breakwater coastline development. The coastline development at the end of the period which the model is calibrated can be seen in figure 4.9. This moment in time is chosen as the background image nicely shows that situation of the original wave climate, while on top of this image the coastlines of the altered wave climate after the first 0.8 year can be seen. The start coastline is shown in blue (this coastline is equal for all runs) and the coastline location at the end of December (after 0.8 years) in green for all mean wave directions.

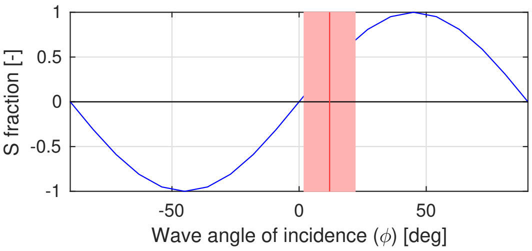


Figure 4.8: standard S/phi curve showing the part of the curve covered by the graph in figure 4.7 by means of the shaded area.

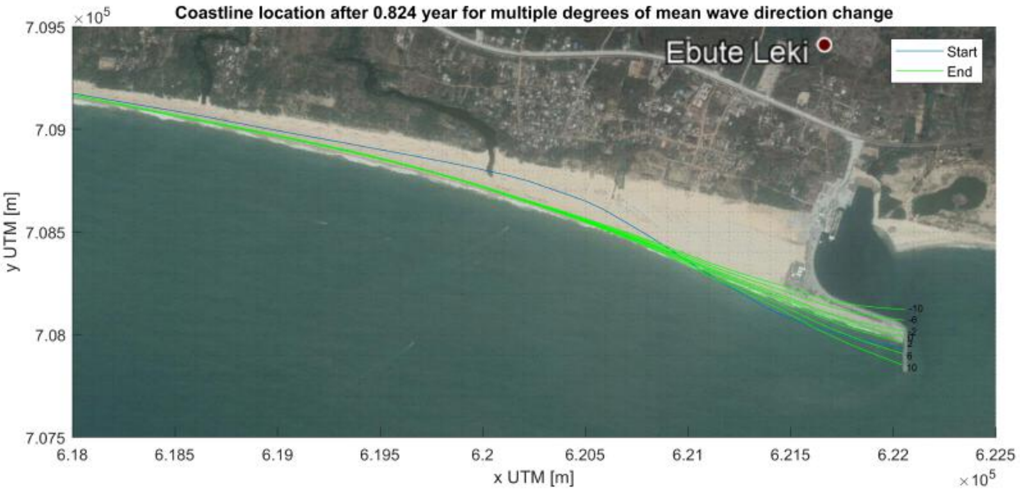


Figure 4.9: The coastline location for each climate at the end of the period for which the model is calibrated. In the background the aerial image used for calibration can be seen.

From high to low the green lines show the -10 to +10 degree wave climates. All decreased directions show extra erosion over the entire length of the breakwater. The amount of erosion increases when getting closer to the groyne. The opposite is true for the mean wave directions which have been turned in a clockwise direction; this gives more accretion of sediment as a result of the larger longshore transport rate. The influence of the mean wave direction is already clearly visible after one year; the influence is large.

Figure 4.10 shows how the breakwater develops over the first two years with time steps of 0.2 years. A period of 2 years is chosen as this has proven to be the period it takes to reach a stable situation, as will be discussed later. This temporal development tells a lot about how the breakwater morphological development is influenced by the mean wave direction. The figure can be read as follows: The lower blue line indicates the starting situation at T=0, which is stated on the right side next to each step in time. The coastline at the second time step, T=0.2 years, is plotted just above the first . Again the blue line indicates the starting situation. The green lines indicate the coastline positions of the altered wave climates. The numbers next to the green lines indicate the amount of degrees with which the mean wave climate is altered. Just like in figure 4.9 the climates are ordered from up to down, from -10 to +10 degrees. For clarity: The y axis indicates a Δy value, rather than the real yUTM coordinates.

Figure 4.10 also shows some clear differences between the reaction of the breakwater for the different climates. Already from the start the wave directions turned in clockwise direction impose more accretion near the groyne, while the opposite is true for the counterclockwise rotated wave direction. Not only is the amount of cross shore movement different for each climate, also the resulting coastline orientations are different, indicating a change of the equilibrium orientation of the coastline. The coastline orientation is increasing with

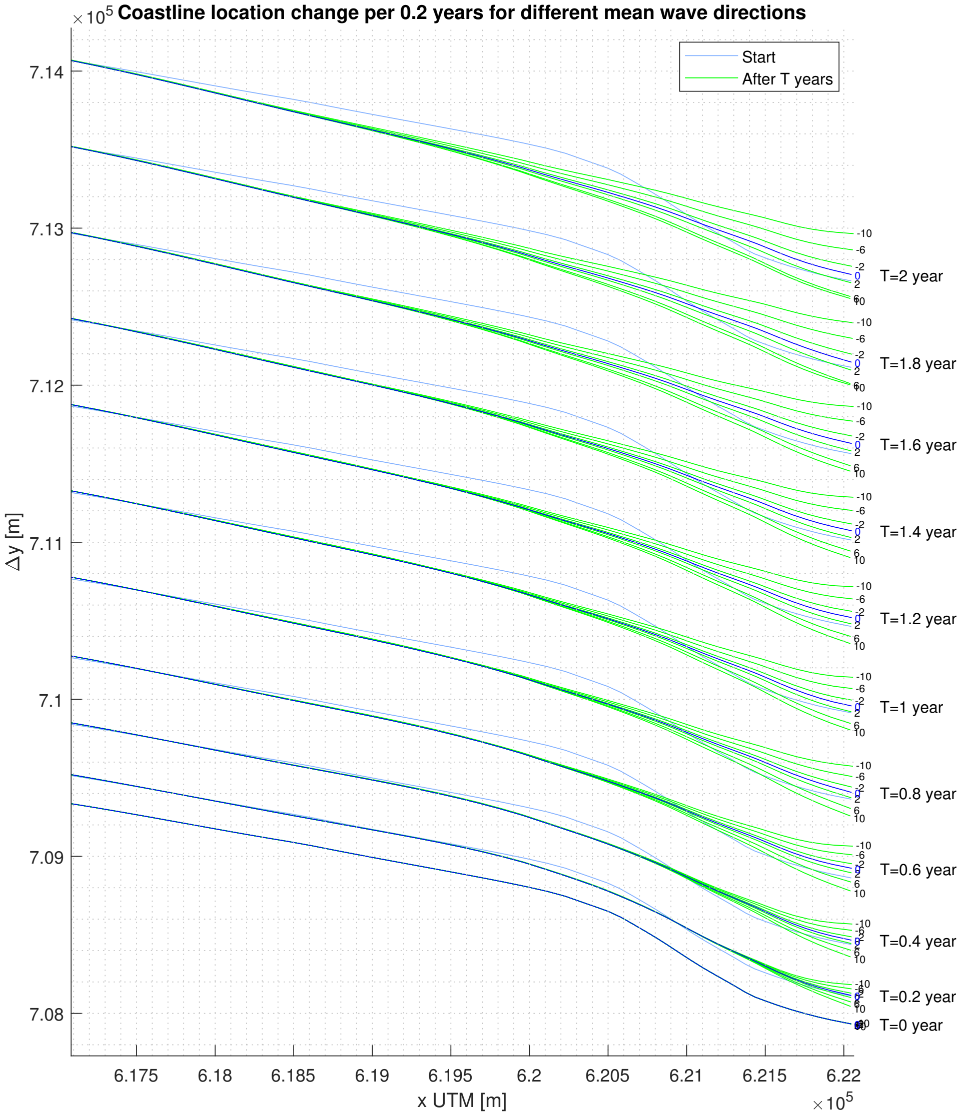


Figure 4.10: The development of the entire coastline per climate alteration for steps of 0.2 years up to 2 years is shown. Time increases in vertical upward direction. On the x axis the xUTM coordinate can be found, while on the y axis δy is used. In bright blue the development of the original climate is shown, while in green the development of the altered climates are shown.

an increasing mean wave direction, confirming that the equilibrium coastline orientation is indeed a phenomenon to keep in mind during the design of the breakwater.

Figure 4.11 shows the minimal cross shore coastline location over the entire breakwater length for each step in time per wave climate. The graph is created by finding the minimal value of the cross shore location relative to the starting position of that coastline location. Figure 4.12 is made to indicate the ‘critical’ locations along the longshore direction of the breakwater. This figure shows the maximum coastline retreat found in the 10 year simulation period for all cross sections over the entire breakwater length.

The green lines of figure 4.11 and 4.12 thus indicate the maximum amount of coastline retreat for all wave climates. Figure 4.11 does that per time step and figure 4.12 over the longshore direction. Red crosses mark the locations when and where the coastline retreat is maximum per wave climate, the so called critical locations in both space and time. Several phenomena are interesting when looking at these graphs: The first one being the amount of maximum erosion over the longshore direction for the original wave climate in figure 4.12. The maximum is for the entire sandbar around 80 meters of erosion for the ten year period. In figure 4.11 it can be checked that this is during the first one or two years, as from then on the minimal coastline location increases again. Secondly, these graphs show that for the wave climates that

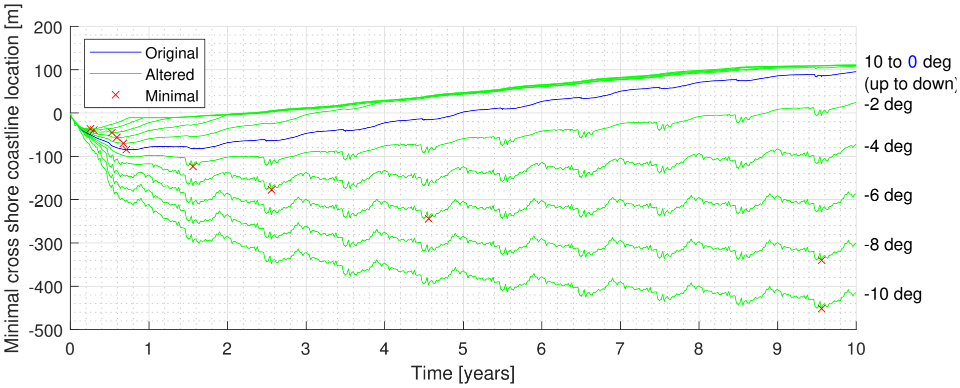


Figure 4.11: The minimal cross shore coastline location over time for all cross sections over the entire breakwater length are shown by means of a blue line for the original climate and green lines for the altered climates. A red asterisk indicates the minimum per climate.

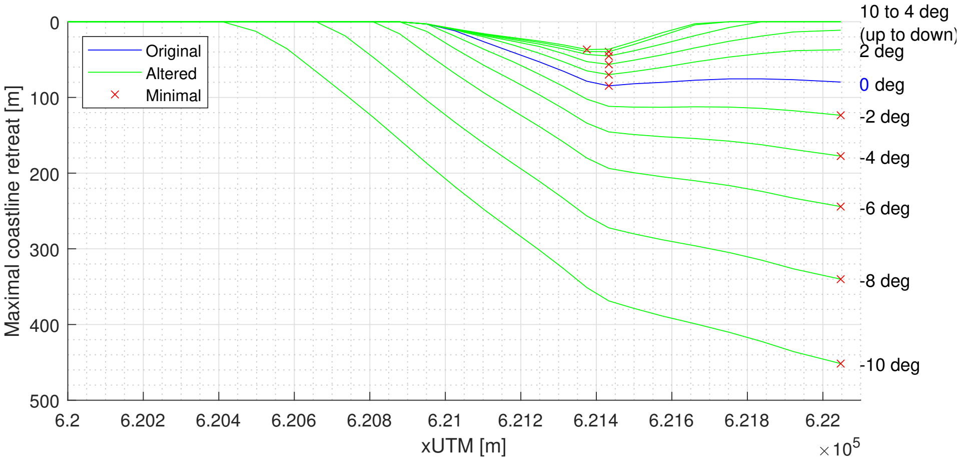


Figure 4.12: The maximal coastline retreat per cross section over the breakwater length. The lines indicate the maximal amount of coastline retreat in the 10 year modelling period. A red asterisk indicates the minimum per climate. Note that the amount of coastline retreat increases in downward y direction.

turned in a clockwise direction the maximum amount of erosion is lower than the original situation and higher for the counterclockwise rotated mean wave direction. For the clockwise rotated climates the maximum amount of erosion is around 621.4km xUTM which is exactly the location where the corner of the connection between the sandbar and the coastline connecting the sandbar to the original coastline starts. Figure 4.13 shows this location. In blue the start coastline is shown as it was just after finishing construction and in red the cross section at 621.4km xUTM is shown.

For the climate rotated in counterclockwise direction the maximum amount of erosion can be expected near the groyne. This is due to the fact that the more waves are rotated in counter clockwise direction, the more sediment is transported from the sandbar in western direction. As there is no supply of sediment from the eastern side of the groyne, large amounts of erosion are the result. For the -8 and -10 degree climate it is not even sure yet whether or not the maximal amount of coastline retreat is reached after 10 years, as the minimums are in the last years of modelling and the maximum amount of erosion still seems to be decreasing. The third thing to notice are the -2, -4 and -6 wave climates. These climates impose a much larger amount of erosion, however the amount could still be considered accept-

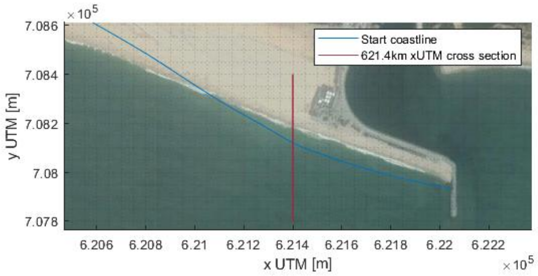


Figure 4.13: The 621.4km xUTM cross section shown as a red line on top of the aerial image of 24-12-2018. The blue line indicates the starting position of the coastline.

able. When these maximum amounts of erosion are known a priori, they could be coped with. Especially the -2 wave climate is interesting, as it shows more erosion that the original wave climate, however the minimal location of the coastline in cross shore direction still start increasing after a minimum is reached in the second year. Hence, considering the initial width of the Lekki breakwater was circa 170 meters, the -2 wave climate would also have been survived by the Lekki wave climate. Figure 4.14 indicates that a wave climate with an average of 2 degrees lower than the average of 2018 is not out of the ordinary and thus could have been the wave climate of 2018. The figure shows what the variations over the yearly averaged wave directions have been since 1992 for the Lekki wave climate. The 2018 climate had an average direction of around 201.9 degrees North, while the minimal value which has occurred is 200.0 degrees North in 2010. Assuming the amount of wave energy would have been the same for 2010, construction of the breakwater in 2010 (circa -2 degrees from 2018) could have led to significantly more erosion during the first two years (up to 40 meters).

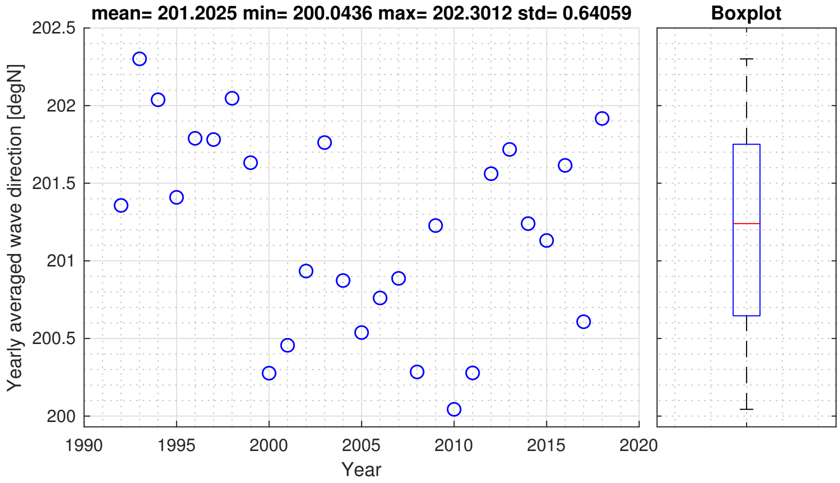


Figure 4.14: Yearly averaged wave direction from 1992 to 2018. Left graph shows the yearly mean direction per year and the right graph shows a box-plot of all values.

