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# THE BEHAVIOUR OF THE SANDY SHORES OF THE MARKER WADDEN

The morphological development of sandy shores in a lake system and application of design formulae and models

**MASTER THESIS**

IN CIVIL ENGINEERING AND MANAGEMENT
UNIVERSITY OF TWENTE

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** Image cover: Aerial view of the southwest beach of the Marker Wadden, June 2017. Source: Photographed by Straystone.*

# THE BEHAVIOUR OF THE SANDY SHORES OF THE MARKER WADDEN

*The morphological development of sandy shores in a lake system and application of design formulae and models*

in partial fulfilment of the requirements for the degree of

**Master of Science**

In Civil Engineering and Management

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# PREFACE

This report is the result of my MSc thesis as the final part of my study Water Engineering and Management. This thesis has been performed at Boskalis Westminster N.V. at the department Hydronamic. During the past months, I focused on the understanding of the morphological behaviour of the sandy shores of the newly constructed Marker Wadden. To do so, field monitoring has been executed in order to analyse the initial behaviour during the first months after realization. Subsequently, it is investigated whether the observed developments could be simulated by equilibrium models and process-based numerical modelling.

I really enjoyed working on this interesting project and to be the first one to study the behaviour of these new constructed beaches. I would like to thank my colleagues and colleague MSc students at Hydronamic who created a pleasant working environment. Furthermore, I would like to thank Thomas Vijverberg (Boskalis) and Bas Borsje (University of Twente) for their daily support, ideas and constructive feedback. Also, I would like to thank Jan Ribberink and Denie Augustijn (University of Twente) for their valuable advice.

Reaching the end my study career, I can conclude that although it has been a quite long journey, it was well worth the effort. I am proud to reach this point and can say that everything is possible if you have perseverance. I would like to express my appreciation for the ongoing support I received from my girlfriend Eline, my family and my friends during my study.

I hope you enjoy reading my thesis!

Coen Steetzel

Papendrecht, July 2017

# ABSTRACT

In 2016, Boskalis started working on the Marker Wadden, one of the largest nature restoration projects in western Europe. The aim of the project is to transform the ecologically impoverished Lake Marken into a dynamic area rich in animal and plant life, through the creation of nature islands using sand, clay and fine sediment. The sandy shores of the Marker Wadden are exposed to the hydrodynamic conditions in Lake Marken and are aimed to protect the marshlands behind it. Therefore, it is important that these sandy shores are constructed in such a way that they are morphological stable, in both cross-shore and longshore direction. Since knowledge on the behaviour of these newly constructed sandy shores in a lake system is limited, the sandy shores were primary designed using results of the pilot project Houtribdijk -a research on the morphological development of a sandy foreshore in a lake system-, combined with well-known conservative design formulae and numerical models. The usability of these design methods however, is for this specific situation – without tidal fluctuations, relative shallow and short waves – still uncertain.

From the collected bathymetry data of both the southwest beach and northwest beach of the Marker Wadden, analyses are performed focussed on describing the morphological development and the developed cross-shore profile shape. It is investigated whether the observed behaviour can be described by equilibrium methods and if the cross-shore profile shape can be reproduced by the numerical morphological model XBeach.

Analyses on the cross-shore profile evolution, show that a profile shape is formed with an almost horizontal plateau at 0.5 m (northwest beach) and 0.7 m (southwest beach) below the average water line and a steep slope of about 1:10 around the water line. Based on the analyses of the morphological development, this profile is formed within a several months to a dynamic equilibrium situation, especially at the southwest beach the profile was formed quite fast. This features seem characteristic for these sandy beaches, at least at this location in Lake Marken.From the analyses of the cross-shore profile, it is found that because of the plateau, formulae to describe equilibrium profiles are only appropriate for the first few meters below the water line. Furthermore, simulations show that reproduce the observed profile evolution is still difficult by a one-dimensional numerical model XBeach. The development of the plateau and the steep slope around the water line seems to be a challenge to simulate. Especially, the physical relationship between the wave height and the water depth on the cross-shore profile morphology, which develops the plateau, must be investigated in more detail.

Considering the morphological stability of the shoreline, it can be concluded that the significant variation of the dominant waves affects the orientation of the beach, which makes it that the beaches are very morphological dynamic. From a sediment balance follows that the net volume loss from the area of southwest beach is marginal, and it is concluded that the volume balance is closed for the area of interest. At the northwest beach a longshore gradient to the northwest results in a net volume loss. The application of longshore sediment transport formulae are appropriate to explain the morphological developments, the computed magnitudes were all in the same order of magnitude that was observed.

In order to get a better understanding of the processes regarding the morphological development of sandy shores in lake systems and improving design formulae and numerical models, it is recommended to continue monitoring of sandy shores and measure the local hydraulic conditions to assess the physical relation between the morphological developments and the local hydraulic conditions.

# List with symbols

| **Symbol** | **Unit** | **Description** |
|---|---|---|
| A | - | Dean parameter |
| $C_d$ | - | Drag coefficient |
| c | $ms^{-1}$ | Wave celerity |
| h | m | Water depth |
| $D_{50}$ | mm | Median grain diameter |
| $D_{90}$ | mm | Grain diameter in which 90% passes through sieve |
| E | $Jm^{-2}$ | Wave energy |
| F | m | Fetch |
| g | $ms^{-2}$ | Gravitational acceleration (g ≈ 9,81 $ms^{-2}$ ) |
| H | m | Significant wave height (also known as $H_{1/3}$) |
| $h_0$ | m | Water depth where bottom is horizontal |
| k | - | Parameter to determine the equilibrium profile |
| L | m | Wave length |
| $L_0$ | m | Wave length at deep water |
| n | - | Ratio between group celerity and wave speed |
| Pl | $Ns^{-1}$ | Potential longshore transport |
| Q | $m^2day^{-1}$ | Volume transport |
| Re | - | Reynolds number |
| $S_0$ | - | Direction coefficient slope (slope is 1:$S_0$) |
| S* | - | Sediment liquid parameter |
| $T_p$ | s | Significant wave period |
| $u_{10}$ | $ms^{-1}$ | Wind speed at 10 m height |
| $u_h$ | m | Horizontal water movement |
| u | $ms^{-1}$ | Shear velocity |
| $W_f$ | | Fall velocity in water |
| x | m | Distance |
| α | ° | Angle of wave incidence |
| Δ | - | Relative density (($\rho_s$ - $\rho_w$)/ $\rho_w$) |
| κ | - | Constant |
| ν | $m^2s^{-1}$ | Kinematic viscosity |
| $\rho_s$ | $kgm^{-3}$ | Density sediment |
| $\rho_w$ | $kgm^{-3}$ | Density water (≈1000 $kgm^{-3}$) |
| ψ | - | Shields parameter |
| Ω | | Dimensionless fall velocity |

# Contents

# 1. PROBLEM ANALYSIS

## 1.1 Introduction

Currently, Lake Marken is about 70,000 hectares and together with Lake IJssel one of the largest natural freshwater lakes in Europe. The lake used to be part of the Zuiderzee, a saltwater inlet of the North Sea. Lake Marken was created in 1976 when the Houtribdijk between Lelystad and Enkhuizen was completed. Originally, the morphodynamics were driven by tidal currents, but by construction of the Houtribdijk this influence disappeared (Van der Weij, 2005). The dike had a major impact on the underwater environment of the lake. Fine sediment that was previously carried away by the tidal currents to Lake IJssel, fell to the bottom of Lake Marken where it settled like a blanket, making the water of the lake turbid. The concentration of suspended matter increased significantly, causing the transparency to decrease to only 30 cm (Kiwa Water Research, 2007). When you would take a look from above, you will see it directly; the colour of Lake IJssel and Lake Marken is clearly different. North of the Houtribdijk the water is fresh and clear, while south of the dike the water is remarkably turbid, as can be seen in the left-hand plot in Figure 1-1. At several places a thick layer of fine sediment is deposited on the bottom of the lake what has a major impact on soil organisms. The silt covers the bottom like a suffocating blanket, moreover, this silt blanket swirls easily and thus ensures continuous turbidity in the lake. These large amounts of suspended silt hamper the grow of plants and mussels. This makes life hard or even impossible for many plants and animals. In addition, strong wind enhances the turbidity of the water because it brings the silt at the bottom in suspension.

All these problems caused the amount of fish and bird population to decline significantly over the last decades. Furthermore, Lake Marken is surrounded by dams and dikes since construction of the Houtribdijk. The natural shores and shallow waters have disappeared and the natural balance is disturbed. Other negative factors are the limited habitat diversity and the unnatural water level fluctuation (lower in winter and higher in summer). This all together makes Lake Marken currently an ecological very unnatural and poor ecosystem. The project Marken Wadden is a project with the aim to transform the ecologically impoverished Lake Marken into a more dynamic area rich in animal and plant life. The right-hand plot in Figure 1-1 presents an overview of Lake Marken, with an indication of the location of the project Marker Wadden.


*Figure 1-1. Left-hand plot: The very silty water in Lake Marken (right) compared to the clean water in Lake IJssel (left) (Boskalis, 2015a). Right-hand plot: An overview of Lake Marken with the location of the Marker Wadden (Boskalis World, 2017).*

### Concept of the Marker Wadden

The aim of the project Marker Wadden is to build a system of natural islands with marshes and shallow waters and at the same time address this silt problem by creating various levels under water. This enables to create a bright future for Lake Marken with clear water and valuable nature with more diverse habitats. Moreover, Lake Marken is located on an important route for migratory birds. Various migratory birds depend amongst other on Lake Marken as wintering area to rest, the Marken Wadden is the ideal location for these birds. The Marker Wadden is currently one of the largest nature restoration projects in western Europe. The Marker Wadden can be seen as an innovation in the field of hydraulic engineering because the approach is different from existing projects.

The project will transform the ecologically impaired Lake Marken into a dynamic area rich in animal and plant life, through the creation of nature islands using sand, clay and fine sediment. Building with Nature techniques play a key role in the project. One innovation being introduced into the project is building with fine sediment. Fine sediment is too soft to build an island, therefore, this will be resolved by building ring dikes of sand to contain the sediment. In outline, the plan consists of a system of natural islands. Natural shores provide gradual transitions from land to water and will give fish more opportunities to spawn and feed. As a result, large numbers of birds such as terns and waders will return to the area because there will be more food for them. Beaches, sand banks and low dunes, linked by a rock dam will protect the Marker Wadden against storms. Various levels under water allow sediment to settle in shallow areas and creeks, thus creating a natural water purification system. In addition, a special trench will be constructed to collect the fine sediment from Lake Marken. This 'sediment trap' will make the turbid water clear again. The captured sediment will be used to construct more islands in the future. Because such a plan is financially hard to realize at once, the plan is implemented in modules A, B, C and D.

The design of the Marker Wadden and the different modules are presented in Figure 1-2. In September 2015, Natuurmonumenten and Rijkswaterstaat have commissioned Boskalis a contract to realize the first phase of the Marker Wadden. The first phase consists of modules A+B and C. Modules A+B were built first in combination with the trench to collect the fine sediment. In March 2016, Boskalis started work on the first of the Marker Wadden. In this first phase, the inner part is built with Holocene clay material. Along the boundaries, sandy shores and sandy dams have been created to protect the soft muddy material.

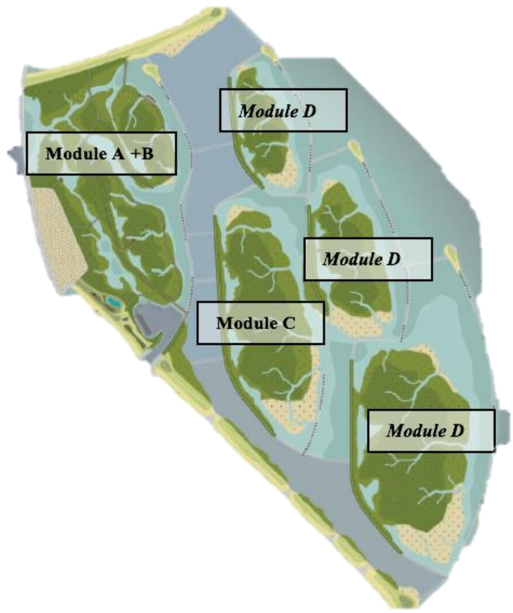



*Figure 1-2. Design of the Marken Wadden (Boskalis, 2015a).*

## 1.2 Research objective

The primary focus of this MSc thesis is on the sandy shores of the Marker Wadden. These sandy shores are exposed to the hydrodynamic forces in Lake Marken and are aimed to protect the marshlands behind it. Therefore, it is important that these sandy shores are designed in such a way that they are more or less morphological stable, in both cross-shore and longshore direction. Since knowledge on the behaviour of newly constructed sandy shores in a lake system is limited, the design of the sandy shores of the Marker Wadden is based on knowledge and lessons learned from previous projects. The usability of conservative rules of thumb and simple empirical formulae for equilibrium profiles is for this specific situation – without tidal fluctuations, relative shallow and short waves – somewhat questionable. Moreover, as there are no such beaches present in Lake Marken now, it is still unknown whether these formulae and models can be applied in this lake with its specific conditions and wind forcing. The sandy shores of the Marker Wadden were therefore primarily designed using insights of the Building with Nature pilot along the Houtribdijk, combined with well-known conservative design formulae and models.

The main objective of this study is to analyse and describe the morphological development and the developed cross-shore profile shape of the sandy beaches of the Marker Wadden. To reach this objective, it is investigated whether the observed behaviour can be described by equilibrium methods and if the cross-shore profile shape can be reproduced by the numerical morphological model XBeach.

Apart from being very useful for the project Marker Wadden, this new knowledge is also relevant for the design of other sandy shores in shallow lake systems and can be used to improve design formulae and methods in order to design sandy shores with more certainty in other locations with similar conditions.

## 1.3 Research questions

In order to achieve the objective of this MSc thesis study, five research questions have been defined. The five research questions of this study are the following:

**1.** Which design formulae and models are commonly used for sandy shores and which methods are used for the design of the sandy shores of the Marker Wadden?

**2.** What is the initial behaviour, both in cross-shore and longshore direction, of the sandy shores of the Marker Wadden in the first months after construction?

**3.** How can the observed developments at the two beaches be related to the local hydraulic conditions?

**4.** Are the classical design formulae and models, for cross- and longshore sediment transport and profile evolution, able to describe the observed developments and which adjustments in the formulae/models are required to improve them and to use them for the design of such sandy shores?

**5.** What is the expected long-term development of the sandy shores of the Marker Wadden, based on obtained insights and (if possible) the application of (improved) models?

## 1.4 Methodology

In order to study the morphological behaviour of the sandy shores of the Marker Wadden, frequent field monitoring has been carried out after completion of the first phase of the Marker Wadden. This field monitoring consists of surveying the bathymetry and topography of the beaches. To explain the observed behaviour also meteorological and hydraulic data has been gathered. All these data have been analysed in order to study the observed morphological behaviour of the sandy shores. Besides comparing the observed behaviour with the morphological development of the pilot project along the

Houtribdijk, it is investigated whether the observed behaviour can be described by equilibrium profiles and sediment transport formulae. It is examined if the initial morphological evolution can be reproduced by the application of the numerical model XBeach. Also an expectation is provided on the expected long-term development of the sandy shores of the Marker Wadden. In addition, recommendations are given for both sandy shores in lake systems in general and specific for the project Marker Wadden. Finally, the well-known design formulae to explain the equilibrium profiles and numerical model XBeach are discussed whether they can be applied for the design of such sandy shores in this lake, focussing on both components that perform well as the parts that need further improvement.

## 1.5 Report outline

In this report, a total of seven chapters can be found, including the introductory chapter. In the second chapter focuses on the sandy beaches of the Marker Wadden. The environmental conditions are discussed which are related to the sandy beaches and the design is extensively elaborated. The third chapter provides a theoretical background several relevant processes and elements regarding to the understanding of the morphological behaviour of the beaches. Herein, the processes of sediment transports which are responsible for the cross-shore and alongshore evolution of beaches are extensively elaborated. The fourth chapter consists of an explanation of the field monitoring and covers a comprehensive analysis of the observed morphological behaviour of the southwest beach and northwest beach. Both the cross-shore and alongshore evolution are analysed. The sediment characteristics, settlements of the subsoil and the sediment balance are discussed as well. The fifth chapter focuses on the application of the examined equilibrium formulae and process-based numerical model XBeach. The sixth chapter contains a discussion of this study. Herein, the field monitoring and analyses, equilibrium formulae and XBeach model results and the relation to the pilot Houtribdijk are discussed. Finally, the report closes with the conclusions and recommendations of this study. In the conclusions the research questions will be answered, hereafter recommendations are provided for the project Marker Wadden, sandy beaches in lake systems and more general further research.

# 2. THE SANDY BEACHES OF THE MARKER WADDEN

The primary focus of this study is on the sandy shores of the Marker Wadden: the southwest beach and the northwest beach. The orientation normal to the shoreline of the southwest beach is 225°N of the northwest beach 340°N as can be seen at left-hand plot in Figure 2-1. Because only a part of these beaches has been constructed at the start of my graduation, the focus will be on the southwest beach and the western part of the northwest beach as indicated by the black-dashed boxes at the right-hand plot. All the information about the design of the beaches is obtained from the design reports of the sandy shores of the Marker Wadden (Arcadis, 2016a).

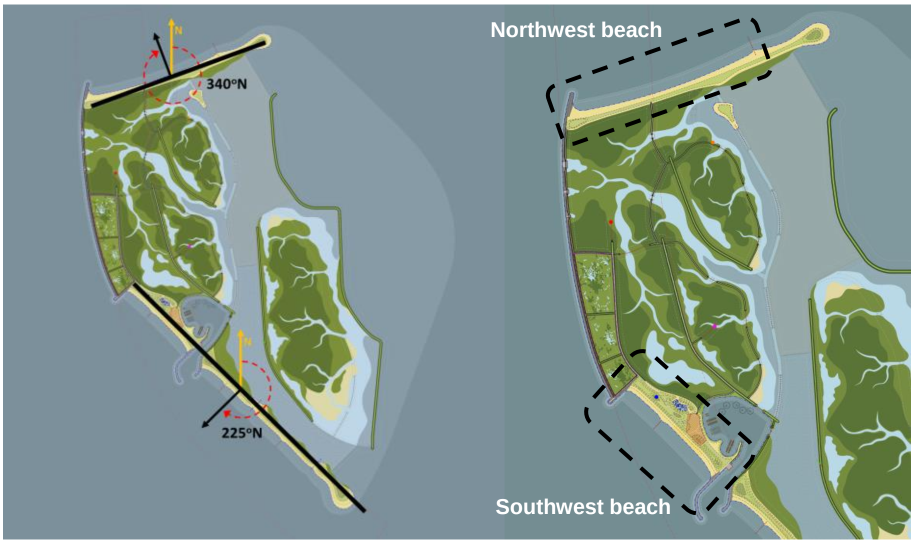



*Figure 2-1. Overview of the beaches indicated by the red-dashed boxes (Arcadis, 2016a).*

The shoreline orientation of the southwest beach is perpendicular to the dominant wave direction which is 225°N. As previously described, the sandy shores of the Marker Wadden were primarily designed using insights of the pilot Houtribdijk. For example, the shoreline orientation of the pilot is equal to the southwest beach. A brief summary of the pilot project is therefore provided below.

### Pilot project Houtribdijk

The obtained knowledge of the pilot project along the Houtribdijk has been used for the design of the sandy shores of the Marker Wadden. The pilot project was carried out in order to investigate the crucial aspects of designing, constructing and maintaining a natural, vegetated foreshore (Ecoshape, 2016a). The sandy foreshore consists of a large quantity of sand, which is placed before the existing dike (right-hand plot in Figure 2-2). This body of sand reduces the strength of the waves, thereby eliminating or reducing the impact of the waves on the dike. Thanks to the foreshore, the dike itself does not have to be reinforced. A sandy foreshore is in many places cheaper to construct and maintain than a traditional dike reinforcement. Moreover, it is more sustainable and enhances natural and recreational values of the area.

In this project, a sandy foreshore was created as a pilot, which is part of the Dutch Flood Protection Program (HWBP). With the knowledge gained during this project the concept can be applied with more certainty in other locations, such as been done for the Marker Wadden. The pilot is located on the Houtribdijk between the cities Enkhuizen and Lelystad (left-hand plot in Figure 2-2). A foreshore test section of 450 meters in length was constructed in the summer of 2014, consisting of a body sand of approximately 70,000 m³, varying in width and height. In the spring of 2015, different types of vegetation were planted on the foreshore. By using this setup, various situations can be tested simultaneously for their effectiveness. The foreshore test section will be monitored for four years, so until the spring of 2018. Monitoring includes water levels as well as wave height measurements. Two cameras have been placed to make pictures of the site every hour during daylight conditions. Besides this, a topographic survey is performed several times per year. All the gathered data are analysed to answer a series of pre-defined research questions.

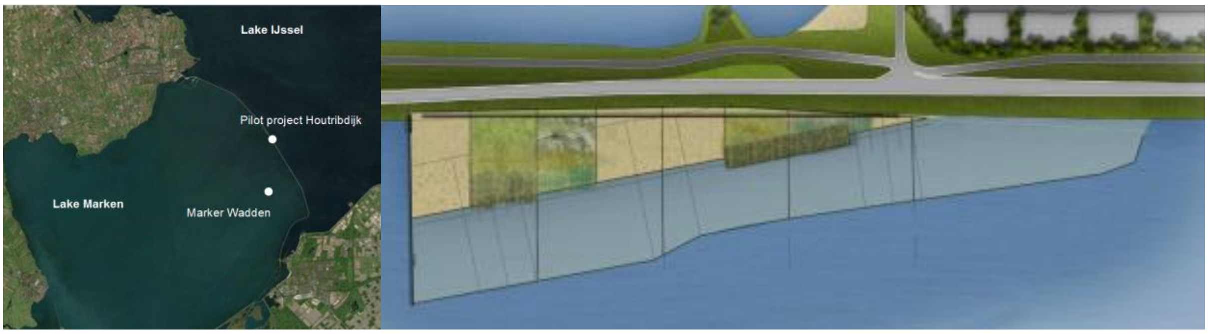



*Figure 2-2. Left-hand plot: Location of the pilot project. Right-hand plot: Lay-out of the test section with four sections of each 100 m wide (Ecoshape, 2016).*

## 2.1 Environmental conditions

For the purpose of design calculations and analyses to prove that the design meets the requirements, the environmental conditions are required that may occur at the project location. In this section, the available data and the applied assumptions regarding issues as wind, water level, waves and currents are addressed.

### 2.1.1 Sediment characteristics

To create the sandy beaches of the Marker Wadden, sand is extracted form a sand pit northwest of the project site. Sediment samples show that Pleistocene sand is present in the soil layer below NAP -10 m (Fugro, 2013). The layers above this Pleistocene sand are used for the realization of the marsh areas of the Marker Wadden. The top layers consist of silt and loam. Laboratory tests has shown that the sand in the Pleistocene layer, approximately between NAP -10 m and NAP -30 m, has a $D_{50}$ of 0.265 mm (0.155 to 0.585 mm). For the realization of the sandy beaches of the Wadden Marker the profile parts between NAP -2 m and NAP +1.0 m – the so-called morphological active zone – is made of the sand from the Pleistocene layer between NAP -18 m and NAP -30 m and is approx. 0.35 mm ± 0.11 mm (mean ± standard deviation). For the purposes of the design calculations a conservative assumption has been made in the most cases, where the grain diameter is set at $D_{50}$ = 0.20 mm.

### 2.1.2 Wind and wave conditions

Despite wind is not a hydraulic condition, it is one of the most important drivers for all the hydraulic processes in Lake Marken such as water levels, waves and currents. Figure 2-3 shows the representative wind climate for Lake Marken. As can be seen the dominant wind directions are the sectors south-west, which occur about 60% of the time. Wind blows over the water and creates a shear stress on the water surface, due to this shear stress the upper part of the water will move in the direction the wind is blowing.

When the moving water approaches the shore the shear stress is balanced with an opposing water level gradient (wind set-up). If the area where the wind is blowing is large enough compared to the total area of water the opposite side of the water area experiences a set-down. The wave data has been established based on the Brettschneider methodology (Brettschneider, 1952). The wave height is estimated based on water depth, fetch and wind speed. The wave direction is by definition equal to the wind direction.

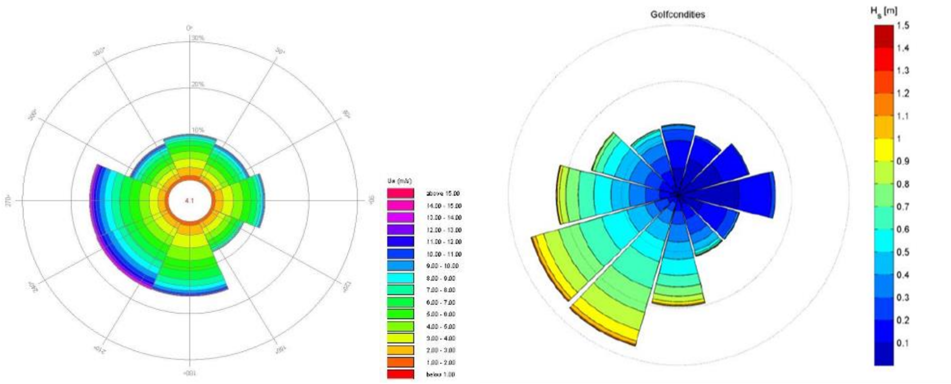



*Figure 2-3. Left figure: Visualization of the representative wind climate for Lake Marken (Royal HaskoningDHV, 2013). Right figure: Wave climate according to the Brettschneider methodology (Arcadis, 2015).*

In addition to the wave climate determined by Brettschneider, an alternative wave climate is determined which is based on a more sophisticated method in which the Delft3D-SWAN model (Deltares, 2016a) is used in order to make an estimation of the local wave conditions. This sophisticated method takes, among others, the inclination of the water level in the lake and wave processes such as refraction into account.

### 2.1.3 Water levels

The current water levels in Lake Marken are -0.40 NAP m during the winter period and -0.20 m NAP during the summer period. This means the water level in the winter is 0.2 m lower compared to the summer. The transition from winter level to summer level takes place in de period between March 15 and April 15, the transition from summer to winter level takes place in the period between September 20 and October 15. During the winter months the water level changes in Lake Marken are often affected by precipitation and high water discharges. The average water depth at the project location is approximately 4.6 m relative to winter level.

## 2.2 Design of the southwest beach

The southwestern boundary consists actually of two parts: northwest and southwest of the harbour. Because the south-eastern part of the beach was not yet constructed at the start of my graduation, this study focusses on the north-western part of the beach, as is visualized in Figure 2-4. This beach is also known as the recreation beach, because this beach will be the only open beach for tourists and lies close to the harbour where they can moor. The beach is enclosed by a hard structure in the northwest and the northern breakwater of the harbour. The total length of this beach section is 650 meters. The beach its most important function is to protect the marshland behind it against erosion due to incoming waves from the dominant southwest direction. Besides this, the sandy beach ensures that the Holocene material in the marshland remains enclosed within the different

*Figure 2-4. The design of the southwest beach (Arcadis, 2016a).*

compartments. The southwest beach should be, in terms of design and dimensioning, high and wide enough to prevent the marshlands behind it against incoming waves. The theoretical design profile is shown in Figure 2-5.

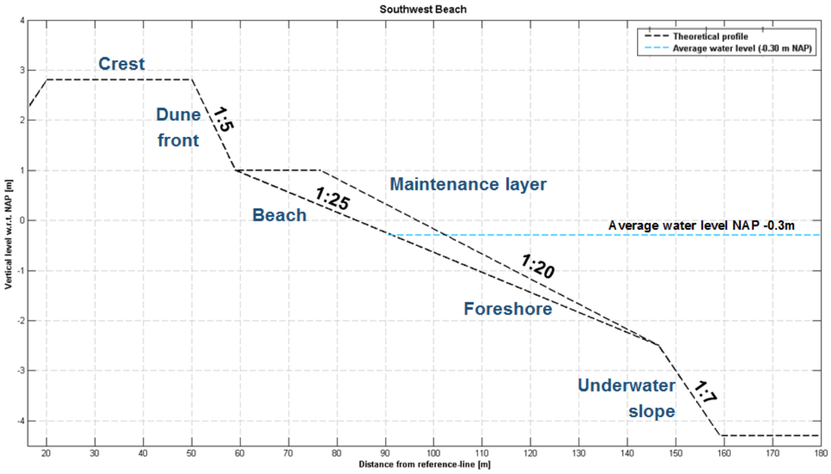



*Figure 2-5. Theoretical design profile of the southwest beach (northwest of the harbour) including buffer layer (Arcadis, 2016).*

The beach consists of a gently slope and a dune with a crest at NAP +2.8 m and a minimum width of 30 m. The central part of this beach section is even wider because the recreational areas behind it, which among others consists of a sand plateau and water playground. Because the robust design of the profile, more than enough margin is taken into account to compensate for example erosion as a result of storms. The most important characteristics of the design profile at southwest beach are provided below. It must be noticed that the design profile could be deviate from the final profile due to changes of the design. In addition, the construction profile deviate from the design profile as well, because it takes into account among others the settlements of the subsoil also.

*Table 2-1.Characteristics of the design profile of the southwest beach.*

| Characteristics | |
|---|---|
| Slope of the beach and shallow foreshore | 1 : 25 |
| Slope deep foreshore (below NAP -2.5 m) | 1 : 7 |
| Slope dune front | 1 : 5 |
| Slope backside dune | 1 : 7 |
| Crest level dune | From NAP +2.8 m |
| Minimal crest width | 30 m |
| Minimal beach width (excl. buffer) | 30 m |
| Grain size beach (NAP -2 m to NAP +1 m) | 0.350 mm |
| Buffer layer | 20.000 $m^3$ |

## 2.3 Design of the northwest beach

The northwest boundary of the Marker Wadden consists of one long stretched beach and is known as the northwest beach. At the west side of the beach a hard structure is present and the eastern side is robustly designed with an open end. Like the southwest beach, the most important function is to protect the marshland behind it against erosion due to waves approaching the beach from the north and northwest direction. Besides this, the beach has a lee function for the shallow water zones and for the marshland behind it. The total length of

*Figure 2-6. Detail view of the design of northwest beach (Arcadis, 2016a).*

this beach section is approximately 1,400 m. Figure 2-6 shows a detailed view of the design of northwest beach. The beach is designed in order to protect the area behind in such a way that no waves reach into that area. Moreover, the beach ensures that the dredged holocene material remains enclosed within the compartments.

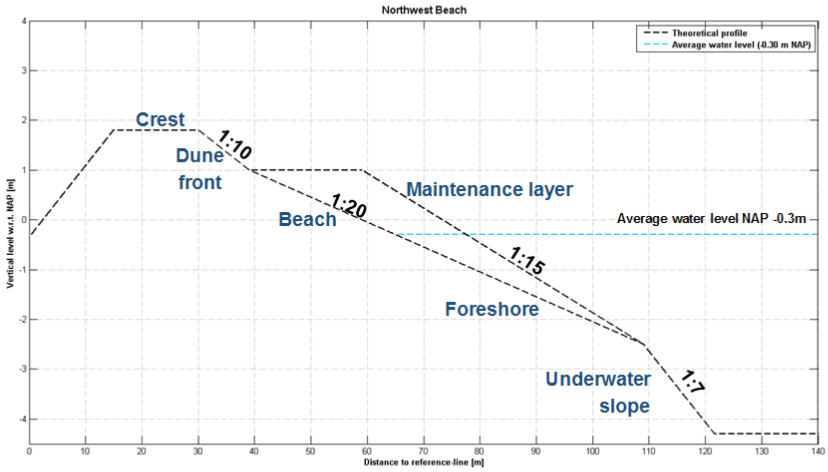



*Figure 2-7. Theoretical design profile of the northwest beach (Arcadis, 2016).*

The northwest beach is in terms of design and dimensioning high and wide enough to prevent from wave overtopping or erosion. It consists of a gently underwater slope with a dune behind it with crest level around NAP +1.8 m, as can be seen in Figure 2-7. Because of the robust design of the profile more than enough margin is taken into account to compensate for example erosion as a result of storms. The most important characteristics of the design profile at the northwest beach are presented below.

*Table 2-2. Characteristics of the design profile of the northwest beach.*

| Characteristics | |
|---|---|
| Slope of the beach and shallow foreshore | 1 : 20 |
| Slope deep foreshore (below NAP -2.5 m) | 1 : 7 |
| Slope dune front | 1 : 5 |
| Slope backside dune | 1 : 7 |
| Crest level dune | From NAP +1.8 m |
| Minimal crest width | 15 m |
| Minimal beach width (excl. buffer) | 25 m |
| Grain size beach (NAP -2 m to NAP +1 m) | 0.350 mm |
| Buffer layer | 20.000 $m^3$ |
| Buffer at northeast end of the beach | 45.000 $m^3$ |

## 2.4 Morphological stability of the cross section

The sandy beaches have an important lee function, to prevent erosion of the marshlands behind it and to reduce the swell in the shallow water zones. In order to preserve this function for a longer period, the design of the sandy beaches should be morphological sufficient stable. There is made a distinction between the stability of the cross section (perpendicular to the shoreline), and the stability of the shoreline (longshore direction). In this section the morphological stability in the cross section will be discussed. For the design calculations of the beach, there are two types of profile development considered: the profile deformation during year-round conditions and the profile deformation during storm conditions.

### 2.4.1 Cross-shore erosion

The design of the sandy beaches, above and below the water level, is based on knowledge and lessons learned from previous projects. The usability of conservative rules of thumb and simple empirical formulae for equilibrium profiles, such as Dean or Vellinga, is for this specific situation in lake Marken – without tidal forces, relative shallow and short waves – somewhat questionable. The sandy shores were designed using results of the Building with Nature project along the Houtribdijk, combined with well-known design formulae and design models for longshore and cross shore transport. The design of the cross section is primarily based on assumptions which were also applied for the pilot project Houtribdijk and the survey measurements, which were obtained as part of an extensive ongoing monitoring program. The assumptions for the pilot project are again based on experience of sandy foreshore reinforcement projects along the Dutch coast (known as the Zwakke Schakels) and Maasvlakte II.

#### Comparison with the pilot Houtribdijk

In order to estimate the stability of the beach profiles during normal (year round) conditions, observed morphological development in similar situations with sandy beach profiles was examined. Primarily the morphological development of the pilot Houtribdijk was used for the design, since this is a very similar situation. Besides the similar slope gradient, the shoreline orientation is equal to the orientation of the southwest beach of the Marker Wadden (southwest orientated). Moreover, the sand, coming from Lake Marken, which is used for the construction of the pilot project is equal to the sand which is used for the Marker Wadden. The sand is relatively coarse with an average grain diameter ($D_{50}$) of 0.350 mm with a rather wide distribution as well. Because of this, it is very likely that the sandy beaches of the Marker Wadden will develop in the same way as the pilot project along the Houtribdijk.

Figure 2-8 shows the measurements for the characteristic central transect (shore#12) of the pilot. In this figure the measurements T1 (September, 2014) to T15 (March, 2017) are presented. The thick black line (T1) shows the characteristic shape of the more or less stable profile which is formed in the first months after realization. Basically, the profile shape arose even within one month as can be seen. The black-dashed line represents the initial profile, so without the constructed sandy foreshore.

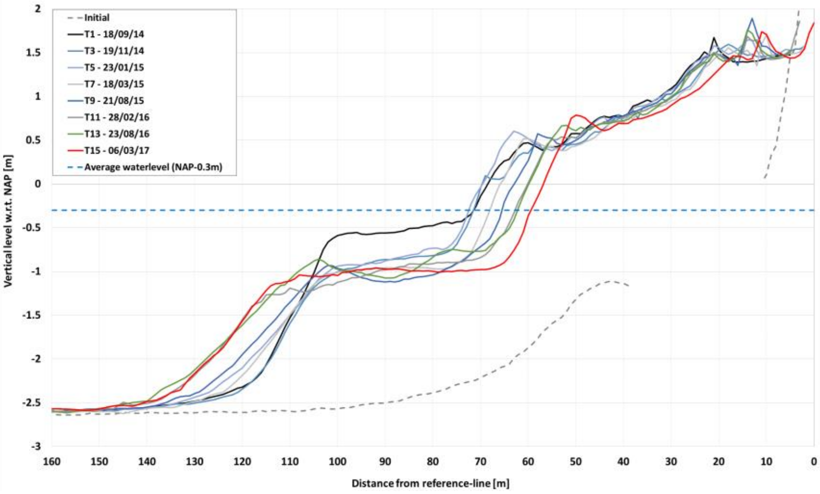



*Figure 2-8. Characteristic shape of the cross section in the central part of the pilot Houtribdijk, including the cross profile at the position of transect location # 12 (Arcadis, 2016).*

It can be seen that the shaped equilibrium profile deviates from a straight 1:25 slope; as provided in the design. The measurement results show an equilibrium profile for a southwest oriented sandy beach, consisting of relatively coarse sand (average approximately 350 mu), which consist of:

- An underwater slope (below NAP -1 m) of approximately 1 in 15
- A relatively flat plateau of +/- 30 m width, around NAP -1 m
- A steep slope around the water line of approximately 1 in 10
- A small swash berm with a max to NAP +0.5 m.
- A stable, gently sloped beach, accordance the constructed profile.

In Figure 2-9 both the characteristic profile of the pilot Houtribdijk and the design profiles of the southwest beach and northwest beach are visualized. The figure shows that the profiles, in terms of volume of sand in the active zone, corresponds quite well with each other for the southwest beach, the difference in this example is only 4 $m^3$/m. The expected sand loss that occurs due to formation of the equilibrium profile at the northwest beach, is about 5 to 10 $m^3$/m.

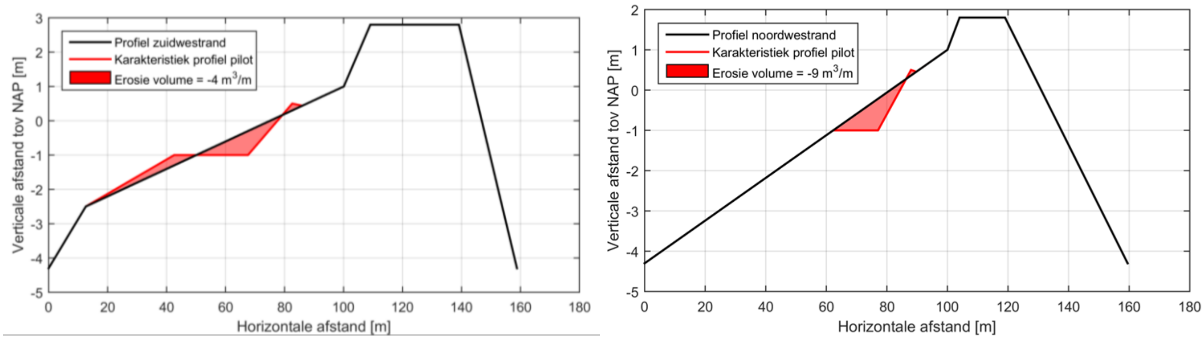



*Figure 2-9. Comparison between the design profile of the southwest beach (left) and northwest (right) and he pilot Houtribdijk(Arcadis, 2016).Vertical axis: the level w.r.t NAP. Horizontal axis: distance from bottom of the lake.*

### 2.4.2 Previously performed morphological calculations

In addition to the profile analysis in relation to the pilot Houtribdijk, some exploratory calculations were performed with the CROSMOR model for the beaches of the Marker Wadden. However, it should be noted that there are still many open research questions regarding the application of this model for the prediction of long-term morphological development of sandy shores in lake systems. In Figure 2-10 the calculation results are shown of a situation that comes close to the design of the southwest beach. The figure shows the calculation results after a simulation period of 1 year and 5 years. The various calculations indicate that the profile slope around the water line gets steeper and that sand is deposited on the plateau just below the water line. This shape is more or less in accordance with the trends observed at the pilot Houtribdijk, although the plateau is around the water line. These calculations, show that on the location of the beach (above summer level) up to 5-15 $m^3$/m sand can disappear (redistribution to form a plateau) in the first months after construction due to the formation of the equilibrium profile. The calculated morphological behaviour in the deeper parts of the profile is not consistent with the observations at the pilot Houtribdijk, and is therefore not considered in more detail.

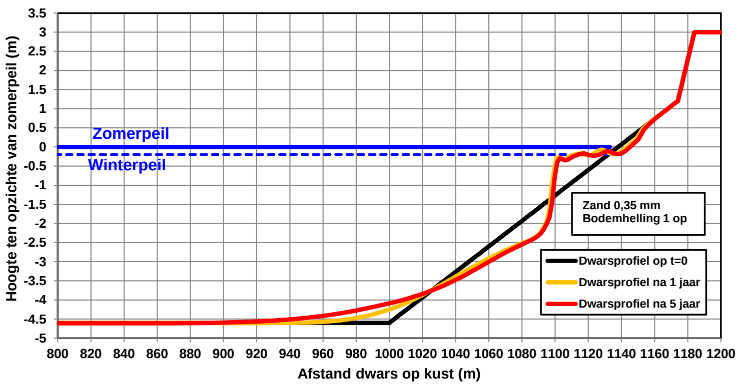



*Figure 2-10. Calculated profile development of the southwest beach with the CROSMOR model, based on a schematically wave climate, a bottom slope of 1:30 and a $D_{50}$ of 350mu (Arcadis, 2016).*

## 2.5 Morphological stability of the shoreline

This section is relating to the morphological stability of the orientation and position of the shoreline. It is investigated what the potential impact will be of longshore sediment transport. The most important factor with regard to the morphological stability (in relation to longshore transport) is the so-called equilibrium orientation of the beach. This equilibrium orientation is the shoreline orientation for which the net longitudinal transport is equal to zero, and is therefore dependent on the local wave climate. For the purposes of the design, a wave climate used which is based on the Brettschneider methodology and the Delft-3D wave climate.

