Pilot Sand Groynes Delfland Coast

Efficiency and practical feasibility of a pulse nourishment

MSc thesis report
Roderik Hoekstra
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Project name: Pilot Sand Groynes Delfland Coast
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MSc-thesis

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PREFACE

This thesis report concludes my Master of Science in Coastal Engineering at the faculty of Civil Engineering and Geosciences of the Delft University of Technology. The research has been performed for the project ‘Combinatie Delflandse Kust’, responsible for nourishing the Delfland Coast as one of the Zwakke Schakels (‘weak links’) along the Dutch coast. For this research a consortium was set up consisting of the Dutch dredging companies Boskalis and Van Oord, research institute Deltares and the Delft University of Technology.

First of all, I would like to thank my graduation committee. It was quite a challenge to keep you all up to date about the progress, but your overwhelming enthuasiasm and interest in this innovative research has always been my major motivation to get the most out of it. I would like to thank prof. Stive for chairing the committee. Special thanks go to Stefan. He employed me with this job after a succesful collaboration we had during my internship for Boskalis. I could not have wished a better graduation research to conclude my study and start my professional carreer with! I would like to thank Mark for his enthuasiasm and support on the monitoring and data processing part. Special thanks also go to Arjen for his daily support at Deltares and recommendations in very diverging fields! Matthieu for his support on the monitoring part in Ter Heijde and his valuable contribution to the morphological analysis. Dirk-Jan for sharing his extensive knowledge and experience with me throughout the entire research and Gerben for his enthuasiasm and for providing stunning tools for data visualizations.

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Roderik Hoekstra,

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Project name: Pilot Sand Groynes Delfland Coast
SUMMARY

The 15km coastal stretch between Hoek van Holland and Scheveningen in the Netherlands, called the Delfland Coast, is assigned as one of the Zwakke Schakels (in English: ‘weak links’) along the Dutch coastline. That means that this part of the coast is recognized as not being sustainable for the coming 50 years and in urgent need of reinforcement to guarantee the safety of the hinterland against the impact of the sea. The project ‘Combinatie Delflandse Kust’ is currently working on reinforcement of the Delfland Coast by artificially nourishing sediment in the coastal system. The sediment buffer in the upper parts of the coastal profile, from the native dunes until a depth of -5m NAP is replenished. The project started in November 2008 near Hoek van Holland, working upward north aiming to finish in the year 2011.

In September 2009 the project arrived at the coast of Ter Heijde, a town halfway between Hoek van Holland and Scheveningen. The coastal profile of the Ter Heijde coast is characterized by the presence of a relatively high elevated subtidal bar. Due to the presence of this pronounced subtidal bar, the nourishment design of the upper shoreface (-0.70m NAP - -5m NAP) is suspected not to be fully realizable according to the contract requirements, using the nourishment options provided by the contract. The employed dredging vessels can not pass the subtidal bar to directly nourish the sediment in the upper shoreface. Another option provided by the project contract is to dump the sediment between the -5m and -8m depth contour; due the steep slope of the seaward side of the subtidal bar at the Ter Heijde coast, the sediment storage capacity in this part of the coastal profile is limited.

Three so called sandgroynes have been constructed to additionally realize the design on the upper shoreface. The sandgroynes are constructed from the shoreline in seaward direction, appearing in the formation of peninsulas. Each sandgroyne contains about 200,000m³ of sediment; the sediment in the sandgroynes is anticipated to be evenly redistributed over the Ter Heijde site area stretching about 2.5km in longshore direction, by the impact of waves and currents. The sandgroynes have been constructed to overcome an operational restriction, but serve as pilot for assessing the future perspective of the nourishment techniques using the potentials of the natural system. The objectives of this study are 1) to evaluate the morphological evolution and the practical aspects of the pilot executed in Ter Heijde and 2) to use the experience and observations from the pilot project to assess the sandgroynes as a common efficient method to nourish the shoreface.

An extensive monitoring campaign is initiated to monitor the construction and evolution of the sandgroynes. Regular bathymetry surveys have been executed, implementing different kind of survey platforms to be able to cover the entire coastal profile and to maximize the survey area in longshore direction. Besides the bathymetry data, sand samples have been taken, dredging progress logs have been collected and photos have been taken on a daily basis.
Data analysis points out that under moderate to rough, dominant southwesterly wave conditions the sediment has been redistributed mainly in longshore, northward direction. The data does not indicate offshore losses of sediment beyond the -5m depth contour. The wave-induced longshore current is identified as the dominant driving force of the sandgroyne sediment redistribution. In stormy conditions, the sandgroynes in the Ter Heijde configuration are absorbed in the coastal system within a period of a week time.

A process-based, numerical simulation model is implemented to simulate the morphological behavior around sandgroynes for a range of alternative wave scenarios. The model results point out that the tidal current on itself is not able to absorb the sandgroynes into the coastal system within the period of a season. Based on the year-average wave climate along the Delfland coast, it is anticipated that the trend of sediment redistribution of sandgroynes along the Delfland coast will be in longshore, northward direction. Northwesterly waves will generate a southward directed sediment transport. Depending on the weather conditions and the design of the sandgroynes, the redistribution will occur on a scale of 5-10km in longshore direction.

Under the governing, strict contract requirements of the project ‘Combinatie Delflandse Kust’ sandgroynes are not an efficient method to nourish the shoreface. Sediment was not maintained in the Ter Heijde site area, resulting in additional sediment to be nourished to realize the design. Besides, the monitoring campaign has been extensive and complex. The survey area was larger than anticipated for, required multiple survey platforms to be able to survey the coastal profile uninterrupted and the survey was limited by the severe meteorological and hydrodynamic conditions.

It is recommended to assess the morphological behavior of sandgroynes in a different coastal configuration than the configuration of the Ter Heijde coast. A uniform sloping coastal profile, a profile characterized by multiple bars or a coastline with another coastline orientation might influence the morphodynamics around sandgroynes.

It is recommended to apply sandgroynes under flexible requirements when settlement is based on hopper volumes instead of realizing design profiles. From a morphology point of view it can be concluded that the sandgroyne is an effective nourishment method as the sediment is retained in the active part of the coastal profile (above the -5m depth contour). Contract settlement based on hopper volumes instead of design profiles will significantly reduce the amount of required survey operations. For further development of the sandgroynes as a general applied shoreface nourishment method, it is recommended to opt for long-term maintenance contracts. Such a contract allows contractors to install permanent facilities and work with flexible nourishment schedules.
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1. INTRODUCTION

1.1 Background

Maintaining the coastline of South- and North-Holland (see Figure 1-1) is of crucial importance for the Randstad urban agglomeration. The coast protects the low-lying hinterland against the impact of the sea. Besides, the coast has ecological values and provides an area for several forms of recreation and harbor areas with considerable socio-economic importance.

Presently, the Dutch coastline is maintained according to the strategy of ‘Dynamic preservation’ (in Dutch: ‘Dynamisch handhaven’). The basic coastline (in Dutch: Basis KustLijn) is preserved by regularly nourishing sand to the coast at the locations where the basic coastline is exceeded. This approach of maintaining the coastline is flexible and relatively cheap, however based on ‘preservation’ and adapted to observed ‘sea level rise’.

For coastal development and creation of nature, another approach is desirable, in which sand is brought into the coastal system in excessive amounts. The resulting buffer can cope with the consequences of the climate change, as well as with an increasing demand for recreational and natural areas. The climate change will result in sea level rise and intensified and more frequent occurring storms. Sustainable safety and the development of the Dutch coast require innovations in the nourishment procedures currently handled. Large quantities of sand are brought in all in once, reducing the construction costs and increasing the opportunities for recreational use. The sediment in these mega-nourishments is anticipated to be redistributed by waves, wind and currents in conformity with the ‘building with nature’ principle. Besides, the mega-nourishments conduct development of permanent of temporary nature and recreation in the form of new dynamic dune areas and beach lagoons.

In September 2008, the Delta Committee presented its recommendations how to keep the Netherlands safe and climate proof for the coming 100 years [Veerman, 2008]. One of the recommendations is to nourish large volumes of sediment in the coastal system and use the potentials of the nature to maintain the coast, ‘building with nature’. In this context, an upcoming pilot project is the realization of the so called ‘sand engine’. The ‘sand engine’ will contain about 20 Mm³, serving as a sediment influx for the coastal system.
1.2 Zwakke Schakel: Delfland Coast

Ten areas along the Dutch coast are recognized as not being sustainable for the coming 50 years and in need of short term reinforcements. The concerning areas of which six are located in the province Zuid-Holland are shown in Figure 1-2. The Delfland coast is one of the Zwakke Schakels presently under construction by the joint venture ‘Combinatie Delflandse Kust’, in which two major Dutch dredging companies Boskalis bv and Van Oord Nederland bv are united. The Delfland coast is the 15km long coastal stretch from Hoek van Holland until the southern breakwater of the port of Scheveningen (see also Figure 1-3). The project started in November 2008 and comprises seaward extension of the dunes, the beach and the upper part of the shoreface by means of artificial sand nourishments to maintain a sufficiently large sediment buffer in the upper part of the coastal profile. A minimum amount of sediment is required to protect the hinterland against the effects of severe storms. However, the sediment buffer is gradually decreasing under influence of a net northward directed sediment transport. Therefore, nourishments are regularly executed to restore the sediment buffer.

An additional area is assigned for the development of a new natural area to compensate for the adverse effects of the construction of the Maasvlakte 2 (extension of the Port of Rotterdam) on the local nature, besides the physical reinforcements of the coastal protection. This area, called ‘Duincompensatie’ (in English: ‘Dune compensation’) is located near ‘s-Gravenzande, marked by the white rectangle in Figure 1-3.

The project contract prescribes cross-shore design profiles from the native dunes down to a depth of -5m NAP, see Figure 1-4. The design profiles are defined in each Jarkus-raai, a grid system along the Dutch coast, to be accomplished by artificial sediment nourishments. This requires placement of the sediment in the dunes, the beach and the upper shoreface. In this study, the following definitions are assigned to the distinguished parts of the coastal profile; the dunes, the beach and the upper shoreface (see Figure 1-4):

- Dunes: coastal area with an elevation upwards of +3m NAP depth contour.
- Beach: coastal area with an elevation between the +3m NAP depth contour and the Mean Low Water Level (MLWL: -0.70m depth contour).
- Upper shoreface: coastal area with an elevation between the MLWL and the -5m depth contour.
Figure 1-4 Arbitrary cross-shore profile at the Ter Heijde coast indicating the principle of nourishing sediment to reach a design profile.

Photo 1-1 Aerial photo taken near Hoek van Holland on 6 January 2009, illustrating the nourishment progress (source: www.Delflandsekust.nl).

Photo 1-1, taken in January 2009, illustrates the nourishment progress of the southern part of the project area up to ‘s-Gravenzande after a few months of dredging operations.

For the nourishments executed, the required sediment is supplied by means of a 2 km long sinker pipeline laying on the seabottom and orientated perpendicular to the coastline, see Photo 1-2. Dredging vessels connect to this sinker pipeline offshore, subsequently pumping a sediment-water mixture through the pipeline onshore. Once arrived onshore, further transport to the exact desired location on the beach or on the dunes is realized by an easily adjustable network of pipelines on the beach.

Photo 1-2 Aerial photo of the Ter Heijde site area, indicating the track of the sinker pipeline laying on the sea bottom (property: Van Oord Nederland).

Photo 1-3 Illustration of two techniques to nourish the shoreface; rainbowing sediment from a seabased dredging vessel and rainbowing from the shoreline (property: Van Oord Nederland).
For realization of the design in the upper shoreface, the project contract allows for two nourishment options:

1. Nourishing sediment directly on the upper shoreface (between MLWL and -5m NAP depth contour) according to the design profile.
2. Nourishing sediment on the deeper shoreface (between -5m NAP and -8m NAP), but double the amount required according to the design.

Evidently, the first option is most cost effective as the sediment is nourished according to the design. The upper shoreface is nourished partly by landbased dredging equipment, with sediment delivered through the sinker pipeline, and partly by rainbowing sediment from a sea based dredging vessel. Both techniques are shown in Photo 1-3. For the second option the sediment is directly dumped (in Dutch: ‘klappen’) by the dredging vessel between the -5m and -8m depth contour, but double the amount according to the design has to be nourished, because it is anticipated that in this area 50% of the nourished sediment is will be lost in offshore direction beyond the -8m depth contour.

### 1.3 Problem & solution

#### 1.3.1 Problem

For the coast of Ter Heijde, halfway between Hoek van Holland and Scheveningen, the design in the upper shoreface is expected to be not realizable by both the nourishment methods proposed in the project contract. The Ter Heijde coastal profile is characterized by a relatively high elevated and steep subtidal bar. This has the following consequences for the nourishments to be executed according to the nourishment methods proposed:

1. The subtidal bar limits the access to the upper shoreface for the employed dredging vessels. The dredging vessels can not directly nourish the sediment in the upper shoreface as illustrated in Photo 1-4.
2. Due to the relatively steep seaward slope of the subtidal bar, the storage capacity for nourished sediment between the -5m and -8m NAP depth contour is limited, also taking into account that double the amount of sediment according to the design has to be nourished.

Figure 1-5 presents an arbitrary cross-shore profile at the Ter Heijde coast, indicating the two contract options to nourish the upper shoreface and the according restrictions. It is expected that the design in the upper shoreface can not be fully realized by the two nourishment options provided by the project contract.
Cats & Van der Sluijs [2009] estimated that about 35% of the design on the upper shoreface can be nourished from the shore, for the remaining amount another method should be proposed. For detailed sediment volume estimations is referred to their report.

Figure 1-5 Arbitrary cross-shore profile at the Ter Heijde coast, indicating the two options to nourish the upper shoreface and the accompanying operational restrictions.
1.3.2 Solution: sandgroynes

An alternative method to additionally nourish the upper shoreface has been proposed; the construction of three so-called sandgroynes\textsuperscript{1} (in Dutch: ‘zandhoofden’). These nourishments are realized from the shoreline in seaward direction and appear in the formation of peninsulas, see Photo 1-5. The sandgroynes serve as a sediment input to nourish the remaining part of the design in the upper shoreface that can not be realized from the shore. It is anticipated that the sediment in these concentrated nourishments is redistributed by wind, waves and currents, according to the design profiles over the Ter Heijde coast. Construction of the sandgroynes has the following benefits:

- The sandgroynes overcome the supposed limited sediment storage capacity at the Ter Heijde coast.
- The sandgroynes are realized from the shore, landward of the -5m NAP depth contour. Supposing that the sediment will remain landward of this depth contour, this is the most cost effective nourishment option.

<table>
<thead>
<tr>
<th>Sandgroyne 1</th>
<th>137.000 m³</th>
<th>Constructed: 15 Oct – 20 Oct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandgroyne 2</td>
<td>194.000 m³</td>
<td>Constructed: 31 Oct – 6 Nov</td>
</tr>
<tr>
<td>Sandgroyne 3</td>
<td>201.000 m³</td>
<td>Constructed: 7 Nov – 9 Nov</td>
</tr>
</tbody>
</table>

Photo 1-5 Aerial photo, taken on the 10\textsuperscript{th} of November, illustrating the sandgroyne nourishments realized near Ter Heijde (property: Van Oord Nederland).

Several characteristics of the three sandgroynes are presented right of Photo 1-5, indicating that an amount of about 530.000m³ of sediment is nourished in the sandgroynes. The sandgroynes are constructed with a maximum elevation of +1.5m NAP, almost entirely inundating during high tide. Just after realization, the dimensions of the dry part of the sandgroyne are about 200m both in longshore and in cross-shore direction.

\textsuperscript{1} ‘sandgroyne’ is still an unofficial term in the coastal engineering field. ‘Sand’ refers to the material, ‘groyne’ refers to the shape of the structure; built perpendicular to the shoreline.
1.4 Research framework

The construction of the sandgrovynes overcomes an operational restriction, as described in the previous paragraph, but will serve as a pilot project to assess nourishments, using the potentials of the natural system to nourish the shoreface in conformity with the ‘building with nature’ principles.

Cats & Van der Sluijs [2009] performed a feasibility study of the sandgroyne nourishment method for the project ‘Combinatie Delflandse Kust’. It was concluded that under the governing contract requirements and the operational restriction the sandgrovynes are the most cost effective way to nourish the upper shoreface in Ter Heijde. The optimal use of the transport capacity of the natural system, the positive effect on the local ecology and the development of the dunes [Damsma, 2009] suggest the sandgrovynes as a general effective nourishment technique for long-term maintenance of the coastline.

Walstra & Mol [2009] performed a preliminary study assessing the morphological behavior of sandgroyne nourishments. The morphological study is based on simulations with an existing model, predicting the morphological response of 3 sandgroyne nourishments with comparable magnitude and dimension as the 3rd sandgroyne illustrated in Photo 1-5. Based on the simulation results, the following was hypothesized:

- The sediment will be evenly redistributed in longshore direction, initially filling the gaps between the three sandgrovynes.
- For an average wave climate (Hs=1.25m), the sandgrovynes are absorbed into the coastal system in the order of several months.
- During storm conditions the sandgrovynes are absorbed into the coastal system in the order of several days.
- The offshore losses of sandgroyne sediment seaward of the -5m depth contour are limited.
- The tidal current, without wave forcing, is not capable to absorb the sandgroyne sediment in the coastal system.
- Leeside erosion caused by the presence of the sandgrovynes is not observed.
- In a short phase directly after completion of a sandgroyne, the swimmer safety is endangered due to increased flow velocities near the sandgrovynes.

Both studies recommended to conduct an extensive monitoring campaign, to verify the expected morphological behavior. The results of the pilot project can be used to assess whether the sandgrovynes are a general applied method to nourish the shoreface. Besides, the acquired fielddata can be used to further develop the simulation model as the model set-up of the preliminary morphology study was very basic. Further development of the simulation model can be an important aspect to assess the morphological effects of similar, prospective nourishments.

For the sandgroyne pilot project a consortium has been formed, consisting of the Dutch dredging companies Van Oord and Boskalis, employing the project ‘Combinatie Delflandse Kust’, research institute Deltares and the Delft University of Technology. The assessment of the sandgroyne nourishments is executed for the project Combinatie Delflandse Kust, in the framework of a Master thesis research project for the Delft University of Technology in the field of coastal engineering. The project ‘Combinatie Delflandse Kust’ facilitates the monitoring part of the sandgroyne nourishments and provides the data, whereas Deltares provides knowledge, tools and the facilities for the analysis part. The survey data and results of this study will be become available for Van Oord, Boskalis, Deltares and the Delft University of Technology.
1.5 Research objectives and questions

The following research objectives are proposed for this study:

- Assess the morphological evolution and practical aspects of the sandgroynes constructed at the Ter Heijde coast.
- Use the site specific knowledge from the Ter Heijde pilot project to create a future perspective of sandgroyne nourishments as a common applied method to nourish the shoreface.

The following research questions will be answered to fulfill the research objectives:

1. What has been the spatial scale of redistributed sediment of the sandgroynes executed near Ter Heijde, over the period between September 2009 and January 2010?
2. Which hydrodynamic processes dominate the morphological behavior of sandgroyne nourishments?
3. What is the trend of longshore and cross-shore redistribution of sandgroyne sediment for representative conditions along the Dutch coast?
4. Based on the experience from the Ter Heijde pilot, what are the important design criteria of the sandgroyne nourishments?
5. In which configuration can the sandgroynes be an efficient method to nourish the upper shoreface at the Delfland Coast?

1.6 Approach

In the months October, November and December 2009 three sandgroyne nourishments have been constructed at Ter Heijde. During these months, a monitoring campaign was initiated to study the evolution of the sandgroyne nourishments. The acquired field data will be used to 1) analyze the morphological evolution of the sandgroynes, 2) to facilitate the set up of a numerical simulation model and 3) to evaluate the practical aspects of sandgroyne nourishments.

A numerical simulation model is applied 1) to determine the site local hydrodynamics and 2) to determine the trend of redistributed sediment of the sandgroynes as executed in Ter Heijde, for several alternative, representative wave conditions along the Holland coast.

The practical aspects of sandgroynes will be evaluated, taking into account the morphological response as indentified in the data analysis and the model simulations. The Ter Heijde pilot will be evaluated; the observations and experience will be used to create a future perspective of sandgroynes as a common applied shoreface nourishment method.

The results of the preceding steps lead to research conclusions and recommendations, to generally assess the concept of sandgroyne nourishments as a common applied method to nourish the shoreface.
1.7 Report outline

Chapter 2 describes the project area Delfland coast as one of the Zwakke Schakels along the Dutch coast. The prevailing hydrodynamic and meteorological conditions, as well as the coastal characteristics are described. Besides, an overview of previously executed nourishments at the Ter Heijde coast is provided and the nourishment procedure of the nourishments for the site near Ter Heijde between September 2009 and January 2010 is described.