Figure 4.15 shows the maximal amount of erosion relative to the original climate (85m) in both time and space for all different mean wave direction climates. The influence of the mean wave climate is clear: An increase of the mean wave direction decreases the maximum amount of erosion while the opposite is true for a decrease of the mean wave direction. Interesting to note is the location of the original (0 degree) wave climate in this graph: Left of this point the maximum amount of erosion increases fast, while right of the point a very slow decrease can be seen.

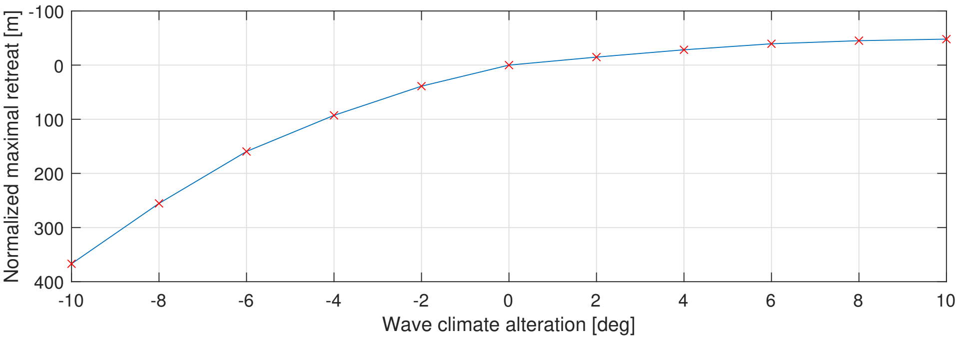


Figure 4.15: The maximal amount of coastline retreat relative to the original wave climate (85m) per wave alteration. Note that positive values (downward y direction) indicate an increase of the coastline retreat and negative values indicate a decrease.

4.3.3. Sub conclusions

In this section the influence of the mean wave direction on the morphological development of the sandbar breakwater is discussed. The central question was:

How is the Lekki sandbar breakwater development influenced by variations in the mean wave direction?

The average wave direction has a large influence on the morphological development of the sandbar breakwater as the net yearly transport rate is affected. The influence of the mean wave direction can be seen best when comparing the maximal amounts of cross shore erosion per degree of mean wave direction change.

An increase of the wave direction (clockwise rotation) results in increasing sediment supply from the west and over the entire breakwater less erosion is present than for the original wave climate. The maximum amount of erosion is found at the corner between the sandbar and the coastline connecting the sandbar to the original coastline.

The opposite can be said for the climates for which the wave direction is decreased (counterclockwise rotation): The supply of sediment drops and the amount of erosion increases significantly. The maximal amount of erosion is near the groyne. This can be explained by the fact the more sediment transport over time is directed in eastern direction with further decreasing mean wave direction. As no sediment can be supplied from east of the groyne, more erosion will be the result.

The yearly average wave direction in Lekki varies between 200 and 202 degrees North between 1992 and 2018. The mean wave direction of 2018 was 201.9 degrees North. When the wave climate would have had a mean wave direction of 200 degrees North in 2018 (and while assuming the wave energy to be divided equally) an extra amount of 40 meters of erosion could have been expected. This is an amount which still could be handled by increasing the initial breakwater width or performing maintenance.

4.4. Directional variation

In this section the influence of the directional variation on the morphological development of the sandbar breakwater is discussed. This will give an answer to the research question:

How is the Lekki sandbar breakwater development affected by larger variations of the wave direction?

By answering this research question also an answer will be given to the question of how important it really is the have a unidirectional narrow bandwidth wave climate. First the method on how the directional variation of the Lekki wave climate is increased. Then the results of the model runs are discussed and the conclusions are presented.

4.4.1. Method

The directional variation of the time-series of the original Lekki wave climate is altered by increasing the standard deviation with a certain factor. The goal is to create a climate with a larger standard deviation, but the same mean wave direction. This is done by subtracting the mean wave direction from all entries of the wave direction time series. The result of this calculation is then multiplied by a specified factor. The factors 1.5 to 5 with a step size of 0.5 are used. This results in a total of 8 new wave climates. The resulting climate for the factor 5 can be seen in figure 4.16. The other climates are made likewise. To illustrate the effect of these wave alterations, a wave rose of the original and of the factor 5 climate can be found in figure 4.17. Note that for these wave roses the scale is different.

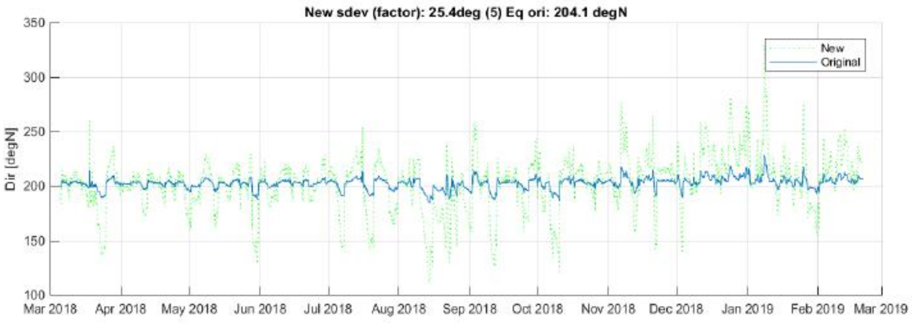
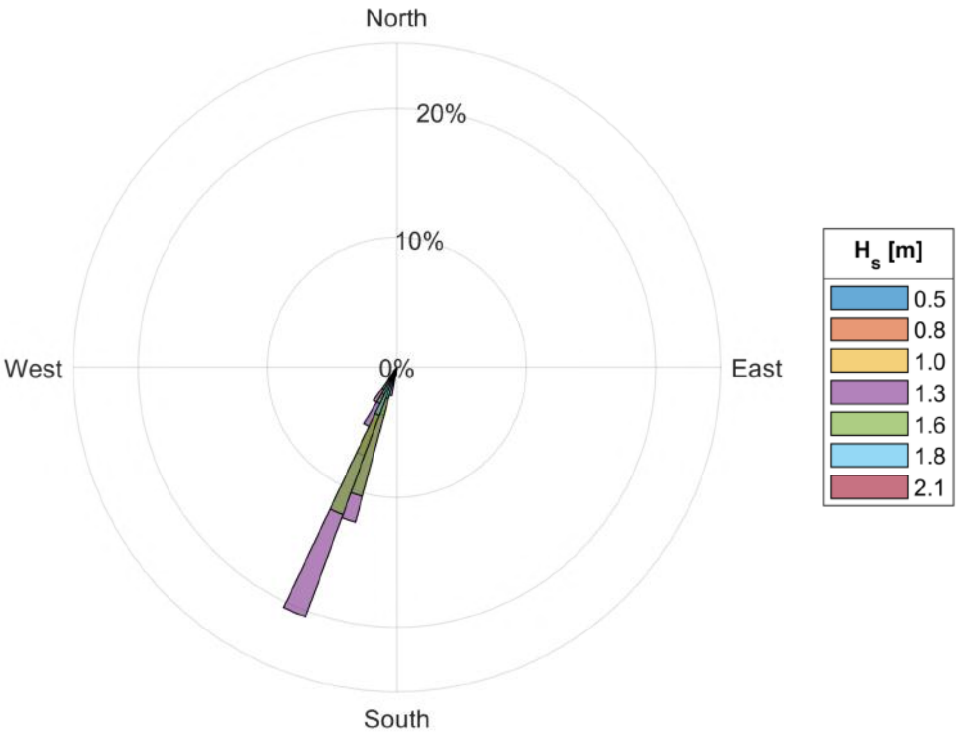


Figure 4.16: The original time series of the wave direction shown in blue and the altered directional spreading (factor 5) shown in green.



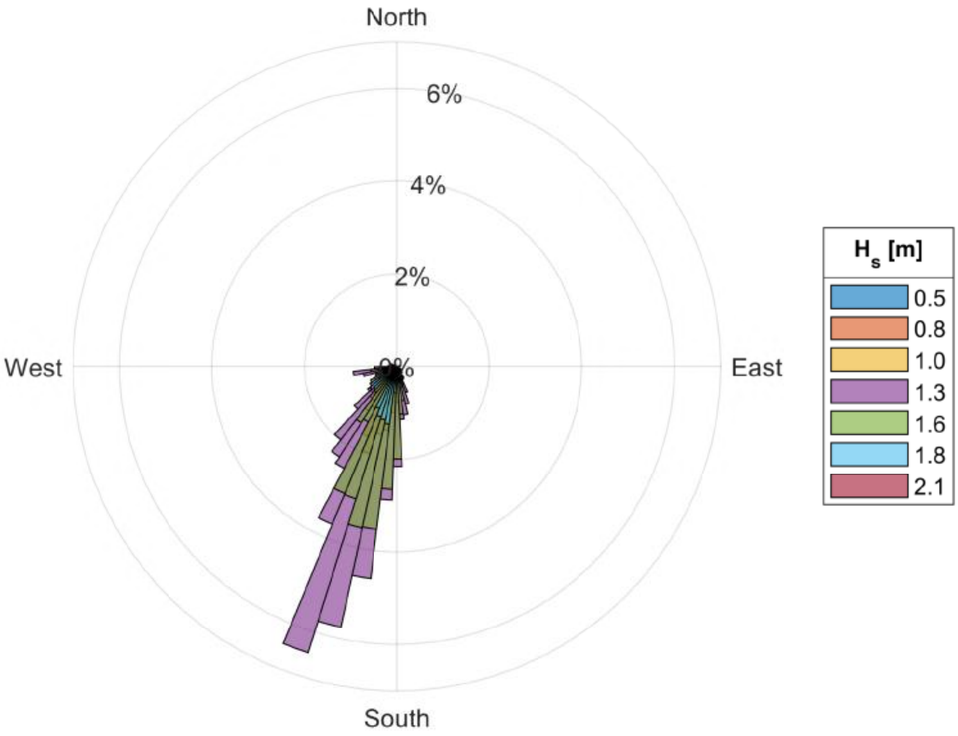


Figure 4.17: Wave roses indicating the amount of directional variation of the original wave climate (upper figure) and the climate with a factor 5 increase of the standard deviation of the wave direction (lower figure).

Dir factor [-]	1	1.5	2	2.5	3	3.5	4	4.5	5
Standard deviation [deg]	5.1	7.6	10.2	12.7	15.3	17.8	20.3	22.9	25.4
Unused percentage [%]	0	0	0	0	0	0.2	0.2	0.3	0.4

Table 4.3: Table showing the spreading factors with the corresponding influence on the wave climate. The second row shows the standard deviation per factor. The third row the percentage of waves that have been turned past the wave climate and are therefor "unused" by the model.

The factor 5 has proven to be a sufficiently large maximum value as the standard deviation is already 25.4 degrees. The increase in standard deviation comes with a drawback: Some waves are rotated that much from the mean direction that they go past the coastline orientation and will not create any sediment transport anymore. Table 4.3 shows the factors, the standard deviations belonging to the factors and the percentage of wave entries that is pushed past the coastline orientation. The values for factor 3.5, 4.5 and 5.0 are above zero, but still considered small enough.

4.4.2. Results

Just like for the mean direction alterations, the results of the runs with more directional variations are discussed by comparing the longshore transport rates and morphological development to the transport and development of the original Lekki wave climate. First the longshore transport rates are discussed. Then the morphological development as a result of the sediment transport. The coastline development is then analysed to find the cross sections with the maximal coastline retreat per time step, as these are the locations which are most critical for the breakwater design. This coastline retreat is used as a measure to quantify the influence of the directional variation on the morphological development of the sandbar breakwater at Lekki.

The volume of sediment passed through a cross section just updrift of the breakwater (617.5km xUTM) for all wave climate alterations is shown in figure 4.19. The sediment transport is shown like this rather than using the yearly transport rate per wave alteration (as used for the mean wave climate alterations) as the increase in variation of the passed volume over time is clearly visible in this graph type.

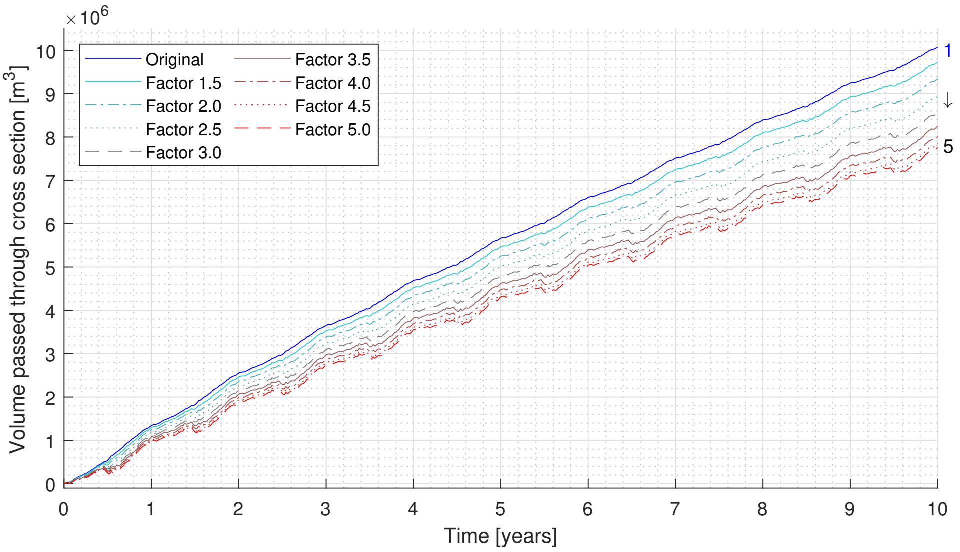


Figure 4.18: The sediment transport over time through the 617.5km xUTM cross section, which is just updrift of the breakwater.

The first thing to notice about this graph is the fact that the total transported amounts deviate; they decrease with an increasing directional variation. In the ideal situation at the end of the year the net transport volume would have been equal. This would then only show the effect over the directional variation over the year. Now also the effect of a decreasing yearly transport rate should be taken into consideration. The decreasing net sediment transport is the result of the method for creating the new wave climates. Figure 4.19 shows the influence of increasing the standard deviation of the wave climate on the distribution of the wave energy over the angle between the original coastline (190.5 degrees North) and the wave direction, indicated by Φ. In the same graph the S/ϕ curve is plotted to show how the sediment transport is influenced by the wave direction. This S/ϕ curve is created by using CERC with all values set to 1 expects for the wave direction, which is set from -90 to 90 degrees. This graph shows that with increasing standard deviation, the fraction of the wave energy that has moved from the left side of the 0 degree line to the right side also increases. Hence the amount of sediment transport in eastern direction decreases, while the amount of sediment transport in western direction increases. This explains why the net longshore sediment transport decreases with increasing standard deviation. One can also see the rate of decrease of the net transport decreasing significantly between factor 4 and 5. The longshore transport rate is maximum at ϕ is (-)45 deg. The wave energy of the Lekki wave climate is divided such over the directional spectrum that a small peak of wave energy can be seen just left of the 45 degree line for the factor 4.0 climate (see also the detail; lower graph of figure 4.19). Just to the right of the 45 degree line the factor 4.5 and a little further the factor 5.0 wave energy peak can be seen at around 46 and 50 degrees respectively. The transport thus increases for the climates up to factor 4 after which the increases stagnates due to a larger fraction of the wave energy having past the 45 degree marker.

