Morphodynamics of mega-nourishment

Integrated model approach for the design and management of mega-nourishment

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Dynamics of mega-nourishment

Integrated model approach for the design of mega-nourishments

by

ing. Timon Pekkeriet

A thesis submitted in partial fulfillment of the requirements for the degree of

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Morphodynamics of mega-nourishment
Acknowledgement

This thesis report forms the final stage for the fulfilment of the Master of Science program at the Faculty of Civil Engineering. Its main objective is to provide new insight in the morphodynamics of mega-nourishments by an integrated model approach.

I would like to acknowledge Deltares for the opportunity to perform research to such a unique project like the sand-engine. Also, I would like to acknowledge several people for all their support during my study in Delft and during this thesis period in particular:

The graduation committee for their discussions, advice, support and feedback during the realization of this thesis and the focus given to this thesis. Special thanks to my daily supervisors Arjen Luijendijk and Jaap van Thiel de Vries for their guidance and valuable input during my entire stay at Deltares.

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Timon Pekkeriet

Delft, December 2011
Abstract

Introduction

In 2003 a first proposal for identification of seaward development, preliminary in combination with residential building, was presented in the Chamber of Deputies and within the States-Provincial (South-Holland), by respectively Geluk and Waterman. In response to this proposition, the ministry (VROM) together with the province started an investigation, but concluded there was no support for seaward development financed through residential housing. Consequently, the initial proposal was adjusted. A feasibility analysis was made for seaward extension together with extensive possibilities for nature and recreation. A follow-up investigation (2005) indicated a large need for nature and recreation in the conurbation of Western Holland. In 2006 commission Tielrooij urged the necessity of a combined approach of the Delfland coast for sustainable long-term flood protection with expanding spatial qualities. The commission recommended a research into innovative civil methods for sustainable flood protection and expanding spatial qualities, with a focus on mega-nourishment.

In April 2008, an agreement is signed, by all concerning governmental stakeholders, for coastal expansion according to the principle “Building with Nature”. This agreement enables the start of a process to examine and investigate the execution of a so-called “Zandmotor” (hereafter sand-engine) at the Delfland coast. The design phase was under the management of the Province South-Holland (2008-2009).

Early 2009, the Environmental Impact Assessment “pilot project sand-engine” was published, in autumn 2009 the decision was finished regarding the financial costs for the Province and the Department of Waterways and Public Works. In March 2011, the execution of the sand-engine started near the Delfland coast, see Figure 1. The preparatory phase was under the management of the Department of Waterways and Public Works (2010).

Figure 1 Location of the mega-nourishment 'sand-engine' near the Delfland coast.

In September 2008, the committee Veerman presented their report, Working together with water. The report describes possibilities to change the policy regarding integrated coastal management. Their recommendations and conclusions involved the applicability of large-
scale nourishments to counter balance sea level rise in the future in combination with additional space for nature and recreation. The introduction of mega-nourishments could work out as an alternative instead of the present nourishment policy.

Also in 2008, the five-year innovation and research program Building with Nature (hereafter BwN) (2008-2012) started, which is operated by the EcoShape foundation. This program investigates opportunities for projects in hydraulic engineering by using the dynamics of the natural system. The sand-engine is part of the program, for sustainable development of the Dutch coastal system, which has to provide insight into long-term coastal management of the Dutch coast.

**Lack of integrated approach during design phase**

The Environmental Impact Assessment for the pilot project the sand-engine is based on long-term morphodynamic predictions, made with a single numerical software model called Delft3D. This model calculated the morphological development of the sand-engine for 20 years in advance, using averaged meteorological conditions. After the EIA and during the construction of the sand-engine new problems and questions arose among stakeholders, concerning e.g. groundwater flow, swimming safety, impact of storm events, aeolian transports, etc. These uncertainties were not modeled and simulated, and are not included in the EIA. In order to reduce these uncertainties a new approach is presented for the design phase of mega-nourishments.

**New model approach**

Because there was a lack of an integrated design approach during the EIA phase of the sand-engine, this thesis contributes to the development of an idealized design approach for mega-nourishments. Due to this idealized design approach, multiple physical processes can be integrated using several numerical models for accurate long-term modeling of mega-nourishments. One integration, in this idealized design approach, concerns the impact of storm events within long-term morphological predictions. The integration of storm events within long-term morphodynamic predictions, is developed within this thesis, by coupling two numerical software models, Delft3D and XBeach. Delft3D functions as base core, generating long-term morphodynamic predictions, and via XBeach, storm events are simulated at several points in time. The main objective of this thesis is an impact assessment of storm events on the long-term (5 years) morphodynamic development of the sand-engine and adjacent coastline.

**Impact storm events substantial on long-term morphodynamics predictions**

For the assessment of the impact of storm events on the morphological development of the sand-engine, a reference scenario is made for comparison. The reference case predicts the morphological development of the sand-engine with average meteorological conditions for five years in advance. During the reference case, the western face of the sand-engine erodes due to the flow contraction induced sediment transports. In addition, a spit from the northern side of the sand-engine develops towards the adjacent coast. The net transport of sediments along the Dutch coast is from the south to the north. During the morphological development of the sand-engine, accretion occurs at the south side, because the sand-engine blocks this net sediment transport. Consequently, erosion occurs at the north side, near Kijkduin.
During storm events, the morphodynamic process of the sand-engine is accelerated. Furthermore, considering five-year morphological predictions, a number of mild storm events (1/1 year) have more impact than a single severe storm event (1/100 year). The cumulative impact of frequent mild storm events provide a substantial morphodynamic change. During severe storm events (1/100 year and 1/1000 year) the pronounced hooked shape of the sand-engine remains intact. However, during severe storm events, especially after some years, the spit of the sand-engine becomes sensitive for breaching. This breaching occurs due to overtopping and overwash processes, which can be the result of high surge levels and/or high wave conditions.

**Recommendation for future mega-nourishments**

Due to model integration it will be possible to compute multiple physical processes during long-term predictions of mega-nourishments, concerning e.g. siltation, aeolian transports, ground water table, storm events, etc. The importance of storm events is elaborated in this thesis, however more research is recommended towards the cumulative impact of frequent mild storm events. In addition, extensive investigations and impact assessments are recommended towards the other mentioned physical processes, certainly considering the long-term perspective of mega-nourishments.
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1 Introduction

In 2003 a first proposal for identification of seaward development, preliminary in combination with residential building, was presented in the Chamber of Deputies and within the States-Provincial (South-Holland), by respectively Geluk and Waterman. In response to this proposition, the ministry started an investigation, but concluded there was no support for seaward development financed through residential housing. Consequently, the initial proposal was adjusted. A feasibility analysis was made for seaward extension together with extensive possibilities for nature and recreation. A follow-up investigation (2005) indicated a large need for nature and recreation in the conurbation of Western Holland. In 2006 commission Tielrooij urged the necessity of a combined approach of the Delfland coast for long-term flood protection with expanding spatial qualities. The commission recommends a research into innovative civil methods for sustainable flood protection and expanding spatial qualities, among which mega-nourishment is recommended.

1.1 Motive

1.1.1 Second Delta committee, Building with Nature

In September 2008 the committee Veerman presented their report, Working together with water. The report describes possibilities to change the policy regarding integrated coastal management. Their recommendations and conclusions involved the applicability of large-scale nourishments to counter balance sea level rise and provide coastal protection in the future. The introduction of mega-nourishments could work out as an alternative of the present nourishment policy. Through long-term natural forcing, redistribution of a mega-nourishment will have to provide a gradual build out of the adjacent coastline.

Recently a pilot mega-nourishment project was initiated, called the sand-engine Figure 1.1. This new approach in nourishment strategy has to counter balance sea level rise in combination with extra space for nature and recreation. Therefore, this new mega-nourishment strategy can lead to long-term sustainable development of the Holland coast.

Figure 1.1 Aerial view of the Delfland coast, finished construction sand-engine (11 July 2011, www.flickr.nl).
In 2008, the five-year innovation and research program Building with Nature (hereafter BwN) (2008-2012) started. The program enables investigations to opportunities for projects in hydraulic engineering, using the dynamics of the natural system. By integrating ecodynamics in the design and development process, forces of nature are used to produce hydraulic engineering ‘infrastructure’ and to create new opportunities for nature at the same time (www.ecoshape.nl). With new insights and knowledge, nature itself becomes the driving force behind the sustainable development of hydraulic engineering infrastructure. The EcoShape Foundation operates the BwN program, which contains four major cases. One of these cases contains the Holland coast; the Holland coast case is again subdivided in work packages. The sand-engine is part of the work package for the sustainable development of the Dutch coastal system, enabling insight for long-term coastal management of the Dutch coast.

1.1.2 Role of stakeholders in design process

For obtaining societal support, it is important for a project like the sand-engine to consider the surrounding environment and to involve a wide range of stakeholders. Therefore, besides long-term flood protection, nature and recreation are treated at the same level of importance.

The development in the design phase of the sand-engine started with decisions and solutions at a large scale which gradually shifted to issues at a smaller scale. At policy level, the approval for construction at policy level was based on the Environmental Impact Assessment (hereafter EIA). The EIA in turn, is based on long-term morphodynamic predictions. With morphodynamic analyses and predictions most elementary uncertainties and questions are answered. However, several issues are still uncertain or have recently appeared and form a pressing matter for the involved stakeholders. Analyses and investigation of the daily discussion directed by the stakeholder platform will provide insight in those questions and uncertainties. An overview will be necessary to grasp most pressing issues. Examples of pressing issues and uncertainties are swimming safety, changes in ground water level, impact of storm events, silt accumulation, etc. These issues are not or insufficient investigated during the EIA phase. For measurement and maintenance purposes of the sand-engine and for the design of future mega-nourishments an inventory, and if feasible prioritization, of these pressing issues will provide insight for further research.

1.1.3 Sand-engine design

Besides the hooked shaped sand-engine, other shapes and possibilities of mega-nourishment were investigated during the EIA. An island, submerged, and other salient shaped mega-nourishments were part of the EIA investigation. The decision for the implementation of the hooked shaped mega-nourishment between Ter Heijde and Kijkduin is based on optimal accomplishment of the goals stated for the sand-engine:

1. Long-term flood protection (and long-term reduction in maintenance cost of the coastal system) through innovative coastal upgrading due to working with nature.
2. Long-term flood protection in combination with additional space for nature and recreation.
3. Innovation and knowledge development of the coastal system due to (field) experience from the pilot project the sand-engine.

Finally, based on the EIA, the hooked shaped peninsula was recommended. The hooked shaped peninsula was nominated for its high ecological and recreational qualities and for its innovative coastal upgrading. Not unimportant, the peninsula is an eye-catcher and so giving a new impulse and international allure to Dutch hydraulic engineers.
The pilot project sand-engine is built as a mega-nourishment near the Delfland coast, close to seaside resorts Ter Heijde and Kijkduin. The project has started in March 2011, and together with additional nourishments up- and down drift of the sand-engine, was finished in November 2011. The construction of the hooked-shaped peninsula was finished on 11 July 2011, which can be seen on the aerial photograph, Figure 1.1.

The peninsula reaches one kilometer in offshore direction, measured from the dune foot. The width is about two kilometers in alongshore direction, with a crest height of +3.5m NAP. With a slope of 1:100, from the -11m NAP depth contour, the volume of sand that has been nourished amounts 18,5Mm$^3$. Because of the hooked shaped peninsula, a flow contraction of the tidal and wave-induced currents will occur. The flow contraction will result in dynamic morphology and changes in local currents.

From the perspective of recreation, these changes in local currents can induce problems for swimming safety. However, one objective in sand-engine project is to manage and monitor the development of the currents related to recreation and make measures if necessary. In anticipation, preliminary prohibition for swimming is set. In the near future, this measure may be canceled if swimming safety is convincing.

1.1.4 Role and limitations of models (tools)

From the previous paragraph, it becomes clear that the EIA is based on long-term morphodynamic predictions with Delft3D. Several important aspects concerning mega-nourishment are not included in the Delft3D simulations.

A brief insight in several important aspects is already given in the preceding paragraph. For instance, Delft3D can not include storm events integrated at a long time scale for the simulation of mega-nourishment. From the stakeholder platform questions arose about the impact of storm events. After the EIA, additional research was done into the impact of storm events for the initial shape of the sand-engine using the numerical model XBeach (Van Thiel de Vries et al., 2009). This research indicated a substantial impact of single storm events on morphodynamics.

Besides storm events, ground water level, aeolian transport, silt accumulation, etc are aspects, which have not been included during the design phase, but concerns the stakeholder platform nowadays. These aspects can be simulated using different models or in the near future with those who are still in development, like modeling aeolian transports.

So, in the design phase of the pilot sand-engine limited tools are used. As numerical models evolve in time and new models are being developed, a new integrated modeling approach is foreseen which can be applied in the design and evaluation phase of (future) mega-nourishments and to assess the required maintenance of such nourishments.
1.2 Problem definition

The approval for the sand-engine pilot project is based on the EIA, in which long-term morphodynamic predictions are analyzed, these predictions were based on a single numerical model. During the design phase of the sand-engine, there was too little integrated perspective.
After the approval, the discussion on mega-nourishment and maintenance plans for the sand-engine continued. This continuing discussion from the stakeholder platform, resulted in further questions and uncertainties concerning the sand-engine and future mega-nourishment (e.g. ground water table, siltation, impact storm events, swimming safety, etc.). Lessons can be learned and the present sand-engine pilot project can provide improved insight in the design process for future mega-nourishments.

1.3 Research objective

The objective of this thesis is to develop an integrated model approach for the design of mega-nourishments, which can also serve as input for maintenance issues concerning the sand-engine and (future) mega-nourishments. This will be achieved by coupling and integrate numerical models and new tools, enabling interaction between multiple hydro- and morphodynamic processes on various spatial and temporal scales. The sand-engine will be used as input to develop this integrated model approach for the design of mega-nourishments.

Looking closely at the problem definition, the above objective has been divided into three sub-objectives to achieve full advantage of the integration of numerical models:

1. Investigate the sensitivity of storm events on long-term morphodynamic development of the sand-engine and adjacent coastline.
2. Investigation of the effect of silt accumulation during the long-term morphological development of the sand-engine.
3. The impact assessment of the different scenarios by means of quantifiable indicators covering long-term flood protection and partly nature and recreation.
1.4 Study approach

The approach to achieve the prescribed objective – “development of an integrated model approach for the design of mega-nourishments.” – will start with a discussion on mega-nourishment. The daily discussion of the sand-engine will be analyzed, resulting in questions and uncertainties that need further investigation. This unique pilot project has multifarious topics and disciplines which can be investigated. However, only the topics addressed in the objective will be explored and investigated in this thesis. 

For the sub-objectives, site-specific research of the Delfland coast is necessary. Hydrodynamics and morphodynamics will be investigated to provide insight in the environment of the Delfland coast. The Delfland coast and sand-engine will be schematized in the numerical models Delft3D and XBeach. From previous numerical studies of the sand-engine, the settings will be used or adjusted to define the hydrodynamic conditions. In the numerical models Delft3D and XBeach, hydro- and morphodynamics will be simulated for the given coastline. The purpose for each of the numerical models is stated below:

1. Delft3D - Computes flow hydrodynamics, sediment transport rates and resulting bed level changes. This enables the simulation of long-term predictions of the sand-engine, by means of averaged hydrodynamics. Within Delft3D also a module is available to include silt in the morphological calculations.
2. XBeach - Dune erosion model, which is capable of simulating dune erosion and overwash processes. Aiming at, simulating storm events in combination with long-term morphodynamic predictions in Delft3D.

In this thesis, an interaction between Delft3D and XBeach will be established, as visualized in the second picture in Figure 1.2. The use of the qualities of the two numerical models will enable an integrated model approach for long-term simulation of mega-nourishment. Several scenarios will be generated, concerning the questions from the stakeholder platform.

![Figure 1.2 Coupling of the numerical models Delft3D and XBeach.](image)

Through application of the integrated models, several aspects can be treated that have not been taken into account in former design- and management plans of the sand-engine. Uncertainties and questions regarding storm events and siltation effects will be answered with this integrated model approach. The morphological processes will be analyzed and can be visualized with aid of quantifiable indicators with respect to long-term flood protection, nature and recreation. Firstly, several indicators will be identified (paragraph 2.7), and secondly, most evident indicators will be used for the simulation analyses and impact assessments.
1.5 Thesis hypothesis

The sand-engine mega-nourishment is a unique project: never before has such a large scale nourishment been executed. Consequently, long-term morphodynamic predictions of the sand-engine has a certain inaccuracy, with respect to real time hydro- and morphodynamics. In this thesis, pressing questions and uncertainties regarding the morphodynamic of mega-nourishment will be investigated. The expectations of the integrated numerical models are given step-wise.

1. Storm events will substantial increase the distribution of the sand from the sand-engine to areas north and south of the sand-engine and will have impact on long-term morphodynamics. (The local community in the surrounding area believes one or only a few storm events will be enough to distribute the majority of the sand and so erasing the pronounced shape of the sand-engine).

2. The first three to four years erosion to the down drift coast will occur near Kijkduin, because the sand-engine blocks the net alongshore sediment transport towards the north. Storm events will be advantageous in decreasing the initial erosion period near Kijkduin, sand will be distributed faster in down drift direction.

3. Severe storm events will result in a closure of the lagoon or into a breach of the hooked-shaped sand-engine. A breach or closure will presumably occur after some years of morphological development, when erosion processes have decreased the buffer of the sand-engine.

4. Scenarios, in which a breach or a closure will occur, will lead to substantial impact on nature, recreation and long-term flood protection.

5. Lee side areas near mega-nourishments provide shelter for average hydro-dynamics, for wave conditions from southwest as well as northwest direction. Therefore, fines suspended in the water column, like mud and silt will settle in these low energetic areas. The sedimentation of fines will provide opportunities for nature, but will be a concern for recreation.
1.6 Report outline

After stating the problem definition, objectives and study approach, this thesis starts with a description of the sand-engine area, the Delfland coast, and a review concerning the hydrodynamic and morphodynamic characteristics (Chapter 2). At the end, Chapter 2 elaborates on the design phase of mega-nourishments with a special focus for the sand-engine. In Chapter 3 the applicability of several numerical models is explained, regarding the design phase of mega-nourishments. The focus of this Chapter is directed towards the integration of these numerical models, providing opportunities to integrate multiple physical processes during the design phase of mega-nourishments. In Chapter 4 an explanation of the applied numerical models is provided, together with schematizations of boundary conditions. The most important topic of this Chapter concerns the elaboration of the interpolation techniques between Delft3D and XBeach.

In Chapter 5 an extensive study is described towards the morphodynamics of a reference scenario for the sand-engine with only average hydrodynamics. In addition, the impact of various wave climates is presented together with analysis of morphodynamic simulations including silt. Next, in Chapter 6 the reference scenario of the sand-engine is used for comparison with morphodynamic simulations including storm events. An extensive morphodynamic impact assessment is provided concerning the impact of storm events during the long-term development for mega-nourishments, based on the sand-engine.

Finally, this thesis report ends with conclusions and recommendations concerning the morphodynamics of mega-nourishment and the sand-engine. For applicability these conclusions and recommendations are separated and identified for policymakers and researches.
2 Description Delfland coast

The sand-engine project will be used as input to develop an integrated model approach for the design of future mega-nourishments. The sand-engine is constructed near the Delfland coast. Therefore, a description of the Delfland coast will be important for site specific features, and to gain insight in the local hydro- and morphodynamic processes.
First, a background and brief history of the Delfland coast will be described. Next, the hydrodynamics will be explained, followed by the physical processes regarding sediment transport. These physical processes are the bases for the morphodynamic changes of the coastal system.
For insight in the maintenance policy of the Delfland coast an overview of the maintenance nourishments from the past will be provided. Also the present policy regarding maintenance nourishments will be explained and the new strategy regarding mega-nourishments will be discussed. An inventory of design aspects and quantifiable indicators concerning the design and management of mega-nourishments will provide an introduction into the next chapter on model integration.

2.1 Background

For centuries, the Delfland coast is subject to erosion. In 1784, several groins, ‘Delflandse hoofden’, were built to decrease the coastline erosion rate. In 1972, the construction of the van Dixhoorn driehoek was realized, see Figure 2.1. This was an excess of sand originated from the extension of the Rotterdam harbor. In 1990, a new nourishment policy for the whole Dutch coastline was initiated to counter balance erosion processes with annually 6 Mm$^3$ sand, which is still effective today (from 2000 annually 12 Mm$^3$).
Every year the ministry of waterways and public works makes measurements of the Dutch coastline. In 2003, the ministry indicated twelve spots along the Dutch coastline, which are expected to provide insufficient protection after the year 2020, due to new insights into higher wave forcing. These twelve spots are called the weak links (‘Zwakke Schaken’s’). Preparations and plans were made to reinforce these weak links, increasing safety level up to the new standards for sea defense. The reinforcement of all weak links have to be finished before the year 2016.
One of the weak links is the Delfland coast, with seaside resorts Ter Heijde and Kijkduin. The coastal strengthening of the Delfland coast started in November 2008 and was finished in March 2011. Main activities at the Delfland coast were the construction of a new dune ridge at the seaward side of the present dunes and the extension of the beach, including a large nature area (Spanjaardsduin) near s’Gravenzande. The beach has been widened with 100 meter and heightened with 2 meter. The nourished sand submerges the former groins ‘Delflandse hoofden’.
Figure 2.1 Aerial view Delfland coast, start construction weak link (Dec 2008, www.delflandsekust.nl).
2.2 Hydrodynamics

2.2.1 Tide

The tide is a vertical movement of the water, which operates due to the gravitational forces of the sun, but even more by the moon. Consequently, this causes periodical varying water levels. In conjunction with the periodical change in water levels, also a horizontal water movement occurs. The horizontal water movement is known as the tidal current. Because the water mass is unequally distributed across the globe, the tidal signal is not everywhere the same. The tidal signal can be diurnal, semi-diurnal, mixed or no tide at all, dependent on the presence of land masses, the water depth, the shape of a coastal system or basin and the distance to the equator (Bosboom and Stive, 2010).

The Delfland coast experiences a semi-diurnal tide, the tidal propagation is presented in Figure 2.2. The interaction of the gravitational forces exerted by the moon and the sun generates a tidal wave at the southern hemisphere. The tidal wave propagates through the Atlantic Ocean reaching Great Brittan and propagating further around the Shetland Islands near Scotland into the North Sea basin.

Figure 2.2 Propagation of the tide through the southern part of the North Sea (http://www.kustatlas.be).