![Overview of the dredging progress, survey data availability and hydrodynamics during the Ter Heijde nourishment campaign.](image)

Chapter 3 describes the monitoring campaign initiated to collect field data. An overview will be given of the data parameters collected and the usefulness of the data. Figure 1-6 presents on which dates bathymetry survey data are available, indicated by the vertical black lines. Although more bathymetry data is available, on the dates marked by the black lines bathymetry data is available covering a substantial part of the Ter Heijde site area. More information is provided in Chapter 3.
Chapter 4 focuses on the morphological analysis. The priority of this chapter is to identify the processes dominating the morphodynamics around sandgroyne nourishments. This is performed by analyzing the acquired field data, aggregating the bathymetric changes to the observed hydrodynamic and meteorological conditions. A numerical simulation model is implemented to verify the morphological response for several alternative wave scenarios. The morphological analysis is performed for a period between two consecutive bathymetry surveys, marked in yellow in Figure 1-6.

Chapter 5 discusses the practical aspects of the sandgroyne nourishments, in the perspective of the dredging industry. In this context, the experience and observations from the Ter Heijde pilot in combination with simulation results of a number of sandgroyne alternatives will be used to identify the relevant sandgroyne design criteria.

Chapter 6 presents an overview of the conclusions drawn for the different aspects of the research and answers the research questions as formulated in Paragraph 1.5.
2. PROJECT AREA: DELFLAND COAST

2.1 Introduction

The Delfland coast, assigned as one of the Zwakke Schakels (‘weak links’) along the Holland coast is subject to an artificial nourishment assessment study presented in this report. The Delfland Coast comprises the 15km long stretch of coast between the towns of Hoek van Holland and Scheveningen. The location of the Delfland coast is visualized in Figure 2-1.

![Figure 2-1 Plan view of the Netherlands, indicating the Delfland coast (left) and a plan view of the Delfland coast itself (right), located between the towns of Hoek van Holland an Scheveningen (Google Earth).](image)

This chapter deals with the prevailing hydrodynamic conditions and coastal processes present in the area, focusing on the surfzone part of the coastal profile (see Appendix A). The information will be used to understand the autonomous behavior of the Delfland coastal system. Besides, an overview will be provided of all previous artificial sediment nourishments executed in the area to create a perspective of the nourishment campaign currently undertaken. The chapter will be concluded with a general description of the nourishment campaign executed between September 2009 and January 2010 near Ter Heijde by the project ‘Combinatie Delflandse Kust’, to give an introduction on the analysis performed in the following report chapters.
2.2 Hydrodynamics

2.2.1 Tide

The tide is a phenomenon associated with the combined effects of the rotation of the Earth and the gravitational forces exerted by the sun and the moon. The interaction generates a long wave that propagates through the oceans and coastal waters, resulting in a periodic rise and fall of the sea water level (vertical tide) and an according tidal current (horizontal tide). Although the interactions between planetary bodies are predictable, the shape of the sea floor bathymetry and local meteorological conditions change the propagation of the tidal wave; this makes the actual observed effects referred to as the horizontal and vertical tide unique for each location.

Figure 2-2 presents a plan view of the propagation of the tidal wave through the North Sea. The tidal wave is generated on the southern hemisphere and transported through the Atlantic Ocean northward. The figure shows that the tidal wave in the North Sea propagates around the Great Brittan island in southern direction and consequently up northward along the Dutch coast. The dominant, semi-diurnal constituent of the tide in the North Sea (M2 and S2) occur with a returning period of approximately 12 and half hours.

The tide causes a northward-directed flood current, reaching a maximum of 0.8m/s and a southward-directed ebb current, reaching a maximum of 0.7m/s. The tidal asymmetry then causes a residual current in the order of 0.1m/s in northward direction (Van Rijn, 1997). The range between high and low waters, referred to as the tidal range, varies along the Dutch coast. Scheveningen, just north of the Delfland coast, experiences a tidal range of about 1.5m during neap tide and about 2m during spring tide.
2.2.2 Wind

Figure 2-3 and Figure 2-4 show wind climates for two different characteristic periods, respectively for the summer season (from April to September) and the winter season (October to March) over the years 1979 until 2001. For both periods the wind climates are visualized by means of wind roses based on timeseries as recorded by 3 different monitoring stations in the North Sea (in chronological sequence starting from the one located most offshore: The Europlatform, the IJmuiden munitiestortplaats, Noordwijk meetpost). For each wind rose the different bars represent the distribution of wind directions and the length of the bar the relative frequency of occurrence. The different colors represent the wind velocity classes distinguished. A larger version of the wind climate plots is included in Appendix F.

Within the two seasons, distribution of the wind direction and magnitude shows the same trend. Concerning the winter season, the prevailing directional sector is south to west (clockwise). The occurrence of high wind velocities (15m/s and up) contributes 5-10% to each of the directions considered. For the summer season the prevailing directional sector is south-west to north-west, still the dominant direction is south-west. Wind velocities upwards of 15m/s hardly occur, in general less than 2% of each distinct direction.

The wind climates monitored by the monitoring stations in the North Sea show fair agreement, both in direction and velocity. Therefore it is assumed that the same trend of wind direction and velocity is observed locally at the Ter Heijde site; local winds are an important parameter when analyzing aeolian transport, local wind set-up and wind induced currents. More details about the local effects of wind are given in Appendix A.
2.2.3 Waves

Figure 2-5 and Figure 2-6 show wave climates for the summer season (from April to September) and the winter season (October to March) over the years 1979 until 2001. For both periods the wave climates are visualized by means of wave roses based on timeseries as recorded by 3 different monitoring stations in the North Sea. For each wave rose the different bars represent the distribution of wave directions and the length of the bar the relative frequency of occurrence. The different colors represent the wave height classes distinguished. A larger version of the wave climate plots is included in Appendix F.

![Figure 2-5 Wave climate for the summer season (April-September), based on wave timeseries recorded by several stations in the North Sea over the years 1979-2001.](image1)

![Figure 2-6 Wave climate for the winter season (October-March), based on wave timeseries recorded by several stations in the North Sea over the years 1979-2001.](image2)

Comparing the wave climates of the summer and winter seasons, demonstrates that the occurrence of both the wave height and direction is distributed more uniformly in the winter season. For instance, waves with a significant wave height of 2.5m up hardly occur during the summer season. Besides, the summer season clearly demonstrates the prevailing wave direction is north-west, closely followed by south-west. Concerning the winter season, the occurrence of waves with a significant wave height of 2.5m up is about 10% for each of the offshore directions. This means that on one out of ten days a wave height of at least 2.5m is observed, on average. Still the north-west and south-west direction is dominant over the other directions (south-west prevailing for the winter season), however dominancy is less pronounced in comparison with the summer season.

Southwesterly waves are mainly generated by local winds. The dominance of the south-west occurring waves is therefore in accordance with the dominance of south-west occurring winds as demonstrated in the previous subparagraph. North-west occurring waves are commonly generated further offshore than the area considered in Figure 2-5 and Figure 2-6, by interaction of large scale pressure areas. These long-crested swell waves are not affected anymore by local winds when entering the North Sea, and therefore showing a lower correlation with the occurrence of local north-west directed winds.

Refraction causes shore propagating waves to gradually bend towards shore normal incidence as a result of the decreasing depth. The figures for both the summer and winter season demonstrate this process, as the range of occurring directions for the most shoreward located station (Noordwijk meetpost) seems to have decreased...
compared to the more offshore located stations (Europlatform & IJmuiden munitiestortplaats). With respect to the shore located area subject to this study, it is commonly adopted that this process will further affect the shore propagating waves towards shore normal incidence.

Waves approaching the shore will eventually break. In case of oblique incident waves, part of the wave energy is transformed in the generation of a longshore current. This process, including its effects will be further explained in Appendix A.

2.3 Sediment budget

The research focuses on the evolution of the nourishments executed in the scope of the Ter Heijde nourishment campaign, but will interfere with the autonomous behavior of the Delfland coast. A sediment budget model, describing the yearly-averaged sediment transports, is set up to get an impression of the autonomous behavior of the project area.

Figure 2-7 shows the sediment budget model for the stretch of coast between Hoek van Holland up to and including Scheveningen [Van Rijn, 1994]. These transport figures have been transformed to the study area, stretching from Ter Heijde, northward up to and including Kijduin (KM 105.000 – KM 112.600); the result is presented in Figure 2-8. For this stretch of coast a sediment balance has been set-up based on the acquired field data of the Ter Heijde nourishment campaign, presented in Chapter 4. The theoretical sediment balance presented in this chapter and the sediment balance based on the Ter Heijde field data will be compared to validate potential sediment losses or gains.

The sediment transport values from Van Rijn [2004] have been transformed to values representative for the study area, using basic, linear interpolation rules. The aim is to create a rough impression of the sediment balance for
the study area, to validate the sediment balance of the period associated with the Ter Heijde nourishment campaign in 2009. Figure 2-8 indicates that an amount of 30,000 m³ of sediment, based on yearly averaged conditions, is eroded out of the study area. This figure is excluding the effects of the sand nourishments regularly executed.

The sand budget model presented in Figure 2-7 has been calibrated using the yearly-averaged sand volume changes derived from bathymetry data (Jarkus-data base) collected during the period 1964-1992. This period overlaps the period considered for determination of the year-averaged wave climate (see Figure 2-9, a larger version is included in Appendix F), presenting data from 1979-2001. As expected, the dominant southwesterly waves contribute to a net northward directed longshore sediment transport. The longshore transport near Hoek van Holland is zero due to the presence of the Rotterdam harbor barriers extending far beyond the surfzone (-8m NAP) and the presence of a deep approach channel, acting as a sand trap for the tide related transport. The shoreward directed transport across the -8m depth contour is the result of a balance of onshore and offshore directed transports; the driving processes are described in Appendix A. The landward directed sediment transport across the +3m depth contour represents the aeolian transport of beach sediment to the dunes. In Chapter 4, the sediment budget model will again be referred to.

For a more accurate representation of the local sediment balance, it is recommended to consult long term, season specific datasets covering the study area (if available) and/or use simulation models.
2.4 Interventions Ter Heijde coast

2.4.1 Previous nourishments

The Delfland coast has been subject to several previous executed, artificial sediment nourishment campaigns in the past. In contradiction to the actual nourishments undertaken (project ‘Combinatie Delfland coast’), the previous nourishments were all executed in the scope of the general Dutch coastline maintenance policy. The current executed nourishments are part of the reinforcement of the ‘Zwakke Schakels’ of the Dutch coast, under the responsibility of provinces and water authorities. The actual nourishments therefore can be considered as an additional nourishment campaign and do not interfere with the regular executed nourishments on national scale. More details of nourishments executed in the past are provided in Appendix A.

In the past decennium, about 7 million m$^3$ of sand has been nourished near Ter Heijde; that is a yearly average of 700,000 m$^3$ per year (present nourishments not included). The nourishments executed in the second half of 2009 near Ter Heijde comprise an amount of 2.5 million m$^3$ of sand.

2.4.2 Nourishment campaign September – December 2009

The nourishment campaign including the sandgroyne nourishments has been executed near the village Ter Heijde from September until December 2009. Before September 2009, the project operation was down due to the summer season. After December 2009, the nourishments for the considered area had been completed and continued on the beach of Kijkduin, a few kilometers north of Ter Heijde. A plan view of the site for the period between September and December 2009 is given in Figure 2-10, enclosed by the white rectangle. The area stretches 2.3km in coastal alongshore direction. Details on dredging technical aspects of the nourishments campaign between September and December 2009 are provided in Appendix C.

Figure 2-10 Plan view of the site area in the period from September until December 2009, near Ter Heijde village (Google Earth).
The contract of the project 'Combinatie Delflandse Kust' virtually subdivides the entire stretch of coast subject to execution (Hoek van Holland until Scheveningen) into alongshore separated compartments. On average, each compartment stretches about 500m of the coast. This system of subdivision formally allows intermediate completion of parts of the project; each compartment can individually be delivered as soon as it complies with the contract requirements. The compartments are consecutively numbered upward north, starting south near Hoek van Holland with compartment 1, ending in Scheveningen with compartment … . The compartments belonging to the Ter Heijde site area, between September 2009 and January 2010, are presented in Figure 2-11.

Table 2-1 presents the required amounts of sediment to be nourished on the Ter Heijde site according to the design profiles. The design profiles are determined for each Jarkus-transect along the Delfland coast. The Jarkus transects belong to a grid system used by the Dutch government to analyze the coastal evolution of the entire Dutch coast. Each year the elevation along the Jarkus-transects is surveyed. The evolution of the Jarkus-transects will be used to determine the nourishment program. The submerged part and the dry part of the profile conduct different nourishment methods, accordingly distinction is made for the wet part (the shoreface), and the dry part (the dunes and the beach).

<table>
<thead>
<tr>
<th>NOURISHMENT DESIGN September – December 2009</th>
<th>Part of the coastal profile</th>
<th>Sediment volume design ( x 10^6 m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compartment 9 – Compartment 12B</td>
<td>TOTAL</td>
<td>2.35</td>
</tr>
<tr>
<td></td>
<td>Shoreface</td>
<td>1.17</td>
</tr>
<tr>
<td></td>
<td>Beach &amp; Dunes</td>
<td>1.18</td>
</tr>
</tbody>
</table>

Table 2-1 Overview of the nourishments design figures for the Ter Heijde coast, to be realized between September and December 2009.

Appendix D additionally presents the figures for each individual compartment. Obviously, summing up the presented figures for the subdivisions made in alongshore direction (compartments) and in cross-shore direction (distinct parts of the coastal profile) leads to the total amount. The total amount presented in Table 2-1 refers to the status of the project for the considered area in September 2009: 2.35 Mm³ has to be nourished in order to fulfill the contract requirements for this area. Approximately half of the amount is to be nourished in the dunes and on the beach, the other half in the shoreface.
3. MONITORING CAMPAIGN

3.1 Introduction

The first part of this research is the monitoring part of the sandgroyne nourishments realized near Ter Heijde in October and November 2009. The execution and evolution of the sandgroynes have been monitored intensively, conducting regular bathymetry and beach surveys, taking sand samples, collecting dredging progress logs and figures, and making photographs of dredging activity and sandgroyne evolution. Figure 3-1 presents an overview of the frequency and dates of the executed bathymetry surveys, the project nourishment progress, and the meteorological conditions represented by the rolling average of the significant wave height during the Ter Heijde nourishment campaign.

![Figure 3-1 Overview of the data collected during the monitoring campaign.](image)

The experience and observations during the nourishment campaign near Ter Heijde, in combination with the results of the data analysis, will eventually lead to the integral assessment of sandgroyne nourishment. This chapter briefly describes the monitoring procedures followed and the usefulness of the data collected. For an evaluation of the monitoring campaign, as a part of the practical implication of the sandgroynes, is referred to Chapter 5.
3.2 Overview of the collected data

3.2.1 Bottom elevation data

During the Ter Heijde nourishment campaign, regular bathymetry and beach surveys have been undertaken by a team consisting of project survey staff and some PhD- and MSc- students from the Delft University of Technology. The data will be used to analyze the morphological behavior of the nourishments executed near Ter Heijde. Three monitoring platforms have been implemented:

- Project survey car, equipped with RTK (Real Time Kinematic) and a single beam echo sounder (Photo 3-1)
- TU Delft jetski, equipped with RTK and a single beam echo sounder (Photo 3-2)
- Project survey vessel, equipped with a multi beam echo sounder (Photo 3-3)

Figure 3-2 presents an overview of the coastal profile covered by each of the implemented survey platforms. The instantaneous water level allows the jetski during high tide to connect to the part surveyed by the survey car during low tide. Hence the survey car commonly operated during low water, the jetski commonly during high water. Full data coverage of the areas surveyed by the jetski and the survey car is crucial as the intertidal zone and the shallow part of the shoreface is probably the most dynamic part of the coastal profile and considered to be the most affected by the sandgroyne nourishments.

The priority of the surveys was to maximize the survey area in longshore direction. The sand originating from the sandgroynes was transported predominantly in northward, longshore direction. The spatial scale of sediment redistribution was in the order of several kilometers at least. The planning of bathymetry surveys is limited by several factors, so it is of crucial importance to carefully plan the surveys and to optimally implement the survey platforms.
The following factors are relevant for the survey planning:

- **Dredging activity**: for safety reasons it is not allowed to survey close to dredging operations. Safety has priority over the urgent need of data.
- **Meteorological conditions**: Severe meteorological conditions potentially result in dangerous situations caused by high waves and strong winds (especially in the surfzone where the waves break: the operational area for the jetski), obstructing the sea based survey platforms to operate. Besides the safety issue, severe conditions also reduce the quality of data.
- **Tidal situation**: According to the adopted procedure, landsurveys are to be executed at low water; bathymetry surveys at high water. Note that the mentioned tidal phases usually last for several hours only, return on different times every day (daily inequality) and are potentially affected by local meteorological conditions (wind & wave set-up).

As a survey platform, the jetski is unique because of its limited draught, therefore suitable to survey the shallow part of the shoreface, not to be covered by the survey vessel (requiring a larger depth), neither by the survey car (restricted to the dry part of the coastal profile). Implement the jetski only on the specific part of the cross-shore coastal profile that can not be surveyed by the alternative survey platforms, enables to maximize the survey area in longshore direction, an important aspect for the principle of the sandgroyne nourishments.

Although the meteorological conditions in October, November and December 2009 have not been favorable for executing frequent surveys, still a number of quality datasets representing the bathymetry at certain moments have been acquired. An example of one of the datasets, including field data acquired by all three survey platforms, is presented in Figure 3-3. This dataset contains field data surveyed on the 2\textsuperscript{nd}, 3\textsuperscript{rd} and 4\textsuperscript{th} of December 2009.

![Figure 3-3 Google Earth image showing the Ter Heijde site including the location of datapoints surveyed by the different implemented survey platforms.](image)

**Figure 3-3 Google Earth image showing the Ter Heijde site including the location of datapoints surveyed by the different implemented survey platforms.**
Each data point indicated in Figure 3-3 carries coordinates in three dimensions: two coordinates define the location in the horizontal plane (x and y in the RD coordinate system) and one in the vertical plane (the elevation referred to NAP). The datasets presented in Figure 3-3, obtained with the survey platforms provided with a single beam echo sounder (the jetski and survey car), represent the transects covered in cross-shore direction. The transects have a cross-shore orientation as the most significant bathymetry variations occur in cross-shore direction, thus requiring the highest resolution. The data resolution is about 5m in cross-shore direction and 25m in longshore direction. The data surveyed by the project survey vessel, equipped with a multibeam echo sounder, is provided on a regular, high resolution grid. Figure 3-3 shows that there is some overlap of the areas covered by each of the implemented survey platforms. The overlap is used for relative validation of the surveyed data, by comparing the data of the same area surveyed by different survey platforms. Overall, the bathymetry data surveyed by the different survey platforms corresponded fairly well; diverging in the order of several centimeters maximum.

3.2.2 Hydrometeo data

Paragraph 2.2 presents an overview of the wave and wind climates in the North Sea for two distinct seasons, the summer season and the winter season; Figure 3-4 shows wave roses representing the wave climate for the period associated with the nourishment campaign near Ter Heijde; October, November and December. Figure 3-4 shows the wave climate over the years 1979-2001, Figure 3-5 over the year 2009. A larger version of the wind climate plots is included in Appendix F.

Figure 3-4 Wave climate of the period from October until December in the years 1979-2001, based on wave timeseries recorded by several stations in the North Sea.

Figure 3-5 Wave climate of the period from October until December in 2009, based on wave timeseries recorded by several stations in the North Sea.

Figure 3-4 represents the average wave climate by considering the same period over 23 years in total. Comparing the wave climate of 2009 with the averaged wave climate clearly indicates some differences. In 2009 especially the southwesterly waves were dominant. Overall, the higher waves, represented by the red colored classes in both figures, were dominant in October - December 2009 compared to the representative wave climate.

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2 The RD coordinate system (in Dutch: 'Rijksdriehoekstelsel') is the Dutch national standard for geographical indications.

3 The NAP reference level (in Dutch: 'Normaal Amsterdams Peil') is the Dutch national standard for indicating elevations.
3.2.3 Grain size distributions

Throughout the monitoring campaign, sand samples have been taken at and adjacent the site area. The sand samples have been sieved and sediment characteristics have been derived. Appendix H presents the results of the sand sample analysis. The grain size is a design parameter of the sand groynes, so interesting to monitor from the dredging industry point of view. For the sandgroyne nourishments a relatively large grain size has been used ($D_{50} \approx 280\mu m$) compared to the size naturally found in the area ($D_{50} \approx 200\mu m$).