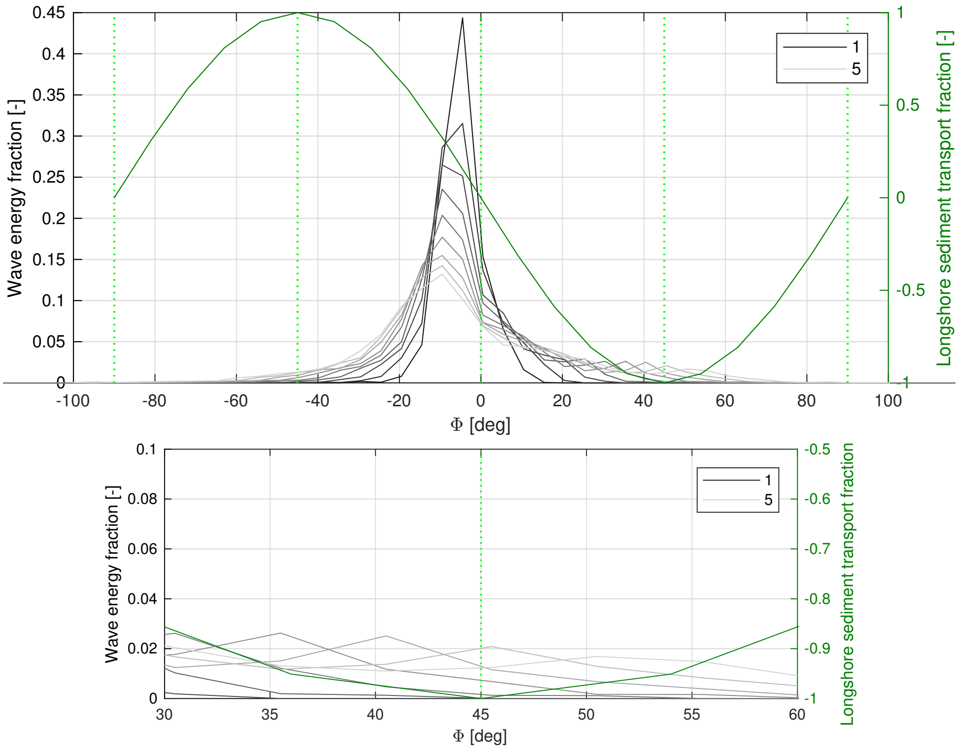


Figure 4.19: (Upper graph: Distribution of the wave energy over the wave direction relative to the coastline orientation (Φ). In green the S/ϕ curve indicates the fraction of the potential transport rate that can be expected as a result of a certain wave angle. Lower graph: Detail of the upper graph from Φ=30 to 60, indicating the peak of the waves shifts from the left side of the 45 degree mark to the right with increasing variation.

Despite the method for creating the wave climate not being optimal, the results of the calculations still give a valuable insight in the influence of the directional variation on the morphological development of the breakwater. The results will be discussed while keeping this in mind.

So, what can be learned from the graph in figure 4.19? The variation of the net longshore transport over time increases with an increasing directional spreading. This can be seen by looking at the increasing wiggle size. Increasing variation over time is a logical result of the wave directional variation increasing in time. More variation in the sediment transport is expected to also change the morphological development over time. In figure 4.20 the coastline development of the sandbar breakwater for the first two year is shown.

The figure can be read as follows: The lower blue line indicates the starting situation at T=0, which stands on the right side of the graph. The coastline at the second time step, T=0.2 years, is plotted just above the first timestep. Again the blue line indicates the starting situation. The green lines indicate the coastline positions of the altered wave climates. The y axis indicates the deltaY value, rather than the real yUTM coordinates.

The lines are that close together that it's impossible to make them distinguishable. This is also the reason why this graph is shown; The coastline evolution for the different climates over time shows only very little variation. Or in other words: The morphological development seems to experience almost no influence from an increase in directional variation. At T=0.8 and T=1.8 the largest differences can be seen. Climates with more variation show more accretion near the groyne. Also when looking at the evolution of the entire coastline over time, it is visible that climates with a higher amount of directional variation are located closer to the land than the climate with less variation. This however the result of the decrease of the net longshore transport with increasing variation, as described before.

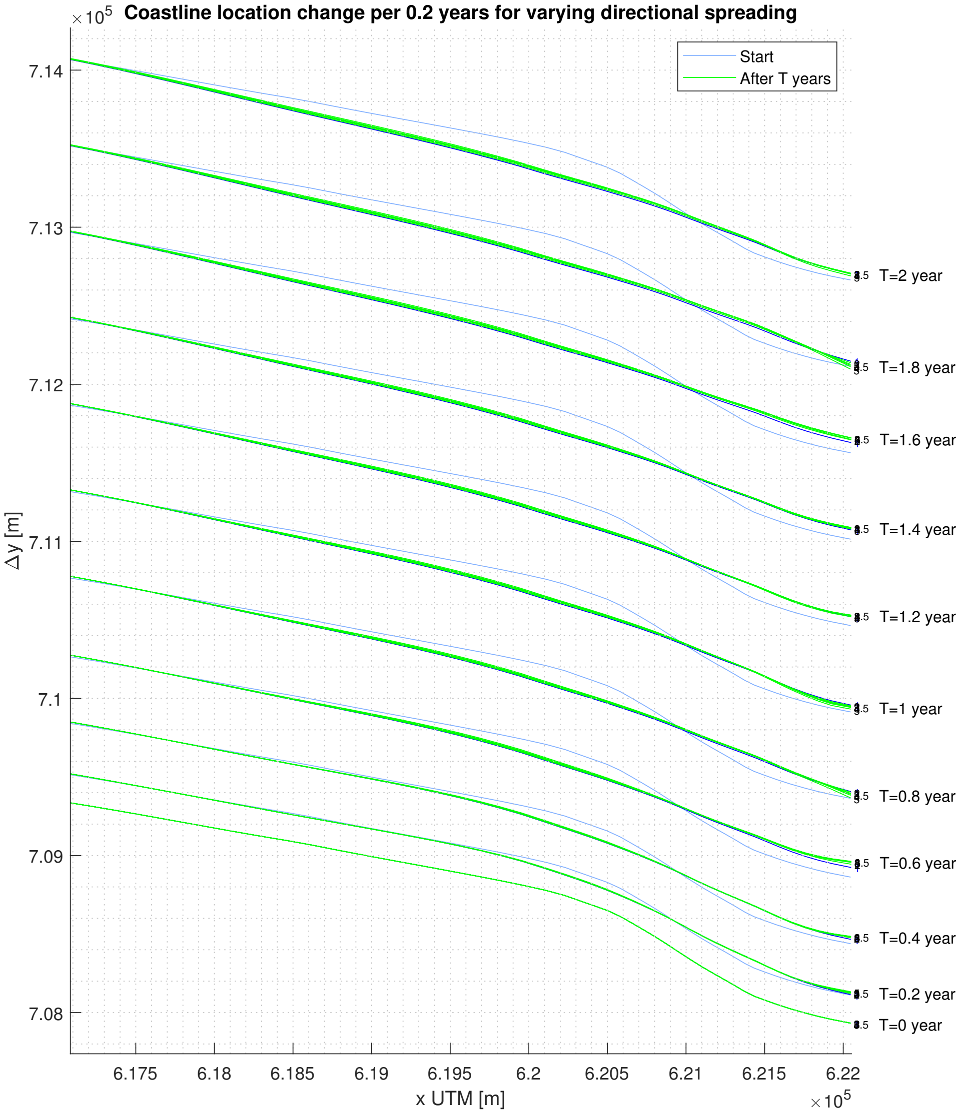


Figure 4.20: The development of the entire coastline per climate alteration for steps of 0.2 years up to 2 years is shown. Time increases in vertical upward direction. On the x axis the xUTM coordinate can be found, while on the y axis δy is used. In bright blue the development of the original climate is shown, while in green the development of the altered climates are shown.

The entire coastline evolution changes only very little by an increased directional variation. But what does this mean for the maximum amount of erosion that can be expected and where does this erosion occur? Two graphs are made to quantify these amounts. Just like for the mean wave direction; Figure 4.21 shows the minimal cross-shore coastline location over the entire breakwater length for each step in time per wave climate. The graph is created by finding the minimal value of the cross shore location relative to the starting position of that coastline location. Figure 4.22 is made to indicate the 'critical' locations along the longshore direction of the breakwater. This figure shows the maximum coastline retreat for all cross sections over the entire breakwater length.

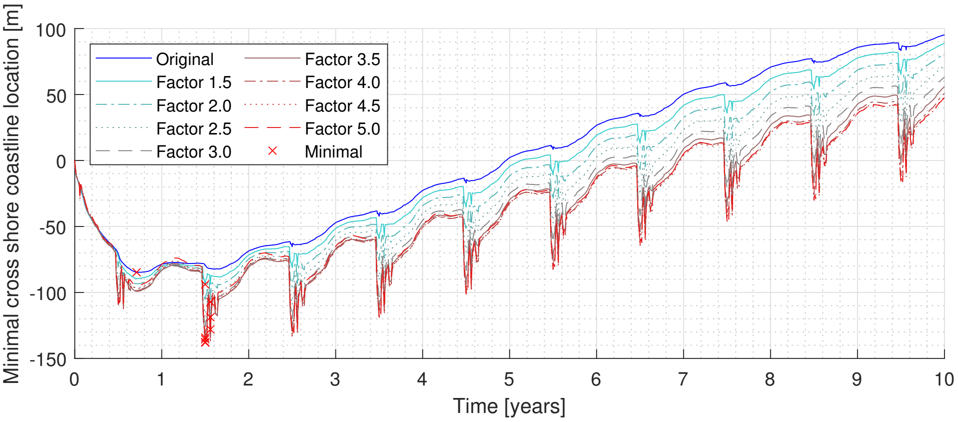


Figure 4.21: The minimal cross shore coastline location over time for all cross sections over the entire breakwater length are shown by means of a blue line for the original climate and changing colour and line style for the altered climates. A red asterisk indicates the minimum per climate.

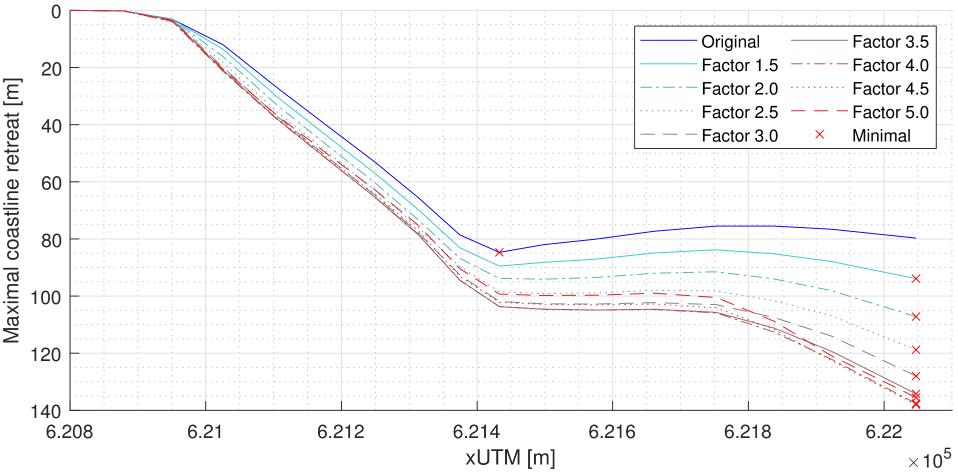


Figure 4.22: The maximal coastline retreat per cross section over the breakwater length. The lines indicate the maximal amount of coastline retreat in the 10 year modelling period. A red asterisk indicates the minimum per climate. Note that the amount of coastline retreat increases in downward y direction.

In these figures the influence of the directional variation is clearly shown by the wiggles in the minimal coastline location; The wiggles increase with an increased amount of directional variation. Also the influence of the decreasing net transport is visible; the maximal value of the minimal cross shore coastline location slowly decreases over time for climates with more directional variation. This effect increases over the years and is still small at the end of the first and second year; circa 5 and 12 meters respectively. The red X's show the minimal cross shore location in time for figure 4.21 and along the longshore direction for figure 4.22. For the original wave climate the minimum is reached in the first year. For the altered climates the minimums are reached in the second year, with values going down to as low as -138 meters. Taking into account a correction for the difference in net longshore transport of 9 meters, which is the estimated amount at the half of the second year, a maximum of 129 meters of erosion can be expected for the climate with the maximum amount of directional variation; the climate with a 25.4 degree standard deviation. Which is 44 meters more than the original situation (85 meters). The sandbar of the Lekki breakwater had an initial width of about 170m, all climates would thus not have resulted in a breach.

What also is important to note is wave climate with the largest amount of standard deviation is not the climate which induces the most coastline retreat. The factor 4.5 climate induces more erosion. This effect can also be attributed to the rate of decrease of the LST as explained with the help of figure 4.19.

The location of the maximum amount of erosion shifts from the corner between the sandbar and the coastline connecting the coastline for the original wave climate to the original coastline (close to the cross section shown in figure 4.13) to the groyne for the wave climates with an increased directional variation, as can be seen in figure 4.22. This figure also shows that the erosion at the 621.4km xUTM cross section (at the corner discussed above and as shown in figure 4.13) does not increase much with an increase in the directional variation. This increase in erosion can be partly attributed to the change in net longshore transport. The main influence of the directional variation of the wave climate on the morphological development of the breakwater is thus near the groyne. More variation results in more coastline retreat. To summarise these findings, figure 4.23 is made. This figure shows the maximum erosion (or maximum coastline retreat) for each of the wave climates by means of the red X's of figure 4.21 and 4.22. The maximum coastline location retreats up to factor 4, but from then the retreat stops and the minimal coastline locations starts increasing again. This phenomenon confirms the explanation on why the rate with which the net longshore transport decreases per directional variations. Per increase of standard deviation the wave energy is pushed more and more towards the maximal transport angle (45 degrees) until factor 4 is reached and a large amount is pushed passed the 45 degree line, thus decreasing the transport in eastern direction. Less erosion is the result.

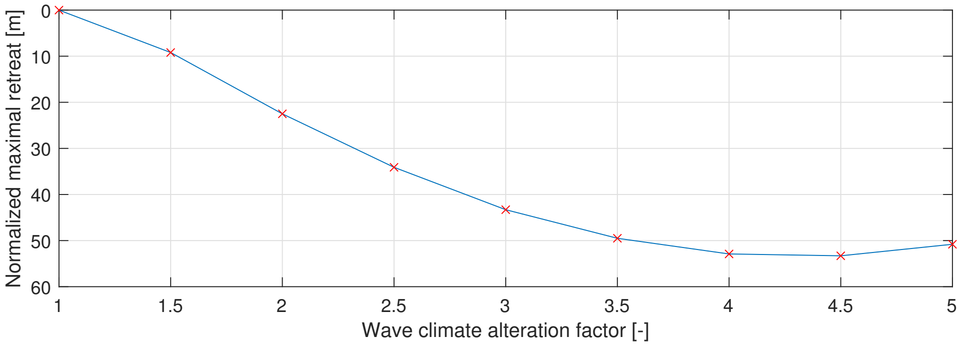


Figure 4.23: The maximal amount of coastline retreat relative to the original wave climate (85m) per wave alteration. Note that positive values (downward y direction) indicate an increase of the coastline retreat and negative values indicate a decrease.