### Equilibrium orientation of the shoreline

From the wave climate for the Marker Wadden according to Brettschneider, it follows that the equilibrium orientation of the southwest beach is equal to 225°N. Compared to the Brettschneider-wave climate the Delft-3D wave climate produces a difference of 8° in shoreline orientation. Especially for longer-shore sections, even a limited rotation of the shoreline can lead to relatively large shifts. The design of the Marker Wadden is based on the results from the Brettschneider wave climate. The results with the D3D-wave climate is considered to be indicative of the uncertainties that exist with regard to the effect of the wave conditions. The calculated equilibrium orientations for the northwest beach are very different from each other for both wave climates. The Brettschneider wave climate leads to an equilibrium orientation of approx.  45°N (= NO), and for the Delft-3D wave climate follows an orientation of approx. 340°N (~ NNW). The calculated equilibrium orientation that follows from the Brettschneider is in fact exactly the opposite of the orientation of the southwest beach. As part of the design of the northwest beach is chosen for a shoreline orientation equal to 340°N, in accordance with the equilibrium orientation in accordance with the Delft3D climate. For the determination of the size of the gross and net long transports various calculations were conducted using both the XBeach model and the transport model of Van Rijn (2014). The gross and net sediment transport rates are summarized in Table 2-3.

*Table 2-3. Overview of the gross and net sediment transports according to the S-Phi curves (Arcadis, 2016)*

| Beach | Shoreline orientation<br>*° w.r.t N* | Gross transport<br>*m3/year* | Net transport<br>*m3 / year* |
|---|---|---|---|
| Southwest beach | 225 | 0 – 15,000 | 0 – 5,000 |
| Northwest beach | 340 | 0 – 3,500 | 0 – 2,000 |

In addition, with the longshore transport formula of Van Rijn the sensitivity of the grain diameter on the longshore transport was assessed. This shows that the net longshore transport is about 30% smaller for a $D_{50}$ of 0.35 mm then for a $D_{50}$ of 0.20 mm.

# 3. THEORETICAL BACKGROUND

In this chapter a theoretical background is provided to give a general review of the processes that explains the morphological behaviour of the sandy shores. The review is split up in four sections, namely sediment transports, cross-shore transport, longshore transport and finally numerical modelling. The understanding of sediment transport is of great importance when it comes to cross-shore and alongshore evolution of beaches, the corresponding morphological processes are therefore provided in section 3.1. The cross-shore and alongshore evolution processes are discussed in section 3.2 and 3.3, respectively. The corresponding design methods which are commonly used for the equilibration of the cross-shore profile and the shoreline evolution for sandy beaches are also treated in section 3.4.

## 3.1 Sediment transport

The understanding of sediment transport is of great importance when it comes to cross-shore and alongshore evolution of beaches. The description of beach changes are most often conducted by considering the cross-shore and longshore processes separately. The longshore processes are mainly characterized by dynamically variables by changes in shoreline (i.e. its structure and spatial-temporal evolution). Bottom transformation in the cross-shore direction is determined first of all by a cross-shore profile, its shape and temporal changes. Sediment can be transported in three distinct modes, in bed load, suspended load and in wash load.

There are actually two processes which play a role in the sediment transport. First, the process that bring sediments into motion. The sediment on the bed is transported when it is exposed to large enough forces (shear stresses) caused by water movements. These movements can be caused by the current, the wave orbital velocities or a combination of both, the latter being the most common situation. Once the sediment is in motion, due to hydrodynamic processes, this will result in movement and transport of the sediments. When in an active hydrodynamic environment mainly the bed load and suspended load will have an impact on the bed level changes

The hydrodynamic processes occur when waves approach the shoreline and transform over the beach profile. In these processes, a distinction can be made between cross-shore sediment transport and longshore sediment transport. The most relevant parameters for sediment transport along a shoreline are the wave and current conditions, water level, bathymetry and sediment characteristics (Mangor, 2004).

## 3.2 Cross-shore transport

Cross-shore transport refers to the movement of beach and nearshore sediments perpendicular to the shore by the combined action of wind and waves, tides and the shore-perpendicular currents produced by them (van Rijn, 2006). These forces usually result in an almost continuous movement of sediment, either in suspension in the water column (suspended transport) or in flows at the surface of the bed (bedload transport). This movement occurs varying rapidly with time. At any moment, some sediment in the area of interest will have an onshore direction while other sediment is moving generally offshore. Unlike longshore transport, which is difficult to observe, cross-shore transport can result in large and highly visible changes in the beach configuration over intervals as short as one day. Furthermore, there are different processes which influence cross-shore transport. In deep water, there is no perceptible motion at the bottom due to the waves and thus no bedload transport and suspended sediment. Sediment which is already in suspension can be transported. There are different processes that yield cross-shore transport and has been further discussed in more detail in section 2.4.1 of the literature study (Steetzel, 2017).

### 3.2.1 Cross-shore evolution

A cross-shore profile changes over time. The onshore and offshore sediment transport is closely related to the shape of a beach profile. Research has revealed that a beach profile tends to have an average, characteristic form, which is referred to as the theoretical equilibrium profile (or natural profile). Sand placement during and after project construction may not correspond to the natural profile of the time of placement. The equilibrium profile has been defined as a statistical average profile, which maintains its form apart from small fluctuations (Dean et al., 1990). This equilibrium profile will be reached if environmental variables are constant, which actually means that the hydrodynamic processes should be always the same. However, in practice this rarely happens of course. The beach profile will continuously try to reach a different equilibrium profile due to changes of the environmental variables. The beach is therefore continuously in motion and is called the dynamic equilibrium concept. It can be assumed that if all the forces in the cross-shore profile are in balance, there is no net cross-shore sediment transport and the profile is in equilibrium. A change in hydrodynamic conditions will disturb the balance of forces and cause a change in profile shape. In reality, the hydrodynamic conditions are constantly changing and so is the corresponding equilibrium profile.

### 3.2.2 Equilibration of the cross-shore profile

An important part of the cross-shore behaviour is the transformation process between the initial constructed profile and the final equilibrium profile. This process is called equilibration and takes place in the first months – to years - after construction (Council, 1995). Most of the time, the constructed profile is steeper than the equilibrium profile and the shoreline will move shoreward during the equilibration and will become more gentle. The magnitude of this movement depends amongst others on the grain size. Because of this, there is a need to determine the shift of the shoreline due to the equilibration process and the time scale in which this occurs. Dean (1977) concluded from generally observed characteristics of equilibrium profiles that the equilibrium profiles tend to be concave upward. Also he founds that finer sediments give milder slopes and steeper waves give flatter slopes. Furthermore, sediments tend to be sorted (finer sediments in deeper water and coarser sediments in shallower water). However, this based on coastal areas which is clearly different from lake systems where the sorting is different due to the lack of tidal influences It can be assumed that, if all the forces in the cross-shore profile are in balance, there is no net cross-shore sediment transport and the profile is in equilibrium. A change in hydrodynamic conditions will disturb the balance of forces and cause a change in profile shape. In reality, the hydrodynamic conditions are constantly changing and so is the corresponding equilibrium profile. This is called the dynamic equilibrium concept. Several empirical and semi-empirical relations exist to determine a dynamic equilibrium profile and are discussed in the next section. During the process of profile equilibration, most of the volume remains within the cross-section, and is simply redistributed across the profile as is schematically visualized in Figure 3-1.

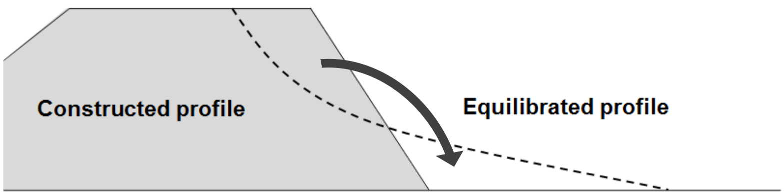



*Figure 3-1. Schematically view of profile equilibration due to cross-shore transport at coastal areas.*

### 3.2.3 Design methods

The onshore and offshore cross-shore sediment transport is closely related to the shape of a beach profile. Researches, such as Bruun (Bruun, 1954) and Dean (Dean, 1977), have tried to provide the appropriate equations of beach profile changes according to different parameters such as the diameter of the sediments, density, wave break height and other characteristics. Equilibrium beach profiles are based on the slope of the beach in relation to the force of gravity and the resistance of the sediment against movement; the shear stress (Dean et al., 1990). There are different concepts which all make use of different parameters in order to describe a certain profile. However, most of these concepts are usually applied and calibrated for coastal areas instead of lake environments. In this section different concepts will be described to determine the equilibrium cross-shore profile.

#### Dynamic equilibrium profile

The equilibrium profile which is developed by Dean (Dean, 1977) is expressed in equation [3-1].

$$h(x) = Ax^m \qquad [3\text{-}1]$$

Where *h* is the water depth, *x* is the offshore distance (where x=0 at the mean water line) and A is the shape factor (also known as the Dean parameter). The formula of Dean [3-1] was developed for beaches along the ocean and is based on beach profiles in Denmark (Bruun, 1954) and the east and west coast of the United States (Dean, 1977).The formula is calibrated based on the east and west coast of the US. The depth *h* in the equilibrium profile increases exponentially with the distance x from the shoreline, as can be seen in the formula. Based on fitting to natural upper shoreface profiles, Dean has suggested an average value of m = $2/3$ (Dean, 1987). The model is quite simple with only one parameter, namely the shape factor A. However, there are some disadvantages. One disadvantage of the model is the vertical asymptote which occurs if x=0, in reality this will of course never happen. Another disadvantage of the model is that no soil depth is used. So when the bottom is reached at a certain depth, where for example a rock layer is presented, this does not appear in the model. The model will show much deeper a horizontal bottom. A third disadvantage is that the formula is monotonically decreasing, possible sand banks are not displayed in the model. The only parameter that must be determined is A, which ensures that the formula is simple to apply. There are many methods to determine the A parameter. Dean has developed several methods to calculate this parameter. In this section different formulas are given in order to determine the A parameter. These methods are all based on sediment characteristics, so wave characteristics are not taken into account in the model of Dean. This implies that the results of the model are only reliable in wave conditions which are similar to the circumstances under which the model is calibrated. In Table 3-1 an overview is provided of the different methods to describe the equilibrium profiles.

*Table 3-1. Overview of the methods to determine the equilibrium profile.*

| Method | Description |
|---|---|
| Hanson and Kraus (1989) | A parameter is based on the grain diameter of the sand |
| Dean et al. (1990) | A parameter is based on the fall velocity |
| Kriebel et al. (1991) | A parameter is based on the fall velocity |
| USACE (2002) | A parameter is based  on various empirical studies |
| Wright et al. (1986) | Bottom is included as input parameter |

The different methods are based on various approaches to determine the A parameter. Hanson and Kraus (1989) have determined the A parameter based on the grain diameter of the sand and made use of ranges in grain size distribution. Dean et al. (1990) and Kriebel et al. (1991) have determined the A parameter based on the fall velocity. The latter is applicable for sediment where the grain diameter $D_{50}$ ranges from 0.1 mm to 0.4 mm. According to Kriebel et al. (1991) and Hughes (Hughes, 1993) the following formula is advised for sands where the grain diameter $D_{50}$ ranges from 0.1 mm to 0.4 mm. USACE (2002) found the A parameter by various empirical studies and recommended A-values for grain diameters between 0.1 to 1.09 mm. Another method to determine the equilibrium profile is developed by Wright et al. (1986). In contrast to the other methods, the grain characteristics cannot be implemented as variable and it is not determined by the A parameter. The model of Wright has a variable parameter for the bottom depth and a K parameter which determines the steepness of the profile. Furthermore, none of the equilibrium model takes the wave properties into account. The corresponding formulas to describe the equilibrium profiles are presented in Appendix A.1.

### 3.2.4 Storm behaviour

Another important aspect in the design of sandy shores is the storm response of the profile. A wide beach with a high berm acts like a stockpile of sand, which satisfies the sand demand during storm events. It is known that during strong onshore winds a net offshore transport occurs (USACE, 2002). Given the timeframe of this MSc thesis, computational modelling of the storm behaviour is hardly feasible. Therefore, the storm behaviour of the equilibrated profile has been determined according to the equation of Vellinga (1986). This dune erosion prediction model is described in appendix A.1 in more detail. It must be noticed that this method was primarily derived for relatively high storm surges combined with wave action at coastal areas.

## 3.3 Longshore transport

Longshore transport is the transport of sediments within the surf zone, directed parallel to the shoreline. This sediment transport is caused by a longshore currents and/or waves approaching the beach oblique to the shoreline. Sediment transport along the shore and surf zone is influenced by the swash (occurs in the direction of prevailing wind), which moves the sediments up the beach at the same angle of the incoming waves, and moves the sediments back down to the water due to the influence of gravity.

### 3.3.1 Alongshore evolution

Gradients in longshore transport, play a large role in the evolution of a shoreline. If there is a slight change of sediment supply, wind direction, or any other coastal influence, the longshore sediment transport can change significantly, having an impact on the formation and evolution of a beach system or profile. If the dominant wave direction is perpendicular to the shoreline, there is no longshore transport by waves. Hence, there is no longshore transport and the shoreline will not change either. The dominant wave direction is the direction from which most of the wave energy comes. This is usually the direction from which most of the waves are coming. However, it may also be that sometimes a more powerful wave comes from another direction, which makes that this direction is dominant (van Rijn, 2011). Longshore transport plays a significant role in the behaviour of the system. A longshore transport gradient can cause significant shore variability. So basically, the sedimentation and erosion processes along the shoreline are the result of differences in onshore and/or offshore transport and gradients of longshore sand transport induced by changes of:

- shoreline orientation (e.g. gradual or abrupt);
- shoreface topography (e.g.  local steep slopes, hollows or scarps);
- wave-current conditions and mean water level conditions;
- sediment supply (e.g. sources like cliff erosion).

Shoreline changes can be simply understood by considering the sediment continuity equation for the littoral zone, which is roughly the surfzone, with alongshore length Δy and vertical layer thickness h. The sand volume balance reads:

$$h\left(\frac{\Delta y_s}{\Delta t}\right) + \frac{\Delta Q_{LS}}{\Delta x} - q_s = 0 \qquad [3\text{-}2]$$

Where:

| | | |
|---|---|---|
| y | cross-shore coordinate | m |
| x | longshore coordinate | m |
| $y_s$ | shoreline position | m |
| h | thickness of active littoral zone layer | m |
| $Q_{LS}$ | longshore transport rate (bed-load plus suspended) | $m^3s^{-1}$ |
| $q_s$ | source, sink or cross-shore transport contribution | $m^2s^{-1}$ |

Basically, equation [3-2] states that a coastal section erodes if more sediment is carried away than supplied and vice versa coastal accretion occurs if there is a net supply.

### 3.3.2 Design methods

For the morphological stability of the shoreline various sediment transport formulas can be used. In this research the following formulae have been studied:

- Kamphuis (Kamphuis, 1991)
- CERC (USACE, 2002)
- van Rijn (van Rijn, 2014).

These transport formulas are based on different approaches. The CERC formulation is the most widely used alongshore transport formulation, and is rather simple. The basic assumption is that the flux integrated over the surf zone is proportional to the energy dissipation within the surf zone. Furthermore, the formula does not account for particle size and beach slope. For the Kamphuis-formula the effects of particle diameter and bed slope are included as well. The longshore sediment transport formula of van Rijn is a more recent and advanced alongshore transport formulation. In this formula the particle size, the steepness of the beach, the wave height and the breaker angle at the breaker line are taken into account as well. In appendix A.2, the methods are described in more detail and the formulas are presented.

## 3.4 Numerical modelling

In order to determine the beach evolution, various numerical models are available. Given the limited time, only the cross-shore evolution will be considered by using a one-dimensional XBeach model. Deltares, together with UNESCO-IHE and TU Delft have developed the open-source, freeware numerical model XBeach (Roelvink et al., 2009). The model is used for the computation of nearshore hydrodynamics and the morphodynamical response during storm-events, such as dune erosion, overwash and scour around buildings. Deltares uses this model in research projects, consultancy and advice, such as the assessment of dune safety in complex situations. The one-dimensional approach neglects alongshore variability in sediment transport due to alongshore differences in the bathymetry, but also due to alongshore variation in wave run-up due to wave directional spreading.

### Transport formulation

Sediment concentrations are modelled with the help of a depth-averaged advection-diffusion scheme with a source-sink term for equilibrium sediment concentrations (Roelvink et al., 2009). In XBeach the one-dimensional sediment transport equation is used as presented in equation [3-3].

$$\frac{\partial hC}{\partial t} + \frac{\partial hCu^E}{\partial x} + \frac{\partial}{\partial x}\left[D_h h \frac{\partial C}{\partial x}\right] = \frac{hC_{eq} - hC}{T_s} \qquad [3\text{-}3]$$

For which $D_h$ is the diffusion coefficient, $C$ the sediment concentration, $h$ the water depth, $u^E$ the Eulerian velocity, $C_{eq}$ the equilibrium sediment concentration and $T_s$ the adaption time.

The deposition and entrainment of sediment is determined by the sink-source term. The entrainment or deposition is calculated by difference in the actual sediment concentration and the equilibrium sediment concentration. In general sediment transport formulations, the equilibrium sediment concentration is related to the Eulerian velocity magnitude (short-wave-averaged velocity observed at a fixed point), the orbital velocity and the fall velocity. The orbital velocity is dependent on the wave height, wave period and water depth. The fall velocity is derived from a formulation primarily depended on the median grain-size. Sediment entrainment or deposition is related to the grain-size, wave height, wave period and water depth.

$$u_{orbital} = \frac{\pi H_{rms}}{T_p \sinh kh} \qquad [3\text{-}4]$$

The sediment transport formulation used in the XBeach model later in this research is the Van Thiel-Van Rijn transport equation.

# 4. FIELD MONITORING AND ANALYSES

This chapter focuses on the conducted field monitoring and provides a comprehensive analyse of the observed behaviour of the beaches. This chapter starts in section 4.1 with a description of the available bathymetric and topographical data. Subsequently, in section 4.2 the obtained meteorological and hydraulic data are described. An analysis of the morphological behaviour is performed for the southwest beach and the northwest beach, respectively in section 4.3 and 4.4. In which firstly the morphological developments of the bathymetry and topography are described per time interval. Subsequently, the cross-shore evolution and the alongshore evolution are extensively analysed. Furthermore, the settlement and sediment characteristics are discussed. The analyses conclude with a sediment balance in order to describe and explain the volume changes.

## 4.1 Field monitoring data

The conducted field monitoring consists of a field survey of the bathymetry and topography. The bathymetric survey has been executed by a survey boat with a multibeam echosounder (SeaBat 7101) to measure the bathymetry of the bed. Bathymetric maps represent the three-dimensional features and illustrats the underwater situated part of the beach. The topography covers the part of the beach above the water line. This has been surveyed by using GPS equipment (Trimble R10 - GNSS System) and measures the exact location and corresponding level. The coordinates are directly converted to the RD-system (Rijksdriehoeksstelsel) and the level is denoted with respect to NAP. The main advantage of GPS over other techniques is the speed of data capture. Surveying of the beaches has been mainly carried out by surveyors of the survey department of Boskalis, both the bathymetry and the topography. Apart from that, I have measured the beaches by myself several times by using the GPS equipment to measure the topography of the beach, i.e. the part below the water line where the survey boat could not measure due to the limited water depth.

*Figure 4-1. Bathymetric survey by the survey boat  (left) and the beach survey with GPS equipment (right).*

The results of the measurements of the southwest beach and the northwest beach are provided in Figure 4-2. As can be seen the bathymetric survey provides a surface whereas the topography consist of topographic points which are measured in fixed transects with intervals of 20 meters.

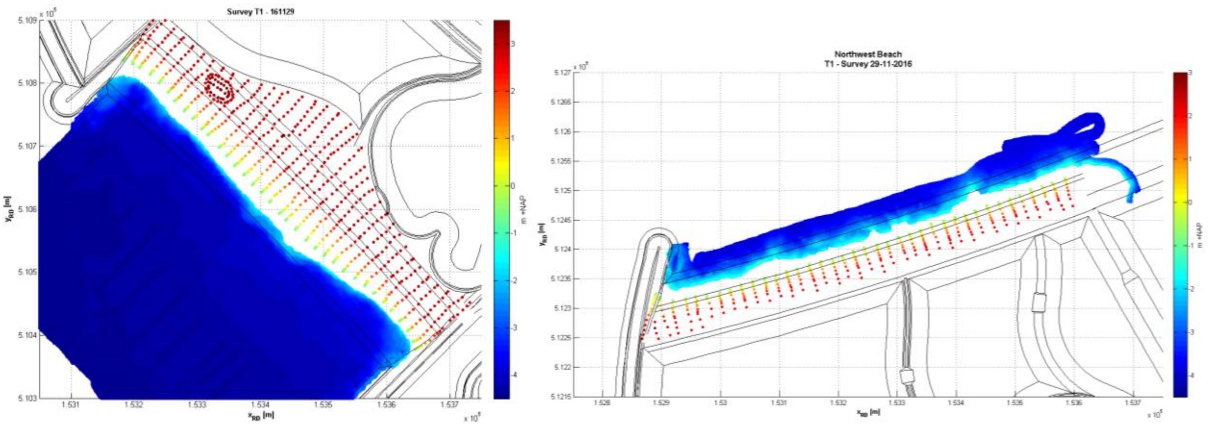



*Figure 4-2. Result of the combined data set (bathymetry + topography) of the southwest beach (left figure) and northwest beach (right figure).*

### 4.1.1 Frequency of the monitoring

Frequent field monitoring has been carried out after completion of the first phase of the Marker Wadden. An overview of the executed field monitoring is given in Figure 4-1. The first data set was obtained the 29th of November 2016, this was just after construction of the northwest beach and recreation beach. This field monitoring has been continued on a monthly basis, this frequency has been chosen because the behaviour of the sandy shores can be clearly observed on a monthly basis. When monitoring would be carried out more frequently this takes a lot of time and moreover it provides not directly an added value.  An important note on the frequency of the field monitoring is that the time of the survey cannot be set on a fixed date. The survey of the beaches needs to be fit in de overall planning and moreover the weather conditions plays an important role. For example, during the period of the field monitoring several storms took place. The date of field monitoring were therefore sometimes shifted a few days when it was not possible to measure due to the weather conditions

*Table 4-1. Overview of the executed field monitoring until May 2017 for bathymetry and topography.*

| Southwest Beach | Northwest Beach |
|---|---|
| 29-11-2016 | 29-11-2016 |
| 18-01-2017 | 18-01-2017 |
| 06-02-2017 | 14-02-2017 |
| 03-03-2017 | 14-03-2017 |
| 04-04-2017 | 15-04-2017 |
| 05-05-2017 | 09-05-2017 |

### 4.1.2 Data quality

The observed data have been checked on its quality. The data quality is important as it directly influences possible outcomes of further analyses. Therefore, the data quality has been assessed by analysing the data for missing values, outliers and other peculiarities. This has been done by checking the data set by a visual inspection, subsequently outliers and other peculiarities were removed from the data set. Initially, the data has been checked on its quality by the surveyor of the survey department of Boskalis where after I received the data. Subsequently, a second check on deviations has been carried out by myself. The measuring accuracy is also important as part of the data quality check. The Trimble R10, to measure the topography, has an accuracy of 12 mm. The multibeam SEABAT 7101, to measure the bathymetry, has an accuracy of 12.5 mm. For the purpose of this research, the measurements are accurate enough. In addition, due to some missing data at the shallow underwater part of the beach (see Figure 4-2) some preliminary processing was needed in order to fill the missing data. To fill the gap of the missing data ,some sort of interpolation was required. Different methods were applied to fill this gap. It has been found that linear interpolation can be applied only for the first survey because of the small gap and the limited affected shape of the profile. However, for the other surveys it appears to deviate from the reality. Subsequently, several interpolation methods have been tested to see if they provide a better outcome. However, it has been found that the outcome with the various interpolation methods are incorrect and do not fits the reality. The main reason for this was the varying distance of the unknown part. After some trial and error, it has been concluded that interpolation does not fit the real cross-shore profile. In section 4.3 and 4.4 this will be further discussed.

## 4.2 Meteorological and hydraulic data

In order to explain the observed behaviour of the sandy shores of the Marker Wadden, some meteorological data is required to estimate the wave conditions at the Marker Wadden. Based on this meteorological data subsequently a real wave climate has been conducted. This is required to study the relationship between the behaviour of the sandy shores of the Marker Wadden and the hydraulic conditions in Lake Marken. Meteorological data has been gathered from the measuring station at the pilot project along the Houtribdijk, a measuring station on top of the Houtribdijk (close to the pilot project) and the measuring station in the Bataviahaven, Lelystad. The locations of the measurement stations are shown in Figure 4-3.

Next to the test section of the pilot project Houtribdijk, about 4km away from the Marker Wadden, wind measurement equipment has been placed which measures the meteorological data since the 19th of November, 2014. The data is gathered as part of the extensive monitoring program of the pilot project. The data is obtained per hour and consist of wind speed and wind direction. The measuring station on top of the Houtribdijk appears to measure higher wind speeds due to the up-pushing wind in front of the dike and is therefore not representative for wind speeds near the water surface. The wind direction, however, is used and compared with the other measuring stations.


*Figure 4-3. Overview of the metrological measurement stations (Boskalis World, 2017).*

The measuring station Bataviahaven nearby Lelystad is only used for the wind direction, because the wind speed is significantly different from the measuring station near the pilot project. The measuring stations on top of the Houtribdijk and in the Bataviahaven is not always reliable because of frequent missing data. Therefore, the metrological data of the pilot project is the most reliable and is the most appropriate data. As part of the extensive monitoring program of the pilot project also hydraulic data is measured. The gathered hydraulic data consists of water levels, wave heights, directions and current velocities. Given the fact that the measurement location is not located near the Marker Wadden, this hydraulic data cannot directly be used for this study. However, the data can be used in order to validate the wave climate according to the Brettschneider method for the Marker Wadden.

### 4.2.1 Wave climate by Brettschneider method

The wave climate is defined as the distribution of wave height, wave period, and direction averaged over a period of time for a particular location (Van der Weij, 2005; Wiegel, 1964). The wave climate depends both on prevailing winds and storms and on the bottom topography, which tends to modify the waves. An important reason for knowing the wave climate of a region for engineering design calculations is the fact that the wave climate will determine the effect of storms. The currents and waves are mainly wind driven in the shallow Lake Marken. Wind can be characterized by the direction, the duration and wind force. In the absence of the wind climate, long term wind data can be used to derive the long term wave climate (significant wave heights). An appropriate method to generate wave characteristics from wind characteristics, such as the wave height (*H*) and wave period (*T*), is the method of Brettschneider (Brettschneider, 1952; USACE, 2002)

### Brettschneider method

The combined formulae of Brettschneider in which both the water depth as the fetch are given in equation [4-1] and equation [4-2].

$$H = 0.283\left(\frac{u^2}{g}\right)\tanh\left(0.53\left(\frac{gd}{u^2}\right)^{0.75}\right)\tanh\left(\frac{0.0125\left(\frac{gF}{u^2}\right)^{0.42}}{\tanh 0.53\left(\frac{gd}{u^2}\right)^{0.75}}\right) \quad [4\text{-}1]$$

$$T = 2.4\pi\left(\frac{u}{g}\right)\tanh\left(0.833\left(\frac{gd}{u^2}\right)^{0.375}\right)\tanh\left(\frac{0.077\left(\frac{gF}{u^2}\right)^{0.25}}{\tanh 0.833\left(\frac{gd}{u^2}\right)^{0.375}}\right) \quad [4\text{-}2]$$

Where:

| | | |
|---|---|---|
| $T$ | wave period | [s] |
| $u$ | wind velocity at 10 m above surface | [$ms^{-1}$] |
| $g$ | gravity acceleration | [$ms^{-2}$] |
| $F$ | fetch | [m] |
| $d$ | water depth | [m] |
| $H$ | wave height | [m] |

By knowing the water depth, wind speed and fetch length, the wave height and wave period can be determined at any location by using the Brettschneider method. However, in the formulae [4-1] and [4-2] is the increase of wave height as result of the wave processes refraction and shoaling is not taken into account. For a wave climate it is important to know from which direction and how often most important waves come from. Research by Bouws (1986) for the Royal Dutch Metrological Institute (KNMI), shows that the Brettschneider method is readily applicable to Lake Marken where the wave climate is directly related to the wind climate. In that case, in absence of comprehensive wave data, the wave climate can be determined based on the wind climate. Because the wave climate depends on the water depth and fetch, the wave climate varies per location. In order to obtain the wave climate at a certain location, it is necessary to know the wind speed and direction and the fetch and water depth for each direction.

## 4.2.2 Wave climate Marker Wadden

In order to determine whether the meteorological data obtained at the pilot project is appropriate to use for the Marker Wadden, the wave height ($H_s$) and wave period ($T_s$) are computed for the pilot project according to Brettschneider. The results were compared with the measured hydraulic data at the pilot project. It has been found that the results give slightly higher values for the wave height and wave period. However, this can be explained by the assumptions which were made such as a constant water depth in the lake, where actually at the pilot the lake is shallower and thus causes lower wave heights. Moreover, the Marker Wadden is located more central in the lake where in general the wave heights are higher as well.

An alternative to determine the wave climate is to use the Delft3D-SWAN model, which is based on a more sophisticated method to make an estimation of the local wave conditions. This method takes, among others, the inclination of the water level in the lake and wave processes such as refraction into account. However, considering the limited time of this research it is not possible to use such an extensive model to predict the local wave conditions. Based on this, it can be concluded that for the purpose of this research, the Brettschneider method is readily applicable and the observed meteorological data of the pilot project can be used to determine the wave climate for the Marker Wadden. For the purpose of further research, it should be considered to install some measuring stations in order to measure the local wave conditions near the beaches of the Marker Wadden.

## 4.3 Analysis of the southwest beach

In this section, an extensive analysis will be given of the morphological behaviour of the southwest beach of the Marker Wadden. In this section these topics are addressed in more detail:

- Morphological developments
- Cross-shore evolution
- Alongshore evolution
- Settlements
- Sediment characteristics
- Sediment balance

### 4.3.1 Morphological developments

Field monitoring of the local bathymetry and topography of the southwest beach has been carried out on a monthly basis in the period between October 29th 2016 until May 5th 2017. In Table 4-2 an overview of the surveys is presented of the southwest beach.

*Table 4-2. Overview survey of the monitoring period of the southwest beach with remarks.*

| Survey | Date | Remarks |
|---|---|---|
| T1 | 29-11-2016 | First survey after construction |
| T2 | 18-01-2017 | |
| T3 | 06-02-2017 | |
| T4 | 03-03-2017 | |
| T5 | 04-04-2017 | Completely covered survey |
| T6 | 05-05-2017 | |

#### Bathymetry and topography per survey

Based on the conducted field measurements, the observed morphological development is visualized by combining the bathymetry and the topography data (see section 4.1). Below an overview of the surface plots is provided for each conducted survey of the southwest beach. Figure 4-4 shows the situation just after construction conform the end survey of 29-11-2016. Given the fact that measurements were conducted in two different ways the data sets are combined. However, these data sets do not have overlap, as can be seen by the white surface. Depending on the weather conditions this gap is smaller or larger. The surface plot of survey T5, measured at April 4, 2017 completely covers the area. When the weather conditions were very favourable, so no wind and no waves, the part below the water line was measured with GPS equipment and wearing a wader suit. The other surveys were unfortunately not completely covered. The other development surface-plots are presented in appendix C.1.

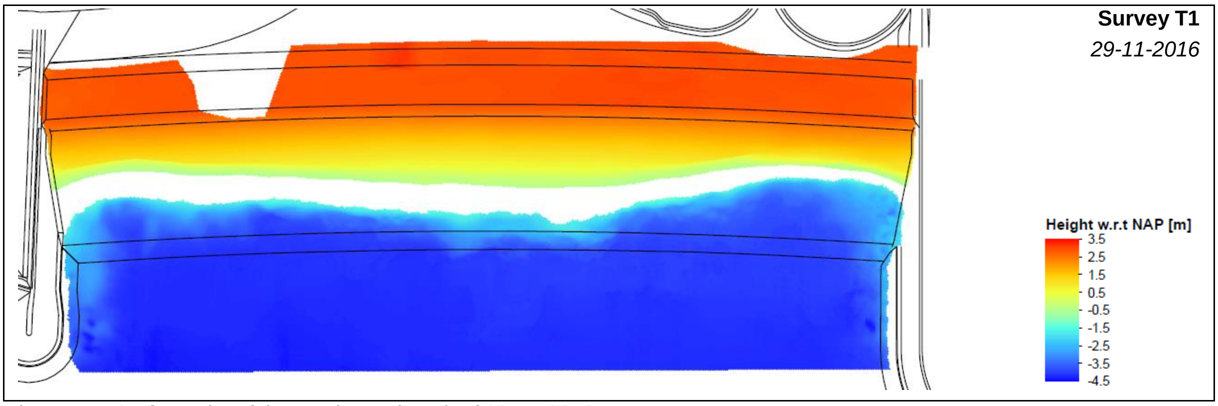


*Figure 4-4. Surface-plot of the southwest beach of 29-11-2016.*

### 4.3.2 Cross-shore evolution

This section describes the cross-shore evolution of the southwest beach. In order to explore the evolution of the cross-shore profile and their variation in longitudinal direction, 16 cross-shore profiles are further investigated in more detail. Figure 4-5 shows an overview of all these cross-shore profiles.

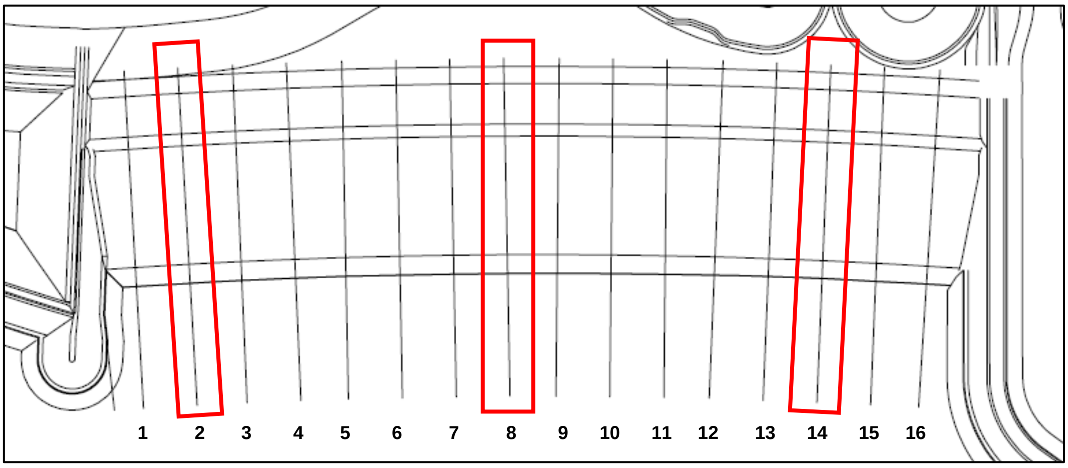


*Figure 4-5. Overview of the cross-shore profiles of the southwest beach. The red boxes indicates the characteristic cross-shore profiles for the northwest section, the central section and the southeast section.*

The spacing between the individual cross-shore profiles is 40 meters. In order to distinguish the variation in longitudinal direction, three characteristic cross-shore profiles are determined for the northwest section (#2), the central section (#8) and the southeast section (#14), as indicated by the red boxes. Also the morphologically development has been investigated in terms of volume of sediment in the active zone, to do so the redistribution of sediment within the cross section is examined. For the three characteristic cross-shore profiles the displacement of the sediment has been investigated.

#### 4.3.2.1 Natural characteristic of the cross section

In this section the characteristic features of the cross-shore profiles are described, such as the underwater slopes, plateau, swash berm and the steepness of the beach slope. Looking at the different cross-shore profiles it appears that the central section represents the most characteristic shape of the southwest beach. Figure 4-6 represents the measurement results for the characteristic central transect (#8) where the results are shown of the months after construction. After the first measurement no working activities have been carried out on the beach and the profile has formed by natural conditions. The solid lines represent the measurements (bathymetry and topography) and the dashed lines represents the linear interpolated part in between. The varying horizontal distance between the two separate measurements can be explained by the weather conditions of the day of measuring (i.e. higher waves due to higher wind speeds).

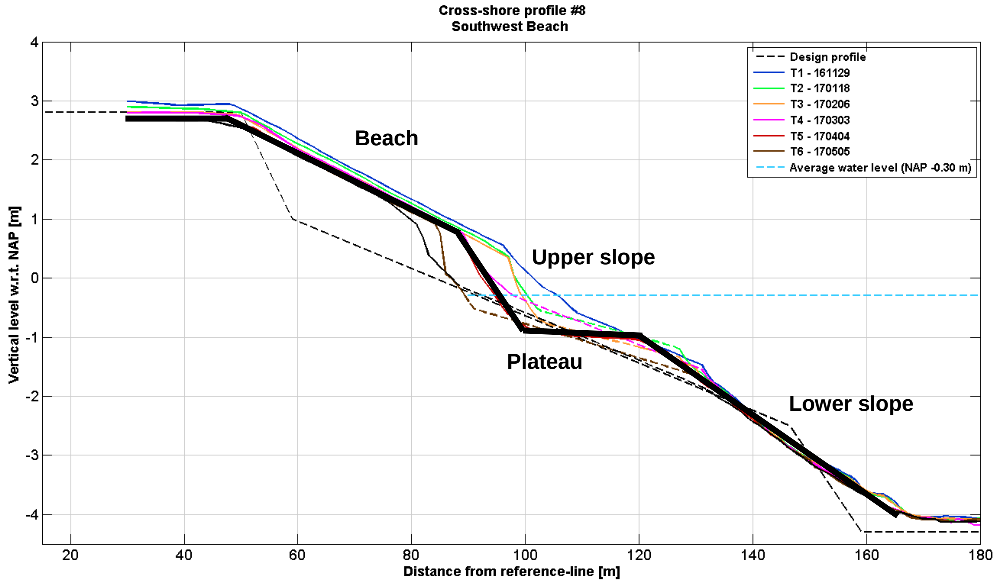



*Figure 4-6. Schematisation of the characteristic cross-shore profile shape of the southwest beach.*

The red line (T5) shows the characteristic shape of the profile which is formed in the first 4.5 months after construction. Basically, this profile shape arose within a few months. The plateau formation around the NAP-1.0m level is characteristic for the southwest beach and has been formed quite rapidly since construction. Over the entire length this has been plateau has been observed.

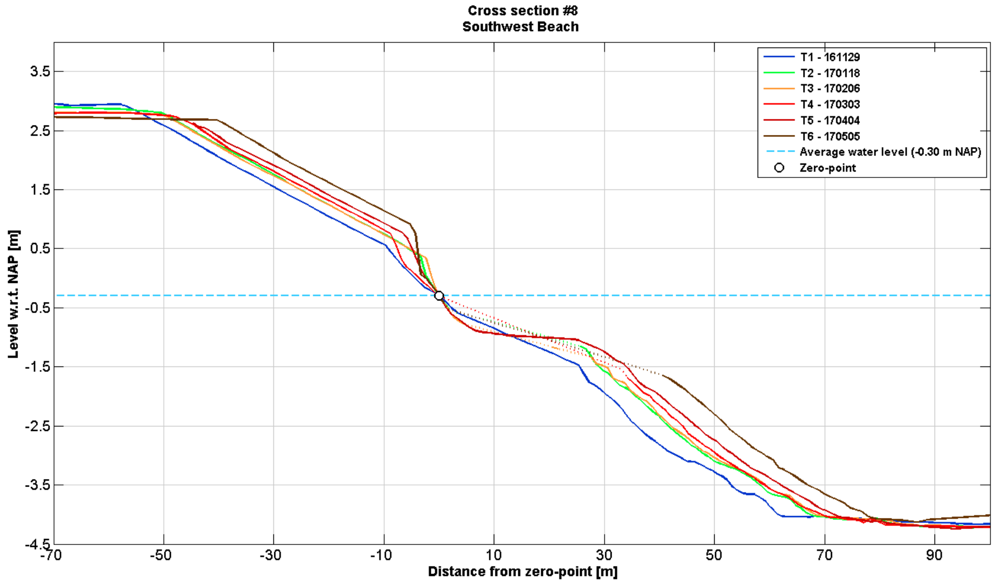



*Figure 4-7. Cross-shore profile #8 of the southwest beach w.r.t average water level at NAP-0.3m*

As can be seen the shoreline regression is clearly visible, which makes it that the shoreline has every time another position. It has also been observed that the slope around the water line changes over time, it seems the slope is getting steeper. Therefore the same profiles are presented in Figure 4-7 in such a way zero position is fixed where it intersects with the average water level at NAP -0.3 m. From this, the development of the relative steep slope of 1:9 around the water line has been noticed and the ongoing expansion of the underwater slope (below NAP -1.0m). Unfortunately the data around the water line and below are not complete for every survey.

### 4.3.2.2 Variation in longitudinal direction

In longitudinal direction the cross-shore profiles are not everywhere equally shaped and vary quite significantly over 650 meters. In this section the characteristic cross-shore profiles are presented for the northwest section, central section and the southeast section of the southwest beach as shown in Figure 4-5.