From an analysis point of view, the divergent sediment characteristic can be used as a measure to track the sediment originating from the sandgroynes. It is important to realize that the results of an analyzed sand sample should always be compared with the characteristics of the sediment naturally found on the same location. The grain size of 200$\mu m$ mentioned is averaged; but for instance in the swash zone (the zone of wave action on the beach) usually a somewhat larger grain size is naturally found. This indicates that a larger grain size can not be directly related to sediment originating from the sandgroynes, without having reference information.

3.2.4 Photos

Photos have been taken on a daily basis, recording dredging operations and coastal features related to the Ter Heijde nourishments. The photos will be used as a support for observations and conclusions derived from the data analysis, model simulation results and practical implication evaluation throughout the report. Unless otherwise stated, all the photos presented in this report are taken by the research author.

3.2.5 Dredging progress logs

The personnel operating on site logs all the information about each nourishment session executed, for instance the onshore location of the discharge point and the amount of sediment pumped in. The gross amount of sediment pumped in is provided by the dredging vessels. The sediment volumes present in the hopper can be estimated with an inaccuracy of about 1%. A loss factor of 12% is used to account for the sediment losses from the moment it is pumped in the sinker pipeline offshore until it is surveyed. Under the governing contract requirements, the survey results are used to settle the contract requirements, not the data provided by the dredging vessel. The loss factor of 12% takes the following aspects into account:

- The measuring inaccuracy of the dredging vessel
- The loss of sediment while it is transported through the pipeline
- The finer particles not even accumulating
- The accumulated sediment that is transported away before it has been surveyed, actually ‘establishing’ the nourishment.

For the evaluation of the nourishments executed, the pumped amounts of sediment will be compared with the survey results, indicating the redistribution and potential losses of sediment. All the pumped up sediment quantities given in this report represent net quantities; the loss factor of 12% has been taken into account. For more information on the nourishment procedures is referred to Appendix C.
4. MORPHOLOGICAL ANALYSIS

4.1 Introduction

In this chapter, a morphological analysis will be performed to study the morphological evolution of the sandgroyne nourishments, realized in October and November 2009. An extensive monitoring program was initiated to acquire field data and facilitate a thorough analysis of the effectiveness of the sandgroynes. The results of this chapter will be used to assess the following morphology related hypotheses formulated in Chapter 2, proposed by Walstra & Mol [2009].

- The sediment will be evenly redistributed in longshore direction, initially filling the gaps between the three sandgroynes.
- For an averaged spring wave climate, the sandgroynes are absorbed in the coastal system in the order of several months.
- During storm conditions the sandgroynes are absorbed in the coastal system in the order of several days.
- The offshore losses of sediment seaward of the -5m depth contour are limited.
- The tidal current, without wave forcing, is not capable to absorb the sandgroyne sediment in the coastal system.
- Leeside erosion caused by the presence of the sandgroynes is not observed.
- In a short phase direct after completion of a sandgroyne, the swimmers safety is endangered due to increased flow velocities near the sandgroynes.

This chapter adresses three aspects of the sandgroyne nourishments:

1. The sediment redistribution of the Ter Heijde nourishments, for the period between September 2009 and January 2010.
2. Impact of the November 2009 storm on the morphology of the sandgroyne nourishments.
3. Morphological evolution of the sandgroynes, for a range of representative conditions along the Holland coast by implementation of a numerical simulation model

The first aspect actually presents the result of the nourishments based on a quantification of the redistributed sediment. An overview is presented of the amount and location of the pumped sediment volumes during the Ter Heijde nourishment campaign. These data will be compared with the result of the bathymetry ‘insurvey’ and the ‘outsurvey’, indicating where the sediment has accumulated.

The second aspect to be analyzed concerns the impact of the storm in the last two weeks of November 2009 on the morphology of the sandgroynes, based on the fielddata. The strategy starts with the observation of sediment motion on single sandgroyne scale, aiming to aggregate the observations to the elementary hydrodynamic and sediment transport processes towards a larger spatial scale. Figure 4-1 presents the spatial scales consecutively considered in the analysis of the impact of the November storm. The sandgroyne nourishments all have been realized in the Ter Heijde site area.
For the third aspect, a numerical simulation model will be used to simulate the morphological behavior of the sandgroynes for a range of alternative scenarios. The aim is to verify the processes that drive the redistribution of the sandgroyne sediment, as identified in the data analysis, and to get more general insight in the morphological evolution of sandgroynes under influence of some alternative conditions.

Each of the mentioned aspects will be treated consecutively in the subsequent paragraphs.

### 4.2 Sediment redistribution of Ter Heijde nourishments

#### 4.2.1 Approach

In this paragraph a quantification of the sediment redistribution of the entire Ter Heijde nourishment campaign between September 2009 and January 2010 is presented. In this context the following quantifications are distinguished:

- Design volumes
- Net nourished volumes
- Surveyed volumes
The design volumes represent the amount of sediment that is required to settle the contract requirements. The design volumes are determined by subtracting the instantaneous state of the cross-shore profile from the design profile; the difference is the amount of sediment that has to be nourished (per stretching meter coast) to reach the design profile, see Figure 4-2. Subsequently the longshore stretch of coast that is represented by the cross-shore profile determines the absolute sediment volume.

The net nourished volumes represent the volumes originating from the hopper barge, corrected for all the potential losses with a common adopted factor of 12% (see Chapter 2). These net nourished volumes actually represent the amount of sediment pumped up during the Ter Heijde nourishment campaign.

The surveyed volumes represent the morphological evolution of the coast over a certain period, under influence of the autonomous behavior of the coast and the nourishments. The surveyed volumes are determined by subtracting two consecutive bathymetry surveys. The principle is the same as indicated in Figure 4-2. For this paragraph the surveys of September 2009 and January 2010 are used.

The above mentioned volume parameters will be compared, which allows for an analyzation of the nourishments executed. This relatively long period is preferred for setting up a sediment balance as an insurvey and outsurvey dataset, covering all the Ter Heijde site operations both in temporal and spatial scale, is available.

4.2.2 Assumptions

Beach nourishments aim to realize the design profiles for the dry part of the coastal profile, comprising the beach and the dunes. Part of the sediment pumped up however, will also flow in the shoreface. Photo 4-1 and Photo 4-2 illustrate possible effects on the shoreface as a result of beach nourishments executed. The sandgroyne nourishments aim to fill the remaining part of the design in the shoreface.
Photo 4-1 shows an image of the effects of a nourishment session executed in the dunes. The outflow system, preventing the dune area to be filled from flowing over, causes an outflow flowing back into the sea. Residual amounts of suspended sediment and the momentum affect the status of the beach and the shoreface. Photo 4-2 shows a nourishment executed close to the shoreline. Whether it is intended or not, sediment will indefinitely flow into the shoreface. These two pictures indicate that sediment formally pumped in the dry part of the coastal profile (the beach and the dunes) will partly accumulate on the shoreface.

For the analyzation of the nourishments executed, it is assumed that the design in the dunes and on the beach is exactly realized throughout the Ter Heijde nourishment campaign and still realistically represented by the outsurvey of January 2010. This is a theoretical, but reasonable assumption because:

- The design in the dunes and on the beach is accurately constructed by careful allocation of the sediment discharge and implementation of dozers.
- For the temporal scale considered, the morphology of the dunes and the beach is not so much affected by the dynamics of nature as the shoreface is.

The assumption facilitates an estimation of the total amount of sediment pumped up that accumulated either in the dunes and on the beach or in the shoreface. Especially with respect to the sandgroyne nourishment intend to nourish the shoreface, it is important to get an impression of the contribution of both nourishment types to the morphology of the shoreface. The accompanying figures will be presented in the subsequent sub-paragraph.

4.2.3 Design and nourishment quantifications

Beach nourishments have been executed over the entire site length. The specific locations of the sandgroyne nourishments are presented in Figure 4-3. The figure shows the Ter Heijde site area including a representation of the bottom as surveyed on the 6th of November 2009. The first two sandgroynes already had been realized: the first one has already been partly absorbed in the coastal system; the second one is just completed. The third
sandgroyne is not yet realized on the presented survey date, nevertheless the prospected location is marked by the black circle. Photo 4-3 shows a photo taken of the second sandgroyne on the 7th of November. Note that the second sandgroyne approaches a mushroom like shape. This shape is strongly associated with the method of execution; more details are provided in Chapter 5.

Figure 4-3 Plan view of the site area, including a representation of the bathymetry with the sandgroyne nourishments (surveyed on 6 November 2009).

Photo 4-3 Photo of the second sandgroyne (taken in northern direction on the 7th of November).

Figure 4-4 presents the design volumes for the Ter Heijde site as from September 2009, and the volumes actually pumped up throughout the entire nourishment between September 2009 and January 2010. It has been assumed that all the sediment has been nourished within the boundaries of the Ter Heijde site. Distinction is made for the dry part (beach & dunes: upwards of -0.70m NAP) and the submerged part (shoreface: -0.7m NAP - -5.0m NAP) of the coastal profile. Table 4-1 shows the accompanying values, presented in million cubic meters. Hence, in theory the nourished volumes should correspond to the design volumes.
A number of remarks should be made about the results presented in Figure 4-4 and Table 4-1:

- The figures presented concern the nourishments executed over the entire nourishment period and do not contain any information about the order of execution. More information on the approach and execution is provided in Chapter 5.
- Although the sandgroyne nourishments initially have been realized in an area overlapping both the beach and the shoreface with an elevation up to +1.5m NAP; the sediment is supposed to nourish the shoreface and therefore considered as a ‘shoreface nourishment’.

The most important observations to be derived from Figure 4-4 and Table 4-1:

- As assumed in the previous sub-paragraph, the amount of sediment nourished on the beach and dunes is according contract requirements.
The remaining amount of sediment pumped up in the scope of the beach nourishment (0.77 Mm³) is assumed to have settled in the shoreface, that is about 40%.

The positive sediment balance of +0.13 Mm³ indicates that more sediment has been pumped up during the Ter Heijde nourishment campaign than required according to the design.

Of the total amount of sediment nourished in the shoreface (1.3 Mm³), 41% is realized by the sandgroyne nourishments and 59% by the beach nourishments.

A substantial part of the sediment settled in the shoreface in the scope of the beach nourishments, is sediment that had to be nourished additionally due to the severe weather conditions resulting in instant sediment losses; transported out of the Ter Heijde site area in northward direction.

4.2.4 Sediment redistribution

This sub-paragraph aims to verify whether the amounts of sediment that can be derived from the bathymetry surveys actually correspond to the pumped amounts of sediment, presented in the previous sub-paragraph. An important aspect is the redistribution of sediment originating from the sandgroyne nourishments. In this context the ‘insurvey’, surveyed just before the start of the Ter Heijde nourishment campaign in September 2009, will be compared with the ’outsurvey’, surveyed just after the Ter Heijde nourishment campaign in January 2010. This relatively long period is preferred for quantification of the sediment redistribution as it is certain that the total amount of sediment pumped up during the Ter Heijde nourishment campaign is contained both in the temporal and spatial scale considered. That justifies the comparison of the pumped amount of sediment with the bathymetry surveys. The bathymetries are represented in Figure 4-5, including a sedimentation/erosion plot presenting the morphological evolution. A larger version is included in Appendix F.
The area considered stretches about 8.5 km in longshore direction. Obviously the Ter Heijde site area, indicated by the black rectangle and stretching about 2.5km in longshore direction, shows major changes in the morphology as this area has been subject to artificial sand nourishments. The most significant changes are observed from the dunes until the shoreface to a depth of about -5m. Southward of the site area, erosion is observed in the swash zone of the coastal profile, resulting in a retreat of the shoreline of about 50m. This area was nourished before the summer of 2009. North of the site area, between KM 105.000 and KM 110.300, sedimentation is observed, dominantly between the -2m and -5m depth contour. The sedimentation area enclosed by KM 105.000 and KM 106.000 in longshore direction and by the -5m and -8m depth contour in cross-shore direction is the result of new rainbowed hopper volumes in the scope of the Kijkduin nourishment campaign, which started mid-January 2010. These volumes are not taken into account in the sediment redistribution analysis, focusing on the Ter Heijde nourishment campaign only.

Figure 4-6 presents a quantification of the sediment balance per profile stretching from the dunes until a depth of -5m NAP, for the planform area and period considered in Figure 4-5. The figure includes the redistribution of the sediment nourished in the scope of the Ter Heijde nourishments, but interferes with the autonomous behavior of the coast in the area. The results of the sediment balance presented in Figure 4-6 will be compared with yearly
averaged sediment transports in and out of the coastal system as a result of the morphodynamic autonomous behavior.

Figure 4-6: Plot of the sediment volume balance per profile, for the period between September 2009 and December 2010.

A number of observations can be made from Figure 4-6:

- The position of the sandgroynes marked by the thin, black dashed lines is clearly reflected in the survey data; showing peaks in the sediment volume balance.
- The area south of the Ter Heijde site (KM112.600 – KM113.500) has been suffering severely. The coastal retreat is about 100m³/m, likely associated with the reformation of the coast towards an equilibrium state after it has been brought out of equilibrium by the sediment nourishments executed just before the summer of 2009.
- The evolution of the site adjacent areas north and south of the Ter Heijde site differs. Supported by the prevailing south-west conditions in the period considered, the northern area seems to be affected by the nourishments realized on the Ter Heijde site showing a decreasing positive trend in northern direction. The area south of the Ter Heijde site shows a negative sediment balance.

The evolution of the area south of the Ter Heijde site is likely much less affected by the nourishments executed on the Ter Heijde site. Assuming that the negative balance visible in the area south of the Ter Heijde site reflects the autonomous behavior of the entire Ter Heijde and Kijkduin coast presented in Figure 4-5, it can be concluded...
that the northern site adjacent area, showing a positive sediment balance in Figure 4-6, has been affected by the nourishments executed on the Ter Heijde site. Table 4-2 presents a quantification of the survey results for the Ter Heijde site and the site adjacent areas north and south, derived from Figure 4-6.

<table>
<thead>
<tr>
<th>Surveys</th>
<th>Survey south (10^4 m³)</th>
<th>Survey Ter Heijde site (10^4 m³)</th>
<th>Survey north (10^4 m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total</strong></td>
<td>-0.10</td>
<td>1.90</td>
<td>0.24</td>
</tr>
<tr>
<td><strong>Shoreface</strong></td>
<td>0.02</td>
<td>0.85</td>
<td>0.15</td>
</tr>
<tr>
<td><strong>Beach &amp; dunes</strong></td>
<td>-0.12</td>
<td>1.05</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Table 4-2 Overview of the survey results for the Ter Heijde site and the site adjacent areas north and south, for the period between September 2009 and January 2010.

Figure 4-7 and Table 4-3 present the sediment volumes associated with the design, the nourishments and the difference between the surveys of September 2009 and January 2010. The survey results follow from Figure 4-6 and Table 4-2. The balance presented in Table 4-3 represents the balance between the nourished sediment volumes and the volumes derived from the survey of September 2009 and January 2010 in the site area and the northern site adjacent area. The survey of the area south is not included in the ‘survey’ column as it was assumed that this area is not affected by the Ter Heijde site nourishments.

Figure 4-7 Bar diagram presenting the design volumes the nourished volumes and the surveyed volumes.
Design (10⁶ m³) | Nourishments (10⁶ m³) | Survey (10⁶ m³) | BALANCE (10⁶ m³)
---|---|---|---
Total | 2.35 | 2.48 | 2.14 | -0.34
Shoreface | 1.17 | 1.30 | 1.00 | -0.30
Beach & dunes | 1.18 | 1.18 | 1.14 | -0.04

Table 4-3 Overview of the design, the pumped amounts of sediment and the survey results for the Ter Heijde site and northern site adjacent area between September 2009 and January 2010.

A number of observations can be made about the results presented in Figure 4-7 and Table 4-3:

- The sediment volume derived from the surveys misses 0.34 Mm³ of sediment compared to the amount of sediment pumped up.
- As expected, the biggest contribution to the negative balance is observed in the shoreface. This part of the coastal profile is the most dynamic part, consistently subject to the impact of waves and currents.
- On average, the sediment balance is about +50m³/m northward and -100m³/m southward of the site.

Instead of the sandgroyne nourishments, a more conventional nourishment method to nourish the shoreface could have been opted for; the effect of these nourishments would have resulted in a seaward coastal extension similar to the extension of the southern site adjacent area. Referring to the observed evolution of the southern site adjacent area, significant sediment losses then should have been accounted for as well.

4.2.5 Validation of sediment redistribution

Chapter 2 presented the year-averaged sediment budget model, transformed to the area considered in this paragraph. The local sediment budget model is again presented in Figure 4-8, indicating an averaged sediment loss of 30.000m³ per year; whereas Table 4-3 presents a sediment loss of 0.34 Mm³ in a season of 4 months. Although the transport rates in Figure 4-8 represent a different temporal scale, still the major difference between the observed losses and the averaged losses, representing the autonomous behavior, suggests that a substantial part of the sediment losses can be related to the nourishments executed in Ter Heijde. This sub-paragraph aims to qualitatively transform the transport vectors towards season representative vectors.

The presented yearly-averaged sediment loss, as a result of the autonomous behavior of the coastal

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4 Presents summation of beach and sandgroyne nourishments, separately presented in Table 4-1
5 Presents summation of the survey of Ter Heijde site and northern site adjacent area, separately presented in Table 4-2
system, is supposed to be somehow underestimated, especially for the area and period considered in this research. Based on the limited availability of data and the framework of the research, a quantitative review of the sediment budget model is not made; however a number of qualitative grounds can be mentioned to transform the averaged, seasonal sediment losses towards the observed losses:

- The observed wave climate evidently deviates from the averaged wave climate in the season, where the sediment budget model is based on (for visualizations of the wave climates is referred to Chapter 3). The more intense and dominant south-western wave climate supposedly contributes to a percentage increase of the longshore sediment transport vectors. That indicates an increased, negative longshore sediment transport gradient.

- The sediment transport vector across the -8m depth contour is the most uncertain quantification of the transport vectors included in the sediment budget model. The vector is a collection of different bidirectional processes, mostly season or wave condition dependent. Van Rijn [1997] states that net offshore transport is generally dominant during conditions with breaking waves. In this context, the season and intense wave conditions observed in this research suggest a less dominant offshore directed sediment transport across the -8m depth contour.

Another aspect that can be used to validate the sediment losses, based on more recent data, is the yearly averaged amount of sediment nourished in the area, presented in Appendix B. Data of local executed, artificial sand nourishments indicate that in the past decennium a yearly-averaged amount of 700,000m³ of sediment has been nourished in the Ter Heijde coast area. Assuming the coastline is dynamically maintained based on a fixed, reference coastline, the yearly-averaged nourishment values should roughly correspond to the year-averaged sediment losses. In this context, the averaged amount of nourished sediment puts the observed sediment losses (0.34 Mm³), although not representative for a similar period, in a reasonable perspective. Based on this information, it can be concluded that the observed sediment losses can be substantially related to the sediment losses as a result of the autonomous behavior of the system.

4.2.6 Conclusions redistribution of sandgroyne sediment

- Based on the severe, SW conditions observed, the area north of the Ter Heijde site has been affected by the nourishments executed near Ter Heijde, on a scale of at least 5km. Further northward, data is not sufficiently available to draw a conclusion from.

- Although sediment has been transported relatively far in longshore direction, the sedimentation/erosion plot in the previous sub-paragraph indicates that the sediment has been retained in the active zone of the coastal profile (landward of the -5m depth contour).

- As a result of the autonomous behavior of the coastal system, it is roughly estimated that sediment losses in the order of several hundred thousand cubic meters have to be accounted for in the study area, independent of the Ter Heijde nourishment method applied in the season from September 2009 until January 2010.

- Based on the evolution of the southern site adjacent area and the conditions observed, adopting a more conventional nourishment method based on a regular longshore nourishment interval, instead of the sandgroyne nourishments, would also have resulted in significant sediment losses.

- Offshore sediment losses can not be quantified for the considered period as the offshore part is not covered by both datasets.
4.3 Impact of the November 2009 storm

Right after realization of the third, most southern located sandgroyne nourishment on the 9\textsuperscript{th} of November (see also Appendix E), the site was exposed to a stormy period for the remaining duration of the month. Consistent offshore wave heights of 2-3m and maxima up to 5m occurred. The morphological response of the sandgroyne nourishments on the impact of the storm is analyzed for the period between the 16\textsuperscript{th} of November and the 2\textsuperscript{nd} of December 2009 to identify the dominant processes in the redistribution of the sandgroyne sediment. This specific period has been chosen based upon the following reasons:

- For both dates, local bathymetry data are available surveyed during the monitoring campaign.
- All three sandgroynes have been realized and are still present in this period, which allows observing possible interaction between the sandgroyne nourishments, next to the morphological evolution of single sandgroyne nourishments. Though it should be noted that none of the sandgroynes still has the initial, most protruding shape from right after they were completed, in particular the first one which has visibly been absorbed for a substantial part. The sandgroynes are all in an advanced evolution phase. In this context the morphological evolution presented in this sub-paragraph is not representative for the morphological evolution just after completion of a sandgroyne.
- Production rates of the project beach nourishments were poor in this period, due to the bad weather conditions. Therefore insignificant quantities of nourished sediment are incorporated in the data, facilitating a quality morphodynamic analysis.