In figure 4.24 the yearly standard deviation of the wave direction is plotted for the Lekki wave climate for 1992 to 2018 based on the data of the data analysis. The NOAA data used in the sensitivity study only covers 2017-2019 and can therefore not be used to determine the long term variations. The standard deviation for 2018 based on this data set (4.7 degrees) is slightly different from the value of 5.1 degrees as can be seen in table 4.3. There are two reasons for this; one being the difference between the models used (NOAA and SWAN vs WaveClimate) and the second one being the period over which the standard deviation is calculated (January 1st to December 31st vs March to March). Despite of these annotations, the graph still gives a valuable insight into the variations of the standard deviation over the years. The variations are very small; a minimum value of 4.5 degrees in 2008 and a maximum value of 5.6 degrees in 1998 indicate only a bandwidth of 1.1 degrees over the years. This value is very small compared to the values created for the sensitivity study; the step from the original wave climate to the factor 1.5 wave climate already increases the standard deviation by 2.5 degrees. The directional variations tested during this study thus impose much larger standard deviations than would occur at Lekki.

4.4.3. Sub conclusions

In this section the influence of the directional variation of the wave climate on the morphological development of the sandbar breakwater is discussed. The central question was:

How is the Lekki sandbar breakwater development influenced by larger variations of the wave direction?

A larger amount of variation of the wave direction results in an increase of the variation of the transport rate and thus in an increase of variation of the morphological development. Larger amounts of coastline retreat are seen for an increase in variation varying from 9 meters of extra erosion for a standard deviation of 7.6 degrees (factor 1.5) to 33 meters of extra erosion for climates with a standard deviation of 20.3 to 22.9 degrees (factor 4 and 4.5) giving a total erosion of 118m. For the Lekki wave breakwater, which had an initial width of about 170m, the extra variation would not have resulted in a breach, but could have resulted in a critical

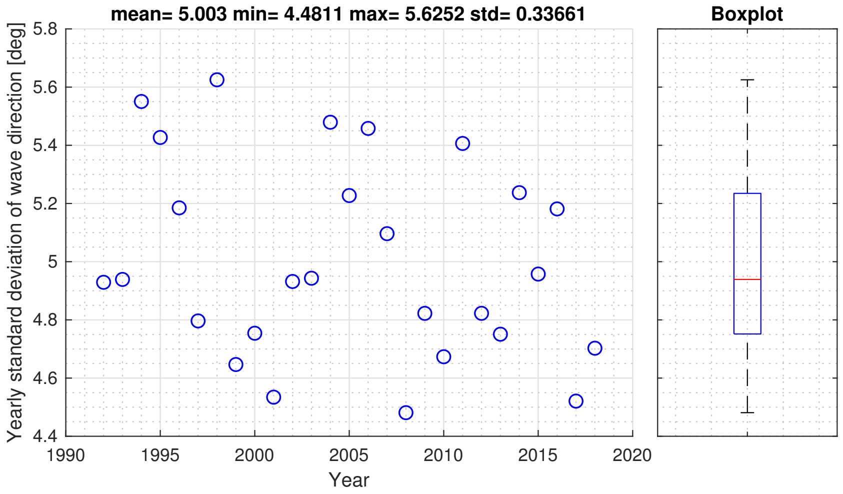


Figure 4.24: Yearly averaged wave direction from 1992 to 2018. Left graph shows the yearly mean direction per year and the right graph shows a boxplot of all values.

situation.

Then the secondary research question:

Is a unidirectional narrow bandwidth wave climate necessary for the Lekki sandbar breakwater to become stable?

Based on this study, the answer to this question is no. An increase of the directional variation (increase of the bandwidth), results in an increase of the coastline movement over time; Large fluctuations of the coastline locations are visible. The amount of coastline retreat will thus also increase. However this is a temporary decrease rather than a structural decrease. The maximum amounts of the coastline retreat for climates with a larger amount of directional variation could even have been survived by the Lekki breakwater.

4.5. Wave event sequence

In this section the influence of the wave climate sequence on the morphological development is discussed. The central question is:

How is the Lekki breakwater morphological development affected by a different sequence of the wave climate?

Or in other words: What is the importance of the chronological order of waves for the coastline development of the sandbar breakwater? First the method of creating the wave climates is discussed. Then the results of the model runs are discussed by analysing the effect on the longshore transport and the coastline development.

4.5.1. Method

Countless variations of the chronological order of the time series can be imagined. Waves of certain directions could be clustered and moved to for example the start or maybe the end of the year. As it is not possible to model the countless variations that could be made it was decided to model two outer limits: From high to low (descending over time) and from low to high (ascending over time). The sorting will be done for wave events, rather than individual waves. Sorting waves based on individual entries of the time series would result in the climate being perfectly sorted for one of the parameters. The other parameters however would be scattered completely randomly and any form of connection to the original authentic climate would be gone. Therefore it is decided to base the sorting on wave events in which wave entries over a certain period will always remain together. The events are then ordered on the median value of either the wave direction or wave height of each event. The median is chosen rather than the mean as the median is not as sensitive to peaks in the time series.

The swell waves arriving at Lekki are generated thousands of kilometres away, resulting in a typical pattern of the wave period over time. First waves with a long period period arrive and later waves with a shorter period. This pattern is the result of swell waves arriving sorted from longer and faster waves to shorter and slower waves. The duration of each high to low period cycle varies between 0.5-7.5 days. These patterns are used to define wave events. Each wave event being separated by a local minimum with a minimal prominence value of 1.0 second. The prominence value indicates how far the period should have dropped before a minimum is defined as a local minimum. A value of 1 second filters out any small wiggles which are not the true end of events. In figure 4.25 the local minima (or start and end of each event) is shown by means of a green asterisks for the entire time series. A zoomed in detail from January 8th to January 26th 2019 is given in figure E.1 in appendix E. In this figure the effect of the prominence value can be seen by the asterisks skipping local minima which do not define the end of an event.

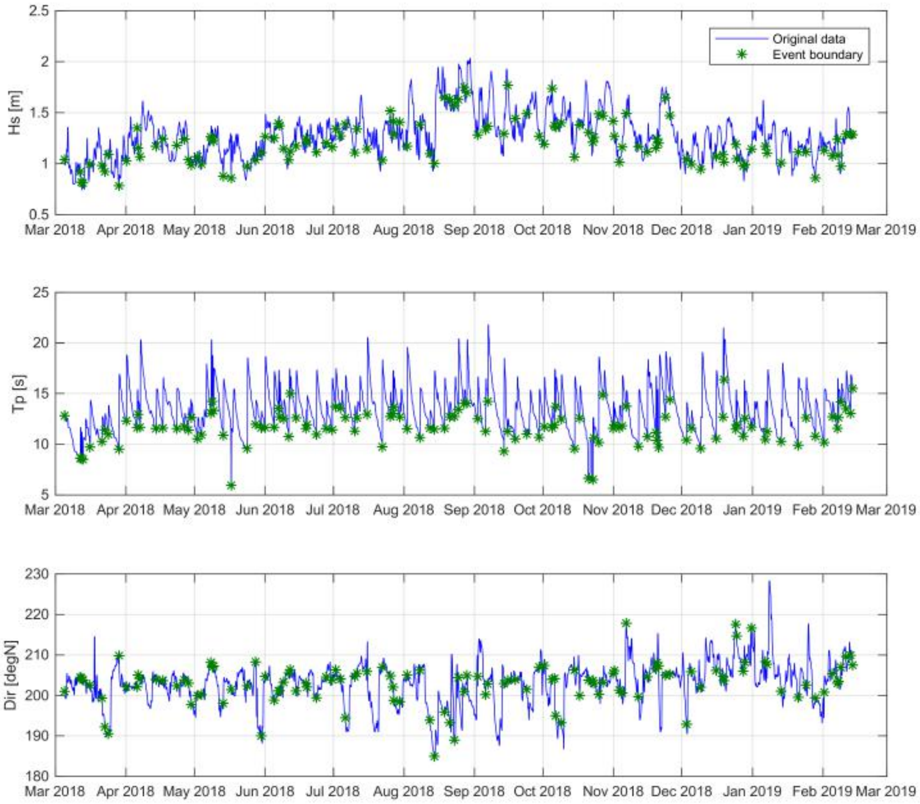


Figure 4.25: The original wave climate in combination with the event separators (green asterisks). From up to down the wave height, period and direction are shown.

4.5.2. Results

Just like the previous two wave alterations, the results of this section are discussed by comparing longshore transport rates and morphological development under the influence of the new climates to the original climate. First the results of the climate alterations are discussed. Then the longshore transport rates are discussed, followed by the morphological development as a result of this transport. The coastline development is then analysed to find the cross sections with the maximal coastline retreat per time step, as these are the locations which are most critical for the breakwater design. The coastline retreat is used as a measure to quantify the influence of the directional variation on the morphological development.

As the climate change proves to have very little influence on the overall coastline development, the two year temporal development of the entire breakwater is not shown for this alteration. Variation is however visible in the location of the maximal amount of coastline retreat. This variation and the locations of interest will be discussed in detail.

Wave climates

Four new climates are made; for the wave height and the wave direction both an ascending and a descending climate. In figure 4.26 the resulting wave climate is shown for the events sorted by descending median wave height. Three plots show the time series of the wave height, wave period and wave direction from up to down. The three climates belonging to the other wave alterations can be found in appendix E.

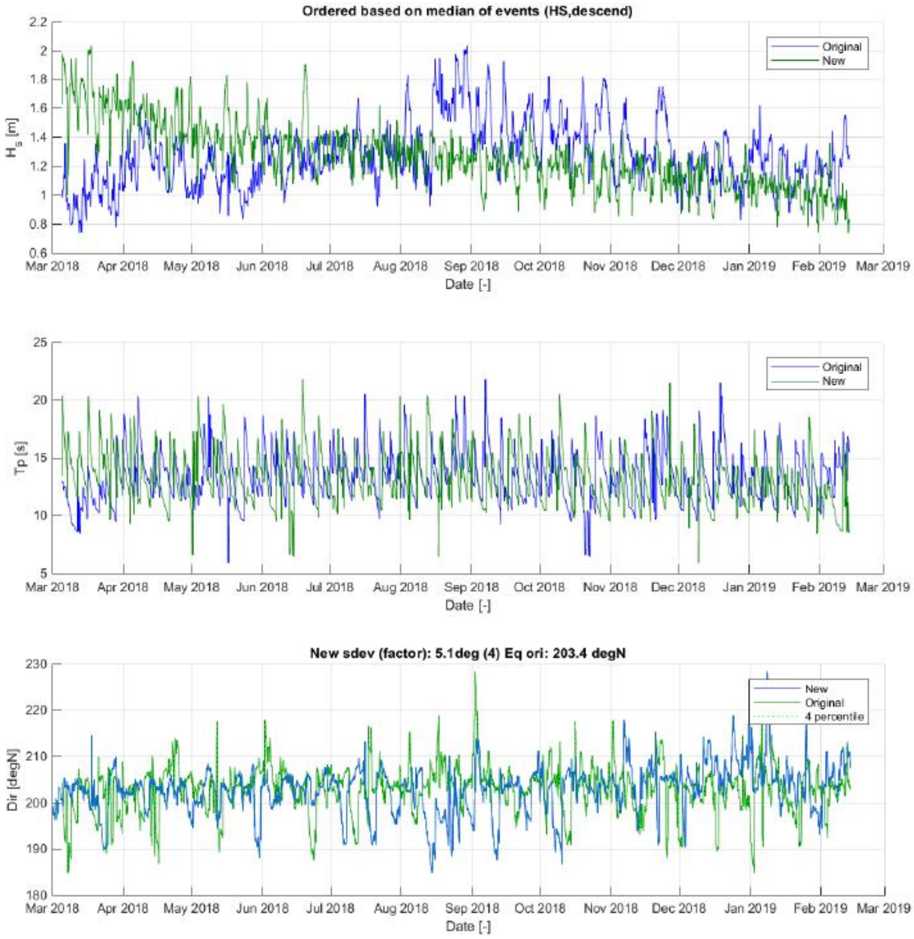


Figure 4.26: The Lekki wave climate ordered by means of descending median wave height per wave event.

The ordering by wave height is easy to distinguish in figure 4.26. Where the original wave climate had its peak from August to December, the new wave climate starts with these wave events. The events based on period keep the characteristic high to low period events together well. As already discussed shortly in the method and what also is clearly visible in when looking at the wave climate time series is the low correlation between the wave parameters. The correlation coefficients are calculated to check the amount of correlation. The results are shown in table 4.4. A correlation of 0.38 between the wave period and wave height is the highest value. This effect is however hard to distinguish in the wave climate time series. Wave direction and wave height are uncorrelated as r=-0.04. The correlation between the wave direction and period has a value of r=0.005 also indicating no correlation. The absence of (high) correlation coefficients indicates that ordering the wave climate by one of the parameters does not also order one of the other parameters in the same way.

This is a positive feature of the wave climate for this study, as it will result in showing the effect of ordering one of the parameters only.

Correlation, r [-]	H_s	T_p	Dir
H_s	-	0.38	-0.04
T_p	0.38	-	0.005
Dir	-0.04	0.005	-

Table 4.4: Correlation coefficients for the different wave parameters of the Lekki wave climate between March 2018 and March 2019.

Model results

First the influence of the wave sequences on the sediment transport at the cross section just updrift of the breakwater (617.5km xUTM) is analysed to show how the chronological order of the wave height and direction influences the net longshore transport. In figure 4.27 the results are shown by means of the volume passed through the cross section, the net transport, over the first year. The transport for the year two to nine are very similar and can be seen in appendix E. In this graph the longshore transport belonging to the original climate is shown in blue, the climates ordered by direction are shown in continuous lines and the climates ordered by wave height are shown by striped lines. Ascending and descending order is indicated by green and red colour lines respectively.

The most interesting thing to notice about figure 4.27 is transported volumes for both ascending ordered climates are very similar and both descending ordered climates are also very similar. Secondly, the transported volume of the ascending climates is relatively similar to the calibration climate during the first half year: First the transport rate (slope of the graph; dS/dt) is low, which is due to the waves resulting in the lowest longshore transport rate (lowest angle or lowest wave height) happening first. Over the year the rate increases. The descending climates show opposite development over the year; with first a high transport rate followed by a decreasing rate the second half year. This means that the original climate tends more toward the ascending ordered climates than the descending ordered climates. Whether or not this will result in equal morphological development will be discussed by means of comparing the coastline responses.

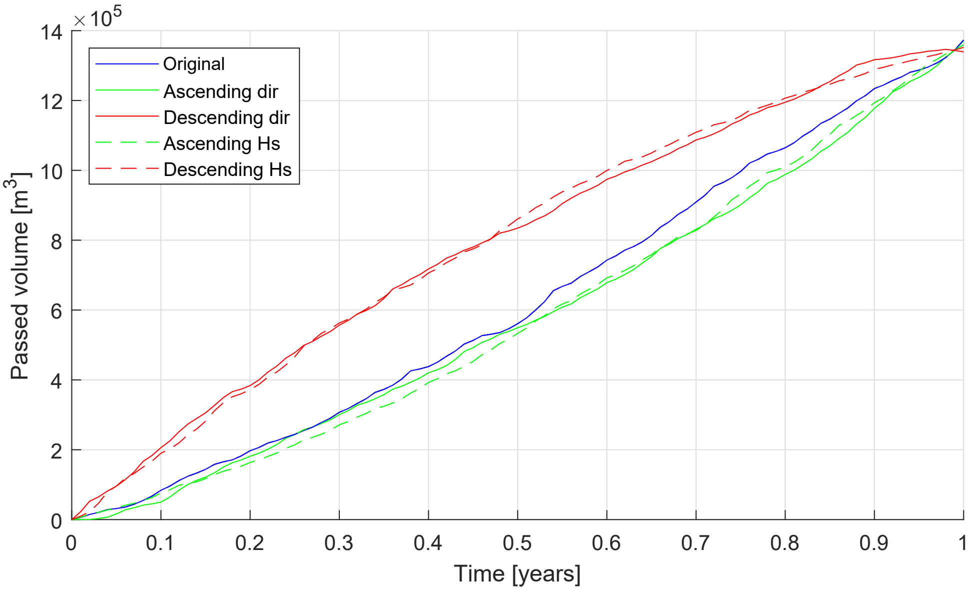


Figure 4.27: The sediment transport over time through the 617.5km xUTM cross section, which is just updrift of the breakwater.