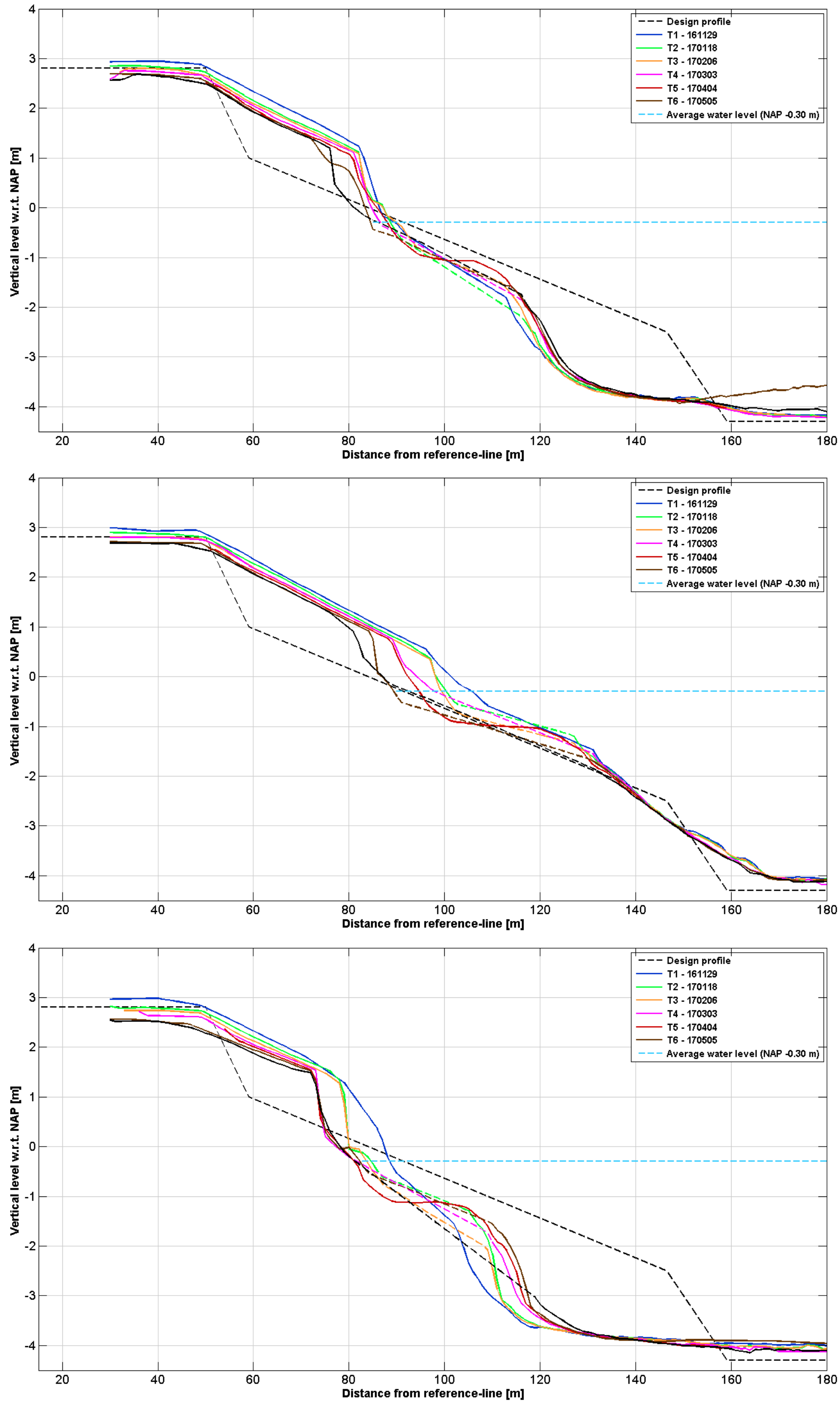



*Figure 4-8. Cross-shore profiles of the north-western section #2 (upper) , central section #8 (middle) and south-eastern section #14 (lower).*

As can be seen, the characteristics of the profile shape varies in alongshore direction. In comparison with the central section, the slope of the cross-shore profile at the outer sections are steeper. As results that the height of the vertical scarp is also higher at the outer sections. Here, the profiles were initially steeper constructed. Due to practical considerations during construction, it was chosen to keep it like that, because there was already enough sand available in the entire beach section. Therefore it has been decided to not extend the beach and let the natural processes take its course. From the first measurement, regression of the shoreline is observed, which is about 5-6 meters at the outer sections and almost 17 meter at the central section. This is can be explained by the changing shoreline at the central section of the beach. Here, initially the beach was wider compared to the outer sections. Moreover, the impact of the changing (increasing) water level, from winter to summer level, is also part of the regression of the shoreline.

A vertical scarp up to 1.0 m in height due to erosion is mainly observed at the outer sections. At the central section a small vertical scarp is observed up to 0.3 m. In particular at the south-eastern part of the beach, the location and height of this vertical scarp seem to be quite stable given the fact that the last 3 surveys show almost exactly the same. This is probably related to the fact that the waves did not reach so far and the rotation of the shoreline, i.e. only high waves approaching the shoreline from the right direction affect the location of this vertical scarp. The volume losses of sand is partly due to settling of the sand package as can be observed at the higher part of the profile. In general, the active zone is between NAP -1.0 m and NAP +1.0 m. Above and below these levels no significant changes over time is observed, except for the southeast section of the beach where sedimentation can be observed below the level of the plateau.

The red line (T5) shows a plateau formation around NAP -1.0 m at all the cross sections, which is developed from the beginning since construction. The width of the plateau varies between 5 and 15 meter, in which at the central section the plateau is the widest. Looking at the cross sections, mainly erosion can be observed above the plateau level. Below this level only sedimentation is observed at the outer sections. Which indicates that there is a sediment loss in mainly at the central part of the beach. The table below summarizes the variations of the characteristics of the cross-shore profiles in longitudinal direction. The cross-shore profile of the central section (#8) is the most characteristic of the southwest beach.

*Table 4-3. Summary of the cross-shore profile characteristics of the northeast, central and southwest sections.*

| | North-eastern section | Central section | South-western section |
|---|---|---|---|
| Crest level dune | NAP +2.8 m | NAP +2.8 m | NAP +2.8 m |
| Beach slope | 1 : 20 | 1 : 20 | 1 : 20 |
| Height vertical scarp | ± 0.6 m | ± 0.3 m | ± 1.0 m |
| Slope around the water line | 1 : 7 | 1 : 9 | 1 : 8 |
| Plateau width | ± 5 m | ± 15 m | ± 10 m |
| Underwater slope | 1 : 7 | 1 : 15 | 1 : 5 |
| Depth of closure | NAP -3.8 m | NAP -2.5 m | NAP -3.8 m |

## 4.3.3 Alongshore evolution

In order to analyse the alongshore evolution, the differences between the surveys are described in this section. To do so, the development per interval is presented where after the observed erosion-sedimentation patterns are discussed in more detail. Followed by an analyses of the alongshore evolution of the shoreline.

### 4.3.3.1 Describing the development per interval

The morphological development of the southwest beach will be addressed during the first months after construction. For each time interval an overview is provided which presents the differences in height between the surveys. The surface-plots shows the erosion-sedimentation patterns due. The colours indicates bed level differences in meters. The blue parts refers to erosion and red parts refers to sedimentation. The small height differences (-/+10 cm) are set aside to emphasize the major erosion-sedimentation patterns. Unfortunately, the missing data of the shallow part of the beach is not taken into account for this analysis of the morphological development. The legends as presented in Figure 4-9 applies for all the surface-plots and wave roses provided on the next page. An extensively explanation of the wind and wave conditions per time interval is provided in appendix B.1.

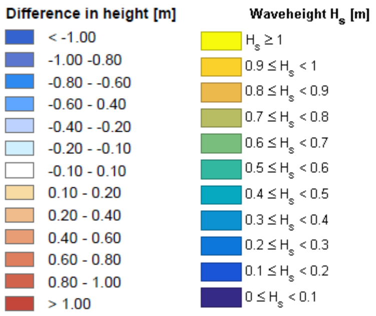



*Figure 4-9. Legends surface-plots (left) and wave roses (right).*

**Analysis of the morphological developments per period**

Analysis of the morphological developments show that the erosion and sedimentation patterns clearly can be explained by the wave conditions during the periods. The volume loss due to vertical settlements is clearly visible at the upper parts of the beach (10-20 cm) at the first period. In combination with the extensive wind and wave data analysis (see appendix B.1), the patterns can be explained quite well. The transport gradients can be determined by the dominant wave directions.

When most of the waves coming from another direction than the southwest, no significant morphological changes are observed. For example period T2-T3, the wind direction during this period was mainly from the southeast, so the waves were not exposed to the southwest beach. Moreover, the weather conditions was quite calm. During the period T3-T4, the first spring storm occurred on February 23, which came from the west-southwest direction (252 ° w.r.t. North) and so clearly exposed to the southwest beach, in particular the south-eastern part of the beach. The wave attack during this storm event has clearly led to the decline of the profile.

Furthermore, it can be seen that each period the central section erode and that outer sections accrete. The initially wider constructed beach at the central section experience mainly erosion. The eroded sediment seems to be transported to the outer sections.

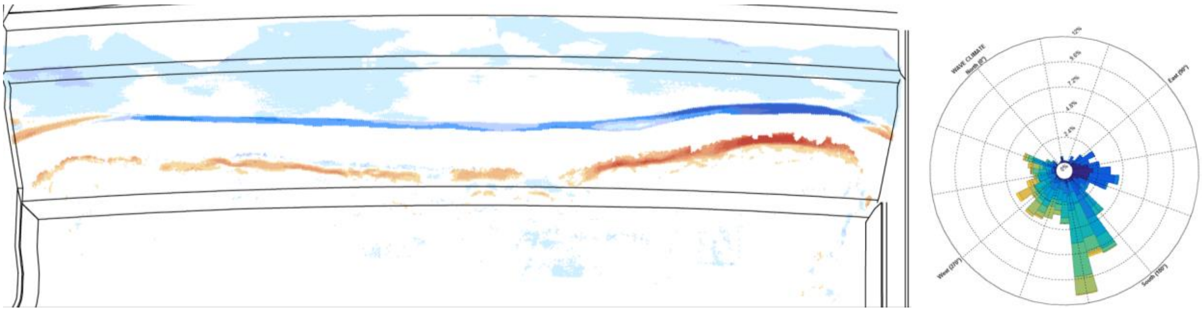


*Figure 4-10. Morphological developments T1-T2 and corresponding wave rose (29/11/16 – 18/01/17).*

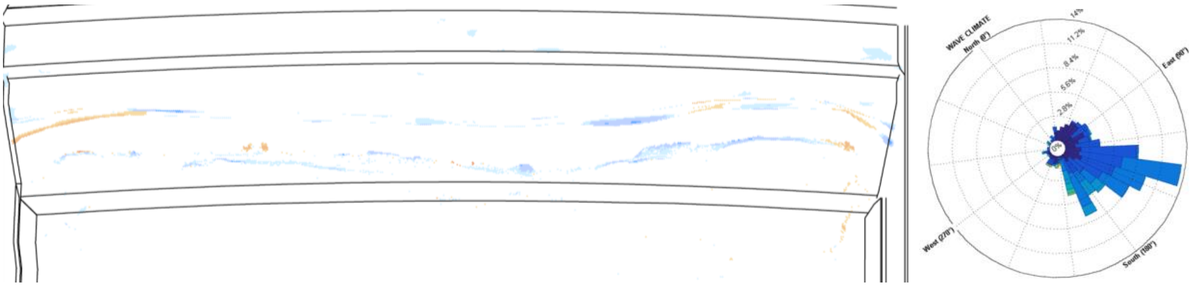


*Figure 4-11. Morphological developments T2-T3 and corresponding wave rose (18/01/17 – 06/02/17).*

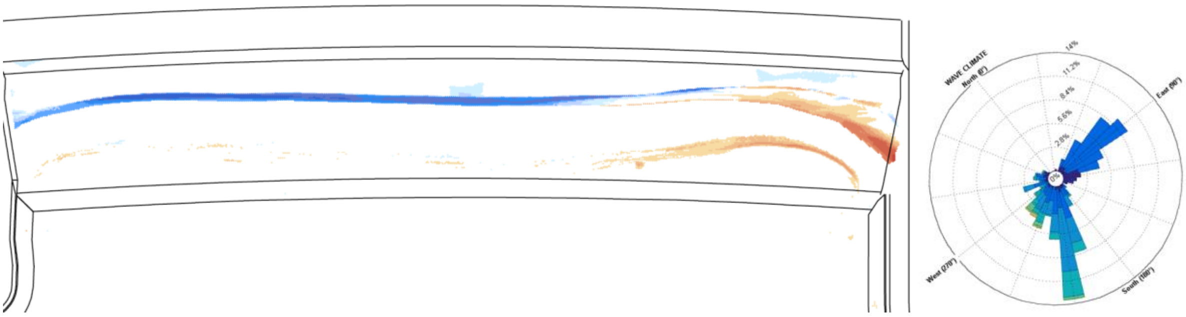


*Figure 4-12. Morphological developments T3-T4 and corresponding wave rose (06/02/17 – 03/03/17).*

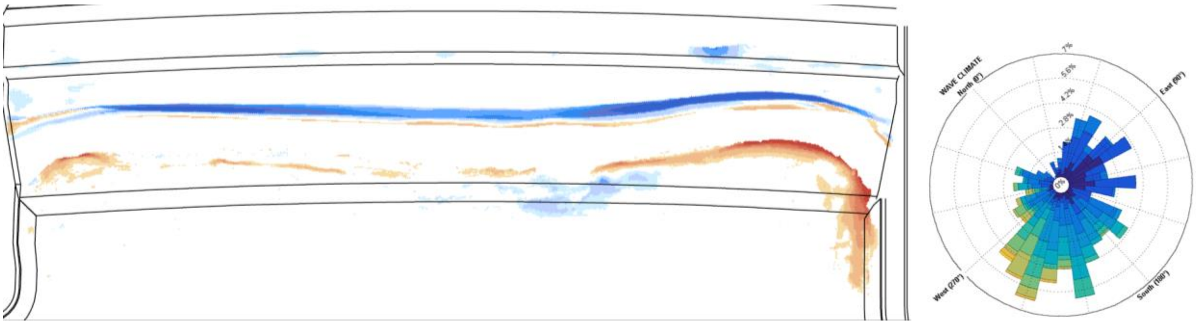


*Figure 4-13. Morphological developments T4-T5 and corresponding wave rose (03/03/17 – 04/04/17).*

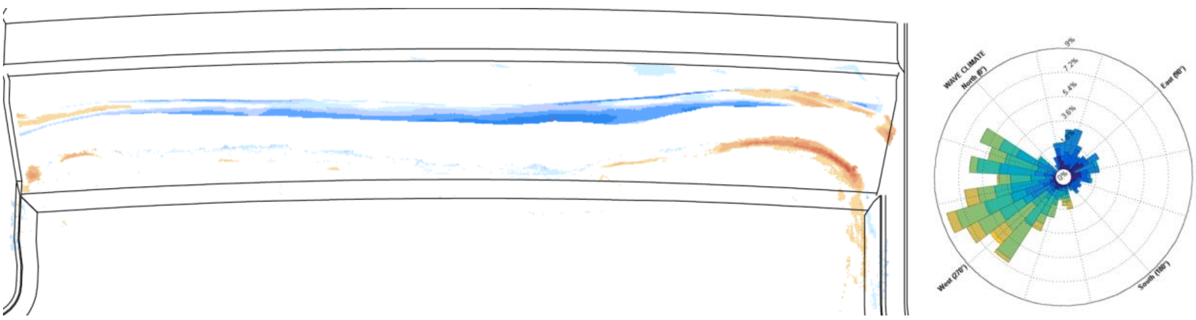


*Figure 4-14. Morphological developments T5-T6 and corresponding wave rose (04/04/17 – 05/05/17).*

### General morphological developments (T1-T5)

Based on the first survey at 29-11-2016 (T1) and the survey at 05-05-2017 (T5), a more detailed analyses of the general erosion-sedimentation patterns is provided. The result of the surface-plot is shown in Figure 4-15. It can be concluded that the general developments show regression of the shoreline over almost the entire length of the beach, except the outer sections where the beach is enclosed by the breakwaters. Moreover, it seems that the shoreline becomes more straight because of the sediment of the central section has been moved to the outer sections. This is clearly visible by the sedimentation spots at the outers sections of the beach. Especially at the southeast part of the beach, a lot of sedimentation can be observed. The accretion along the south-eastern breakwater can be explained due to a swirl effect which occurs when waves approach the beach from the southwest. Furthermore, the volume losses due to settlements of the subsoil at the upper part of the beach can be observed.

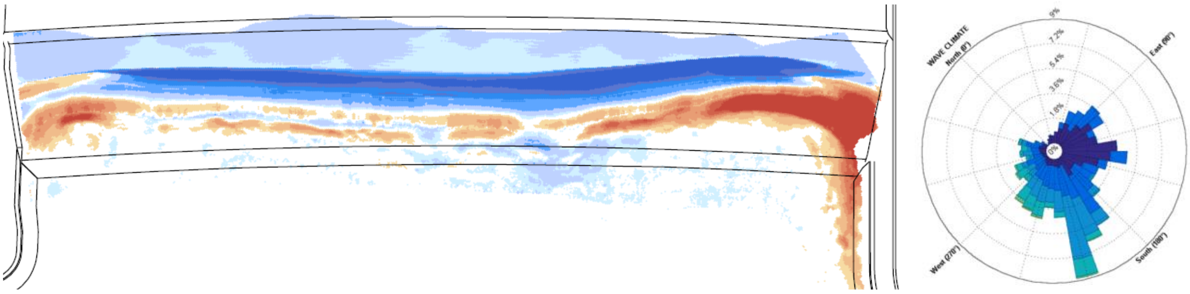


*Figure 4-15. General morphological developments T1-T5 and corresponding wave rose.*

### 4.3.3.2 Alongshore evolution of the shoreline position

In this section, the evolution of the shoreline position is discussed between survey T1 and T6. In order to analyse the alongshore evolution, the shoreline position around the water line at NAP -0.3 m and the shoreline position around the vertical scarp at NAP +0.5 m are examined.

### Shoreline position around the water line (NAP -0.30 m)

In Figure 4-16 the evolution of the shoreline position around the average water line is schematized. The green line represents the shoreline position at 29-11-2016 (T1) and the red line represents the shoreline position of the last survey at 05-05-2017 (T6). From the observations, it can be seen that a straight shoreline has been developed and is changed to an orientation of about 225 °N, as initially designed as well. In the central section, the shoreline shows a regression of about 18 m. At the north-western part of beach, the shoreline position has not changed significantly. At the other side of the beach near the south-eastern structure, the shoreline has been moved significantly offshore directed, about ±20 m.

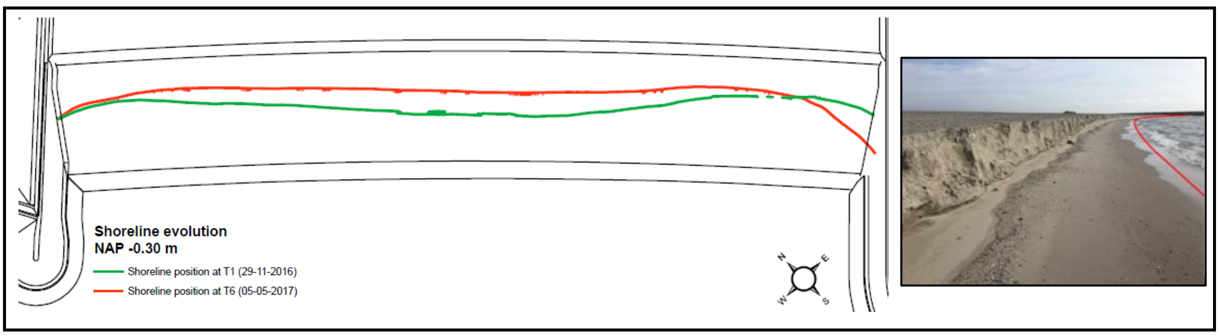



*Figure 4-16. Shoreline position around the water line (NAP -0.30 m).*

### Shoreline position at the vertical scarp (NAP +0.50 m)

In Figure 4-17 the evolution of the shoreline position of the NAP + 0.5 m line is shown. This line is at the height of the vertical scarp, which is present over the entire length of the beach. The green line represents the shoreline position at T1 (29-11-2016) and the red line represents the shoreline position at T6 (05-05-2017). This line clearly indicates the backward movement forced by the wave attacks. As can be seen in the figure below in the central section of the beach, the shoreline has been moved about 12 meters in landward direction. At the outer sections of the beach near the structures, no significant displacements can be observed.

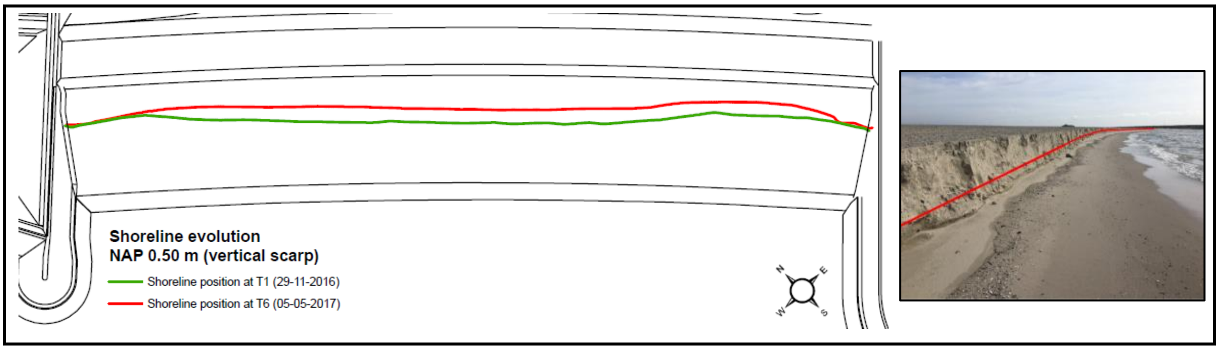



*Figure 4-17. Shoreline position of the NAP +0.50 m line, at the level of the vertical scarp.*

The evolution of the shoreline is clearly visible in an aerial view of the southwest beach presented in Figure 4-18. Where initially the beach was wider in the central section, it has been gradually adjusted to a straight lined beach. Moreover, the vertical scarp can be observed in the outer sections of the beach. In the central section, where initially the beach was constructed with a more gentle slope, the vertical scarp cannot be observed.

*Figure 4-18. Aerial view of the southwest beach (13 June 2017) (Photographed by: Straystone).*

## 4.3.4 Settlements

In this section, first the extend of settlement at the beach is discussed. In the figure below a map is presented showing the settlement between measurement T1 and T5. The map shows the spatial variation of settlement at the southwest beach. According to this map about 3,500 m$^3$ is lost due to settlement, however, it only covers a part of the beach. In general, the further land inwards the higher the settlement rate. The settlement varies roughly between 10 and 30 cm, with an average of 26 cm. It should be noticed that these measurements are not completely accurate, measurement deviations for the GPS equipment (±12 mm) need to take into account as well. However, for the purpose of this study the accuracy is sufficient.

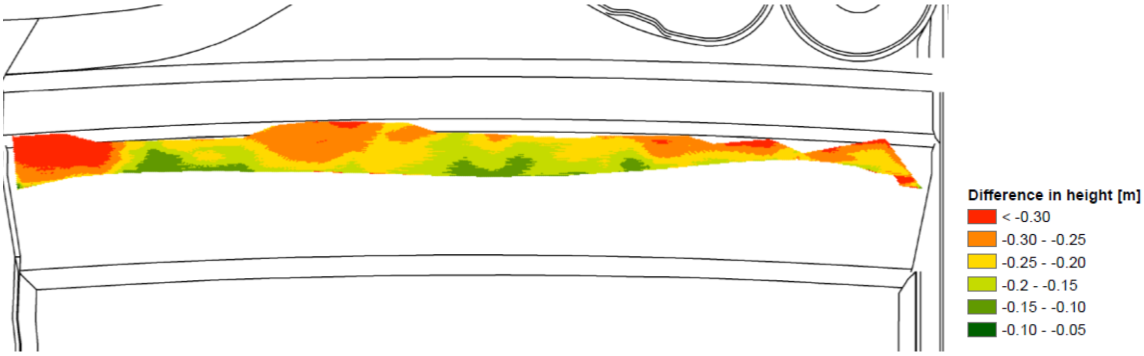



Figure 4-19. Sand losses due to vertical settling at the southwest beach in the period T1-T5

As can be seen in the map, the extend of settlement varies a lot in space, both in longitudinal direction and in cross-shore direction. Figure 4-20 shows a schematic diagram in order to calculate the volume losses due to settlement of the subsoil the average settlement in cross-shore direction. The average settlement on top of the beach is about 26 cm where the height of the sand package is the largest. As the height of the sand package decreases the settlement reduces as well, therefore it is assumed that at the bottom the settlement is reduced to zero. Based on this schematic average cross-section the volume losses are determined at 9.985 $m^3$.

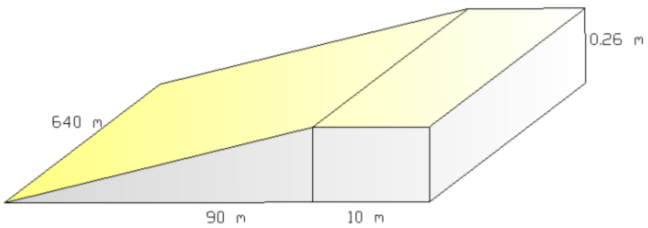



*Figure 4-20. Schematic diagram for the calculation method to determine volume losses due to settlement of the subsoil between T1 and T5 for the southwest beach.*

### 4.3.5 Sediment characteristics

In this section the sediment characteristics of the southwest beach are described and analysed. The focus is on the grain size and the distribution of grain size along the beach. Sediment samples were taken at several locations in October 2016, as can be seen in the overview provided in Figure 4-21. The sediment samples were brought to the lab where the grainsize distribution was determined. By means of a sieve curve the sediment characteristics were determined (conform NEN 5753).

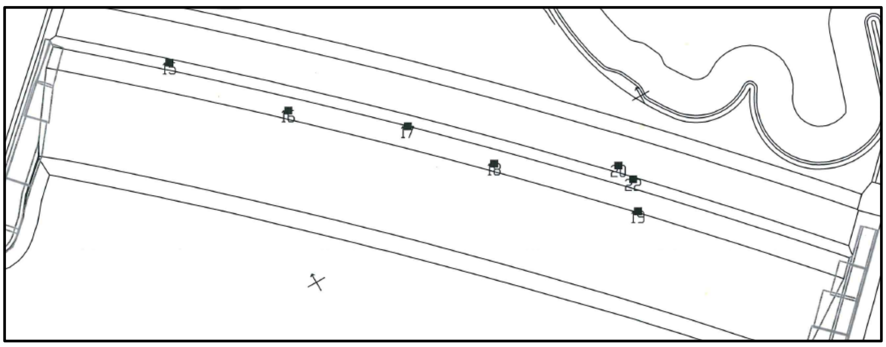


*Figure 4-21. Locations of the sediment samples taken at 13-10-2016 at the southwest beach.*

The sediment characteristics of the sediment samples are given in the table below. At each location two sediment samples were taken at different depths, its however not completely clear at which depth which sample is taken. Looking to the spatial differences between the sediment samples the following can be concluded. The $D_{50}$ varies considerably; between 214 and 394 μm and shows an average of about 300 µm. Looking at the spatial variance, the $D_{50}$ at the central part (330 µm) seems to be higher compared to the outsides, respectively 240 µm (NW) and 290 µm (SW). Moreover, the variance of the grainsize distribution is quite large as well. The ratio $D_{90}/D_{10}$ provide information on the spreading inside a sediment sample, for example a high ratio indicates a poorly sorted sample and a low ratio indicates a well sorted sample. The $D_{90}$ /$D_{10}$ ratio varies from 3.48 to 11.34.

*Table 4-4. $D_{10}$, $D_{50}$ and $D_{90}$ results of the sediment samples taken at 13-10-2016 at the southwest beach.*

| Sediment sample | $D_{10}$ (µm) | $D_{50}$ (µm) | $D_{90}$ (µm) | $D_{90}$ / $D_{10}$ |
|---|---|---|---|---|
| 15-1 | 117 | 214 | 407 | 3.48 |
| 15-2 | 145 | 269 | 610 | 4.21 |
| 16-1 | 161 | 355 | 832 | 5.17 |
| 16-2 | 142 | 292 | 700 | 4.93 |
| 17-1 | 150 | 394 | 1701 | 11.34 |
| 17-2 | 151 | 294 | 677 | 4.48 |
| 18-1 | 141 | 259 | 524 | 3.72 |
| 18-2 | 180 | 363 | 746 | 4.14 |
| 19-1 | 159 | 318 | 867 | 5.45 |
| 19-2 | 180 | 385 | 1673 | 9.29 |
| 20-1 | 130 | 228 | 746 | 5.74 |
| 20-2 | 147 | 284 | 814 | 5.54 |
| 22-1 | 140 | 265 | 966 | 6.90 |
| 22-2 | 140 | 259 | 892 | 6.37 |
| **Averaged** | **148.8** | **298.5** | **868.2** | **5.77** |
| **Lowest** | **117.0** | **214.0** | **407.0** | **3.48** |
| **Highest** | **180.0** | **394.0** | **1701.0** | **11.34** |

### Additional sediment samples

In the additional measurement campaign sediment samples were taken that could provide information on the sediment characteristics in relation to the cross-section. Especially the grain size distribution within the cross-shore profile is interesting in order to investigate if relation can be found between the grainsize and the depth. This was also done for the pilot project along the Houtribdijk, where they extensively monitored the sediment characteristics for a grain size distribution analyses. The monitoring has shown that the finer sediment particles were found lower in the profile while the coarser sediment particles were found higher at the beach. From this analysis, the sediment distribution seems depend on the depth. Field samples taken in November 2014 at the pilot show the following results as presented in Figure 4-22. From about NAP -1.5 m towards the shoreline, the figure shows a more or less parallel displacement of the grain size distribution (black, red, green and yellow) to a more coarser median grain size ($D_{50}$). The samples above the shoreline level (yellow, blue and pink), so above ± NAP -0.3 m, shows a tilt of the grain size distribution and have more or less the same median grain size ($D_{50}$). The boxplots (right-hand plot) confirm that the $D_{50}$ depends on the depth, where the amount of finer sediments increases by an increasing depth.

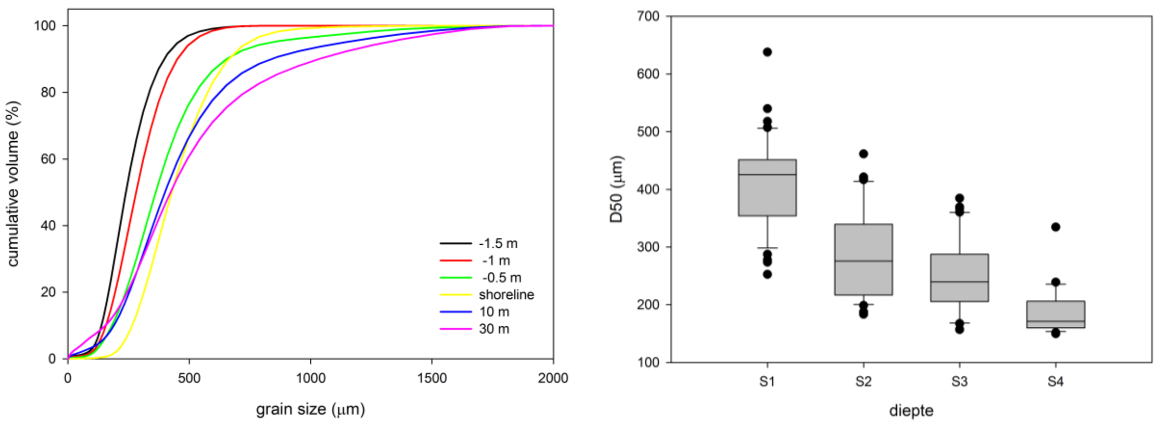



*Figure 4-22. Left-hand plot: grain size distribution below the water line and above the water line. Right-hand plot: Boxplots of the $D_{50}$ at the underwater transects. S1= 0.5m, S2 = 1.0m, S3=1.5m and S4 =2.0m (depths) (Ecoshape, 2017).*

At several locations, sediment samples were taken at the southwest beach, as can be seen in the overview provided in Figure 4-23. The additional sediment samples were taken at May 18$^{th}$ 2017 at 15 locations. The sediment samples were brought to the lab where the grainsize distribution was determined. By means of a sieve curve the sediment characteristics were determined.


*Figure 4-23. Left-hand plot: Locations of the sediment samples taken on 18-05-2017 at the southwest beach. Right-hand plot: box-plot of the sediment samples at different heights.*

An overview of the sediment characteristics is provided in Table 4-5. Here is the $D_{10}$, $D_{50}$ (median), $D_{90}$ and the $D_{90}/D_{10}$ ratio presented.

*Table 4-5. $D_{10}$, $D_{50}$ and $D_{90}$ results of the sediment samples taken at 18-05-2017 at the southwest beach*

| Sediment sample | $D_{10}$ (µm) | $D_{50}$ (µm) | $D_{90}$ (µm) | $D_{90}$ / $D_{10}$ |
|---|---|---|---|---|
| 1 | 152 | 314 | 1155 | 7.59 |
| 2 | 151 | 294 | 814 | 5.39 |
| 3 | 161 | 313 | 732 | 4.54 |
| 4 | 182 | 350 | 879 | 4.83 |
| 5 | 150 | 312 | 694 | 4.62 |
| 6 | 164 | 337 | 1134 | 6.94 |
| 7 | 155 | 331 | 710 | 4.58 |
| 8 | 167 | 304 | 683 | 4.10 |
| 9 | 214 | 424 | 705 | 3.30 |
| 10 | 141 | 235 | 513 | 3.63 |
| 11 | 137 | 221 | 410 | 3.00 |
| 12 | 285 | 515 | 760 | 2.67 |
| 13 | 370 | 630 | 1190 | 3.24 |
| 14 | 261 | 477 | 710 | 2.73 |
| 15 | 199 | 398 | 885 | 4.45 |
| **Averaged** | **192.6** | **363.7** | **798.3** | **4.37** |
| **Lowest** | **137** | **221** | **410** | **7.59** |
| **Highest** | **370** | **630** | **1190** | **2.73** |

At the southeast section of the beach, the median grainsize ($D_{50}$) is higher around the shoreline and just below the water level (around the plateau). An explanation for this could be that the initial construction profile at the this part the slope is steeper compared with the rest of the beach. In general it can be assumed that a steep slope is characterized with coarser sand. Moreover, due to erosion of the vertical scarp, just above the water line, sand is displaced to the lower parts. Subsequently, the finer sediments are washed out with the result that the coarser sediments remains. This explains that around the shoreline and at the plateau the median grainsize is higher and the variance of the grainsize distribution is lower (lower $D_{90}/D_{10}$ ratio). Nearshore wave action result in a relatively high energy environment whereas in deeper water, the relative energy is less. Unfortunately no sediment samples were taken below NAP -0.8 m. This would provide interesting information in order to analyse the sediment characteristics in more detail and compare the results with the pilot. In order to gain insight in the temporal distribution of the grain size distribution more sediment samples should be taken in the future as well. Looking at the spatial variance in longshore direction, the median grainsize measured at the shoreline seems to increase from northwest to southeast (left to right). Moreover, the median grainsizes at the southeast part at the beach (sample 10 and 11) are remarkably lower compared to the samples, respectively 235 µm and 221 µm.

### 4.3.6 Sediment balance

The observations from the surface plots, as shown in section 4.4.1, are further investigated by analysing the sediment balance for the area of the northwest beach. The volume changes due to settlement of the subsoil, aeolian sediment transport, cross- and longshore sediment transport are determined by subtracting the surface-covering survey of April 5, 2017 from the survey in November 29, 2016. The total volume difference between these surface plots was determined at 9,800 $m^3$. Sediment losses due to settlement of the subsoil are derived from subtracting the surface plots, from this the average settlement is determined at 0.26 m at the upper part of the beach. Subsequently, by a triangle approach the theoretical total volume of settlement was determined at 9,985 $m^3$. Because the beach is enclosed by the breakwater at the northwest side and the breakwater of the harbour at the southeast side, the system must be theoretically closed ($Q_{in} = Q_{out} = 0$). The length of the breakwaters are designed that the sediment remains within in the area. So theoretically, the sediment volume should be the same, except the volume loss due to settlements. In addition it is assumed that there is no sediment loss in cross-shore direction. An important note for the survey plot of T1 is that linear interpolation has been applied to fill the gap of the 'unknown' area. Hereby is assumed that it corresponds quite well with the reality. However, this may lead to deviations in the volume balance and should therefore be considered as well. Combination of the volumes results in the sediment balance for the southwest beach as shown in Figure 4-24.

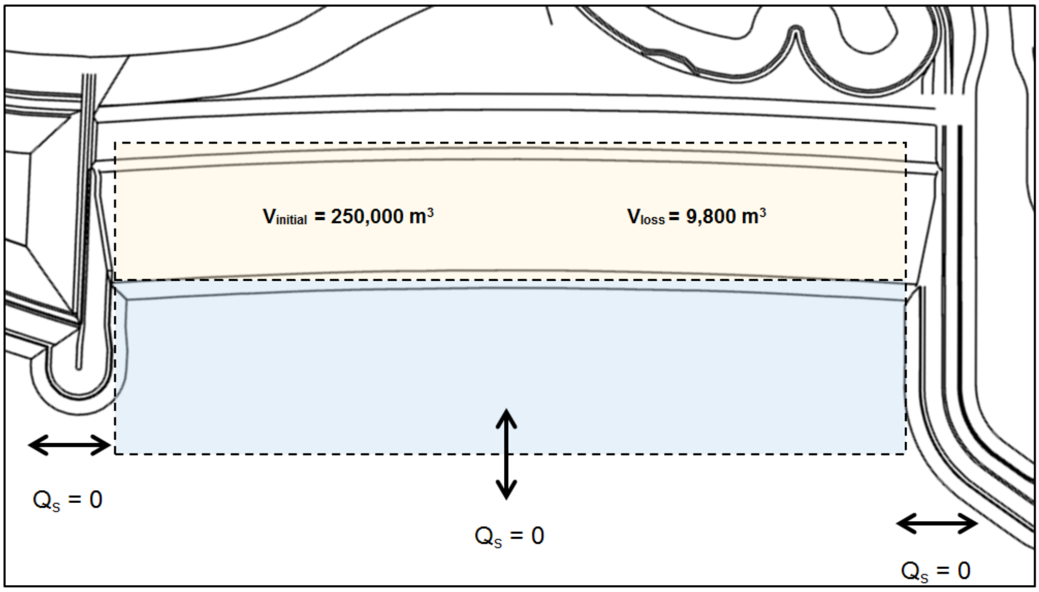



*Figure 4-24. Schematically overview of the sediment balance of the southwest beach, according to the volume changes 4 months after construction (period T1-T5).*

The initial measured volume at T1 was determined at about 250,000 $m^3$. Subtracting the surface-plot from T5 gives a volume change of about 9,800 $m^3$. This is $\pm$13 centimetres per square meter loss, when it is divided by the surface area (75,000 $m^2$). Based on the morphological development surface-plots it is assumed that the system is closed. This automatically means that the sediment balance is closed also, because no sediment comes in the system and no sediments leaves the system. The difference can therefore be related to the sediment losses due to settlements.

Now the different sources of the volume change are known, it is of interest to trace the movement of sediment within the area. This is done by dividing the entire area of the southwest beach into layers and sections. Volume changes are calculated with respect to the volumes that were measured at April 5 (T5), because this survey covers the entire beach and therefore gives the best insight in the sediment displacements within the system.

#### 4.3.6.1 Distribution in vertical layers

For a further analysis, the cross-shore profile is divided in three layers in order to distinguish the active profile in the middle. The layers are, from a morphological point of view, behaving differently of which the middle layer is the most active zone. The layer distribution has been shown in Figure 4-25 and are respectively:

A) The top layer above NAP + 0.5 m;
B) The middle layer below NAP + 0.5 m and above NAP -2.5 m;
C) Under layer below NAP - 2.5 m.

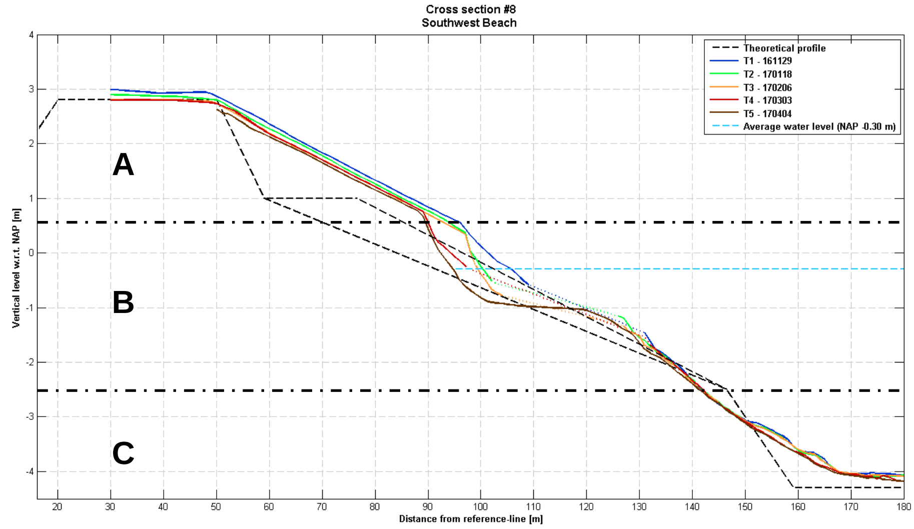



*Figure 4-25. The layer distribution of the cross-shore profile at the central section of the beach: upper layer A, middle layer B and lower layer C.*

The contour lines of NAP -2.5 m and NAP 0.5 m have changed during the first and the last survey, this can be seen in Figure 4-26. The area in between the lines is the most active zone. In particular the NAP -2.5 m contour line has changed at the southeast part and the NAP 0.5 m contour line at the central section. It is clearly visible that the southeast section of the beach has changed the most as a result of the initial constructed steep slope and the accretion in this area due to the longshore gradient.