To perform the morphodynamic analysis, pre-storm and post-storm bathymetry data will be presented in the form of sedimentation/erosion plots and evolution of cross-shore profiles. The aim is to relate actual hydrodynamic and meteorological conditions and locally present coastal features and characteristics to the observed morphological evolution. The results should lead to verification of the hypotheses formulated in the preliminary morphological study [Walstra & Mol, 2009] (see Chapter 2) and should contribute to general understanding of the short-term morphodynamics around similar nourishments.
4.3.1 Hydrodynamic and meteorological conditions

During the monitoring campaign, local bathymetry data has been recorded in high resolution. Meteorological and hydrodynamic data is also available, however not as a part of the considered monitoring campaign and therefore not locally recorded. Several monitoring platforms are located offshore in the North Sea, continuously recording data of hydrodynamic and meteorological processes and readily available. The offshore wave data as recorded by the Europlatform monitoring station (see Figure 4-9) will be used as boundary condition for a process based, numerical simulation model to transform the wave characteristics towards the nearshore (depth ~ 10m), representative for the site local morphodynamics. Wind fields occur on such a large spatial scale that the wind field is considered as uniform over the area considered in Figure 4-9. The wind data of the monitoring station at the Hoek van Holland Noorderdam (see Figure 4-9) is used. Wind is an important driving force for aeolian transport on the beach, local generated wind waves and surface currents, and water level set-up.

Figure 4-10 shows time series of respectively the wave height, wave direction and wind speed of the month November 2009. The colors of the curves refer to the colors of the monitoring platforms marked in Figure 4-9, the vertical black lines to bathymetry survey dates. Appendix F presents times series for a substantial period of the Ter Heijde nourishment campaign; the months October, November and December 2009.
The figure indicates calm offshore wave conditions occurred during the first half of the month, with an averaged wave height of 1-2m and a number of peaks up to 3 and 4m. However, the second half of November shows a more intense climate. Especially in the period from the 22\textsuperscript{nd} until the 29\textsuperscript{th} of November, with an average wave height of 3m and peaks up to 5m, coming from south-west. By refraction, the waves have been transformed from consistent offshore south-western orientation towards consistent nearshore western orientation by the simulation model, indicated in Figure 4-9. A period of swell waves coming from north-west is observed early December 2009. The offshore significant wave height has decreased with 1-2m to an averaged nearshore significant wave height of 1-2m and peaks up to 3m. Wind speed varies between 10-15m/s, classified as level 6-7 on the scale of Beaufort and classified as ‘powerful’ (officially in Dutch: ‘krachtig’) by the Dutch meteorological institute KNMI.

The yellow marked period between the surveys of the 16\textsuperscript{th} of November and the 2\textsuperscript{nd} of December is subjected to a morphodynamic analysis.

### 4.3.2 Nourishment progress

During the period considered for the morphodynamic analysis, beach nourishments have been executed despite the severe weather conditions. Figure 4-11 shows a pre-storm bathymetry and a sedimentation/erosion plot for
the considered period (also included in Appendix F). The sedimentation/erosion plot is a result of the pre-storm and the post-storm bathymetry, derived from bathymetry surveys. Besides the morphological evolution, the plot also shows the locations where beach nourishments have been executed; the concerning profiles are marked by the bold red line. In a time span of two weeks, only 100,000 m³ of sediment has been nourished. On average, this is about 7,000 m³ per day, where normal production rates reach 25,000 to 30,000 m³ per day. The production rates for the considered storm period were about 5 times less compared to the normal production rates. Although these rates are relatively low, still the sedimentation and erosion spots showing up in these areas require careful interpretation with respect to the interpretation of the sandgroyne nourishments.

As presented in the chapter introduction, the morphological data analysis is performed distinguishing different, increasing spatial scales. The increasing spatial scales are consecutively considered in the subsequent sub-paragraphs.

4.3.3 Morphodynamics on sandgroyne scale

Photo 4-4 illustrates the impact of the storm on the morphology of the nourishments (both pictures are taken during high tide). The picture on the left, taken before the storm, shows a symmetric shape of the third sandgroyne nourishment. The picture on the right, taken at the end of the storm shows a rather asymmetric shape; the shape seems to have changed into a spit-like formation caused by the dominant longshore, northward directed current during the storm. This evolution will be further established in this sub-paragraph.
Zooming in on the sedimentation/erosion plot in Figure 4-11, results in the plot presented in Figure 4-12. This plot allows for an interpretation of the morphological evolution on sandgroyne scale, focused on the nourishment itself. The most southern located sandgroyne is preferred (at profile KM 111.900), because

- The morphology of this sandgroyne is supposed to be the least affected by additional, meantime beach nourishments, see Figure 4-11.
- This sandgroyne is the most recent one realized and instantly constructed (see also Appendix E), therefore still least affected by meantime impact of the natural system. This enables analyzing the morphological evolution starting from an early stage in the evolution process.

As mentioned in the previous sub-paragraph, the short storm on the 14th of November affected the morphology of each of the sandgroynes. This means that at the start of the morphology analysis the southern sandgroyne is in an advanced evolution phase, not fully representative for the phase just after completion. Photo 4-5, taken on 10 November 2009, shows the southern sandgroyne just after completion and a northward located rubble mound groyne. The influence of the rubble mound groyne on the morphodynamics will be assessed.
The following observations can be made concerning the morphological evolution presented in Figure 4-12:

- The impact of the waves is clearly reflected in the location of the erosion spots showing up on the sandgroyne nourishments in Figure 4-12. The erosion spots show up where the local shore normal is orientated towards the nearshore incoming wave direction, which is west. This observation agrees with the expected impact of the waves; theoretically most intense with shore normal incidence. The impact of waves causes a cross-shore sediment transport from the foreshore (between +1m and -1m depth contour) seaward to the -4m depth contour at 400m cross shore distance, where obviously sediment is deposited (see also profile KM 112.100 plot in Figure 4-14). This transport is driven by the wave undertow, see Appendix A.

- Near the -4m depth contour, between the 400m and 500m cross-shore offset, a ripple pattern of sediment accumulation seems to have developed, with a horizontal length scale in the order of a hundred meters and a vertical length scale of up to one meter. This is at the landward slope of the subtidal breaker bar. Figure 4-12 shows that this pattern starts south of the sandgroyne nourishment and proceeds northward in longshore direction beyond the sandgroyne nourishment. Further northward, not included in Figure 4-12, this pattern seems to continue, however less pronounced. It is questionable whether this is formed by physical processes or caused by inaccuracies coming along with the data processing.
- Through the heart of the sandgroyne nourishment (between profiles KM 111.800 and KM 111.900 in Figure 4-12) the entire submerged part of the coastal profile is subject to erosion (see also profile KM 111.850 plot in Figure 4-14). The sandgroyne nourishment causes flow contraction; the longshore current is forced to converge and the velocity increases, resulting in scouring around the top of the sandgroyne. The process of flow contraction is illustrated in a conceptual model presented in Figure 4-13.

- Just down drift of the observed erosion spot a pronounced sedimentation area appears (between profiles KM 111.600 and KM 111.800 in Figure 4-12). A number of circumstances likely cause this sedimentation. The first one is the divergence of the current flow, allowing the velocity magnitude to drop reducing the sediment transport capacity. The second circumstance is the presence of a rubble mound groyne, partly trapping the sediment transported in northward direction.

Similar to the visualizations in the previous paragraph, treating the sediment balance over a large planform and temporal scale, a sediment balance of the area considered in this sub-paragraph is presented in Figure 4-15.
intention of the sediment balance is to qualitatively support the identification of the dominant processes, derived from the planform and cross-shore erosion/sedimentation plots. For this period, data coverage of the upper beach and dunes is lacking, therefore the sediment balance represents the foreshore and the upper shoreface only (+1m - -5m NAP).

A quick observation suggests that the appearance of the sedimentation and erosion fairly corresponds to the observations related to the planform morphological evolution derived from Figure 4-12. Remarkable is the total positive sediment balance of about +10,000m³ over the area considered. The potential accumulation of sediment from the intermediate executed beach nourishment should be taken into account. Although hard to quantify, the effects are expected to be in the same order of magnitude as the sediment balance quantification, definitely not larger. Nevertheless the sediment balance does not indicate significant sediment losses, though suggested by the previous identified dominant longshore processes. The balance could be caused by the following circumstances:

- Under the conditions observed, the sandgroyne related sediment transport rates balance the autonomous transport rates. As long as there is no gradient in longshore sediment transport, the overall sediment balance remains unchanged.
- The influence of the rubble mound groyne is more dominant than expected, trapping a substantial part of the updrift delivered sediment.
- The sandgroyne itself functions as a trap for longshore transported sediment. The sandgroyne supposedly only functions as a groyne in the early stages just after realization with a notable protrusion.
The reason for the erosion and sedimentation being in balance can be a combination of the above mentioned aspects. In order to firmly establish these suggestions, more frequent datasets or implementation of a thorough validated model with sufficient resolution is required.

In the framework of the research, the morphological evolution on sandgroyne scale is not further elaborated. However, the observations and suggestions will be referred to in the following analysis scales in the subsequent sub-paragraphs.

4.3.4 Morphodynamics on Ter Heijde site scale

The next step is to evaluate the morphodynamics of the Ter Heijde site during the same period, including the other sandgroyne nourishments by extending the study area. The aim is to verify whether the morphodynamic trends observed for the most southern located sandgroyne in the previous sub-paragraph, are also observed for the remaining two sandgroynes. This sub-paragraph also deals with the mutual interaction of the three sandgroyne nourishments (and the rubble mound groyne) as far as this can be derived from the data. Figure 4-16 shows the sedimentation/erosion plot.

For the two most northern located sandgroynes, the local sedimentation/erosion patterns show the same trend in comparison with the trend observed at the most southern located sandgroyne: the impact of waves is dominant on the area with shore normal orientation towards the incident wave approach angle, resulting in offshore directed sediment transport driven by the wave undertow. A pronounced sedimentation area shows up between the northern and middle sandgroyne. Although it is expected that this sedimentation area is partly caused by intermediate beach nourishments; indefinitely part of the sediment originates from an updrift sediment influx (middle sandgroyne) delivered by the longshore current. This suggests the capability of the most northern located sandgroyne to function as a sediment trap. The influence of groyne like structures on longshore sediment...
transport will be evaluated for the considered storm period since longshore transport is a key parameter in this research and two types of groynes frequently occur on the Ter Heijde coast:

- The static, rubble mound groynes. Although these groynes are relatively short and by far not extending the entire surfzone, its influence on the supposed, intensified longshore sediment transport as a result of the increased input of sediment by the sandgroyne nourishments will be examined.
- The temporarily present sandgroyne nourishments. Although its main function is to supply sediment to the shoreface, as supposed by the term itself, sandgroynes potentially interfere with longshore sediment transport as well, especially in the early phase just after realization.

![Conceptual model of hydrodynamic and morphological processes around a groyne.](image)

Figure 4-17 illustrates a conceptual model of the hydrodynamic and morphological processes on a stretch of coast interrupted by a groyne. The groyne partly extends the surfzone, representative for the situation of both the sandgroynes and the rubble mound groynes at the Ter Heijde coast. Locally, sedimentation is expected both at the updrift and downdrift side of the groyne. Updrift sedimentation is expected to be caused by trapping sediment transported along with the longshore current. The groyne is not extending the entire surfzone, which means that sediment will also pass the groyne. Deceleration of the flow velocity downdrift of the groyne causes a return flow, resulting in sedimentation directly downdrift of the groyne. Further downdrift the flow patterns will re-establish, however the transport capacity has significantly reduced with respect to the sediment concentration, as sediment transported along with the current has accumulated around the groyne. Therefore erosion is expected further downdrift.

The influence of the rubble mound groyne at profile KM 111.650 on the longshore sediment transport seems to be overwhelmed by the sandgroynes and dredging operations. Though both updrift and downdrift sedimentation is observed in accordance with the processes described in the conceptual model. The northern sandgroyne, located at profile KM 110.700, was completed more than a month before the start of the period subject of this morphodynamic analysis, thus not expected to have a significant influence on the longshore transport. However, the pronounced sedimentation area updrift of the northern located sandgroyne, around profile KM 110.900, suggests differently. Although meantime beach nourishments contributed to this sedimentation area, it is still expected that part of the sediment is trapped by the most northern located sandgroyne.

The middle and southern located sandgroyne, respectively at profile KM 111.100 and KM 111.900 and still a pronounced feature along the coastline, potentially interact as well. The updrift located sandgroyne functions as a sediment influx; sediment is transported along with the longshore current and trapped by the northern sandgroyne. The sedimentation area updrift of the middle sandgroyne is the result of a number of different processes, so quantification of the contribution of longshore process is retained from. Nevertheless it is suspected that the sediment transported along with the longshore current contributed to the sedimentation area. A
sandgroyne nourishment on itself does not seem to be able to trap a significant amounts of sediment during calm to moderate conditions and the short time frame in which the sandgroyne can be reasonably considered as a ‘groyne’. An increased, updrift input of sediment is crucial.

It can be hypothesized that accurate planning of the construction of sandgroyne nourishments can influence the sediment transport. The combination of two sandgroynes in which one of them functions as an (increased) sediment influx in moderate to rough conditions and one as a sediment interference has potential in manipulating the sediment redistribution. In this context it is important that a dominant longshore current is present and both sandgroynes are realized within a short timeframe.

In Figure 4-18 the evolution of two cross-shore profile is presented. The left profile represents the evolution of the sedimentation area between the northern and middle sandgroyne; the right profile represents the evolution of the sandgroyne itself. Although the initial profiles, representing the 16th of November, strongly deviate; in about two weeks time both profiles seem to evolve towards a more constant sloping, equilibrium profile. Both profiles representing the 2nd of December adapt to an averaged slope of 1/40.

For this analysis scale, again a sediment balance is included to support a few of the observations made and possible to do some additional observations. The sediment balance is presented in Figure 4-19. The planform area has been extended to cover the entire Ter Heijde site, corresponding to the analysis scale considered in this sub-paragraph. The cross-shore is remained constant, representing the foreshore and the upper shoreface (+1m - -5m NAP). It should be noted that part of the additional nourished sediment in the considered period (±100.000m³) will be incorporated in the sediment balance. The overall sediment balance presented in Figure 4-19 approaches zero. The fact that the sediment balance approaches zero in combination with nourishments executed suggest that sediment has been transported out of the site area. Besides this general observation, the following observations can be made:
Compared to the southern sandgroyne, the same erosion and sedimentation patterns appear for the middle sandgroyne, to a lesser extent for the northern sandgroyne as well.

The longshore stretch of erosion around the middle sandgroyne is somewhat narrower and more intense. This can be associated with the middle sandgroyne being slender and more protruding compared to the southern sandgroyne, therefore increasing the morphodynamic sensitivity.

Obviously, concentrated sedimentation areas appear downdrift of the southern and middle sandgroyne. Downdrift of the northern sandgroyne, a groyne like structure to trap sediment is missing. The sediment is expected to be transported northward over a larger spatial scale.

### Figure 4-19 Sediment balance of the foreshore and upper shoreface (+1m - -5m NAP) on site scale for the period between 16 November 2009 and 2 December 2009.

#### 4.3.5 Morphodynamics on Ter Heijde coast scale

The study area has been extended in longshore direction, further northward. Figure 4-20 shows the sedimentation/erosion plot, now considering an area of more than 4km in longshore direction. At profile KM 109.400 another rubble mound groyne is present. In reality more groynes are present, however either physically covered by the nourishments executed or with minor length thus not expected to influence the morphodynamics. The rubble mound groyne at profile KM 109.400 clearly influences the morphodynamics; ath the southern side
longshore processes seem to dominate, at the northern side cross-shore processes. Southward, sediment settles around the -2m depth contour. However, directly north of the groyne a different trend seems to arise. Sediment still settles in the same part of the profile (around the -2m depth contour), but coming along with erosion patterns right above and below in the profile. This pattern proceeds until profile KM 109.000; from this profile up northward actual data of the pre-storm situation is not available. Figure 4-22 shows two characteristic cross-shore profiles of profile KM 109.200, representing the area north of the groyne, and profile KM 109.700, representing the area south of the groyne, confirming the observation.

Figure 4-20 Sedimentation/erosion plot representing the period of the last two weeks of November 2009, focused on the Ter Heijde coast.

Figure 4-21 Conceptual model of hydrodynamics around a rubble mound groyne, indicating cross-shore processes dominate the morphodynamics downstream of the groyne.

The presence of the rubble mound groyne at profile KM 109.400 is clearly reflected in the sedimentation/erosion patterns. North of the breakwater (characterized by the left plot in Figure 4-22) autonomous, cross-shore processes seem to dominate as the area and the intensity of the erosion spots seem to balance the sedimentation spots. The area south (characterized by the right plot in Figure 4-22) is subject to sediment depositions, likely originating from the sandgroynes as the analysis showed out that sediment is transported along with the longshore current. The current north of the site is not affected anymore by the physical presence of the sandgroyne nourishments, the current speed will drop allowing the sediment to settle.
Overall the data analysis indicates that locally the wave impact is an important parameter in the morphodynamics around sandgroynes. Under the conditions observed, a moderate to rough waveclime with dominant southwesterly waves, sediment is transported both in cross-shore and longshore direction. The cross-shore transport is driven by the wave induced undertow, proportional to intensity of the wave height and redistributes sediment from the foreshore seaward to the -4m depth contour. The longshore transport is dominantly driven by the wave induced longshore current, proportional to the intensity of the wave height and the angle of approach, and redistributes the sediment in longshore direction from the sandgroynes roughly between the -1m and -5m depth contour. Besides, the data analysis does not indicate significant offshore losses of (sandgroyne) sediment, seaward of the -5m depth contour. The influence of the rubble mound groynes on the site area seems to be overwhelmed by the dredging operations. North of the site area the influence of the groyne located at profile KM 109.400 is noticeable, however not suspected to significantly influence the longshore redistribution of sandgroyne sediment.

4.3.6 Overview of sediment transport vectors

Figure 4-23 presents an overview of the sediment transport vectors during the period between 16 November and 2 December, derived from the sedimentation/erosion patterns in combination with the actual meteorological and hydrodynamic conditions. The figure summarizes the results of the data analysis.
A few observations from Figure 4-23 are pointed out:

- The wave-induced longshore current is identified to be the dominant driving force in redistributing the sandgroyne sediment.
- The longshore current converges near the sandgroynes, locally increasing the sediment transport capacity.
- Transported sediment accumulates over an area stretching in the order of 10km, either trapped by the physical presence of the sandgroynes in the Ter Heijde site area or accumulating north of the Ter Heijde site area where the longshore current stabilizes.
- Cross-shore sediment transport occurs locally near the sandgroynes. Sediment is dominantly transported in offshore direction, from the intertidal zone towards the -4m depth contour.
- The rubble mound groynes ("Delflandse hoofden") do not have a significant influence on the redistribution of sandgroyne sediment, because of its limited length.

### 4.4 Alternative wave scenarios

The data analysis performed in the previous paragraph suggests that the wave induced longshore current is an important parameter in the redistribution of sandgroyne sediment. The physical presence of the sandgroynes causes flow contraction of the longshore current, locally increasing the flow velocity. This effect will increase the sediment transport capacity of the sandgroyne sediment. During the consistent offshore, south-west directed waves part of the sandgroyne sediment has been transported in northward direction, in contradiction to one of the hypotheses formulated in Chapter 2. The concerning hypothesis formulates that the sediment would be evenly...
redistributed in both longshore directions, initially filling the gaps between the three sandgroynes. Other hypotheses have been confirmed by the data analysis: no significant offshore losses have been observed and in storm conditions the sandgroynes are substantially absorbed in the coastal system in the order of several days.

A numerical simulation model for nearshore coastal areas is applied to perform a sensitivity analysis on the impact of the wave induced longshore current on the sandgroyne nourishments by varying the wave boundary conditions. The results lead to further assessment of the hypotheses formulated in Chapter 2.

The following hypotheses will be verified:

- The tidal current, without wave forcing, is not capable to absorb the sandgroyne sediment in the coastal system.
- Offshore, north-west directed waves will redistribute the sandgroyne sediment more evenly in both longshore directions.
- In calm to moderate wave conditions, the redistribution of sandgroyne sediment occurs on a smaller spatial scale.