Figure 2.3 presents the tidal signal near Hoek van Holland, this is the tidal signal three days after full moon. The tide has an asymmetry with respect to the falling and rising of the tide. On average, the falling tide takes eight hours and four minutes, and the rising lasts four hours and 21 minutes. Therefore, the semidiurnal constituent of the tide has a return period of about 12 hours and 25 minutes. The dominant tidal component is the M2 component, it has an amplitude of 1m and a frequency of 28.98 degrees/hour of the tidal wave. This corresponds with the return period of \( \frac{360^\circ}{28.98^\circ/hr} = 12.42 \text{hrs} \).
If there is rising tide, the horizontal tidal current along the Dutch coast is towards the North, with falling tide towards the South. This is the horizontal water movement, the speed is dependent of the water depth and can be calculated with the linear wave theory:

\[ c = \sqrt{gd} \quad (2.1) \]

When assuming an average depth of 20 meters in the southern North Sea basin, the tidal speed is about 15m/s. The particle velocity is of a different order and is on average 0.5 m/s (Holthuijsen, 2007a). The difference in duration of falling and rising tide results in a maximum flood current of 0.8 m/s and a maximum ebb current of 0.7 m/s. The residual current is 0.1m/s and directed northward. (Van Rijn, 1997)

In this thesis report often coastal engineering terminology is used, indicating specific parts in the coastal zone. Figure 2.4 presents a cross-shore profile of a sediment coast, like the Delfland coast, via which this terminology can be explained. In Dutch coastal policy, the coastal zone is defined from the dune rows to the -20m NAP depth contour, offshore. This is the morphological active part of the coastal system, with a varying width of 10 to 15 kilometers. From the dune foot, the nearshore is defined to the -8m depth contour, from the -8m depth contour and further offshore, the offshore zone or in case of the Dutch North sea, the continental shelf is defined. Within the near shore zone is given; the surf zone, the area where the waves break, the wet beach or fore shore, the area between the extreme water lines and the beach, which remains dry under normal conditions.
2.2.2 Wind

Wind can be of great importance in coastal systems. Wind generates waves, can induce currents and can produce a substantial water level set-up. Moreover, at the interface between water and land, wind can produce aeolian processes, which can have substantial influence on the morphodynamics of a coastal system. In front of the Delfland coast a number of survey stations and buoys are located, collecting data regarding amongst others the wave and wind climate. Figure 2.5 visualizes the wind climate along the Delfland coast, from two survey stations; survey station Noordwijk (MPN) and Europlatform (EUR). The two datasets of the wind climate are presented by means of wind roses. The measured wind data represents the distribution of the wind direction ($\theta_{\text{wind}}$), the values of the wind speed ($V_{\text{wind}}$) and the length of the bar represents the relative frequency of occurrence. The collected wind data has been measured every three hours in the period 1979-2001.

![Wind roses for survey stations Noordwijk and Europlatform.](image)

Figure 2.5 Wind rose, survey stations Noordwijk and Europlatform, based on time series 1979-2001 (Tonnon et al., 2009).

The wind roses in Figure 2.5 show equal distribution of the wind direction and wind speed. The average wind direction along the Delfland coast is 40% from SW. The higher wind velocities, of 15m/s and up, occur 5 to 10% on annual bases. Storm periods are indicated when wind speeds of 17m/s and higher are reached (Beaufort 8) (Augustijn et al., 1990).

2.2.3 Waves

The wave climate along the Dutch coast has a majority of southwesterly wind-generated waves and additional swell waves from the north. The amplitude and period of the waves are dependent on wind speed and fetch. The fetch is the distance by the wave propagation, which is acted upon consistently from its generation to its full growth by the wind velocity and direction. This fetch distance is often limited by a coastline. However, storm winds from the north, with a large fetch distance, allow wave heights over 5m. Swell waves are waves generated by wind, but have propagated out of the domain of generation. Swell waves are often created by storms thousands of kilometers away from the beach where they break. They are no longer forced by the wind and can travel large distances. If the distance is large enough the long waves become more stable, creating long crests and having their own individual propagation speed.
Figure 2.6 visualizes the wave climate along the Delfland coast, from the same two survey stations; survey station Noordwijk (MPN) and Europlatform (EUR). The survey stations are standing in relative shallow and deep water, respectively. The MPN station is in 18 meter water depth and EUR station in 32 meter water depth. The measured wave data represents the distribution of the wave propagation direction ($\theta_{\text{wave}}$), the significant wave height ($H_s$) and the length of the bar represents the relative frequency of occurrence. The collected wave data is measured every three hours from the period 1979-2001.

![Figure 2.6 Wave rose, survey stations Noordwijk and Europlatform, based on time series 1979-2001 (Tonnon et al., 2009).](image)

Figure 2.6 indicate two dominant wave propagation directions, from ZW and from NNW. A clearly visible difference between the datasets of the two survey stations, are the waves from the north. At survey station MPN the waves come from an angle of 320ºN and the waves at EUR from an angle of 350ºN. This difference is mainly due to depth-induced refraction, hence, the waves near MPN are more perpendicular directed towards the coastline.

An interesting comparison can be made with the wind roses from the preceding section. The wind direction is mainly southwesterly, whereas the wave roses indicate also waves from the north. Local southwesterly wind generate waves from the southwest and swell waves, generated at large distances, are from the north.

In Figure 2.7 the significant wave heights of both survey stations are plotted in the same diagram. The diagram indicates a strong correlation. The correlation coefficient given by $r$ has a value of 0.92. If the datasets would be uncorrelated the correlation coefficient would be equal to zero, when fully correlated the coefficient would be 1.

The wave heights from survey station EUR are higher then the waves near survey station MPN. On average the difference is about 0.2m. This difference in wave height is mainly caused by dissipation of wave energy due to bottom friction (Tonnon et al., 2009). Research in this wave climate is important for the schematization of the model set up in Delft3D and will be further explained in Chapter 4.
The wave roses in the figures 2.6 represent a year averaged wave climate. However, during a year there is a temporal variation in wave climate. In the winter season, from November to February, the average wave height reaches 1.7m. In the summer season, from May to August, the average wave height is substantially lower, 1m. In Figure 2.8 average wave heights of amongst others the survey stations EUR and MPN are given, indicating the average wave heights every month. In addition, the averaged wave heights are plotted for survey stations; Eierlandse Gat (ELD) and IJmuiden munitiestortplaats (YM6) (Van de Rest, 2004).

Research from Van de Rest compares datasets from several survey stations along the Dutch coast. This research indicates minimal spatial difference of the most important wave parameters, provided that water depth is taken into account. The high correlation coefficient from Figure 2.7 confirms the research from Van de Rest.
2.2.4 Storm events

The Dutch coast is subject to a rough sea state. Storm events occur throughout the year. Research over the years 1964 until 2001 indicates a yearly variation in storm events. In some years only 10 storm events occur, whereas other years are very intense with over 50 storm events. The sum of the average annual duration of storm events in the period 1964-1996 amounts 500 hours/year. The average occurrence between summer and winter is very pronounced. In summer seasons storm events occur once a month, they last for nine hours. In winter seasons however, storm events can occur five times a month and last on average for 15 hours. The approach angle of the majority of the storm events is southwest to west (Van de Rest, 2004). However, severe storm events are usually northwesterly due to their high surge levels (large fetch distance) and therefore cause a large impact at the dune foot.

Storm conditions can have substantial impact on the coastal system. In case of a meganourishment like the sand-engine, the coastal system is no longer in its equilibrium state. Storm events can produce substantial changes on the morphological development of the meganourishment and its adjacent coastline (Van Thiel de Vries et al., 2009). However, the interaction between extreme hydrodynamic forcing and long-term morphodynamic processes is not yet known.

For long-term Dutch coastal protection insight in the dynamics of storm events is of great importance. The main concern during storm events is dune erosion and breaching of dunes. The main process that triggers dune erosion is the wave run up in the swash zone, due to the interaction between short and long (infragravity) waves. The main characteristics of storm events, are the surge level, the wave height (wave run up), the wave period and the duration of the storm.

![Storm Oktober 2007 near Delfland coast](www.delflandsekust.nl).

Figure 2.9 Storm Oktober 2007 near Delfland coast (www.delflandsekust.nl).
2.3 Physical processes of sediment transport

2.3.1 Distribution of sediment transport

Sediment transport can be subdivided by bed load transport and suspended load transport. The transport is usually defined as a volume per running meter over a certain period of time. The bed and suspended load transport is dependent on the characteristics of the material and the driving forces on the material. The driving forces are dependent on the water movement. The water movement at the bed induces a bed shear stress, when a critical value is reached grains will be set in motion. The bed shear stress is exerted by currents or oscillatory water motion due to waves. Current related transport is induced by tide, wave, wind and density gradients in the water. The oscillatory water movement due to the waves is mainly responsible for stirring up the sediment, bringing sediment in suspension. Consequently, sediment transport in a coastal system is usually a combination of current and wave related transport.

Figure 2.10 visualises the two components in sediment transport. The sediment transport is proportional to the velocity of the water movement and the concentration of material in the water column. The bed load is defined in the layer near the bed.

![Figure 2.10 Sediment transport modes (Bosboom and Stive, 2010).](image)

2.3.2 Cross-shore and alongshore sediment transport

Sediment transport in the coastal area can be divided by cross-shore and along-shore transport. Cross-shore transport is perpendicular to the coastline and is mainly driven by wave action in the surfzone (the surfzone is the area from the depth contour where the waves start to break). Cross-shore transport determines the cross-shore profile of the beach and the surfzone. Because the wave action has a dominant contribution in the cross-shore transport, the cross-shore profile is subject to changes in the wave climate throughout the year.

Alongshore sediment transport is the sediment transported parallel to the coastline. The previous paragraph describes the sediment transport proportional to velocity of the water movement and the concentration of material in the water column. In Figure 2.11 the currents related to the tide, waves and wind are given as a top view near an uniform coastline. Here the tidal currents are given during ebb and flood period, in combination with waves approaching the coastline under an angle. In the surfzone the waves induce a wave driven current due to wave breaking, enhancing the flood current or counter act the ebb current.

Moreover, the wave related current is dominant for the alongshore transport inside the surfzone and tide related current is the dominant factor outside the surfzone. The residual
sediment transport is subject to the presence of the wave climate and of the asymmetry in the tidal signal explained in paragraph 2.2.1 (Van de Graaff, 2006).

Figure 2.11 Tide and wave related currents, left picture opposing current direction, right picture coinciding current direction (Bosboom and Stive, 2010).

Dynamic coastal morphology is the consequence of spatial gradients in net sediment transport rates. If a coastline area is visualized like in Figure 2.12 and $S_{in}$ is equal to $S_{out}$ then there is a stable coastline, if $S_{in}$ is larger or smaller then $S_{out}$ then accretion respectively erosion occurs. The Dutch coastline moves forth and back due to the oscillation of spatial gradients in sediment transport rates.

Figure 2.12 Sediment transport gradients (Bosboom and Stive, 2010).
2.3.3 Silt

The most part the North Sea lies on the European continental shelf. The upper layer of the seabed in front of the Dutch coast mainly consists of sand. In this non-cohesive sand layer, 2% consist of cohesive material, known as silt or mud. In a rough sea state, waves can bring the cohesive particles in suspension. If the orbital motion of the waves is felt by the seabed, the orbital motion can exceed a critical bed shear stress at which the fine particles will come in suspension. Currents induced by the tide, waves or wind can pick up the fines and transport them over large distances. In high energetic wave conditions, like in the winter season, many fines are brought into suspension. Beside the Dutch seabed, the majority of the suspended sediments in the Dutch coastal zone originate from the English Channel and the Flemish Banks. Suspended matter concentrations appear to be mainly determined by the wave heights. This results in high concentrations during stormy winter seasons, 100mg/l (= 0.1kg/m^3), and low concentrations during calm summer seasons, 20mg/l. Moreover, research from Suijlen en Duin (2002) indicate an annual average silt concentration of 25mg/l. The average sedimentation velocity of fines in the water column is set to 0.25mm/s. Near the Delfland coast, the area of interest in this thesis, is the outflow of the ‘Nieuwe Waterweg’. This river outflow is no source of sediment, on the contrary, this river has a net inflow of suspended sediment from sea and causes for substantial maintenance dredging of the Rotterdam harbor.

Figure 2.13 Sediment plume sand-engine just after completion, July 2011 (www.flickr.com).

In harbors and lagoons, fines in the water column can accumulate near the bed. Those areas are usually sheltered by waves, at which the bed shear stress is to low for fines to re-suspend. In lagoons, the accumulation of fines can provide a nice habitat for nature. The mud content of the bed is an important parameter for the bottom quality, because nutrients and pollutants tend to adhere to, or be part of, cohesive sediments [Wang, 1996]. However, in case of silt accumulation near a beach meant for tourism, recreational values will decrease. Therefore, in this thesis, the lee-side area of the sand-engine has been investigated for siltation processes. The development of siltation near mega-nourishments can be of great importance for nature and recreation.
Suspended matter concentrations are highly variable in time and space. In the Figures in Appendix B this variability is presented along the Dutch coast for a mean summer and winter period. In the area close the coastline, the highest concentrations can be noted, this is due to the breaking of the waves propagating into shallow water. Taking into account the variability in the concentration levels, it is estimated that the net northward transport of suspended matter in the coastal zone (ca. 70km wide) ranges between about 6 and 60Mton per year. This transport highly depends on the wave climate during a specific year, as well as on the flux of sediments from the English Channel and the Flemish Banks. Looking more closely to the band along the coast (<10km), the flux of sediments is estimated in the order of 20Mton/year. These large fluxes of suspended matter also strongly affect the navigational depth of the channels to the Dutch sea ports, causing the need for substantial maintenance dredging (Suijlen and Duin, 2002).
2.4 Sediment balance

2.4.1 Coastal transport system

Coastal morphology can be studied at several scales. The focus of this thesis is on the meso-scale or dynamic-scale level of the Delfland coast. Concerning the meso-scale level, the interaction of constituent processes of waves, currents and sediment transport gives the principles of morphodynamic behavior. The forcing at meso-scale is seasonal and interannual variations in the tide and weather conditions, and artificial interventions.

Processes at meso-scale can be studied by looking at initial sedimentation, erosion patterns and morphodynamics over a period of years. The most dynamic area is the surfzone, between the dune foot +3m NAP and the -8m NAP. Sand extraction areas are located seaward of the -20m NAP depth contour, from this depth on no morphodynamic changes are expected for the Dutch coastline.

A comparison to multiple sediment transport studies along the Dutch coast is made in Van de Rest (2004). In Figure 2.14 a focus for the alongshore sediment transport near the Delfland coast is given. The x-axis presents the distance measured from Den Helder, Hoek van Holland is located at 120km and Scheveningen at 102km. The y-axis presents the averaged annual alongshore sediment transport in 1000m$^3$/year. The several studies indicate a range of about 50,000 to 150,000m$^3$/year. Figure 2.14 presents the net annual sediment transports, excluding the pores. Near Hoek van Holland the alongshore sediment transport is zero or negative. This morphological phenomenon is initiated from the large groin called the ‘Noorderdam’ reaching 4.2 kilometres in sea. Negative sediment transport values indicate a transport to the south, due to net currents from large scale eddies formed by the groin.

![Average annual alongshore transport in the surfzone (Van de Rest, 2004).](image-url)
The coastline is continuous oscillating forth and back, searching for an equilibrium. Building a mega-nourishment changes the coastline over a large distance in alongshore and offshore direction. A mega-nourishment will result in a morphological response, which affects a large area of the adjacent coastline.

2.4.2 Maintenance nourishments 1986-2007

The ‘van Dixhoornsdriehoek’ was constructed in 1972 with an amount of 19Mm$^3$ sand. For maintenance the ‘van Dixhoornsdriehoek’ is annually (period 1976-2007) nourished with 0.2Mm$^3$ sand. The northern part of the Delfland coast is also subject to erosion and from 1986, several nourishments have been executed. Figure 2.15 and Figure 2.16 indicate the trend of nourishment volume over time.

![Figure 2.15 Nourishments between Hoek van Holland and Kijkduin from 1986 – 2007 (Excluding maintenance nourishments ‘Van Dixhoornsdriehoek’), (Tonnon et al., 2009).](image1)

![Figure 2.16 Nourishments locations between Hoek van Holland and Kijkduin from 1986 – 2007 (Excluding maintenance nourishments ‘Van Dixhoornsdriehoek’), (Tonnon et al., 2009).](image2)

In 1986, a single dune reinforcement was built together with a beach nourishment. The majority of the nourishments is placed on the beach or shore face. From 2000, there is a slight tendency towards nearshore nourishment or submerged nourishment. Excluding the
'Van Dixhoornsdriehoek' the Delfland coast requires annually 0.7Mm³ sand in the period 1990-2007. The average return period for nourishments is about two years.

The nourishments from 1976-2007 have served multiple objectives. The nourishments concerning the 'Van Dixhoornsdriehoek' were aimed at maintaining the coastline shape. The dune reinforcement from 1986 was constructed for flood protection. Furthermore, the beach nourishments from 2003 and 2004 were emergency measures, to guarantee flood protection. Next, large submerged nearshore nourishments were executed on approval. Together these nourishments result in an indefinable timeline picture for coastal maintenance.

The present policy is to maintain the coastline as it is defined in 1990 (the 'Basis kustlijn', BKL). The norm for the coastline from 1990 is stated as a volume per running meter, indicated as the 'Momentane Kustlijn' MKL. It is the volume over the profile, from the dune foot down to the -4.4m NAP depth contour, see Figure 2.17. Every year the beach and nearshore is measured. The annual tendency of the MKL volume is compared with the BKL volume. If the measured MKL volume indicates a decline below the BKL volume, the beach and/or nearshore will be nourished. The volume for the nearshore nourishment is defined as twice the shortage compared to the BKL volume. Generally the sand is nourished at the -5m NAP depth contour.

Figure 2.17 Sand volume per running meter, from +3m down to -4.4m NAP.
2.4.3 Maintenance coastal foundation

The active coastal foundation is defined as the surface area (~1850 km$^2$) from the dunes to the -20m NAP depth contour, from Hoek van Holland up to the Marsdiep basin, Figure 2.18. Together with the Wadden Sea and the Western Scheldt area they present the total coastal system (7000 km$^2$). The present nourishment policy for this coastal system is about 12Mm$^3$ of sand to counter balance a Sea Level Rise (hereafter, SLR) of 18 cm/century, for the total surface area.

![Figure 2.18 Overview active coastal foundation ~1850km$^2$ (Workplan BwN HK4.1, 2009).](image)

For years, SLR is a much-discussed subject. Multiple investigations have been performed considering SLR. For a lower boundary limit the period 1900-2007 is considered, with a SLR of 18 cm/century. Calculations of an average SLR from 1950 to 2007 results in 20 cm/century, which corresponds with the present SLR, investigated by the KNMI ‘Koninklijk Nederlands Meteorologisch Instituut’ (2006). Therefore, a SLR of 20 cm/century is held as middle value. For the upper limit a SLR of 30 cm/century is stated. In Table 2.1, the nourishment volumes are given, corresponding with the three SLR scenarios (De Ronde, 2008).

<table>
<thead>
<tr>
<th>Maintenance nourishment w.r.t. SLR</th>
<th>Lower limit 18 cm/century</th>
<th>Middle value 20 cm/century</th>
<th>Upper limit 30 cm/century</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wadden Sea</td>
<td>4.5</td>
<td>5</td>
<td>7.5</td>
</tr>
<tr>
<td>Coastal foundation</td>
<td>7.5</td>
<td>8.4</td>
<td>12.5</td>
</tr>
<tr>
<td>Western Scheldt</td>
<td>0.5</td>
<td>0.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Total coastal system</td>
<td>12.5</td>
<td>13.9</td>
<td>20.8</td>
</tr>
</tbody>
</table>

Table 2.1 Maintenance nourishment w.r.t. SLR (De Ronde, 2008).
Beside the nourishment maintenance for SLR, there are additional losses in the coastal system that requires maintenance nourishments. These additional losses are given in Table 2.2. For the Wadden Sea area, this concerns mainly the side effects from the closure of the ‘Zuiderzee’ 1932 (‘Afsluitdijk’), upper line in Table 2.2, which initiated the development towards a new equilibrium that will take some centuries.

For the Delfland coast, the main loss of sediment concerns the maintenance dredging of the approach channel of the Rotterdam harbor. Sand is being dredged to remain a continuous navigational depth. Sometimes this sand is being sold or otherwise being dumped outside the coastal system. Therefore, this sand is being extracted from the coastal system and can be regarded as an additional lose.

Table 2.2  Other sediment losses in the coastal system (De Ronde, 2008).

<table>
<thead>
<tr>
<th>Sediment loss in the coastal system</th>
<th>Lower limit</th>
<th>Middle value</th>
<th>Upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side effects closure ‘Zuiderzee’, ‘Lauwerszee’</td>
<td>1</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Maintenance dredging Rotterdam navigation channel</td>
<td>0,8</td>
<td>0,8</td>
<td>2,3</td>
</tr>
<tr>
<td>Maintenance dredging Wadden sea navigation channels</td>
<td>0</td>
<td>0,6</td>
<td>0,6</td>
</tr>
<tr>
<td>Sand extraction areas Western Schelde</td>
<td>0</td>
<td>0</td>
<td>2,6</td>
</tr>
<tr>
<td>Sand extraction areas Zeeschelde</td>
<td>0</td>
<td>1</td>
<td>1,5</td>
</tr>
<tr>
<td>Bed subsidence Wadden Sea by gas extraction</td>
<td>1,1</td>
<td>1,1</td>
<td>3,2</td>
</tr>
<tr>
<td>Bed subsidence Wadden Sea by salt extraction</td>
<td>0</td>
<td>0</td>
<td>1,5</td>
</tr>
<tr>
<td>Maintenance safety 7 seaside resorts</td>
<td>0</td>
<td>0</td>
<td>0,1</td>
</tr>
<tr>
<td>Influence ‘Zwikke Schakels’</td>
<td>0</td>
<td>0</td>
<td>0,6</td>
</tr>
<tr>
<td>Total coastal system</td>
<td>2,9</td>
<td>6,5</td>
<td>17,4</td>
</tr>
</tbody>
</table>

For the Delfland area, part of the coastal foundation, the required quantity of annual nourishment can be divied by three factors. For SLR, the middle value is considered.

1. To counter balance SLR of 2 mm/year, 0.20 Mm$^3$/year is required. These values are deduced from rules of thumb (Mulder, 2008) stating 7 Mm$^3$/yr per 1 mm/yr SLR for the total coastal system (7000 km$^2$), giving ~2 Mm$^3$/yr for the coastal foundation (1850 km$^2$) and 0,20 Mm$^3$/year for the Delfland coast.

2. Net sediment transport loss in alongshore and offshore direction, requires about 0.10 Mm$^3$/year.

3. Sand loss due to harbor- and approach channel maintenance, requires 0.8 Mm$^3$/year.

Adding these quantities, the Delfland part of the coastal foundation requires maintenance nourishment of about 1.10 Mm$^3$/year.
2.5 A discussion on mega-nourishment

Present day maintenance policy for the Dutch coastal foundation enables annual nourishment of about 12 Mm$^3$ sand to counter balance 1.8 mm/year (18 cm/century) SLR. However, recent research from De Ronde (2008) indicates a SLR of 2 mm/year (20 cm/century), together with additional losses in the coastal system, 20 Mm$^3$ of maintenance nourishments is required.

In a report on climate-adaptation options for the Netherlands over the coming century, with an outlook to 2200, the Delta Committee 2008 issued the following recommendations regarding the coastal system (www.deltacommissie.nl):

**To 2050**

The Committee’s choice is to ‘build the coast with nature’. Coastal safety along the sandy shores of Zeeland, Holland and the Wadden Islands is maintained by beach nourishment. Tidal channels will be relocated where necessary. Until 2050 the Committee assumes that 85 million m$^3$/year of sand will be needed, assuming that until 2050 sea level will rise by 12 mm/year.

To meet the needs of society, the Committee advises that beach nourishment be conducted on such a scale that the beach will migrate seaward in the coming century. This will deliver great added value to Dutch society. Sand-extraction sites will have to be reserved soon. Research must also be conducted soon to determine how such large volumes can be distributed as efficiently as possible in terms of the ecology, economy and energy efficiency.

**Post 2050**

Beach nourishment will be maintained at pre-2050 levels or be reduced, depending on the actual rate of sea level rise. If it rises by less than 12 mm/year (1.30 m in 2100), then any surplus sand available at that time will contribute to extra coastal space, offering extra safety for the post-2050 period.

A more elaborate explanation of this recommendation can be found in Appendix A.

Present policy is focused on soft beach and shoreface nourishment. A new combined strategy is studied originating from the tendency toward seaward extension, together with an extra impulse for nature and recreation.