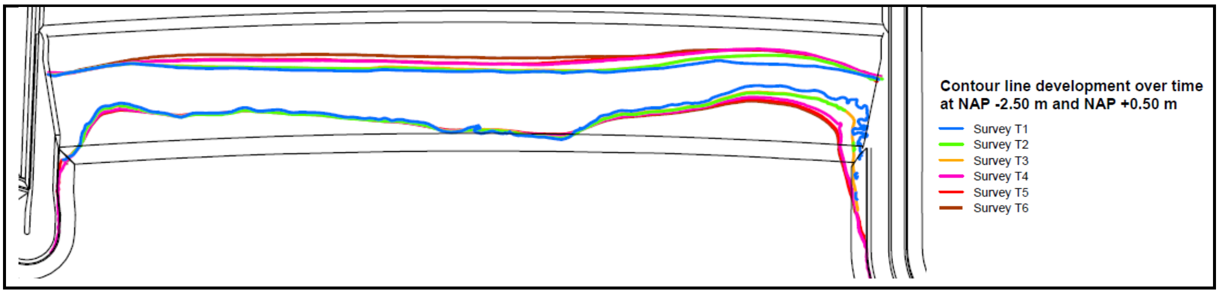



*Figure 4-26. Contour lines NAP -2.5 m and NAP 0.5 m for the surveys T1 to T5.*

Based on this sediment distribution, an analysis has been performed in order to get insight in the volume changes within the three layers. Table 4-6 shows the volume change of the southwest beach per layer. As can be read in the above table, the volume change in the active zone is positive. This means sand is added in this layer which most likely comes from layer A. The contour lines have changed significantly over time (see Figure 4-26), which affects the surface of the layer and so the volume differences. The surface differences emphasize this as well. Whereas the surfaces of layers A and B are decreased, the surface of layer B is increased. Looking at the total volume differences there is a total volume loss of 9,700 $m^3$. This volume loss can be explained by the settlement of the subsoil.

For which in layer A the most volume loss is expected and in layer C the least. The average loss per square meter is computed at 13 cm in the period between T1 and T5.

*Table 4-6. Overall volume change between T1 and T5  according to bathymetry and topography surveys.*

| Layer | Volume difference ($m^3$) | Surface difference ($m^2$) | Average loss per $m^2$ (m) |
|---|---|---|---|
| A ( >0.5 ) | - 28,300 | - 4,500 | - 0.05 |
| B ( >-2.5 < 0.5) | 23,250 | 7,250 | - 0.07 |
| C ( <-2.5 ) | - 4,650 | - 2,750 | - 0.08 |
| **Total** | **- 9,700** | | **- 0.13** |

### 4.3.6.2 Distribution in horizontal sections

In order to further investigate the volume changes in longitudinal direction the southwest beach is divided into 4 sections, as can be seen in Figure 4-27. The sections have been determined in such a way that they are logically classified in longshore direction, given the longitudinal variation of the cross-shore profiles.

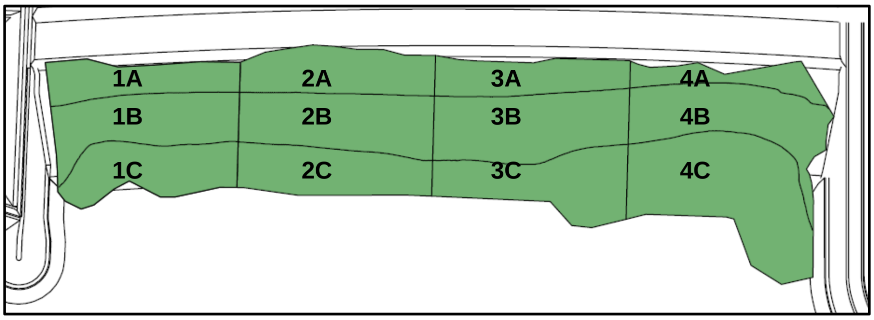



*Figure 4-27. Schematically overview of the classification of the volume-sections.*

### 4.3.6.3 Total volume changes

Now the vertical layers and horizontal sections are determined, the development of total volume changes per layer and sections are discussed. Table 4-7 summarizes the volume differences observed between T1 and T5. As can be seen, the total volume loss is determined at about 9,900 $m^3$. The volume loss in the central sections are clearly higher compared to the outer sections, which was also observed at the cross-shore and alongshore evolution. In particular, the volume at 4B is significant higher compared to the other volume quantities. This indicates a sediment supply from the central section in southeast direction. However, because of the interaction between the layers it is still difficult to compare these volume changes with the potential cross-shore and longshore sediment transports. Moreover, unequal distribution (between layers and sections) of sediment losses due to settlement of the subsoil, makes it even more difficult.

*Table 4-7. Overview volume differences ($m^3$) between survey T1 and T5.*

| | Section 1 | Section 2 | Section 3 | Section 4 | Total |
|---|---|---|---|---|---|
| Layer A | - 3,739 | - 7,753 | - 7,805 | - 8,521 | **- 27,818** |
| Layer B | 2,855 | 3,573 | 3,663 | 13,053 | **23,144** |
| Layer C | - 1,011 | - 280 | - 695 | - 3,219 | **- 5,205** |
| **Total** | **- 1,895** | **- 4,460** | **- 4,837** | **1,313** | **- 9,879** |

## 4.4 Analysis of the Northwest beach

In this section, an extensive analysis of the morphological behaviour of the northwest beach is performed. The topics are addressed as described in the previous section.

### 4.4.1 Morphological development

Field monitoring of the locally bathymetry and topography of the northwest beach has been carried out on a monthly basis in the period between October 29th 2016 until May 9th, 2017. In Table 4-8 an overview of the surveys is presented.

*Table 4-8. Overview survey of the monitoring period of the northwest beach with remarks.*

| Survey | Date | Remarks |
|---|---|---|
| T1 | 29-11-2016 | First survey after construction |
| T2 | 18-01-2017 | |
| T3 | 14-02-2017 | |
| T4 | 14-03-2017 | Completely covered survey |
| T5 | 14-04-2017 | |
| T6 | 09-05-2017 | |

#### Bathymetry and topography per survey

Like the southwest beach, the observed morphological development is visualized by combining the two bathymetry and topography data sets. Below an overview of the bathymetry and topography surface plots is provided for each survey of the northwest beach. In this case, the surface plot of survey T4 completely covers the area, measured at March 14, 2017.

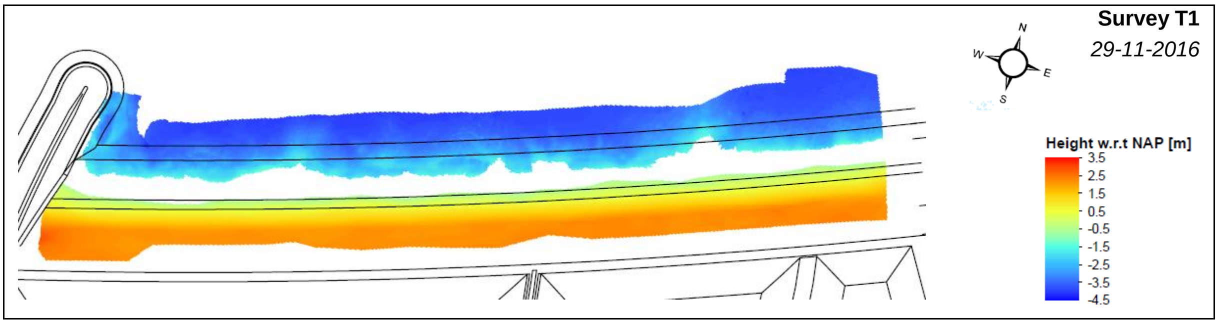



*Figure 4-28. Surface-plot of the northwest beach of 29-11-2016*

### 4.4.2 Cross-shore evolution

This section describes the cross-shore evolution of the northwest beach. In order to explore the evolution of the cross-shore profile and their variation in longitudinal direction, 17 cross-shore profiles are further in detail investigated. Figure 4-29 shows an overview of all these cross-shore profiles. The spacing between the individual cross-shore profiles is 40 meters.

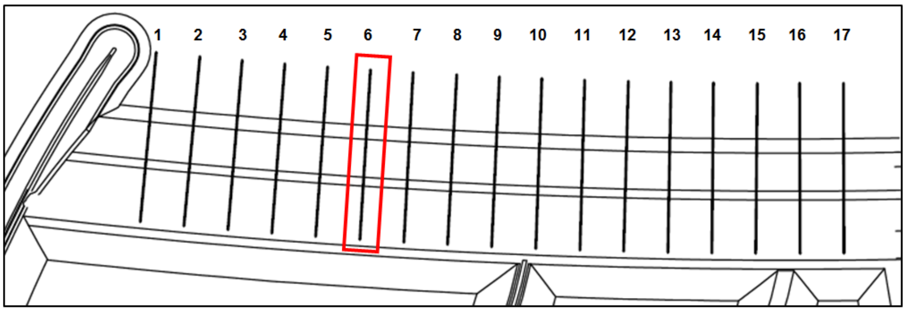



*Figure 4-29.Overview of the cross-shore profiles of the northwest beach. The most characteristic cross-shore is indicated by the red box.*

In order to distinguish the variation in longitudinal direction, the idea was to determine three characteristic cross-shore profiles for the western section, the central section and the eastern section. However, after the first measurement (November 29, 2016) no working activities have been carried out until the end of February. Since then, several activities have taken place, including the landfall of a floating pipeline and excavation works. Unfortunately, these activities had significantly influenced the profile development. Whereas the profile normally has formed by natural conditions, some interruptions has result that the cross-shore profiles (after T4) are unusable for this research. The working activates were mainly carried out at the central and eastern part of the beach. Therefore is chosen to focus on the cross-shore profiles of the western section of the beach. Based on this, it turns out that cross-shore profile 6 reflected the most characteristic shape of the beach.

#### 4.4.2.1 Natural characteristic of the cross section

In this section, the natural characteristic features of the cross-shore profiles have been described. Cross-shore profile 6 represents the most characteristic shape of the northwest beach. Figure 4-30 represents the measurement results for this transect. Here the monthly measurement results are shown of the first 5 months after construction (T1-T6).

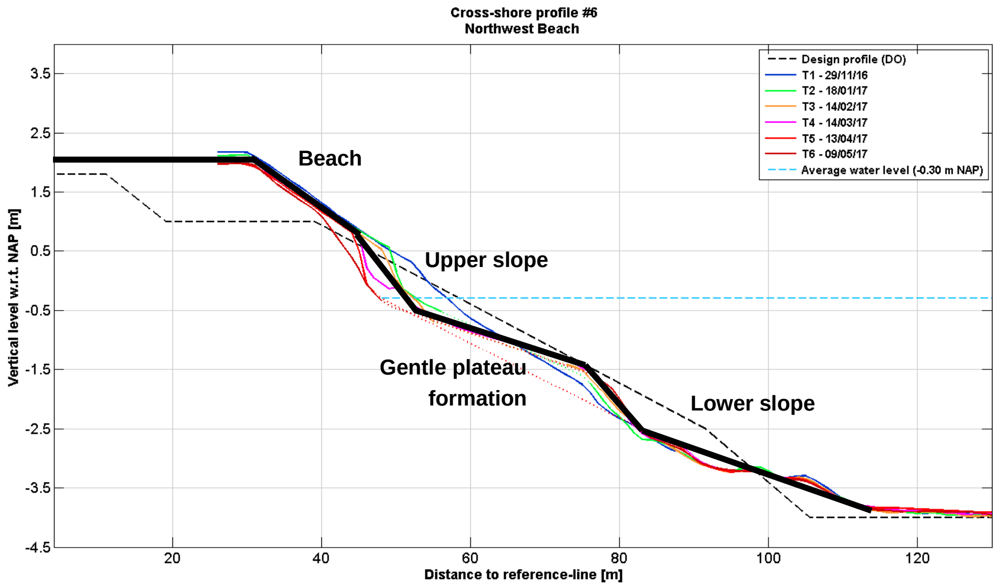



*Figure 4-30. The characteristic cross-shore profile evolution of the northwest beach.*

The solid lines represent the measurements (bathymetry and topography) and the dashed lines represents the interpolated part between. The pink line shows the characteristic shape of the profile which is formed in the first 3 months after construction. The profile development is further described in more detail in the following section.

#### 4.4.2.2 Variation in longitudinal direction

In longitudinal direction the cross-shore profiles are not equally shaped and vary quite significantly in longitudinal direction over the entire length of the beach (680m). In this section the characteristic cross-shore profiles are presented for the western section (#3), central section(#6) and the eastern section (#16). The cross shore profiles are presented in

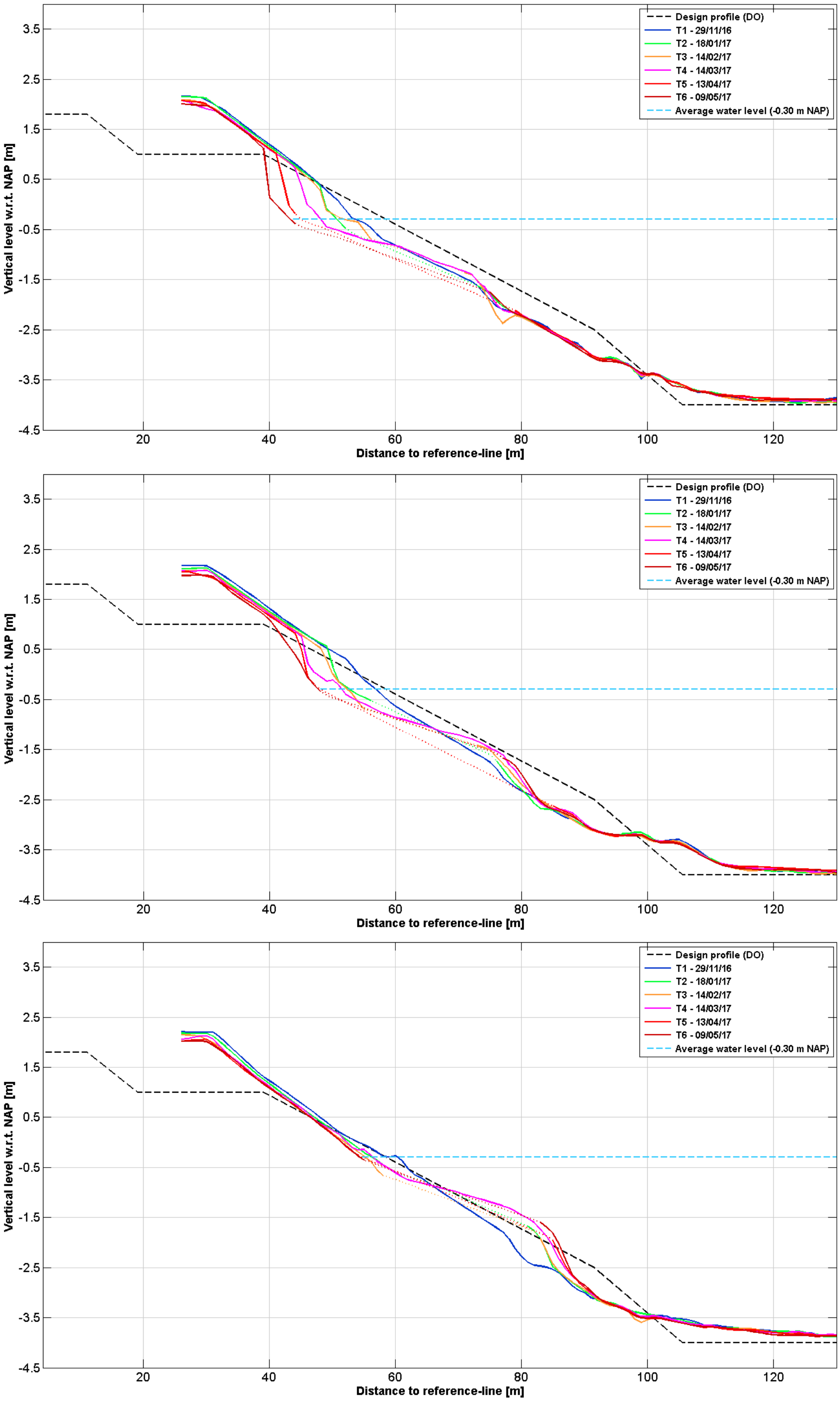



*Figure 4-31. Cross-shore profiles of the western section #3 (upper), central section #6 (middle) and eastern section #16 (lower).*

As can be seen in Figure 4-31, the characteristics of the profile shape varies in alongshore direction. From the first measurement, regression of the shoreline is observed over the entire length of the beach, which is about 10 meters at the western section and 2 meters at the eastern section of the beach. The regression of the shoreline is thus the most at the western part of the beach. The impact of the changing (increasing) water level, from winter to summer level, is also part of the regression of the shoreline. The backward movement of the shoreline can clearly be seen in the upper figure. In contrast with the southwest beach, no typical plateau formation can be seen yet looking at pink line (survey T4). A vertical scarp as observed at the southwest beach is also observed at the northwest beach. The vertical scarp is the highest at the western section (up to 1.0 m). At the eastern section no vertical scarp is observed. The volume losses of sand is partly due to settling of the sand package as can be observed at the higher part of the profile. In general, erosion above NAP -0.8 m can be observed and sedimentation below this level. At the western section near the structure only erosion is visible, which means there is a significant volume loss from the cross section. This indicates that there must be a longshore gradient which moves the sand in longitudinal direction. The central section shows both erosion and sedimentation. The further to the east, the more sedimentation can be observed. Looking at the cross section there is clearly a surplus of sedimentation. This patterns indicates a transport gradient in eastern direction. The table below summarizes the variation of the characteristics of the cross-shore profiles in longitudinal direction.

*Table 4-9. Summary of the cross-shore profile characteristics of the northeast, central and southwest sections.*

| | Western section | Central section | Eastern section |
|---|---|---|---|
| Crest level dune | NAP +2.0 m | NAP +2.0 m | NAP +2.0 m |
| Beach slope | 1 : 10 | 1 : 12 | 1 : 11 |
| Height vertical scarp | ± 1.20 m | ± 0.50 m | - |
| Slope around the water line | 1 : 7 | 1 : 10 | 1 : 10 |
| Slope around NAP -1.0m | 1:24 | 1:26 | 1:28 |
| Underwater slope | 1 : 8 | 1 : 6 | 1 : 5 |
| Depth of closure | NAP -2.0 m | NAP -2.5 m | NAP -3.2 m |

### 4.4.3 Alongshore evolution

In order to analyse the alongshore evolution the differences between the surveys are described in this section. Firstly, the development per interval is presented where after the observed erosion-sedimentation patterns are further discussed. Secondly, the alongshore evolution of the shoreline is addressed.

#### 4.4.3.1 Describing the development per interval

The morphological development of the northwest beach are addressed during the first months after construction. For each interval, an overview is provided which presents the differences in height between the surveys that show the erosion-sedimentation patterns. In this section an explanation of the observed development per interval is provided. The corresponding wind and wave conditions per interval are provided in appendix B.2. The legends as presented in Figure 4-9 applies for all the surface-plots and wave roses provided on the next page

Analysis of the morphological developments show that the erosion and sedimentation patterns at the northwest beach clearly can be explained by the wave conditions during the periods as well. In the central part and in particularly in the eastern part sedimentation is observed, which indicates on a transport gradient in eastern direction. In general, some regression of the shoreline can be observed. Looking at the average wave direction during the first period, the waves mainly came from the south-southwest direction (210 ° w.r.t. North). Given the orientation of the beach most of the waves were not exposed to the beach. At the western part of the beach little changes can be observed caused the breakwater which protects this area. However, looking at the most important events during this period some height waves were exposed to the northwest beach. The maximum wave height ($H_s$) was 0.87 m with a wave period ($T_p$) of 3.3 s and was measured at the 13$^{th}$ of January. In addition, some spots can be observed of volume losses due to vertical settlements at the upper parts of the beach. The differences during the second period are limited. This can be explained by the wind direction that was mainly from the east and southeast, thus the waves were mainly not exposed to the northwest beach. Moreover, no storm events or high waves were measured during this period (see appendix B.2). The third period, shows clearly a different pattern compared to the previous intervals. The erosion and sedimentation spots are the results of working activities during this period. The landfall of the pipeline, sand displacements by excavators and floating pipeline in front of the beach have a great impact on this analysis.

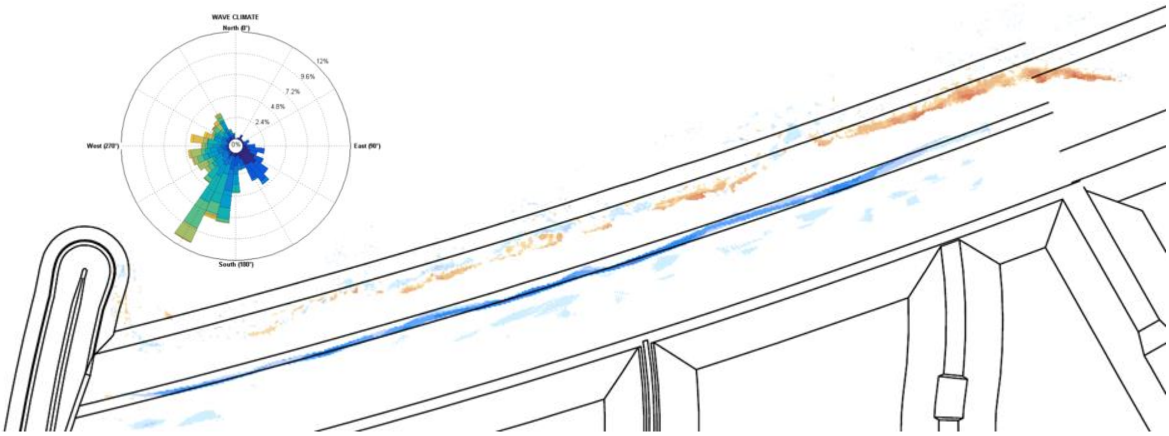



*Figure 4-32. Morphological developments T1-T2 and corresponding wave rose (29/11/16 – 18/01/17).*

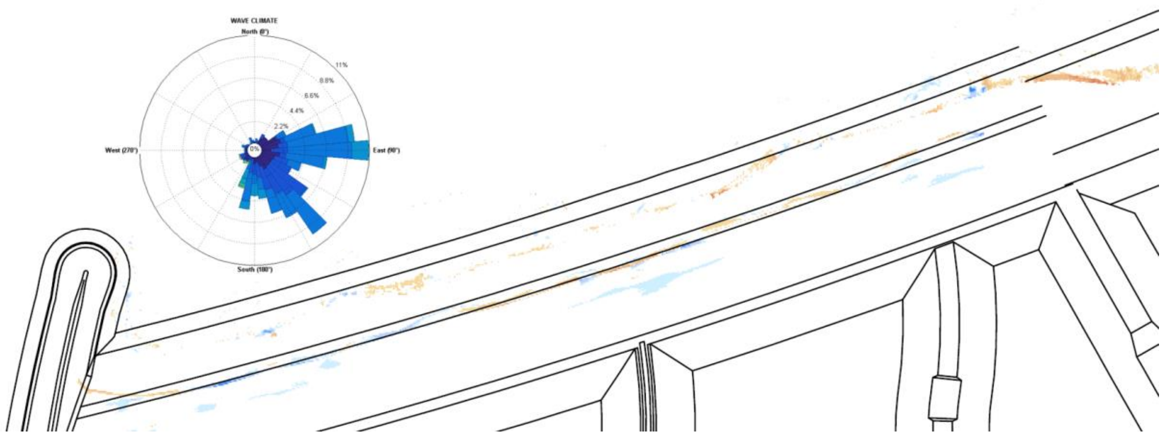



*Figure 4-33. Morphological developments T2-T3 and corresponding wave rose (18/01/17 – 14/02/17).*

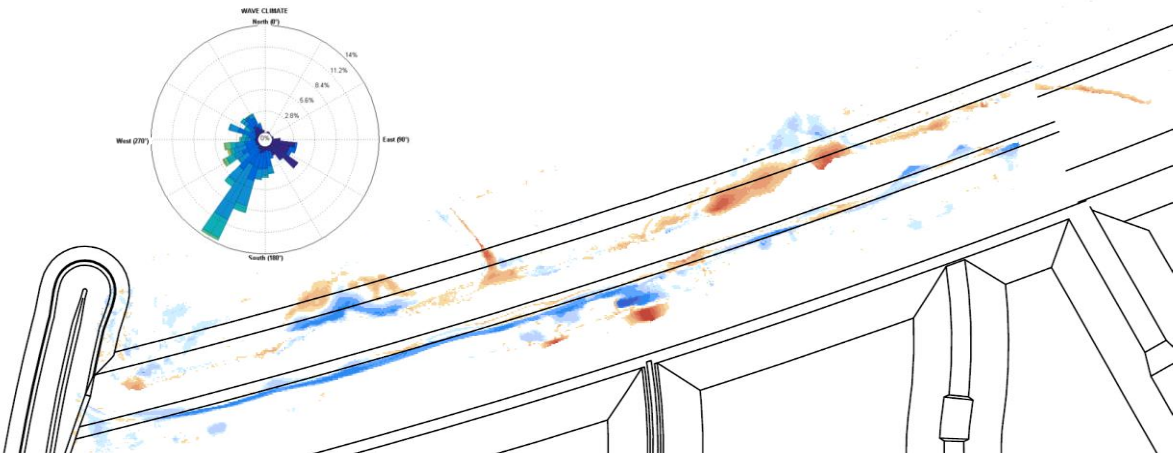



*Figure 4-34. Morphological developments T3-T4  and corresponding wave rose (14/02/17 – 14/03/17).*

These working activities clearly affects the morphological development, which is observed at the other intervals (T4 –T5 and T5-T6) also. Therefore, it is chosen to omit the observed morphological development of the time intervals T4-T5 and T5-T6 in this analysis. Because of this, the morphological developments plots are presented in appendix D.

### General morphological development

Based on the first survey at 29-11-2016 (T1) and the survey at 14-03-2017 (T4), which covers the whole area of interest, a more detailed analyses of the erosion-sedimentation patterns can be provided. The surface map below represents the morphological development during this 3,5 months. As can be seen, the impact of the activities are clearly visible by the deviated patterns. Furthermore, it can be seen that the shoreline is shifted in landward direction over the whole length of the beach and an increase of accretion in northeast direction. However, due to the activities it makes it quite difficult to distinguish the natural processes from the man-made interventions.

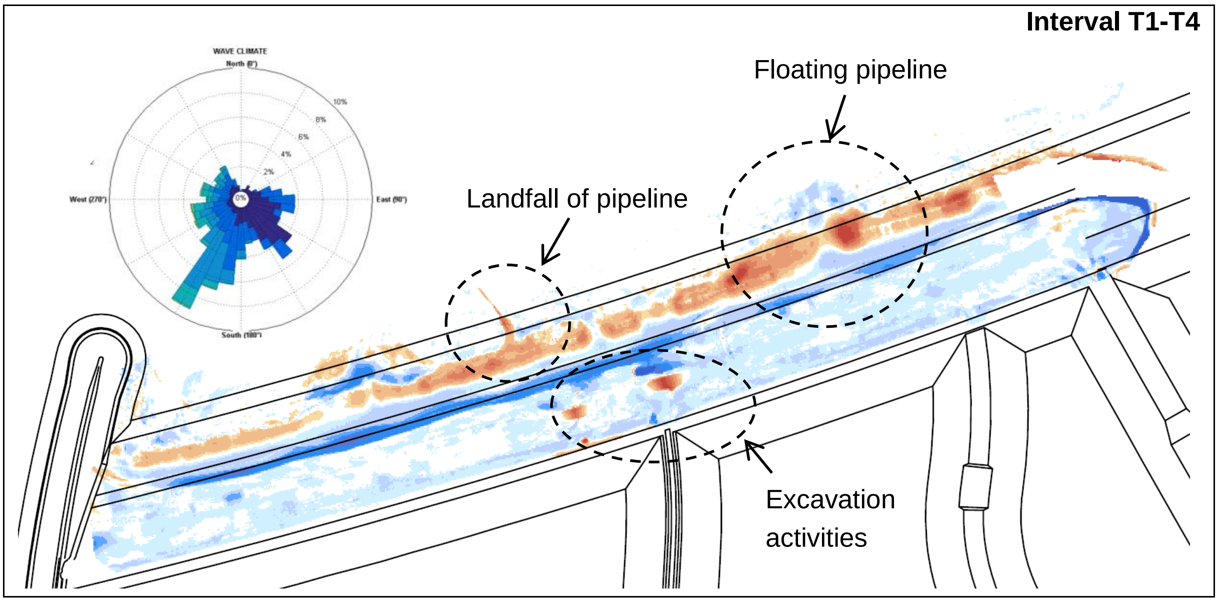



*Figure 4-35.Surface plot of the morphological development between T1 and T4.*

#### 4.4.3.2 Alongshore evolution of the shoreline position

In Figure 4-16 the evolution of the shoreline position around the average water line is schematized. The green line represents the shoreline position at T1 (29-11-2016), the red line represents the shoreline position at T6 (09-05-2017). The regression of the shoreline is over the entire beach almost the same. Except for the western part (left) of the beach near the breakwater structure and where the working activities took place.

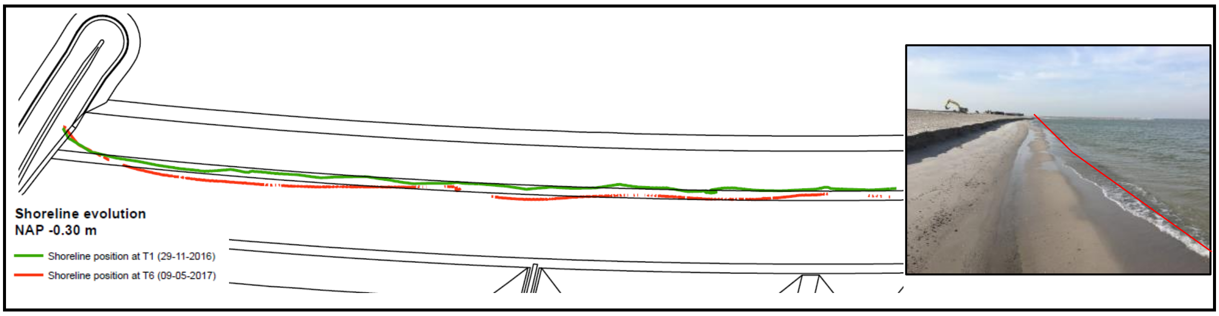



*Figure 4-36. Shoreline position around the water line (NAP -0.3m) at T1 and T4.*

### 4.4.4 Settlements

In this section the extent of sediment losses due to settlement is discussed. It is assumed that the initial bottom level is basically equal over the whole area, so the difference of settlement only depends on the extend of the load of the sand package. In the figure below, a map is presented showing the settlement between measurement T1 and T4. According to this map, about 4.250 $m^3$ sand disappeared, which only covers the part above NAP 0.5m. In general, where the height of the sand package is the largest the most settlement is expected. The settlement varies roughly between 5 and 20 cm, with an average of 9 cm. It must be noticed that these measurements are not completely accurate, measurement deviations for the GPS equipment (±12 mm) needs to be considered as well. However, for this purpose the accuracy is enough. Apart from this, the impact of the working activities are clearly visible as can be seen by the red spots in the central section of the beach.

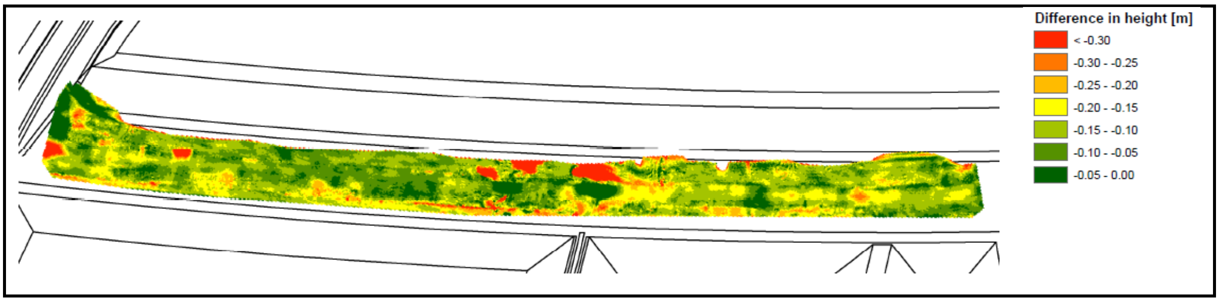



*Figure 4-37.Difference in height at the upper part of the northwest beach in the period T1-T4.*

Subsequently, by a triangle approach as shown in Figure 4-38, the theoretical total volume of settlement was determined. It is assumed that the settlement is the largest where the sand package is the largest. As the height of the sand package decreases the settlement reduces as well, therefore at the bottom the settlement is reduced to zero. Based on this schematic average cross-section the volume losses is determined according to the dimensions as shown in the schematic diagram, resulting in a total volume of 3,975 $m^3$. In section 4.4.6 is the sediment balance of the northwest beach determined, where this quantity has been considered in more detail.

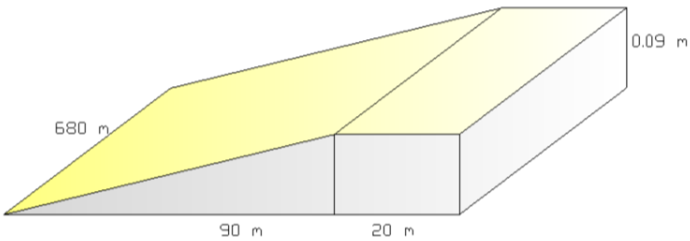



*Figure 4-38. Schematic diagram for the calculation method to determine volume losses due to settlement of the subsoil between T1 and T4 for the northwest beach.*

### 4.4.5 Sediment characteristics

This section contains the sediment characteristics of the northwest beach. At several locations sediment samples are taken at the southwest beach, as can be seen in the overview provided in. At the northwest beach sediment samples were taken in September (2016) at 14 locations. The sediment samples were brought to the lab where the grainsize distribution was determined. By means of a sieve curve the sediment characteristics were determined (conform NEN 5753). The locations of the sediment samples are given in Figure 4-39.

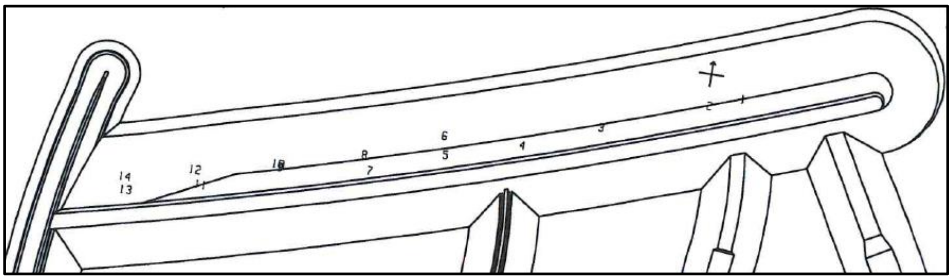


*Figure 4-39. Locations of the sediment samples taken at the northwest beach.*

The $D_{50}$ of the sediment samples are given in Table 4-10. Looking to the spatial differences between the sediment samples, the following can be concluded. The average median grainsize was determined at 312 µm. However, there can be observed some spatial variance. The average median grainsize in the central section of the beach (samples 5-10) is about 270 µm, whereas the average median grainsize for the eastern section (samples 11-14) and western section (samples 1-4) are 347 µm and 342 µm, respectively. Unfortunately, the $D_{10}$ and $D_{90}$ values are not available of this samples. However, it can be expected that the spread of the grain size distribution is quite large as well, given the fact that the same material has been used for the southwest beach.

*Table 4-10. Sediment samples taken at the northwest beach (September 2016).*

| Sediment sample | $D_{50}$ (µm) |
|---|---|
| 1 | 338 |
| 2 | 338 |
| 3 | 312 |
| 4 | 379 |
| 5 | 252 |
| 6 | 300 |
| 7 | 267 |
| 8 | 329 |
| 9 | 245 |
| 10 | 225 |
| 11 | 317 |
| 12 | 367 |
| 13 | 358 |
| 14 | 344 |
| **Averaged** | **312** |
| **Lowest** | **225** |
| **Highest** | **379** |

### 4.4.6 Sediment balance

The observations from the surface plots, as has been shown in section 4.4.1, are further investigated by analysing the sediment balance for the area of the northwest beach. The volume changes due to settlement of the subsoil, aeolian sediment transport, cross- and longshore sediment transport are determined by subtracting the surface-covering survey of March 14, 2017 from the survey in November 29, 2016. The total volume difference between these surface plots was determined at 5,600 $m^3$. Sediment losses due to settlement of the subsoil are derived from subtracting the surface plots, from this the average settlement is determined at 0.09m at the upper part of the beach. Subsequently, by a triangle approach the theoretical total volume of settlement was determined at 3,975 $m^3$. At the western side of the beach a breakwater blocks sediment supply and discharge, in the eastern side the beach has an open end. So in contrast to the southwest beach is the northwest beach not a theoretically closed system. Besides volume loss due to settlements, sediment could leave the system at the east due to a longshore gradient. Also is assumed that there is no sediment loss in cross-shore direction. An important note for the survey plot of T1 is that linear interpolation has been applied to fill the gap of the 'unknown' area. Hereby is assumed that it corresponds quite well with the reality. However, this may lead to deviations in the volume balance and should therefore be considered as well. Combination of the volumes results in the sediment balance for the northwest beach as shown in Figure 4-40.

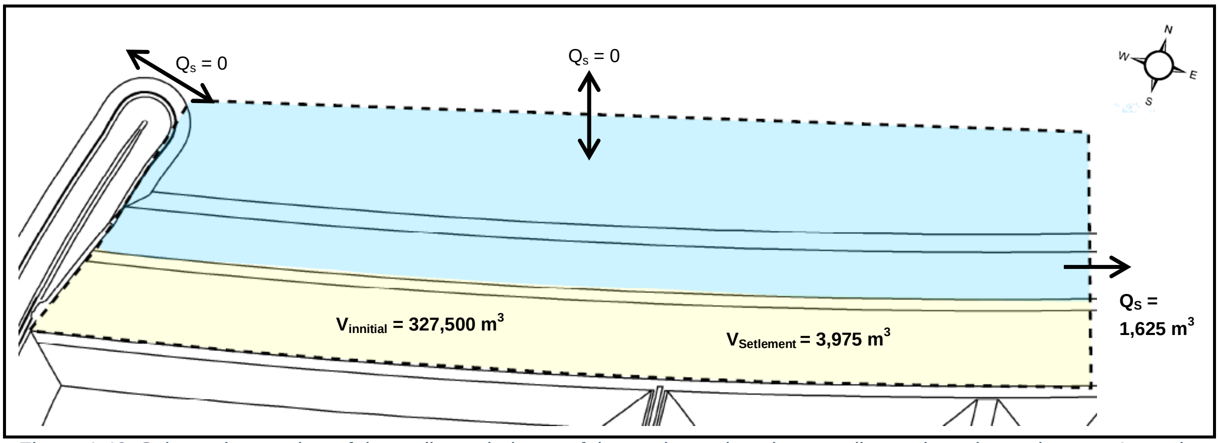



*Figure 4-40. Schematic overview of the sediment balance of the northwest beach, according to the volume changes 4 months after construction (period T1-T4).*

The initial measured volume at T1 was determined at about 327,500 $m^3$. Subtracting the surface plot from T4 gives a volume change of only 5,600 $m^3$. Which is $\pm$7 centimetres per $m^2$ loss when it is divided by the surface area (82,200 $m^2$). According to this quantities, about 70% of the volume losses is caused by settlement of the subsoil, namely 3,975 $m^3$. Given the fact that there is no longshore sediment transport in western direction (left), due to the presence of the breakwater, the remaining volume losses should assigned to an eastward longshore sediment gradient. Based on this, it is assumed that about 1,625 $m^3$ is caused by the longshore transport in eastern direction. This last loss equals about 5,000 $m^3$/year which is somewhat higher than originally expected, where ~2000 $m^3$/year was expected to be realistic. However, it should be remarked that the sediment transport rates are quite uncertain due to the working activities that took place and the relative short period on which it is based on. Since these interventions have significantly affects the morphological development at the northwest beach there are a lot of uncertainties. Therefore, it has been chosen to not go further in detail into this sediment balance.

## 4.4.7 Most recent survey (T7)

Because of calm weather conditions during the last survey on June 19, 2017, the shallow underwater part of the northwest beach has been measured as well. Initially this survey results would no longer be included in the analysis, however, the results were quite interesting and valuable for this research. Although, it was too late to include all the results in this report, the results have been analysed shortly. According to this survey, it has been found that the near-horizontal plateau also appears at the northwest beach. The surface plot of this survey is presented in Figure 4-41.

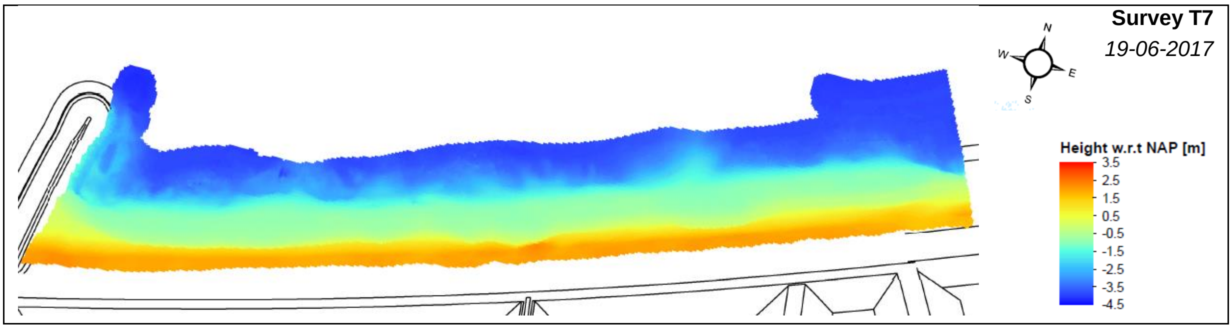



*Figure 4-41. Surface plot of the survey T7 (19-06-2017).*

As can be seen, the plateau formation is clearly visible (light blue area). Figure 4-42 presents the profile development between T1 and T7. It shows that the plateau is formed around NAP -0.8 m. Based on this, it can be concluded that also at a different shoreline orientation and therefore other wave conditions, a near-horizontal plateau forms at the shallow part of the beach. Although it not occurred as fast as at the southwest beach, such a plateau formation seems characteristic for sandy beaches in this part of Lake Marken.