Upon the formulated hypotheses, several scenarios have been simulated. An overview of the simulated scenarios is given in Table 4-4. The reference scenario is a hindcast scenario, representing the scenario with conditions observed between 16 November and 2 December 2009.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Wave climate</th>
<th>Dominant offshore wave direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>reference scenario (16 Nov – 2 Dec 2009)</td>
<td>moderate/rough</td>
<td>south-west</td>
</tr>
<tr>
<td>alternative scenario 1</td>
<td>no waves</td>
<td>no waves</td>
</tr>
<tr>
<td>alternative scenario 2</td>
<td>moderate/rough</td>
<td>north-west</td>
</tr>
<tr>
<td>alternative scenario 3</td>
<td>calm/moderate</td>
<td>south-west</td>
</tr>
</tbody>
</table>

Table 4-4 Overview of the simulation scenarios
The aim is to establish the influence of the waves and the wave induced longshore current, by observing timeseries of the surfzone current and by observing the bathymetric evolution over the period the model has been validated for (16 November – 2 December 2009). First the results of the reference scenario will be presented to show the capacity of the simulation model to reproduce the morphological evolution as observed. Consequently, the results of each of the simulated alternative scenarios will be compared with the simulation results of the reference scenario. The bathymetric evolution is presented by plots presenting the initial and final bathymetry situation, sedimentation/erosion plots, and by plots indicating the movement of sandgroyne sediment and sediment transport vectors. The location of the wave characteristics and longshore current timeseries presented throughout the paragraph, including a representation of the initial bathymetry on the 16th of November, are presented in Figure 4-24.

4.4.1 Reference scenario: 16 November – 2 December 2009

In this sub-paragraph the capacity of the simulation model to reproduce the morphological changes observed in the period between 16 November 2009 and 2 December 2009 is presented. This has been an important validation step in setting up the model. For more details about the model set-up is referred to Appendix H. Figure 4-25 presents the sedimentation/erosion derived from the fielddata (left plot) and the simulated sedimentation/erosion (right plot), both representing the same period.
Overall the sedimentation/erosion patterns are well comparable. Two differences are pointed out and explained:

- The simulation result (right plot) does not show sedimentation patterns at the south side of the two most southern located sandgroynes (marked by the black circles in the left plot), with shore normal orientated in western direction. This can be explained by the set-up of the simulation model. In the field data analysis it was concluded that these sedimentation patterns are caused by wave-induced cross-shore transport; the model is a 2DH simulation model (1 vertical layer), not simulating cross-shore wave-induced sediment transport. This is an aspect that should be taken into account for further development of the model.

- In the left plot sedimentation/erosion patterns as a result of dredging operations are marked by the black arrow. Logically, dredging operations are integrated in the fielddata, but not in the simulation.

Figure K- 5 in Appendix K presents a matrix of sediment transport vector plots. The sediment transport vectors represent averaged sediment transports in m³ per hour in and out of the Ter Heijde site area, distinguishing different fractions (sandgroyne sediment, environment sediment) horizontally and different transport directions (nett, gross northward, gross southward) vertically. The following can be observed:

- Southward directed sediment transport is not observed, for both the sandgroyne and environment fraction.
- The sandgroynes do not seem to significantly interfere with the autonomous longshore sediment transports, represented by the plots in the right column. The outflow of sediment at the north side approaches the inflow of sediment at the south side.
Sandgroyne sediment is dominantly redistributed in northward direction. The model simulation results indicate an average northward directed sediment transport gradient in the order of 70 m³/hour. That is about 25,000m³ of sandgroyne sediment considering the entire period between 16 November and 2 December.

The settings used for the simulation of which the result is presented in the right plot of Figure 4-25, will also be used for simulating alternative wave scenarios. An overview of the model set-up is provided in Appendix H.

4.4.2 Alternative scenario 1: no waves

For this scenario the influence of the tide- and wind-induced current on the sandgroynes will be evaluated by eliminating the waves in the simulation. Figure 4-26 presents time series of the longshore current velocity near the middle sandgroyne for the reference and the alternative scenario, at a depth of about 4m. Hence, for the alternative scenario the longshore current is generated by the tidal and wind forcing only, for the reference scenario the longshore current is generated by tidal, wind and wave forcing.

The following observations can be made on the longshore current:

- The tide- and wind-induced current shows a regular velocity pattern, though dominant in northern direction driven by the dominant southwesterly wind during the considered period. The velocity reaches maximum speeds of about 0.7 – 0.8m/s.
- The tide and wave induced current shows a more irregular pattern. The supposed influence of single wave characteristics (intensity and direction) will be treated in the subsequent scenarios.

Figure 4-26 Longshore current velocity near the middle sandgroyne.

The following observations can be made on the longshore current:

- The tide- and wind-induced current shows a regular velocity pattern, though dominant in northern direction driven by the dominant southwesterly wind during the considered period. The velocity reaches maximum speeds of about 0.7 – 0.8m/s.
- The tide and wave induced current shows a more irregular pattern. The supposed influence of single wave characteristics (intensity and direction) will be treated in the subsequent scenarios.

Figure K- 2 in Appendix K presents the simulation results of the morphological evolution over two weeks of both the reference simulation and the scenario simulation, driven by the above analyzed hydrodynamics. Figure 4-27 presents the simulation results represented by the sedimentation/erosion patterns.
Figure 4-27 Simulation results of the sedimentation/erosion of the reference scenario (including waves) and the alternative scenario (excluding waves).

For the alternative scenario it can be observed that there is no morphological evolution over a period of two weeks time. Figure K-6 in Appendix K, presenting the averaged sediment transport vectors in m³/hour, confirm this observation. It can be concluded that the tide- and wind-induced current on itself is not capable to redistribute the sandgroyne sediment over a period of two weeks time. It is expected that under conditions with minor or no wave action, the sandgroynes will not be absorbed in the coastal system within a season of a few months time.

As already concluded in the data analysis, the impact and effects of the waves are crucial in the redistribution of the sandgroyne sediment. The subsequent paragraphs treat the influence of single wave characteristics on the sandgroynes.

4.4.3 Alternative scenario 2: wave direction NW

For this scenario the influence of the offshore wave direction on the sandgroynes will be evaluated. The offshore wave boundary condition has been transformed from dominantly south-west in the reference scenario to north-west in the alternative scenario. The wave and wind propagation field on the 20th of November 2009 are presented in Figure 4-28, both representative for the observed conditions during the considered period. The left plot indicates the west to north-west directed waves imposed at the model domain boundary, though instantly bending towards south-western to western orientation. The instant adaptation is likely caused by the wind forcing; intense and dominant south to south-west orientated as indicated in the right plot of Figure 4-28. Consequently, the waves approach the coast under an angle, causing a northward directed wave-induced current. This is not a realistic process for offshore north-west directed waves in the North Sea. For the relatively small North Sea, the wave and wind direction fields are usually well correlated. Offshore north-west directed waves are commonly associated with a north-west orientated wind field and approach the shore likewise. In reality north-west orientated waves cause a southward directed wave-induced current. The wind forcing should be always be taken
into account when varying the wave boundary conditions to realistically simulate coastal processes, especially for the North Sea coast where the wind is a determining parameter. The simulation is not representative for the North Sea, still the simulation results are analyzed for general understanding of the nourishment behavior.

Figure 4-28 Wave and wind propagation field for simulation of the alternative wave scenario

Figure 4-29 presents the offshore and nearshore wave height and direction timeseries for the reference scenario and the alternative scenario. On the 2\textsuperscript{nd} of December, a period with swell waves coming from north-west was observed; for this period the wave characteristics remain unchanged. The offshore significant wave height has not been changed, presented by the two coinciding curves in the left plot. The bold curves present the wave characteristics transformed to the nearshore (depth ~ 10m), by the simulation model.
Figure 4-29 Offshore and nearshore wave characteristics for the reference scenario and the alternative scenario 1.

The nearshore transformation of the significant wave height is similar for both the reference and alternative scenario. Although the offshore wave directions differ about 90 degrees, both wave conditions bend towards western orientation, dominantly driven by the wind. The observed wind conditions, dominant S to SW remain unchanged. Still, the difference in nearshore approach angle is about 25 degrees over the entire time serie until the swell wave period. The orientation of the coastline normal near Ter Heijde is also presented in the right plot, suggesting that both wave conditions generate a net northward directed wave induced longshore current. Appendix A presents a theoretical relation between the wave angle of approach and the longshore sediment transport, suggesting that the wave conditions for the alternative scenario generate a larger northward directed sediment transport.

Figure 4-30 presents the longshore current velocity near the middle sandgroyne, at a depth of about 4m. The longshore current is dominantly driven by the tide and by the (oblique incident) breaking waves.

Figure 4-30 Longshore current velocity near the middle sandgroyne
The following observations can be made on the longshore current:

- For both scenarios the trend of the longshore current velocity is correlated to the nearshore significant wave height.
- Western incident, nearshore waves with a significant wave height upwards of about 2.0m clearly influence the longshore current:
  - The longshore current is consistently north-west directed, not shifting direction driven by tidal forcing
  - A difference in the nearshore approach angle influences the current velocity; proportional to the angle of incidence compared to the shore normal orientation.
- For nearshore waves up to 2.0m significant wave height, a difference in nearshore approach angle does not significantly influence the longshore current velocity and direction.
- Swell waves coming from north-west do not significantly influence the longshore current.

Supposed that the longshore current is the main driving force for the redistribution of sandgroyne sediment, in calm wave conditions the redistribution of sandgroyne sediment will show the same trend, irrespective of the wave approach angle.

Figure K-3 in Appendix K presents the simulation results of the morphological evolution over two weeks of both the reference simulation and the scenario simulation, driven by the above analyzed hydrodynamics. Figure 4-31 presents the simulation results represented by the sedimentation/erosion patterns.

![Simulation results of the sedimentation/erosion of the reference scenario (SW directed waves) and the alternative scenario (NW directed waves).](image)

The following can be observed in the sedimentation/erosion plots:
Although not very clear, the bathymetry plots show that the shoreline has retreated slightly more under influence of the offshore southwesterly waves.

The sedimentation and erosion patterns of both scenarios are comparable; however the intensity is larger for the offshore southwesterly waves. This suggests equal processes drive the morphological evolution, however the effects are less pronounced.

The plots showing the sandgroyne sediment movement clearly indicate net northward sediment transport for both scenarios. Referred to the white polygons, marking the boundaries of the sandgroynes, more sediment has moved out of the site area under influence of the offshore southwesterly waves.

Both wave conditions generate a net northward longshore sediment transport; however the longshore transport generated by the southwesterly waves is larger than for the northwesterly waves. Supposed that the longshore current is the main driving force of the redistribution of sandgroyne sediment, the intensity difference of the morphological evolution occurs during periods facing wave heights upwards of about 2.0m.

4.4.4 Alternative scenario 3: wave intensity calm-moderate

For this scenario the influence of the significant wave height on the sandgroynes will be evaluated. Figure 4-32 presents the offshore and nearshore wave height and direction timeseries for the reference and the alternative scenario. For the alternative scenario, the offshore significant wave height imposed at the model domain boundaries has been decreased significantly, indicated in the left plot of Figure 4-32. The strong windfield pushes the wave height up as the waves propagate towards the nearshore. Still a difference with the nearshore significant wave height of the reference scenario is noticeable. The offshore wave direction imposed at the boundaries remains unchanged; however the right plot indicates a highly varying offshore wave direction. This is explained by the relatively low energy waves imposed at the boundary, pushed up under influence of the strong windfield. The wave direction therefore instantly adapts to the wind direction field.

![Figure 4-32 Offshore and nearshore wave characteristics for the reference scenario and the alternative scenario 3.](image)

Figure 4-33 and presents the longshore current velocity near the middle sandgroyne, at a depth of about 4m, for both the reference and the alternative scenario.
The following observations can be made on the longshore current, similar to the observations for the previous scenario:

- As observed for the previous simulation scenario, the longshore current velocity trend is proportional to the nearshore significant wave height.
- A difference in the nearshore significant wave height does not affect the direction of the longshore current.
- For waves with a significant wave height upwards of 2.0m, the longshore current velocity notably increases proportional to an increasing significant wave height.

Figure K-4 in Appendix K presents the simulation results of the morphological evolution over two weeks of both the reference simulation and the scenario simulation, driven by the above analyzed hydrodynamics.
The following can be observed in the sedimentation/erosion plots:

- The trends of the sedimentation and erosion patterns are comparable, again indicating that the same processes drive the sandgroyne sediment redistribution. Logically, for the calmer wave climate, the erosion and sedimentation patterns are less intense.
- The redistribution of sandgroyne sediment occurs on a smaller spatial scale for the calmer wave climate scenario, in the order of several hundred meters, whereas for the reference scenario the redistribution seems to occur on a spatial scale in the order of several kilometers (not covered by the simulation plots). This effect is indicated by the sedimentation/erosion plots where the erosion and sedimentation patterns seem to balance each other fairly well. The effect is also notable in the bathymetry evolution plots, where the protrusions of the sandgroynes are still well visible, though migrated a little bit northward.
- The sedimentation/erosion plot does not show significant offshore losses of sediment, both for this wave scenario alternative as well as for the previous wave scenario alternative.

As expected, both intensity varying southwest wave climates cause a net northward sediment transport. The influence of the varying intensity on the morphology is clearly noticeable.

Figure K-8 in Appendix K presents the averaged sediment transport vectors derived from the model simulation results. The plots in the center column indicate that the calm to moderate wave conditions did not transport the sandgroyne sediment out of the Ter Heijde site area. In general, calm to moderate wave conditions are not capable to redistribute the sandgroyne sediment over an area larger than a few hundred meters over a period of two weeks time.
4.5 Conclusions

This paragraph presents the conclusions of the results presented in this chapter, focussing on the morphological evolution of the sandgroyne nourishments. The hypotheses related to the morphological evolution prepared by Walstra & Mol [2009] and formulated in Chapter 1 will be used as a guideline to formulate the conclusions.

Overall, the chapter indicates that the morphodynamics around sandgroynes are mainly driven by the impact of waves:

- The erosion areas at the sandgroynes correspond to the (refracted) incident wave orientation. Locally the waves cause a wave-induced offshore sediment transport.
- The sedimentation patterns northward of the Ter Heijde site indicate a dominant, northward directed, longshore current. The wave-induced longshore current is dominant in the longshore redistribution of the sandgroyne sediment as the tidal current is not able to redistribute the sediment.

The hypotheses formulated in Chapter 1 will be consecutively treated.

- The sandgroyne sediment will be evenly redistributed in longshore direction, initially filling the gaps between the three sandgroynes.
- The volumetric and morphological fielddata analysis pointed out that under moderate to rough southwesterly conditions, the sandgroyne sediment is mainly redistributed in northward direction on a spatial scale of 5-10km. The simulation results indicate that under these conditions about 25,000m³ of sandgroyne sediment has been transported in northward direction out of the Ter Heijde site area, over a period of two weeks time. In this context the oblique incident waves, generating a northward directed longshore current is identified to be the main driving force. Referred to the Delfland coast shore normal, the trend of sandgroyne sediment redistribution along the Delfland coast will be in northern direction. Supported by the model simulation results, both offshore north-west and south-west directed, wind-generated waves, prevailing along the Dutch coast, are transformed towards western orientation in the nearshore by refraction and wind-forcing. The western orientated waves will generate a net northward directed sediment transport. Swell waves coming from north-west do not significantly influence the longshore current and therefore do not influence the longshore redistribution of sandgroyne sediment.

The results of this study reject the hypothesis formulated by Walstra & Mol [2009]. The difference in the trend of sediment redistribution is caused by the difference in shore incident wave direction, see Figure 4-35. Figure 4-35 compares the model set-up and simulation results of the schematized model used for the preliminary morphology study [Walstra & Mol, 2009] (left) and for the model used in this study (right). The wave vectors presented in the upper-left plot indicate that the waves arrive perpendicular to the shoreline where the sandgroynes are located. This means that there is no wave-induced longshore current and therefore the sandgroyne sediment redistribution is supposed to be cross-shore dominated as indicated by the transport vectors in the sedimentation/erosion plot. The upper-right plot presents the model set-up and simulation results for the sandgroynes constructed in the scope of the Ter Heijde pilot project. Bathymetry, coastline orientation and hydrodynamics are representative for the Ter Heijde pilot project. The upper right plot indicates that the waves approach the shore under an angle, generating a
wave-induced longshore current. The bottom right plot indicates that the sandgroyne sediment redistribution is dominated by longshore orientated transport.

Figure 4-35 Comparison of the simulation results of the preliminary morphology study [Walstra & Mol, 2009] and the simulations performed based on the Ter Heijde pilot data.

The comparison of both simulation results indicates that in case of shore perpendicular incident waves, the sandgroyne sediment will be evenly redistributed in longshore direction, driven by wave-induced cross-shore transport. In case of oblique incident waves, the sandgroyne sediment redistribution will be dominated by the wave-induced longshore current.

In this context it is recommended to assess the morphological evolution of sandgroynes when the pilot project would have been executed in the northern part of the Dutch coast, where the coastline orientation is expected to be more perpendicular to the shore incident wave direction. A different trend of sediment redistribution could be observed.

- The offshore losses of sediment seaward of the -5m depth contour are limited.
- Although redistributed in longshore direction in the order of 5-10km, the sandgroyne sediment has been retained in the active zone of the coastal profile (upwards of the -5m depth contour), both considering the
entire period of the Ter Heijde nourishment campaign from September 2009 until January 2010 and the short storm period from 16 November until 2 December 2009.

- **For an averaged spring wave climate, the sandgroynes are absorbed in the coastal system in the order of several months.**
  - It is expected that during an averaged spring wave climate, the sandgroynes will be absorbed in the coastal system within a period of one to two months. The third simulation wave scenario simulated the morphological evolution of the sandgroynes over a period of two weeks, under influence of a wave climate with nearshore wave heights in a range between zero and two meters, representative for a spring wave climate. The simulation shows moderate morphological evolution over a period of two weeks time. Based on this result it is expected that under an averaged spring wave climate, with possible calmer and more severe conditions, the sandgroynes will be absorbed within a period of one to two months.

- **During storm conditions the sandgroynes are absorbed in the coastal system in the order of several days.**
  - The field data analysis pointed out that under a nearshore wave climate characterized by an averaged wave height of 2m and peaks up to 3m, the sandgroynes are substantially absorbed in the coastal system within two weeks time. It is expected that the sandgroynes will be absorbed within several days for wave conditions with wave heights upwards of 4m. Longshore current velocities approaching a value of 1.0m/s, associated with nearshore significant wave heights upwards of 2.0m, are required to cause substantial morphological evolution of the sandgroynes.

- **The tidal current, without wave forcing, is not capable to absorb the sandgroynes in the coastal system.**
  - Supported by the model simulation results, the tidal current, without the influence of waves, is not capable to redistribute the sandgroyne sediment in a period of two weeks time. Minor morphological evolution is expected to be observed for a period in the order of several months.

- **Leeside erosion caused by the presence of the sandgroynes is not observed.**
  - Leeside erosion is not observed. The possible erosion is expected to be overwhelmed by the executed nourishments. Besides, the sandgroynes do not extend the entire surfzone, still allowing sediment to pass the sandgroyne and accumulate directly downdrift. The classic coastal engineering theory of observed downdrift erosion accounts for groynes extending the entire surfzone.

- **In a short phase direct after completion of a sandgroyne, the swimmers safety is endangered due to increased flow velocities near the sandgroynes.**
  - This hypothesis will be assessed in the next chapter.
Project name: Pilot Sand Groynes Delfland Coast
5. PRACTICAL IMPLICATION

5.1 Introduction

This chapter focuses on the practical implication of sandgroyne nourishments. For an integral assessment of the efficiency of sandgroyne nourishments, it is crucial to consider some relevant design criteria. The presence of a subtidal bar was the direct reason to look for an alternative nourishment method to nourish the upper shoreface (landward of the -5m depth contour). The sandgroyne nourishments have been preferred as it was expected that the pumping lengths, delivering the sediment onshore, would be reduced. Consequently the natural system would take over the redistribution of sediment over the Ter Heijde shoreface according to the design. Nevertheless complications were foreseen realizing the design according to the regular imposed cross-shore design profiles.

In this chapter the entire pilot project executed in Ter Heijde will be evaluated from a dredging industry point of view, by considering the above mentioned and other relevant aspects. The experience and observations will be used to create a future perspective for the sandgroynes.