Increasing instantly from 12 Mm$^3$/year to 85 Mm$^3$/year nourished sand is a big step, most likely a first step will be made by increasing nourishing maintenance up to 20 Mm$^3$/year. To simplify decision-making, the pilot project sand-engine will provide improved insight in large-scale nourishment for long-term flood protection, ecology and recreation.

Coastal nourishments of 20 Mm$^3$/year is from a sand budget and financial point of view still very manageable, but little is known about the coastal response to such large volumes of sand nourishment and little is known about new societal benefits that could be gained with such increased nourishment volumes (BwN – Holland Coast HK4.1 Work Plan, 2009).
2.6 Design phase large-scale nourishment

The design of the sand-engine is chosen in such a way that it will benefit multiple purposes. Besides long-term flood protection, nature and recreation were important aspects in the optimization of the design.

New knowledge incorporated in aggregated and coupled models, will provide tools to support the decision-making, planning process and the design of optimal, long-term strategic options for sustainable development of the Holland Coast. Strategy development in close interaction with a stakeholder platform, will guarantee optimal conditions for implementation.

While developing strategies for large-scale nourishment, the leading BwN principles are that:

1. optimal use is made of natural processes;
2. opportunities for nature development are maximally exploited;
3. measures accommodate for natural dynamics and maximizing potentials of the eco-morphodynamic system.

This thesis aims to provide the necessary scientific support and a quantitative context of integrated model coupling for large-scale mega-nourishment. The dominant part of this thesis focuses on extreme events, like storm conditions. Enabling the impact assessment of extreme events in long-term modeling, quantitative indicators will be identified. Indicators can provide insight in the impact of extreme events at mega-nourishment and the adjacent coastline. Indicators for long-term flood protection, nature and recreation are for example the MKL- (Momentane Kust-Lijn) volumes, the dune area [m2/m'] or the available beach width. These indicators are essential for close interaction with the stakeholder platform, it can also provide a criteria assessment for the design and implementation of future mega-nourishments.
2.7 Inventory design aspects and indicators

Mega-nourishments can be designed to serve nature, recreation and long-term flood protection; these topics are generic design aspects. In the list below, the generic design aspects are subdivided into indicators enabling a consistent and comprehensive evaluation during the design process of a mega-nourishment. The indicators provide a proficient tool, enabling a quantitative and qualitative assessment of generic themes. Such values can provide clarity, but most of all model results can be translated on behalf of the main topic for involved stakeholders. The indicators are elaborated in the proceeding paragraph, assigned with their unit and state of research.

Long-term flood protection

- Coastline migration
  - MKL volumes
  - MKL position (w.r.t. RSP), beach width
  - Sediment transport
  - Bathymetry development
  - Gravity point assessment
  - Cumulative erosion/sedimentation
- Dune strength, dune area, dune development

Recreation

- MKL position (w.r.t. RSP), beach width
- Swimming safety
  - Currents, eddies
  - Slope (cross-section)
  - Cliff forming (cross-section)
- Siltation
  - Location (hot spots)
  - Thickness sand/silt layer, ratio

Nature

- Dune-, intertidal- and subtidal area. (aeolian processes)
- Siltation
  - Location (hot spots)
  - Thickness sand/silt layer, ratio
- Groundwater table
- Water quality (salt intrusion)
- Biodiversity, benthos and vegetation

Technical realization

- Execution, dredging possibilities
- Nourishment design
- CO2 emission
- Cost/feasibility
2.8 Design aspects covered in EIA sand-engine

By means of the indicators given in the previous paragraph, a detailed overview is presented in Table 2.3. From studies to the sand-engine (especially the EIA), this overview states which indicators are investigated.

Some indicators have been treated only preliminary or are still uncertain and should be investigated in more detail, given in orange, red indicates insufficient are no research. Consequently, this table provides insight for further research and assessment analysis to future mega-nourishment projects.

Table 2.3 Overview design aspects by means of indicators.

<table>
<thead>
<tr>
<th>Long-term flood protection</th>
<th>Unit</th>
<th>EIA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coastline migration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MKL volumes</td>
<td>[m³/m']</td>
<td></td>
</tr>
<tr>
<td>MKL position (w.r.t. RSP), beach width</td>
<td>[m]</td>
<td></td>
</tr>
<tr>
<td>Sediment transport volumes</td>
<td>[m³/m']</td>
<td></td>
</tr>
<tr>
<td>Bathymetry development (Contour lines)</td>
<td>[m]</td>
<td></td>
</tr>
<tr>
<td>Gravity point assessment</td>
<td>[m]</td>
<td></td>
</tr>
<tr>
<td>Cumulative erosion/sedimentation</td>
<td>[m]</td>
<td></td>
</tr>
<tr>
<td>Dune strength/development, dune area</td>
<td>[m³/m']</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Recreation</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>MKL position (w.r.t. RSP), beach width</td>
<td>[m]</td>
<td></td>
</tr>
<tr>
<td>Swimming safety</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Currents, eddies</td>
<td>[m/s]</td>
<td></td>
</tr>
<tr>
<td>Slope, cross-shore profile</td>
<td>°</td>
<td></td>
</tr>
<tr>
<td>Cliff forming</td>
<td>[m]</td>
<td></td>
</tr>
<tr>
<td>Siltation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Location (hot spots)</td>
<td>[m]</td>
<td></td>
</tr>
<tr>
<td>Bed composition sand/silt ratio</td>
<td>[m]</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nature</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dune-, intertidal- and subtidal area</td>
<td>[m²/m']</td>
<td></td>
</tr>
<tr>
<td>Siltation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Location (hot spots)</td>
<td>[m]</td>
<td></td>
</tr>
<tr>
<td>Bed composition sand/silt ratio</td>
<td>[m]</td>
<td></td>
</tr>
<tr>
<td>Groundwater table</td>
<td>[m]</td>
<td></td>
</tr>
<tr>
<td>Water quality (Salt intrusion)</td>
<td>[kg/s]</td>
<td></td>
</tr>
<tr>
<td>Biodiversity, benthos and vegetation</td>
<td>[kg/m²]</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Technical realization</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Execution, dredging possibilities</td>
<td>[m³/s]</td>
<td></td>
</tr>
<tr>
<td>Nourishment design</td>
<td>[m²/m']</td>
<td></td>
</tr>
<tr>
<td>CO2 emission</td>
<td>[kg/m³]</td>
<td></td>
</tr>
<tr>
<td>Cost/feasibility</td>
<td>[Euro/m³]</td>
<td></td>
</tr>
</tbody>
</table>
2.9 Description features Bornrif near Ameland

The sand-engine is a new invention in the strategy of mega-nourishment. The processes and impact of such a project is widely unknown due to the unique character of the invention. The Bornrif located at Ameland can provide improved insight in the processes and impact of the sand-engine. Namely, the Bornrif exhibits a similar shape and order of magnitude as the sand-engine.

Research to the Bornrif is done, partly to identify similarities with the sand-engine project (Achete, 2011). Therefore, a hind cast of the morphological development of the Bornrif is established, using the numerical model Delft3D.

2.9.1 Findings Bornrif for comparison analysis sand-engine

1. The tip of the hook heads towards the adjacent coast forming a bay. The period for the tip of the hook to reach the coast is around three years, see Figure 2.19.
2. A lagoon is formed when the tip of the hook reaches the adjacent coast. A connection with the surrounding sea maintains due to a meandering channel. This channel increases in length with accretion of the tip of the hook.
3. After merging with the adjacent coast, the shape adjusts to an equilibrium with the wave directions. From this point on the morphological changes slow down.
4. Despite the similarities between the Bornrif and the sand-engine, the western edge of the Bornrif is part of an estuary inlet, whereas the sand-engine is part of a uniform sandy coastline. However, a divergence point of waves appears, relative to the shape of the hook. The direction of sediment transports is similar, but near the sand-engine a recirculation cell is formed.
5. The presence of an ebb-tidal delta near the Bornrif influences the wave breaking and the wave induced currents. These forces can lead to a different morphological development, mostly concerning the tip of the hook. The sand-engine can show a more diffusive pattern, see top pictures in Figure 2.19.
6. The ratio between the length and width of the lagoon can be an indication for the morphological development of the sand-engine. The development of the lagoon in time can be represented as a ratio trend, enabling quantification for comparison.

The Bornrif case can provide opportunities for validation analysis concerning the sand-engine pilot project and future mega-nourishment projects. Validation analysis can be made with monitoring data from the sand-engine or with forecasting models, simulating similar-shaped mega-nourishments.
Figure 2.19  Comparison morphodynamics Bornrif_sand-engine (Achete, 2011).
3 Integrated modeling approach for design of mega-nourishments

The previous chapter describes the characteristics of the Delfland coast and elaborates on the present nourishment strategy and on a pilot project for a potential new nourishment strategy. This potential new nourishment strategy implies the implementation of mega-nourishments. General and specific design aspects for mega-nourishments are given and a special focus is made for the design phase of the sand-engine pilot project. The main objective of this chapter is to assess and identify the potential and limitations of several numerical models to cope with long-term morphological modeling of mega-nourishments. This chapter describes and provides model opportunities to integrate multiple physical processes concerning the morphological development of mega-nourishments. Due to model integration a new design approach for mega-nourishment can be provided. This integrated model approach may provide improved insight and assessment on the impact of mega-nourishments on nature, recreation and long-term flood protection.

3.1 Design cycle for mega-nourishments

Throughout the design phase of the sand-engine questions and uncertainties were solved starting on a large scale and gradually shifting to a smaller scale. After the approval for the construction of the sand-engine, based on the EIA, new questions and uncertainties rose concerning the sand-engine and future mega-nourishments. In Figure 3.1 the design cycle is given which was applied for the sand-engine, this figure however, is adjusted for an integrated design approach for future mega-nourishments (indicated in the red square). The stakeholder platform provides input for investigation into pressing uncertainties like storm impact, silt accumulation, swimming safety, etc. These pressing issues are classified under generic design aspects like long-term flood protection, nature and recreation. To enable research and analyses in the pressing issues, they are translated into specific design aspects (coastline migration, dune area, etc.) which can be quantified by means of indicators (paragraph 2.8). By translation, the specific design aspects can be linked to numerical models, at which present pressing uncertainties can be investigated. Integration and coupling of those models can provide a new approach in covering and handling design aspects and uncertainties, combining the specific qualities/capabilities of the numerical models. The output of the numerical simulations will then have to be assessed by the same indicators. This enables the stakeholder platform to perform direct analyses concerning the development of a mega-nourishment.
Figure 3.1  Design cycle for mega-nourishments, including new opportunities regarding model integration.
3.2 Application and limitation of numerical models

Knowledge of the available numerical models is necessary to know their capabilities for application purposes but also their limitations. Figure 3.2 provides parameters and application ranges on spatial and temporal scales of several numerical models which can be used regarding mega-nourishments (Huisman and Luijendijk, 2010). The application ranges are combined with pictures of the corresponding scale of the mega-nourishment. The figure also provides some model specific design aspects that can be simulated by XBeach (dune erosion model), DUNE model (aeolian transport model), Delft3D (morphodynamic area model) and UNIBEST (coastline model). The design aspects from paragraph 2.7 can be linked to the available numerical models.

![Figure 3.2 Numerical models with their application ranges in time and space (Huisman and Luijendijk, 2010).](image)

3.2.1 XBeach - Dune erosion and cross-shore profile model

The numerical model XBeach is a process-based model that can simulate cross-shore profile changes, dune erosion and long shore sediment transport (in 2DH) on a time scale of storms up to months (Van Thiel de Vries et al., 2008). XBeach has been developed by Deltares for the US army Corps of Engineers after the hurricane Ivan (September 2004). XBeach includes a wave model that is coupled to a flow model. These models compute the propagation of short and long (infragravity) waves, as well as the transfer of energy between the short and the long waves, which is essential for dune erosion. XBeach simulations are computationally intensive, but due to usually small domains the computational time is still very acceptable (Huisman and Luijendijk, 2010).
3.2.2 DUNE – Aeolian transport model

The DUNE model is an existing process-based aeolian transport model for desert situations, which has been extended and modified by Muller (2011) for coastal applications. The DUNE model is a combination of three physical processes. Firstly, analytical equations that give a quantitative description of the turbulent wind field over a certain terrain. Secondly, a model that describes the saltation, which leads to the evolution of a sand surface. And finally, a model for avalanching that takes transport of sand due to gravity into account. Presently aeolian sediment transport models are usually developed for areas like deserts. The DUNE model can now also simulate the contribution of wind blown sediments in the coastal system. However, modeling the effects of nourishments on dune morphology in a coastal system is still an relatively unknown area.

3.2.3 Delft3D – Morphodynamic area model

The Delft3D model is a multi-dimensional (2DH or 3D) hydrodynamic (and transport) simulation program which calculates non-steady flow and transport phenomena resulting from tidal and meteorological forcing on a curvilinear, boundary fitted grid (Lesser et al. 2001 and 2004). The advantage of Delft3D is its capability in processing the morphodynamics of complex features and non uniform coasts. Delft3D consist of a FLOW and SWAN model, for which in the FLOW model currents like tides, wind driven currents, etc are computed and wave conditions can be computed with the SWAN model. The two models can also be coupled within Delft3D, hence e.g. wave driven currents can interact with tidal currents. By means of these hydrodynamics the transport of cohesive and non-cohesive sediments can be computed. Delft3D can handle problems and projects on a wide spatial scale from harbours to tidal basins to timeframes up to years. Therefore, Delft3D is very suitable for handling complex geometries like mega-nourishments (Huisman and Luijendijk, 2010).

3.2.4 UNIBEST - Coastline model

UNIBEST-CL+ is a 1D coastline model that computes coastline changes as a result of wave driven longshore sediment transport at specific locations along the coast (WL | Delft Hydraulics, 1994). The longshore sediment transports result in coastline migration, which in turn effects the longshore sediment transport. UNIBEST can handle the impact of hard structures (e.g. harbor moles, revetments and groins) on uniform coastlines. The morphodynamic development of complex geometries like the sand-engine cannot be handled, but (mega-) nourishments can be included as a source input in the model.
3.3 New features and advantages for integrated modeling

The preceding paragraph elaborates on the application of numerical models, at individual basis. In this paragraph the numerical models are described based on an integrated modeling approach. Figure 3.3 presents an integrated model approach, which can be applied for the design phase of mega-nourishments, incorporated several models and modules. Delft3D functions as the core in this integrated model approach, also links are provided giving the information exchange between the models and modules.

![Figure 3.3 Idealized integrated model system for large-scale coastal projects.](image)

In Figure 3.3, the links between the different models and modules are numbered and described below. The focus of these descriptions is to provide insight in new features and advantages for integrated modeling.

1) Delft3D – XBeach

Delft3D lacks a good representation of the swash zone (the zone where the waves break and run up the cross-shore profile). The cross-shore profile changes are not resolved well in this area. The XBeach model performs better here, Figure 3.4, because of the transfer of energy between the short and long (infragravity) waves are taken into account.

![Figure 3.4 Model application of Delft3D and XBeach in the swash zone.](image)
This representation is important for features like dune erosion, overwash and inundation that happen during storm events. The morphological changes during a storm event at the sand-engine, with an occurrence of 1 in 10 years, has roughly the same amount of distributed sand considering 6 months of average conditions (Van Thiel de Vries et al., 2009). Therefore, the features in the swash zone during storm events are essential for the long-term development of mega-nourishments. Besides the integration of morphodynamic features like dune erosion and overwash, the coupling between Delft3D and XBeach enables also an interaction of the changes of the bathymetry beneath the closure depth and the bathymetry in shallow water. Average hydrodynamics in Delft3D will influence the bed in shallow water of the surfzone, during storm events simulated with XBeach, sediments from deeper water can also be activated, participating in the morphodynamic development.

2) Delft3D mud-module

In the morphological model Delft3D, the bed level and bed composition can depend on sand as well as mud, and was proposed by van Ledden & Wang (2000). Computing morphodynamic processes with a sand- as well as a mud module in Delft3D, enables analyses and assessment of siltation processes near mega-nourishments, which can have feedback on the morphodynamic response of mega-nourishments. The siltation processes can also be computed with the Delwaq module of Delft3D, however in the Delwaq module there is no morphodynamic feedback possible.

3) XBeach – Mud-module

Long-term predictions for mega-nourishments are calculated with average hydrodynamics in Delft3D. If those predictions are also based on siltation processes, calculated with the mud-module, siltation layers can develop near lee-sides of mega-nourishments. These siltation areas can appear and develop due to sheltering from (averaged) hydrodynamic conditions. A model integration between the Delft3D mud-module and XBeach can provide long-term predictions incorporating the impact of storm events. This model integration would not only provide insight in the impact of storm events on the long-term morphodynamic behavior of mega-nourishments, but also of the impact of storm events on siltation areas. Where lee-sides are provided with shelter for averaged hydrodynamic conditions, storm conditions could occasionally reach the sheltered areas and stir up the siltation layer, which has been accumulated there over a certain period.

4) & 5) Delft3D – Modflow

Like for both links in the model integration, the impact of large-scale coastal projects like mega-nourishments can be substantial on the groundwater table in the area of concern. Moreover, mega-nourishments located near a coastline can enhance the fresh water zone, see Figure 3.8. Beside the groundwater table, a study from Dey et al. (2011) describes the influence of groundwater flow on the sediment transport near the bed. The significance of this study lies on the hydrodynamic process in such a physical system that may result in modifying the flow resistance, sediment entrainment, and morphological characteristics of a streambed.
6) Delft3D – UNIBEST

The application range for mega-nourishments on spatial and temporal scale of Delft3D is limited, see Figure 3.2. Integrating a coastline model, like UNIBEST with Delft3D, can provide long-term predictions for longer stretches of coastline on a longer time scale. The model integration with UNIBEST can be established via substituting annual transport volumes from Delft3D. Next to it, the adjacent coastline response of mega-nourishments, modeled via annual transport volumes, can have morphodynamic feedback on the mega-nourishment.

7) & 8) Delft3D Delwaq – DUNE

Vegetation near mega-nourishments can induce stabilizing areas, via the roots and leaves vegetation can reinforce a body of sand and can capture sand, moved by aeolian transport. Vegetation under water can also influence the sedimentation and erosion patterns near the bed layer. Via the Delft3D Delwaq-mor module, the morphodynamic feedback of vegetation for mega-nourishments can be incorporated. An additional model integration with a wind model can enhance the modeling predictions for the topography of mega-nourishments, including e.g. marran grass.

9) Delft3D – DUNE

A model integration between Delft3D and a wind model, like DUNE, will provide the interaction of the topographical response of mega-nourishments due to aeolian transport, with the morphodynamic response of mega-nourishments due to sediment transport. An elaboration on the new features via this model integration is provided in appendix C.

10) DUNE – XBeach

The coupling of XBeach and Dune is in fact a coupling between several physical processes; XBeach resolves hydrodynamics (flow and waves) and their resulting morphological change, whereas Dune calculates the shear stress field caused by wind and its resulting morphological change of the inter-tidal area and the dry area. In principle, these processes will operate independently from one another. However, the similarities between them is that they both cause a change in bed level and are both influenced by the same bed level. This means both models have to exchange bed level information between each other. The coupling of these two morphodynamic models provides the ability to integrate the changes and nourishment from the inter-tidal area to the dry area due to aeolian transports, with the morphodynamic changes due to storm conditions, like dune erosion and overwash. This numerical coupling will be studied and assessed by Bieman (2011).
3.4 Key processes not covered in design process of the sand-engine

This paragraph describes a number of important physical processes and provides model opportunities to integrate those processes concerning long-term morphological modeling for mega-nourishments. These physical processes are described because they are considered important and form a pressing matter to the stakeholder platform. In this thesis the impact of storm events and siltation on the long-term morphodynamic development of the sand-engine will be further investigated. The other processes, which are also described in this paragraph, provide information and opportunities for future research to integrated long-term modeling of mega-nourishments. Integration and interaction of all processes and numerical models aims for an idealized model approach for the design of mega-nourishments.

An idealized model approach is presented in Figure 3.5. Herein, integration of multiple physical processes can be established via coupling of numerical models. These numerical models are optional, more models can be available for simulating the presented physical processes. With arrows, the direction of the information exchange is given, added with specific parameters (e.g. the bathymetry, hydrodynamics, annual sediment transport, etc.). The morphodynamic area model Delft3D will function as the core in this idealized model approach.

In the list below the sum of processes is given, which could be added in an integrated model approach for the design of future mega-nourishments and other large-scale coastal projects. These processes are not covered in the design process of the sand-engine.

- Morphodynamic response due to storm events (XBeach)
- Siltation processes near lee-sides (Delft3D mud-module)
- Groundwater table (Modflow)
- Large-scale coastline modeling via annual sediment transports (UNIBEST)
- Feedback from vegetation on sediment transport (Delft3D Delwaq-mor)
- Aeolian transport (Dune)
In the design process of the sand-engine only Delft3D is used. In this thesis, the coupling with XBeach is made possible, see Figure 3.5, which enables the morphodynamic feedback of storm events regarding the long-term morphodynamic development of mega-nourishments. Next to that, siltation processes are investigated near the sand-engine. Investigation to siltation processes are established by using the mud module incorporated into Delft3D. The other processes are not covered in this thesis, but opportunities are given for further research into model integration.

3.4.1 Storm events

Problem definition

The long-term morphological development of the sand-engine and adjacent coastline is simulated with Delft3D (during the EIA). In these simulations, hydrodynamic forcing is represented by a reduced average wave climate of twenty years. The wave climate is measured from stations along the Delfland coast. Considering twenty years of wave climate, several peak periods and storm events are present. Through averaging, a reduced wave climate is generated, which is used for hydrodynamic boundary conditions for long-term morphodynamic simulation of the sand-engine. Storm events have become part of an average reduced wave climate, and their individual specific features are not included. The individual hydrodynamic mechanism of storm events like the setup of the water level, the high wave conditions and the storm duration are absent in long-term morphodynamic EIA simulations with Delft3D.

Modeling approach

Storm events can be simulated with the numerical model XBeach, elaborated in paragraph 3.2. For long-term morphodynamic predictions Xbeach is a far too complex model and will take too much simulation time. Delft3D is most suitable for generating longer-term morphodynamic simulations, which is a necessity for predicting long-term development of mega-nourishments. Therefore, an interaction of Delft3D and XBeach enables long-term morphodynamic simulations including storm events, elaborated in chapter 4.

Figure 3.6 Numerical model coupling in time and space (Huisman and Luijendijk, 2010).

The second picture in Figure 3.x visualizes an interaction of Delft3D and XBeach for a long time scale. The applied model approach is an integrated model tool providing interaction between storm events simulated with XBeach and average hydrodynamic conditions for long-term morphodynamic development simulated with Delft3D.
3.4.2 Siltation (sand-mud module in Delft3D)

Problem definition

Near low energy areas or lee-sides of mega-nourishments siltation may occur due to the settling of fines in the water column. These fines in the water column originate from rivers, shores or from the top layer of the bed. Siltation is especially expected in summer seasons, when hydrodynamics are calm and fines have time to settle. Siltation areas can result in ecological benefits, but also in recreational restrictions.

The assessment of siltation processes in time and space near the sand-engine, is not yet thoroughly investigated. Preliminary research from the EIA indicates substantial siltation in the lee-side of the sand-engine, sheltered from waves. This research was executed with a 1D point model. Results were analysed for several locations near the lee-side and via expert judgment a quantitative siltation assessment was given. A clear spatial and temporal assessment (2DH) of the siltation processes near the lee-side of the sand-engine is missing.

Uncertainty about the influence of annual hydrodynamic conditions on siltation processes near the lee-side is present. Will there be enough wave penetration for fines to stay in suspension, or will there be enough sheltering of the sand-engine for fines to settle? Also the impact of storm events is not investigated. Storm events can have substantial impact on low energy areas around the sand-engine. They can penetrate the low energy areas and dissolve the developed siltation layer.