The differences in longshore transport rate over the year between the different wave climate sequences translates into a variation of the coastline location, as can be seen in figure 4.28 for both height (upper graph) and wave direction (lower graph). These figures show the maximum amount of erosion at any cross section of the sandbar over time. Or in other words: At any moment in time the cross section showing the largest amount of retreat or the smallest amount of accretion in relation to the coastline location at the start of the model run, is shown in this figure. Figure 4.29 shows the longshore location corresponding to the maximum coastline retreat. This figure shows the minimal coastline location for each cross section for the entire modelled period. In all four graphs the original climate is indicated by a blue line, the ascending climate by a green line and the descending climate by a red line for both the height as the direction.

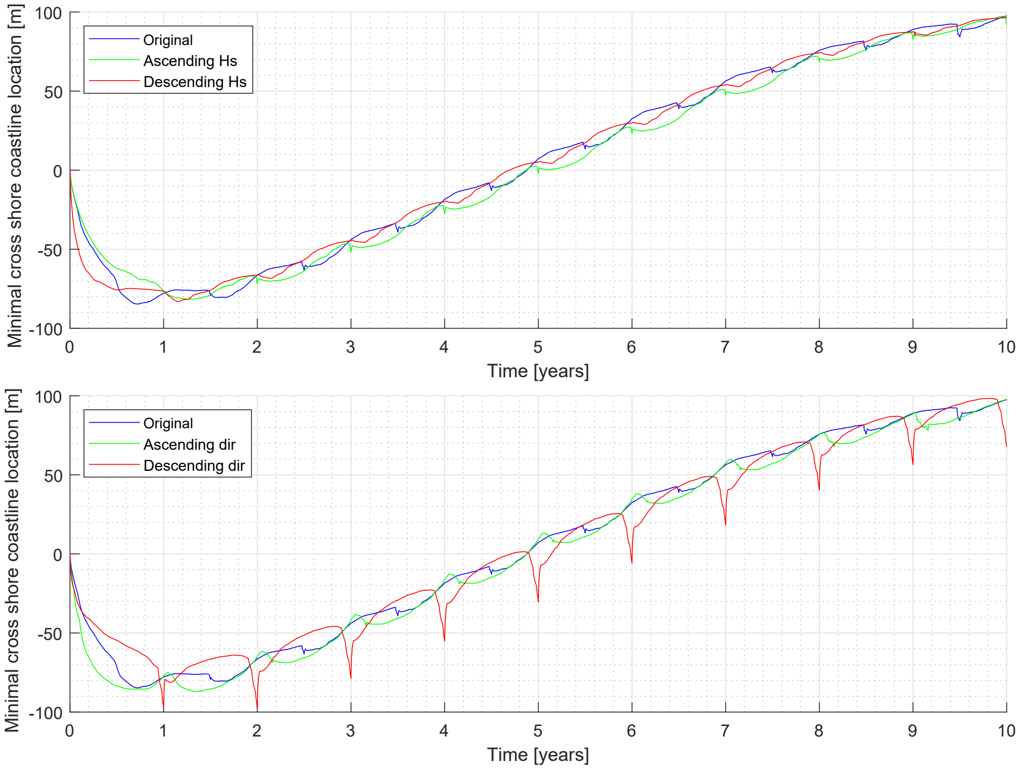


Figure 4.28: For both the climates order by height and direction the minimal cross shore coastline location over time are shown by means of a blue line for the original climate and green lines for the altered climates. Each line indicates the maximal amount of coastline retreat somewhere on the breakwater. A red asterisk indicates the minimum per climate.

The differences in sediment transport rate over the year, result in fluctuations of the minimal coastline location for both wave height and direction. The development starts with a period of 1 to 2 years of erosion for all climates. After that period the coastline slowly starts accreting over the entire shoreline. In terms of maximal coastline retreat, the most influential climate alteration is the climate ordered by a descending wave climate. With 98m of coastline retreat, a descending direction proves to create the largest amount of erosion of all sequences. For the climates with different sequences (original, ascending direction and de- and ascending height) the maximum amount of erosion never passes the 90m mark. The larger influence of the descending direction can be explained by looking closely at how the sandbar breakwater develops just after construction has finished. This has been discussed in detail in figure 3.11 from the previous chapter. When the first waves that reach the just finished breakwater are from western direction, a transport in the eastern direction over the entire coastline and sandbar breakwater length will be the result. This results in a larger amount of accretion near the groyne. Also the coastline will adjust during this period to a smoother more continuous coastline (image 2 figure 3.11). The orientation of the smooth coastline is such that the descending wave direction will rotate past the shore normal at some point resulting in transport in western direction for the rest of the year. This effect can be seen in figure 4.28: At the end of each year the coastline retreats rapidly due to the waves generating a transport in western direction. The result is a larger amount amount of erosion than the other sequences near the groyne. A second reason for the large increase can be the absence of the shadow effect of the breakwater. Waves that come from an eastern direction will in reality be blocked by the groyne, but this effect is not modelled in this study. As the last waves each year all come from western direction, this results in a large amount of erosion at the tip.

The location of the maximal amount of coastline retreat over the longshore direction is presented in figure 4.29 for the wave height and the wave direction. The maximum locations are indicated by a red X. Just like for

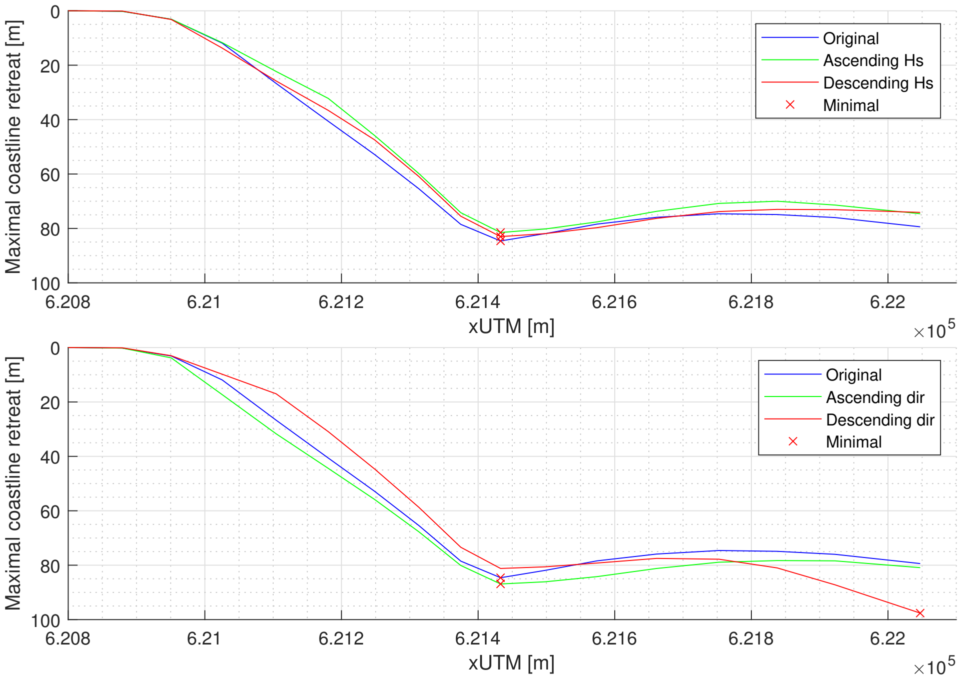


Figure 4.29: The maximal coastline retreat per cross section over the breakwater length for the climates ordered by wave height (upper figure) and the climate ordered by wave direction (lower figure). The lines indicate the maximal amount of coastline retreat in the 10 year modelling period. A red asterisk indicates the maximum amount of retreat over the entire coastline per climate.

the mean direction and directional variation climate alterations, the maximal amount of coastline retreat is at the 621.4km xUTM cross section for all sequences except the descending direction sequence, for which the maximum is near the groyne. For the climates with the maximum at 621.4km xUTM the amounts of retreat are very close to the original wave climate, indicating the influence of the chronological order of waves on the morphological development is low, for these climates.

For other locations in the world it could be possible that seasonal variability of the wave direction results in a climate which shows similarity to the climate ordered by descending wave direction. For the combination of a Lekki like sandbar breakwater design and a wave climate which shows this kind of behaviour a larger amount of cross shore erosion should be expected.

4.5.3. Sub conclusions

The main goal of this subsection was answering the question:

How will the coastline develop when the wave climate has a different sequence over time?

The order of occurrence of the mean wave height and mean wave direction does influence sediment transport rates and with that morphological development of the breakwater. The main differences are in the rate with which the morphological development occurs. For all climates except the climate ordered by a descending direction the maximum amount of coastline retreat is very close to the 87 meters of the original wave climate. The descending direction climate shows 98 meters of erosion, which is only a slight increase. The location of the maximum amount of erosion is near the groyne for the descending direction climate, the other climates have their maximum at the 621.4km xUTM mark (figure 4.13).

4.6. Discussion sensitivity study

The research has been performed while taken into account as many processes as possible. A well calibrated model was setup and is used to research the influence of several parameters of the wave climate on the sandbar breakwater at Lekki. Some (fundamental) decision were made which are elaborated below:

1. In this sensitivity study mainly the influence of the wave direction on the development of the breakwater has been researched. This was decided as it was expected that the wave direction would have more influence that the wave height and period. However the influence of the wave height and period is also important for the development, as these parameters determine transport rates as well.
2. The effect of local storms on a construction like the sandbar breakwater should not be forgotten. Storms can impose dozens of meters of coastline retreat during one event. In Lekki these kind of storms don't occur, however when considering building the sandbar breakwater at other locations this phenomenon should certainly be taken into account.
3. The model used for this research, Unibest, calculates sediment transport based on the coastline orientation, sediment and water characteristics, and wave parameters. The model takes into account linear refraction, non linear dissipation by wave breaking and bottom friction. The model does this however only once in the LT (longshore transport) module which is used to calculate transport rates for the entire wave climate time series series all at once. There is no interaction between coastline development and the wave climate in the CL module. For the larger part of the breakwater this will be no problem, however close to the groyne effects like sheltering and diffraction of waves could give other results in real life than that are modelled during this study.
4. During the sensitivity study the wave climates are created for 1 year. This climate is then repeated 10 times to calculate the 'ten year development'. This is of course not realistic as wave climates tend to have variations over the years (see for example figure 4.14). For the sake of determining the influence of (small) climate alteration, this is considered to be fine. When one wants to predict the development of a sandbar breakwater for design purposes, these variations should be taken into account.

4.7. Conclusions sensitivity study

The wave sensitivity study is performed to research the influence of the wave direction on the morphological development of the sandbar breakwater. With this study an answer can be given to research question 2a and 2b:

2. How sensitive is the sandbar breakwater concept in general to variations in the wave climate?
    (a) Which direction related wave climate variations are of significant influence on the Lekki sandbar breakwater development?
        i. What is the effect of the mean wave direction?
        ii. What is the effect of the directional variation?
        iii. What is the effect of the event sequence?
    (b) Is a unidirectional narrow bandwidth wave climate necessary for the Lekki sandbar breakwater to become stable?

For all but a few climates the morphological development is characterised by first erosion and thus the maximal amount of coastline retreat and thereafter steady accretion sets in. This takes about 1 to 2 years. The climates for which the mean direction is rotated in counter clockwise direction are the exception, as after some amount of rotation erosion will not stop during the modelled period.

The mean wave direction is the climate alteration that imposes the largest differences on the morphological development. This is due to the longshore transport rate changing significantly. For the Lekki wave climate the yearly variation of the mean wave direction proved to be such that the mean wave direction could have been -2 degrees different during the first year. This would have imposed an extra coastline retreat of 40 meters. Climates which are rotated in clockwise direction impose a large supply of LST and make that the breakwater erodes less than the original Lekki wave climate. The maximum amount of erosion is on sandbar corner (at 621.4km xUTM, figure 4.13). The climates imposing more erosion, counter clockwise rotated, impose the maximum amount of erosion near the groyne.

An increase of directional variation imposes more erosion. The increase of erosion is however relatively small: Up to 33 meters extra, relative to the original climate for an increase of the standard deviation of the wave direction of a factor 4 to 4.5 (corresponding standard deviation is 20.3 and 22.9 degrees respectively). This proves that although the amount of erosion increases, the breakwater still becomes stable, as for all climates accretions sets in during the second year. This also answers the question whether or not a unidirectional narrow bandwidth wave climate is really necessary.

The effect of the sequence of wave events is the smallest of the tested wave climate alterations. Changing the chronological order of the climate based on the wave height does not change the coastline retreat (significantly), only the rate of change over the year is affected. The same is true for the climate ordered by an ascending wave direction. For all of these three climates the maximum amount of coastline retreat is at the 621.4km xUTM cross section (figure 4.13). For the climate ordered by a descending direction the situation is slightly different. The maximum amount of coastline retreat is not only more (+10 meters relative to original climate), but also the location is near the groyne. This change of amount and location is the result of all waves at the end of the year imposing a transport in western direction.

5

Discussion, conclusions and recommendations

The sandbar breakwater concept is based on the principle of applying a minimal nourishment which is then adjusted and supplied by natural processes. Of course it is possible to just apply a huge amount of sediment at locations with unfavourable conditions. This would however not results in the true application of how the concept is intended to be used. While keeping this in mind it is thus very important to understand how such a structure develops under certain wave conditions. This study aimed to do just that. Of course some limitations were necessary; the Lekki breakwater is used with several variations of the original wave climate, instead of testing all possible wave climates and corresponding breakwater designs. This results in the understanding of how the Lekki breakwater would have reacted when the wave climate was different during its first year after construction (and thereafter). The translation from these results to ‘understanding how such a structure develops under certain wave conditions’ is difficult. The three tested alterations show how the breakwater reacts to deviations from the original climate specific for the Lekki breakwater. When considering building a breakwater somewhere around the world, the wave climate will, in most situations, not be equal to the Lekki climate or one of the tested variations. It is however possible that similarities in the wave climate are present. These similarities will be the base for discussing how the results of this research can be used for applications of sandbar breakwaters at other locations around the world without directly making use of a hydrodynamic model. With that, research question 2c, 2 and the main research question will be answered:

How is the coastline evolution of the sandbar breakwater concept affected by directional variations in the wave climate?

2. *How sensitive is the sandbar breakwater concept in general to variations in the wave climate?*
    (c) *To what extent can the sensitivity of the Lekki breakwater to wave climate variations be translated to the sensitivity of the sandbar breakwater concept in general?*

5.1. Discussion

in chapter 4 the influence of the mean wave direction, directional variation and the sequence of waves on the morphological development of the Lekki breakwater are discussed. The study showed that the Lekki sandbar breakwater could have ’survived’ many of the alterations done. This does of course not automatically mean that the sandbar breakwater design of Lekki can simply be copied and build at comparable climates. But it does mean that the concept has some resilience against different wave conditions. The study also shows the influence of the wave conditions on the LST.