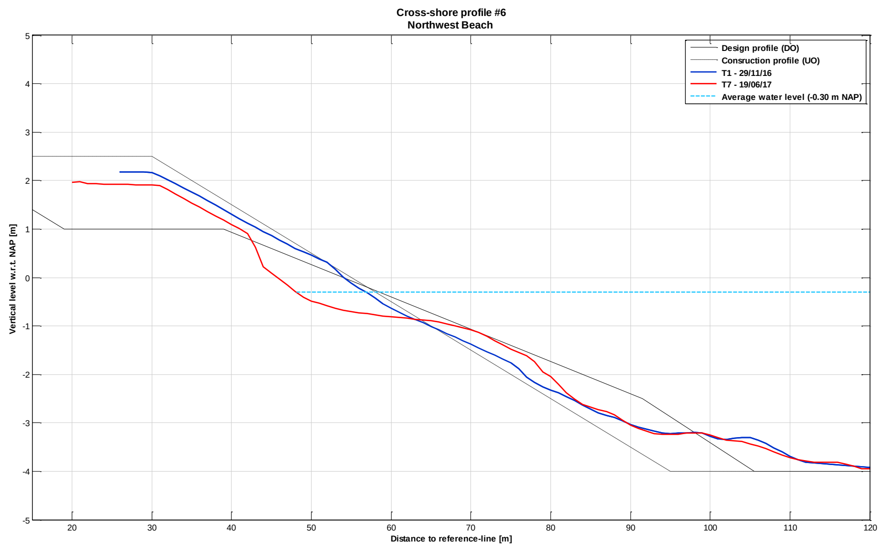



*Figure 4-42. Characteristic cross-shore profile development of the northwest beach between T1 and T7.*

# 5. APPLICATION OF DESIGN FORMULAS AND MODELS

One of the research questions was to investigate to what extent morphological design formulae and models can be used for the design of such sandy beaches and whether they are capable to simulate the profile developments as observed in the first months after construction. This chapter focuses on the application of the classical design formulae and models. For now, the design of the sandy beaches of the Marker Wadden is largely based on the morphological development of the pilot project along the Houtribdijk. However, the aim is to design such beaches by using validated equilibrium formulae and numerical models and, moreover, to understand the most important processes which are responsible for the characteristic profiles which are observed. It has been investigated whether the observations can be simulated for both the cross-shore and longshore sediment transport. Although, it is still difficult to distinguish these processes.

In order to validate the design methods for the stability of the cross section, several empirical formulae for equilibrium profiles have been compared with the observed developments. The equilibrium profiles which are investigated are Wright (1986), Hanson and Kraus (1989), Dean et al (1990), Kriebel et al. (1991) and USACE (2002), see section 3.2.3. For the morphological stability of the shoreline the sediment transport formulas of CERC (USACE, 2002), Kamphuis (1991) and van Rijn (2014) have been investigated, see section 3.3.2. Furthermore, the model which is used for the design of sandy beaches, is the process-based numerical model XBeach. Considering the limited time for this MSc thesis, the focus will be on this model. Like the design computations, it is chosen to use the 1D - XBeach model in order to simulate the observed developments in the cross section of the most characteristic profile. The computed meteorological and hydraulic conditions during the first months after construction are used as input for the models in order to perform the simulations as realistic as possible.

## 5.1 Cross-shore profile evolution

In this section, the equilibration process and the evolution of the cross-shore profile has been investigated as described in section 3.2.2. First, the equilibrium profiles are examined based on various equilibrium formulae. Subsequently, the observed cross-shore profile evolution is examined using a one-dimensional XBeach model. The aim is to compare the measured cross-shore profiles with the well-known equilibrium formulae and to determine if they can be used to design sandy beaches in lake systems such as Lake Marken. The use of the numerical model XBeach is examined in order to determine whether a 1D-model is capable to simulate the observed behaviour of the cross-shore evolution. Especially, the presence of the plateau formation has been investigated in more detail, which clearly differs from the standard equilibrium profiles at coastal systems.

### 5.1.1 Equilibrium profiles

In this section the measured cross-shore profiles are compared with equilibrium formulae, as has been described in section 3.2.3. First, the equilibrium profiles for the southwest beach have been studied, whereafter the equilibrium profiles of the northwest beach are addressed.

#### 5.1.1.1 Southwest beach

The characteristic cross-shore profile for the southwest beach, which was measured at 04-04-2017 (T5), is used as reference. The observed profile shape has formed in the first 4.5 months after construction. In contrast to the other surveys, this survey completely covers the total cross-section, so including the shallow underwater part of the beach. The parameter settings are presented in Table 5-1. Here, the average $D_{50}$ are used as measured around the shoreline, which was about 0.35 to 0.40 mm (see Table 4-4).

*Table 5-1. Parameter settings for the southwest beach for the applied equilibrium models.*

| Model | $D_{50}$ = 0.35 mm | $D_{50}$ = 0.40 mm |
|---|---|---|
| Wright (1986) | Bottom depth - 4.0 m below water line<br>K value = 0.035 | Bottom depth - 4.0 m below water line<br>K value = 0.035 |
| Hanson and Kraus (1989) | Median grainsize $D_{50}$ = 0.350 mm | Median grainsize $D_{50}$ = 0.400 mm |
| Dean et al. (1990) | $D_{50}$ = 0.350 mm<br>Fall velocity $W_f$ = 0.0047 cm/s * | $D_{50}$ = 0.400 mm<br>Fall velocity $W_f$ = 0.0053 cm/s * |
| Kriebels, Kraus and Larson (1991) | $D_{50}$ = 0.350 mm<br>Fall velocity $W_f$ = 0.047 m/s * | $D_{50}$ = 0.400 mm<br>Fall velocity $W_f$ = 0.053 m/s * |
| USACE (2002) | A value is set on 0.135* * | A value is set on 0.145** |

* *Fall velocity $W_f$ is determined as described in chapter 15 of Engineering Hydrology (Ponce, 1989)*
** *A-value based on table A-1 in appendix A.*

The recommended K-value ($10^{-4}$ -$10^{-6}$) for the equilibrium profile of Wright (1986) seems not representative for shallow lake systems where the water depth is relatively shallow compared to coastal systems for which the K-value is validated originally. Therefore the K-value is adjusted to 0.035 which gives a more realistic profile. In Figure 5-1 the equilibrium profiles are given for a $D_{50}$ of 0.35 and 0.40 mm. The distance on the horizontal axis is given in offshore direction measured from the location where the profile intersects the average water line.

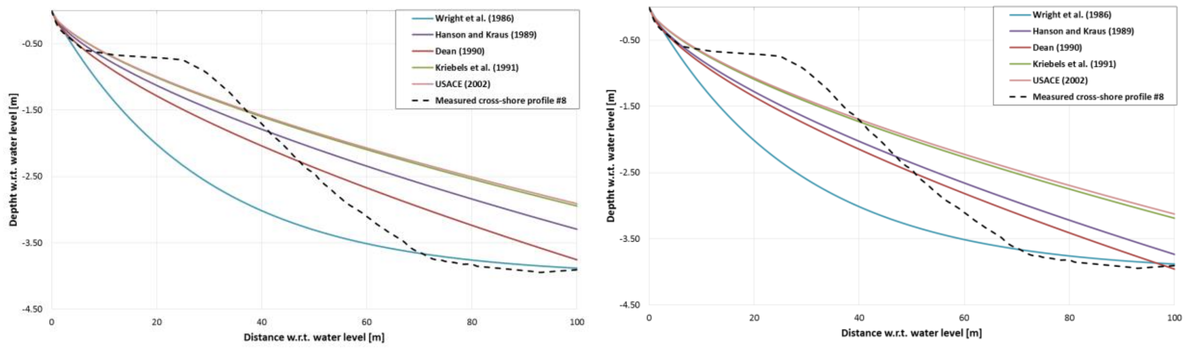



*Figure 5-1. Equilibrium profiles for $D_{50}$ = 0.350 mm (left-hand plot) and for $D_{50}$ = 0.400 mm (right-hand plot).*

As can be seen in the figures, none of the equilibrium profiles show the plateau formation, which developed in the first months after construction. However, the plateau formation cannot described by these simple equations, because this is not included in the equations. Only the first meters below the water line seem to fit the profiles. In Figure 5-2 a more detail view is given of the first meters.

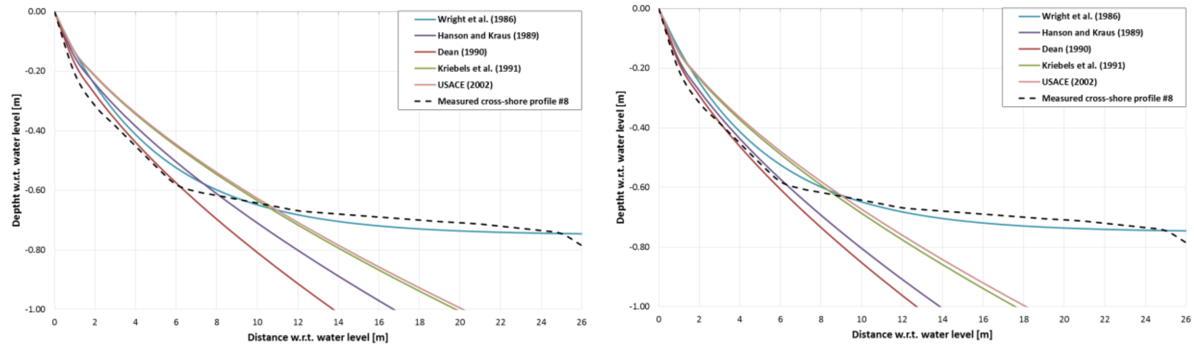



*Figure 5-2. Detailed view of the equilibrium profiles for $D_{50}$ = 0.35 mm (left-hand plot) and for $D_{50}$ = 0.40 mm (right-hand plot).*

Based on the first 7 meters, the equilibrium profiles of Dean (1990) and Hanson and Kraus (1989) closely fit the first meters of the observed profile for a $D_{50}$ of 0.40 mm. When the parameter settings for the equilibrium profile of Wright et al. (1986) are set at a bottom depth of 0.75 m (water depth at the plateau) and the K-value at 0.2 the measured profile can be described quite well. Because the bottom is included as input parameter, the depth at which the equilibrium profile ends can be indicated. However, because of the plateau the model cannot describe the whole equilibrium profile including the lower part.

### Equilibrium profile according to Vellinga (1982)

In addition the equilibrium profile of Vellinga has been examined. This dune erosion prediction model is based on the observation that a typical erosion profile develops during storm surges. Since several storms in the past period have occurred and this could be indicative for the profile which has been developed, the erosion profile of Vellinga has been investigated as well. However, as can be seen in Figure 5-3 the erosion profile does not fit the measured profile. The predicted slope seems to be far more gentle compared to the steep measured profile.

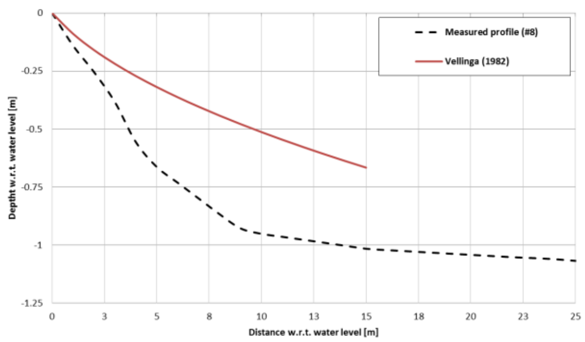



*Figure 5-3. Equilibrium profile according to Vellinga (1982) with a $D_{50}$ of 0.35 mm.*

#### 5.1.1.2 Northwest beach

For the northwest beach, the characteristic cross-shore profile is examined as well. The characteristic cross-shore profile of the northwest beach, which was measured at 14-03-2017, is used as reference. This survey completely covers the total cross-section, so including the shallow underwater part of the beach. The parameter settings are presented in Table 5-2. The average $D_{50}$ are used as measured around the shoreline, which was about 0.25 to 0.40 mm.

*Table 5-2. Applied equilibrium methods with corresponding parameter settings for the northwest beach.*

| Method | $D_{50}$ = 0.25 mm | $D_{50}$ = 0.30 mm |
|---|---|---|
| Wright (1986) | Bottom depth - 4.0 m below water line<br>K value = 0.025 | Bottom depth - 4.0 m below water line<br>K value = 0.025 |
| Hanson and Kraus (1989) | Median grainsize $D_{50}$ = 0.25 mm | Median grainsize $D_{50}$ = 0.30 mm |
| Dean et al. (1990) | $D_{50}$ = 0. 25 mm<br>Fall velocity $W_f$ = 0.0028 cm/s | $D_{50}$ = 0.300 mm<br>Fall velocity $W_f$ = 0.0041 cm/s |
| Kriebels, Kraus and Larson (1991) | $D_{50}$ = 0. 25 mm<br>Fall velocity $W_f$ = 0.028 m/s | $D_{50}$ = 0.300 mm<br>Fall velocity $W_f$ = 0.041 m/s |
| USACE (2002) | A value is set on 0.115 | A value is set on 0.125 |

As can be seen in the figures, in first months 3.5 months a plateau formation as is observed at the southwest beach cannot be seen yet. However, after 25 meters the profile get clearly steeper. The first 25 meters seems to fit quite well.

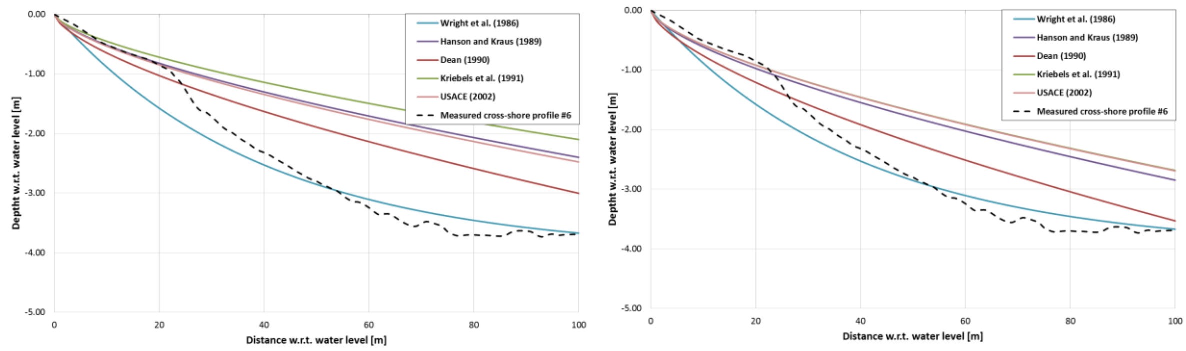



*Figure 5-4. Equilibrium profiles for $D_{50}$ = 0.25 mm (left-hand plot) and for $D_{50}$ = 0.30 mm (right-hand plot).*

In Figure 5-5 a detailed view of the first meters is given. It seems that the equilibrium profiles of Wright (1986) fits quite well for the first 5 meters for which the K-value is set at 0.012. Although, the model of Hanson and Kraus (1989) comes closest to the measured cross-shore profile between 9-18m (for a $D_{50}$=0.250mm), the equilibrium profile deviates from the measured profile in the first few meters. The other equilibrium profiles give a much steeper slope just below the water line.

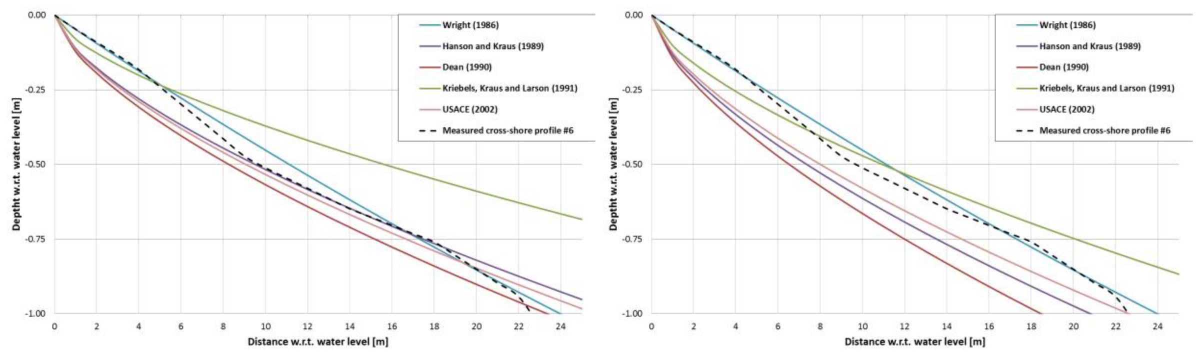



*Figure 5-5. Detailed view of the equilibrium profiles for $D_{50}$ = 0.25 mm (left-hand plot) and for $D_{50}$ = 0.30 mm (right-hand plot).*

### 5.1.2 Results of the XBeach computations

In this section, the observed cross-shore profile evolution has been examined by simulating the behaviour of the southwest beach and the northwest beach by using the numerical model XBeach. In particular, the plateau formation at the southwest beach is interesting to examine by a this numerical model. Various simulations have been performed in order to study whether the observed development of the sandy cross-shore profile can be modelled by using a 1D XBeach model. The grid and bathymetry are based on the characteristic cross-shore profiles, as measured on November 29$^{th}$ 2016.

The XBeach model is forced by waves on its offshore boundary and are described by the wave boundary conditions. As input for the model, the wave conditions and water levels are imposed as computed for the time interval between November 29$^{th}$ 2016 and April 4$^{th}$ 2017 for the southwest beach and March 14$^{th}$ 2017 for the northwest beach. Here is assumed that all the waves approaches the beach perpendicularly. In order to generate a schematic wave climate, the wave conditions were divided into wave events of which subsequently wave-spectrum boundary conditions were determined. To do so, the spectral wave boundary conditions can vary both in space and in time and therefore can simulate the observed wave conditions during this period. The spectral wave boundary conditions are enabled using a JONSWAP wave spectra. The influence of water level setup is also taken into account by applying time-varying water levels. Given the fact that XBeach supports a variety of physical processes from generic, like waves and flow, to very specific settings, first some exploratory simulations have been performed. Moreover, since time is limited during this MSc thesis, it makes it difficult to perform extensive research on the XBeach model.

#### 5.1.2.1 XBeach results southwest beach

In this section the XBeach results are presented for the characteristic cross-shore profile of the southwest beach. Figure 5-6 shows the XBeach results of the computed profile evolution. For the simulations the following sediment characteristics are used as input: $D_{50}$ = 0.35 mm, $D_{10}$ = 0.2 mm and $D_{90}$ = 0.8 mm. The dashed black line represents the initial profile, the black solid line the measured profile at T5 and the red solid line the computed profile at T5, which is about 4 months later.

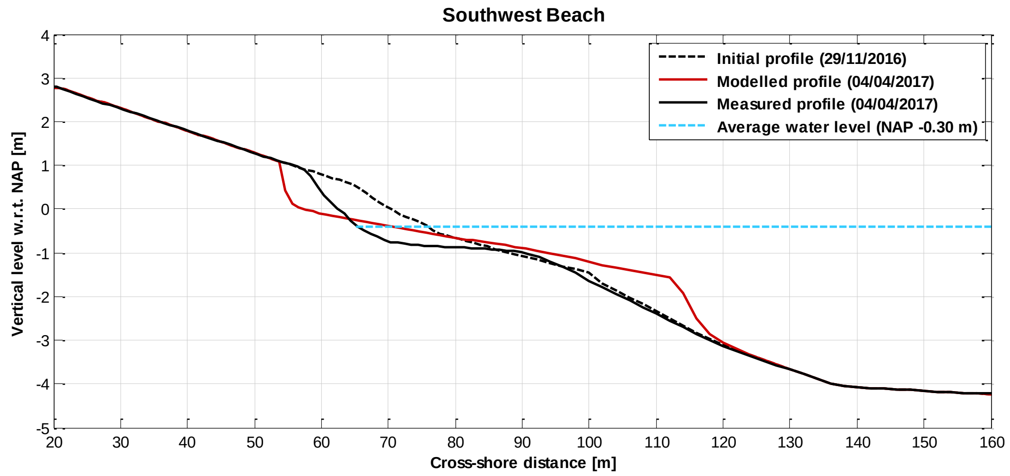



*Figure 5-6. XBeach results for the characteristic cross-shore profile of the southwest beach ($D_{50}$=350 μm).*

The results show that the basic XBeach-model is not capable to exactly reproduce the typical observed profile shape, with features like the near horizontal plateau around NAP -1.0 m and the slope around the water line. Although, the model presents a gentle slope of 1:30, XBeach does not predict the measured profile observations with a plateau. Whereas below NAP -1.0 m no significant changes have been observed in the measured profile, the XBeach-model gives clearly some sedimentation. The modelled steep slope is about 1:5 whereas a gentle slope of 1:15 is measured. The extending of the lower slope however, can be explained by the a closed volume balance which is assumed in this XBeach model. Sediment transport in longitudinal direction that could lead to a gross volume loss in the cross section is not taken into account in this 1D model. This should be investigated by extending the model in longitudinal direction (2D-model). Furthermore, the model predicts that the vertical level of the gentle sloped foreshore is higher located compared with measured profile.

By further analysing the results, the upper slope is quite different in the computed profile. The model result in a near vertical scarp, where a 1:10 slope is observed. Because of this, erosion is overestimated and the model shows clearly more a landward shift of the shoreline (about 5 meters). Possibly, this has to do with the schematic wave climate which has been used as input. For instance, it is assumed that all the waves approach the beach more or less perpendicularly, what is in fact not completely the case. Apart from that, the wave climate is based on Brettschneider, causing the local influences are not taken into account. This could result in probably an overestimating of the wave conditions, i.e. higher wave heights what subsequently leads to overestimating the erosion profile.

In order to investigate the sensitivity of the XBeach model some additional simulations have been performed. Figure 5-7 shows the simulation results with variation of the median grainsize. The effect of the grainsize diameter results only in the extent of erosion/sedimentation. The profile shape does not change significantly. More erosion can observed when the median grainsize is finer, about 4 meters regression of the shoreline between a $D_{50}$ of 0.250 and 0.450 mm.

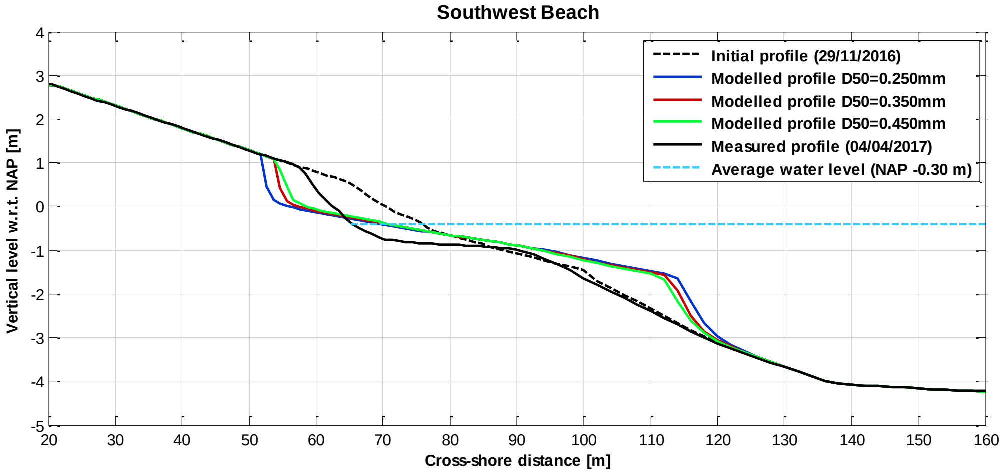
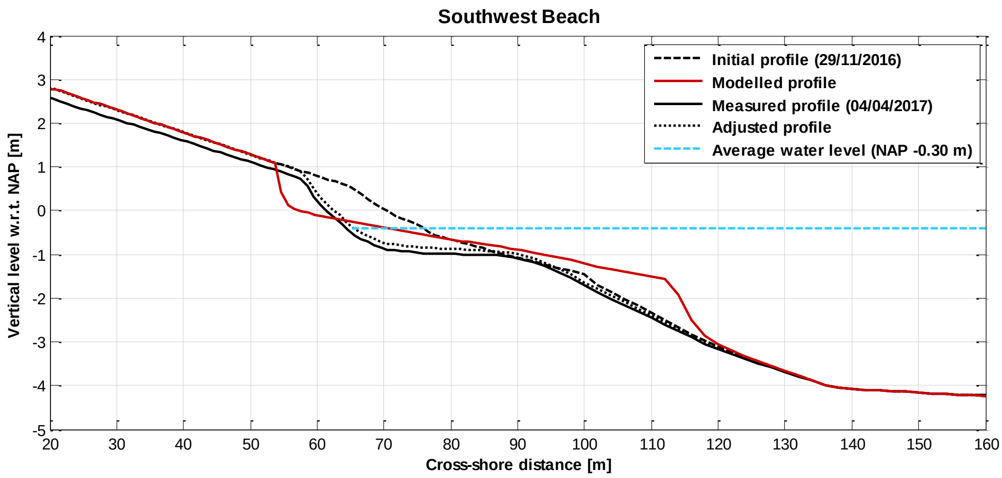



*Figure 5-7. XBeach results with variation of the median grainsize (D50).*

Furthermore, it was found that the adjustment of the profile, to compensate the volume loss as result of settlement of the subsoil, could not compensate the height difference around the plateau formation, see appendix the figure below.




If the model results will be different when the peak events (storm events or period of high waves) are schematized more concentrated was also investigated. However, no significant changes were observed.

### 5.1.2.2 XBeach results northwest beach

Regarding to the northwest beach, various XBeach simulations have been performed as well. Figure 5-8 shows the XBeach results of the profile evolution for the characteristic cross-shore profile. The median grainsize $D_{50}$ is set at 0.30 mm. The solid black line represents the initial profile and the red solid line the measured profile at T4 (March 14$^{th}$, 2017), which is about 3.5 months later.

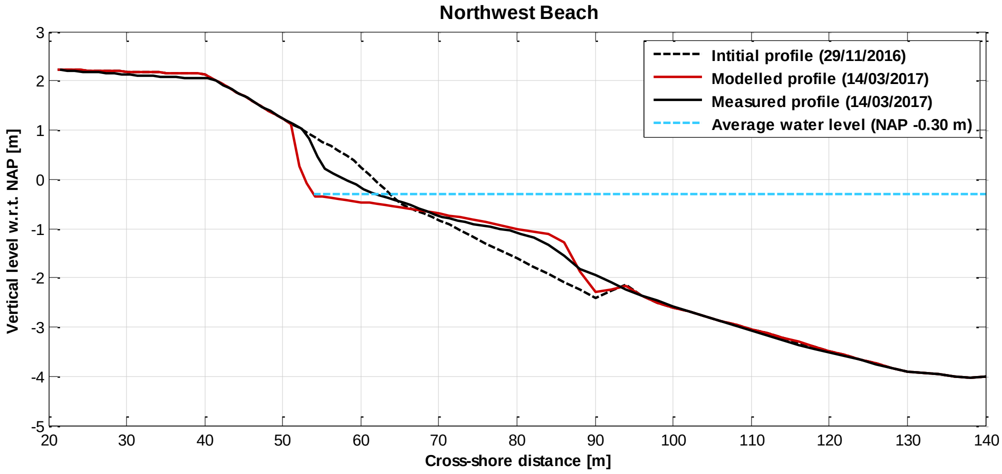



*Figure 5-8. XBeach results for the characteristic cross-shore profile of the northwest beach (D50=300 µm).*

Compared with the southwest beach, the XBeach results seem to correspond significantly better. In contrast to the southwest beach, the modeled slope of the upper profile is steeper than observed but seems quite good. The typical plateau as observed at the southwest beach is not yet developed in the first 3.5 month. Especially the slope between 70 and 85 m gives the same gradient (1:30). Above the water line, XBeach overestimated the erosion profile. However, the location of the erosion profile comes close to the measured profile, only 2 m difference. Again the typical erosion profile is visible with a steep slope, the computed slope around the water line seems to differ from the measured 1:10 profile. Overall, the observed profile at the northwest beach can be simulated quite good. The application of the XBeach model and processes that are responsible for the characteristics of the cross-shore profile are further discussed in chapter 6.

## 5.2 Alongshore profile evolution

In this section, the alongshore profile evolution of the shoreline is discussed for the southwest beach. To do so, the theoretical longshore sediment transport is computed and is subsequently compared with the observed morphological behaviour. From the analysis of the northwest beach, it has been found that the working activities have disturbed the morphological development significant. Therefore, it has been chosen to not discuss the alongshore profile evolution of the northwest beach in more detail but focus on the southwest beach.

### 5.2.1 Shoreline evolution per interval

The analysis of the stability of the shoreline of the southwest beach has shown that the equilibrium orientation of the shoreline is designed in such a way that no net longshore transport will occur (assuming the Brettschneider method). However, this does not mean there will be no longshore transport at all at the southwest beach. The net transport is the sum of the longshore transport in both directions, so gross to the left and gross to the right. The net transport may thus be zero, while the gross transports are very large (but equal). Shoreline changes can be simply understood by considering the sediment continuity equation for the littoral zone (see section 3.3.1). In order to determine the potential longshore sediment transport the equilibrium formulae of CERC (USACE, 2002), Kamphuis (1991) and Van Rijn (2014) are used. These sediment transport formulae are extensively described in section 3.3.2. The input parameters and corresponding values are presented in Table 5-3.

*Table 5-3. Input parameters for calculation of the potential longshore sediment transport.*

| Input parameters | Value |
|---|---|
| Sediment density | 2650 $kgm^{-3}$ |
| Bulk density of sand bed | 1600 $kgm^{-3}$ |
| Breaker coefficient ϒ | 0.4 |
| Median grain size ($D_{50}$) | 300 μm |
| Slope of the beach (surf zone) | 1:15 |
| Offshore water depth | 4.6 m |

The potential longshore sediment transport is based on the shoreline orientation. Therefore, the orientation has been measured every 40 m at the beginning of each time interval. The slope of the surf zone is set at 1:15, which is the averaged slope below the plateau formation. However, the beach slope at the surf zone is actually not a simple slope. The plateau in the surfzone causes actually less sediment transport as expected. So in fact, the transport magnitudes are likely to be somewhat lower in reality.

The morphological development as determined based on the field observations, should be explained by means of the direction of the sediment transports. The positive and negative values represent the longshore sediment transport, respectively in, northwest and southeast direction. The longshore sediment transport calculations per period are shown in appendix E.

### 5.2.2 Shoreline evolution in general

In addition, the total potential sediment transports are computed for the time interval T1-T5. This interval covers the period between 29-11-2016 and 04-04-2017. The results are presented in Figure 5-9. The corresponding transport magnitudes are presented in appendix E. The tipping point appears to be at about 160 m north-west of the centre. Left of this point, the sediment transport is directed northwest (left). This explains the accretion near the structures. Right of the tipping point the sediment transport is in southeast direction (right). In the central section the sediment transport is limited, where after it increases in southeast direction. The potential transport at 180m is significant, which corresponds quite well with the morphological observations. The net sediment transport is directed southeast. The positive value corresponds to a northwestern transport (left directed) and the negative values to a southeastern transport (right directed). From this analysis, it can be concluded that the computed longshore sediment transport can be quite well explained by means of the morphological development map. The directions seem to correspond quite well with the observed locations of erosion and sedimentation.

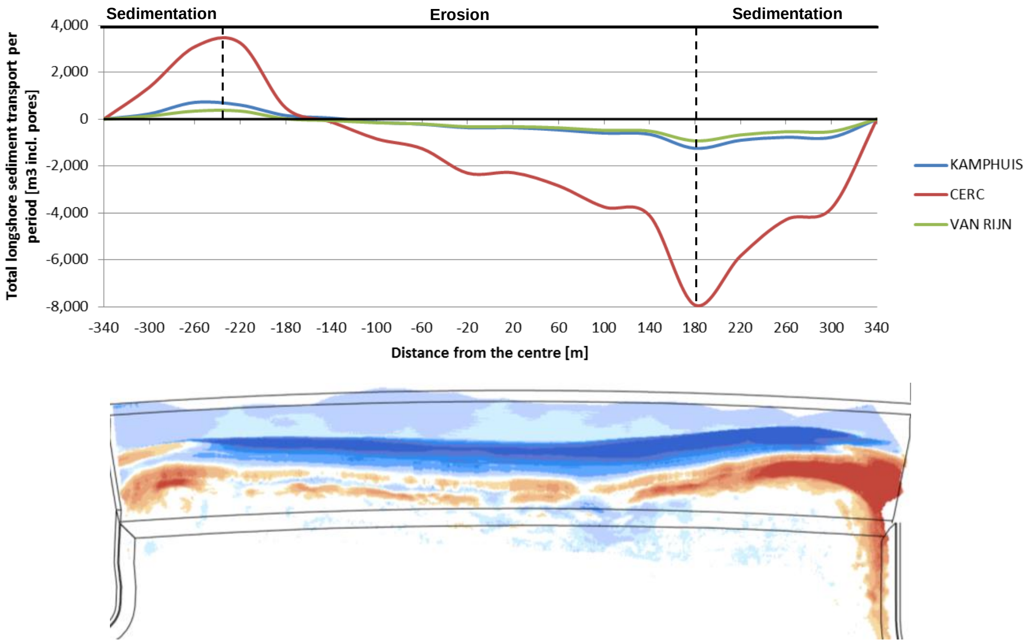



*Figure 5-9. Upper plot: Potential longshore sediment transport. Lower plot: The morphological development for this interval.*

By making a distinction between the transport directions, the magnitudes of the erosion and sedimentation patterns can be determined by the peaks in the figures (-240m and +180m) . The corresponding magnitudes are presented in Table 5-4.

*Table 5-4. Sedimentation and erosion patterns derived from the potential longshore sediment transport.*

| Direction | KAMPHUIS [$m^3$ incl. pores] | CERC [$m^3$ incl. pores] | VAN RIJN [$m^3$ incl. pores] |
|---|---|---|---|
| Northwest direction (+) | 715 | 3,252 | 347 |
| Southeast direction (-) | -1,245 | -7,970 | -926 |

The magnitudes, as presented in the table above, should be correspond with the volume changes as presented in the sediment balance in Table 4-7. Taking into account the volume losses due to settlements and the interaction of cross-shore and longshore sediment transport, this is quite difficult. For example, in section 4 (south-eastern part) about 1300 $m^3$ sand is added during the first months (see Table 4-7). Neglecting the volume loss of settlements (25% of the total loss) this is in the order of 3700 $m^3$. Based on these assumptions, it can be concluded that the potential transport rates are somewhere in between the formulas of Kamphuis/Van Rijn and CERC. Nevertheless, the order of magnitude seems to be quite reasonable.

# 6. DISCUSSION

In this chapter, the discussion is presented in which the following topics are discussed:

- Lake system
- Characteristics of the cross-shore profile
- Usability of applications to describe the observed behaviour
- Relation to the pilot project at the Houtribdijk

## 6.1 Lake system

The hydrodynamic environment of a lake system is much different with respect to a coastal system. The absence of tidal influences is the most important difference. The water level can fluctuate in time because of wind set-up or man-induced water level variations, but the spatial scale of fluctuation is negligible when compared to a coastal system with a tide. Another significant difference in a lake system is that the wind is the primary forcing mechanism on the beaches of the Marker Wadden as wind-generated waves and wind set-up. Because Lake Marken has a limited fetch and a low varying water level, the wave environment is called low-energetic.

### Correlation water level and wave height

Considering wind set-up and set-down, it seems that there is a distinct relation between the local water level and the significant wave height (Ecoshape, 2017). In particular, the winds from the western sectors (SW – NW) produce both waves and set-up, resulting in locally higher water levels and higher wave heights. Off winter season, when the water level is less affected by rain events, there is a strong relation between the wave height and water level setup. Especially during the winter months the water level changes in Lake Marken are often affected by precipitation and high water discharges. Although these results are obtained for the pilot location, similar tendencies are expected for the location of the Marken Wadden as well.

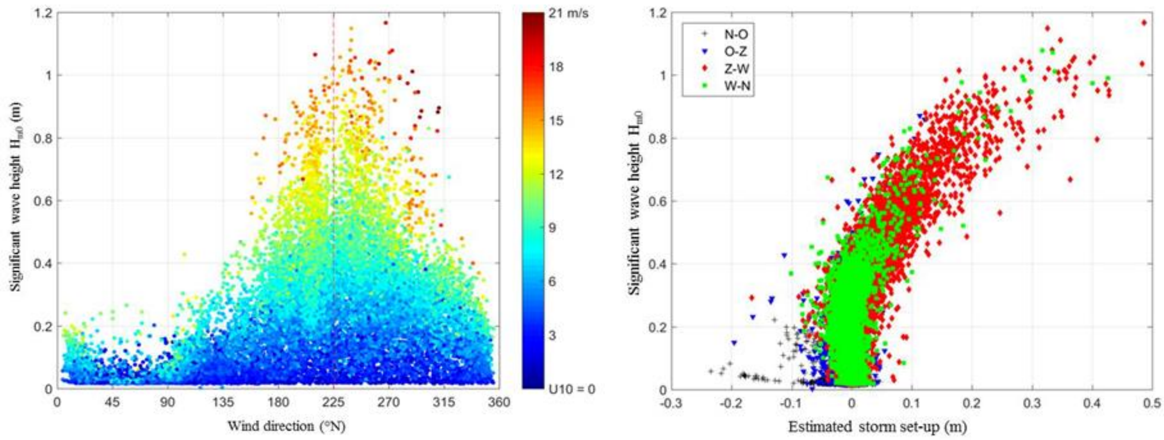



*Figure 6-1. Left-hand plot: Wave height as function of wind direction and wind speed. Right-hand plot: Correlation water level and wave height. (Ecoshape, 2017).*

From this can concluded that there is a strong relation between water level setup and wave height due to the wind-dominated character of the lake system. For the wind directions from the eastern sections the wave heights are limited and there is water set-down, while for the wind directions from the western sections the wave heights are higher and there is water setup. The response of the wave heights and water levels seems quite similar, because there are no combinations observed with high water setup and low waves or high waves and little water setup. Based on these findings the water setup an set down can be determined for the expected water levels at the Marker Wadden.

## 6.2 Characteristics of the cross-shore profile

In this section, the characteristics of the cross-shore profile are discussed in more detail. To provide a better understanding of the morphological processes which caused the profile shape, an explanation of the processes is provided that could be responsible for the morphological development.

Latest insights suggest that the plateau levels, NAP -0.8 m for the northwest beach and NAP -1.0 m for the southwest beach, are related to the relation between the water level and wave height and thus to the lower boundary of the active zone (van Ekdom, 2017). The absence of tide, dominantly present in coastal systems as described in the previous section, is the reason for the strong correlation between the wave height and water depth. The fact that the wave heights at the northwest beach are relatively lower compared to the southwest beach, will probably be the reason for the slightly higher level of the plateau for this location. The strong correlation between the wave height and water depth seems to be the cause of the formation of the plateau with a limited equilibrium depth.

From analyse the morphological developments, it is found that the lowest morphologically active profile level is the level of the plateau and is defined as the equilibrium plateau level. Looking at the wave breaking process, wave breaking causes transport and gradients on the cross-shore profile. If no waves are breaking no transport gradients would occur and thus no morphological development. If waves are breaking, transport gradients are present on the profile. When the waves breaking on the plateau, this caused transport gradients and caused the plateau level to be lowered (increase in water depth). Subsequently, the plateau level is lowered to a level for which no waves are breaking on the plateau anymore. Finally, an equilibrium level is reached. Which seems to be the case for the southwest beach at NAP -1.0 m, however, this is not (yet) the case the northwest beach.

The equilibrium width of plateau is not yet clear, because only data is available of the first months after construction. Although, it is known that wave driven alongshore current is the responsible process for both the onshore and offshore boundary of the plateau at NAP -1 m. It depends on the wave climate which is responsible for the rotation of the shoreline. At the outer sections near the breakwaters, the cross-shore current is dominant over the alongshore current where the current is deflected offshore and the sediment is deposited to lower profile levels. The length of the breakwaters is linked to the offshore boundary of the plateau width. It is assumed that the plateau width will increase until the shoreline has reached its equilibrium orientation w.r.t. the overall wave climate.

Both in cross-shore as in longshore direction a great variety of sediment diameters is present. This will have an impact on the transport processes. From the analyses of the sediment characteristics it is concluded that the median grain size is sorted along the cross-shore profile, this is also found at the pilot Houtribdijk. A relationship between median grain-size and profile level is found, with small median grain-size at lower profile level and coarse grain-size at higher profile levels. Around the water line, wave driven alongshore transport will first pick up the finer sediment, as these sediment have the lowest resistance. At the profile levels where there is alongshore transport, a coarsening of the median grain size will occur because of the finer sediments are washed out. Subsequently, the finer sediments are transported alongshore and finally will deposited to greater depths. This would explain the sorting of the sediment along the cross-section. For example, at the outer sections of the southwest beach the intimal slopes of the beach were steeper and it is found from the sediment samples that, around the waterline and at the plateau, the median grain sizes where coarser (see section 4.3.5). Therefore it is very likely that the slope of the beach is related to the local median grain size. However, because of the limited sediment samples at greater depths, this cannot be determined with certainty.