With respect to nature, the mud content of the bed is an important indicator for the bottom quality, because nutrients and pollutants tend to adhere to, or be part of, cohesive sediments [Wang, 1996].

Modeling approach

In the existing process-based sand (van Rijn, 1993) and mud models (Teisson, 1997), a representative grain size is often used for determining sediment transport rates, and mud content variations in time and space are not taken into account. Moreover, morphological models usually only exist for non-cohesive sediments. Nowadays in the morphological model Delft3D, the bed level and bed composition can depend on sand as well as mud, and was proposed by van Ledden & Wang (2000).

By means of an integrated model using the sand-mud module in Delft3D, siltation processes near mega-nourishments can be analysed and assessed. A second possibility is the usage of the Delft3D module Delwaq. However, morphodynamic changes cannot be included in this module.
3.4.3 Other processes concerning mega-nourishments

At the begin of this paragraph an idealized model approach is presented. In this thesis the impact of storm events and siltation processes are investigated. The other processes are briefly introduced here and are elaborated with a modeling approach in appendix C.

**Aeolian transport (DUNE)**

In a coastal zone, the sand transported landwards by the wind is the primary input of sediment into a dune system. The source of this sediment can only be found in the small range between the low tide level and the fore dunes. Exchange of this sediment from the dune foot back to the beach can take place during storm events. In the case of a mega-nourishment an excess of sediment is placed in the nearshore area. Rules of thumb estimate an annual aeolian transport along the Delfland coast of 30m$^3$/m$^2$ on average (S. de Vries, personal communication). Regarding the sand-engine project area (2x1 km) and lifetime (20 years), this comes down to 30 m$^3$/m$^2$/yr x 2000 m = 60,000 m$^3$/yr sediment transport along the sand-engine area. Insight into the interaction between the lower and upper (wet-dry) part of the sand-engine is therefore of great importance.

During the development of the sand-engine aeolian transport can induce the formation of local dunes. Due to the formation of dunes, the tip of the hook can become higher compared to the shape of the initial profile. A higher cross-shore profile of the sand-engine can provide resistance against high surge levels during storm events and thus can prevent submerging and overwash of the sand-engine.

![Aeolian sediment transport sand-engine 18 july, 2011](www.flickr.com)

**Vegetation and benthos (Delft3D-module; delwaq)**

Near uniform coastlines with high hydrodynamic conditions hardly any vegetation is present on the beach or in the nearshore area. However, with the presence of complex geometries at uniform coastlines like the sand-engine, lee-side areas can be formed. In these areas were hydrodynamic energy is low, vegetation has opportunities to settle and grow. Vegetation near mega-nourishments can induce stabilizing areas, via the roots and leaves vegetation can reinforce a sand body and can capture sand, moved by aeolian transport. Water quality determined by the concentration of oxygen, nitrate, etc. is important for the growth of vegetation, benthos and fish. Water quality will be an issue for the dune lake at the
sand-engine and for the low energy area at the north side of the hooked shape. Vegetation can be an indicator to determine the water quality.

**Feedback of adjacent coastlines (UNIBEST)**

For a certain spatial extend the morphodynamic development of the sand-engine has been simulated with Delft3D. However, the impact of the sand-engine on a larger spatial scale is unknown.

If the sand-engine pilot project meets the expectations, it can provide an alternative for present nourishment policy. Moreover, a new nourishment strategy can be implemented (paragraph 2.5), in which multiple mega-nourishments can be placed at different locations along the Dutch coast. However, the impact of multiple mega-nourishments on a large spatial and temporal scale, as well as their mutual interaction is unknown.

**Hydrology (Modflow)**

In December 2008 the coastal upgrading of the Delfland coast started as a reply on the national coastal upgrading program ‘Zwakke Schakels’. A new seaward dune ridge together with beach and nearshore nourishments were constructed along the seaside resorts Ter Heijde and Kijkduin. During the construction of the new dune ridge, some problems occurred regarding the ground water table in the surrounding area. One major problem was the temporary flooding of some nearby dwellings (cellars) due to an upcoming ground water table. A second problem were the side effects on the nature area between Ter Heijde and Kijkduine, called Solleveld. In this nature area, a fresh water extraction site is located. With large dune and beach nourishments, salt intrusion could negatively influence the fresh water table in this fresh water extraction area. These problems were unaccounted for and triggered the stakeholder platform. Mega-nourishments, especially when attached to the shoreline, can lead to similar problems. Mega-nourishments can also lead to positive side effects regarding the ground water table. On a long temporal scale, mega-nourishments will increase the dune and nearshore area and can increase the ground water table and hence a fresh water extraction site.

Ground water side effects in relation with (mega-) nourishments is a new issue concerning the stakeholder platform. A lot of research must be made when future mega-nourishments will be initiated.

![Ground water characteristics near a coastline](image)
3.5 **Indicators regarding model integration for storm events and siltation**

Through optimal application of the model integration with XBeach and the mud-module in Delft3D, a number of (extreme) scenarios have been generated. The hydro- and morphodynamics of the scenarios are analysed. The assessment of their impact on nature, recreation and long-term flood protection is of great importance. Enabling a consistent and comprehensive evaluation of the scenarios, some quantifiable indicators can be applied (paragraph 2.8), which will return in Chapter 5 and 6. The physical processes like storm events or siltation can be assigned to the generic and specific design aspects, which are subdivided into a number of indicators. Hence, quantification and impact assessment of several scenarios and the physical processes is possible.

The list below only identifies the indicators for the model integration of Delft3D with storm events and siltation processes, for a complete list of all the mentioned physical processes, from Figure 3.5, reference is made to appendix C-3.

**Long-term flood protection**
- Coastline migration
  - MKL volumes
  - MKL position (w.r.t. RSP), beach width
  - Ratio trend
  - Sediment transport
  - Bathymetry development
  - Gravity point assessment
  - Cumulative erosion sedimentation analysis
- Dune strength, dune area, dune development

**Recreation**
- MKL position (w.r.t. RSP), beach width
- Swimming safety
  - Currents, eddies
  - Slope (cross-section profile)
  - Cliff forming (cross-section profile)
- Siltation
  - Location (hot spots)
  - Thickness sand/silt layer, ratio

**Nature**
- Dune-, intertidal- and subtidal area. (aeolian processes)
- Siltation
  - Location (hot spots)
  - Thickness sand/silt layer, ratio
- Biodiversity, benthos and vegetation
3.6 Conclusions

- In this chapter, an inventory is presented of various physical processes that have not been taken into account during the design phase of the sand-engine. Moreover, during the design phase of the sand-engine there was a lack in an integrated approach regarding the long-term morphological predictions and impact assessment of the sand-engine (e.g. the integration of siltation, aeolian transport, storm events, etc).

- An idealized model approach is presented, which can lead to improved long-term predictions of mega-nourishments for the design phase or management phase of future mega-nourishments. Due to the integration of multiple models and tools, various physical processes can be integrated into long-term morphodynamic predictions.

- In this thesis, one integration link from the idealized model approach, is realized concerning the impact of storm events on long-term morphodynamic predictions. This integration link will provide improved insight into long-term predictions of mega-nourishments.
4 Numerical models

The morphological development of the coastal system is subject to complex interaction between currents, waves, sediment transport and bed level variations. Moreover, the entire Dutch coastline is subject to human interference such as dredging and nourishments (except for the coast of Schiermonnikoog) and several hard structures. During the past decades several numerical models have been developed to simulate the physical processes and the interaction between physical processes to predict morphological development in coastal systems.

This chapter describes the application of the numerical models Delft3D and XBeach and elaborates on the interpolation methods for model integration. For each numerical model the settings and schematizations of the physical processes and area characteristics will be explained.

4.1 Morphodynamic modeling

Nowadays there are three major types of morphodynamic modeling. First, the process-based morphodynamic modeling. This modeling principle aims at describing the physical processes to best knowledge with mathematical-physical principles. Data sets are used for calibration and validation purposes, where after the model is able to predict the morphological development for a specified time scale. The second morphodynamic modeling approach concerns the parametric models. These models are considered as reduced process-based models, where the dominant processes are modeled by means of parameterization. And thirdly the behavior-orientated models, which assumes that a system evolves towards an equilibrium state, which is known beforehand from longer term data sets (Tonnon, 2005). The morphodynamic modeling in Delft3D and XBeach is process-based and depth averaged, conform the first mentioned type of morphodynamic modeling.

4.2 Delft3D model

The long-term morphodynamic predictions for the sand-engine are calculated with the process-based numerical model Delft3D. Delft3D contains several modules, these modules calculate the processes of the hydrodynamics (flow & waves), sediment transport, morphodynamics, water quality and ecology. Figure 4.1 presents an overview of these modules. It is a schematic representation what will happen during each time step of a simulation.

A modeler/user starts with an initial bathymetry, loaded from datasets or is user-defined from a specific project location. The applied bathymetry is attached to a numerical grid, each grid point contains a bathymetry value. When the bathymetry is defined, the boundary conditions can be implemented at the offshore and lateral boundaries of the numerical grid (e.g. tidal flow, wave conditions, sediment characteristics, etc.), see Figure 4.1. Based on the boundary conditions, the hydrodynamics and other physical processes can be computed throughout the numerical grid.

The module Delft3D-Flow is the central module, which provides the hydrodynamic basis. After a specified amount of time steps, the output from the Flow-module can be given as input for the Wave-module. The Wave-module is based on the spectral wave model SWAN (Simulating WAves Nearshore), which simulates the evolution of wind-generated waves in coastal waters (Holthuijsen, 2007b). The wave output, in turn, is substituted back to the Flow-
module, generating wave driven currents, turbulence, bed shear stress and stirring up of sediment due to wave oscillations. After the online coupling of Flow and Wave, the corresponding sediment transport is calculated according to an applied sediment transport formulation. A detailed description of the physics and formula, which are used in the Flow and Wave module is given in Appendix D.

Bed level changes are determined based on divergence of the sediment transports and define the morphologic behaviour. At every time step the bathymetry is updated and finally a new set of computations is executed for the following time step. Morphodynamic changes take place over longer periods of time than hydrodynamic changes. In order to predict morphodynamic changes with hydrodynamic simulation 1 to 1, would take too long, regarding the simulation time. In order to overcome that problem a morphological acceleration factor is implemented during the process-based modeling of the sediment transport (Lesser, 2004). The morphological acceleration factor multiplies the sediment fluxes to and from the bed by a constant factor, hereby accelerating the morphological development.

4.2.1 Model schematization

The model grid applied in the Delft3D-Flow module is a curvilinear grid, following the coastline curvature of Delfland. The grid is 9.4 kilometers in alongshore direction and 4 kilometers in offshore direction to the -15m NAP depth contour. The model grid is positioned between the following two alongshore RSP (‘Rijksstrandpaal’) coordinate points, from 112 kilometer to 104 kilometer (measured from Den Helder), the applied model grid is given in red, Figure 4.2. Along the landside boundary of the model grid the seaside resorts Ter Heijde and Kijkduin are located.

This model grid is extracted from a larger grid, given in black, Figure 4.2. During the EIA investigation (Environmental Impact Assessment), morphological predictions of the sand-engine were simulated, which also investigated the side effects of the extension of the Rotterdam harbor (‘2e Maasvlakte’) and of the Scheveningen harbor. Therefore, the applied model grid in these morphological predictions is 26 kilometer in alongshore direction and 15 kilometer in offshore direction to the -23m NAP depth contour, including the two harbors. Because the focus of this thesis has a more generic approach for the impact of mega-nourishments at its surrounding coastal system and a focus on morphodynamic model integration, the implementation of such a large grid is not required.
Figure 4.2  Visualization of the flow grid, near the seaside resorts Ter Heijde and Kijkduin.

Moreover, the advantage of using a smaller model grid is the ability of using a higher resolution, hence more accurate morphological predictions can be made. Due to higher resolution of the Delft3D model grid, more detailed computations and visualizations can provide improved insight into hydro- and morphodynamics near the sand-engine. The detailed modeling can also provide more insight into local currents regarding e.g. swimming safety or siltation. The number of grid cells of both model grids is roughly the same, so the absolute simulation time is roughly the same, assuming an equal time step. The place in the model grid (Figure 4.2, in red) with the highest resolution is located near the sand-engine. There, the grid cells are 35m in alongshore direction and 20m in cross-shore direction. The model grid resolution in x- and y- direction is usually a compromise to account for accurate longshore tidal propagation and accurate cross-shore wind wave propagation.

A high accuracy for flow calculation on gently sloping bathymetries is achieved with grid resolution cross-shore 10 - 30m and longshore 80 – 200m. For wave calculation, an accuracy is needed with grid dimension alongshore up to 1000m and in cross-shore 10m (Plant et al., 2008).

The model grid used in the Wave-module is larger then the flow grid, and extends in southern and northern direction, see Appendix D.6. Application of a larger wave grid minimizes the boundary side effects of the wave field, which results in a more accurate Flow-Wave coupling. In Appendix D.6 also the wave schematization is elaborated, explaining among others the derivation of the 10 wave conditions that have been used during the long-term morphodynamic predictions with Delft3D.
4.2.2 Morphology validation, sediment transport Delfland coast

For the process-based simulation of sediment transports, several transport formulae are available in the Delft3D-Flow/Wave module. To determine which formula must be applied, a validation study is performed with existing studies to sediment transports along the Delfland coast.

In Delft3D, the bathymetry of the Delfland coast is applied without sand-engine simulating time averaged hydrodynamics. These simulations resulted into net sediment transport volumes along the Delfland coast. Two simulations have been generated, investigating two commonly used transport formula, Van Rijn 1993 (default) and Van Rijn 2004, Figure 4.3.

Figure 4.3 Annual alongshore sediment transport, Van Rijn 1993 and Van Rijn 2004.
Figure 4.3 provides sediment transport volumes for transects perpendicular to the coastline, from the dune foot +3m NAP to the -8m NAP depth contour and from the -8m NAP depth contour to the -12m NAP depth contour. These sediment transport volumes can now be compared to available sediment transport volumes from several studies and data sets of the Delfland coast.

In a study from Van de Rest (2004), a comparison has been made between several studies to sediment transport volumes along the Dutch coast, which are based on JARKUS data. In Figure 4.4 a detailed overview from the Delfland coast is given for the sediment transport volumes along the Delfland coast. The volumes in these studies are also given for transects from the dune foot +3m NAP to the -8m NAP depth contour, perpendicular to the Delfland coastline. The sediment transport volumes from the Van Rijn 2004 Delft3D simulation are plotted in the same figure, given in red. Quick analysis indicates a good resemblance between the range of volumes from the several studies.

The sediment volumes from the +3m NAP to the -8m NAP depth contour in Figure 4.3 deviate not very much: the volumes according to Van Rijn 1993 are an order of about 30,000 m$^3$ higher. The difference which can be distinguished is in the transects from the -8m NAP to the -12m NAP depth contour, given in Figure 4.3. The sediment transport volumes in this area deviate a factor 10 between the Van Rijn 1993 and Van Rijn 2004 transport formula. The sediment transport volumes in this deeper water area can not be validated with the comparison study of Van de Rest, because the study concerns sediment transports to the -8m NAP depth contour and not further.

Validation data for the -8m NAP to the -12m NAP area, is also obtained from JARKUS data, but from a different research (Delft Hydraulics, report H1887). The most nearby available data
are the sediment transport volumes given for transect 103 km, near Scheveningen. The sediment transport volumes from this JARKUS data are given for the -20m NAP depth contour and -8m NAP depth contour, presented in Figure 4.5. Therefore, it is necessary to interpolate these volumes, for the sediment transport volume at the -12m depth contour. Also the cross-shore distances from the depth contour line to the +3m NAP depth contour are given in this figure.

![Figure 4.5](image_url)

Figure 4.5 Average annual alongshore sediment transports, given for -20m NAP and -8m NAP depth contour.

With the values at the -20m NAP and -8m NAP depth contour, and the distances from the dune foot, the sediment transport can be interpolated for the -12m NAP depth contour. Hence, with the sediment transport volumes at the -12m NAP and -8m NAP depth contour, the total volume through this transect can be calculated given in Table 4.1, and visualized in the dashed area in Figure 4.5.

<table>
<thead>
<tr>
<th>Depth [m]</th>
<th>Distance from +3m [m]</th>
<th>Sediment transport [m³/m³/yr]</th>
<th>Sediment transport [m³/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-8</td>
<td>1.000</td>
<td>40</td>
<td>-</td>
</tr>
<tr>
<td>-20</td>
<td>9.000</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>-12</td>
<td>1.900</td>
<td>37</td>
<td>-</td>
</tr>
<tr>
<td>-8/-12</td>
<td>1.000/1.900</td>
<td>-</td>
<td>33.500</td>
</tr>
</tbody>
</table>

Table 4.1 Interpolated sediment transport volumes from JARKUS data.

The order of the sediment transport volume through this transect (33.500 m³/yr through the -8m/-12m area) corresponds with the sediment transport volumes given by the transport formula of Van Rijn 2004, Figure 4.3. Therefore, together with the Van de Rest (2004) validation, in further long-term morphodynamic simulations of the sand-engine the transport formula of Van Rijn 2004 is applied.
4.3 XBeach

In this thesis, the numerical model XBeach is used to simulate extreme hydrodynamic storm conditions and assess the impact of storm events on the long-term morphological development near the sand-engine. XBeach is an acronym for "eXtreme BEACH behaviour model" and was developed by a consortium of Deltares, Delft University of Technology, IHE-Unesco and the University of Miami. XBeach is a process-based numerical model to simulate nearshore hydrodynamics and morphodynamics during storm events near beaches, dunes and (barrier) islands. The model is able to predict dune erosion, overwash and breaching (Roelvink et al., 2009).

4.3.1 Model schematization

XBeach is a 2DH depth-averaged numerical model and solves coupled 2DH horizontal equations for wave propagation, flow, sediment transport and bottom changes for varying (spectral) wave and flow boundary conditions. The schematic modeling steps are similar to the Delft3D modeling approach. The difference lies within the computations of the hydrodynamic part, XBeach takes into account the variation in wave height in time and space and resolves infragravity (long) waves created by this variation. The infragravity waves, together with high surge levels result in swash hydrodynamics that cause for most of the beach and dune erosion (Van Thiel de Vries, 2006).

![Schematic overview XBeach modeling.](image)

The default hydrodynamic modeling approach used in XBeach is called the surf beat approach. The surf beat approach resolves the swash hydrodynamics in dissipative conditions with a 2DH formulation of the incident wave groups and accompanying infragravity waves over a given bathymetry. Due to the forcing of the wave groups, infragravity waves are formed. In the Non-linear Shallow Water Equations (NSWE), the wave group forcing drives the longshore and cross-shore currents. The bed friction term for incident waves and for longshore current predictions is given by the description of Feddersen et al. (2000). Further model parameters are presented in Appendix E.
Sediment transport

The sediment transport processes can be computed numerically in XBeach via two sediment transport models. A choice can be made between the adapted formulation by Soulsby-Van Rijn (Soulsby, 1997) and the more recent sediment formulation by Van Rijn (2007). The latter is the default transport model in XBeach. Due to sediment stirring by breaker-induced turbulence and a combination of short- and long-wave orbital motion, the transport processes are very complex in the nearshore area. A sediment advection diffusion equation is used, which accounts for sediment entrainment on a temporal and spatial varying scale that varies with the water depth and sediment fall velocity (Galapatti, 1983).

Morphological updating

Through the sediment transport computations the bed level change can be computed. The bed level changes are based on the spatial gradients in sediment transport. For managing the computational time of the simulations, every timestep can be multiplied with a morphological acceleration factor. For the sediment processes during storm events, from the dry beach or dune face to the swash zone (dune erosion), an avalanching model is applied. In this model a critical slope for wet sand and dry sand is applied, which accounts for more easily movement of saturated sand then dry sand. The erosion of the dune face by slumping is mainly triggered by the long wave swash run-up, which initiates avalanches on the previously dry beach and dune face. The dune face is flooded during the run-up and this results in instability due to a smaller critical wet-slope (Van Thiel de Vries et al., 2009).

4.3.2 Model grid

For XBeach a rectilinear grid is used, located between RSP (‘Rijksstrandpaal’ coordinate system) 112 kilometer and RSP 105 kilometer. The angle of the grid coincides with the local orientation of the coastline near Ter Heijde, which is 42 degrees in clockwise direction. The grid is 8.5 kilometers in alongshore direction and 3.5 kilometers in offshore direction to the -14m NAP depth contour, Figure 4.7.

The resolution of the grid is much higher then the resolution used in the grids for Delft3D. The highest resolution is again located near the sand-engine and is 20m in alongshore direction and 5m in cross-shore direction.
4.3.3 Tide schematization

In the long-term morphological predictions performed by Delft3D, an averaged tidal signal is used. In XBeach any water level time series can be imposed. The water elevation during the storm events simulated in XBeach consists of multiple factors. The development of the water level \( h(t) \), with respect to NAP, is computed by (Steetzel, 1993):

\[
\eta(t) = h_0 + h_a \cos \left( \frac{2\pi(t - t_{ma})}{T_a} \right) + h_s \cos^2 \left( \frac{\pi(t - t_{ms})}{T_s} \right) \tag{4.1}
\]

The three terms on the right hand side represent the mean water level \( (h_0 = 0.45 \text{ m}) \), the tidal amplitude \( (h_a = 1.00 \text{ m}) \) and the surge effect \( (h_s = 1.95 \text{ m for a storm form 330 °N}) \). The values given, represent a storm event, which occurs once in the 100 years. \( T_a \) and \( T_s \) represent respectively the duration of the astronomical tide \( (T_a = 12h25) \) and the storm duration \( (T_s = 32.5h) \). The simulations of the storm events in this thesis are based on the assumption that the maximum tidal elevation and the maximum surge height coincide \( (t_{mas} = 16.25hrs) \). Therefore, the three terms on the right hand side can be added together resulting in a maximum water elevation of \( \eta_{\text{max}} = 3.4 \text{ m} \).
In this thesis a storm duration of 32.5 hours will be considered. Later, the influence of the storm duration will be assessed regarding the processes of dune erosion, overwash and breaching of the sand-engine.

In Figure 4.8 two tidal signals are presented, each for one lateral boundary of the model grid. Between the two lateral boundaries a phase shift is present, which coincides with the tidal propagation along the Delfland coast. Using formula 2.1, the tidal propagation speed in a water depth of 14m is about 12 m/s. The model grid is 8500m in alongshore direction, giving a phase shift of 8500m/11.8m/s = 720 s, which is 12 min or 0.2 hours.

\[
\begin{align*}
H_{mo}(t) & = H_{mo} \cos^2 \left( \frac{\pi(t-t_{ms})}{T_w} \right) \quad (4.2) \\
T_p(t) & = T_p \cos^2 \left( \frac{\pi(t-t_{ms})}{T_w} \right) \quad (4.3)
\end{align*}
\]

The terms on the left hand side of the two formulations represent the wave height \((H_{mo})\) and the peak wave period \((T_p)\). In Figure 4.9 the development of the wave height and the wave period are given in blue. For simulation purposes the wave height and the wave period have been subdivided in intervals of 2.5 hours.
In paragraph 4.3.1 it is stated that the wave height varies on the wave group time scale. This requires that the input time series contain wave height fluctuations on the wave group time scale. The wave height fluctuations are established by using a standard JONSWAP (Joint North Sea Wave Project) spectrum, with the wave heights and peak periods given in the intervals in Figure 4.9. For all generated storm events in this thesis, the spectral peak enhancement factor of the JONSWAP spectrum is 3.3 and the directional spreading is 20° (Van Thiel de Vries et al. 2009). Further elaboration on this topic can be found in Van Dongeren et al. (2003).
4.4 Integrated model approach

In paragraph 3.3, an idealized model approach is presented. In which Delft3D and XBeach are coupled, see Figure 3.3 and Figure 3.5. This paragraph focuses on the coupling techniques and elaborates on the numerical interpolation techniques, enabling the coupling of the two models. Also insight in the interpolation errors is given and other options are provided for computational running of coupled models.