That LST is important was already shown in figure 3.11: In the time just after construction, the initial layout in combination with the wave direction imposes LST in two direction. It is the balance between the amounts of transport in these two directions that determines whether or not very large amounts of coastline retreat will occur. This is also shown by the results of the alteration of the mean wave direction; which has a very large influence on the maximum amount of coastline retreat. This result could be generalised as follows: It is always necessary to have one dominant direction of the LST in the direction of the breakwater, which is in the Lekki situation from West to East (left to right in figure 3.11).

One dominant direction of the LST can only be reached when the sum of the wave energy from waves coming from a certain direction is highest on one of the sides of the shore normal line. This can either be the result of a wave climate such as the climate at Lekki, or a bidirectional climate with one dominant direction, or a climate with a large bandwidth of the direction with most wave energy on one side of the shore normal, or one of many other possible climates. In short; there are countless possibilities for which the sandbar breakwater could be feasible and as much, maybe more, where it is not. This feasibility is thus a result of the sensitivity of the breakwater to the wave conditions. Some possible wave conditions have been created and tested during the sensitivity study, but also countless other possibilities exist which were not feasible to research during this study. For these conditions a comparison could be made to the results of this study, or detailed (modelling) research could be done to asses the feasibility. This also shows to what extent the results of this study could be used for the general application of the sandbar breakwater concept: It is possible to use the results to make an assessment of the feasibility of a successful application, however quantifying amounts of erosion is one step to far.

5.2. Conclusions

The data analysis followed by the sensitivity study have been performed to increase the understanding of the sandbar breakwater concept. This final conclusions section will answer the main research question and question 2(c):

How is the coastline evolution of the sandbar breakwater concept affected by directional variations in the wave climate?

2. *How sensitive is the sandbar breakwater concept in general to variations in the wave climate?*
    (c) *To what extent can the sensitivity of the Lekki breakwater to wave climate variations be translated to the sensitivity of the sandbar breakwater concept in general?*

The analysis of the sensitivity of the sandbar breakwater shows how the sandbar breakwater like structure develops under the wave climate at Lekki and variations of this climate. These results can be used for assessing the feasibility of a sandbar breakwater under other wave conditions by comparing the wave climate of any location to the climate at Lekki, or one of the alterations made to that climate. Based on any similarities an estimation of the behaviour of a sandbar breakwater at that location could be made without the need for complex computations.

Taking it one step further; based on the sensitivity study the following can be said about the sensitivity of the model of the sandbar breakwater at Lekki and can also be true for similar structures in general under the influence of other wave climates:

- Small variations (order of degrees) in the mean wave direction could lead to a significant increase of coastline retreat (order of tens to hundreds of meters).
- Variations of the directional variation (standard deviation of the wave direction) lead to a maximum of several dozens of meters of coastline retreat.
- And lastly, when considering the seasonality of a wave climate, an increase of the amount of coastline retreat near the groyne can be expected when the wave direction turns from the favourable directions to the unfavourable directions over time.

These conclusions show to what extent the results of the sensitivity study can be generalised; as it is not possible to give an amount of erosion belonging to a certain kind of wave climate, but rather an indication of what kind of influence the tested wave alterations (mean direction, directional variation and wave climate sequence) have on a sandbar breakwater like structure in general can be given.

5.3. Recommendations

Based on this study recommendations can be made on what to consider when one want to construct a sandbar breakwater type of structure somewhere around the world without directly making use of a hydrodynamic model. As this study mainly focused on the morphological development of the breakwater in a swell wave climate only requirements based on this will be discussed. This means that phenomena like downdrift erosion and the functionality of the harbour basin due to wave penetration are not discussed. Future research could supplement and improve this list. The two main requirements are:

1. Coastline type: The coastline should be sandy and an abundance of sand should be present (also after several years there should be no disturbance of the updrift supply of sediment).
2. Wave climate: The wave climate should consist of wave directions which impose a sufficiently large LST volume in one direction.

All wave climates have a certain yearly mean wave direction, a standard deviation around this mean and a certain seasonality (wave sequence). When the wave climate and the coastline orientation at some location is known a comparison between the considered location and the results of this research can be made. This could be done in two, possibly consecutive, ways: 1) By simply comparing the considered wave climate to the wave climate at Lekki in terms of the height, period and direction, and/or 2) by going one step further and calculating the LST rates and comparing the outcomes to the results of chapter 4. When the wave climate seems to be similar to the Lekki wave climate, the first step would probably already give a reasonably well first estimation of whether or not a sandbar breakwater would be feasible at that location. Most climates will however be significantly different, or show for example only a similarity for one of the parameters. For climates like this it could be favourable to know what the LST rates are. When a large net amount of LST is calculated the sandbar breakwater could be a feasible option.

For an estimation of the yearly net LST amounts one could look for example at figure 4.7 on page 39, which shows the LST volumes for different mean wave directions at Lekki. The most critical value of -4 degrees shows a transport rate of about 500.000 m^3/year, which could be seen as the absolute minimal value needed for the breakwater at Lekki to survive just barely.

This value of 500.000 m^3/year should be treated as a first hint of whether or not a sandbar breakwater could be a feasible option. The value is purely based on the Lekki wave climate and breakwater design. It could be possible that with small adjustments of the breakwater design (e.g. increasing the buffer or changing the angle of the coastline) a lower amount would suffice, this was however outside the scope of this thesis. Further research by using for example a one-line and/or 2D-H model is recommended.

5.3.1. Future research

To increase the understanding of the possibilities of the sandbar breakwater like structures the following topics can be interesting to follow up on this research:

1. This research did not investigate how (local) storm events can influence the (coastline) development of the sandbar breakwater. As many coastlines around the world are prone to such storms it can be favourable to research this influence.
2. This research only looked at the morphological development of the sandbar breakwater, but did not take into account the effect the wave climate alterations have on wave penetration into the basin. It could very well be that (some of) the considered climates form good conditions for the morphological development, but constant wave penetration into the basin prevent ships from being able to (un)load. The influence of the wave climate on the wave conditions inside the basin should therefore also be considered.
3. Future research could be done on finding the optimal design in terms of the initial layout; parametric design. Thus finding the smallest possible initial nourishment while still maintaining enough buffer at the sandbar. Some of the results of this study could already be used to determine which width would have been sufficient for the sandbar if one of the altered climate would have been the design climate.

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List of terms

Term	**Nederlands**	**Definition**
Accretion	Aanzanding	Increase of the the amount of sand (result of sedimentation, opposite of erosion)
Bathymetry	Bathymetrie	Spatial elevation of the sea bed
Breakwater	Golfbreker	Elongated structure preventing wave penetration into harbours
Calibration	Kalibratie	Adjusting a (computation) model to simulate measurements as closely as possible
Coastline orientation	Kustlijn orientatie	Angle of normal line of stretch of coastline relative to North
Conceptual model	Conceptueel model	A representation of a system used to help understand the subject the model represents
Cross shore sediment transport	Dwarstransport	Transport in perpendicular direction to the coastline
Directional variation	Richting variatie	Amount of variation of the wave direction
Downdrift	Benedenstrooms	Strech of coastline in the direction LST moves towards
Equilibrium coastline orientation	Evenwichts kustlijn orientatie	Orientation of the coastline resulting in no, or only small amounts of, sediment transport
Erosion	Erosie	Removing of sand by natural processes (opposite of accretion)
Groyne	Kribbe	Shore perpendicular structure usually to trap sediment and break waves
Hindcast model	Terugrekenmodel	Model that simulates effects of measured phenomena
Longshore sediment transport (LST)	Langstransport	Transport of sediment in shore parallel direction
Model	Model	Simplified representation of reality
Morphology	Morfologie	Changing of the bathymetry as a result of sediment transport
Nourishment	Suppletie	Human process of supplying sand
Overtopping	Golfoverslag	Waves flowing over the breakwater
Rubble mount breakwater	Lichaam van stortsteen	Breakwater made of loose material, usually rocks
S/phi curve	S/phi curve	Graph indicating amount of sediment transport belonging to a certain wave angle
Sandbar breakwater	Zandige golfbreker	Breakwater of which the wave breaking part is replaced by or supplemented with sand
Sediment transport	Sedimenttransport	The natural movement of sediment by waves and/or currents

Term	**Nederlands (Dutch translation)**	**Definition**
Sequence	Rij (Opeenvolging)	A series of related things or events, or the order in which they follow each other (Cambridge dictionary)
Stability	Stabiliteit	Resistance to being changed
Surveys (Bathymetrical ...)	Peiling	Measurement of sea bed elevations
Swell waves	Deining	Waves that are no longer sustained or being generated by wind, generated far away
Swell waves	Deining	Waves that are no longer sustained or being generated by wind, generated far away
Time series	Tijdserie	Parameter values over time
Unidirectional	unidirectioneel	Only comming from one (or a small range of) direction(s)
Updrift	Bovenstrooms	Strech of coastline in the direction LST comes from
Validation (of model)	Validatie	To check the outcome of a (computational) model to a measured outcome
Wave climate	Golfklimaat	Wave conditions at a specific locations
Wave parameters	Golfparameters	Wave height, period and direction
Wind waves	Windgolven	Waves being still being generated nearby location of interest

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A

Wave data comparison

A.1. Waveclimate VS NOAA

BMT ARGOSS uses an 'in-house improved' version of the NOAA Wavewatch III hindcast model to calculate wave characteristics using wind-data (Groenewoud and Hulst, 2016). Offshore gridpoints with a distance of 0.5 degree longitude and latitude can be selected for the calculation of the offshore wave climate. The so-called Shallow Water Wave Ray Tracing (SWRT) model, is used to make the offshore to nearshore transformation. This model has however a few limitations as it does account for sheltering, refraction, shoaling, local growth, white capping and wave breaking, but does not account for diffraction, reflection, currents, water level variations, non-linear wave interaction, current refraction and bottom friction. (Groenewoud, 2016).

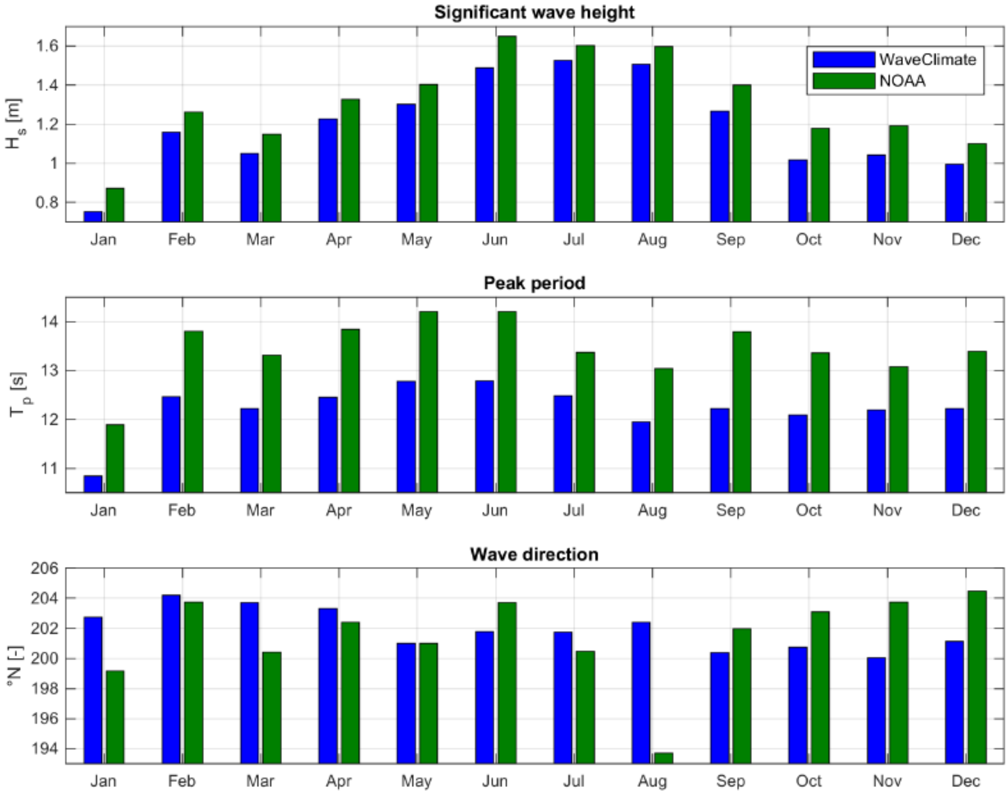

Figure A.1: Comparison between the significant wave heights, Peak period and wave direction of the NOAA and WaveClimate wavedata for the year 2018 averaged per month. The average differences are: 0.116m, 1.21s and -0.438°.

A.2. WaveClimate VS wave buoy

Boskalis supplied wave data from a WaveRider buoy which has been used to measure wave height and direction from 23-12-2017 to 29-03-2018 just offshore of the location where the breakwater was to be build. The data has been compared to the hindcast wave data from WaveClimate. The results for the significant wave height can be seen in figure A.2 and for the direction in figure A.3.

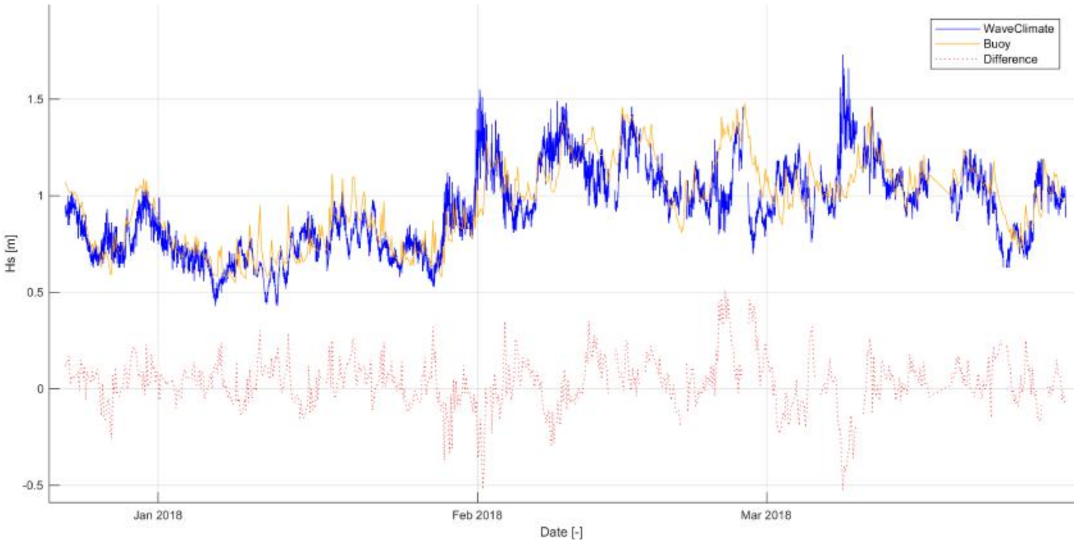

Figure A.2: Waveclimate significant wave height versus the wave buoy significant wave height

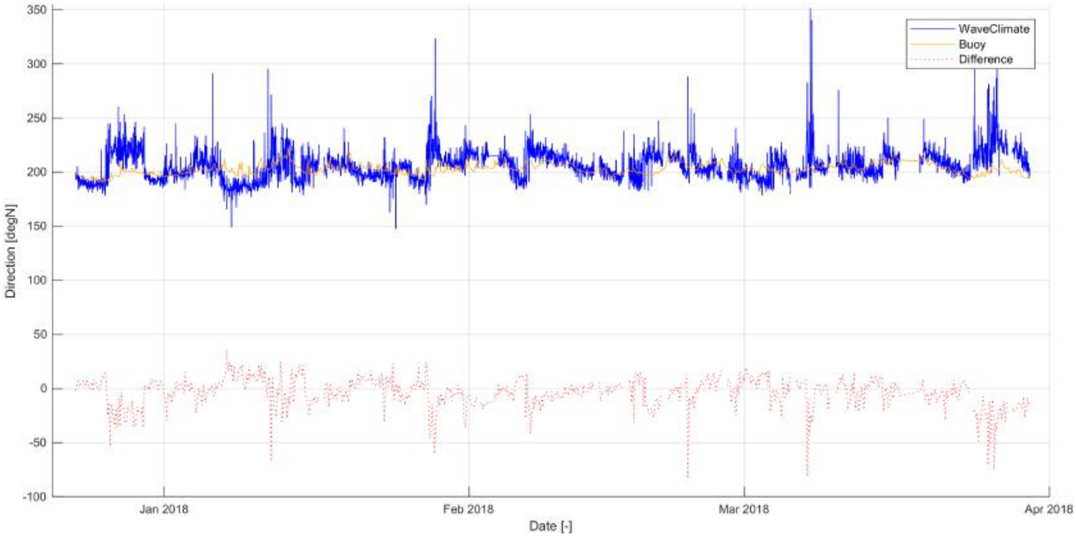

Figure A.3: Waveclimate wave direction versus the wave buoy wave direction

Both figure show a rather good resemblance of the wave climate measured by the Waverider bouy by the WaveClimate model. The average deviation of the significant wave height is +0.03 meters and of the wave direction is -3.9 degrees. Which can be considered small for both wave characteristics. The WaveClimate data is therefore considered sufficiently accurate to use for further research.