Due to the lack of wave forcing, the orbital velocity near the plateau that brings sediment in suspension is limited, and thus the sediment transport at the plateau is limited as well. The occurrence of a stable and steeper beach around the water line is probably due to the presence of coarser sediment fractions in the supplied material from the bottom of the lake. Moreover, at the upper slope of the profile the water depth decreases and the waves are breaking caused sediment is brought into suspension. Finer sediments will be brought into suspension easier and will be transported, as result that the coarser remains behind. This material will not be brought into suspension and will as bed-load be transported onshore. Here, the alongshore sediment transport is dominant and the is transporting the sediment alongshore. At the outer sections, where the longshore sediment transport is blocked by the breakwaters, the cross-shore current is dominant which transports the sediment towards lower levels.

Depending on the existing beach level at higher elevations, a swash bar may be developed. This is also observed at the outer sections of the southwest beach near the structures. Due to the absence of strong offshore directed transport processes during low-energy conditions the coarser sediments remain on the beach and act as a kind of protective layer for the finer sediments below and behind it.

### Analyses of similar beaches

An analysis of similar beaches in Lake Marken by Van der Weij (2005) prove that beaches with steep shores and a flat underwater plateau are typical in Lake Marken. It seems that these sandy beaches at some locations, due to the fixed water level and high amount of cross-shore transport, erode quite fast. Concerning the processes of sediment transport, the orbital movement of the waves seems the main process of sediment transport. As part of the pilot Houtribdijk, Deltares studied the morphological processes that formed the plateau, which is also observed at the Marker Wadden. Deltares states that a possible reason could be that the by wave driven offshore sediment transport is higher in comparison with the onshore sediment transport (Deltares, 2016c). As result that shallow gentle foreshores developed at locations where the offshore sediment transport is higher, because the undertow current at steeper slopes result in an imbalance of the cross-shore transport. As the cross-shore profile is more gentle, the amount of sand losses also decreases.

In addition, the presence of ripples at the plateau would enhance the offshore transport. Besides that, it appears that the sediment at the plateaus of natural beaches is often consolidated and therefore difficult to erode. Whether the beaches of the Marker Wadden will erode as well is not yet clear, because of the limited bathymetry data set that is collect so far. Further monitoring of the beaches will provide evidence for that.

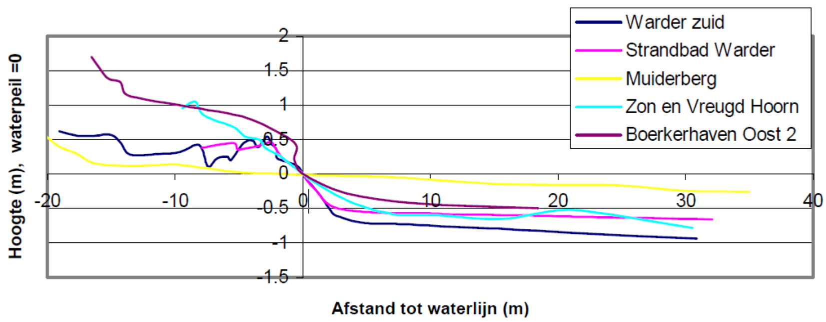



*Figure 6-2. Cross-shore profiles of five investigated beaches. The beach at Muiderberg is a constructed sandy beach and is protected against wave attack. The other beaches have steep slopes around the water line and a shallow plateau (Van der Weij, 2005).*

Van der Weij (2005) prove that the natural beaches tend to a gentle cross-shore profile with a slope of about 1:70. Around the water line a steep but stable slope (1:4 – 1:13) could occur, when enough coarse material is present. See Figure 6-2 for the investigated cross-shore profiles in Lake Marken. Van der Weij studied the cross-shore profile of five beaches in Lake Marken. He found that beaches where the waves influence on the beach profile the beach slope is steep and where the waves have no or less influence on the beach profile the beach slope is gentle. In addition, the sediment grain size has great influence on the beach slope, the coarser the grain size the steeper the profile, which is observed at the northwest and southwest beaches of the Marker Wadden also. The southwest beach shows a steeper profile compared to the northwest beach. The beach profile seems to be a monotonically decreasing curve where the slope is steep around the water line and turns in almost a horizontally bed. The location in the lake and the corresponding wave conditions are of great importance to the profile shape of the beaches.

## 6.3 Usability of applications to predict the observed behaviour

In this section first the usability of the equilibrium profiles formulae are provided. Subsequently the application of the XBeach model and the longshore sediment formulae are discussed.

### Equilibrium profiles

Due to the plateau, only the first few meters below the water line can be used to compare the equilibrium profiles with the measured profiles. In particular the sediment characteristics determines the shape of the equilibrium profile. The influence of the median grainsize ($D_{50}$) is the greatest for the model of Kriebels et al. (1991), followed by Dean (1990) and finally Hanson and Kraus (1989). The median grainsize however is not exactly known. It has been assumed by an estimation based on the measured sediment characteristics (see section 4.3.5 and 4.4.5). Moreover, the median grainsize is not equal over the cross-shore profile. The equilibrium profiles assume however, a relatively constant median grainsize over the whole beach profile, as can be observed at coastal beaches where the tidal influences cause a vertical distribution of the wave energy along the cross-shore profile and so the gradually vertical distribution of the grainsize. Besides that, it must be noticed that the accuracy of the measurements is somewhat uncertain, given the fact that the topographical points are interpolated to determine the levels in between. Because only the first meters are considered and that the conclusion is based on just only a few data points, it is uncertain if this is accurate enough.

The model of Wright has a variable parameter the bottom depth ($h_0$) and the K-value, which determines the steepness of the profile. However, the recommended K-value ($10^{-4}$ -$10^{-6}$) for the equilibrium profile of Wright (1986) seems not representative for shallow lake systems and is therefore calibrated based on the measured profiles. Also it depends which bottom depth is assumed. When the bottom depth of the plateau is assumed, it gives better results.

An important note is that the equilibrium profile mainly forms in the first months after construction. Given the observations of the cross-shore profiles of both beaches, this appears to be so. The equilibrium profile might not be reached completely at the moment of measuring. The plateau formation cannot be modelled by using these equilibrium formulae because it is not included in the formulae at all. It must be noticed that latter conclusions are based on dynamic profiles, which seems to still adjust to its equilibrium profile. Van der Weij (2005) found that the equilibrium profile of the investigated beaches can be described with the equilibrium profile of Kriebel et al. (1991). However, for the beaches of the Marker Wadden this seems not to be the case.

### XBeach model

As described in the previous section, a comparison between the sediment transport behaviour in a lake system and in coastal areas is complicated due to the presence of tides. A coastal cross-shore profile experiences different transport regimes within a tidal cycle for the same wave conditions of which the average effect is still unknown. A vertical tide causes a vertical distribution of the wave energy along the cross-shore profile. In order to analyse the effect of tides on the cross-shore profile evolution, a number of XBeach-simulations has been performed by Deltares as part of the pilot Houtribdijk (Deltares, 2016c). The results show that the presence of a vertical tide leads to a significant decline of the shoreline (see Figure 6-3). In addition, the tide results in a steeper profile, without a plateau. These results support previous findings that the absence of the tide (as in a lake) would lead to the development of a gentle foreshore profile (plateau formation) which strongly deviates from the equilibrium profile of Dean.

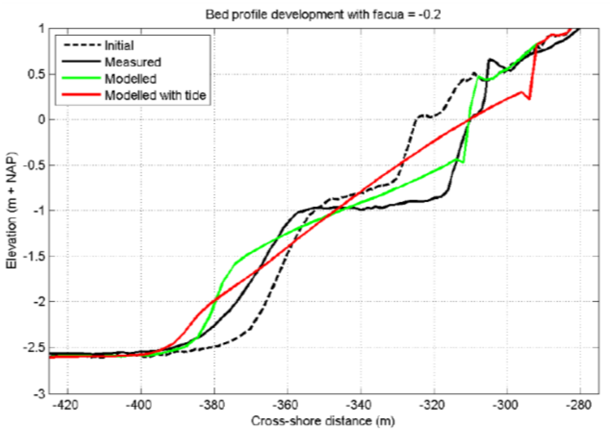



*Figure 6-3. XBeach results for the simulations of transect #12 of the pilot Houtribdijk with and without the tidal influences (Deltares, 2016c).*

The XBeach simulations show that reproduce the observed profile evolution is still difficult by a one-dimensional numerical model XBeach. It is found that, despite of using a wide range of input settings, the developed profile shape could not be sufficiently reproduced. In particular, the development of the plateau and the steep slope around the water line seems to be a challenge to simulate. Whether the presence and role of the plateau is related to cross-shore or longshore transport is still a question. The physical relationship between the wave height and the water depth (as described in the previous section) on the cross-shore profile morphology must be investigated in more detail. Concerning to this, ongoing research in the framework of the pilot Houtribdijk is aiming to improve this. Addition monitoring is under investigation in the form of a two-way approach: ADV's on the plateau itself to measure velocities and wave heights (1) and partial removal of the plateau up to the steep slope near the water line (2). This will lead to additional insights to improve the XBeach-model as well. In case of erosion (as present in the central section of the southwest beach) it seems that the longshore gradients are responsible for the landward shift of the water line.

Since the waves only play a role above a certain level the landward shift of the active zone results in a plateau formation automatically. At the outer limits of the beach (near the structures), the cross-shore transport seems to be more important. Extending the model to a two-dimensional version, in order to take the effect of the longshore sediment transports into account, should give better results. Finally, both in cross-shore as in longshore direction a great variety of sediment diameters is present. This will have an impact on the transport processes. In the basic version of the XBeach model only one diameter can be used.

### Alongshore profile evolution

In order to investigate the morphological stability of the shoreline of the southwest beach, the longshore sediment transport formulas of CERC (2002), Kamphuis (1991) and van Rijn (2014) have been applied. It can be concluded that the longshore sediment transport formulae can compute the morphological development quite well. The directions seem to correspond with the observed locations of erosion and accretion. It has been found that at the south-eastern part of the beach about 1,300 $m^3$ is deposited during the first months. taking into account the volume loss due to settlements (25% of the total loss) this is in the order of 3,000 - 4,000 $m^3$. Based on these assumptions, it seems that the CERC-formula overestimates the transport (7,970 $m^3$) and the formulae of Van Rijn and Kamphuis underestimated the transport (925 and 1,250 $m^3$). Moreover, it is still difficult to translate the calculated potential longshore sediment magnitudes to the sand volumes that were determined in the sediment balance. As expected, the northwest beach will gradually lose sand due to the net longshore sediment transport in north-eastern direction. From the sediment balance, follows a sediment loss of about 5,600 $m^3$ in the first 3,5 months (T1-T4), of which 70% seems related to the settlement of the subsoil and 30% to the longshore sediment transport. This last loss equals about 5,000 $m^3$/year, which is somewhat higher than originally expected ~2,000 $m^3$/year as was calculated in the design reports. It should be remarked that the transport rates are quite uncertain because of the working activities that took place at the northwest beach and the relative short period on which this estimate is based. Because of this, no detailed longshore sediment transport calculations are performed as well.

## 6.4 **Relation to the pilot Houtribdijk**

In this section, the observations of the beaches of the Marker Wadden are compared with the results of the pilot Houtribdijk. In order to estimate the stability of the cross-shore profile of the southwest beach and the northwest beach, the observed morphological development of the Pilot Houtribdijk has been used for comparison. The differences and similarities are discussed below.

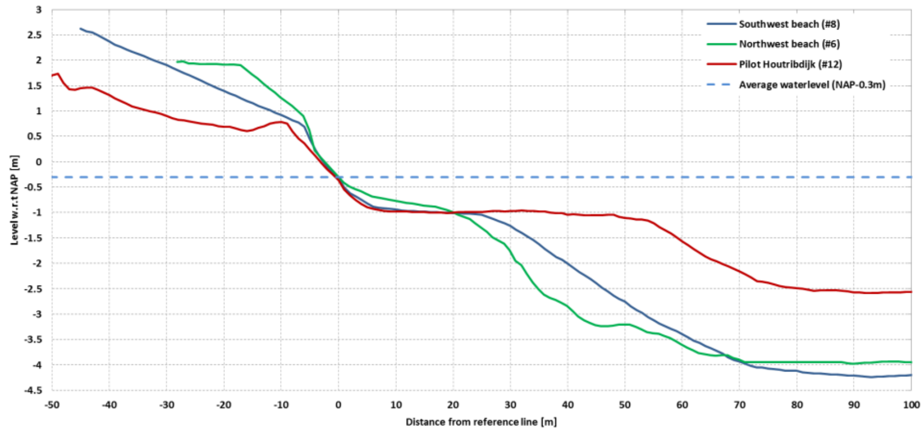



*Figure 6-4. Characteristic cross-shore profiles of the southwest beach (#8) and the northwest beach (#6) compared with the characteristic profile of the pilot Houtribdijk (#12).*

In Figure 6-4, all characteristic profiles are shown in such a way that the zero position is fixed at the location where it intersects with the average water level at NAP-0.3 m. The characteristic cross-shore profiles, that are observed at the central section of the southwest beach (profile #8 according to survey T5) and the northwest beach (profile #6 according to survey T7), are compared with the results of the pilot Houtribdijk (profile #12). In Figure 6-4 it can be seen that the basic shape of the profiles around the water line corresponds quite well. In particular, the cross-shore profiles of the pilot and southwest beach (having a comparable orientation) show a flat plateau formation around NAP -1.0 m. Only the width of this plateau is significant larger at the pilot. This has to do with the timespan but could also be related to the typical lay-out of the pilot (including the presence of the sheet pile wall). The cross-shore profile at the pilot has been measured 2.5 years after construction, in contrast to the 4 months at the southwest beach and 6 months at the northwest beach. It seems that the typical plateau formation also appears at the northwest beach, although this occurred not as fast as at the southwest beach.

The orientation of the beach and corresponding calmer wave conditions play an important role in the development of such a plateau. The steep slope around the water line is also remarkable, which is about 1:10, both at the pilot and the beaches of the Marker Wadden. In contrast to the pilot, a clear swash-berm is not (yet) observed, however, this could still develop in the future. On the other hand, a vertical scarp as high as is observed at the southwest beach is not observed at the pilot. Both the presence of the berm and the scarp seem to be related to the initial slope of the profile at higher elevations.

# 7. Conclusions and Recommendations

## 7.1 Conclusions

The research presented in this thesis has improved the understanding of the processes that governed morphological behaviour of the beaches of the Marker Wadden in the first months after construction. The research objective was to analyse and describe the morphological development and the developed cross-shore profile shape of the sandy beaches of the Marker Wadden. To reach this objective, it is investigated whether the observed behaviour can be described by equilibrium methods and if the cross-shore profile shape can be reproduced by the numerical morphological model XBeach. In this section the conclusions are presented. This answers the research questions as posed in section 1.3, which are repeated below for convenience.

*Which design formulae and models are commonly used for sandy shores and which models are used for the design of the sandy shores of the Marker Wadden?*

It is found that both the equilibrium formulae and longshore sediment transport formulae, are usually used and designed for situations in coastal systems instead of lake systems. Researchers, such as Bruun (1954) and Dean (1977), have tried to develop appropriate equations that describe beach profile changes as a function of different parameters, such as the diameter of the sediments, density, wave breaker height and other characteristics. In order to examine the cross-shore profile evolution, the equilibrium profile of Dean (1977) is commonly used. This equilibrium profile is given by $h(x) = Ax^m$. Based on fitting to natural upper shoreface profiles, Dean has suggested an average value of m=2/3. The model is quite simple with only one parameter, which is the shape parameter A. There are many methods to determine the value of this A parameter. Dean has developed several methods to calculate this parameter. Subsequently, researchers such as Hanson and Kraus (1989), Kriebel et al. (1991) and USACE (2002) has proposed an equation for parameter A. Another method to determine the equilibrium profile is developed by Wright (Wright et al., 1986), which is based on the bottom depth and the underwater slope. Furthermore, to determine the equilibrium profile due to extreme conditions such as storm events, Vellinga (1982) proposed a relationship between cross-shore distance and profile depth for erosive beach profiles. For the morphological stability of the shoreline, the longshore sediment transport formulas of CERC (USACE, 2002), Kamphuis (1991) and van Rijn (2014) are commonly used. The most widely used formula is the CERC-formula, for which the basic assumption is that the flux integrated over the surf zone is proportional to the energy dissipation within the surf zone. However, this CERC-formula does not account for particle size and beach slope. For the Kamphuis-formula the effects of particle diameter and bed slope are included as well. The longshore sediment transport formula of van Rijn is a function of the particle size, the steepness of the beach, the wave height and the breaker angle at the breaker line.

Since knowledge on the behaviour of newly constructed sandy shores in a lake system is limited, the design of the sandy beaches were mainly designed using the results of the Building with Nature pilot project along the Houtribdijk. In addition, several computational calculations for longshore and cross-shore transport have been performed. In order to estimate the morphologic stability of the cross-section for year-round conditions, the numerical CROSMOR model has been used. For the morphologic stability of the cross section during storm conditions, additional calculations have been carried out with both the numerical models XBeach and CROSMOR. For the morphological stability of the shoreline the longshore transport formula of Van Rijn (2014) has been used in order to determine the gross and net longshore transport rates. For the purpose of the design two wave climates are determined, which are based on the Brettschneider methodology and the more complicated wave model Delft3D-SWAN.

*What is the initial behaviour, both in cross-shore and longshore direction, of the sandy shores of the Marker Wadden in the first months after construction? And how can the observed developments at the two beaches be related to the local hydraulic conditions?*

### Cross-shore evolution

Analyses on the cross-shore profile evolution, show that a profile shape is formed with an almost horizontal plateau at 0.5 m (northwest beach) and 0.7 m (southwest beach) below the average water line and a steep slope of about 1:10 around the water line. Based on the analyses of the morphological development, this profile is formed within a several months to a dynamic equilibrium situation, especially at the southwest beach the profile was formed quite fast.

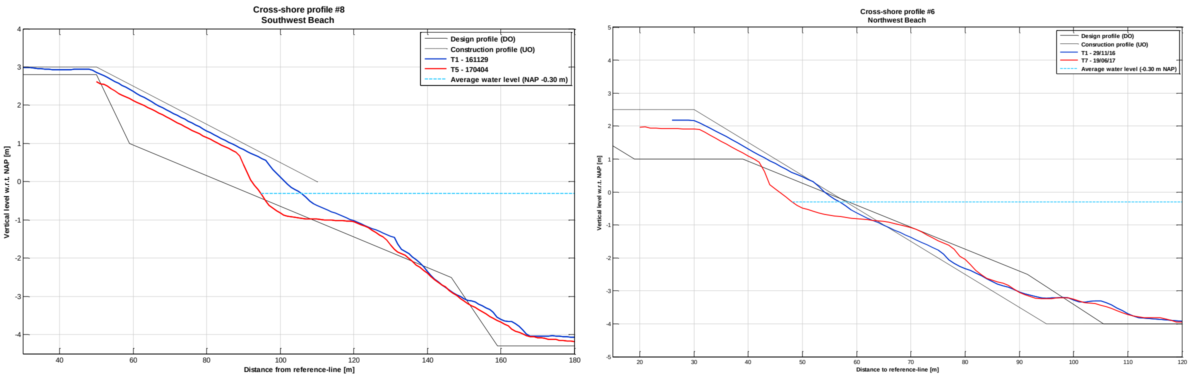



*Figure 7-1. Characteristic cross-shore profiles of the southwest beach (left-hand figure) and the northwest beach (left-hand figure).*

The correlation between the wind setup and wave height affects mainly the cross-shore profile. It is observed that the higher waves coincide with high water levels at this part of the lake. Winds from the SW-NW directions produce both waves and set-up. Especially during storm events both the water level and wave height increases rapidly. The fact that the wave heights for the northwest beach are relatively lower is probably the reason for the higher level of the plateau for this location. The orientation of the beach and corresponding calmer wave conditions play an important role in which time such a plateau develops. During the first months after construction the dominant wave direction was from other directions than from northwest, which explains that limited morphological changes took place in this period. In general, at the central part of the southwest beach no significant sedimentation has been observed below the plateau. Above this level, erosion of the shoreline occurred. It seems that the longshore gradients are responsible for this erosion and so the landward shift of the water line at the central section. Since the waves only plat a role above a certain level, the landward shift of the active zone results in a plateau formation automatically. Although at the southwest beach no accretion can be observed below NAP -1.0 m yet, this may occur in the future. For now, this is probably due to the longshore gradient at the central part of the beach. When the shoreline is changed to a more or less equilibrium state, the underwater slope may extent in offshore direction. This has been observed at the pilot Houtribdijk as well (see Figure 2-8). Additional surveys are required to provide evidence for that. At the outer limits of the beach near the structures, where initially the beach slope was steeper constructed, the cross-shore transport seems more important. At the northwest beach, limited sedimentation can be observed below the plateau. The characteristic cross-shore profiles of the southwest beach and northwest beach are presented below. An overview is provided in Table 7-1 of the characteristics of the cross-shore profiles of both the southwest beach and the northwest beach.

*Table 7-1. Summary of the cross-shore profile characteristics of the southwest beach and northwest beach.*

| | Southwest beach | Northwest beach |
|---|---|---|
| Crest level dune | NAP +2.8 m | NAP +2.0 m |
| Beach slope | 1:20 | 1:20 |
| Height vertical scarp | 0.3 m - 1.2 m | 0 – 0.80 m |
| Slope around the water line | 1:7 -1:9 | 1:7 – 1:10 |
| Level of plateau | NAP -1.0 m | NAP -0.8 m |
| Plateau width | 5 – 15 m | 0 – 10 m |
| Underwater slope | 1:7 - 1:15 | 1:5 - 1:15 |
| Depth of closure | NAP -2.5 m – NAP -3.8 m | NAP -2.0 m – NAP -3.2 m |

## Alongshore profile evolution

Primarily wave driven alongshore transport is responsible for the largescale morphological development of the beaches. The effect of the hydrodynamics on the beaches of the Marker Wadden is the morphological development of the shoreline and can be explained by the changing orientation and the locations where the beach is eroded and sediment is deposited. The significant variation of the dominant waves affects the orientation of the beach, which makes it that the beaches are very morphological dynamic. This can be explained by the surface-plots of the morphological development as presented below, according to the most recent (complete covering) surveys.

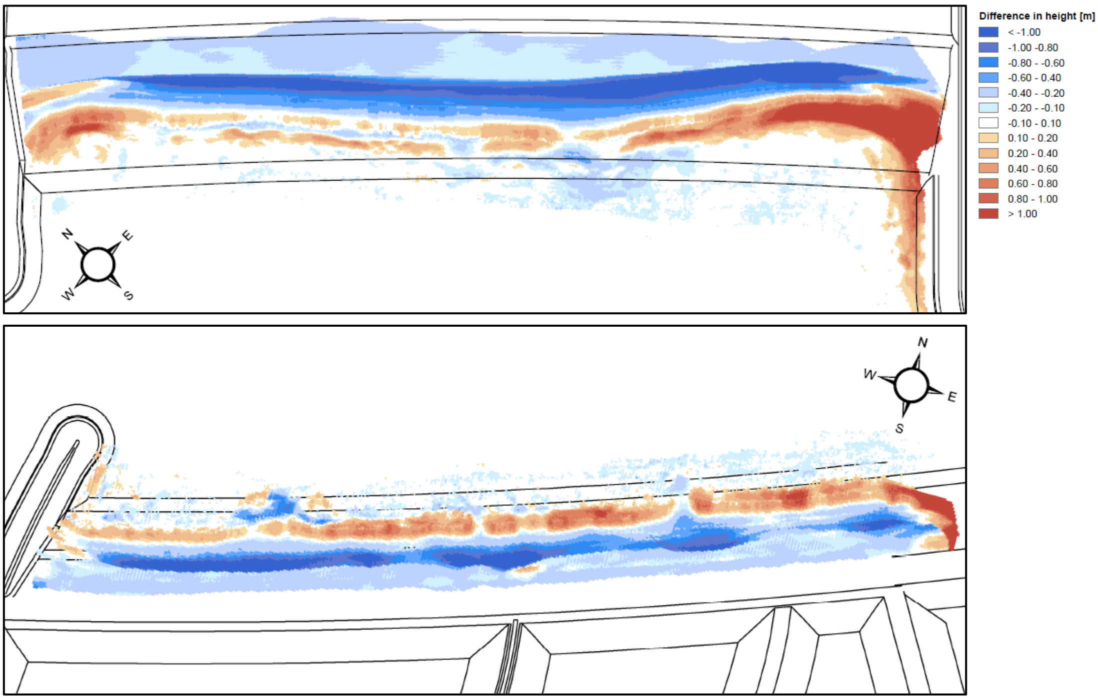



*Figure 7-2. Surface plots of the morphological developments of the southwest beach (upper plot) between T1 and T5 and northwest beach (lower plot) between T1 and T7. In which blue is erosion and red is sedimentation.*

From the surface-plots of the southwest beach, mainly erosion of the shoreline can be observed in the central section and accretion at the outers sections (see upper plot in Figure 7-2). The eroded sediment at the central section has been transported by a longshore gradient to the outer sections. In particular, the accretion near the southeastern breakwater of the harbour (right-hand side in upper plot) is clearly visible. The cross-shore transport due to the initially steeper constructed slope contributes also to the sedimentation at this part of the beach. Where initially the beach was wider in the central section, it has been gradually adjusted to a straightened beach contour (see Figure 4-18). Hereto, the average shoreline orientation has changed to about 225° w.r.t. North, as was originally designed as well. This confirms that the beach seems to develop into a morphological stable situation.

At the northwest beach, regression of the shoreline can be observed over the entire length of the beach. Also noticeable is the increasing sedimentation in the northeastern direction (lower plot in Figure 7-2). This indicates a longshore transport gradient in northeast direction. The beach will therefore gradually lose sand due to a net longshore sediment transport in northeastern direction. In addition to this, it must be noticed that working activities have interrupted the natural developments. Since the end of February, several activities have taken place, such as the landfall of a floating pipeline and excavation activities.

*Are the classical design formulae and models, for cross- and longshore sediment transport and profile evolution, able to describe the observed developments and which adjustments in the formulae/models are required to improve them and to use them for the design of such sandy shores?*

**Equilibrium profiles**

It can be concluded that the equilibrium profiles cannot be described with the equilibrium formulae. In particular, the presence of the near-horizontal plateau makes it that only the first few meters (measured from the water line) of the observed profiles can be described. The characteristic profiles of both the southwest beach and northwest beach are studied. It is found that for the southwest beach, the equilibrium profiles of Dean (1990) and Hanson and Kraus (1989) closely fit the first 7 meters of the observed profile for a $D_{50}$ of 0.40 mm. When the parameter settings for the equilibrium profile of Wright et al. (1986) are set at a bottom depth of 0.75 m (water depth at the plateau) and the K-value at 0.2, the measured profile can be described quite well including the plateau. For the characteristic profile of the northwest beach, it has been found that the equilibrium profile of Wright et al. (1986) fits quite well for the first 5 meters However, because of the plateau the model cannot describe the whole equilibrium profile including the lower part.

Another limitation of the equilibrium formulae is that only one sediment diameter can be applied, the median grainsize ($D_{50}$) varies namely in cross-shore direction. It has been found that the finer sediment particles were found lower in the profile, while the coarser sediment particles were found higher at the beach. The equilibrium profiles assume however a constant median grainsize, as usually can be observed at coastal beaches. It appears that the grainsize is of great importance to determine the beach slope. furthermore, an important note is that the equilibrium profile mainly forms in the first months after construction. However, the equilibrium profile might be not reached yet at the moment of measuring, e.g. see latest insights of the northwest beach.

**Cross-shore profile evolution using XBeach**

Both the cross-shore profiles of the southwest beach and northwest beach are examined (see Figure 7-3). It is found that reproducing the observed profile evolution by using a one-dimensional XBeach model is still difficult. Where at the cross-shore profile of the northwest beach the results were quite reasonable, the developed profile shape of the southwest beach could not be sufficiently reproduced. In particular, the development of the plateau and the steep slope around the water line seems to be a challenge to simulate. The model result in a near vertical scarp, where a 1:10 slope is observed. Because of this, erosion is overestimated causing the model shows clearly more a landward shift of the shoreline. Possibly, this has to do with the schematic wave climate which has been used as input.

For instance, it is assumed that all the waves approach the beach more or less perpendicularly, what is in fact not completely the case. Apart from that, the wave climate is based on Brettschneider, causing the local influences are not taken into account. This could result in probably an overestimating of the wave conditions, i.e. higher wave heights what subsequently leads to overestimating the erosion profile. Focusing on reproducing the observed profile shape, it can be concluded that the one-dimensional XBeach model is not yet applicable to simulate the observed profile shape exactly. However, depending on the purpose of the results, for example the location of the erosion profile, the model results of the northwest beach seems to be quite reasonable. The physical relationship between the wave height and the water depth (as described in the previous section) on the cross-shore profile morphology must be investigated in more detail to improve the XBeach model. Furthermore, to improve the XBeach model the following aspects must be studied in more detail: varying of sediment characteristics in the cross-section, the effect of orbital velocity near the plateau that brings sediment in suspension, the undertow currents that are responsible for offshore sediment transport and the application of a two-dimensional XBeach model.

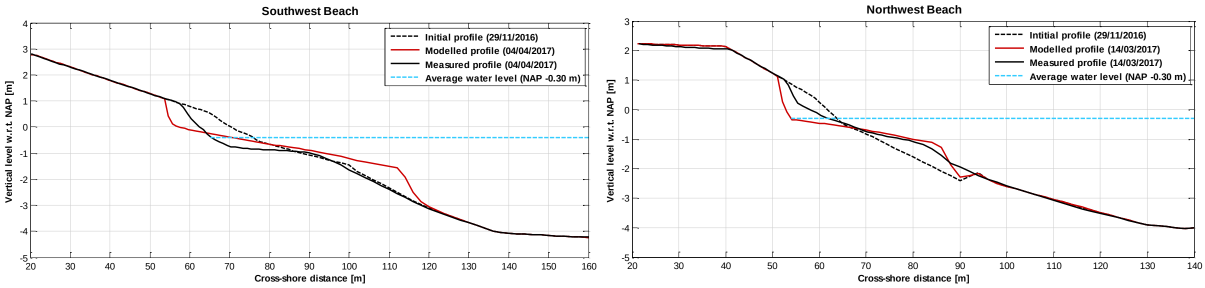



*Figure 7-3. XBeach results of the southwest beach (left plot) and northwest beach (right plot).*

### Longshore sediment transport formulae

The potential longshore sediment transport has been calculated for the southwest beach, after which it is compared with the field observations. It seems that the methods that are used to predict the longshore transport are quite well applicable. The directions of the potential sediment transports corresponds quite well with the observed behaviour of the beaches. Besides that, it is still difficult to translate the computed longshore sediment magnitudes to the observed sand volumes that was determined for the sediment balance. Looking at the differences between the methods, the CERC-formula gives somewhat higher results compared to Kamphuis and Van Rijn. However, the computed magnitudes are all in the same order of magnitude that was observed.

> *What is the expected long-term development of the sandy shores of the Marker Wadden, based on obtained insights and (if possible) the application of (improved) models?*

Looking at morphological developments of the southwest beach, it seems that it is more or less morphological stable. From analyses of the observed behaviour, it shows that a straightened shoreline has been developed. The initial constructed steep slope at the southeast side of the beach near the harbour has been corrected by a sand supply provided from longshore sediment transport. Moreover, from the sediment balance it follows that the total volume loss can be attributed to the settlements of the subsoil. Furthermore, although no accretion can be observed below NAP -1.0 m in the central part of the beach, this may occur in the future. The absence of sedimentation below this level is probably caused due to the longshore gradient to the outer sections of the beach. When the shoreline has been changed into a more or less equilibrium state, the underwater slope in the central section may extent in offshore direction making the plateau wider. However, the behaviour of the beach depends strongly on the wave conditions and dominant wave direction. This makes the orientation of the shoreline is very dynamic, because the shoreline directly adjusts to the specific wave conditions. Given the dominant wave direction is about 225 ° w.r.t North, it is expected that the extending part of the southwest beach will be morphological stable as well. It is however important to construct the beach with a straight gradual shoreline, so without interruptions e.g. local steep slopes, hollows or scarps.

As expected, the northwest beach will gradually lose sediment due to the net longshore sediment transport in north-eastern direction. From the sediment balance follows a sediment loss of about 5,600 $m^3$ in the first 3.5 months, of which 70% seems related to the settlement of the subsoil and 30% to the longshore sediment transport. This last loss equals about 5,000 $m^3$/year which is somewhat higher than originally expected (~2,000 $m^3$/year). However, it should be remarked that this transport rate is quite uncertain because of the working activities that took place and the relative short period on which it is based on. Moreover, in the first months after construction the highest transport rates are expected also. Therefore, it should be very valuable to keep monitoring this beach to get a better insight in the yearly sediment transport rates and subsequent losses. However, it can be concluded that the predefined expectations of stability of the shoreline seems to be likely.

## 7.2 Recommendations

Throughout the research, some assumptions were used and several observations were made, that ask for additional research. These recommendations are summarized below and can be divided into three categories, namely: project Marker Wadden, sandy beaches in lake systems and more general further research.

### 7.2.1 Project Marker Wadden

Regarding to the project Marker Wadden the following recommendations are provided:

- It is observed that the initially constructed cross-shore profile, with a constant slope, quite fast adjusts to a profile with near-horizontal plateau at the shallow foreshore. It appears that it does not matter whether the initial constructed slope was steeper or more gentle: the horizontal plateau will develop. So for the construction it might be beneficial to construct the profile with a plateau, however it is very time consuming to profile it in such a form.

- Regarding to the extending of the southwest beach and northwest beach, it is important to construct the beach with a straight gradual shoreline without interruptions e.g. local steep slopes, hollows or scarps. It is therefore important that the volume per meter beach ($m^3/m$) below NAP +1.0 m is everywhere equal. Volume differences within the active zone lead to erosion and sedimentation patterns, which then disturbs the volume balance because a section erodes if more sediment is carried away than supplied and vice versa. At the open ends of the beaches, it is important to have enough sand buffer. The beach should therefore be slightly wider in order to retain the sand and so limit sand losses due to longshore sediment transport. Differences above NAP +1.0 m, such as the presence of sandy dunes, does not affect the shoreline evolution.

- It is important to continue monitoring the development of the beaches frequently. Especially the sections that are not enclosed on both sides, thus the existing northwest beach and extending southwest beach at the other side of the harbour entrance. This holds also for the shallow sandy dams on the lee side of the Marker Wadden. In order to relate the local hydraulic conditions to the morphological development of the beaches, it should be considered to place two hydrodynamic measuring stations which measures the local hydraulic conditions (e.g. wave height, wave period and wave direction). It would be valuable to place one at the existing northwest beach and another at the open end of the new southwest beach. Together with the monitoring of the beaches this will provide valuable information in order to better understand the morphological processes that govern both the initial and long-term behaviour. Moreover, the hydraulic data will provide insight in the currents at the edges of the Marker Wadden.

### 7.2.2 Sandy shores in a lake systems

Regarding to the sandy shores in lake systems the following recommendations are provided:

- In order to better understand the relation between the hydraulic processes and the morphodynamic behaviour of shores, it is recommended to collect bathymetric field data and hydraulic conditions at other (future) projects in lake systems. Proposed locations to collect these data are the reinforcement project along the Houtribdijk and the sandy shore along the norther part of the project Markermeerdijken.

- It is necessary to measure the local hydraulic conditions in order to assess the physical relation between the morphological developments and the local hydraulic conditions. Especially the relation between these conditions and the level of the plateau is interesting. Moreover, it is also useful to consider other beaches at the same time, given the fact that each location has its specific conditions. Consequently, one can learn from each other. In addition, it is important to collect as much relevant monitoring data as possible by frequently monitoring these constructed beaches, especially for predicting the long-term behaviour. The Marker Wadden is just constructed while the monitoring program at pilot Houtribdijk is nearing its end as well.

### 7.2.3 Further research

To elaborate on the presented results in this thesis, it is proposed to execute further research. The following recommendations are provided:

- The physical relationship between the wave height and the water depth on the cross-shore profile morphology, which develops the plateau as observed at the Marker Wadden, should studied in more detail. In addition, the relation between the wind-generated wave forces in a lake system – without tidal fluctuations, relatively shallow water depths and short waves- and the morphodynamic behaviour of sandy shores is also an interesting phenomenon to be studied. The lack of wave forcing mechanisms (compared to coastal systems) in a lake system seems to be crucial to better understand the morphodynamic behaviour of a sandy shores in a lake system such as Lake Marken.

- Regarding to the application of numerical models, the XBeach model results emphasize that the developed profile shape could not be sufficiently reproduced. In particular, the steep slope around the water line as well as the plateau formation. Further research would be valuable in order to understand the processes that are responsibly that forms the plateau and to understand its morphological function. Further research regarding numerical modelling should be focused on:

  - *Varying sediment characteristics in the cross-section;*
  - *Effect of orbital velocity near the plateau that brings sediment in suspension;*
  - *Undertow currents that are responsible for offshore sediment transport;*
  - *Apply 2D version of the model, in order to take the effect of the longshore sediment transports into account.*

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# APPENDICES

| | |
|---|---|
| **Appendix A:** | Design methods |
| **Appendix B:** | Wind and wave data |
| **Appendix C:** | Bathymetry per period |
| **Appendix D:** | Bathymetry differences per period |
| **Appendix E:** | Longshore sediment transport |

# Appendix A: Design methods

In this appendix the design methods are presented to describe the equilibrium profiles and the longshore transport. The following design methods are addressed:

- Equilibrium profiles;
- Longshore sediment transport formulae;
- Closure depth.

## A.1 Equilibrium profiles

### Hanson and Kraus (1989)

Hanson and Kraus (1989) have determined the A parameter based on the grain diameter of the sand. They made use of measurements which were carried out by Moore (1982). Based on these measurements, they determined the following ranges in grain size ($D_{50}$).

| | | | |
|---|---|---|---|
| $A = 0.41{D_{50}}^{0.94}$ | if | $D_{50} < 0.4$ | where 0.41 has the unit ($m^{0.33}/mm^{0.94}$) |
| $A = 0.23{D_{50}}^{0.32}$ | if | $0.4 < D_{50} < 10$ | where 0.23 has the unit ($m^{0.33}/mm^{0.32}$) |
| $A = 0.23{D_{50}}^{0.28}$ | if | $10 < D_{50} < 40$ | where 0.23 has the unit ($m^{0.33}/mm^{0.28}$) |
| $A = 0.46{D_{50}}^{0.11}$ | if | $40 < D_{50}$ | where 0.46 has the unit ($m^{0.33}/mm^{0.11}$) |

Because they made use of ranges in grain size distribution, there is a function overlap at the transition between the ranges. For example, a grain with a diameter of 10 mm gives an A-value of 0.48, while a grain with a diameter of 11 mm will give a lower value of 0.45. In reality the A value will increase with an increasing grain diameter. Because Hanson and Kraus only make use of the grain diameter, material properties are neglected if other material then sand is used.

### Dean et al. (1990)

Dean et al. (1990) has determined the A parameter based on the fall velocity. The parameter A is hereby calibrated according the measured sandy beach profiles of the east and west coast of the United States. The A parameter is expressed as presented in equation A-1.

$$A = 5.08{W_f}^{0.44} \qquad \text{[A-1]}$$

Where $W_f$ is the fall velocity [$ms^{-1}$] of the sediment and 5.08 is a constant.

### Kriebels, Kraus and Larson (1991)

According to Kriebel, Kraus, and Larson (1991) and Hughes (1993) the following formula is advised for sands where the grain diameter $D_{50}$ ranges from 0.1 mm to 0.4 mm. Like Dean, the A parameter is determined according to the fall velocity, as can be seen in equation A-2.

$$A = 2.25\left(\frac{{W_f}^2}{g}\right)^{1/3} \qquad \text{[A-2]}$$

Where $W_f$ is the fall velocity of the sediment [$ms^{-1}$] and $g$ is the acceleration of gravity [$ms^{-2}$].

### USACE (2002)

The United States Army Corps of Engineers (USACE, 2002) recommends the beach equilibrium concept based on equation **Error! Reference source not found.**], since this relation had been found mpirically by Bruun (1954) and has been confirmed by various empirical studies. They found empirically that the A parameter can be determined as follows:

$$A = 0.067W_f^{0.44} \qquad \text{[A-3]}$$

Where $W_f$ is the fall velocity of the sediment [cms$^{-1}$]. A summary of the recommended A-values for sand are provided below.