4.4.1 Coupling concept / Modeling approach

The coupling of Delft3D and XBeach can be visualized as numerical simulations in series, were the output from one model is the input for the other and vise versa, presented in Figure 4.10.

![Series coupling of Delft3D and XBeach, visualizing the bathymetry exchange.](image)

Delft3D will function as the core of the model integration, therefore the model series will start with Delft3D. In Delft3D, several years of morphological development of the sand-engine will be simulated for average hydrodynamic conditions. At the end of the Delft3D simulation, the morphological developments have resulted into a changed bathymetry of the sand-engine. This bathymetry is extracted from Delft3D and interpolated on to the XBeach model grid, Figure 4.7 and Figure 4.11. XBeach is then provided with a bathymetry of the sand-engine after several years of morphological development. With this bathymetry, XBeach can simulate a specified storm event, resulting into a following morphodynamic response to the sand-engine. After the XBeach simulation, the post-storm bathymetry is interpolated to Delft3D to continue the long-term morphological development of the sand-engine in Delft3D, with average hydrodynamic conditions.
4.4.2 Interpolation methods

The model grid of Delft3D is larger than the one from XBeach. Moreover, the majority of the Delft3D grid covers the XBeach grid, Figure 4.11. The use of two identical grids is also possible. However, XBeach handles a much higher resolution for more complex hydrodynamic computations. A grid with the same resolution for Delft3D would take too much simulation time. Beside that, Delft3D uses a curvilinear grid and XBeach uses a rectilinear grid. The implementation of two different grids in this thesis has two reasons. At the moment of building the model coupling, XBeach was not jet fully capable of computations with a curvilinear grid. The second, more simple reason, is to know if it is feasible to use two different model grids without to many return errors, which is elaborated on in paragraph 4.4.4. The bathymetry values from Delft3D are interpolated to the grid points of XBeach and vice versa. For the interpolation steps, four methods are useable (Matlab Manual);

- Linear, based on triangle linear interpolation
- Nearest, based on nearest neighbor cells interpolation
- Cubic, based on triangle cubic interpolation
- v4, based on a MATLAB 4 griddata method

Both the cubic and v4 interpolation methods produce smooth surfaces. Finally, the cubic interpolation method between Delft3D and XBeach gave the smallest interpolation error and is applied for the interpolation between Delft3D and XBeach.

Figure 4.11 Partially overlap model grids, Delft3D (green) and XBeach (blue).
4.4.3 Considerations for coupling

The coupling of Delft3D and XBeach demand some caution regarding the coupling steps. With the application of model coupling it will often be the case that different model grids are used, with a different origin or size or a slightly different angle. Like in Figure 4.18, a distinct difference and a partially overlap with the XBeach model grid is visible. During the first interpolation from Delft3D to XBeach not all grid points near the land boundary are assigned with a bathymetry value. These empty grid cells are filled up by extrapolating the last (dune) cells. It is important for the land boundary to have a high and thick dune ridge. If not, during a simulation, water can breach or overflow the land boundary, resulting in simulation errors.

The second interpolation from XBeach to Delft3D encounters the same problem, only then grid points near the offshore boundary are missing bathymetry values. Due to the fact that these grid points concern bathymetry values in a water depth of about 14 m and because a storm duration of about 32.5 hours is considered, no substantial morphological changes are present. Therefore, these grid points in Delft3D can be assigned with bathymetry values from the latest time step from the preceding Delft3D run.

Another issue which requires attention, concerns the bathymetry profile near the offshore boundary in the XBeach simulations. These simulations require a straight adaption ramp at the offshore boundary to properly solve for the boundary conditions. If a straight adaption ramp is not applied at the offshore boundary, unrealistic flows are generated.

![Figure 4.12](image-url) Straight adaption ramp at the offshore boundary in XBeach.

After a simulated storm event with XBeach, the bathymetry is interpolated back to the Delft3D model grid. The straight ramp at the offshore boundary has to be excluded during this interpolation step.
4.4.4 Interpolation errors

For the assessment of the interpolation error, one complete coupling cycle is analysed. A short model coupling is simulated, running Delft3D-XBeach-Delft3D, without any sediment transport and hence no morphodynamic change. Therefore, in theory, the initial sand-engine bathymetry in the first Delft3D run must be identical to the sand-engine bathymetry of the second Delft3D run, after two interpolation steps exchanging bathymetry with XBeach. For the assessment of the interpolation error, the bathymetry of the first Delft3D run is compared with the second Delft3D run. In Figure 4.13 a top view and two cross-section are presented, herein the two bathymetry sets have been subtracted from each other. Across the hook of the sand-engine, the two cross-shore profiles from both Delft3D runs have been subtracted. The largest interpolation errors occur near sharp changes in bathymetry, so near the bottom and the top of the sand-engine and near the dunes. The order of the interpolation error is about five millimeter (0.005m) and is considered acceptable with respect to long-term morphodynamic changes.
Figure 4.13  Interpolation error after one coupling cycle, Delft3D-XBeach-Delft3D.
4.4.5 Computational techniques

The long-term Delft3D predictions are generated using ten computers at once. A five year morphodynamic simulation of the sand-engine, would take approximately three days of simulation time. The XBeach simulations, predicting the morphodynamic response of storm events are generated with eight computers and take approximately three hours of simulation time. These simulation times are provided for stand-alone generation of the models.

Within Deltares, there are several possibilities for running coupled models. In Figure 4.14 three possibilities are presented, the most left picture is applied in this thesis. Via the software program matlab, simulations for Delft3D and XBeach are send to the Linux Cluster, were about 400 processors are available for the generating the morphological simulations. The matlab program directs the Delft3D and XBeach simulations and provides the conversion (interpolation) between the models. Matlab can be executed from a local desktop, a Delft3D simulation is send to the Cluster during which matlab waits for the simulation is complete and returns the output. Next, matlab performs the conversion, running the interpolation steps providing the input for the XBeach simulation and sends the XBeach simulation to the Cluster. The disadvantage of this method is; a local desktop has to be stand-by for the complete model cycle with simulations of two numerical models.

![Figure 4.14 Computational techniques for running coupled models e.g. Delft3D-XBeach-Delft3D.](image)

The second method is presented in the second picture of Figure 4.14. This method will perform a model coupling cycle directly on the Cluster, via a prescribed linux script file. The advantage is there is no need for a local desktop to direct the model coupling. The disadvantage is the need for a (floating) linux matlab license, which is expensive. The extra risk of method 2 for a floating license user is that the script can halt at any one of the conversion steps if no matlab license is available.

The third method performs a model coupling cycle via the scripting language Python. The flexibility of such a scripting language is higher than that of standard Linux scripts, it can be made platform independent (hence run on both Windows and Linux), and is easy to learn such that adjustments for the model coupling can easily be made. Python is a scripting language, instead of Python use can be made of any other scripting language like Perl, Tcl, etc. The advantage of Python over other scripting languages is that it has excellent support for numerical operations (B. Jagers, personal communication). Furthermore, there are Python
toolboxes that support many of the features that matlab has (hence it may even be possible to use python scripts rather than fortran code for the conversion steps). The advantage of method 3 over methods 1 and 2, is that it is uses only freely available open source tools. The Python approach has been used at Deltares in various river applications over the last 7 years.

4.5 Conclusions

- The long-term morphological predictions in Delft3D are mainly based on the sediment transport formulations. For the Delfland coast, the sediment transport formulation of Van Rijn 2004 is applied. This formula results into values corresponding with former studies in annual sediment transport volumes in this area (Van de Rest, 2004).

- For accurate morphological predictions, relative small model grids are used within Delft3D and XBeach, respectively 9.4 by 4 and 8.5 by 3.5 kilometers, allowing higher resolutions.

- Considering the interpolation technique between Delft3D and XBeach, the implementation of two exact the same model grids would result in no interpolation errors, with different grids overlap and marginal interpolation errors occur.

- During this thesis, all the simulations have been generated on the cluster within Deltares. Frequently during these simulations some queuing waiting time occurred (due to series coupling), next to several generating problems, therefore research in other generating techniques is recommended.
5 Morphodynamic analysis Delfland coast and sand-engine

During the EIA phase of the sand-engine, morphodynamic predictions were made for 20 years in advance. The focus of this thesis is not a full lifetime prediction of the sand-engine, but the design and assessment of a new integrated model approach for mega-nourishments, applied for the sand-engine. Therefore, morphodynamic predictions of the sand-engine in this thesis are generated for five and ten years in advance, enabling also manageable simulation time of the models.

This chapter elaborates on the Delfland coast, the Delfland coast including the sand-engine, the sand-engine with varying wave climates and siltation processes near the sand-engine. Each paragraph has a uniform structure, commencing with the hydrodynamics, analyzing the sediment transports and resulting morphodynamics and giving the indicators as described in paragraph 3.5. The assessed scenarios of the sand-engine will be used as reference cases in chapter 6 for the impact assessment of storm events via model integration.

5.1 Delfland coast

5.1.1 Hydrodynamics

Before generating and analyzing a morphodynamic simulation of the sand-engine a preliminary assessment is made of the hydrodynamics near the Delfland coast and the sand-engine. This will provide insight in the morphodynamic processes near the sand-engine in the proceeding paragraphs.

Along the Delfland coast without the sand-engine, the tidal currents reach maximum velocities of 0.4m/s during falling tide and 0.5m/s during rising tide, see Figure 5.1. This figure presents a moment during rising tide. In the figure, two observation points are visualized as green dots, from these observation points two velocity profiles are given at 50m and 150m perpendicular from the coastline, these velocities values are absolute. The tidal currents move parallel to the coastline and the velocities decreases when moving closer to the coastline.

Figure 5.1  Tidal characteristics near a uniform Delfland coast, giving the water level elevation and the corresponding velocities at 50 and 150m from the coastline.
5.1.2 Sediment transport

Through hydrodynamic forcing of wind-, wave- and tide induced currents, a net annual sediment transport is induced towards the north, see Figure 5.2. This figure presents annual sediment transport volumes (x 1000 m$^3$) through transects perpendicular and parallel to the Delfland coast. The transects are given in the surfzone from the +3m NAP to the -8m NAP depth contour and in deeper water from -8m NAP to the -12m NAP depth contour. In the surf zone, dominated by wave-induced currents, the highest sediment transport volumes can be distinguished. These simulated sediment transports with Delft3D, correspond with others studies, validation is elaborated in paragraphs 2.4 and 4.2.2.

![Figure 5.2](image)

*Figure 5.2  Annual alongshore sediment transport volumes near a uniform Delfland coast (x 1000 m$^3$).*

5.1.3 Indicators

For Dutch coastal maintenance and flood protection a number of indicators have been specified in the past, regarding amongst others the MKL (Momentane Kust Lijn) volume and position and dune foot position (van der Biezen et al., 1995).

For a uniform Delfland coast the MKL volume and position and the dune foot position are presented in Figures 5.3, 5.4 and 5.5. These indicators, given for the Delfland coast, will provide a comparison tool for the following paragraphs, which analyzes the Delfland coast including the sand-engine and its morphological development.

The MKL volume is described in paragraph 2.4.2, the MKL position is the MKL area per running meter divided with the vertical height of that area, giving a distance with respect to the RSP (RijksStrandPaal) line, which roughly indicates the average low water line (van der Biezen et al., 1995).
The dune foot position is defined as the +3m NAP contour at the seaward side. The majority of the dune foot position is located seaward of the RSP-line, from Kijkduin and further up north the dune foot position is located landward of the RSP-line.

The indicators represent the bathymetry of the uniform Delfland coast, which is derived from design profiles for the dune and beach reinforcement of the ‘Zwakke Schakel Delflandse kust’ (2008-2011). This design bathymetry can slightly deviate from the bathymetry executed by the contractor Van Oord and Boskalis. A good representation of the Delfland bathymetry is important, because a coastline bathymetry has influence on the sediment transports and later on the sand-engine models will be simulated, integrated with the Delfland bathymetry.

Figure 5.3, 5.4 and 5.5 Respectively MKL volume, position and Dune foot position of the Delfland coast (including the reinforcement 2008-2011) without sand-engine, serving as reference case.
5.2 Sand-engine with average hydrodynamics, reference case

The hydrodynamics along a uniform Delfland coast are presented in the preceding paragraph. In this paragraph the hydrodynamics and morphodynamics will be explained near the Delfland coast including the sand-engine, commencing with the initial design bathymetry of the sand-engine.

5.2.1 Hydrodynamics

At a uniform Delfland coast the order of the tidal flood and ebb currents are respectively 0.5m/s and 0.4m/s. Near the sand-engine however, the peninsula induces a local flow contraction of the alongshore currents. Again two velocity profiles are presented from two observation points, located at 50m and 150m from the 0m NAP depth contour, in respectively 1.5m and 3.5m water depth, near the west side of the sand-engine.

These velocity profiles indicate an increase of the tidal currents due to the flow contraction, with respect to a uniform Delfland coast, up to 0.9m/s with rising tide. However, the currents near the west side of the sand-engine can even be higher. If, for example, the tidal flood current coincides with wave-induced currents from the south west, the flow velocities near the west side of the sand-engine can be enhanced and reach values up to 1.1m/s.

Also, in the top view in Figure 5.6 at the northeast side of the sand-engine also an eddy (a horizontal water circulation) is visible. During rising tide this eddy starts developing and has a maximum current velocity of 0.3m/s, also during falling tide an eddy develops at the south side. These eddies are the combined result of the high currents and of a sudden change in a uniform coastline, giving flow separation.
5.2.2 Sediment transport

The sediment transport volumes in Figure 5.7 is the result of the wind-, wave- and tide-induced currents (Figure 5.6). Moreover, Figure 5.7 presents the annual sediment transport volumes, excluding the pores, over transects from +3m NAP to the -8m NAP depth contour and from -8m NAP to the -12m NAP depth contour, following the initial bathymetry contour lines of the sand-engine. The values indicate the total net sediment transport over five years, which contains both bed- and suspended load transport.

Figure 5.7  Average annual sediment transport volumes (x 1000m$^3$) near the sand-engine, in perpendicular transects to the -8m and -12m NAP depth contour, averaged over five years.

Because of a residual northward tidal current (paragraph 2.2.2) and the wave climate, the overall net sediment transport around the sand-engine is directed towards the northeast. At the southwest side of the sand-engine sediments accrete, due to the blockage effect of the surf zone induced by the sand-engine.

The sediment transports further along the coast, at the northeast side of the sand-engine are relative low compared to a uniform Delfland coast, this is because of the lee-side effect and a less pronounced surf zone. The largest sediment transports can be found at the west side of the sand-engine. These large transport volumes near the west side are the result of a continuously present flow contraction of the tidal currents induced by the sand-engine, increasing the tidal currents from 0.5m/s (uniform coastline) up to 0.9m/s.

The distribution of the sand around the tip of the hook is mainly directed towards the adjacent coast. The exact morphological direction development of the tip of the hook is strongly dependent on the wave climate and will be elaborated in paragraph 5.3.
Focus at the hook and lagoon of the sand-engine

In Figure 5.8 an enlarged visualisation of the tip of the hook is presented, which gives a detailed overview of the sediment transport volumes during the first five years. The highest transport values can be found in a relatively small band around the sand-engine, to the -3m NAP depth contour. Especially sand from the west side of the sand-engine is distributed around the tip of the hook moving towards the adjacent coast, creating a very pronounced tidal channel. A tidal channel is a connection between an enclosed area (like the lagoon of the sand-engine) and the surrounding sea. In Appendix F the morphological development of the sand-engine is presented for every year. The tidal channel is created within the first year after construction.

The tidal channel develops with an equilibrium depth of 0m NAP and is therefore dry mainly during the ebb period. The water flow in the tidal channel is for the most part during rising tide, during which the highest flow velocities are reached, see Figure 5.9. During falling tide, water from the lagoon flows back through the tidal channel. The meandering morphological development of this tidal channel can initiate erosion of the adjacent coastline, which also happened with the analogue coastal feature ‘the Bornrif’, paragraphs 2.9 and 6.5.4.

During the morphodynamic simulations some observation points were positioned around the sand-engine, assembling specific datasets like the water level elevation and the flow velocities. In Figure 5.9, the water level and flow velocity are presented in the same graph for an observation point located in the tidal channel. This figure indicates currents in the tidal...
channel if the water level reaches values of 0m NAP and higher, the velocity graph presents absolute values. During rising tide the highest flow velocities are measured, reaching values up to 1.2m/s and 0.4m/s during falling tide. Because of the high flow velocities the tip of the sand-engine will not fully attach to the adjacent coastline, creating a meandering tidal channel. The existence of the tidal channel regarding the impact of storm events will be discussed in paragraph 6.5.6.

Figure 5.9 Tidal signal in the tidal channel near the sand-engine with absolute velocity values. The high velocity peak during rising tide indicates water flows into the lagoon, the smaller velocity peak indicates water outflow during falling tide.

5.2.3 Indicators and morphological development

Due to the sediment transports induced by the currents, the sand-engine and the adjacent coastline is subject to a continuously morphological change. By means of MKL volumes in time (paragraph 2.2.2), bathymetry contour lines and cross-sections an assessment is made of the morphological response of the sand-engine.

In Figure 5.10 and 5.11 the annual MKL volumes are presented during the first five years of the sand-engine. For each year, the same MKL volumes are presented using two different visualizations. The pictures on the left present the MKL volumes in graph form and the pictures on the right in top view of the sand-engine, by means of colored boxes (each box presents 62.500m$^3$ sand).

The black line in the pictures on the left indicates the MKL volumes of the Delfland coastline without the sand-engine. The MKL volumes near Ter Heijde and Kijkduin are about 3500 m$^3$/m' at a uniform Delfland coast. The red line indicates the Delfland coastline including the sand-engine MKL volumes, from the beach dune foot +3m NAP to the lower MKL boundary - 4.4m NAP. The largest MKL volumes can be found in the middle of the sand-engine, at RSP position 109km, also visualized in Figure 5.12. Within five years, the MKL volumes in the middle have decreased at RSP 109km from 9700m$^3$/m' to 8000m$^3$/m'. This is due to the erosion of the west side of the sand-engine. At the south side of the sand-engine a gradually build out develops. The sand-engine acts like a groin, due to the net sediment transport along the Delfland coast to the north, the south side of the sand-engine is subject to accretion. This increase of the MKL volumes near the south side are not due to the
distribution of sand from the sand-engine itself, but due to the accretion of sediments along the Delfland coast. In the Figures F.9-F.11 graphs are presented at three RSP positions, at the south side, in the middle and at the north side of the sand-engine. These graphs provide insight in the rate of accretion or erosion at one specific location at the sand-engine in time.

The graphs and the colored boxes indicate a gradual alongshore distribution of the sand-engine. As well as accretion at the south side, there is erosion of the beach at the north side of the sand-engine. This is not near the tidal channel, but further alongshore, near Kijkduin at RSP 107km. The red boxes indicate a loss in MKL volume with respect to the initial bathymetry of the Delfland coast. Also, in the graphs an erosion pattern is visible, however after 3 years sedimentation takes place due to the alongshore distribution of sand from the sand-engine. In Figure F.10 this trend is presented at RSP 107km. In Figure F.10 an initial decrease of the MKL volume (erosion) is visible and after 3 years the MKL volume increases due to along shore morphodynamic distribution of sand from the sand-engine. The MKL volume is an indicator for flood protection of the hinterland, which is at risk during the first three years near Kijkduin. An additional nourishment at the down drift side of the mega-nourishment can provide a buffer against the erosion process.
Figure 5.10  Morphological annual development of the sand-engine over the first three years, presented with MKL volumes. The boxes in the right plots each represent 62,500 m$^3$ sand.
Morphological annual development of the sand-engine over the fourth and fifth year, presented with MKL volumes. The boxes in the right plots each represent 62,500 m$^3$ sand.

Figure 5.12 presents a top view of the bathymetry development after five years, together with a cross-section across the hook of the sand-engine. The black line represents the initial profile of the sand-engine with a crest height constructed at 3.5m NAP. After five years a lot of sand is eroded, visualized in the cross-section, resulting in an area decrease (top view) above mean sea level. Still a lot of the MKL volume is present. In Appendix F the annual cross-sections of the sand-engine are given, presenting the bathymetry and cross-shore behavior due to the average hydrodynamic conditions.
The annual cross-shore development in Figures F.7, F.8 and 5.12 indicate an increase of the slope at the west side of the sand-engine. This morphodynamic development can have consequences for recreational aspects.

Gravity point assessment

Via gravity point assessment the movement of a mega-nourishment in time along a coastline can be assessed. For the sand-engine the gravity point is calculated, by means of the MKL volumes for every year, given in Table 5.1. The MKL volume is the volume of sand in a coastal cross section per running meter between the -4.4m and +3m NAP bathymetry lines, visualized with the hatched areas in Figure 5.12.

In Figure 5.13 the gravity point is visualized in graph form, with respect to the RSP coordinate system. The first impression is that the sand-engine does not move along the coast. This would be positive, because it would mean an equal distribution of sand towards both the north
and the south. From Table 5.1 however, a slightly gravity point variation is presented, indicating a cumulative southward direction of about 100m in 5 years. The accretion at the southwest side of the sand-engine is therefore larger then the distribution of sand from the sand-engine to the northeast.

In Table 5.1 also the total erosion sedimentation MKL volumes are given. These are absolute values (MKL erosion and sedimentation volumes have been added), this means the values present the total volume that have been moved during a year. Initially there is an increase of the distribution of sand near the sand-engine, however during the years the rate of the morphodynamic process decreases. This is because initially the sand-engine has a pronounced shape, and during the years the shape of the sand-engine is becoming more smooth with its adjacent coastline, resulting in less erosion and sedimentation.

<table>
<thead>
<tr>
<th>Years</th>
<th>Total erosion and sed. [m³]</th>
<th>Gravity point (RSP [km])</th>
<th>Difference (RSP [km])</th>
<th>Direction [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-</td>
<td>108.9896</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>4045</td>
<td>109.0079</td>
<td>-0.01837</td>
<td>18m south</td>
</tr>
<tr>
<td>2</td>
<td>4821</td>
<td>108.9988</td>
<td>0.00916</td>
<td>9m north</td>
</tr>
<tr>
<td>3</td>
<td>4189</td>
<td>109.0443</td>
<td>-0.04559</td>
<td>46m south</td>
</tr>
<tr>
<td>4</td>
<td>3513</td>
<td>109.0480</td>
<td>-0.00361</td>
<td>4m south</td>
</tr>
<tr>
<td>5</td>
<td>3190</td>
<td>109.1085</td>
<td>-0.06059</td>
<td>61m south</td>
</tr>
<tr>
<td>Total</td>
<td>18697</td>
<td>-</td>
<td>-0.11899</td>
<td>119m south</td>
</tr>
</tbody>
</table>

Table 5.1 Gravity point with respect to the MKL volume of the annual morphological sand-engine development.

Figure 5.13 Gravity point with respect to the MKL volume of the initial sand-engine bathymetry and the MKL volume of the bathymetry after five years.
5.3 Sand-engine with different annual wave climates during extreme years

5.3.1 Hydrodynamics

For the long-term predictions of the sand-engine generated with Delft3D an averaged wave climate is used from wave data over the period 1979-2001. During this period, annual variations are present. Especially, the annual wave climate during the years 1993 and 1996 indicates a strong difference with respect to the total average over whole period. Figure 5.14 visualizes the wave climates during those years. The wave climate from 1993 is more south westerly pronounced and the wave climate from 1996 is more northerly pronounced. Both wave climates contain increased wave conditions (Navarro, 2011).