B

Data analysis: Water levels

The water level time series used for determining the tidal variations.

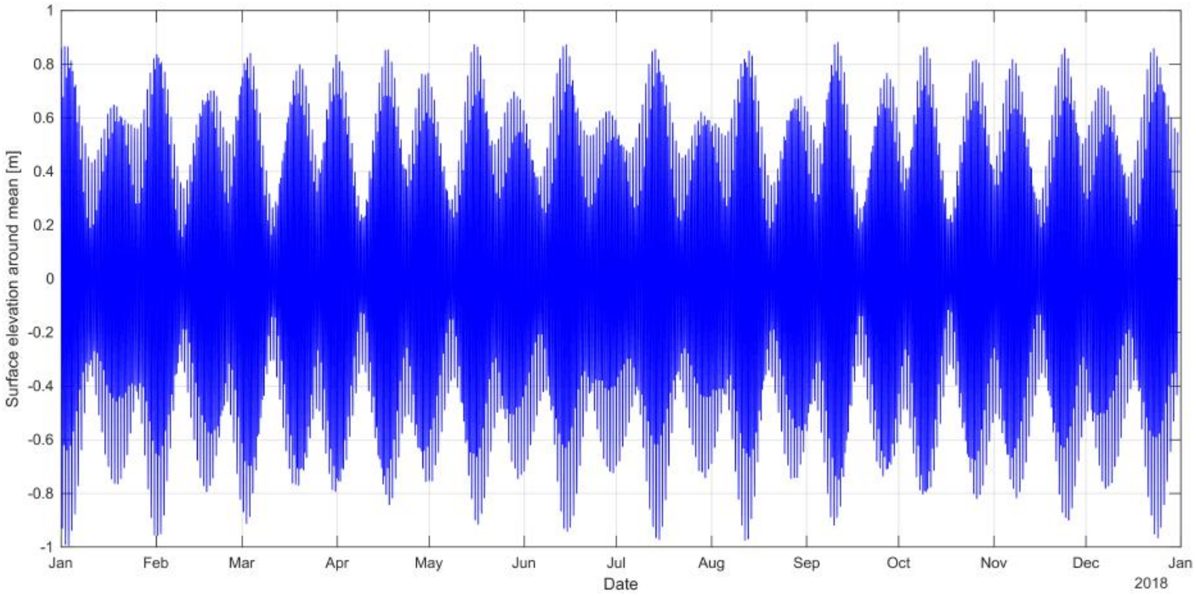

Figure B.1: The water level variations just offshore of the breakwater (6°24'8.42"N and 4° 5'51.51"E) as determined by TPXO.

C

Data analysis: Survey comparison

In figure C.1 the differences between the surveys are shown. The upper figure shows the differences between October and June 2018, the middle figure between October 2018 and February 2019 and the lower figure the difference between June 2018 and February 2019 (As also shown in the main text).

The first thing to note is that none of the images shows the entire area of interest. The area of interest being the area running from the groyne in western direction and stopping where no influence of the breakwater is visible (yet). The surveys of October 2018 not containing the emerged areas means that both the first and the second image only give a very limited overview of what actually happened. The images are however intentionally shown in this report as it does give some insight in the morphological development around the sandbar breakwater. The third image, showing the change between the survey of June 2018 and February 2019, fortunately gives a better overview of the area of interest. The erosion of the sandbar is fully included, however the accretion west of the sandbar is only partly included as this part of the breakwater is not distinctive for the sandbar breakwater.

That being said, it is still possible to see some changes in the upper two figures. The upper image (June 2018 - Oct 2018) shows that erosion has occurred over the eastern part of the sandbar breakwater (621.1-622.0km xUTM). While more to the west (<621.1) sedimentation has occurred. Also near the tip of the groyne a small amount of accretion is visible. The areas north and east of the sandbar are not considered.

The middle image (Oct 2018 - Feb 2019) only shows some accretion at the western part on the upper edge of the available data. It is probable that erosion has occurred at the same location as the first image, however it is not visible in the data.

The lower graph is discussed in detail in the main text.

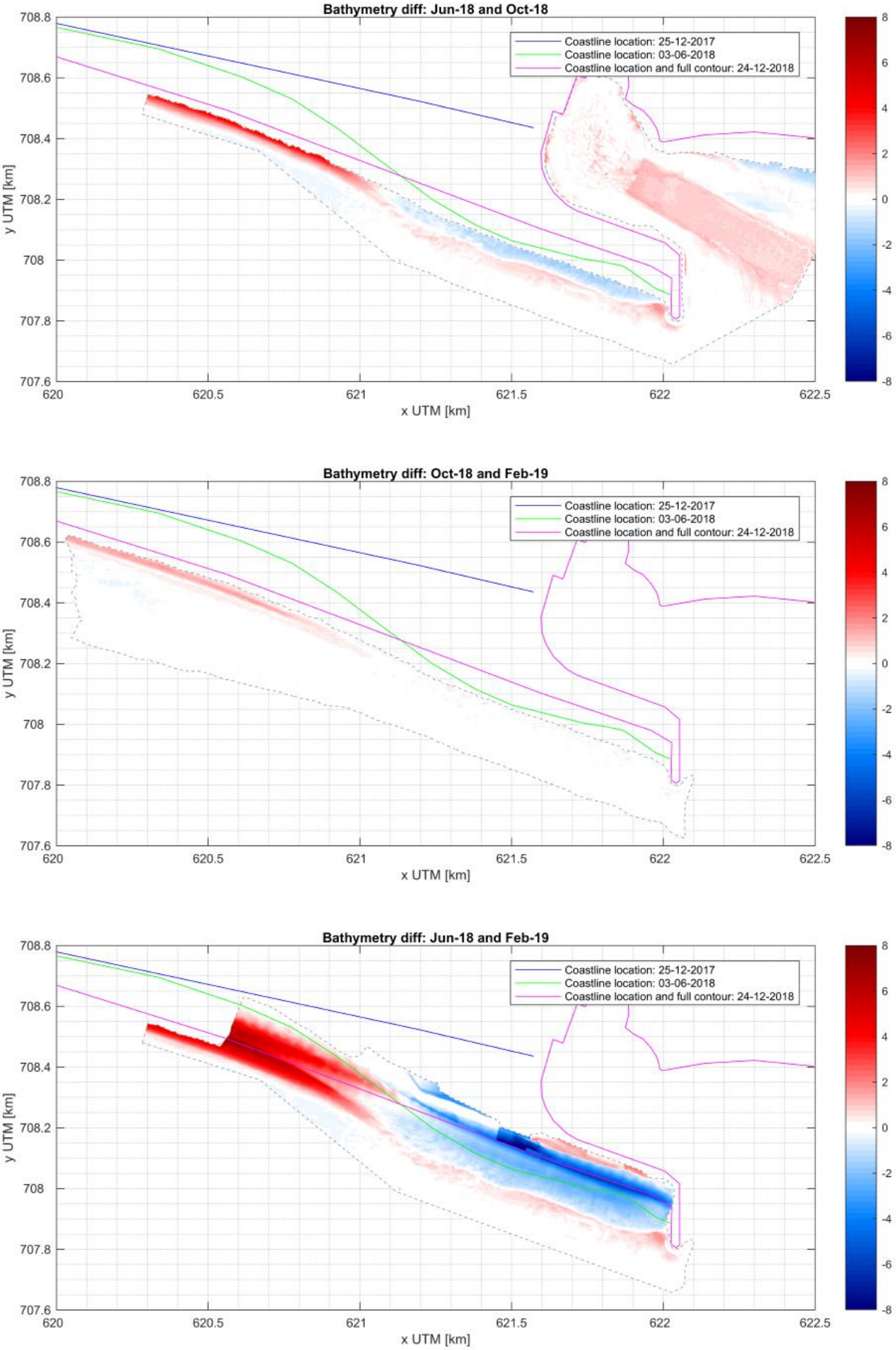

Figure C.1: The change between the survey of June and the survey of October 2018 (Upper image), between October 2018 and February 2019 (middle image), and the change between the surveys of June 2018 and February 2019 (lower image). Please note that the upper two images do not contain the full area as shown in the lower image, as the graph of October only contains the submerged areas. The colorscale indicates the amount of accretion or erosion in meters; accretion in red, no change in white and erosion erosion in blue.

D

Data analysis: Coastline orientation

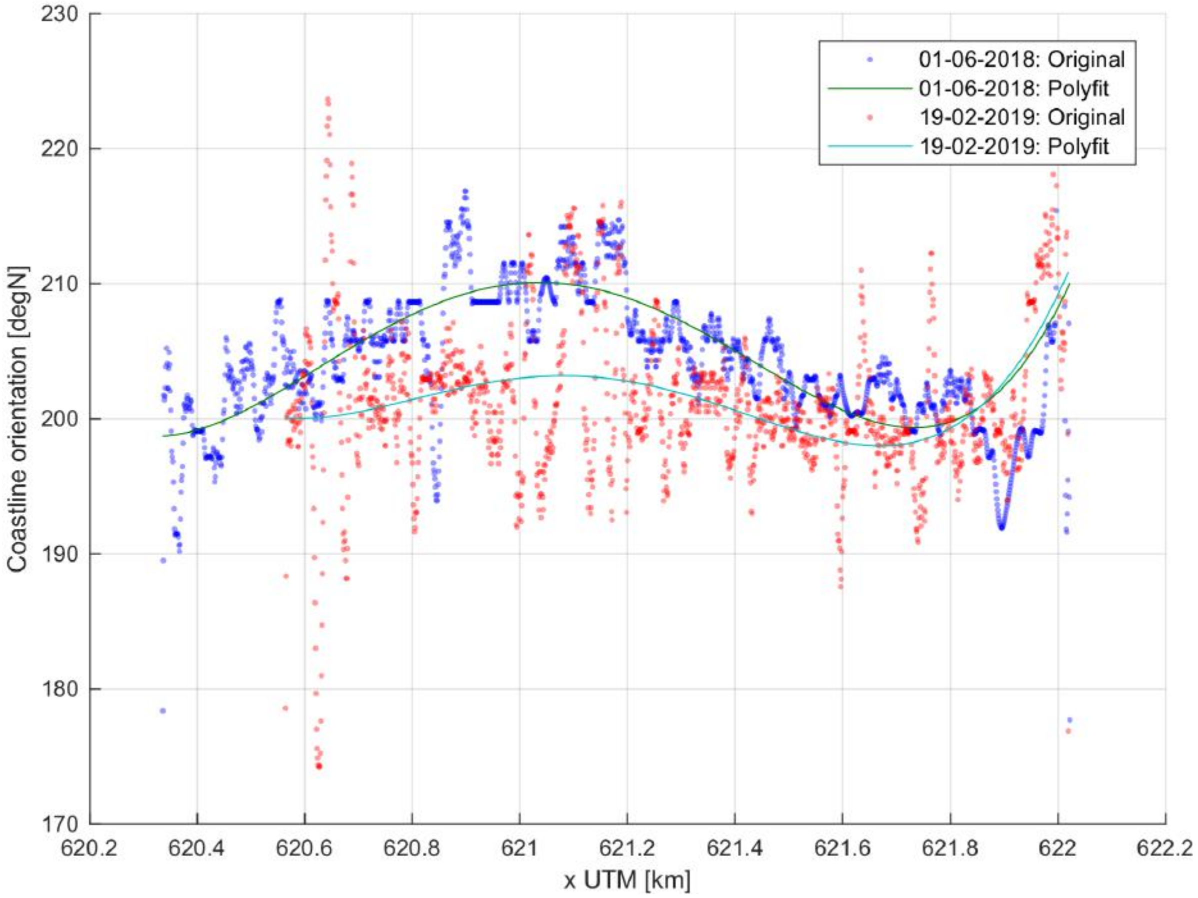

Figure D.1: The scatter plot shows the coastline orientation from the raw coastlines extracted from the surveys of June 2018 and February 2019. The lines shows the polyfit of the scattered data.

E

Sensitivity study: Wave alterations

In this appendix the detail of the how the events are chosen, the three climates belonging to the ascending wave height, and descending and ascending median direction are shown. Also the LST volumes for the entire modelled period are shown for both climates ordered by direction and by height.

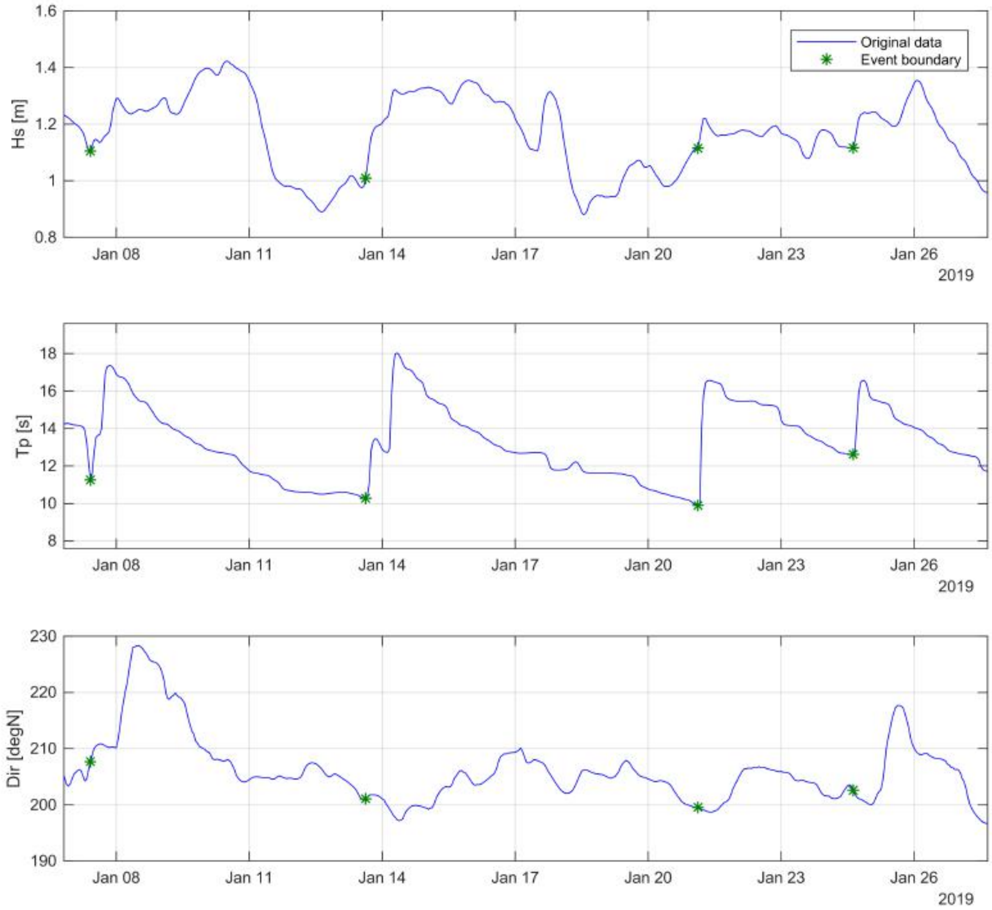

Figure E.1: Detail of 4.25 showing the climate from January 8th to January 26th 2019.