*Table A-1. Summary of recommended A-values [m$^{1/3}$] for diameters from 0.10 to 1.09 mm (USACE,2002). In the left column one finds the first digit of the grain size, in the upper row the second digit of the grain size.*

| $D_{50}$ (mm) | 0 | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.1 | 0.0630 | 0.0672 | 0.0714 | 0.0756 | 0.0798 | 0.0840 | 0.0872 | 0.0904 | 0.0936 | 0.0968 |
| 0.2 | 0.1000 | 0.1030 | 0.1060 | 0.1090 | 0.1120 | 0.1150 | 0.1170 | 0.1190 | 0.1210 | 0.1230 |
| 0.3 | 0.1250 | 0.1270 | 0.1290 | 0.1310 | 0.1330 | 0.1350 | 0.1370 | 0.1390 | 0.1410 | 0.1430 |
| 0.4 | 0.1450 | 0.1466 | 0.1482 | 0.1498 | 0.1514 | 0.1530 | 0.1546 | 0.1562 | 0.1578 | 0.1594 |
| 0.5 | 0.1610 | 0.1622 | 0.1634 | 0.1646 | 0.1658 | 0.1670 | 0.1682 | 0.1694 | 0.1706 | 0.1718 |
| 0.6 | 0.1730 | 0.1742 | 0.1754 | 0.1766 | 0.1778 | 0.1790 | 0.1802 | 0.1814 | 0.1826 | 0.1838 |
| 0.7 | 0.1850 | 0.1859 | 0.1868 | 0.1877 | 0.1886 | 0.1895 | 0.1904 | 0.1913 | 0.1922 | 0.1931 |
| 0.8 | 0.1940 | 0.1948 | 0.1956 | 0.1964 | 0.1972 | 0.1980 | 0.1988 | 0.1996 | 0.2004 | 0.2012 |
| 0.9 | 0.2020 | 0.2028 | 0.2036 | 0.2044 | 0.2052 | 0.2060 | 0.2068 | 0.2076 | 0.2084 | 0.2092 |
| 1 | 0.2100 | 0.2108 | 0.2116 | 0.2124 | 0.2132 | 0.2140 | 0.2148 | 0.2156 | 0.2164 | 0.2172 |

### Wright et al. (1986)

Another method to determine the equilibrium profile is developed by Wright et al. (1986) and is characterized as presented in equation A-4.

$$h(x) = h_0(1 - e^{-Kx}) \qquad \text{[A-4]}$$

Where $h$ is the water depth (m), $h_0$ is the water depth where the bed is horizontal (m), $K$ is a constant ($10^{-4}$…$10^{-6}$) and $x$ is the offshore distance (m). In this formula the bottom depth is needed. Because the bottom is included as input parameter, the depth at which the equilibrium profile ends can be indicated. Therefore, this formula is less limited than the formula of Dean. The vertical asymptote, which occurs in the model of Dean, is not a problem is this model. The grain characteristics cannot be implemented as variables; this is presumably incorporated in the K-value. It is recommended to use a K-value between $10^{-4}$ and $10^{-6}$. The K-value should be determined in more detail by calibration of the model to existing profiles. The formula of Wright is tested with the same measurements which Dean has for testing his equilibrium profile. Wright concludes that his equilibrium profile gives better results than the equilibrium profile of Dean.

### Equilibrium profile according to Vellinga

Vellinga (1982) conducted extensive laboratory experiments to investigate the dune erosion processes due to extreme storm conditions. Vellinga proposed a relationship between cross-shore distance and profile depth for erosive beach profiles. The dune erosion prediction model is based on the observation that a typical erosion profile develops during storm surges. This profile can be represented as a function of the storm surge level, wave height and the settling velocity of the beach sand. The equation of the equilibrium profile is provided in equation A-5.

$$\left\{\frac{7.6}{H_{0S}}\right\} y = 0.47\left[\left(\frac{7.6}{H_{0S}}\right)^{1.28}\left(\frac{w_f}{0.0268}\right)^{0.56} x + 18\right] - 2 \qquad \text{[A-5]}$$

In which $y$ is the depth [m] below still water level, $x$ is the distance [m] from the water line, $w_f$ [m/s] is the fall velocity for the median grain size $D_{50}$ [m/s] and $H_{0s}$ the wave height at deep water. This erosion profile has been verified with field measurements at coastal areas. It should be noted that the dune erosion prediction model is only applicable in situations where a two-dimensional (cross-shore) idealization of the dune erosion process is possible, i.e. where no large longshore transport gradient exists. Furthermore, the dune erosion prediction model was primarily derived for relatively high storm surges combined with wave action.

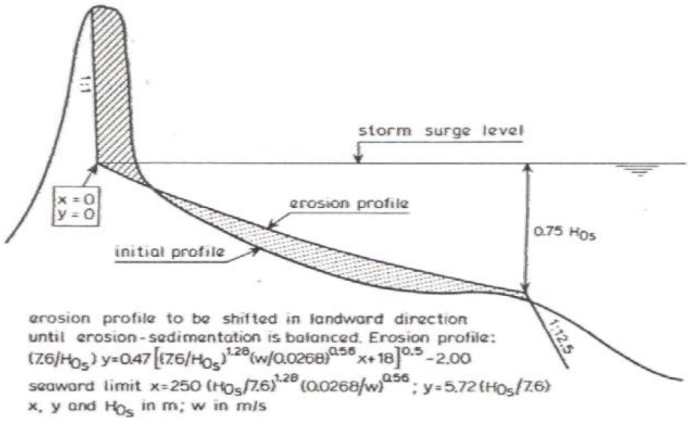



*Figure A-1. Principle of the dune erosion prediction model (Vellinga, 1982).*

## A.2 Longshore sediment transport formulae

### CERC-formula (1984)

The prediction of reliable estimates of longshore sediment transport is of considerable practical importance in coastal engineering. The most widely used formula for longshore transport is the CERC formula (USACE, 1984) and is developed by the US-Corps of Engineers (USACE). The basic assumption behind the CERC formula is that the flux integrated over the surf zone is proportional to the energy dissipation within the surf zone. The CERC-formula gives the longshore sediment transport due to the action of waves approaching the shore at an angle, and reads:

$$Q_s = \frac{I_l}{(\rho_s - \rho)g(1 - n_1)} \qquad \text{[A-6]}$$

Where:

| | | |
|---|---|---|
| $Q_s$ | longshore transport rate | $m^3s^{-1}$ |
| $I_l$ | longshore transport rate (immersed weight) | |
| $\rho$ | density of water | $kgm^{-3}$ |
| $\rho_s$ | density of sediment | $kgm^{-3}$ |
| g | acceleration of gravity | $ms^{-2}$ |
| $n_1$ | sediment porosity ≈ 0.4 | [ - ] |

This method is based on the principle that the longshore transport rate (including bed load and suspended load) is proportional to longshore wave power (P) per unit length of beach; which makes that LT is equal to KP, where K is the calibration coefficient.

$$I_l = KP_l \qquad \text{[A-7]}$$

$$P_l = (E_b c_b \cos\alpha \sin\alpha)_b \qquad \text{[A-8]}$$

Where:

| | | |
|---|---|---|
| K | constant coefficient (0.044 – 0.7) | [ - ] |
| $P_l$ | potential longshore wave energy | $Ns^{-1}$ |
| $E_{br}$ | wave energy on the breaker line | $Jm^{-2}$ |
| $c_{br}$ | wave celerity at shallow water $\left(=\sqrt{gh_{br}}\right)$ | $ms^{-1}$ |
| $\alpha_{br}$ | incident wave direction at the breaker line | ° N |

This leads to the expression as given in equation A-9.

$$Q_s = \frac{K(E_b c_b \cos\alpha \sin\alpha)_b}{(\rho_s - \rho)g(1-n_1)} \quad \text{[A-9]}$$

The CERC formula has been calibrated using field data from sand beaches. However, this CERC formula does not account for particle size and beach slope. It is only valid for sandy conditions (USACE, 2002). Moreover, tidal currents or other alongshore currents are not considered in the CERC formula.

### Kamphuis-formula (1991)

The effects of particle diameter and bed slope have been studied systematically by Kamphuis (Kamphuis, 1991), resulting in a more refined equation for longshore sediment transport. The Kamphuis formula is valid for sand beaches, but is most likely not valid for gravel and shingle beaches. The Kamphuis formula was found to give the best agreement between computed and measured transport rates based on the work of Schoonees and Theron (Schoonees & Theron, 1993, 1996). The Kamphuis formula is presented in equation A-10.

$$Q_{t,mass} = 2.23\frac{\rho_s}{(\rho_s-\rho)}T_p^{1.5}(\tan\beta)^{0.75}(d_{50})^{-0.25}\left(H_{s,br}\right)^2[\sin(2\theta_{br})]^{0.6} \quad \text{[A-10]}$$

Where:

| | | |
|---|---|---|
| $Q_t$ | total longshore sediment transport | $kgs^{-1}$ |
| $\rho_s$ | sediment density | $kgm^{-3}$ |
| $\rho_s$ | fluid density | $kgm^{-3}$ |
| $T_p$ | peak wave period | s |
| $\tan\beta$ | beach slope | [ - ] |
| $d_{50}$ | median grain size | m |
| $H_{s,br}$ | significant wave height at the breakerline | m |
| $\theta_{br}$ | wave angle at breakline | ° N |

Recently Mil-Homens et al. (2013) have made a re-evaluation of the Kamphuis formula based on an extensive set of 250 data points. Most of the data points are in the sand range (<0.6 mm) and low transport range (mild wave conditions). The modified Kamphuis 2013 formula is presented in equation A-11.

$$Q_{t,mass} = 0.15\frac{\rho_s}{(\rho_s-\rho)}T_p^{0.89}(\tan\beta)^{0.86}(d_{50})^{-0.69}\left(H_{s,br}\right)^{2.75}[\sin(2\theta_{br})]^{0.5} \quad \text{[A-11]}$$

### Van Rijn (2014)

The longshore sediment transport formula of van Rijn (van Rijn, 2014) is a function of the particle size, the steepness of the beach, the wave height and the breaker angle at the breaker line. This method computes the longshore transport and gradients and, based on that, the coastline changes over the height of the active zone defined between +3.0 m and -7.0 m NAP , so a layer of 10 m. The longshore transport is described by the following equation A-12.

$$Q_t = 0.00018\rho_s g^{0.5}(\tan\beta)^{0.4}(D_{50})^{-0.6}(H_{s,br})^{3.1}\sin(2\theta_{br}) \qquad [A\text{-}12]$$

Where:

| | | |
|---|---|---|
| $Q_t$ | total longshore sediment transport | $kgs^{-1}$ |
| $\rho_s$ | sediment density | $kgm^{-3}$ |
| $D_{50}$ | median grain size | m |
| $H_{s,br}$ | significant wave height at the breakerline | m |
| $\theta_{br}$ | wave angle at breakerline | ° N |
| g | acceleration of gravity | $ms^{-2}$ |
| $\tan\beta$ | beach slope | [ - ] |

This formula has recently been improved and calibrated with a large number of field data, including conditions with relatively low waves. The formula is valid for sand and gravel. The net annual longshore transport at a particular location can be computed by summation of all contributions of wave heights and wave directions based on the deep water wave climate. The equilibrium position (equilibrium angle) of the beach is the angle at which the net longshore transport is approximately equal to zero.

## A.3 Closure depth

The closure depth ($h_c$) for a given or characteristic time interval is the most landward depth seaward of which there is no significant change in bottom elevation and no significant net sediment transport between the nearshore and the offshore (Kraus & Larson, 1998). Based on field data and correlations with the Shields parameter, Hallermeier (1981) defined the closure depth as defined in equation A-13.

$$h_c = 2.28H_e - 68.5\left(\frac{H_e^2}{gT_e^2}\right) \qquad \text{where } H_e = \bar{H} + 5.6\,\sigma_H \qquad [A\text{-}13]$$

Where:

| | | |
|---|---|---|
| $h_c$ | closure depth | m |
| $H_e$ | effective significant wave height, exceeded only 12hrs per year | m |
| $T_e$ | effective wave period, exceeded only 12hrs per year | s |
| $\bar{H}$ | annual mean significant wave height | m |
| $\sigma_H$ | standard deviation of significant wave height | m |

Which was approximated later by Birkemeier (1985) as $h_c = 1.57H_e$. Nicholls et al. (1996) provided a generalized closure depth for time frames other than one year, resulting in:

$$h_c(t) = 2.28H(t)e - 68.5\left[\frac{H(t)_e^2}{gT(t)_e^2}\right] \qquad [A\text{-}14]$$

Where:

| | | |
|---|---|---|
| t | considered period | years |
| $H_e(t)$ | effective significant wave height, exceeded only 12hr | m |

In the following applications, $h_c$ is assumed to represent the closure depth for profile changes over long (seasonal to years) time scales. For short-term profile changes, e.g. during storms, the breaking depth $h_b$ is a better delineation of the active profile (USACE, 2002). The closure depth ($h_c$) can be determined based on a visual estimation of the closure depth out of measured bottom profiles (field data), relations derived by Hallermeier and Birkemeier or numerical modelling (like XBeach).

# APPENDIX B: WIND AND WAVE DATA

In this appendix the wind and wave conditions per time interval are presented. Since the time intervals between the surveys are not the same for the southwest beach and the northwest beach this is given separately.

## B.1 Southwest beach

In the table below an overview is given of the survey intervals which corresponds to the monitoring of the Southwest Beach.

*Table B-1. Overview of the survey intervals for the Southwest Beach.*

| Period | Interval | Days | Comments |
|---|---|---|---|
| T1 – T2 | 11-29-16 to 01-18-17 | 50 | First period after construction |
| T2 – T3 | 01-18-17 to 02-06-17 | 19 | |
| T3 – T4 | 02-06-17 to 03-03-17 | 25 | Spring storm took place from the southwest |
| T4 – T5 | 03-03-17 to 04-04-17 | 32 | |
| T5 – T6 | 04-04-17 to 04-05-17 | 31 | |

In the sections below the wind climate and wave climate are extensively explained per interval. Also the most important events are given.

## Interval T1 – T2

During this whole period the measured meteorological data at the Houtribdijk was available. The time interval contains the period between 11-29-2016 and 01-18-2017. The wind climate and wave climate are shown in Figure B-1.

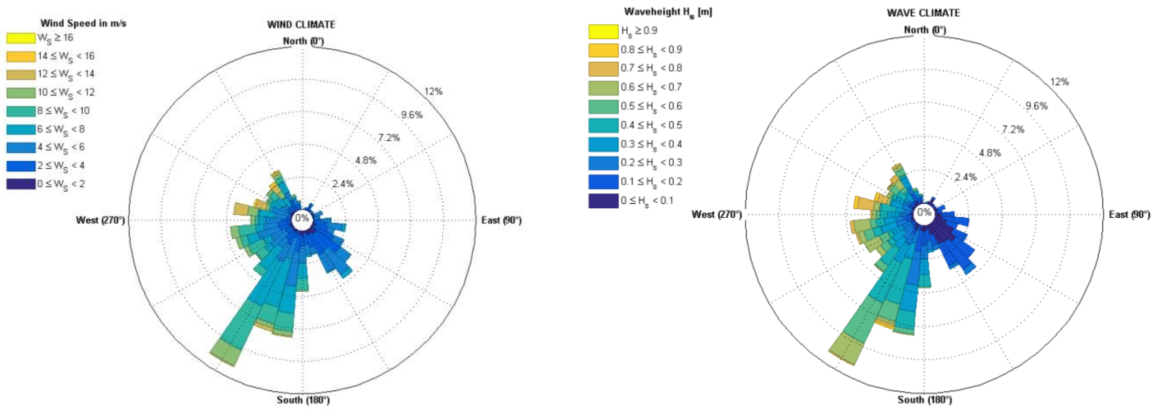
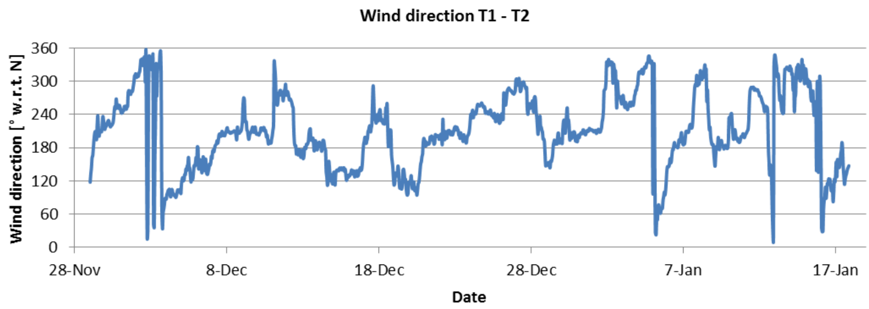



*Figure B-1. Wind climate (left) and wave climate (right) between T1 and T2 for the Southwest beach.*

### Wind climate

The wind direction was mainly from south-southwest (SSW). The average wind direction was 211 degrees with an average wind speed of 5.99 m/s. The maximum measured wind speed was 15.07 m/s and with a wind direction of 320 degrees. The wind direction over time is presented below.




### Wave climate

The maximum wave height ($H_s$) was 0.87 m with a wave period ($T_p$) of 3.3 s and was measured at the 13$^{th}$ of January. The wave direction was from 320 degrees, so from northwest (NW).

### Important events

The most important events which took place during the period are presented in the table below.

*Table B-2. Important events during the period T1-T2.*

| Date | Wind direction w.r.t °N | Wind speed [m/s] | Wave height $H_s$ [m] | Wave period $T_p$ [s] |
|---|---|---|---|---|
| 11-01-2017 | 290 | 14.3 | 0.83 | 3.5 |
| 13-01-2017 | 320 | 15.1 | 0.87 | 3.3 |

## Interval T2 – T3

During this whole period the measured meteorological data at the Houtribdijk was available. The time interval contains the period between 01-18-2017 and 02-06-2017. The wind climate and wave climate are shown in Figure B-2.

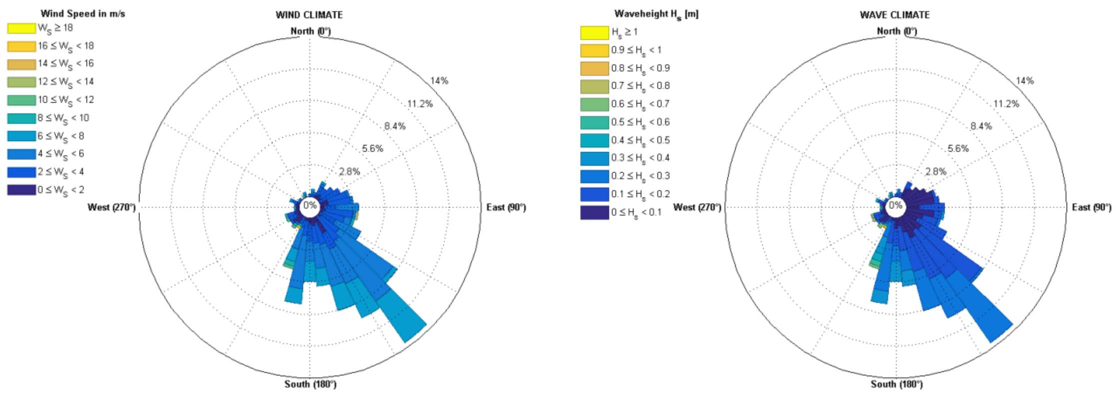
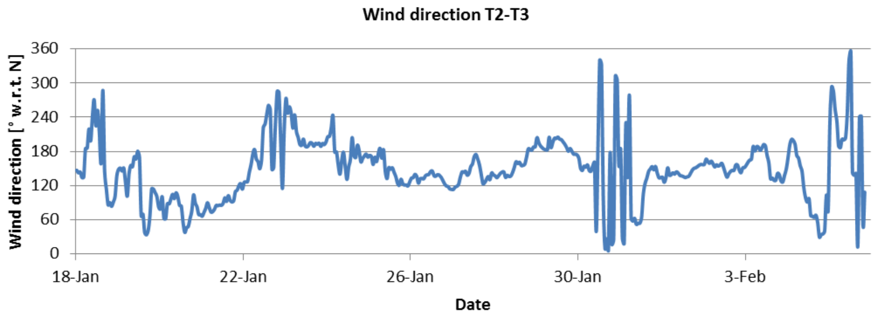



*Figure B.2 Wind climate (left) and wave climate (right) between T2 and T3 for the Southwest beach.*

### Wind climate

The wind direction during this period was mainly from South-East (SE). The average wind direction was 148 degrees with an average wind speed of 4.4 m/s. The maximum measured wind speed was 16.72 m/s. The wind direction over time is presented below.




### Wave climate

The maximum wave height ($H_s$) was 0.94 m with a wave period (T) of 3.8 s and was measured at the 18th of January. The wave direction was from 212 degrees, so from south-southwest (SSW).

### Important events

The most important events which took place during the period are presented in the table below.

*Table B-3.. Important events during the period T2-T3.*

| Date | Wind direction w.r.t °N | Wind speed [m/s] | Wave height $H_s$ [m] | Wave period $T_p$ [s] |
|---|---|---|---|---|
| 18-01-2017 | 212 | 16.72 | 0.94 | 3.8 |
| 29-01-2017 | 332 | 10.21 | 0.55 | 2.8 |

## Interval T3 – T4

During this whole period the measured meteorological data at the Houtribdijk was available. The time interval contains the period between 02-06-2017 and 03-03-2017. The wind climate and wave climate are shown in Figure B-3.

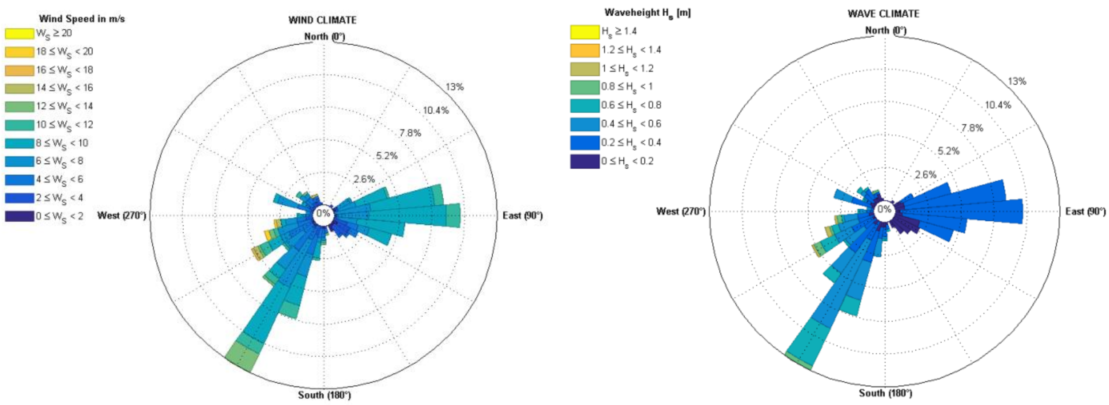
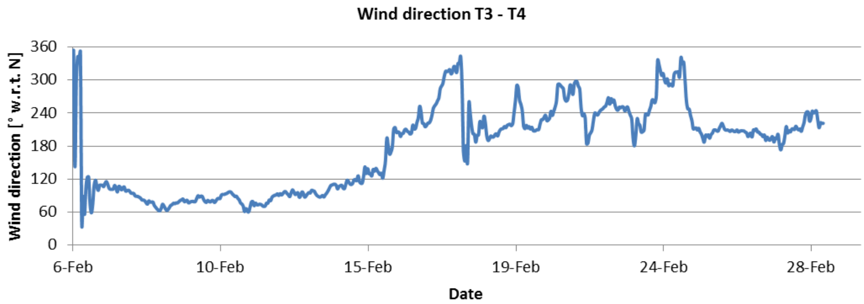



*Figure B-3. Wind climate (left) and wave climate (right) between T3 and T4 for the Southwest beach.*

### Wind climate

The wind direction was mainly from south-southwest (SSW) and from east (E). The average wind direction was 177 degrees with an average wind speed of 7.36 m/s. The maximum measured wind speed was 19.27 m/s and with a wind direction of 253 degrees (SWW). In the first period the wind came mainly from the East thereafter the wind turns to the South-southwest (after 02-15-17). The wind direction over time is presented below.




### Wave climate

The maximum wave height ($H_s$) was 1.09 m with a wave period ($T_p$) of 4.2 s and was measured at the 23$^{th}$ of February. The wave direction was from 253 degrees, so from Southwest-West (SWW).

### Important events

The most important events which took place during the period are presented in the table below. The first spring storm of the season took place at the 23$^{rd}$ of February.

*Table B-4. Important events during the period T3-T4.*

| Date | Wind direction w.r.t °N | Wind speed [m/s] | Wave height $H_s$ [m] | Wave period $T_p$ [s] |
|---|---|---|---|---|
| 23-02-2017 | 253 | 19.27 | 1.09 | 4.2 |
| 28-02-2017 | 210 | 13.28 | 0.79 | 3.4 |
| 02-03-2017 | 260 | 16.04 | 0.95 | 3.8 |

## Interval T4– T5

During this whole period the measured meteorological data at the Houtribdijk was available. The time interval contains the period between 03-03-2017 and 04-04-2017. The wind climate and wave climate are shown in Figure B-4.

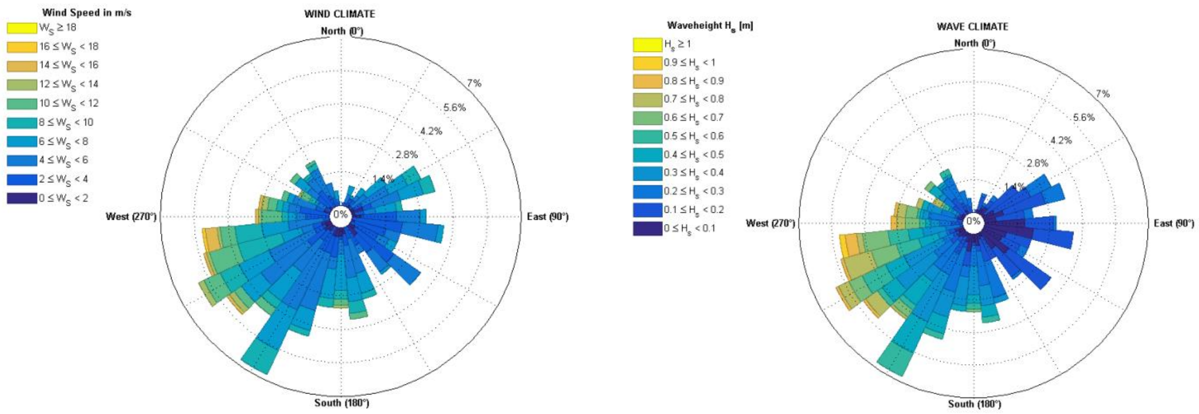



*Figure B-4. Wind climate (left) and wave climate (right) between T4 and T5 for the Southwest beach.*

### Wind climate

The average wind direction was 189 degrees with an average wind speed of 5.60 m/s. The maximum measured wind speed was 14.95 m/s and with a wind direction of 233 degrees (SW).

### Wave climate

The maximum wave height ($H_s$) was 0.90 meter with a wave period ($T_p$) of 3.7 seconds and was measured at the 18$^{th}$ of March. The wave direction was from 256 degrees, so from southwest.

### Important events

The most important events which took place during the period are presented in the table below.

*Table B-5. Important events during the period T4-T5.*

| Date | Wind direction w.r.t °N | Wind speed [m/s] | Wave height $H_s$ [m] | Wave period $T_p$ [s] |
|---|---|---|---|---|
| 09-03-2017 | 297 | 12.31 | 0.74 | 3.3 |
| 18-03-2017 | 256 | 14.95 | 0.90 | 3.7 |
| 20-03-2017 | 233 | 14.40 | 0.89 | 3.7 |
| 21-03-2017 | 268 | 11.78 | 0.75 | 3.4 |

## Interval T5 – T6

During this whole period the measured meteorological data at the Houtribdijk was available. The time interval contains the period between 04-04-2017 and 05-05-2017. The wind climate and wave climate are shown in Figure B-5.

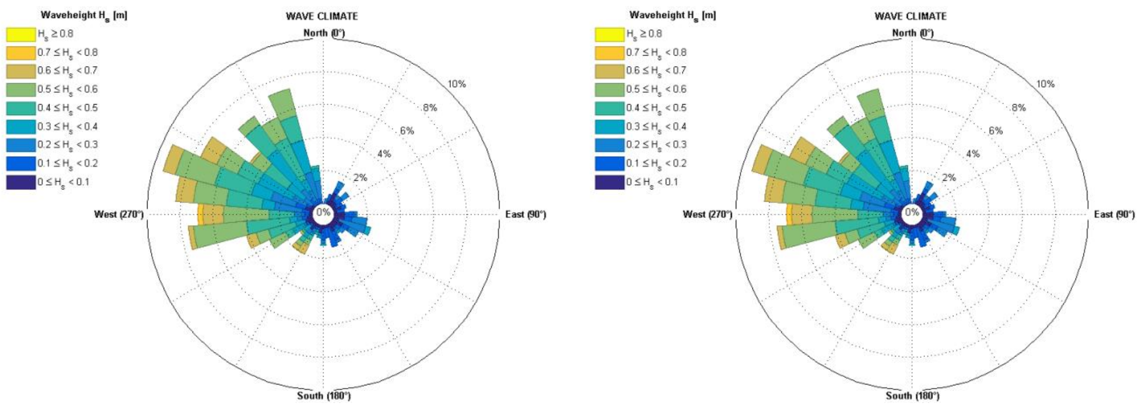



*Figure B-5. Wind climate (left) and wave climate (right) between T5 and T6 for the southwest beach.*

### Wind climate

The average wind direction was 230 degrees with an average wind speed 6.41 m/s. The maximum measured wind speed was 11.82 m/s and with a wind direction of 265 degrees (SW).

### Wave climate

The maximum wave height ($H_s$) was 0.75 meter with a wave period ($T_p$) of 3.4 seconds and was measured at the 12$^{th}$ of April. The wave direction was from 265 degrees, so from southwest.

### Important events

The most important events which took place during the period are presented in the table below.

*Table B-6. Important events during the period T5-T6.*

| Date | Wind direction w.r.t °N | Wind speed [m/s] | Wave height $H_s$ [m] | Wave period $T_p$ [s] |
|---|---|---|---|---|
| 12-04-2017 | 265 | 11.82 | 0.75 | 3.4 |
| 15-04-2017 | 300 | 11.25 | 0.68 | 3.2 |
| 24-04-2017 | 210 | 11.43 | 0.69 | 3.2 |

## B.2 Northwest beach

In the table below an overview is given of the survey intervals which corresponds to the monitoring of the Northwest Beach.

*Table B-7.Overview of the survey intervals for the Northwest Beach.*

| Period | Interval | Days | Comments |
|---|---|---|---|
| T1 – T2 | 29-11-16 to 18-01-17 | 50 | First period after construction |
| T2 – T3 | 18-01-17 to 14-02-17 | 27 | |
| T3 – T4 | 14-02-17 to 14-03-17 | 28 | Spring storm took place |
| T4 – T5 | 14-03-17 to 13-04-17 | 30 | |
| T5 – T6 | 13-04-17 to 09-05-17 | 26 | |

## Interval T1 – T2

During this whole period the measured meteorological data at the Houtribdijk was available. The time interval contains the period between 29-11-2016 and 18-01-2017. The wind climate and wave climate are shown in Figure B-6.

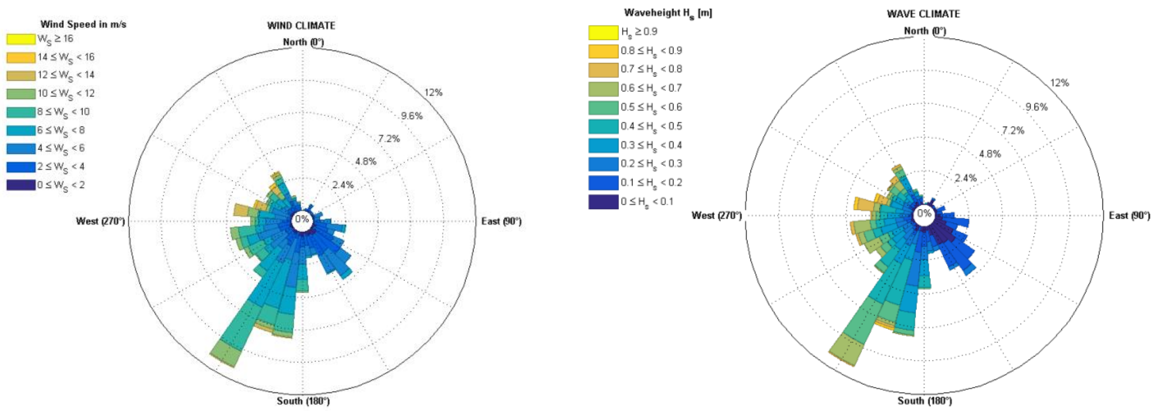
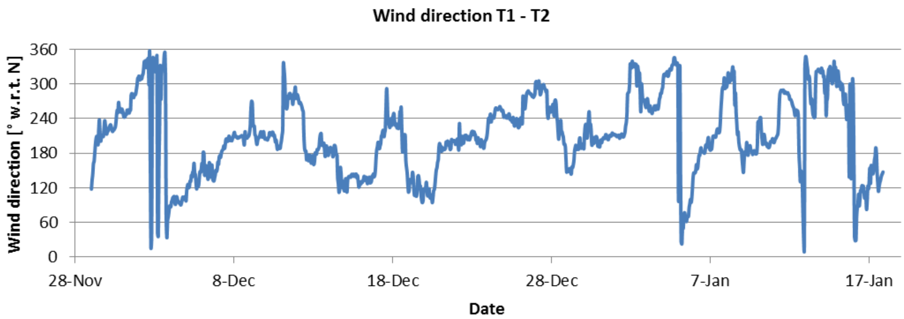



*Figure B-6. Wind climate (left) and wave climate (right) between T1 and T2 for the northwest beach.*

### Wind climate

The wind direction was mainly from south-southwest (SSW). The average wind direction was 211 degrees with an average wind speed of 5.99 m/s. The maximum measured wind speed was 15.07 m/s and with a wind direction of 322 degrees. The wind direction over time is presented below.




### Wave climate

The maximum wave height ($H_s$) was 0.87 m with a wave period ($T_p$) of 3.3 s and was measured at the 13$^{th}$ of January. The wave direction was from 320 degrees, so from northwest (NW).

## Important events

The most important events which took place during the period are presented in the table below.

*Table B-8. Important events during the period T1-T2.*

| Date | Wind direction w.r.t °N | Wind speed [m/s] | Wave height $H_s$ [m] | Wave period $T_p$ [s] |
|---|---|---|---|---|
| 11-01-2017 | 290 | 14.3 | 0.83 | 3.5 |
| 13-01-2017 | 320 | 15.1 | 0.87 | 3.3 |

# Interval T2 – T3

During this whole period the measured meteorological data at the Houtribdijk was available. The time interval contains the period between 18-01-2017 – 14-02-2017. The wind climate and wave climate are shown in Figure B-7.

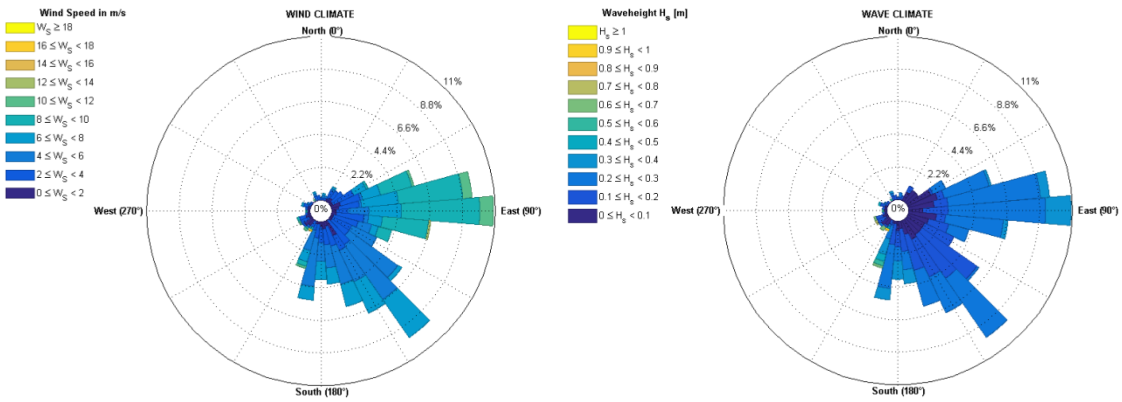
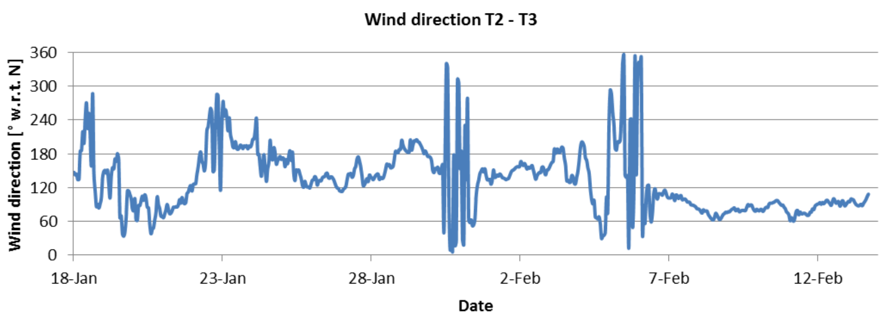



*Figure B-7. Wind climate (left) and wave climate (right) between T2 and T3 for the northwest beach.*

## Wind climate

The wind direction was mainly from the east and southeast. The average wind direction was 132 degrees with an average wind speed of 5.40 m/s. The maximum measured wind speed was 16.07 m/s and with a wind direction of 212 degrees. The wind direction over time is presented below.




## Wave climate

The maximum wave height ($H_s$) was 0.94 m with a wave period ($T_p$) of 3.8 s and was measured at the 18[th] of January. The wave direction was from 212 degrees, so from south-southwest (SSW).

## Important events

The most important events which took place during the first period, between 18-01-2017 and 14-02-2017, are presented in Table .

*Table B-9. Important events during the period T2-T3.*

| Date | Wind direction w.r.t °N | Wind speed [m/s] | Wave height $H_s$ [m] | Wave period $T_p$ [s] |
|---|---|---|---|---|
| 18-01-2017 | 212 | 16.72 | 0.94 | 3.8 |
| 12-02-2017 | 76 | 10.64 | 0.33 | 2.1 |

## Interval T3 – T4

During this whole period the measured meteorological data at the Houtribdijk was available. The time interval contains the period between 14-02-2017 – 14-03-2017. The wind climate and wave climate are shown in Figure B-8.

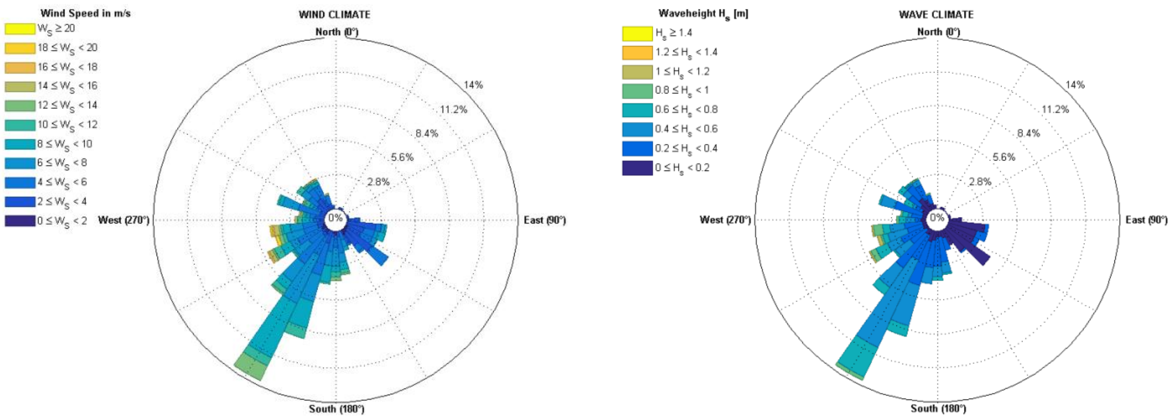
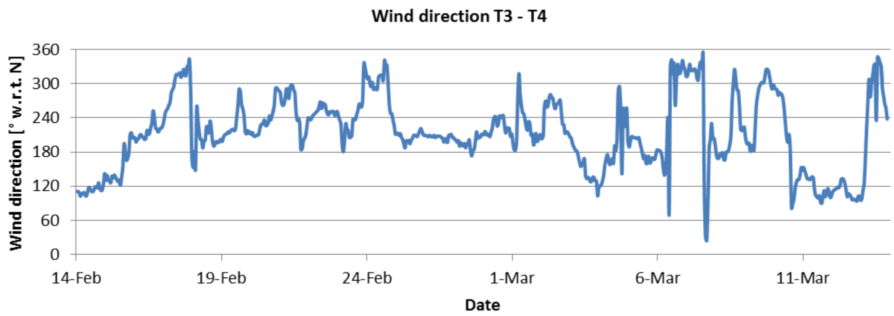



*Figure B-8. Wind climate (left) and wave climate (right) between T3 and T4 for the northwest beach.*

### Wind climate

The wind direction was mainly from the southwest (SW). The average wind direction was 213 degrees with an average wind speed of 6.34 m/s. The maximum measured wind speed was 19.27 m/s and with a wind direction of 252 degrees. The wind direction over time is presented below.




### Wave climate

The maximum wave height ($H_s$) was 1.09 m with a wave period ($T_p$) of 4.2 s and was measured at the 23$^{rd}$ of February. The wave direction was from 252 degrees, so from west-southwest (WSW).

### Important events

The most important events which took place during the period are presented in the table below.