5.2 Evaluation of Ter Heijde pilot

5.2.1 Contract

The project contract prescribes cross-shore design profiles from the native dunes until a depth of -5m NAP. The design profiles are defined in each Jarkus-raai, a grid system along the Dutch coast. On the dry part of the coastal profile, the design levels have to be realized. The principle of design profiles requires accurate placement of the sediment for both the dry and submerged parts of the coastal profile. The coastal profile in Ter Heijde is characterized by the presence of a subtidal breakerbar. The breaker bar limits the accessibility of dredging vessels to directly rainbow the sediment on the upper shoreface. An alternative method to nourish the shoreface was proposed: the construction of sandgroynes. The sandgroynes are concentrated nourishments realized seaward from the shoreline. The sediment in the sandgroynes near Ter Heijde is anticipated to be redistributed in the upper shoreface by the impact of waves, wind and currents over a stretch of 2.5km in longshore direction. Near Ter Heijde three sandgroynes have been realized, each containing an amount of 150.000 to 200.000m³ of sediment.

The sandgroyne sediment has been redistributed in longshore direction, however mainly in northward direction and partly outside of the Ter Heijde site. This means that the design in the submerged part of the coastal profile for the Ter Heijde site has not been fully realized by the sediment originating from the sandgroynes. This resulted in:

- The requirement of additional hopper loads. Based on the data analysis performed in this study, throughout the entire Ter Heijde nourishment campaign 0.13 Mm³ of sediment has been nourished more than required according to the design.
Relatively long pumping lengths. Areas that were supposed to be nourished by the sandgroyne sediment had to be nourished additionally. This was not accounted for in the instantaneous allocation of the sinker pipeline, generally aiming to minimize the pumping lengths as much as possible.

The requirement of additional surveys to determine the residual amount of sediment to pumped in for each design profile.

Implementation of an additional dozer for shaping the sandgroynes

Although the planform evolution of the sandgroynes was different than expected, the data analysis does not indicate offshore losses of sediment (seaward of the -5m depth contour). This is an important requirement of the project contract, stating that when sediment is nourished between the -5m and -8m depth contour, twice the amount of the design has to be nourished. The area offshore of the -8m depth contour is not even included in the contract. The data analysis and the simulation results pointed out that the orientation of sediment redistribution of sandgroyne sediment is in longshore direction.

5.2.2 Design and planning

Several aspects related to the design of the sandgroynes can be considered:

- Production
- Volume
- Shape
- Grain size
- Planning
- Execution

Each of the mentioned aspects will be discussed based on the experience from the Ter Heijde pilot, followed by some important considerations for future, similar projects.

Production

The sandgroynes were supposed to fill the upper shoreface of the Ter Heijde site, stretching 2.3km in longshore direction. The sandgroynes were constructed in the site area, because the sediment was anticipated to be redistributed evenly in both longshore directions. An important restriction for the exact location of the sandgroynes in the site area was to guarantee a sufficiently large distance between the sinker pipeline and the sandgroynes, to reduce the risk of considerable amounts of sediment accumulating on the sinker pipeline, which is laying on the seafloor. A layer of sediment covering the sinker pipeline might cause complications and damage when the sinker pipeline has to be shifted.

The aim is to find an optimal balance between minimal pumping lengths and a sufficiently large distance between the location of the sandgroyne and the sinker pipeline. Minimizing the pumping length increases the production rates. Commonly the production rates are inversed exponentially related to the pumping lengths, indicating that for a linearly increasing pumping length the production decreases exponentially. Figure 5-1 illustrates a theoretical stretch of a coast, representative for the Ter Heijde site, split into two equal stretching parts. For both parts, another nourishment method is used to nourish the coast. The figure illustrates the qualitative relation between the pumping length and a qualitative approximation of the averaged production, marked in red. It can be observed that the averaged productions do not significantly diverge.
Figure 5-1 Theoretical representation of the site illustrating the averaged productions of two different nourishment methods to nourish the shoreface.
Based on the information shown in Figure 5-1, the following can be concluded with respect to application of sandgroyne nourishments:

- Although not quantitatively determined, the minimum required distance between the sinker pipeline and the sandgroyne, several hundred meters for the Ter Heijde site configuration, limits the production.
- A sandgroyne nourishment can be an efficient method when a relatively long stretch of coast is supposed to be nourished, in the order of several kilometers at least. The relation between the pumping length and the production suggests that long pumping lengths significantly pull the production down when applying the ‘regular nourishment’ method for relatively long stretching coasts.

**Volume**

Before the start of the Ter Heijde nourishments, the design volume of the sandgroynes was determined by the residual amount of sediment required in the shoreface, after making an estimation of the amount of sediment that would flow in the shoreface from the beach nourishments. The residual amount was to be accomplished by the sediment in the sandgroynes. For the Ter Heijde pilot, the sandgroynes contained about 500,000 m³ of sediment. As the project contract prescribes that the sediment should be redistributed evenly in each of the distinguished project zones, the sediment was equally divided over the sandgroyne nourishment.

The area supposed to be nourished by the sandgroynes is proportional to the volume of the sandgroynes itself. It has been concluded that sandgroynes can be an efficient nourishment method when executed in a larger configuration, nourishing a larger stretch of the coast. However, different adverse effects should be accounted for when applying the sandgroynes in a larger configuration. The physical presence of relatively large sandgroynes may lead to adverse lee-side effects on the adjacent coast.

**Grain size**

The relevancy of the sediment grain size used for the sandgroynes has already been discussed in Chapter 3. The main consideration for using a relatively large grain size for the sandgroynes ($D_{50}$~280 μm), conducting a steeper natural slope, was to maximize the offshore protrusion of the sandgroynes, but reducing the chance of sediment settling seaward of the -5m depth contour. This approach was preferred to stimulate the sediment accumulating in the deeper parts of the upper shoreface, but without crossing the -5m depth contour. After all, the deeper part of the upper shoreface was the area considered to be complex to realize.

It is commonly expected that for a relatively large, thus heavier grain size the sediment transport capacity will be reduced in comparison with an averaged sediment size. The spatial scale of sediment redistributing will probably be larger for a smaller grain size.

**Planning**

The following approach was adopted for the construction of the first, most northward located sandgroyne:

1. For a certain longshore stretch of the coast: realize the design in the dunes and on the beach.
2. Determine the residual design of the shoreface.
3. Pump the residual amount in the sandgroyne nourishment.
4. Move on to a longshore, adjacent zone of the coast where the procedure repeats.

This approach has been followed for the construction of the first sandgroyne. Although the amount of sediment associated with the design of a certain stretch of the coast is nourished, the design itself is not yet realized. The
coastal stretch nourished by a sandgroyne can be delivered when the sandgroyne sediment has been evenly redistributed. Nevertheless, it could be an appropriate approach when it can be assumed that the sediment in the sandgroyne eventually accumulates according to the design. Soon it appeared that the sandgroyne nourishment did not fully settle the design in the shoreface and additional sediment had to be pumped in. However, in the meantime the sinker pipeline had been replaced and dredging activity had proceeded in the next zone southward. For the new position of the sinker pipeline it was not taken into account that sediment still had to be pumped in an area where the pipeline just came from. Technically it was possible but resulted in a relatively large pumping length, mitigating the production. Besides the decreasing production, the site logistics became more complex as it was necessary to create an additional, long track of pipelines for a relatively small amount of sediment to be pumped in.

For the construction of the second and third sandgroyne an alternative approach was adopted:

1. For a certain longshore stretch of the coast: realize the sandgroyne nourishment.
2. Realize the design in the dunes and on the beach.
3. Evaluate the evolution of the sandgroyne.
4. Pump in additional sediment in the situation the design in the shoreface was not yet settled by the sandgroynes.

This approach allows for an observation period of the sandgroyne evolution while dredging activity is in progress at the same coastal stretch, but in a different part of the coastal profile. However, the amount of sediment to be nourished in the sandgroynes is complex as the approach is contradictory to the principle of the sandgroynes to nourish the remaining part of the design in the shoreface. The remaining part of the design in shoreface, hence the volume of the prospective sandgroyne, is to be estimated instead of relying on survey results.

**Execution**

The only fixed requirement of the construction of a sandgroyne is the amount of sediment that has to be pumped in. Hence the sandgroyne is subject to the forces of nature from the moment the construction has started; the evolution actually coincides with the construction. Due to the highly variable character and major forces of the nature, it is practically impossible to construct a sandgroyne towards a fixed, final shape. Still the operating personnel should be provided with a guideline for the construction. Figure 5-2 presents a drawing illustrating the principle of the sandgroyne construction.
As a first step, a narrow dam was constructed from the beach into the sea to support the pipeline delivering the sediment. The dam required a sufficiently high elevation to guarantee a dry position of the pipeline, independent of the tidal situation, to keep continuous control on its position and orientation. Consequently the sediment had to be pumped in a predefined area, marked in red in Figure 5-2. Dozers were continuously operating to maintain the instant location of the sandgroyne in the sandgroyne reference area. Redundant sediment was to be pushed away seaward or sideward outside of the red area. Regularly, the pipeline had to be extended as the sandgroyne was proceeding in seaward direction. Photo 5-1 illustrates several sandgroyne construction related operations, for instance a dozer pushing away sediment in seaward direction and a wheelloader bringing in a new pipeline element. Appendix E includes figures related to the sandgroyne construction.

Figure 5-2 Schematic representation of the design principle of the sandgroyne construction.

Photo 5-1 Photo illustrating the sandgroyne construction related operations, in the final phase of the construction of the northern located sandgroyne (20 October 2009).

The flexible guideline of the construction of sandgroynes caused confusion with the operating personnel responsible for shaping the sandgroynes. Although they have been briefed about the procedure, they are used to work with a fixed design presented on a digital screen. As discussed earlier, a fixed design is practically impossible, however more attention can be given to employ experienced personnel familiar with the principle.

5.2.3 Monitoring

The project contract, prescribing design profiles on a regular longshore interval, requires a realistic representation of the local bathymetry. For regular beach nourishment projects, surveys are executed implementing two kinds of
survey platforms. During high tide the project survey vessel surveys the submerged part of the coastal profile; consequently the dry part of the coastal profile is surveyed during low tide with a survey car. In theory this sequence of two different surveys is manageable for one surveyor. When there’s still a longshore or cross-shore gap between the land and bathymetry survey, interpolation is justified as the morphological formation is rather constant in both directions. Implementation of the sandgroyne nourishments conducted an intensified survey program:

- Illustrated in Figure 5-3, the sandgroynes appear as a rather abrupt and irregular protrusion in the local bathymetry and partly in the shallow part of the shoreface (approximately -1m - -3m NAP), an area that is hard to survey with conventional survey equipment. Therefore, the survey resolution had to be high and a survey platform capable to survey the shallow part of the shoreface was implemented, both to contribute to a realistic representation of the entire sandgroyne.

- As presented in the previous chapter, the redistributed sediment accumulated mainly between the 0m and -4m depth contour in bar formations. In the context of the previous point, a survey platform capable to survey the shallow part of the shoreface was implemented. For morphologists, full data coverage over the entire profile is important to include all morphological features, not represented by an interpolation. The project survey department is mainly interested in sediment quantities. Although not exact, Figure 5-4 illustrates that sediment quantities are still reliably estimated by an interpolation when for instance the shallow part of the shoreface is not covered by a survey. Bar formations are completely damped out.

- In the evolution phase of the sandgroyne nourishments, the sediment originating from the sandgroynes was redistributed on a relatively large planform scale. This resulted in large areas to be surveyed.
- In the context of the sandgroyne evolution in the previous point, per square meter relatively small sediment quantities were surveyed, in the order of the measuring inaccuracies coming along with the implemented survey platforms and survey conditions. This required additional surveys to be executed, to reduce the dependency on single survey results with questionable accuracy.
The mentioned aspects, directly related to the sandgroyne nourishments, resulted in an intensified and complex survey program. Several other aspects in general limiting survey operations:

- Although normal for the time of the year, the meteorological conditions have been a limiting factor for the scale of the survey operations. Calm conditions are required to guarantee operational safety and quality of data. The meteorological conditions are not directly related to the sandgroyne nourishments, however it should be noted that at least moderate conditions are required to drive the sandgroynes to evolve and consequently to survey, to follow the evolution.
- In addition to the above mentioned limitations, the tidal situation can be a limiting factor. It has been mentioned that bathymetry and landsurveys are restricted to specific tidal conditions. The tidal asymmetry along the Delfland coast, characterized by relatively long low water periods, sometimes obstructed the bathymetry survey to be completed or even executed during daytime.

Clearly, the sandgroyne nourishments conducted an extensive survey program in unfavorable conditions. The relatively large spatial scale and required survey frequency inevitably resulted in the employment of additional survey personnel and survey equipment, involving a lot of effort and expenses. From a survey perspective it can be concluded that nourishments highly dependent on the dynamics of nature are not efficient under the governing contract requirements of design profiles.

### 5.3 Future perspective

From a dredging operational perspective, the previous paragraph points out that three aspects determine the efficiency of the sandgroynes:

- Contract requirements/survey
- Execution/production

This paragraph presents some possible, alternative configurations of sandgroyne nourishments along the Delfland Coast, aiming to optimize the implication of sandgroynes based on the above mentioned aspects. The scenarios are basically elaborated, serving as a guideline for further optimization of the sandgroyne as a common applied nourishment method. For each of the configurations it is assumed that the contract prescribes flexible design criteria, e.g. settlement based on hopper volumes. For this type of contract, survey operations are less required to settle the contract. Each of the configurations will be explained by presenting a schematized visualization of the nourishment set-up and a concise summation of the suspected profits.

#### 5.3.1 Alternative configuration 1

For this configuration the same nourishment procedure as used by the project Combinatie Delflandse Kust is assumed, i.e. a sinker pipeline delivers the required sediment onshore supplied by a dredging vessel. Periodically, the sinker pipeline is shifted to an adjacent zone of the coast as the pumping range of a single sinker pipeline landfall is limited. The principle of periodically shifting sinker pipeline landfalls is illustrated in Figure 5-5. For the project Combinatie Delflandse Kust, the sinker pipeline is shifted on average a few times per year.
Figure 5-5 Schematized plan view of the Delfland Coast, indicating the principle of periodically shifting sinker pipeline landfalls

Figure 5-6 Schematized plan view of the Delfland Coast, indicating that a sandgroyne can reduce the number of sinker pipeline landfalls

Figure 5-6 illustrates that the construction of a sandgroyne can reduce the number of sinker pipeline landfalls assuming a northward directed redistribution of sandgroyne sediment. The sandgroyne, constructed by means of the temporary location of sinker pipeline just south of Ter Heijde, supplies the sediment required for the northern adjacent stretch of coast at Ter Heijde. The volume and location of the sandgroyne determine the scale and the location of the area nourished by sandgroyne sediment. Based on the averaged wave climate for this region (see Chapter 2), a northward directed trend of sediment redistribution should be accounted for.

5.3.2 Alternative configuration 2

This configuration assumes a nourishment set-up based on long-term maintenance of the Delfland Coast (~25 years). Three sinker pipelines are permanently installed, evenly distributed over the coast as illustrated in Figure 5-7.
Each of the sinker pipelines is installed to ‘maintain’ a sandgroyne, see Figure 5-8. The three sandgroynes all together serve as a continuous influx of sediment to dynamically maintain the entire coastline of the Delfland Coast. The three sandgroynes will be maintained by periodically nourishing sediment in the sandgroyne. The ‘maintenance schedule’ depends on the morphological evolution of the Delfland coast and the underlying contract requirements. Compared to the nourishment procedure adopted by the project Combinatie Delflandse Kust, this approach leads to the following potential profits:

- Permanent sinker pipeline installations in theory exorsize the periodical sinker pipeline shifts.
- The risk of sinker pipelines getting covered by a layer of sandgroyne sediment is not relevant for permanent installations as they do not have to be shifted.
- Depending on the contract requirements, applying sandgroynes to maintain the entire Delfland coast significantly reduces the requirement of onshore dredging operations (profile shaping, pipeline shifts, allocation of discharges etc.). Incidentally, dredging operations are required to monitor and maintain the sandgroynes.

For permanent installation of sinker pipelines along the coast, esthetic and safety aspects should be taken into account. These aspects are not considered in this study. The nourishment set-up presented in Figure 5-7 is not realistic, but just to illustrate the principle of permanent installations.

### 5.3.3 Alternative configuration 3

Another configuration, resulting from the previous described alternative, is the construction of one big sandgroyne to maintain the entire Delfland Coast for the longer term. This sandgroyne will also be maintained by a permanent installed sinkerpipeline, regularly supplying a certain amount of sediment in the sandgroyne.

Construction of one big sandgroyne to maintain the coast on the long term leads to the same profits as presented for the previous alternative. Major difference is that the sediment for this configuration will be nourished concentrated on a single location, further reducing the construction costs. Adverse lee-side effects on the coastal morphology as a result of the presence of the sand-engine, appearing as an abrupt protrusion in the nearshore coast, should be accounted for. For the previous described configuration, implying three smaller sandgroynes, adverse lee-side effects are less expected.

This nourishment configuration is going to be adopted for another upcoming pilot, the construction of the so called ‘sand engine’. The sand engine is an excessive amount of sediment nourished concentrated from the shore into the sea, serving as an input of sediment in the coastal system. The sand engine is supposed to

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Figure 5-9  Schematized plan view of the Delfland Coast, illustrating one big sandgroyne nourishing the Delfland coast
dynamically maintain a substantial part of the coastline of the Delfland Coast for the long term. The sand engine is cost efficient and integrates sustainable development of natural areas.

5.4 Alternative considerations

5.4.1 Attractiveness

Photo 5-2 shows a collection of pictures illustrating the attractiveness of the sandgroynes on tourists, fishermen, surfers and even seals (down left picture). The ‘sand engine’ (see Appendix L), expected to be realized near Ter Heijde towards the end of the year 2010, can be an even more popular attraction for tourists, making it an interesting location for watersporters and the hotel and catering industry.

Recently, the Dutch newspaper NRC published an article about a similar type of nourishment executed in Scheveningen, 5-10 km north of Ter Heijde. Besides its main function to serve as a sediment influx for the coastal
system, the article expresses that these kinds of nourishments create perfect surfing conditions. The entire article (in Dutch) is presented in Appendix M.

The sandbar created near Scheveningen is designed by Delft coastal engineers, integrating the wishes of the surfers. The sandbar creates a so called ‘point break’. Incoming waves gradually break along the point break, creating perfect surfer conditions allowing surfers to make long rides.

Although the nourishment has been a temporary ‘facility’ for the surfers as the nourishment eventually is absorbed in the coastal system, the article indicates that different interest groups can profit from these kinds of nourishments. It raises attention and interest from very diverging fields and specialities.

5.4.2 Swimmers safety

A company priority of the involved dredging companies is to guarantee safety, both for its employees and visitors during the execution phase as well as for the prospective users of the completed facilities. In this context Photo 5-3 illustrates that a sign is installed at the beach entrance, warning beach tourist for possible dangerous flow patterns as a result of the nourishment operations. Swimmers safety is considered to be endangered when large offshore directed flow velocities occur. Swimmers can drift away along with the offshore directed flow in seaward direction. The preliminary study performed by Walstra & Mol [2009] concluded that sandgroynes have a negative effect on the swimmers safety, locally increasing the flow velocities. Again the swimmers safety has been assessed locally near the sandgroyne nourishments by implementation of the simulation model, based on the bathymetry data surveyed during the Ter Heijde pilot. For two conditions the offshore directed flow velocities in the Ter Heijde site area have been assessed during an entire tidal cycle. Figure 5-10 presents the simulation results for the condition without waves; the current is generated under influence of the tide and wind only.

Photo 5-3 Photo illustrating a sign installed by the project personnel, warning beach tourist for dangerous flow patterns.
Figure 5-10 Simulation results of the offshore directed flow velocities in the site area for the condition without waves.

Figure 4-5 shows that under calm conditions with minor or no wave action, the offshore directed flow velocities occur very locally during rising tide and reach a maximum value of about 0.5m/s. For the most northern located sandgroyne, which is in the most advanced evolution phase, no significant offshore directed flow velocities are to be expected anymore.

Figure 5-11 shows the simulation results for the condition with moderate to rough waves.
Figure 5-11 Simulation results of the offshore directed flow velocities in the site area for the condition with moderate to rough waves.

Figure 5-11 shows that offshore directed flow velocities occur during the entire tidal cycle, still most intense and widespread during rising tide. The offshore directed flow velocity reaches maximum values of 1.0 m/s. During rising tide, the flow velocity field with an offshore directed component protrudes up to a few hundred meters into the sea.

Both figures clearly indicate that the offshore directed flow velocities are caused by the sandgroyne nourishments. It should be noted that the flow has been simulated in an advanced phase of the sandgroyne evolution, not representative for the sandgroyne shape just after completion. It is expected that the flow velocities are more intense locally near sandgroyne just after completion.