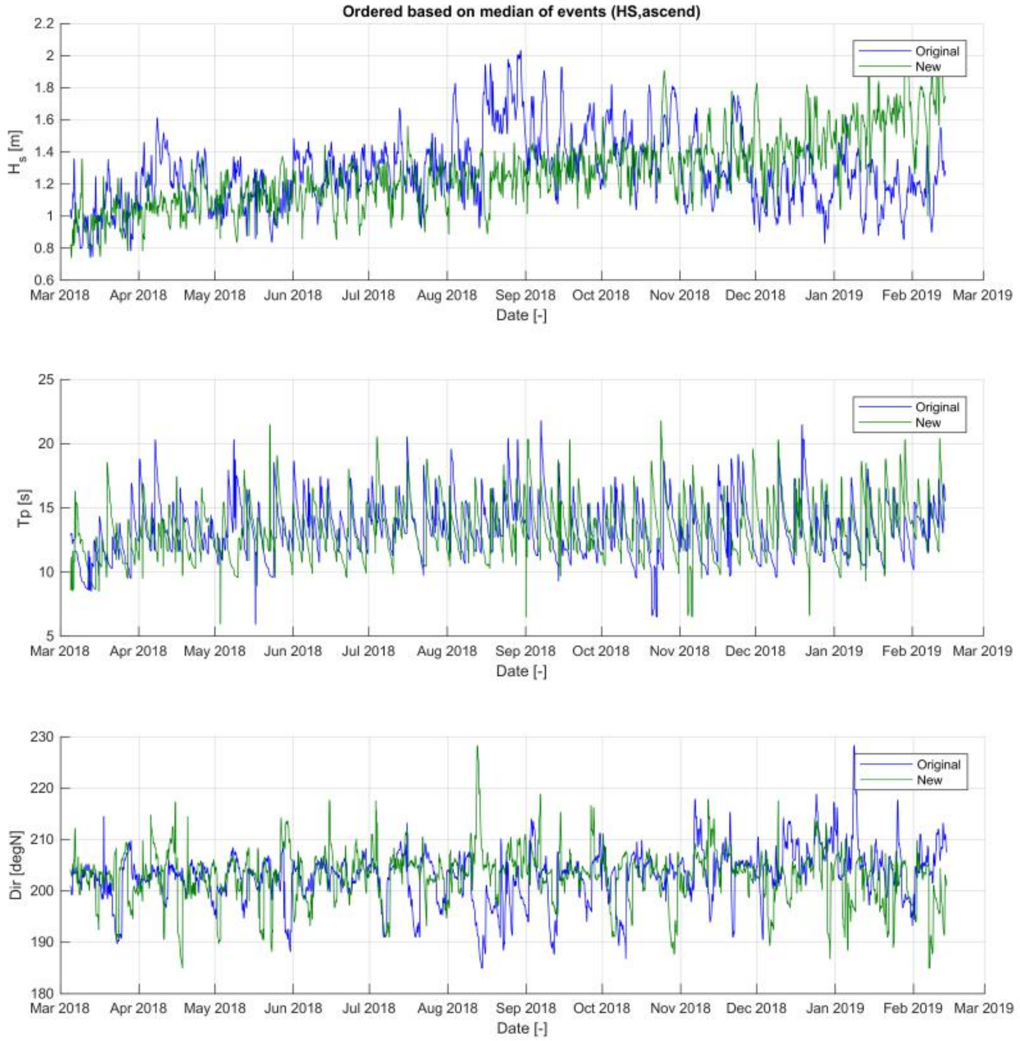

Figure E.2: Ascending median wave height

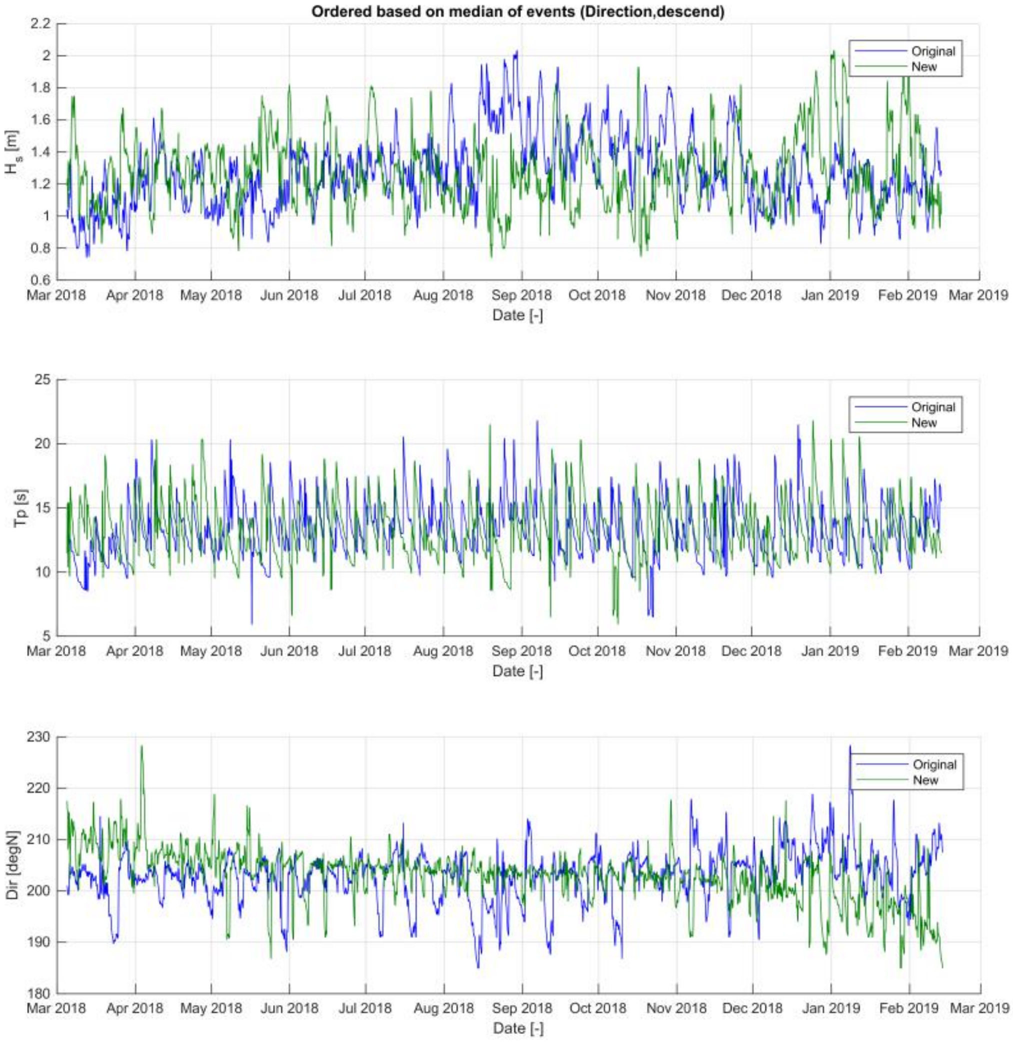

Figure E.3: Descending median direction

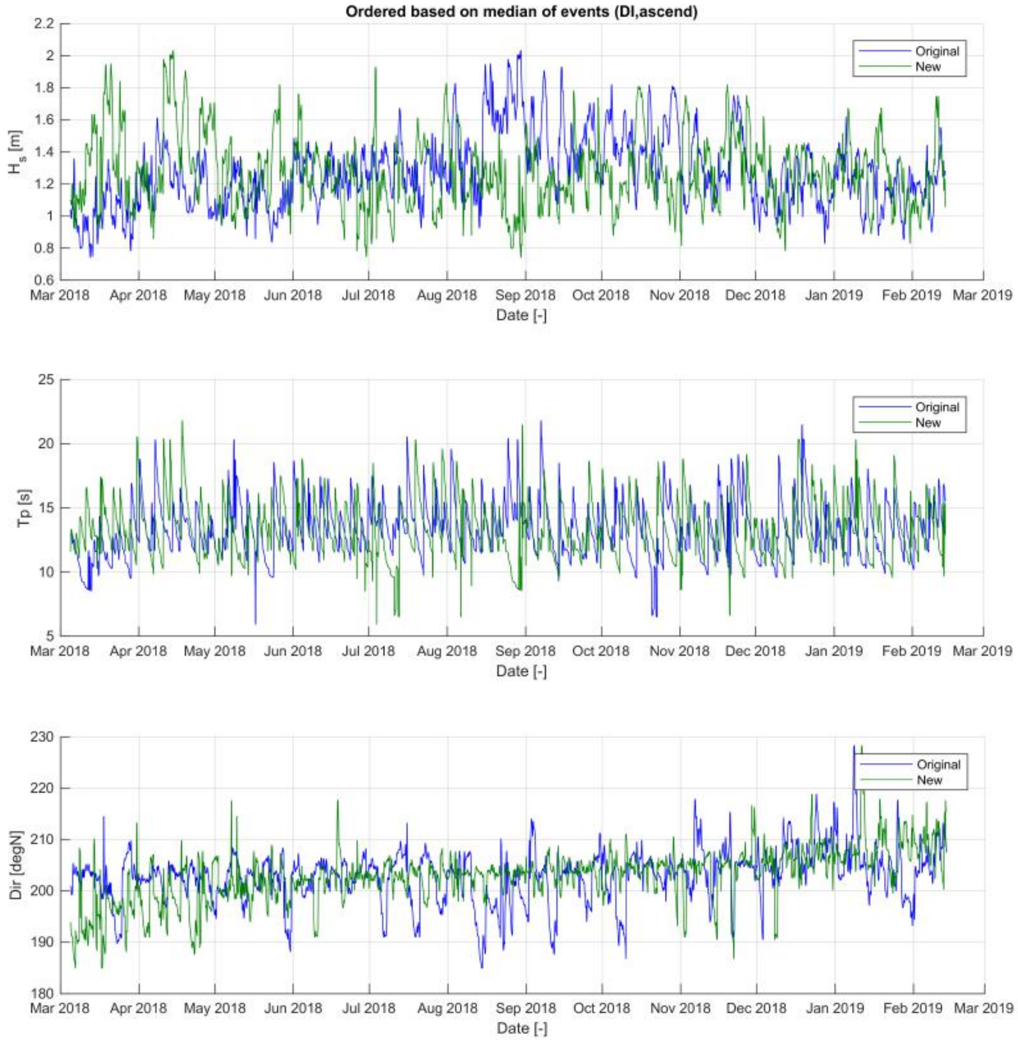

Figure E.4: Ascending median direction

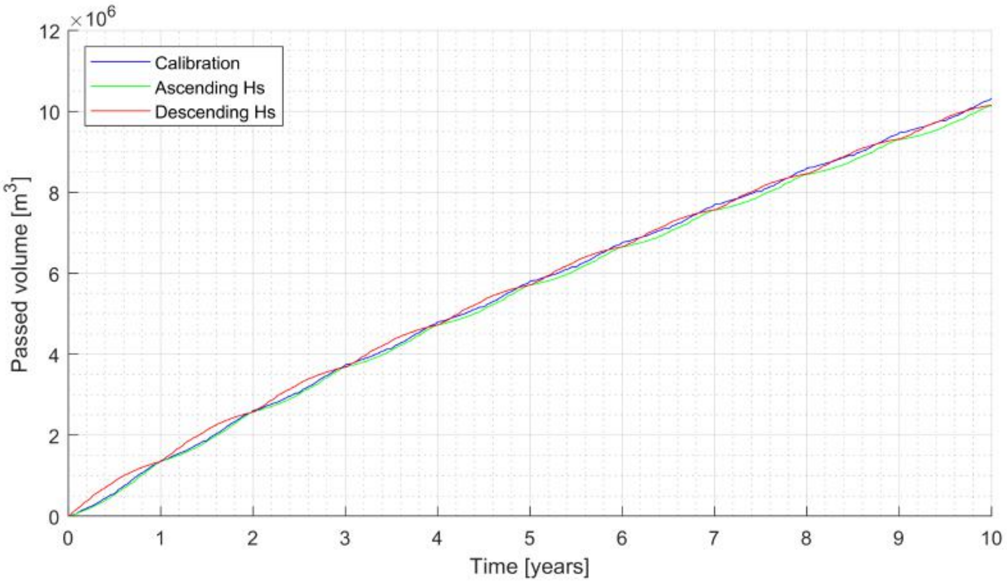

Figure E.5: LST for the climate ordered by wave height

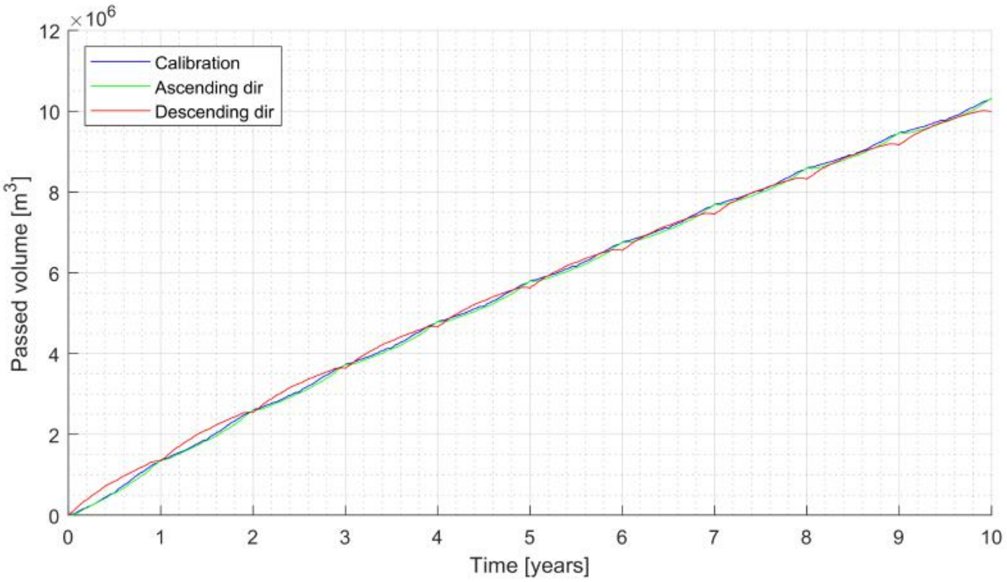

Figure E.6: LST for the climate ordered by wave direction