*Table B-10. Important events during the period T3-T4.*

| Date | Wind direction w.r.t °N | Wind speed [m/s] | Wave height $H_s$ [m] | Wave period $T_p$ [s] |
|---|---|---|---|---|
| 22-02-2017 | 244 | 12.78 | 0.81 | 3.5 |
| 23-02-2017 | 252 | 19.27 | 1.09 | 4.2 |
| 03-02-2017 | 260 | 16.04 | 0.95 | 3.8 |

## Interval T4 – T5

During this whole period the measured meteorological data at the Houtribdijk was available. The time interval contains the period between 14-03-2017 – 15-04-2017. The wind climate and wave climate are shown in Figure B-9

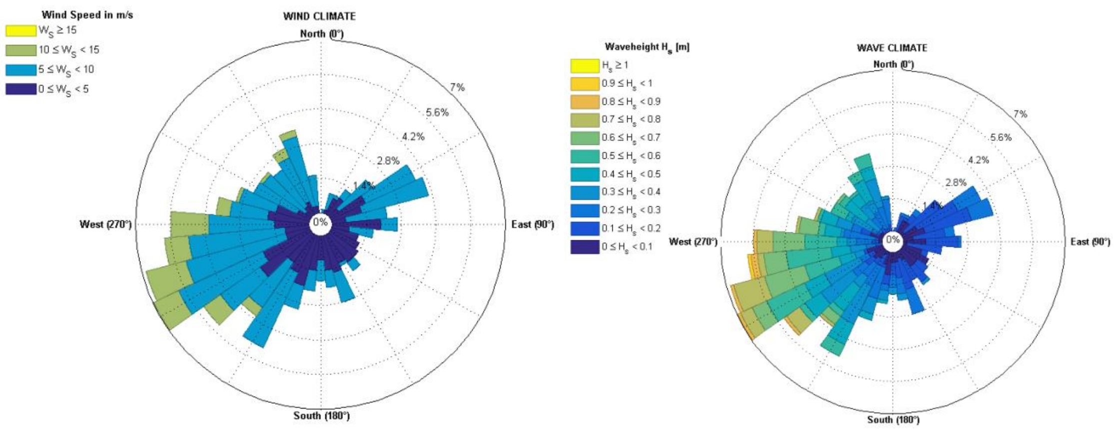
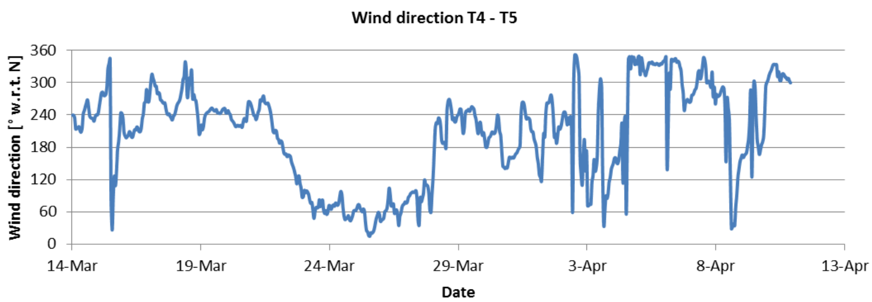



*Figure B-9. Wind climate (left) and wave climate (right) between T4 and T5 for the northwest beach.*

### Wind climate

The wind direction was mainly from the west-southwest. The average wind direction was 204 degrees with an average wind speed of 5.73 m/s. The maximum measured wind speed was 15.95 m/s and with a wind direction of 255 degrees. The wind direction over time is presented below.




### Wave climate

The maximum wave height ($H_s$) was 0.90 m with a wave period ($T_p$) of 3.7 s and was measured at the 18th of March. The wave direction was from 255 degrees, so from west-southwest (WSW).

### Important events

The most important events which took place during the period are presented in the table below.

*Table 0-1. Important events during the period T4-T5.*

| Date | Wind direction w.r.t °N | Wind speed [m/s] | Wave height $H_s$ [m] | Wave period $T_p$ [s] |
|---|---|---|---|---|
| 03-18-2017 | 255 | 14.95 | 0.90 | 3.7 |
| 03-20-2017 | 233 | 14.41 | 0.89 | 3.7 |

## Interval T5 – T6

During this whole period the measured meteorological data at the Houtribdijk was available. The time interval contains the period between 15-04-2017 to 09-05-2017. The wind climate and wave climate are shown in Figure B-11.

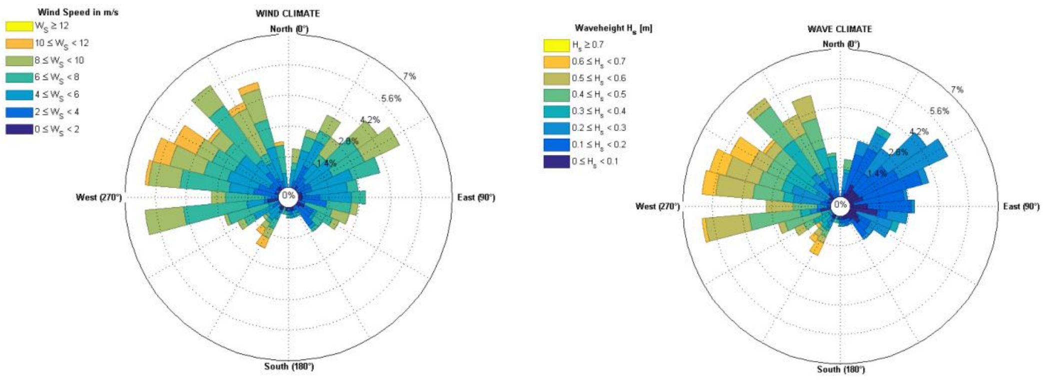
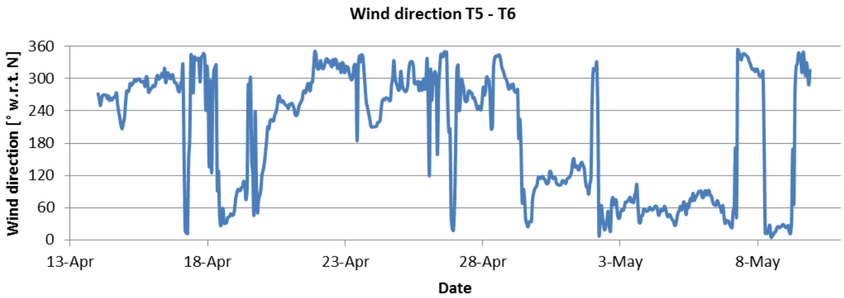



*Figure B-11. Wind climate (left) and wave climate (right) between T5 and T6 for the northwest beach.*

### Wind climate

The wind direction was mainly from the west-southwest. The average wind direction was 198 degrees with an average wind speed of 6.30 m/s. The maximum measured wind speed was 11.44 m/s and with a wind direction of 212 degrees. The wind direction over time is presented below.




### Wave climate

The maximum wave height ($H_s$) was 0.69 m with a wave period ($T_p$) of 3.2 s and was measured at the 24th of April. The wave direction was from 212 degrees, so from southwest (SW).

### Important events

The most important events which took place during the period are presented in the table below.

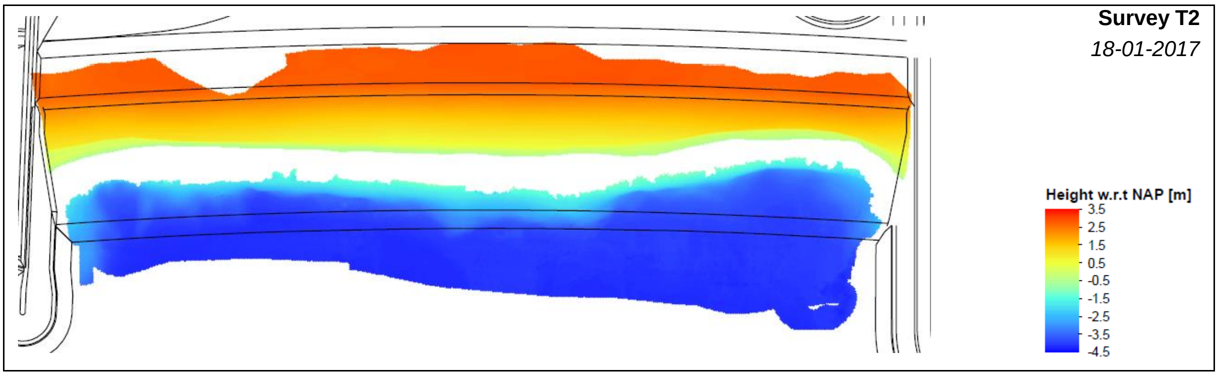
*Table B-12. Important events during the period T5-T6.*

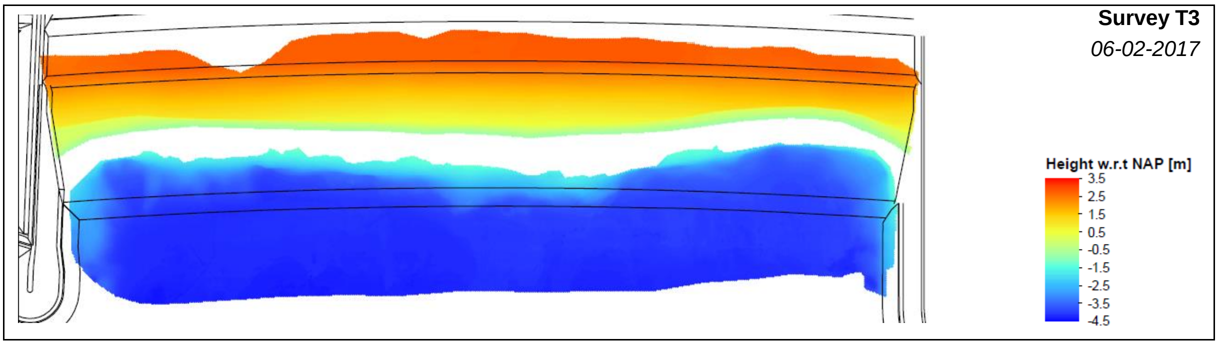
| Date | Wind direction w.r.t °N | Wind speed [m/s] | Wave height $H_s$ [m] | Wave period $T_p$ [s] |
|---|---|---|---|---|
| 04-17-2017 | 300 | 11.24 | 0.68 | 3.2 |
| 04-24-2017 | 212 | 11.44 | 0.69 | 3.2 |

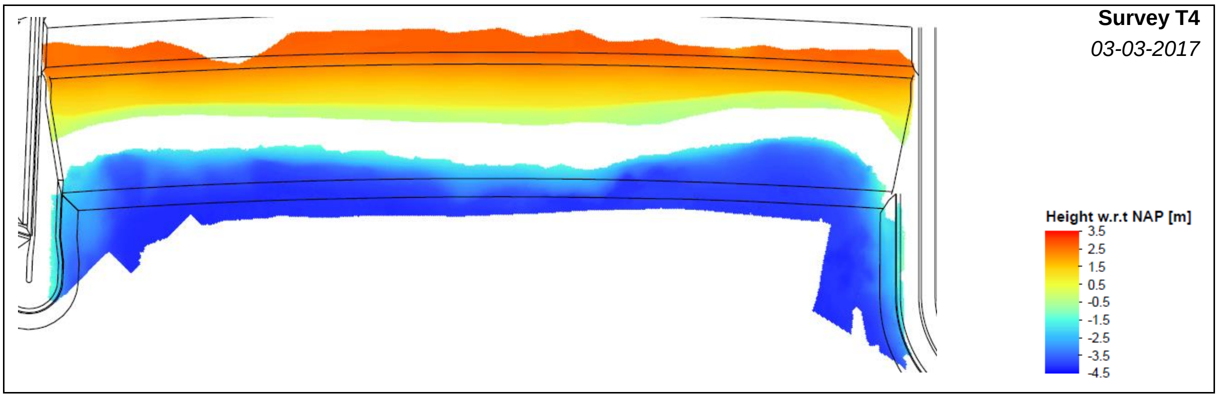
# APPENDIX C: BATHYMETRY PER PERIOD

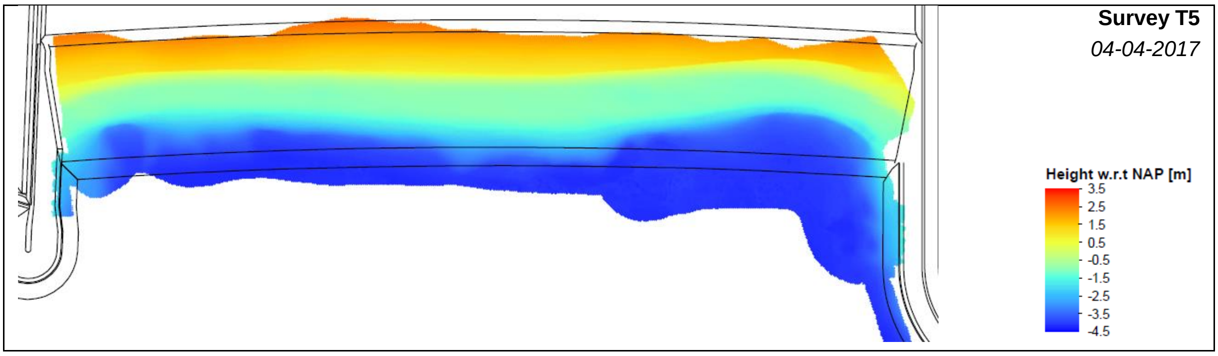
In this appendix, the bathymetry surface plots are presented for the southwest beach and northwest beach.

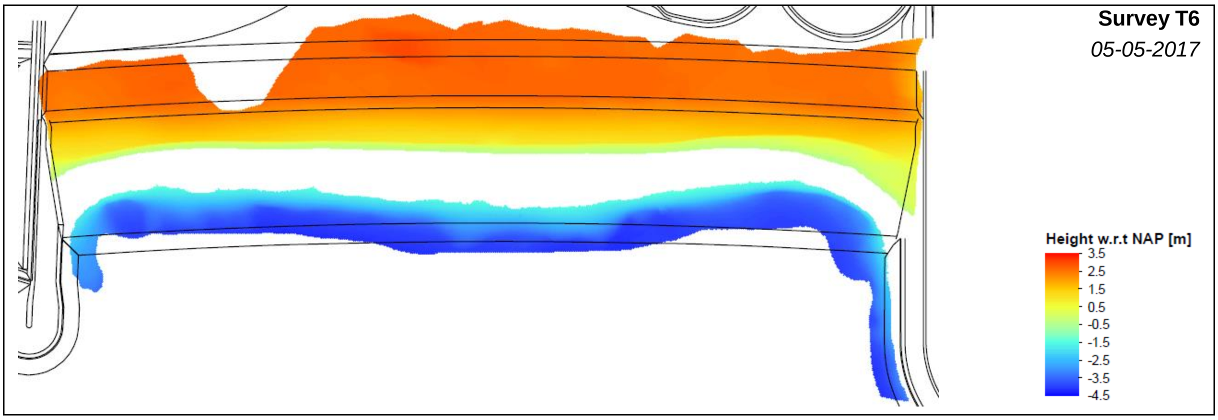
## C.1 Southwest beach



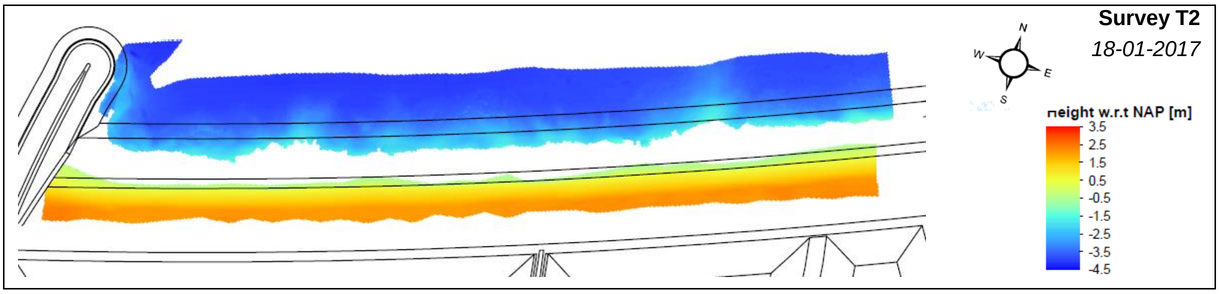



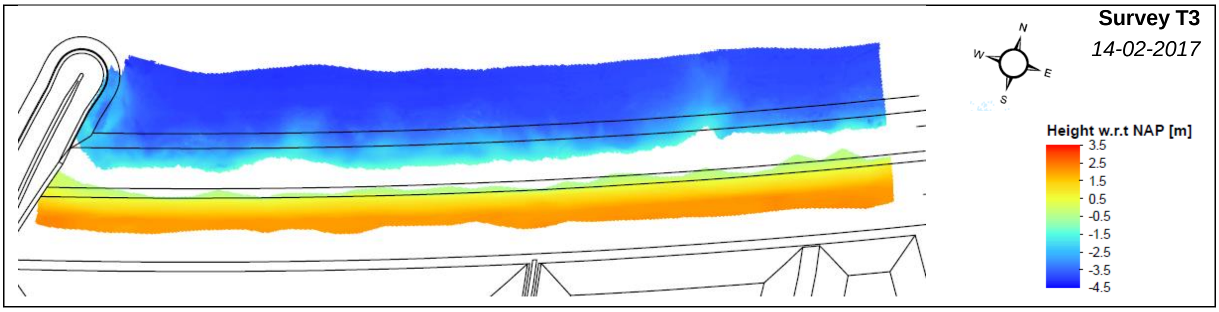



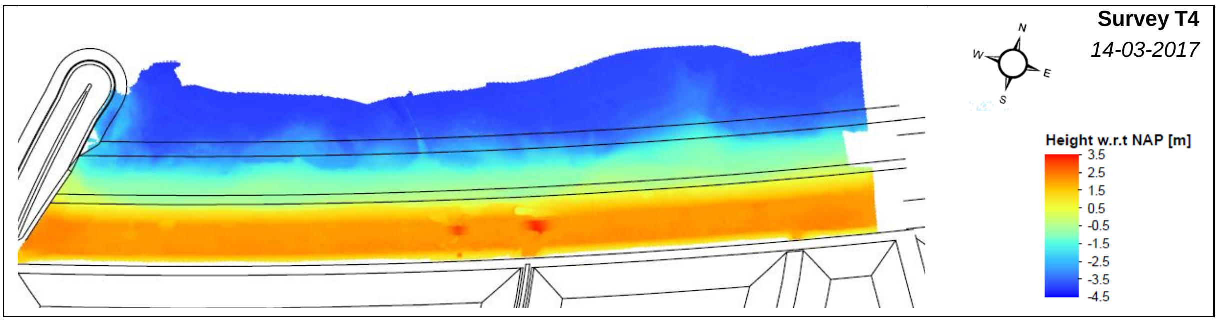



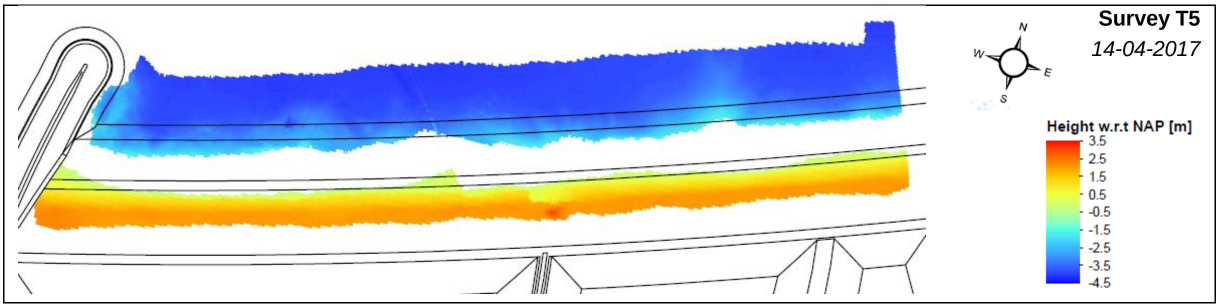


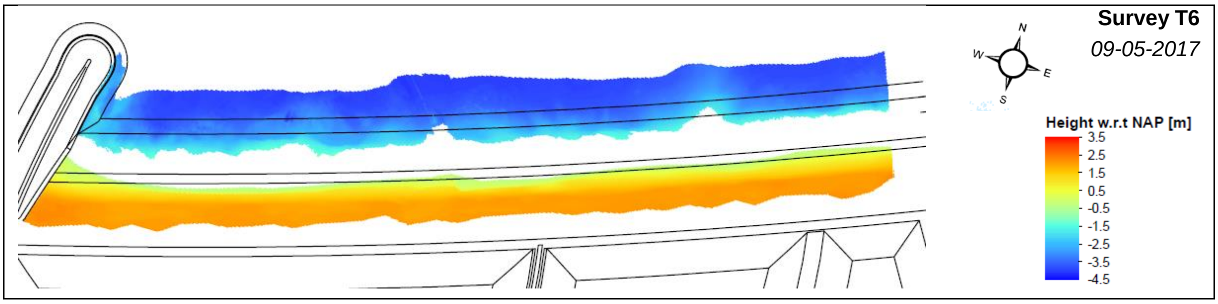

## C.2 Northwest beach




Survey T6
09-05-2017
N
W
E
S
Height w.r.t NAP [m]
3.5
2.5
1.5
0.5
-0.5
-1.5
-2.5
-3.5
-4.5

# APPENDIX D: BATHYMETRY DIFFERENCES PER PERIOD

In this appendix the difference in bathymetry between two measurement campaigns are presented for the time intervals T4-T5 and T5-T6. The difference in bathymetry is determined by subtracting the measured bathymetry for consecutive monitoring periods.

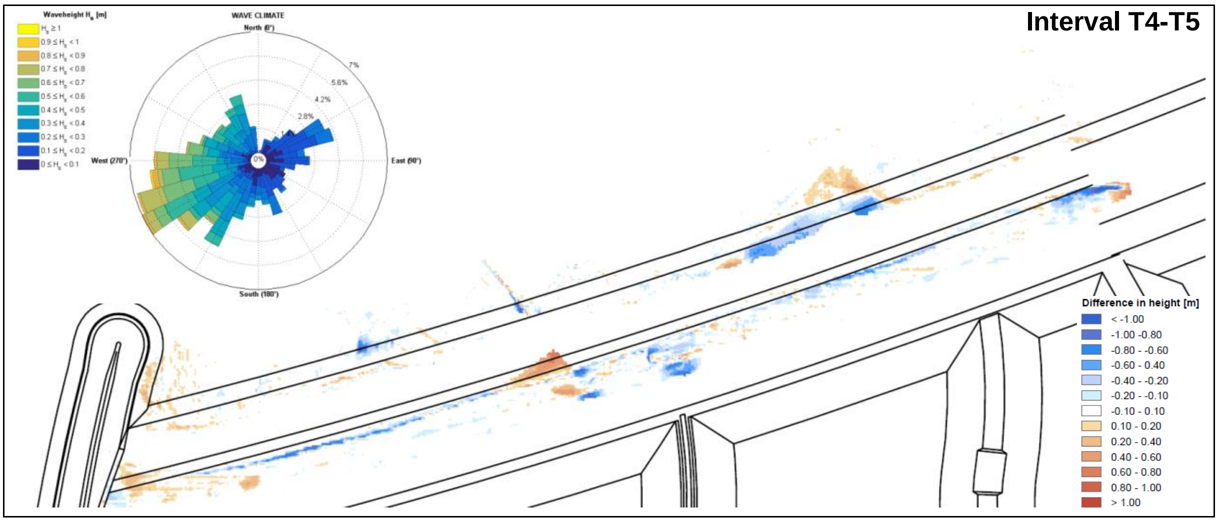



*Figure D-1. Morphological developments of the northwest beach for the time interval T4-T5.*

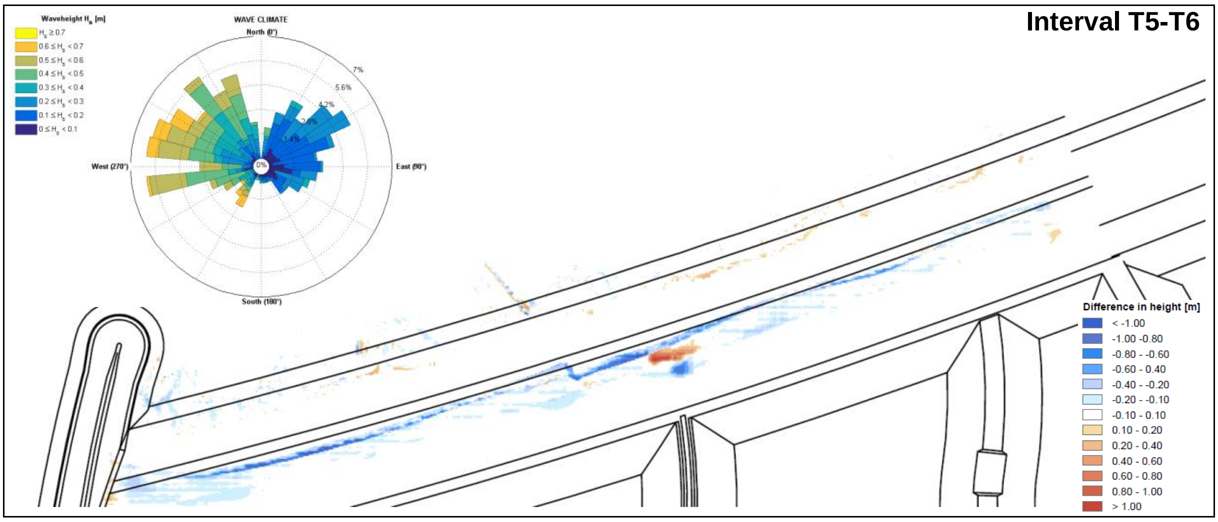


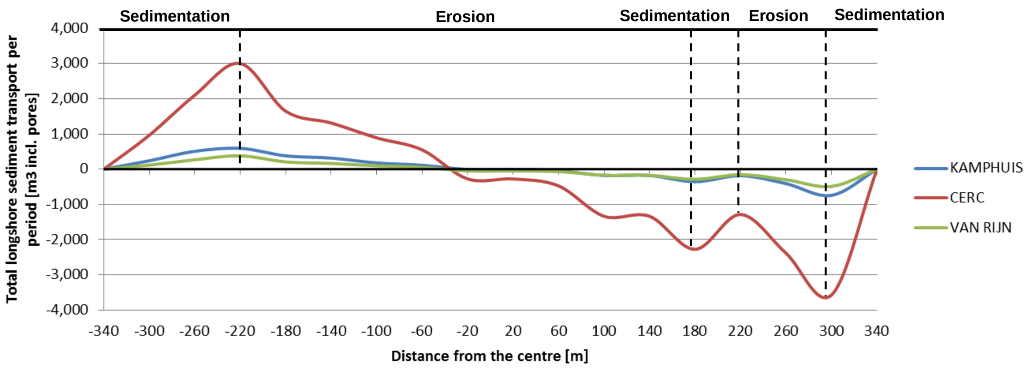

*Figure D-2. Morphological developments of the northwest beach for the time interval T4-T5.*

# APPENDIX E: LONGSHORE SEDIMENT TRANSPORT

In this appendix, the potential longshore sediment transport per location is computed for the southwest beach. In order to calculate the potential longshore sediment transport the equilibrium formulae of CERC (1984), Kamphuis (1991) and Van Rijn (2014) are used. Below the results are presented per time interval.

## Interval T1 – T2

Figure E-1 shows the potential longshore sediment transport at the southwest beach as calculated for the interval period T1 – T2, which covers the period 29-11-2016 to 18-01-2017.



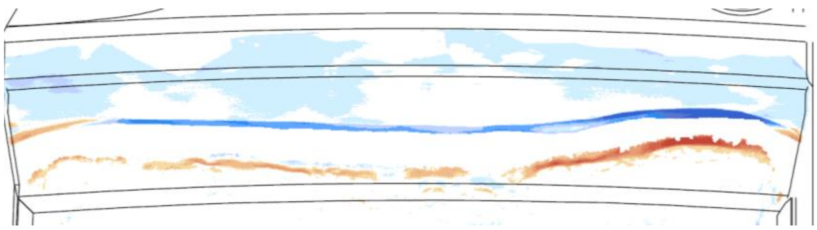



*Figure E-1. Upper plot: Potential longshore sediment transport. Lower plot: The morphological development for this interval.*

As can be seen in the upper plot, the pattern indicates a tipping point at about 40 m left from the centre of the beach. Left from this tipping point the sediment transport is to the northwest and right from this point the sediment transport is to the southeast. Looking at the observed morphological development during this period (lower plot), this pattern can roughly be observed given the accretion in both outer sections of the beach. However, it is still difficult to distinguish the alongshore transport from the cross-shore transport. Moreover, the active zone where the most sediment transport takes place is not covered by the surface plots as presented below. The corresponding transport magnitudes are presented below.

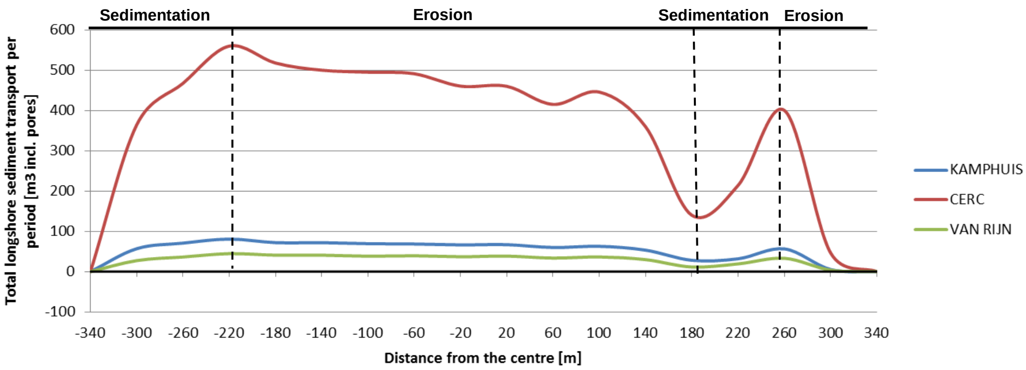
*Table E-1. Computed potential longshore sediment transport of the southwest beach. Time interval T1-T2.*

| Distance [m] * | KAMPHUIS [$m^3$ incl. pores] | CERC [$m^3$ incl. pores] | VAN RIJN [$m^3$ incl. pores] |
|---|---|---|---|
| **20** | 239 | 964 | 117 |
| **60** | 509 | 2101 | 268 |
| **100** | 593 | 3003 | 381 |
| **140** | 380 | 1647 | 207 |
| **180** | 315 | 1312 | 163 |
| **220** | 179 | 891 | 97 |

| | | | |
|---|---|---|---|
| **260** | 111 | 549 | 53 |
| **300** | -7 | -277 | -48 |
| **340** | -7 | -277 | -48 |
| **380** | -46 | -475 | -68 |
| **420** | -177 | -1337 | -172 |
| **460** | -177 | -1337 | -172 |
| **500** | -356 | -2276 | -287 |
| **540** | -184 | -1286 | -155 |
| **580** | -409 | -2388 | -299 |
| **620** | -744 | -3571 | -489 |
| | | | |
| Sum positive | 2319 | 10468 | 1233 |
| Sum negative | -2099 | -13224 | -1683 |
| Gross | 4418 | 23692 | 2916 |
| **Net** | **220** | **-2757** | **-450** |

## Interval T2 – T3

Figure E-2 shows the potential longshore sediment transport for the time interval T2 – T3, which covers the period 18-01-2017 and 06-02-2017.



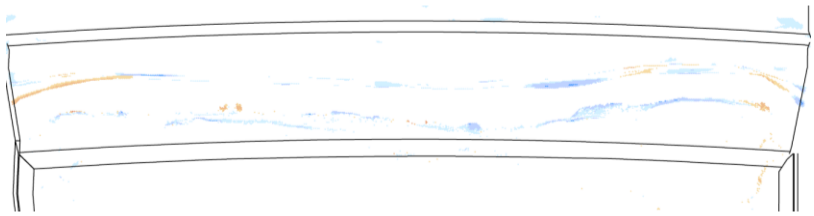



*Figure E-2. Upper plot: Potential longshore sediment transport. Lower plot: The morphological development for this interval.*

FigureAs can be seen, the pattern indicates a northwest-directed sediment transport over the entire length of the beach. However, the magnitudes are relative low, especially according to Kamphuis and Van Rijn, given the relatively calm weather conditions the transport magnitudes were not significantly this period. Looking at the observed morphological development during this period (lower plot), this pattern can roughly be observed given the accretion in the outer southeast section of the beach. It turns out that the potential net sediment transport is for all the equations directed in northwest direction. The corresponding transport magnitudes are presented below.

*Table E-2. Computed potential longshore sediment transport of the southwest beach. Time interval T2-T3.*

| Distance [m] * | KAMPHUIS [$m^3$ incl. pores] | CERC [$m^3$ incl. pores] | VAN RIJN [$m^3$ incl. pores] |
|---|---|---|---|
| **20** | 57 | 364 | 27 |
| **60** | 71 | 467 | 36 |
| **100** | 81 | 560 | 45 |
| **140** | 72 | 518 | 41 |

| | | | |
|---|---|---|---|
| **180** | 72 | 517 | 41 |
| **220** | 69 | 483 | 38 |
| **260** | 69 | 491 | 39 |
| **300** | 66 | 460 | 37 |
| **340** | 67 | 478 | 39 |
| **380** | 60 | 409 | 34 |
| **420** | 63 | 446 | 36 |
| **460** | 53 | 360 | 30 |
| **500** | 28 | 140 | 12 |
| **540** | 32 | 214 | 19 |
| **580** | 57 | 400 | 33 |
| **620** | 5 | 47 | 4 |
| | | | |
| Sum positive | 916 | 6307 | 507 |
| Sum negative | 5 | 47 | 4 |
| Gross | 922 | 6354 | 511 |
| **Net** | **922** | **6354** | **511** |

## Interval T3 – T4

Figure E-3 shows the potential longshore sediment transport for the time interval T3 – T4, which covers the period 06-02-2017 and 03-03-2017.

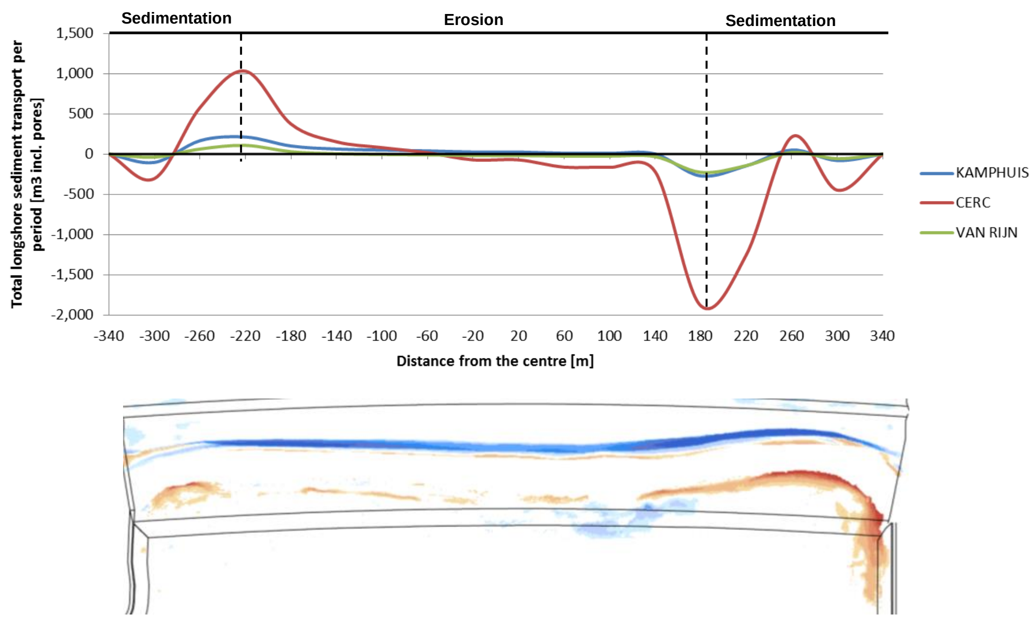



*Figure E-3. Upper plot: Potential longshore sediment transport. Lower plot: The morphological development for this interval.*

The pattern indicates a tipping point at about 40m left from the centre of the beach. Left from this tipping point the sediment transport is to a large extent to the northwest and right from this point the sediment transport is to the southeast. Looking at the observed morphological development during this period this pattern can roughly be observed given the accretion in both outer sections of the beach and less changes in the central section (according to this plot). The corresponding transport magnitudes are presented below.

*Table E-3. Computed potential longshore sediment transport of the southwest beach. Time interval T3-T4.*

| Distance [m] * | KAMPHUIS [$m^3$ incl. pores] | CERC [$m^3$ incl. pores] | VAN RIJN [$m^3$ incl. pores] |
|---|---|---|---|
| **20** | -104 | -304 | -38 |
| **60** | 166 | 577 | 63 |
| **100** | 212 | 1030 | 108 |

| | | | |
|---|---|---|---|
| **140** | 100 | 373 | 30 |
| **180** | 62 | 152 | 3 |
| **220** | 50 | 80 | -5 |
| **260** | 40 | 17 | -10 |
| **300** | 26 | -72 | -18 |
| **340** | 26 | -72 | -18 |
| **380** | 10 | -162 | -26 |
| **420** | 10 | -165 | -26 |
| **460** | 1 | -220 | -32 |
| **500** | -272 | -1996 | -226 |
| **540** | -146 | -1253 | -143 |
| **580** | 50 | 213 | 21 |
| **620** | -80 | -448 | -57 |
| | | | |
| Sum positive | 230 | -1803 | -318 |
| Sum negative | -80 | -448 | -57 |
| Gross | 310 | -1355 | -262 |
| **Net** | **150** | **-2252** | **-375** |

## Interval T4 – T5

Figure E-4 shows the potential longshore sediment transport for the time interval T4 – T5, which covers the period 03-03-2017 and 04-04-2017.

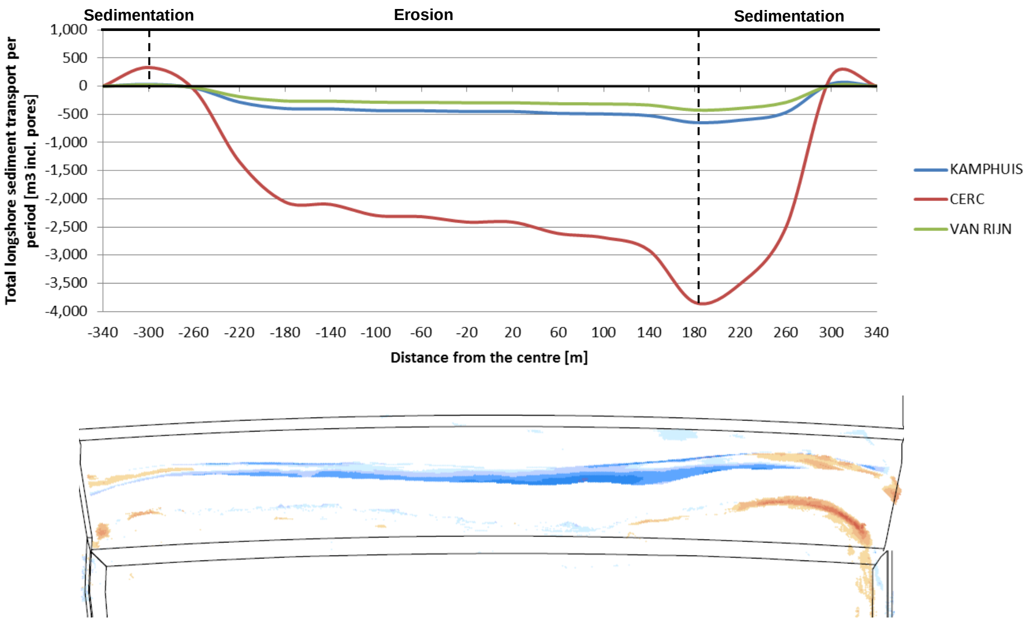



*Figure E-4. Upper plot: Potential longshore sediment transport. Lower plot: The morphological development for this interval.*

As can be seen in the upper plot, the pattern indicates southeast directed sediment transport over almost the entire length of the beach. Looking at the observed morphological development during this period, this pattern can be observed as well, given the accretion in the outer southwestern section of the beach and erosion pattern in the central section of the beach. However, it remains still difficult to distinguish the longshore transport against the cross-shore transport. The cross-shore transport could also be responsible for the erosion in the central section. In contrast to the other periods, the transport magnitudes are clearly higher. The corresponding transport magnitudes are presented below.

*Table E-4. Computed potential longshore sediment transport of the southwest beach. Time interval T4-T5.*

| Distance [m] * | KAMPHUIS [$m^3$ incl. pores] | CERC [$m^3$ incl. pores] | VAN RIJN [$m^3$ incl. pores] |
|---|---|---|---|
| **20** | 33 | 333 | 24 |

| | | | |
|---|---|---|---|
| **60** | -31 | -59 | -22 |
| **100** | -283 | -1341 | -187 |
| **140** | -396 | -2055 | -263 |
| **180** | -402 | -2098 | -266 |
| **220** | -433 | -2296 | -285 |
| **260** | -436 | -2316 | -287 |
| **300** | -449 | -2413 | -294 |
| **340** | -449 | -2413 | -294 |
| **380** | -483 | -2615 | -310 |
| **420** | -492 | -2688 | -316 |
| **460** | -523 | -2915 | -335 |
| **500** | -646 | -3838 | -424 |
| **540** | -603 | -3508 | -393 |
| **580** | -468 | -2510 | -289 |
| **620** | 43 | 178 | 12 |
| | | | |
| Sum positive | -6061 | -32731 | -3940 |
| Sum negative | 43 | 178 | 12 |
| Gross | -6018 | -32553 | -3928 |
| **Net** | **-6018** | **-32553** | **-3928** |

## Interval T1 – T5

Table E-5 gives the computed potential longshore sediment transports over the first 4.5 months.

*Table E-5. Computed potential longshore sediment transport of the southwest beach. Time interval T1-T5.*

| Distance [m] * | KAMPHUIS [m$^3$ incl. pores] | CERC [m$^3$ incl. pores] | VAN RIJN [m$^3$ incl. pores] |
|---|---|---|---|
| **20** | 225 | 1357 | 130 |
| **60** | 715 | 3086 | 345 |
| **100** | 602 | 3252 | 347 |
| **140** | 156 | 483 | 15 |
| **180** | 47 | -117 | -59 |
| **220** | -134 | -841 | -154 |
| **260** | -216 | -1259 | -205 |
| **300** | -364 | -2301 | -323 |
| **340** | -363 | -2284 | -321 |
| **380** | -458 | -2843 | -370 |
| **420** | -597 | -3744 | -477 |
| **460** | -646 | -4112 | -509 |
| **500** | -1245 | -7970 | -926 |
| **540** | -901 | -5833 | -672 |
| **580** | -771 | -4285 | -534 |
| **620** | -775 | -3795 | -530 |
| | | | |
| Sum positive | 4,075 | 19,774 | 2,056 |
| Sum negative | -8,802 | -50,982 | -6,300 |
| Gross | 12,876 | 70,756 | 8,356 |
| **Net** | **-4,727** | **-31,208** | **-4,243** |