The annual wave climates are used to simulate the morphological development of the sand-engine during the first five years and are compared with the five-year morphological development of the sand-engine simulated with the averaged wave climate. An extreme wave climate which last five years is not realistic, but the comparison will provide insight in the variation of morphodynamic response due to different wave climates.

The simulations with the 1993 and 1996 wave climate have been generated with the same 10 wave conditions as is discussed in paragraph 4.2.5. However, the weight factor is adjusted giving the representative wave climate of 1993 and 1996. The resulting wave climates are obtained from the study carried out by Navarro (2011) and are given in Tables F.1 and F.2. By means of a different weight factor, wave conditions from the southwest or from the north can be enhanced. The numerical input for the wave climates is obtained by the study of Navarro (2011), the morphodynamic simulations and assessment is carried out in this thesis.

5.3.2 Sediment transport

Figure 5.15 provides two plots with the resulting sediment transports and the morphodynamic response of the sand-engine due to the wave climates of 1993 and 1996. By using these annual wave climates, morphodynamic simulations have been generated for five years. Distinguished differences can be noticed at the west side of the sand-engine and from the morphological development of the hook of the sand-engine. During southwest conditions...
large sediment transports are induced at the west side of the sand-engine, causing erosion along the sand-engine. This sand is being distributed towards the north east, creating a wide settling area. Whereas with a north dominated wave climate, the sediment transports at the west side of the sand-engine are much less and the sand that is distributed, is forced more towards the adjacent coast. Consequently, the morphological development is strongly dependent of the prevailing wave climate.

In Figure F.13 three cross-sections are presented, visualizing the cross-shore profiles at the middle of the sand-engine, resulted from the three wave climates. In Figure F.15 the cumulative erosion sedimentation pattern is presented between the bathymetry after the two different wave climates. Despite the large sediment transport along shore at the west side of the sand-engine, the cross-shore profile with a southwest-dominated wave climate is less eroded than the profile with the average wave climate. This can attributed to the fact that the eroded sand with southwest conditions is deposited more alongshore the west side of the sand-engine, instead of directed towards the adjacent coast. Therefore, the distributed sand accumulates along the west side of the sand-engine in northeast direction.
Figure 5.15  Morphological comparison between southwest dominated wave climate (1993) and north dominated wave climate (1996).
5.4 Siltation

The five-year morphodynamic simulations of the sand-engine have been generated with sand characteristics only, non-cohesive material. In this paragraph, an analysis is given for five year morphodynamic simulations including cohesive material like silt. During the morphological development of the sand-engine sheltering areas are formed, such low energy areas can result in siltation layers. These siltation layers can have substantial impact on recreational and nature aspects.

5.4.1 Silt schematization

Silt can be defined as cohesive particles with a diameter between 0.02mm and 0.063mm. For including silt sediments in the morphodynamic simulations with Delft3D, two sources have been specified. The first source is the silt content in the bed layer, near the Delfland coast these silt contents are about 2%. The second source is the suspended silt concentrations in the water column. In the morphodynamic simulations with Delft3D the suspended sediments are numerically initiated via an equilibrium definition at the boundaries of the flow grid, dependent on the concentrations in the bed layer and the shear stress, sediments are brought in suspension, this equilibrium approach is elaborated in the Delft3D-Flow User Manual (2007a). In Appendix B, suspended silt concentrations for winter and summer conditions are provided near the Holland coast. These silt concentrations indicate the range for which the simulations have been generated.

5.4.2 Sediment transport

In Figure 5.16 the total sediment transports are given, consisting of sand as well as silt. In comparison with only sand (the non-cohesive sediment transport in Figure 5.6) the net northward sediment transport including silt is slightly higher. The difference can be found in the lagoon of the sand-engine. Silt concentrations in the water column have the ability to settle in that area, due to the sheltering effect of hook of the sand-engine for waves. Due to the absence of high hydrodynamic wave energy, fine sediments are not stirred up again by the shear stress, induced by orbital motion of the waves near the bed. Moreover, if the tidal channel is formed during the years, fine sediments are brought in during rising tide and are ‘captured’ in the lagoon, this will be explained further in this paragraph.
5.4.3 Indicators

In Figure 5.17 the silt mass is given in kg/m$^2$. The morphodynamic simulation of the sand-engine started with a uniform domain value of 500kg/m$^2$, which corresponds to a silt concentration of 2%. After five years the concentration of silt per square meter has increased in the lagoon area of the sand-engine to 800kg/m$^2$. The increase is 300kg/m$^2$ in five years, which means a layer thickness of $300kg/m^2 / 500kg/m^3$ (density silt) = 0.6m. In the cross-section in Figure F.14 across the lagoon, the bed composition is given, indicating the siltation layer.

One of the hypothesizes described in paragraph 1.5 stated, fine sediments in sheltering areas near mega-nourishments will accumulate and form siltation layers due to low hydrodynamic energy. To verify this hypothesis the matter of suspended silt in the water column is measured during the simulation via an observation point in the tidal channel. Figures 5.18 and 5.19 provide these silt values together with the tidal characteristics, giving insight in the siltation processes near the lagoon of the sand-engine. The two plots indicate the suspended matter and tidal characteristics for southwest as well as northwest orientated wave conditions. If suspended silt flows in and there is marginal outflow then silt stays behind in the lagoon and has time to accumulate, resulting in a siltation layer.
Within a year a tidal channel is formed, creating a pronounced lagoon at the sand-engine. Figure 5.18 and 5.19 indicate the suspended silt matter and the water level and velocity in the tidal channel for southwest and northwest wave conditions. During rising tide, the flow velocity is high and silt matter (green line) flows into the lagoon. During falling tide, when water flows out of the lagoon, the suspended silt matter is marginal. This means that suspended silt, what flows into the lagoon, stays in the lagoon and will accumulate. The same graphs are available for sand in Figures F.16 and F.17.

Despite the conclusion of the development of a siltation layer in the lagoon of the sand-engine, during average wave conditions, the impact of storm events on this siltation layer is not assessed. During large storm events, waves can penetrate the lagoon and could dissolve the siltation layer, especially if a breach is forced at the sand-engine, this topic will be elaborated in the following chapter.

Nature

The combination of silt in the lagoon area and sand at the sand-engine will attract a wide range of environmental species. The biodiversity is an important aspect for the ecology, which is one of the goals of this pilot project the sand-engine. An indicator for the biodiversity can also be the monitoring of the different species of birds, different species indicate the variation in marine and environmental life at the ground. The Dutch coastline contains large areas of dune landscape, however there is a lack of dynamic dune areas (ing. L. Linnartz, ecologist ARK Nature development, personal
communication). The majority of the dunes are planted with marran grass, which is dominant and little biodiversity is present. The roots of the marran grass extend 6m into the dune subsoil and works as the reinforcement of the dunes. The sand-engine is a great opportunity for nature, because it provides possibilities for dynamic dunes; the formation of pioneer dunes, quite areas (e.g. for seals), sheltering areas (siltation) and therefore large values in biodiversity.

Figure 5.18  Suspended silt matter in the tidal channel together with water level elevation and absolute velocity for southwest wave conditions.

Figure 5.19  Suspended silt matter in the tidal channel together with water level elevation and absolute velocity for northwest wave conditions.
5.5 Conclusions

- The net transport of sediments along the Dutch coast is from the south to the north. During the morphological development of the sand-engine, accretion occurs at the south side, because the sand-engine blocks this sediment transport. Consequently, erosion at the north side, near Kijkduin, occurs.

- After some years, this erosion pattern near Kijkduin disappears, due to the distribution of sand from the sand-engine towards Kijkduin.

- Via gravity point assessment the conclusion can be made that there is more accretion at the south side of the sand-engine due to the blocking of the net sediment transport along the Delfland coast, then there is distribution of sand from the sand-engine towards the north.

- Compared with the simulations of the Delfland coast and the reference simulations of the sand-engine, the flow velocity around the west side of the sand-engine is about twice as much as for the Delfland coast without sand-engine.

- Within a year a tidal channel starts to develop, analogue to the Bornrif of Ameland (1995). The Bornrif was a natural hooked shaped accretion development, with features similar to the sand-engine.

- Annual wave climates, dominantly from the southwest and from the north have been generated, resulting into different morphological developments of the tip of the sand-engine towards the adjacent coast. The morphological development of the sand-engine is therefore strongly dependent on the prevailing wave climate.

- The lagoon of the sand-engine provides sheltering against waves from all directions. Fine sediments tend to siltate in the lagoon, forming a siltation layer. However, the impact of storm events on such a siltation layer is not investigated.
6 Morphodynamic analysis of storm events via model integration

The coupling between Delft3D and XBeach provides the means to simulate storm events during long-term morphological predictions of the sand-engine, as is described in paragraph 4.4. To provide insight in storm events, this chapter commences with describing the parameters and preliminary statistics of storm events near the Delfland coast. Furthermore, an analysis and impact assessment of frequent and more severe storm events near the sand-engine at different points in time will be given.

6.1 Characteristics of storm events

6.1.1 Probability of occurrence

Before generating storm events with the Delft3D–XBeach coupling near the sand-engine and evaluating the morphodynamic response, some storm specific characteristics are given, providing insight in the probability of occurrence of storm events and their mutual conditions. For insight in the probability of occurrence of storm events table 6.1 presents statistical information. The expected morphological lifetime of the sand-engine is estimated to be about 20 years, at which time the sand-engine will be fully integrated with its adjacent coastline (Tonnon et al., 2009). Table 6.1 provides the probability of storm events per year, consequently the probability of storm events, during the lifetime of the sand-engine (20 years) can be calculated, see formula 6.1 below.

$$\text{Probability in 20 years} = 1 - (1 - \text{probability per year})^{20} \quad (6.1)$$

<table>
<thead>
<tr>
<th>Repetition Time</th>
<th>Probability/Year</th>
<th>Probability in 20 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1.00</td>
</tr>
<tr>
<td>5</td>
<td>0.2</td>
<td>0.99</td>
</tr>
<tr>
<td>10</td>
<td>0.1</td>
<td>0.88</td>
</tr>
<tr>
<td>20</td>
<td>0.05</td>
<td>0.64</td>
</tr>
<tr>
<td>50</td>
<td>0.02</td>
<td>0.33</td>
</tr>
<tr>
<td>100</td>
<td>0.01</td>
<td>0.18</td>
</tr>
<tr>
<td>1,000</td>
<td>0.001</td>
<td>0.02</td>
</tr>
<tr>
<td>10,000</td>
<td>0.0001</td>
<td>0.002</td>
</tr>
<tr>
<td>100,000</td>
<td>0.00001</td>
<td>0.0002</td>
</tr>
</tbody>
</table>

Table 6.1 Probability of occurrence of storm events per year and for twenty years.

The table shows that a storm event with a repetition time of every 20 years has a probability of occurrence of 64% in 20 years time. Even a storm event which has a frequency of exceedance of 1 in 100 years has a probability of occurrence of 18% in 20 years time. Therefore, these severe storm events will also be analyzed to assess their impact on the sand-engine. Later on, extreme storm events (1/1000 and higher) will be used to forced unique scenarios that have been unaccounted for.

In chapter 5, the morphological development of the sand-engine is given for five years in advance, simulated with average hydrodynamics. This five year morphological development will serve as a reference case. In this chapter, an assessment is provided for multiple and
varying storm events at several points in the five year morphological development of the sand-engine and the results will be compared with the reference case. Based on expert judgment, several scenarios with storm events are simulated, a pre-defined statistical assessment (like, which storm event at which point in time, due to e.g. a Monte Carlo assessment) is not provided.

6.1.2 Conditions storm events

While Table 6.1 provides the probability of occurrence of storm events, Table 6.2 presents the hydrodynamic characteristics of those storm events. The water level elevation (tide plus surge effect, paragraph 4.3), the significant wave height and wave period are given. These hydrodynamic conditions are derived and extrapolated via survey datasets, the exact derivation is elaborated in the Guideline on Dune Erosion (in Dutch: ‘Leidraad Duinafslag’ by the Technical Advisory committee for Water defences, TAW, 1984).

<table>
<thead>
<tr>
<th>frequency [-]</th>
<th>h [m]</th>
<th>Hs [m]</th>
<th>Tp [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/1</td>
<td>2.2</td>
<td>4.57</td>
<td>9.09</td>
</tr>
<tr>
<td>1/5</td>
<td>2.6</td>
<td>5.2</td>
<td>9.76</td>
</tr>
<tr>
<td>1/10</td>
<td>2.78</td>
<td>5.46</td>
<td>10.03</td>
</tr>
<tr>
<td>1/20</td>
<td>2.96</td>
<td>5.7</td>
<td>10.29</td>
</tr>
<tr>
<td>1/100</td>
<td>3.4</td>
<td>6.2</td>
<td>10.86</td>
</tr>
<tr>
<td>1/1.000</td>
<td>4.08</td>
<td>6.84</td>
<td>11.57</td>
</tr>
<tr>
<td>1/10.000</td>
<td>4.81</td>
<td>7.39</td>
<td>12.2</td>
</tr>
<tr>
<td>1/100.000</td>
<td>5.58</td>
<td>7.9</td>
<td>12.78</td>
</tr>
</tbody>
</table>

Table 6.2 Hydrodynamic storm conditions with respect to probability of occurrence.

Considering the average hydrodynamics, which are used for the long-term morphodynamic predictions with Delft3D, the tidal signal has a maximum water elevation of 1.5m and maximum wave characteristics of Hs=2.97 with a period of Tp=7s. The storm characteristics in Table 6.2 are substantially higher then the average hydrodynamics. In the upcoming paragraphs, the impact of these storm events near the sand-engine will be assessed by coupling XBeach and the long-term morphodynamic simulations with Delft3D, see Figure 4.17 paragraph 4.4.

Figure 6.1 Water level at +2.6m NAP during a storm event at the Delfland coast, Oktober 2007.
6.2 Impact assessment of frequent storm events at the initial bathymetry of the sand-engine

6.2.1 Hydrodynamics

To provide insight in the impact of storm events, first, the hydrodynamics of two different storm events are analyzed. A comparison is given between a 1/20 and 1/100 year storm event from two different directions (NNW and WSW), presented in Figure 6.2. Near the Delfland coast, storm events are frequently from southwestern or western direction, the heavier storm events are from northern direction. Apart from the directional angle, the numerical modeling of the storm events from either NNW or WSW direction are given the same hydrodynamic boundary conditions.

Figure 6.2  Comparison hydrodynamic characteristics of four different storm events.

Figure 6.2 indicates the depth averaged velocity and direction of the currents during the four storm events from two directions. During storm events from NNW direction, the incident waves drive a southwesterly directed alongshore current. Near the northeast face of the sand-engine this alongshore current is blocked, resulting in a water level set-up. The water level set-up drives the offshore directed current at the north face. The maximum current velocities are measured at the southwestern face of the sand-engine, respectively 2.0 and 2.2 m/s for a 1/20 and 1/100 year NNW storm event. These maximum velocities occur due to the
wave induced currents in combination with the varying shoreline orientation of the sand-engine.

During storm events from WSW direction, the incident waves induce a current at the north side of the sand-engine. The maximum velocities of these currents are about 1.2 m/s and the currents follow a path around the tip of the sand-engine, towards the adjacent coastline, transporting the sediments.

In appendix G in Figure G.1 specific wave characteristics, like the mean wave height and long bound wave height, are given for the storm events.

6.2.2 Morphodynamic response

During the NNW storm simulations at the initial sand-engine bathymetry, substantial bed level changes are predicted. In Figure 6.3 the morphodynamic response is presented for both a 1/20 year storm event from WSW and NNW direction, the post storm bathymetry and cumulative erosion sedimentation near the sand-engine is given.

Figure 6.3  Morphodynamic response of a 1/20 year storm event from WSW and NNW direction and cumulative erosion sedimentation plots.
The largest erosion sedimentation values are present near the northern and northeastern face of the sand-engine, and near the western face of the sand-engine during NNW orientated storm events. These erosion sedimentation areas are the result of the strong hydrodynamic currents explained in the previous paragraph.

During WSW orientated storm events, about 2m sedimentation at the northeastern face occurs, these sediments originate from the western face of the sand-engine. During NNW orientated storm events, about 3m sedimentation at the northeastern face occurs, these sediments originate from the erosion area at the northern face. Also, during NNW orientated storm events, erosion occurs at the western face of the sand-engine and sedimentates at the southwestern face. In both cases, during storm events, a spit develops from the tip of the sand-engine towards the adjacent coastline.

In Figure 6.4 the morphological results are presented for the 1/100 year storm events. The same morphological changes are visible with respect to the 1/20 year storm events, only the morphological values are higher. During a 1/100 year NNW orientated storm event, the sedimentation values are in the order of 4m near the north-eastern face of the sand-engine. Furthermore, during both NNW orientated storm events, sedimentation (order of 1m) occurs in the lagoon of the sand-engine. This is the result of overwash processes at the tip.

Figure 6.4 Morphodynamic response of a 1/100 year storm event from SW and NNW direction and cumulative erosion sedimentation plots.
6.2.3 Indicators

By means of the MKL volume, MKL position, Dune foot position and gravity point analysis an impact assessment is given for the two storm events from two directions. In Figure 6.5 the MKL volumes are given for the initial sand-engine bathymetry and the MKL volumes are given of the sand-engine after a storm event. In Table 6.3 also a gravity point assessment and the point specific MKL volumes are given at RSP position 109, which concerns the transect across the middle of the sand-engine.

Figure 6.5 indicates a substantial change in the MKL volume at the sand-engine during NNW orientated storm events. At the middle of the sand-engine at RSP position 109, the MKL volume decreases most. In Table 6.3 the exact MKL volumes at this position are presented.

Table 6.3 also indicates the total absolute amount of the distribution (erosion and sedimentation) of the MKL volume after storm events near the sand-engine. These values can be compared with the annual MKL volume distribution given in Table 5.1. Compared to the first year of the morphological development of the sand-engine, a NNW orientated storm event has roughly the same impact as a half year sediment transports due to average hydrodynamics.
### Table 6.3: Morphodynamic characteristics of a 1/20 and 1/100 year storm event from WSW and NNW direction.

<table>
<thead>
<tr>
<th>Storm event</th>
<th>Total erosion and sed. [m^3]</th>
<th>RSP 109 km [m^3/m']</th>
<th>Gravity point (RSP [km])</th>
<th>Difference (RSP [km])</th>
<th>Direction [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>-</td>
<td>9692</td>
<td>108,9896</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1in20 NNW</td>
<td>2395</td>
<td>9382</td>
<td>109,0222</td>
<td>-0,03264</td>
<td>33m south</td>
</tr>
<tr>
<td>1in20 SW</td>
<td>630</td>
<td>9652</td>
<td>108,9945</td>
<td>-0,00497</td>
<td>5m south</td>
</tr>
<tr>
<td>1in100 NNW</td>
<td>2817</td>
<td>9321</td>
<td>109,0270</td>
<td>-0,03748</td>
<td>37m south</td>
</tr>
<tr>
<td>1in100 SW</td>
<td>925</td>
<td>9656</td>
<td>108,9913</td>
<td>-0,00173</td>
<td>2m south</td>
</tr>
</tbody>
</table>

In appendix G, Figure G.2 and G.3 presents the dune foot position near the sand-engine pre- and post- an initial storm event. The dune foot position is defined as the +3m NAP contour line. Because the sand-engine has an average height of 3m NAP with an extra (dune)ridge at 3.5m NAP, the dune foot position in Figure G.2 follows the offshore directed sand-engine contour line.

Only after a 1/100 year NNW orientated storm event the dune foot position is substantially affected. This is because, during a 1/100 year storm event the water level reaches +3.4m NAP and the tip of the sand-engine endurance hydrodynamic overwash processes. These overwash processes reach higher areas at the sand-engine and distribute the sand, altering the dune foot position.
6.3 Impact assessment of storm events during the morphological development of the sand-engine

6.3.1 Series coupling

In the previous paragraph an impact assessment has been given for storm events affecting the initial bathymetry of the sand-engine. In this paragraph an impact assessment will be given for storm events during the morphological development of the sand-engine. The first analysis will be of a storm event half way the reference case of the sand-engine, simulated in XBeach at 2.5 year, see Figure 6.6. This series coupling will be compared with the reference case, which is simulated without storm events and is simulated with average hydrodynamics in Delft3D. The reference case is elaborated in paragraph 5.2.

Figure 6.6  Series coupling of Delft3D and XBeach, enabling the simulation of a storm event at 2.5 year, half way the reference case.

6.3.2 Morphodynamic response

By means of the series coupling a storm event near the sand-engine is simulated with XBeach, after 2.5 years of average morphodynamic simulation with Delft3D. In Figure 6.7 and Figure G.4 the morphodynamic response is presented for two storm events, respectively a 1/20 year NNW and a 1/100 year NNW orientated storm event. In the figures also the cumulative erosion sedimentation plots are given. During the average hydrodynamics the tip of the sand-engine will develop, in 2.5 years, towards the adjacent coastline. Especially this tip, near of the sand-engine is affected during a storm event. There is substantial erosion at the northern face of the sand-engine. Furthermore, there are overwash processes at the tip of the sand-engine, depositing sediment in the lagoon. Besides the morphodynamic changes at the tip of the sand-engine, the substantial erosion at the western face is also visible in the figures.
6.3.3 Indicators

The morphological development after a storm event at 2.5 years is presumed with average hydrodynamics in Delt3D for five years and a comparison assessment is made with the reference case of the sand-engine.

In Figure 6.8 several cross-sections are presented across the middle of the sand-engine. The purpose of this figure is the comparison of the sand-engine after several scenarios with storm events and scenarios without storm events. First two top view plots are given with the morphological development of the sand-engine, respectively at 2.5 and 5 years, after a 1/100 year storm event. Next, two plots are given with cross-sections due to average hydrodynamics only and cross-sections at the same moment in time only then after a storm event.

The cross-sections indicate the erosion profile at the western face of the sand-engine after a storm event. Moreover, the difference between a 1/20 year and a 1/100 storm event is the overwash sedimentation in the lagoon of the sand-engine, which can be accounted for the high surge levels during a 1/100 year storm event.

Figure 6.7  Morphodynamic response of the sand-engine, given after a 1/20 year storm event, at 2.5 years, simulated by means of series coupling with Delt3D and XBeach.
The most interesting morphodynamic response of the sand-engine due to storm events can been seen in the cross-sections taken after five years. As the simulation of the sand-engine is presumed with average hydrodynamics, after a storm event at 2.5 years, the impact of that storm event is still visible after five years. This means storm events will accelerate the morphological process of the sand-engine in the long-term morphological development along the coastline.

In Figures G.5 and G.6 the MKL volumes, MKL positions and the dune foot position after the storm events, during the morphological development of the sand-engine are presented, and are compared with the reference case of the sand-engine.
Figure 6.8  Cross-sections at the middle of the sand-engine for comparison assessment of a 1/20 year and 1/100 year storm event at the sand-engine after 2.5 years and 5 years.
6.4 Impact assessment of annual storm events during the morphological development of the sand-engine

6.4.1 Series coupling

In the previous paragraph a morphodynamic impact assessment and comparison has been given of a 1/20 and 1/100 year storm event, half way the five year simulation of the reference case of the sand-engine. In this paragraph an impact assessment and comparison with the reference case will be given of an annual returning storm event, see Figure 6.9. Also in Figure 6.9, a comparison is presented of two equal simulations in time, but with storm events respectively in the beginning and at the end of the five year simulation of the sand-engine.