In general, the simulations performed in this study confirm the conclusions from the preliminary morphology study performed by Walstra & Mol [2009]. Based on the simulation results of this study, it is recommended not to swim locally near the sandgroynes just after completion, independent of the governing wave condition. During conditions with hardly any wave action, swimmers do have to be careful during rising tide, indicating a small field with an offshore directed flow component. In conditions with moderate to rough wave conditions it is recommended not to swim near the sandgroynes until the sandgroynes have been fully absorbed in the coastal system, as far as these conditions are attractive to swimmers at all.
6. CONCLUSIONS & RECOMMENDATIONS

In October and November 2009, three sandgroyne nourishments have been realized at the Ter Heijde coast. The sandgroynes each contained an amount of about 200,000 m³ of sediment. The aim of these nourishments was to nourish the upper shoreface until a depth of -5m NAP over a longshore stretch of about 2.5km, by using the potentials of the natural system to evenly redistribute the sediment in longshore direction. The presence of a subtidal bar, located 400-500m offshore, limiting the storage capacity of sediment to realize the design according to the contract, has been the reason to look for an alternative method to nourish the shoreface. Subsequently the sandgroynes were proposed to 1) overcome the storage restriction and 2) to function as a pilot project for assessing the future perspective of nourishments using the potentials of the natural system.

This chapter presents the research conclusions and recommendations. The following research objectives were formulated in Chapter 2:

- Assess the morphological evolution and practical aspects of the sandgroynes constructed at the Ter Heijde coast.
- Use the site specific knowledge from the Ter Heijde pilot project to create a future perspective of sandgroyne nourishments as a common applied method to nourish the shoreface.

6.1 Conclusions

The main conclusion of this study is that sandgroyne nourishments in the Ter Heijde configuration can be an efficient method to nourish the upper shoreface, but is highly dependent on the contract under which the nourishments are executed. This conclusion will be further elaborated by presenting sub-conclusions, treating different aspects of the sandgroyne nourishments.

From a morphological point of view it can be concluded that the sandgroyne nourishments in the Ter Heijde pilot configuration are an efficient method to nourish the upper shoreface:

- Based on the data analysis, the sandgroyne nourishments did not cause offshore sediment losses (seaward of -5m depth contour).
- The sandgroyne sediment remained in the active zone of the coastal profile above the -5m depth contour, predominant accumulating between the -2m and -5m depth contour.

Moderate to rough wave conditions with oblique shore incidence are required to absorb the sandgroynes in the coastal system. The wave driven longshore current dominates the longshore redistribution of sandgroyne sediment.

- Under calm wave conditions (waves < 1m) the sandgroynes will not be absorbed into the coastal system within the time scale of a season.
- For conditions with nearshore wave heights over of 2m, a sandgroyne is absorbed in the coastal system in the order of two weeks.
Swell waves along the Delfland coast do not contribute to longshore redistribution of sandgroyne sediment as they do not generate a longshore current.

For a wide range of representative wave conditions along the Delfland coast (south-west to north-west), the sediment will be predominantly redistributed in northward direction. In moderate to rough wave conditions the sediment of the sandgroynes in the Ter Heijde configuration is redistributed on a spatial scale in the order of several kilometers.

Both NW and SW offshore directed, wind generated waves refract towards western orientation in the nearshore, causing a nett northward directed longshore current along the Delfland coast.

The influence of the rubble mound groynes (‘Delflandse hoofden’) on the longshore transport is noticeable, however not considered to significantly influence the spatial scale of the longshore sediment redistribution.

For a more detailed explanation of the conclusions related to the morphological behavior of the sandgroyne nourishments is referred to Paragraph 4.5.

From a dredging industry point of view it can be concluded that nourishments dependent on the impact of the natural system are not an effective method under a contract prescribing design profiles:

Although not quantified, the construction costs have not been reduced by applying the sandgroyne nourishments instead of applying a more conventional method to nourish the upper shoreface.

- In moderate to rough wave conditions, the sandgroyne sediment was almost instantly transported, partly out of the site area. This required additional volumes of sediment to be nourished to reach the design. Throughout the entire Ter Heijde nourishment campaign, about 0.13 Mm³ of sediment has been nourished more than required according to the design.
- The minimum distance required between the heart line of the sandgroyne and the location of the sinker pipeline still resulted in a relatively long pumping length. A minimum distance is required to reduce the risk of the sinker pipeline being covered by a layer of sediment.

The monitoring campaign has been intense:
- Implementation of multiple survey platforms and extra survey personnel
- High survey resolution required locally near the sandgroynes
- Frequent surveys required
- Large survey area
- Limiting meteorological and hydrodynamic conditions

**6.2 Recommendations**

**6.2.1 Recommendations for short-term application**

It is recommended to apply sandgroyne nourishments under contract requirements that acknowledge the dynamics of the coastal system. The method of sandgroyne nourishments in the Ter Heijde pilot configuration has proven to be efficient from a morphological point of view. Although redistributed over an area larger than
expected, the sediment is remained in the active zone of the coastal profile. However, the contract requirements are crucial in determining the efficiency of the nourishment method for the dredging industry.

Contract settlement based on hopper sediment volumes is recommended instead of a contract prescribing design profiles. This type of contract, based on the amount of sediment present in the hopper barge and subsequently nourished in the coastal system will significantly reduce the amount of survey operations.

Another important aspect is the duration of the contract. It is recommended to opt for a long-term contract giving full responsibility to the contractors for maintaining the coastline. This type of contract allows the contractor to install permanent facilities and to work with a more flexible nourishment schedule. Mitigating the survey operations, installing permanent facilities and working with a more flexible nourishment schedule could significantly reduce the project costs.

6.2.2 Recommendations for long-term development

The morphological efficiency of sandgroyne nourishments in the Ter Heijde configuration has been established in this study. For further development of the sandgroyne nourishment towards a more general applied shoreface nourishment method along the Dutch coast it is recommended to verify the morphological behavior in other coastal configurations as well.

The sandgroyne pilot project has been executed in a coastal area characterized by the presence of one subtidal bar and by a rather oblique coastline orientation with respect to the incident wave angle and the regular presence of rubble mound groynes.

- It is recommended to verify the morphological behavior of sandgroynes on a coast characterized by multiple or no subtidal bars; both coastal configurations are found along the Dutch coast.
  - It is hypothesized that under moderate to rough wave conditions, part of the wave energy of waves arriving at the Delfland coast shore is dissipated on the subtidal bar before arriving at the sandgroynes. Waves have been identified as the dominant force is redistributing the sandgroyne sediment, indicating that the amount of wave energy arriving at the sandgroynes is crucial.

- It is recommended to verify the morphological behavior of sandgroynes on a coast where the waves will arrive more perpendicular at the shore.
  - It is hypothesized that for coastlines with a more perpendicular orientation towards the incident waves, the redistribution of sandgroyne sediment will show a different trend; the longshore spatial scale will be smaller.

- It is recommended to further verify the effect of rubble mound groynes on the redistribution of sandgroyne sediment.
  - It is hypothesized that rubble mound groynes extending a substantial part of the littoral zone of the coast, the spatial scale of sandgroyne sediment redistribution will be significantly reduced.

Van Son [2009] analyzed the autonomous migration of the subtidal bar at the Ter Heijde coast and concluded that the bar migrates onshore during calm meteorological conditions and migrates offshore in storm conditions. The interaction between the sandgroyne nourishments and the subtidal bar has not been studied. Nevertheless it is
recommended to study the possible interaction to verify whether the sandgroyne nourishments disturb the autonomous behavior of the coastal system. Driven by the stormy conditions, the lifetime of the sandgroynes constructed near Ter Heijde was in the order of several weeks. Therefore it is not expected that the sandgroynes are able to significantly influence the autonomous behavior of the coastal system, associated with much longer time scales.

The design of the sandgroynes, in terms of location, shape, magnitude and grain size, can be further developed. The sandgroynes in the Ter Heijde configuration have been relatively small, constraining the design potentials. In the context of optimizing the design, it is recommended to take into account the risk of a sinker pipeline being covered by an excessive amount of sediment. The aim is to find an optimal balance between minimizing the pumping lengths and reducing the risk of the sinker pipeline being covered by a layer of sediment.

With respect to the contract under which these kinds of nourishments are executed it is recommended to elaborate on the optimal contract form. This study has identified the relevant design parameters and did some general recommendations.

6.3 Sand engine

Another upcoming pilot project is the construction of the ‘sand engine’ at the coast of Ter Heijde, at the end of the year 2010. An artist impression of sand engine layout is presented in Figure 6-1. The sand engine is an input of sediment to dynamically nourish the Delfland Coast for a period in the order of a few years. The sand engine will contain about 20 Mm³ of sediment. The sand engine is expected to be a costs effective method to nourish the coast and integrates development of natural areas.

The sediment in the sand engine is anticipated to be redistributed over the Delfland Coast by the impact waves, wind and currents in conformity with the ‘building with nature’ principle. The same principle is used to absorb the...
sandgroynes, containing an amount of 200,000 m³ each, into the Ter Heijde Coast. More details about the construction of the sand engine are provided in Appendix L.
7. REFERENCES


[CERC, 1984]. Coastal engineering Research Center, Department of the Army, Waterways Experiment Station, “Shore protection manual”.


[Van Son, S.T.J., 2009]. Monitoring and modeling nearshore morphodynamic behavior on storm time scales, MSc-thesis report, Delft University of Technology.


Websites

www.Delflandsekust.nl
www.Kustvisiezuidholland.nl
A COASTAL SEDIMENT TRANSPORT

Sediment transport is defined as the movement of sediment particles through a well-defined plane over a certain period of time. Spatial gradients in sediment transport cause changes in the morphology. In coastal areas, 80-90% of the sediment transport occurs in the surfzone of the cross-shore profile. The surfzone is defined upon wave action and theoretically forms the part of the coastal profile from where the incoming waves start breaking until the waterline; hence the instantaneous width of the surfzone varies with the instantaneous wave and meteorological conditions\(^6\). The location of the surfzone, also called 'breaker zone', in the coastal profile is demonstrated in Figure A-1.

![Figure A-1 Schematic definition of coastal terms [CERC, 1984].](image)

Although sediment transport and morphology changes in the surfzone are three-dimensional, it is customary in nourishment related studies to consider the cross-shore and planform (long shore) evolution separately. A partial justification for this separation is that for many projects, the cross-shore evolution is believed to occur on a shorter time scale than the planform evolution [Dean, 2002]. In this Appendix, the dominant coastal processes contributing to the constituent sediment transport directions will be explained. Figure A-2 presents a schematic illustration of the longshore and cross-shore sediment transport processes in the coastal area.

![Figure A-2 Schematic illustration of the longshore and cross shore sediment transport [Bosboom, 2010].](image)

\(^6\) By approximation the surfzone is defined as the zone valid for the yearly wave climate, defined by the significant wave height \(H_{\text{S},12/2}\). This is the wave height that is exceeded 12 hours per year.
### A.1 Cross-shore transport

Cross-shore sediment transport comprises sediment transport in onshore or offshore direction, perpendicular to the coastline in Figure A-2. Cross-shore transport can change the shape of the coastal profile, however without changing the amount of sediment present in the profile, considering the littoral zone of the coastal profile. Cross-shore transport is commonly associated with the following coastal processes, induced by waves [Van Rijn, 1997]:

- **Net onshore directed transport** due to asymmetry of the near bed orbital velocities with relatively large onshore peak velocities under the wave crest and relatively small peak velocities under the wave troughs. Net onshore transport is commonly dominant in non-breaking wave conditions, hence outside the instantaneous surfzone.
- **Net offshore directed transport** due to the generation of a return current (undertow) in the near-bed layers, balancing the onshore mass flux between the crest and trough of breaking waves. Net offshore directed transport is commonly dominant in breaking wave conditions, hence inside the surfzone.
- **Net onshore-directed transport** due to the generation of a quasi-steady weak current [Longuet-Higgins, 1953] in the wave boundary layer.
- **Net offshore-directed transport** due to the generation of bound long waves associated with variations of the radiation stresses under irregular wave groups (peak velocities and sand concentrations are out of phase).
- **Gravitly-induced transport components** related to bed slopes.

### A.2 Longshore transport

Longshore sediment transport occurs in planform direction, parallel to the coastline and depth contours (perpendicular on the plane of the coastal profile sketched in Figure A-1). Longshore transport is driven by a longshore current, generated either by tide, wind and/or wave forces.

**Tidal current**
The tide generated current is the result of the water level gradient caused by the tidal wave propagating through the oceans and coastal waters. For the Dutch coast, the tidal wave with a period of about 12.5 hours propagates in northern direction. During rising tide, the current flows in northern direction, during falling tide the water flows in southern direction. Along the Dutch coast, the tidal current is most dominant outside the surfzone. Inside the surfzone, the longshore current is dominated by the wave-driven longshore current.

**Wind**
Wind driven currents are generated by a shear stress between the air and water, both with a different density and flow velocity. In cross-shore direction, the resulting shear stress is balanced by a water level gradient (wind set-up or set-down). In longshore direction, the shear stress causes the top layer of the seawater to flow more or less in the same direction as the wind direction. The velocity of the top layer current depends on the duration of the wind condition and its strength.

**Waves**
For waves approaching the coast obliquely, a longshore current is generated in the surfzone. Wave related processes such as shoaling, refraction, and wave breaking cause a difference in radiation stress across the surfzone. Radiation stress is the flux of momentum, carried by the waves. Horizontal gradients in the radiation stress exert a wave-induced net force on the water. Similar to the wind forcing, in cross-shore direction the net...
force is balanced by a water level gradient (wave set-up or set-down). In longshore direction the force induces a net longshore current. Forcing due to this radiation stress is commonly several orders of magnitude larger than forcing due to wind.

The magnitude of the wave driven longshore sediment transport depends on the angle of incidence of deep water waves. The relation of the wave angle of approach with the wave driven longshore transport is presented in Figure A-3. The figure shows that waves approaching the shore perpendicular do not induce a longshore sediment transport as there is no wave driven longshore current. The maximum longshore sediment transport occurs for waves approaching the shore under an angle of somewhat smaller than 45º. For more theory on the relation between the wave approach angle and the longshore sediment transport is referred to Van de Graaff [2006].

A spatial gradient in longshore sediment transport may lead to negative (erosion) or positive (accretion) sediment balances along a certain stretch of coast.

### A.3 Surfzone current velocity field

Figure A-4 presents a 3D schematic illustration of the current velocity field in the surfzone of a coastal profile. The current velocity field gives an overview of the direction of driving forces of the sediment transport over the entire water column.

---

**Figure A-3** Relation of the deep water wave approach angle with the wave driven longshore sediment transport [Van De Graaff, 2006]

**Figure A-4** 3D impression of the surfzone current velocity field comprising a wave driven longshore current and an undertow [Van Dongeren, 1995]
**B OVERVIEW OF PREVIOUS TER HEIJDE NOURISHMENTS**

Figure B-1 shows a plan view of the Delfland coast (left) and a zoom in on Ter Heijde beach (right), including several colored polygons. These polygons represent the areas that have been subject to previous nourishment campaigns. Green colored polygons represent shoreface nourishments, red colored polygons represent beach nourishments and the yellow colored polygon represents landward extension of the dunes.

![Figure B-1: Plan view of the Delfland coast (left) and Ter Heijde beach (right), including a representation of all previous nourishments executed between the years 1970 and 2007 (Google Earth)](image)

The figure shows that the entire stretch of the Delfland coast, in particular the beach, has been subject to nourishments at least once before the actual nourishment campaign started. Near Ter Heijde beach shoreface and beach nourishments as well as landward dune extension has been executed. Table B-1 shows some characteristic figures of the previous executed nourishments. In the past decennium, about 7 million m³ of sand has been nourished near Ter Heijde; that is a yearly average of 700,000 m³ per year. As a reference, the nourishments executed in the second half of 2009 near Ter Heijde comprise an amount of 2.5 million m³.
<table>
<thead>
<tr>
<th>Year</th>
<th>Duration (months)</th>
<th>Type of nourishment</th>
<th>Amount nourished (x 10$^6$ m$^3$, based on survey data)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>unknown</td>
<td>Shoreface</td>
<td>unknown</td>
</tr>
<tr>
<td>2004</td>
<td>12</td>
<td>Beach</td>
<td>1.15</td>
</tr>
<tr>
<td>2003</td>
<td>3</td>
<td>Beach</td>
<td>1.25</td>
</tr>
<tr>
<td>2001</td>
<td>8</td>
<td>Shoreface</td>
<td>3.60</td>
</tr>
<tr>
<td>2001</td>
<td>3</td>
<td>Beach</td>
<td>0.80</td>
</tr>
<tr>
<td>1997</td>
<td>12</td>
<td>Beach</td>
<td>0.85</td>
</tr>
<tr>
<td>1997</td>
<td>3</td>
<td>Shoreface</td>
<td>1.05</td>
</tr>
<tr>
<td>1995</td>
<td>2</td>
<td>Beach</td>
<td>0.30</td>
</tr>
<tr>
<td>1993</td>
<td>2</td>
<td>Beach</td>
<td>1.15</td>
</tr>
<tr>
<td>1986</td>
<td>5</td>
<td>Beach</td>
<td>1.90</td>
</tr>
<tr>
<td>1986</td>
<td>5</td>
<td>Landward dune extension</td>
<td>1.30</td>
</tr>
</tbody>
</table>

Table B-1 Overview of previous artificial nourishments executed near Ter Heijde beach
C DESCRIPTION OF THE DREDGING PROCEDURE

Figure C-1 Plan view of the Ter Heijde area in the period from September 2009 until January 2010, near Ter Heijde village.

The boundaries of the Ter Heijde site presented in Figure C-1 are mainly imposed by the static position of the submerged part of the sinker pipeline, orientated perpendicular to the coastline, see Photo C-1. Dredging vessels couple to the offshore coupling point, subsequently pumping the sediment-water mixture pumped up from one of a range of possible borrow locations further offshore, through the 2 km long sinker pipeline, onshore. Once the submerged pipeline arrives on shore, a pumping length of approximately 600m is available on the beach to still efficiently supply the sediment on the intended locations. Figure C-2 illustrates the nourishment procedure. The track of the submerged part of the pipeline is static, the part on the beach is easy adjustable in terms of length and orientation by means of wheeldozers. During the period mentioned, the submerged part of the pipeline has been shifted once southward, on the 23rd of October (see also Figure C-2). The sinker pipeline replacement is a massive operation and usually takes a full day of work. The pipeline is moved in its entire length of about 2km, escorted by a number of specialized vessels. As the position of the sinker pipeline directly outlines the nourishment area for a period in the order of several months, accurate planning and careful allocation is required.
The figure indicates that from the two different sinker pipeline positions a substantial part of the site area can be covered. Theoretically, the southern part is not covered by the sinker pipeline; however the dunes and the beach of this specific part had been completed before the summer of 2009, so before the considered nourishment campaign. The Google Earth background satellite image, taken on the 2\textsuperscript{nd} of April 2009, confirms the progress by showing dredging operations southward of the indicated work area. The shoreface of the southern part of the work area is aimed to be nourished by the sediment from the sandgroyynes. So theoretically there is no need for this area to be reached for the sinker pipeline indicated in Figure C- 2.
The sediment is delivered by a trailing suction hopper dredger (TSHD), dredging a sediment-water mixture from a borrow location about 10km offshore. Predominantly the ‘HAM 310’, belonging to the fleet of Van Oord, was operating for the project ‘Combinatie Delflandse Kust’ (see Photo C- 2). This TSHD has a hopper capacity of 12,500m³.