![Figure 6.9 Series coupling with Delft3D and XBeach, presenting comparison simulations with annual returning storm events and comparison simulations with storm events respectively in the beginning and at the end, w.r.t. the reference case of the sand-engine.](image)

6.4.2 Morphodynamic response

Instead of generating a 1/20 or a 1/100 year storm event, a 1/1 year northerly orientated storm event is generated on annual basis for a more realistic approach. Next to that, an impact assessment is made in comparison with the larger storm events during the morphological development of the sand-engine. The hydrodynamics, sediment transports and cumulative erosion sedimentation patterns of southwesterly and northwesterly orientated storm events are explained in the previous paragraphs.

In Figure 6.10 the MKL volumes are given across three transects at the sand-engine, respectively at RSP 112, 109 and 107km. Across transect RSP 109km the impact of the storm events is clearly visible. Three lines per plot are given, representing the MKL volumes of the reference case, the simulation from the previous paragraph and the five year simulation with the annual 1/1 year storm events.
At the western face of the sand-engine (plot RSP 109km) continuous erosion is present, indicated with the purple line representing the reference case. The graph with the annual 1/1 year storm events (blue) indicates erosion with every storm event. However, with every following storm event the erosion volume at this transect gets less, this is because the sand-engine is becoming more smooth during its development, which induces a velocity decrease of the flow contraction currents. Compared with the single 1/100 year storm event at 2.5 years, the annual 1/1 year storm events result into more erosion looking at the point in the graph after 5 years.

Also at the down drift side of the sand-engine, near Kijkduin RSP 107 km, the impact of storm events are clearly visible, accelerating the distribution process towards the adjacent coast from the sand-engine. At the up drift side, near Ter Heijde RSP 122km, the impact of storm events are less pronounceable, which corresponds with the cumulative erosion sedimentation plots from paragraph 6.3.2. Storm events have more impact at the spit and at the west side of the sand-engine, subject to flow contraction, then at the up drift side.
Figure 6.10 Development of the MKL volumes near three transect at the sand-engine, presenting the impact of storm events with respect to the reference case.
In Table 6.4 a number of morphological characteristics are given, providing insight in the mutual results after 5 years. Especially the gravity point assessment is remarkable. With four annual 1/1 year storm events in five years, the gravity point of the sand-engine is shifted about 190m southward in comparison to the 120m during the reference case.

<table>
<thead>
<tr>
<th>After 5 yrs</th>
<th>Total erosion and sed. in MKL zone [m3]</th>
<th>RSP 109km [m3/m']</th>
<th>Gravity point (RSP [km])</th>
<th>Difference (RSP [km])</th>
<th>Direction [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>-</td>
<td>9692</td>
<td>108,9896</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Reference</td>
<td>18697</td>
<td>8027</td>
<td>109,1085</td>
<td>-0,1189</td>
<td>119m south</td>
</tr>
<tr>
<td>1/100</td>
<td>19655</td>
<td>7843</td>
<td>109,1283</td>
<td>-0,1387</td>
<td>139m south</td>
</tr>
<tr>
<td>1/1 annual</td>
<td>20506</td>
<td>7704</td>
<td>109,1791</td>
<td>-0,1895</td>
<td>190m south</td>
</tr>
</tbody>
</table>

Table 6.4 Morphodynamic characteristics of a 1/1 and 1/100 year storm event from NNW direction.

6.4.3 Recovery after storm events

In Figure 6.10 at RSP 109km the green line presents the MKL volume for five years with a 1/100 year storm event at 2.5 years. After the storm event, the graph of the MKL volume indicates a decrease in the rate of change with respect to the reference case, moving towards the line of the reference case. This could mean a relative recovery, with respect to the reference case, can take place at the longer term. To investigate this recovery feature a comparison is made between a five year morphological development after an initial storm event and the reference case.

Figure 6.11 presents the MKL volume at the middle of the sand-engine, indicating the erosion pattern at the western face of the sand-engine. After an initial storm event, the sand-engine partially recovers relative to the reference case. This phenomenon brings up questions about the influence of storm events on longer time scales.

![Figure 6.11](image-url)
6.5 Breach or closure

During the thesis process, the question arose if the sand-engine is sensitive for breaching and/or (complete) closure during the morphological development, due to the average hydrodynamics or in combination with storm events. Breaching and closure can affect the major prescribed objectives of this project the sand-engine. For example breaching of the sand-engine can result in a separate island, limiting space for recreation or result in quite areas for nature (e.g. birds and seals).

6.5.1 Numerical forcing

In the long-term predictions from the EIA, in the reference case for five years and in the numerical model integrated simulations so far, including storm events, no breaching or complete closure of the sand-engine occurs. Therefore, several scenarios are simulated to force a breach or closure and investigate what triggers a breach or a closure.

Because of the robustness of the bathymetry of the sand-engine in the initial phase, a breach or closure is forced at the sand-engine bathymetry after five years. At this stage, the sand-engine has eroded at the western face and a spit has developed towards the adjacent coast making the sand-engine more sensitive for breaching or closure.

6.5.2 Scenarios for breaching

In the previous paragraphs 1/1, 1/20 and 1/100 year storm events at several points in time have already been simulated and no breach occurred. However, a 1/100 storm event after five years of morphological development is not yet investigated. Forcing a breach provides insight into unique scenarios that could affect the management phase of the sand-engine. The expectations during a 1/100 year NNW orientated storm event, is a breach at the tip of the sand-engine, due to the incident waves, the high surge level and therefore the overwash processes at this location. Figure 6.12 presents a top view after such a storm event. No breach is visible, however, there are initial features visible for breaching. Therefore, a 1/1000 year storm event is generated at the same point in time, instead of the 1/100 year storm event.

Figure 6.12 Sand-engine bathymetry after a 1/100 year NNW storm event at five years.
During a 1/1000 year NNW orientated storm event a breach occurs at the tip of the sand-engine. Moreover, due to the high water level almost the whole sand-engine is submerged, resulting into breaching of even the dune lake. In order to come up with a more subtle approach to force a breach, a simulation is generated of two 1/100 year NNW orientated storm events, the second storm event immediately follows the first one from Figure 6.12. In Figure 6.14 the result is given after a second 1/100 year storm event. This time, despite the relative lower water level (+3.4m NAP), the tip of the sand-engine gets breached, due to second storm impact. This breaching can be attributed to the NNW incident waves in combination with the high water level. Also, the conclusion can be made that due to two storm events or if a storm holds long enough, the storm period is long, a breach will occur with respect to no breach after only one 1/100 year storm event.
To investigate if the sand-engine gets even more sensitive to breaching a morphodynamic simulation with average hydrodynamics is generated for 10 years after which again a 1/100 year storm event is generated. In this scenario the sand-engine immediately breaches, resulting into a big breakthrough near the west side of the sand-engine, see Figure 6.15.

Figure 6.15 Breach at the sand-engine due to a 1/100 year storm event, after 10 years.
6.5.3 Physical process

For insight into the breaching process, two scenarios have been simulated. These scenarios have to provide insight if breaching is triggered by a high water elevation or if breaching is triggered due to the incident wave impact.

In Figure 6.16 the results are presented for the morphodynamic response due to a 1/1000 year storm event, with respectively the water level and the wave height from a 1/100 year storm event.

![Figure 6.16](image)

**Figure 6.16** Two sand-engine bathymetry plots (at five years), each after a 1/1000 year NNW storm event, one storm event with the water level and the other with the wave height from a 1/100 year storm event.

In the left plot no breach occurs during a storm event with a relative low water level (max +3.4m NAP), but with a wave height corresponding to a 1/1000 year storm event. In the right plot a breach does occur, which can be attributed to the water level corresponding to the 1/1000 year storm event. This scenario corresponds to the impact levels 3 and 4 from Sallenger (2000), respectively the overwash regime and the inundation regime, where the storm surge is sufficient to submerge the ‘island’ and breaching occurs.

In Figure 6.17 the occurrence of the breach after 10 years is visualized. Four plots with the sand-engine bathymetry are presented together with the points in time during the storm event at which these plots are taken. In the second bathymetry picture the breach has occurred and is rapidly getting bigger. The breach process starts at the lagoon side of the sand-engine working its way out to due to the overwash processes. This breach process corresponds to the study of Visser (1998) towards breach growth of sand-dikes.

In Figure G.8 the cross-section across the middle of the sand-engine is given for 5 and 10 years. This figure visualizes that in the cross-shore profile the sand-engine has eroded substantially at the western face in 10 years time. Therefore, the sand-engine gets more sensitive for breaching along the long-term morphological development.
6.5.4 Breach analogue with the Bornrif near Ameland

Near Ameland a natural analogue scenario to the sand-engine developed, showing the same hooked shape spit in 1995. During the years the spit developed towards the adjacent coastline, also creating a tidal channel. However, the spit was breached in 1999, creating a new connection with the sea. The simulations of the sand-engine indicate similarities with the Bornrif scenario. Despite the similarities with the Bornrif scenario, the sand-engine indicate quite some resilience against breaching.
To assess the order of comparison the tidal prism is calculated for both initial scenarios (for the Bornrif, the situation in 1995).

Tidal prism is given by $P = H \times A$, where $H$ is the tidal range and $A$ is the average surface.

$P_{\text{sand-engine}} = 2m \times (600 \times 300m) = 360.000m^3$

$P_{\text{Bornrif}} = 2m \times (1500 \times 500m) = 1.500.000m^3$

**Figure 6.18** Morphological development of the Bornrif scenario near Ameland. This natural morphological development can be an analogue study for the development of the sand-engine. In 1999 the Bornrif was breached and new equilibrium had to develop.
6.5.5 Recovery after a breach

In Figure 6.19 the sand-engine bathymetry is presented just after a 1/1000 year NNW storm event, at which a breach at the tip of the sand-engine occurred, also a plot is provided with the bathymetry one year after the breach occurrence. Due to the average hydrodynamics, sedimentation takes place and the breach recovers. The simulations so far do not result in the development of separate islands after breaching.

![Figure 6.19 Sand-engine bathymetry (5 years) just after a 1/1000 year NNW storm event and one year after the storm event.](image)

In Figure 6.20, a breach again is presented, this time with a sand-engine bathymetry after 10 years. Like in Figure 6.19, after the occurrence of the breach one year of average hydrodynamics are presumed to investigate what will happen after breaching. Again the breach sedimentates, and no separate island is formed.
6.5.6 Closure of the lagoon

During the morphological development of the sand-engine in the reference scenario, a spit immediately develops towards the adjacent coastline, creating a lagoon within the sand-engine. During the years, this spit will not completely attach to the adjacent coastline and a tidal channel is formed, which is dry during ebb and submerged during flood. A closure is defined as; if the spit will completely attach to the adjacent coastline, resulting in a closure of the tidal channel at which no water flows through even at highest flood level.

During the numerical simulations so far, no closure is occurred. During the severe annual wave climates from respectively northern and southwestern direction elaborated in paragraph 5.3, there is a pronounced spit development towards the adjacent coast with a northern dominated wave climate. The wave induced currents drive the sediment transport directly around the tip of the sand-engine towards the coast. Next to that, the southwesterly directed wave induced alongshore current due to waves from the north, follow the Delfland coastline. At the northern face of the sand-engine this alongshore current is blocked. The southwesterly
alongshore current induces sediment transport to the northern face of the sand-engine, which is presented in Figure 5.15 with hydrodynamic conditions from 1996.

**Scenarios for closure**

However, during the northerly dominated wave climate from 1996 also no closure occurs. Therefore, the initial approach for the numerical forcing of a closure of the lagoon, is a five year development of the sand-engine at which point northerly orientated storm events are generated. These northerly orientated storm events are meant to transport the sediments to the northern face of the sand-engine, in order for complete closure of the lagoon. The erosion sedimentation patterns for NNW orientated storm events are already given in Figure 6.7, for northerly orientated storm events the expectation is more sedimentation near the tidal channel.

In Figure 6.21, the results are given for this scenario. However, instead of a closure, again a breach is formed. In Figure 6.22, the cumulative erosion sedimentation patterns are given pre- and post a storm event. The analysis of this breaching, instead of a closure, results in the expectation that the high surge level keeps the tidal channel open and also triggers the breach. Therefore, a new scenario is generated at which the same 1/100 northerly orientated storm event is simulated, but this time with a water level corresponding to that of a 1/1 year storm event.

![Sand-engine bathymetry (5 years) before and after a 1/100 year northern storm event.](image-url)
In Figure 6.23 and 6.24, the result is given for the scenario with a 1/100 year storm event, but with a relatively low water level elevation from a 1/1 year storm event. This time there is indeed no breach, the water level is low, but still no closure of the lagoon is initiated. The conclusion for numerical simulation of the sand-engine so far is, the sand-engine is very resilient for closure. However, the absence of aeolian sediment transports in the simulations could be the key process. Aeolian sediment transports from the southwest can result in sedimentation in the lagoon and near the tidal channel, providing a combined input for the closure of the lagoon.
6.6 Conclusions

- Compared to the reference scenario, single storm events (from 1/20 to 1/100 year) have the same morphodynamic impact as 6 to 8 months long-term predictions, regarding the absolute erosion sedimentation volume.

- Storm events result in acceleration of the morphodynamic process of the sand-engine.

- Northerly orientated storm events have more morphodynamic impact than southwesterly orientated storm events.

- Recovery processes are present after storm events relative to the reference scenario. A full recovery after a single storm event, relative to the reference scenario, takes about 5 to 10 years.

- After predicting five-year morphological development, the scenario with a mild returning annual storm event (1/1 year), has more impact than a single severe (1/100 year) storm event half way the five-year prediction.

- During the long-term predictions of the sand-engine including storm events, the pronounced hook shape of the sand-engine remains intact. Even during an extreme storm event (1/1000 year) the shape of the sand-engine remains stable. However, the dune lake gets breached due to the high surge levels.

- In the initial phase of the sand-engine no breach or closure will occur, based on the executed numerical simulations. During the five years morphological development of the sand-engine, a spit develops towards the adjacent coast. At the connection between the spit and the hook of the sand-engine a breach occurs during severe storm events (1/100 year), due to the high surge levels.
- In all the five-year scenarios of the sand-engine (including storm events from several directions) no complete closure of the lagoon occurs. Instead, within a year a tidal channel is formed, which remains in equilibrium.

- The sand-engine is resilient against breaching or complete closure of the lagoon, especially in the initial phase of the sand-engine.

- During the scenarios at which storm events do result into a breach at the sand-engine, morphodynamic predictions with average hydrodynamics were presumed after the breach occurrence. During these average hydrodynamics conditions, within a year, the breach is sedimentated again, returning to its old equilibrium, with the tidal channel. This means there are recovery processes after breaching with respect to the reference scenario and no substantial impact on the major goals of the sand-engine is induced.
7 Conclusions and Recommendations

This thesis, based on the pilot project the sand-engine, concerns a broad range of stakeholders. The conclusions and recommendations given in this chapter are applicable to all concerning stakeholders. However, separate specific conclusions and recommendations are given in the paragraphs for two major groups; researchers and policymakers. This group specific identification of the conclusions and recommendations increases the applicability.

The main objective of this thesis is, "to develop an integrated model approach for the design and management of mega-nourishments", which can be explained as follows. In the near future, other mega-nourishments like the sand-engine may be constructed within a new coastal maintenance policy. During the design phase of the sand-engine several physical processes were left out. During the design phase of future mega-nourishments these physical processes can be included using an integrated model approach. To achieve the main objective, an idealized model approach is made, which is presented in chapter 3. This idealized model approach enables the integration of physical processes concerning long-term predictions of mega-nourishments, using multiple numerical models. Chapter 3 also elaborates on additional opportunities of integrating multiple physical processes for the design and management phase, provided by model integration.

From the idealized model approach one integration is made applicable during this thesis, the integration of storm events with long-term morphological predictions of mega-nourishments, due to the coupling of two numerical models, Delft3D and XBeach.

The conclusions and recommendations in this chapter are based on long-term (five-year) morphodynamic predictions of the sand-engine with a bathymetry from the design phase. The conclusions and recommendations originating from these predictions can be used for the present management phase of the sand-engine, but take into account the schematizations of the hydrodynamic boundary conditions and the difference between the sand-engine design bathymetry and the sand-engine constructed bathymetry.

The difference between the sand-engine design bathymetry (15Mm³) and the sand-engine constructed bathymetry (18Mm³) is an additional nourishment of about 3Mm³ along the west side of the sand-engine, increasing the slope of the sand-engine from 1:40 to 1:100. In addition, the additional nourishments up- and down drift of the sand-engine are not included into this thesis long-term predictions. The shape however, has not changed, the robustness of the design of the sand-engine was already high and the source of sand from the west side was already infinite to be distributed towards the adjacent coast.

7.1 Conclusions

In paragraph 1.5 a number of hypothesis are given, concerning the morphodynamics of mega-nourishments based on the pilot project the sand-engine. By means of the objectives, which are achieved and treated in the previous chapters, the hypothesis are answered for both researchers and policy makers. In paragraph 7.1.2, an executive summary of the applicable conclusions is presented for policy makers.

1. Storm events will substantial increase the distribution of the sand from the sand-engine to areas north and south of the sand-engine and will have impact on long-term morphodynamics. (The local community in the surrounding area believes one or only
a few storm events will be enough to distribute the majority of the sand and so erasing the pronounced shape of the sand-engine).

Due to the coupling of Delft3D and XBeach several scenarios regarding five year morphodynamic simulations of the sand-engine including storm events are generated. These scenarios resulted into the following conclusions:

- Compared to the reference scenario, single storm events ranging between 1/20 to 1/100 year, have the same morphodynamic impact as 6 to 8 months long-term predictions, regarding the absolute erosion sedimentation volume.
- Storm events result in acceleration of the morphodynamic process of the sand-engine, however, also recovery processes are present after storm events relative to the reference scenario.
- After predicting five-year morphological development, the scenario with mild returning annual storm events (1/1 year), had more impact than a single severe (1/100 year) storm event half way the five-year prediction. This can be attributed to the substantial cumulative impact of the consecutive storm events.
- During the long-term predictions of the sand-engine including storm events, the pronounced hook shape of the sand-engine remains intact. Even during an extreme storm event (1/1000 year) the shape of the sand-engine remains stable. However, the dune lake may get breached due to the high surge levels.

2. The first three to four years erosion to the down drift coast will occur near Kijkduin, because the sand-engine blocks the net alongshore sediment transport towards the north. Storm events will be advantageous in decreasing the initial erosion period near Kijkduin, sand will be distributed faster in down drift direction.

- Due to storm events, the morphodynamic process of the sand-engine is accelerated. Therefore, the spit development of the sand-engine is distributed faster towards the adjacent coast. This sand distribution towards the northeast decreases the erosion period near the beach of Kijkduin.

3. Severe storm events will result in a closure of the lagoon or a breach of the hooked-shaped sand-engine. A breach or closure will presumably occur after a period of years, when erosion processes at the western face have decreased the buffer of the sand-engine.

- Based on numerical simulations, it is unlikely that with the initial geometry of the sand-engine a breach or closure will occur. During the five years morphological development with averaged meteorological conditions at the sand-engine, a spit develops towards the adjacent coast. At the connection between the spit and the hook of the sand-engine a breach may occur during severe storm events (1/100 year), due to the high surge levels and overwash processes.
- In all the five-year scenarios of the sand-engine (including storm events from several directions) no complete closure of the lagoon was computed. Instead, within a year a tidal channel is formed, which remains in equilibrium.
- The sand-engine is resilient against breaching or complete closure of the lagoon, especially in the initial phase of the sand-engine.
4. **Scenarios, in which a breach or a closure occurs, will have substantial impact on nature, recreation and long-term flood protection.**

- During the scenarios at which storm events do result into a breach at the sand-engine, morphodynamic predictions with average hydrodynamics were presumed after the breach occurrence. During these average hydrodynamics conditions, within a year, the breach is filled up again, returning to its old equilibrium, with the tidal channel. This means there are recovery processes after breaching with respect to the reference scenario and no substantial impact on the major goals of the sand-engine is induced.

5. **Sheltering areas near mega-nourishments provides shelter for average hydrodynamics, for wave climates from southwest as well as northwest direction. Therefore, fines suspended in the water column, like mud and silt will settle in these low energetic areas. The sedimentation of fines will provide opportunities for nature, but will be a concern for recreation.**

- During simulations including silt, a siltation layer develops in the lagoon of the sand-engine. Due to the absence of wave induced shear stresses near the bed layer silt can settle. In the lagoon a siltation rate of 10 cm/year is computed. The siltation layer will attract different species, increasing the biodiversity near the sand-engine area.

- During wave conditions from either southwest or northwest the sand-engine provides sheltering, a siltation layer develops during all wave directions. However, the response of the siltation layer due to the impact of storm events is not investigated.

7.1.1 Policy makers

**Design cycle**

- An idealized model approach is presented, which can lead to improved long-term predictions of mega-nourishments for the design or management phase of future mega-nourishments. Due to the integration of multiple models and tools, various physical processes can be integrated into long-term morphodynamic predictions.

**Reference scenario**

- A mega-nourishment like the sand-engine results into coastline accretion of about 3 kilometers towards both the south and the north within 10 years. Therefore, a mega-nourishment is not nourishing the whole Dutch coastline.

- The net transport of sediments along the Dutch coast is from the south to the north. During the morphological development of the sand-engine, accretion occurs at the south side, because the sand-engine blocks this net sediment transport. Consequently, erosion occurs at the north side, near Kijkduin.

- After some years, this erosion pattern near Kijkduin disappears, due to the distribution of sand from the sand-engine towards Kijkduin.
- Within a year a meandering tidal channel starts to develop, analogue to the Bornrif of Ameland (1995).

- During the long-term predictions with severe wave climates from respectively southwestern and northern direction, the morphological development of the sand-engine differs substantially. The development of the sand-engine towards the adjacent coast and the development of the direction of the spit is strongly dependent on the prevailing wave climate.

**Long-term morphodynamic predictions including storm events**

- By means of model coupling it is nowadays possible to include storm events in long-term predictions of mega-nourishments.

- Storm events substantially accelerate the morphological development of mega-nourishments.

- Compared to the reference scenario, storm events have the same morphodynamic impact as 6 to 8 months long-term predictions, regarding the absolute erosion sedimentation volume.

- Especially the frequent milder storm events are important for the long-term morphological development of mega-nourishments.

- The cumulative impact of frequent milder storm events is larger than single extreme storm events.

- During extreme storm events, the shape of the sand-engine remains intact.

- Long-term morphodynamic predictions of mega-nourishments with average hydrodynamic conditions are considered insufficient.

- During the first years of the morphological development of the sand-engine, the sand-engine is resilient against breaching, due to its solid initial profile.

- After some years (5 to 10), the sand-engine gets more sensitive for breaching, due to the erosion of the western face of the sand-engine. A breach is likely to occur near the location where the spit develops towards the adjacent coastline.

- The initial shape of a mega-nourishment is definite for the manner of coastline accretion at the short term (first years), at the longer term (20 years) the initial shape of a mega-nourishment is unimportant, due to its diffusive end result.

### 7.2 Recommendations

#### 7.2.1 Researchers

**Reference scenarios**

- During the tidal cycle, an eddy occurs during rising tide at the northern side of the sand-engine, and an eddy occurs at the southwest side during falling tide.
It is important to further investigate these eddy formations with respect to swimming safety.

- Investigate the stability of the equilibrium situation of the tidal channel by numerical artificial dumping of sand into the tidal channel. This is important, because the meandering tidal channel can cause erosion of the adjacent beach.

- Further investigation towards the dominance of tide-induced sediment transport or wave-induced sediment transport around the sand-engine.

**Long-term morphodynamic predictions including storm events**

- Investigation of the impact of storm events on the siltation layer in the lagoon of the sand-engine.

- Include more storm events during the long-term morphodynamic predictions, especially the frequent smaller ones (1/0.5 year, 1/1 year, 1/2 year, etc.). These storm events tend to distribute the sand from the dry to the wet and redistribute the sand in the cross-shore, being an input for the alongshore processes.