For the HAM 310, the entire cycle of dredging up the sediment-water mixture, sailing to the offshore sinker pipeline coupling point, pumping the mixture through the sinker pipeline and sailing back to the borrow area takes about 5 hours. The dredging and pumping takes about 2 hours, sailing from the borrow location to the sinker pipeline coupling point and vice versa takes about half an hour.
Project name: Pilot Sand Groynes Delfland Coast
## D NOURISHMENT PROGRESS FIGURES

<table>
<thead>
<tr>
<th>NOURISHMENT DESIGN</th>
<th>Part of the coastal profile</th>
<th>Sediment volume design (.10^6 m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>September 2009 – January 2010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compartments</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compartments 9</td>
<td>TOTAL</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>Shoreface</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>Beach &amp; Dunes</td>
<td>0.02</td>
</tr>
<tr>
<td>Compartments 10</td>
<td>TOTAL</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>Shoreface</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>Beach &amp; Dunes</td>
<td>0.20</td>
</tr>
<tr>
<td>Compartments 11</td>
<td>TOTAL</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>Shoreface</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>Beach &amp; Dunes</td>
<td>0.36</td>
</tr>
<tr>
<td>Compartments 12A</td>
<td>TOTAL</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>Shoreface</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>Beach &amp; Dunes</td>
<td>0.19</td>
</tr>
<tr>
<td>Compartments 12B</td>
<td>TOTAL</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>Shoreface</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>Beach &amp; Dunes</td>
<td>0.41</td>
</tr>
<tr>
<td>Compartments 9 – Compartments 12B</td>
<td>TOTAL</td>
<td>2.35</td>
</tr>
<tr>
<td></td>
<td>Shoreface</td>
<td>1.17</td>
</tr>
<tr>
<td></td>
<td>Beach &amp; Dunes</td>
<td>1.18</td>
</tr>
</tbody>
</table>

Table D-1 Overview of nourishment design volumes according to the design.
NOURISHMENT ACHIEVED  
September – December 2009

<table>
<thead>
<tr>
<th>Compartment 9</th>
<th>Beach nourishment</th>
<th>0.13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compartment 10</td>
<td>Beach nourishment</td>
<td>0.15</td>
</tr>
<tr>
<td>Compartment 11</td>
<td>Beach nourishment</td>
<td>0.72</td>
</tr>
<tr>
<td>Compartment 12A</td>
<td>Beach nourishment</td>
<td>0.09</td>
</tr>
<tr>
<td>Compartment 12B</td>
<td>Beach nourishment</td>
<td>0.86</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td>1.95</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Compartment 9 – Compartment 12B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beach nourishment</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
</tr>
<tr>
<td>Sandgroyne 1</td>
</tr>
<tr>
<td>Sandgroyne 2</td>
</tr>
<tr>
<td>Sandgroyne 3</td>
</tr>
</tbody>
</table>

| Sandgroynes TOTAL               | 0.53 |
| **TOTAL**                       | 2.48 |

Table D-2 Overview of sediment volumes pumped up during the Ter Heijde nourishment.
E SANDGROYNE NOURISHMENTS: DESIGN AND CONSTRUCTION

Figure E-1 presents the theoretical design of the sandgroyne nourishments, proposed by Cats & Van der Sluijs [2009].

Figure E-1 Top view (upper sketch) and 3D view (middle and bottom sketch) of the sandgroyne design [Cats & Van der Sluijs, 2009]
Photo E-1 and Photo E-2 shows the sandgroynes at the Ter Heijde coast. The third sandgroyne, see Photo E-2, is representative for a sandgroyne just after completion. Just after completion the dimensions of the dry part of the sandgroynes are about 200m both in longshore and in cross-shore direction.

The construction period and characteristics of the sandgroynes are presented in Figure E-2 and Table E-1.

![Photo E-1 Aerial photo taken on the 10th of November, showing the third, most southern located sandgroyne. Photo is taken in NE direction (property: Van Oord Nederland).](image1)

![Photo E-2 Aerial photo taken on the 10th of November, showing the first and second, both northern located sandgroynes. Photo is taken in NW direction (property: Van Oord Nederland).](image2)

![Construction period of sandgroynes](image3)

*Figure E-2 Representation of the construction periods of the three consecutive realized sandgroynes.*
### Table E-1 Overview of the relevant sandgroyne construction figures.

<table>
<thead>
<tr>
<th>Sandgroyne 1</th>
<th>Location along centerline Delfland</th>
<th>Start construction&lt;sup&gt;7&lt;/sup&gt;</th>
<th>Construction finished&lt;sup&gt;7&lt;/sup&gt;</th>
<th>Net duration (days)</th>
<th>Interruption (days)</th>
<th>Net amount of sediment pumped in (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>KM 110.700</td>
<td>15 October 2009 12.00u</td>
<td>20 October 2009 12.00u</td>
<td>4</td>
<td>1 (bad weather)</td>
<td>137.000</td>
</tr>
<tr>
<td>Sandgroyne 2</td>
<td>KM 110.100</td>
<td>31 October 2009 18.00u</td>
<td>6 November 2009 06.00u</td>
<td>5.5</td>
<td>0</td>
<td>194.000</td>
</tr>
<tr>
<td>Sandgroyne 3</td>
<td>KM 111.900</td>
<td>7 November 18.00u</td>
<td>9 November 18.00u</td>
<td>2 (double hopper capacity)</td>
<td>0</td>
<td>201.000</td>
</tr>
</tbody>
</table>

<sup>7</sup> Rounded to quarters of days
Project name: Pilot Sand Groynes Delfland Coast
Figure K-1 Timeseries of wave height, wave direction and wind speed, relevant for the Ter Heijde site in the months October, November and December 2009.
Figure F- 1 Year-averaged wave climate based on wave timeseries recorded by several stations in the North Sea over the years 1979-2001.
Figure F-2 Wave climate for the summer season (April-September), based on wave timeseries recorded by several stations in the North Sea over the years 1979-2001.

Figure F-3 Wave climate for the winter season (October - March), based on wave timeseries recorded by several stations in the North Sea over the years 1979-2001.
Figure F-4 Wind climate for the summer season (April-September), based on wave timeseries recorded by several stations in the North Sea over the years 1979-2001.

Figure F-5 Wind climate for the winter season (October-March), based on wave timeseries recorded by several stations in the North Sea over the years 1979-2001.
Figure F-6 Wave climate of the period from October until December in the years 1979-2001, based on wave timeseries recorded by several stations in the North Sea.

Figure F-7 Wave climate of the period from October until December in the year 2009, based on wave timeseries recorded by several stations in the North Sea.
G  BATHYMETRY PLOTS
Figure G-1 Representation of the bathymetries from mid-September 2009 and mid January 2010, including the meantime sedimentation/erosion plot
Figure G-2: Representation of the bathymetries on the 16th of November and the 2nd of December 2009, including the meantime sedimentation/erosion plot.
SET UP NUMERICAL SIMULATION MODEL

H.1 Introduction

A numerical simulation model for coastal areas is implemented in this study to:

1. derive the local hydrodynamic conditions near Ter Heijde for the period between the 16th of November and the 2nd of December.
2. perform a sensitivity analysis on the hydrodynamic parameters dominating the morphological behavior of the sandgroyne nourishments.
3. simulate several sandgroyne design alternatives relevant for assessing the efficiency of the sandgroyne nourishments for the dredging industry.

In order to settle the model objectives listed above, the preparational step is to set up the model and verify to which extent the model is able to reproduce the morphology changes as presented in the data analysis. It is not aimed to thoroughly calibrate and validate the model for this case; the intention is to derive some basic morphological developments.

The local hydrodynamic conditions near Ter Heijde will be derived to validate the morphodynamics identified in the previous chapter. Hydrodynamic data is readily available, however on a distance of about 50km off the study area. The model transforms the offshore hydrodynamic data to the nearshore to get a rough impression of the characteristics of local waves and currents.

A basic sensitivity analysis will be performed on the hydrodynamic parameters dominating the morphology of the sandgroyne nourishments. The data analysis showed out that the wave(direction) is a crucial driving force. The sensitivity of this parameter on the morphology will be examined by the simulation model.

The model will also be applied to simulate several alternative sandgroyne nourishments as a guideline for defining the optimal design and conditions of these types of nourishments for the dredging industry. The results of these simulations are presented in the next chapter, focusing on the practical aspects of the sandgroynes. In the next chapter an analysis of the relevant, dredging related aspects of sandgroyne nourishment is provided first; this analysis will lead to a range of interesting simulation alternatives.

The numerical simulation model Delft3D (ref.) is used in this study. Delft3D is a process-based, morphodynamic model based on a set of equations schematizing coastal processes like wind, waves, tides and sediment transport. The application area of the model is shallow coastal areas. A more detailed description of the principles and capabilities of the model is provided in Appendix … (?). In the continuation of the report, the reader is assumed to understand the basics of the model.
H.2 Model set-up

For this study reference is made to a model structure developed for a hindcast study on the Amelander Zeegat. This model allows for a detailed hindcast study for a random location along the Dutch coast, based on meteorological data. Wind, waves, tide and surge is included in the model to simulate local hydrodynamic and morphological processes. The structure consists of a range of coupled model domains, transferring boundary conditions from large, relatively low resolution grids to smaller, higher resolution grids. The following sub-paragraph provides a description of the simulation domains applied in this study.

H.2.1 Grids

Figure H-1 provides an overview of the three model domains applied for the sandgroyne simulation campaign.

**CSM model**
The Continental Shelf Model (CSM model) is a hydrodynamic model covering the north-western part of the European continental shelf, see upper left frame of Figure H-1. The model boundaries are imposed by astronomical components, the meteorological forcing is assimilated by spatial and temporal varying wind and pressure fields, derived from the HIRLAM model of the Dutch meteorological institute KNMI (ref) with a time interval of 3hrs. The relatively large CSM model simulates the propagation of the tidal wave and generation of the surge by meteorological forcing of the entire North Sea. The simulation of waves and morphology is not included in this model.

**Kuststrook model**
The Kuststrook model (in English: ‘coastal strip model’) is a hydrodynamic model as well, covering the coastal area of the Netherlands, see the upper right frame of Figure H-1. In cross-shore direction, the model stretches from the shore to a distance of about 75km offshore. The hydrodynamic boundaries are imposed by timeseries of water levels, derived from the CSM model. Again, meteorological forcing is assimilated by the HIRLAM wind and pressure fields. The Kuststrook model simulates the propagation of the tidal wave and generation of the surge on a higher resolution grid compared to the CSM model, to smoothen the transition from the CSM model to the final, nearshore located model, the Delfland model. The simulation of waves and morphology is not included in the model.
Delfland model

The Delfland model is the final model, simulating the hydrodynamics, waves and morphology in the study area surrounding the sandgroyne nourishments. The model covers the center part of the Delfland coast, stretching about 5.5km in longshore direction and 2km in cross-shore direction, see the lower right frame of Figure H-1. The highest resolution of the simulation grid is 10x15m in the direct vicinity of the sandgroyne nourishments. The hydrodynamic conditions are imposed by timeseries of the Kuststrook model; the offshore boundary by waterlevels, the cross-shore boundaries by Neumann boundary conditions. Neumann boundary conditions are imposed to anticipate on disturbances caused by the wave set-up in the Delfland model, not accounted for in the Kuststrook model. The Neumann boundary conditions are derived from the waterlevel gradient at the offshore point of the boundaries. Meteorological forcing is assimilated by HIRLAM wind and pressure fields.
The propagation and effects of waves are assimilated by three coupled wave domains, see lower left frame of Figure H-1; offshore waves monitored by the Europlatform monitoring station can be transformed to local, nearshore waves conditions. Offshore waverdata from the Europlatform is readily available on an interval of 10 minutes, containing information about the significant wave height ($H_s$), the peak period ($T_p$), the wave direction (Dir) and the directional spreading (Dirspread). Wave characteristics from the Europlatform are imposed uniformly over the offshore and both cross-shore boundaries of the largest wave grid and transformed to local conditions consecutively by the middle size grid and the smallest wave grid. By means of a 20 minute interval, online coupling, the waves are involved in the hydrodynamic calculation of the Delfland flow model.

The morphological evolution is simulated in the Delfland flow model by the hydrodynamic forcing as a result of the wind, waves and tide. A uniform type of sediment is adopted for the entire area ($D_{50}=280\mu m$). The $D_{50}$ is the result of a number of sand samples which have been taken and sieved during the monitoring campaign. Grain size distributions of the sand samples taken are provided in Appendix J. The model simulates the morphological evolution real-time, so the Morfac = 1. Sediment transports are simulated by Van Rijn [2003], distinguishing bed load sediment transport and suspended sediment transport.

<table>
<thead>
<tr>
<th>Grid transition</th>
<th>Resolution ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSM → Kuststrook</td>
<td>± 1:12</td>
</tr>
<tr>
<td>Kuststrook → Delfland Flow</td>
<td>1:10 – 1:50</td>
</tr>
<tr>
<td>Delfland Wave Large → Medium → Fine</td>
<td>1:6 &amp; 1:12</td>
</tr>
<tr>
<td>Delfland Wave Fine → Delfland Flow</td>
<td>1:1</td>
</tr>
</tbody>
</table>

**H.2.2 Bathymetry**

The CSM and Kuststrook model are readily available with an accompanying bathymetry. The Delfland flow and wave domains have been created specially for this study. Actual bathymetries for the Delfland domains are created with field data collected during the sandgroyne monitoring campaign. A number of actual, nearshore bathymetry datasets are available on an interval of about two weeks, each covering a substantial part of the study area and assumed to represent the bathymetry of a single day. In addition two rubble mound groynes, suggested to influence the morphological evolution in the area, have been implemented in the bathymetry.

**H.2.3 Simulation time and time step**

The simulation time depends on the considered period. A period of about two weeks usually takes 5 days of simulation. Preliminary to the start of the morphological simulations on the starting date, a 4-day spin up time of the hydrodynamics is implemented in the model. The simulation time step for the Delfland model is 12sec.

**H.3 Model validation**

The main purpose of the model for this study is to derive a rough spatial scale (with an accompanying temporal scale) of the area influenced by the sandgroyne nourishments for several scenarios and design alternatives. This
purpose does not require a thorough model validation. A basic model validation is performed for the period between the 16\textsuperscript{th} of November and the 2\textsuperscript{nd} of December. The main reason to refer to this period is the limited amount of artificial nourishments executed in this period, potentially interfering with the morphological behavior of the sandgroyne nourishments. For both dates a representation of the bathymetry is available. The bathymetry of the 16\textsuperscript{th} of November will be used as a start bottom for the simulation, the bathymetry of the 2\textsuperscript{nd} of November as a validation for the simulated bottom on the 2\textsuperscript{nd} of December.

H.3.1 Hydrodynamic validation

The hydrodynamics simulated by the model have been validated based on expert judgment, by comparing them to values recorded by several monitoring stations located in the area covered by the simulation domain. The locations of the relevant monitoring stations are presented in Figure H-2. Appendix J includes plots presenting simulated and monitored timeseries of respectively the water level, the wind speed and direction, the significant wave height and peak period, and the current velocity and direction.

![Figure H-2 Relevant hydrodynamic monitoring platforms along the Dutch coast](image)

The figures show that the measured and computed timeseries of the water level, wind and wave characteristics fairly correspond. The frequency and phase of the measured and computed values of the currents also correspond fairly well. Overall, the current velocities are slightly underestimated by the model. Besides, during slack tide the computed current direction turns counter-clockwise, whereas the measured current direction turns clockwise. The difference in current velocity magnitude and current direction is explained by the location of the monitoring platforms close to a breakwater for IJmuiden and near the extension of the Maasvlakte for Hoek van Holland. Both features induce flow contraction, causing increased flow velocities and a change in tidal current shift. These features are not implemented in the simulation bathymetry, therefore showing a different trend. The
differences are locally observed; with respect to the purpose of the model not suspected to have a significant influence on the Ter Heijde hydrodynamics.

H.3.2 Morphological validation

The model has been validated based on two different datasets, representing two consecutive bathymetries of the 16th of November and the 2nd of December. A number of test runs have been conducted, varying some relevant physical parameters influencing the morphological evolution in the simulation. The settings of the simulation that shows the highest level of agreement with the results directly derived from the field data will be used for assessment simulations. Figure H-3 shows the comparison of field data with model simulation for the Ter Heijde site and the area northward, Figure H-4 zooms in on the Ter Heijde site. The model simulation results presented in these figures show the highest level of agreement with the results of the field data. The black polygon visible in both figures marks the area of which high resolution and actual data is available. Outside the polygon, the data can be missing or not fully representative for the considered period; therefore careful interpretation of the morphology in these areas is required.

Figure H-3 Sedimentation/erosion plots of the period 16 November – 2 December 2009, covering the Ter Heijde site area and the area northward. Left plot is based on field data, right plot is the model simulation hindcast.
Overall, the sedimentation and erosion trends are fairly well reproduced by the simulation. A couple of remarks should be made about the morphological validation results shown in Figure H- 3 and Figure H- 4:

- Nourishments have been executed in the period considered. Obviously, the effects are incorporated in the field data, however not in the simulation. Still, the result from the field data and the simulation are supposed to be well comparable as the production was really poor due to the bad weather (~100,000m³ in 2 weeks time).
- Sedimentation at the south side of the two southward located sandgroynes is not reproduced by the simulation. In the data analysis (see Chapter 4) it was concluded that these sedimentation patterns were caused by wave induced cross-shore transport. As the simulation model is a 2DH model, cross-shore transport driven by the wave induced undertow is not properly implemented. This is an aspect that should be taken into account for further development of the model.

Table H- 1 presents an overview of the model settings used for the simulation of which the results are presented in Figure H- 3 and Figure H- 4. Without further explanation, these settings will be used for simulating several
sandgroyne scenarios and alternatives. Default values have been used for the settings not presented in Table H-1.

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediment size</td>
<td>D_{50}</td>
<td>280 μm</td>
</tr>
<tr>
<td>Time step</td>
<td>dt</td>
<td>12 sec.</td>
</tr>
<tr>
<td>Vertical layers</td>
<td>σ</td>
<td>1 (2DH)</td>
</tr>
<tr>
<td>Morphological factor</td>
<td>morfac</td>
<td>1</td>
</tr>
<tr>
<td>Suspended sediment reference concentration factor</td>
<td>sus</td>
<td>0.3 (def.: 1)</td>
</tr>
<tr>
<td>Bed-load transport vector magnitude factor</td>
<td>bed</td>
<td>0.3 (def.: 1)</td>
</tr>
<tr>
<td>Horizontal eddy viscosity</td>
<td>vicouv</td>
<td>3 (def.: 1)</td>
</tr>
<tr>
<td>Horizontal eddy diffusity</td>
<td>dicouv</td>
<td>3 (def.: 1)</td>
</tr>
<tr>
<td>Transport formula</td>
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<td>Van Rijn '03 (def.)</td>
</tr>
<tr>
<td>Roller model</td>
<td>-</td>
<td>YES</td>
</tr>
<tr>
<td>Gamdis</td>
<td>gamdis</td>
<td>-1</td>
</tr>
</tbody>
</table>

*Table H-1 Relevant model simulation settings*
I SAND SAMPLE ANALYSIS
Figure I-1 Grain size distribution of sand sample taken on 21 October 2009.
Figure I- 2 Grain size distribution of sand samples taken on 27 October 2009.
Figure I-3 Grain size distribution of sand samples taken on 3 November 2009.
Figure I-4 Grain size distribution of sand samples taken on 3 December 2009.
Project name: Pilot Sand Groynes Delfland Coast
J HYDRODYNAMIC MODEL VALIDATION PLOTS
Figure J-1 Water level validation plots
Figure J-2 Wind velocity and wind direction validation plots
Figure J-3 Wave height and wave period validation plots
Figure J-4 Current speed and direction validation plots
K SCENARIO SIMULATION PLOTS
Figure K-2 Overview of the simulation results of the reference scenario (including waves) and scenario alternative 1 (excluding waves).
Figure K-3 Overview of the simulation results of the reference scenario (wave direction: SW) and scenario alternative 1 (wave direction: NW).
Figure K-4 Overview of the simulation results of the reference scenario (wave climate: moderate/rough) and scenario alternative 2 (wave climate: calm/moderate).
Sediment transport vectors, Ter Heijde site area

reference scenario (16 November - 2 December 2009)

nett transport (averaged in m³/hour)

gross northward transport (averaged in m³/hour)

gross southward transport (averaged in m³/hour)

fraction: sandgroyne + environment
fraction: sandgroyne
fraction: environment

Figure K-5 Overview of sediment transport vectors for the reference scenario, presented in a matrix distinguishing different fractions (horizontally) and transport directions (vertically)
Figure K-6 Overview of sediment transport vectors for alternative scenario 1, presented in a matrix distinguishing different fractions (horizontally) and transport directions (vertically).
Figure K-7 Overview of sediment transport vectors for alternative scenario 2, presented in a matrix distinguishing different fractions (horizontally) and transport directions (vertically).
Figure K-8 Overview of sediment transport vectors for alternative scenario 3, presented in a matrix distinguishing different fractions (horizontally) and transport directions (vertically).
The sand engine is a large amount of sand to be nourished from the shoreline in seaward direction at the Delfland Coast, forming a peninsula. The sand will be redistributed by the impact of waves, wind and currents, maintaining the coastline on a natural way. The sand engine functions as a long-term sand injection for the Delfland Coast.

The sand engine is a pilot project to be realized just north of Ter Heijde; contain an amount of about 20 Mm³ of sand, stretching about 2km in longshore direction at the connection with the conventional shoreline and protruding about 1.5km into the sea. Besides its primary function to serve as a sediment buffer for a long-term coastal protection, the sand engine creates the opportunity for integration of nature and recreation.

Such a large scale nourishment, highly dependent on the dynamics of the natural system, has never been executed before. The intention is to acquire knowledge and experience about nourishments with this principle. The intention is to realize the first sand engine in the year 2010.
Figure M- 1 Newspaper article published in the Dutch newspaper NRC on 11 March 2011.