- Make a probabilistic investigation (e.g. Monte carlo) for including storm events in the long-term morphodynamic predictions of mega-nourishments.

- For more accurate long-term predictions of mega-nourishments, remove the storm events from an applied wave climate and simulate these storm events with the integrated model coupling of Delft3D and XBeach.

- Further investigation towards the impact of the variability of storm periods on mega-nourishments.

- Include wind in the XBeach storm simulations, wind can substantially influence the wave run up during storm events and therefore enhance the overwash processes.

- Analogue study with Bornrif, for validation purposes.

- Investigation of the impact of a breach near the sand-engine on the swimming safety near the sand-engine.

- The applicability of indicators resulted in being a good asset for the quantitative assessment of various scenarios regarding the long-term morphodynamic predictions of the sand-engine and is recommended for further studies into mega-nourishments.

**Coupling techniques**

- During the series coupling of Delft3D and XBeach, apply the same model grids, in this way no interpolation errors occur.
During this thesis, all the simulations have been generated on the cluster within Deltarcs. During these simulations frequently some queuing waiting time occurred (due to series coupling), next to several generating problems, therefore research in other generating techniques is recommended.

7.2.2 Policymakers

Design cycle

- The Deltacommittee (2008) recommended large annual volumes of sand (85Mm$^3$) being nourished along the Dutch coastline to counter balance the upper limit of sea level rise (1.2m/century). A single mega-nourishment affects about 6 kilometer of the adjacent coastline by offshore accretion. Therefore, regarding the potential new strategy with the implementation of mega-nourishments in the Dutch coastline maintenance policy, multiple mega-nourishments are recommended like the sand-engine for combined impulse for nature and recreation.

- Request more integration of physical processes in the long-term predictions of the mega-nourishment, concerning e.g. siltation, aeolian transports, ground water table, storm events. The importance of these processes on long-term predictions of mega-nourishments have been elaborated throughout this thesis.

- Just before the start of the construction of the sand-engine, some major interventions were agreed between governmental parties concerning the alongshore location and shape of the sand-engine. Strategy and design development in close interaction with a broad stakeholder platform, will guarantee optimal conditions for implementation.

- Good cooperation during the design phase, between the governmental parties and the public sector and sciences institutes.

Reference scenario

- If the meandering tidal channel of the sand-engine results into erosion problems of the adjacent beach near Kijkduin. Investigation is recommended towards the artificial closure of the tidal channel.

- The construction of a mega-nourishment closer to the shore results into more recreational advantages, due to the ability of constructing a mega-nourishment in such a manner that more sand is constructed above the mean water line.

Long-term morphodynamic predictions including storm events

- After some years (5 to 10), the sand-engine gets more sensitive for breaching, due to the erosion of the western face of the sand-engine. A breach is likely to occur near the location where the spit develops towards the adjacent coastline. This can have implications for the management plans of a mega-nourishment, e.g. with respect to swimming safety, recreational possibilities and nature areas.
8 References


Deltares. BwN – Holland Coast. HK4.1 Work Plan, long-term sustainable development Holland Coast, 2009


Appendix A

Delta committee recommendations
In the report on climate-adaptation options for the Netherlands over the coming century, with an outlook to 2200, the Delta Committee 2008 issued the following recommendations regarding the coastal system, see text below. The scope of this task is very wide as can be illustrated by the background information provided by the Delta committee (www.deltacommissie.nl).

Beach nourishment lies at the heart of our present coastal management and offers a good opportunity for a flexible response to challenges posed by future climate change. If the coast (area between -20m and the dune foot) from Zeeland up to the Wadden region is to rise with the sea level, then 7 million m$^3$ of sand will be required for every millimeter of sea level rise$^1$. A rise of 6-12 mm/year (i.e. 65–130 cm in 2100) thus requires 40–85 million m$^3$ of sand every year.

$^1$ Explanation:
Based on the surface area of the active coastal system: coastal foundation, Wadden Sea and Western Scheldt. Closure depth of the coastal foundation is defined as the – 20m contour.

If the current approach of beach nourishment is intensified, adding more sand than is strictly needed for safety, then the coastline will migrate seaward and the dune belt will gradually expand. An extra sand volume of 40 million m$^3$/year, for example, will widen the Holland and Zeeland North Sea coasts by approximately 1 km towards the North Sea in the course of a century. The beach must emphatically not be extended seaward all at once, but gradually, leaving room for ecological processes and being in harmony with spatial planning.

A wider coast offers more space for dynamic nature along coastlines, the quality of which has degraded greatly in the past 150 years. This could be recouped. For that reason it is important to create open, varied, dynamic habitats for plants and animals, with the gradual saline gradients that were present in the past. There will also be more space for recreation and the land can be used locally for high-grade, flood-proof buildings, so that existing coastal resorts can continue to exploit the advantages of their seaside location. Moreover, it would also be possible to construct an underground infrastructure to open up the coast permanently and relieve the rest of the infrastructural network. A further advantage of a wider coast is a larger fresh water reserve in the dunes cutting saline seepage. In short, a wider coast offers new opportunities and can make a significant contribution to an attractive Netherlands.

For safety reasons the Committee considers it wise to take a sea level rise of 130 cm in 2100 as a reference for the sand volumes to be nourished. These volumes can be adjusted if sea level rise turns out to be less rapid. The Dutch part of the continental shelf has plenty of sand for these nourishments but the locations where optimally suited sand is to be dredged should be reserved in the next years in view of the ever-increasing use of space on the North Sea. It should also be assessed if nourishments can be carried out without long-term negative effects on nature, in accordance with current national and EU rules. The methods for dredging and transporting the sand could be made more energy efficient and more ecologically sound by adopting technological improvements and a large-scale approach. This is particularly important if future nourishments have to be carried out on a large scale and for a long time. The possibilities to do so seem promising and further research, especially into the ecological consequences, is required.

It is more cost-effective, though, to extend the coastline seaward via beach nourishment, which also offers possibilities for recreation, ecology and housing (expanding the coastal resorts). This is why the Committee responds to society’s demand for more space for nature and recreation by choosing coastal expansion. The Committee has nothing to say about other functions.
Appendix B

Near-surface total suspended matter concentrations
Figure B.1  Summer means of near-surface total suspended matter concentrations (Hook of Holland – Texel) (Suijlen and Duin, 2002).
Figure B.2  Winter means of near-surface total suspended matter concentrations (Hook of Holland – Texel) (Suijlen and Duin, 2002).
Appendix C

Physical processes in model integration for large-scale coastal projects
Aeolian transport (DUNE)

Problem definition

In a coastal zone, the sand transported landwards by the wind is the primary input of sediment into a dune system. The source of this sediment can only be found in the small range between the low tide level and the fore dunes. Exchange of this sediment from the dune foot back to the beach can take place during storm events. In the case of a mega-nourishment an excess of sediment is placed in the nearshore area. Presently aeolian sediment transport models are usually developed for areas like deserts. Consequently, there is still a scarcity of knowledge with respect to wind driven sediment transport in a coastal system. Aeolian processes will probably have substantial impact on the morphodynamic processes of a mega-nourishment and on nearby dune areas. Rules of thumb estimate an annual aeolian transport along the Delfland coast of 30m$^3$/m' on average (S. de Vries, personal communication). Regarding the sand-engine project area (2x1 km) and lifetime (20 years), this comes down to 30m$^3$/m'/yr x 2,000m = 60,000m$^3$/yr sediment transport along the sand-engine area. Insight into the interaction between the lower and upper (wet-dry) part of the sand-engine is therefore of great importance. Topographical changes of mega-nourishments due to aeolian processes are not included in long-term morphodynamic simulations of the sand-engine. Numerical models like Delft3D generate morphodynamic changes under water, but the interaction between dry and wet i.e. the interaction of the topography and bathymetry is missing.

During the development of the sand-engine aeolian transport can induce the formation of local dunes. Due to the formation of dunes, the tip of the hook can become higher compared to the shape of the initial profile. A higher cross-shore profile of the sand-engine can provide resistance against high surge levels during storm events and thus can prevent submerging and overwash of the sand-engine.

Figure C.1 Aeolian sediment transport sand-engine 18 July, 2011 (www.flickr.com).
**Modeling approach**

One of the aeolian sediment transport models (called “DUNE”) is the model of Sauerman & Herrman, 2002. This numerical model is developed for aeolian sediment transport in desert areas. For generating aeolian sediment transports simulations in coastal areas the DUNE model is modified by Muller (2011). In this MSc thesis, preliminary modifications were made for the application of the modeling aeolian sediment transport in varying dry and wet areas.

For modeling aeolian sediment transport for long-term predictions of mega-nourishments aeolian feedback on the morphodynamic processes have to be established. Formulations for aeolian sediment transport can be implemented in models (e.g. in Delft3D), or a coupling can be establish between Aeolian and morphodynamic models. A possible parallel modeling approach is presented in Figure 3.x, a stepwise explanation is given below.

1. The simulation will start with the initial bathymetry of the sand-engine. Delft3D as well as XDune will start simulation with the initial bathymetry, independently.

2. Both simulations (D3D-DUNE) generate a bathymetry-topography development respectively, over the same period of time.

3. For Delft3D as well as DUNE, the cumulative erosion sedimentation is calculated.

4. These two cumulative erosion sedimentation profiles are added together, forming a total cumulative erosion sedimentation profile.

5. The total cumulative erosion sedimentation profile is added to the initial bathymetry of the sand-engine, forming a new integrated bathymetry.

6. With the newly obtained bathymetry the cycle can start again; the new bathymetry can be send to the two models and two individual simulations can start again.

![Diagram](image)

*Figure C.2 Parallel coupling Dune and Delft3D.*
Vegetation and benthos (Delft3D-module: delwaq)

Problem definition

Near the Dutch coastline hardly any vegetation is present on the beach or in the nearshore area, due to high energetic hydrodynamic conditions. Complex coastal features like mega-nourishments and the sand-engine provides areas were hydrodynamic energy is low and vegetation has opportunities to settle and grow. Over time the sand-engine will be distributed along the adjacent coastline and the initial shape of the sand-engine becomes more smooth. With increasing smoothness the sand-engine loses sheltering areas for vegetation. Figure C.3 visualizes this context, were opportunities for vegetation decreases as the smoothness of the sand-engine increases. [Ye, personal communication].

![Smoothness vs vegetation curve.](image)

Vegetation plays an important role in the roughness or chezy factor near the profile of the bottom. It can hamper the flow for which sedimentation can occur, but it can also give an increase in turbulence. Therefore, these two parameters can determine local erosion or accretion of the bottom bathymetry. On the topography, the dry part of a mega-nourishment, vegetation can work as stabilizing factor. Via the roots and leaves, vegetation can reinforce a sand body and can capture sand, moved by aeolian transport. Vegetation can cause for local, relative hard coastal spots, with respect to the down- and up drift coastline. These stabilized spots near the sand-engine, can have substantial impact on the morphodynamic development. In morphodynamic predictions from the EIA, performed with Delft3D, no vegetation is included.

Modeling approach

Recently a software implementation is made for Delft3D in which vegetation can be included for morphodynamic simulations in the coastal system. In this vegetation module multiple parameters and species can be chosen regarding rate of growth, interaction, density, etc. An extensive modeling approach for long-term morphodynamic predictions of mega-nourishments is to combine the Delft3D vegetation module with the aeolian transport model XDune. XDune already provides opportunities to implemented vegetation characteristics to the topographic profile.
Adjacent coastlines (UniBest)

Problem definition

For a certain spatial extend the morphodynamic development of the sand-engine has been simulated with Delft3D. However, the impact of the sand-engine on a larger spatial scale is unknown. If the sand-engine pilot project meets the expectations, it can provide an alternative for present nourishment policy. Moreover, a new nourishment strategy can be implemented (paragraph 2.5), in which multiple mega-nourishments can be placed at different locations along the Dutch coast. However, the impact of multiple mega-nourishments on a large spatial and temporal scale, as well as their mutual interaction is unknown.

Modeling approach

The morphodynamic development around the sand-engine can be predicted with Delft3D and XBeach. For sediment transports along a more uniform coastline, at larger spatial scale, the coastline model UNIBEST-CL+ can be used. The local morphodynamic development of a mega-nourishment can be simulated with Delft3D, the output can serve as source term in a coastline model like UNIBEST.

![Image](image-url)

*Figure C.4 Coupling of numerical models Delft3D, XBeach and UNIBEST.*

In the most right picture of Figure 3.x a coupling of the numerical models XBeach, Delft3D and UNIBEST is presented. At long-term predictions of mega-nourishments, XBeach will provide bed changes after storm events to Delft3D and Delft3D can substitute e.g. annual longshore transports into the shoreline model UNIBEST.
Hydrology (Modflow)

Problem definition

In December 2008, the coastal upgrading of the Delfland coast started as a reply on the national coastal upgrading program ‘Zwakke Schakels’. A new seaward dune ridge together with beach and nearshore nourishments were constructed along the seaside resorts Ter Heijde and Kijkduin. During the construction of the new dune ridge some problems occurred regarding the ground water table in the surrounding area. One major problem was the temporary flooding of some nearby dwellings (cellars) due to an upcoming ground water table.

A second problem were the side effects on the nature area between Ter Heijde and Kijkduin, called Solleveld. In this nature area, a fresh water extraction site is located. With large dune and beach nourishments, salt intrusion could negatively influence the fresh water table in this fresh water extraction area. These problems were unaccounted for and triggered the stakeholder platform.

Mega-nourishments, especially when attached to the shoreline, can lead to similar problems. Mega-nourishments can also lead to positive side effects regarding the ground water table. On a long temporal scale, mega-nourishments will increase the dune and nearshore area and can increase the ground water table and hence a fresh water extraction site.

Ground water side effects in relation with (mega-)nourishments is a new issue concerning the stakeholder platform. A lot of research must be made when future mega-nourishments will be initiated.

Modeling approach

It is important to gain insight in the interaction of the ground water table and the morphodynamic development of mega-nourishments. A possible model approach, is the usage of the numerical model Modflow.

Modflow is a three-dimensional finite-difference groundwater flow model. It is used to simulate systems for water supply, containment remediation and mine dewatering. Modflow is a modular finite-difference flow model, which is a computer code that solves groundwater flow equations. The program is used by hydrogeologists to simulate the flow of groundwater through aquifers.
Translation output model integration to indicators

Large-scale coastal projects like mega-nourishments can be simulated with the integrated model approach as provided in Figure 3.4. The simulations will be analyzed and assessed. These analyses will provide new insight in the design aspects and indicators for mega-nourishments. The processes from paragraph 3.4.1 to 3.4.3 are described below. For each process the indicators are given for which model integration will provide improved insight and more specific quantification.

Effect of storms on long-term morphodynamic development.
Indicators
- Coastline migration (MKL volumes, RSP position, sediment transport volumes)
- Dune strength/development, dune area
  - Formations of scarps
  - Overwash

Effect of vegetation on short- and long-term morphodynamic development.
Indicators
- Coastline migration (MKL volumes, RSP position, sediment transport volumes)
- Dune strength/development, dune area
- Biodiversity, benthos and vegetation
- Water quality

Effect of siltation near mega-nourishments.
Indicators
- Siltation
  - Location (hot spots)
  - Bed composition sand/silt ratio
- Biodiversity, benthos and vegetation

Effect of aeolian transport on long-term morphodynamic development.
Indicators
- Coastline migration (MKL volumes, RSP position, sediment transport volumes)
- Dune strength/development, dune area

Interaction between large spatial adjacent coastlines and mega-nourishments.
Indicators
- Coast migration (BKL, Beach width, MKL volumes)
- Dune strength, dune area, dune development

Impact of a mega-nourishment on hydrology.
Indicators
- Groundwater table
- Water quality (Salt intrusion)
- Vegetation
Appendix D

Description Flow- and Wave module Delft3D and schematizations
D.1 Delft3D-Flow

The Delft3D-Flow module, which defines the hydrodynamic part of Delft3D, describes non-steady flow and transport phenomena. This concerns flow phenomena where the horizontal scale (in space and time) is substantially larger than the vertical scale (depth). Typical situations are shallow seas, coastal areas, estuaries, lagoons, rivers and lakes.

The Delft3D-Flow module is able to simulate flow and transport phenomena in two-dimension (2D) and three-dimension (3D). If the vertical variation in a water column is quite homogeneous, a depth-averaged approach (2DH) can be applied. The morphological predictions of the sand-engine are also simulated 2DH.

The Flow module is based upon Navier Stokes equations for an incompressible fluid, under shallow water and Boussinesq assumptions. In order to solve the equations, modification is necessary for numerical approximation. Vertical accelerations are assumed to be very small compared to the gravitational acceleration. Using this assumption a set of ‘shallow water equations’ is used which in turn give input for a continuity equation in 2D and two depth-averaged momentum equations in 2D.

The depth-averaged continuity equation in two dimensions is:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial [hU]}{\partial x} + \frac{\partial [hV]}{\partial y} = 0$$

The depth-averaged momentum equations in two dimensions, respectively x- and y- direction are:

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} = -g \frac{\partial \zeta}{\partial x} + fV + \nu_h \left[ \frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} \right] - gU \frac{\sqrt{U^2 + V^2}}{hC^2} + F_x$$

$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} = -g \frac{\partial \zeta}{\partial y} - fU + \nu_h \left[ \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} \right] - gV \frac{\sqrt{U^2 + V^2}}{hC^2} + F_y$$

Where:

- \(U, V\) Depth-averaged velocity in respectively x- and y- direction (m/s)
- \(g\) Gravitational acceleration (m/s²)
- \(\zeta\) Water level according to reference level (m)
- \(f\) Coriolis parameter (1/s)
- \(\nu_h\) Horizontal eddy viscosity (m²/s)
- \(h\) Total water depth (h=d+\(\zeta\)) (m)
- \(d\) Depth towards reference level (m)
- \(C\) Chezy-coefficient (m^{1/2}/s)
- \(F_x, F_y\) Radiation stress gradient in respectively x- and y- direction (m/s²)

The terms in the depth-averaged momentum equations (RHS) include respectively from left to right: horizontal pressure, the Coriolis force, the horizontal Reynold’s stresses, the friction term and the contribution to the momentum by waves.

These equations are solved by numerical approximation, using a finite difference scheme on a staggered grid. This grid arranged the velocity and water level variables at a specific way. The numerical approximation calculates the velocities and water levels for every grid cell,
based on input from the previous grid cells. During the calculation, Delft3D uses the Alternating Direction Implicit (ADI) method, which enables a fast and stable numerical calculation. The ADI-method splits a time step in two stages, allowing both an explicit and an implicit numerical calculation. First, the model equations in x-directions are derived explicitly, for the first half time step. The outcome will be used to calculate the other half time step in y-directions, implicitly. Now the second time step is split again and the process continues.

In order to guarantee numerical stability and accuracy in the Delft3D-Flow module the courant number should be defined. For a courant number below 10, the model equations are solved in a consistent way. A lower courant number can be set by decreasing the time step or by increasing the cell sizes of the grid. Either way, the computational time increases or the model resolution decreases, but the model simulation will become stable and accurate (Delft3D-Flow User Manual, Deltas, 2007a).

D.2 Delft3D-Wave

Waves simulations in Delft3D are resolved with the Delft3D-Wave module. This module is based on the spectral wave model SWAN. The SWAN model is a third generation wave model through which wave simulations are performed (Booij et al., 1999). At each location the spectral energy balance of the waves is resolved simultaneously. The model includes wave propagation, wave generation by wind, non-linear wave-wave interactions and wave energy dissipation for a given topography, wave blocking by flow, water level and current field (Holthuijsen, 2007b). A complete list of the physical processes is presented by Booij et al. (1999) or can be looked up in the Delft3D-Wave User Manual (Deltas, 2007b).

The Delft3D-Wave module has spectral balance equations to calculate the propagation of waves through time and space. The waves are described with the 2D wave action density spectrum rather than the energy density spectrum as in the presence of currents: the action density is preserved whereas energy density is not. The evolution of the wave spectrum is described by the spectral action balance equation (Delft3D-Wave User Manual, Deltas, 2007b):

\[
\frac{\partial N(\sigma, \theta)}{\partial t} + \frac{\partial c_x N(\sigma, \theta)}{\partial x} + \frac{\partial c_y N(\sigma, \theta)}{\partial y} + \frac{\partial c_\sigma N(\sigma, \theta)}{\partial \sigma} + \frac{\partial c_\theta N(\sigma, \theta)}{\partial \theta} = \frac{S(\sigma, \theta)}{\sigma}
\]

- \(\sigma\) Radian frequencies
- \(\theta\) Propagation directions (normal to the wave crest of each spectral component)
- \(c_x, c_y\) Wave propagation speed in respectively x- and y- direction, (m/s)
- \(c_\sigma, c_\theta\) Propagation speed for respectively \(\sigma\) and \(\theta\) (Hz/s), (º/s)
- \(N(\sigma, \theta)\) Action density evolution
- \(S(\sigma, \theta)\) Energy density source or sink term (m²/Hz)

The terms on the left side of the action balance equation represent respectively: the local rate of change of action density in time, the propagation of action density by wave groups in respectively x- and y- direction, the shifting of the relative frequency due to variations in depth and currents and the depth-induced and current-induced refraction. The source or sink term at the right hand side of the equation represent the combined effects of generation by wind, dissipation and non-linear wave-wave interaction.
D.3 Morphological scheme

In this thesis, the long-term morphological predictions of the sand-engine are performed with Delft3D. Therefore, a so-called parallel-online method is applied (Roelvink, 2006) to conduct morphological bed changes, which is an extension of the Delft3D-Online scheme provided in Figure 4.1. By applying this method, multiple wave conditions are calculated simultaneously using one and the same bathymetry. During each time step the separate bed changes per wave condition are multiplied with an on beforehand computed weight factor, and summoned providing a new bathymetry, which in turn is substituted to all wave conditions for the next time step, Figure D.1. This merging process is called MORMERGE. In the merging process the calculated bed changes of each wave simulation are reduced by the corresponding factor of occurrence, or weighted average.

![Parallel-Online scheme to conduct morphological bed changes (Roelvink, 2006).](image)

The parallel-online method provides a big advantage apropos of the standard Flow-Wave online coupling. Through simultaneous calculation of the wave conditions substantially shorter simulation time is needed as to calculating the wave conditions in series. Moreover, the parallel method can handle high morphological acceleration factors.

If a large number of wave conditions is used (10 for the predictions of the sand-engine) the flow boundary conditions per wave condition have to be shifted relative to each other. By doing this, each wave condition is calculated at a different moment in the tidal cycle (Figure D.2). If a phase shift is not applied in the flow boundary conditions, all wave conditions are calculated at a same moment in the tidal cycle, hence giving to high morphological changes.
D.4 Model schematization

Model bathymetry

The bathymetry of the sand-engine and the surrounding coastal area originate from several datasets. The overall coastal bathymetry is based on JARKUS (JAaRlijkse KUStmeting) data and ‘vakloding’ data from 2008, this includes the dune reinforcement and beach enlargement from the upgrading of the ‘Weak link Delfland’. The sand-engine bathymetry is based on design profiles from DHV and is incorporated with the overall bathymetry.

Tide schematization and boundary conditions

The boundary conditions for the Flow-module contain water level gradients at both lateral boundaries, so-called Neumann boundaries, and water level prescriptions at the offshore sea boundary. To simulate the long-term morphological changes over a period of a few days, the bed changes need to be scaled up, therefore a representative morphological tide is used that gives long-term average residual transports. The Flow-module uses a morphological tide, which is derived by simulating the long shore transports during a spring-neap cycle along ten transects along the Dutch coast. From this, the most representative semi-diurnal tide is derived, by the method of Latteux (1995). The morphological tide reads from March 23, 2001 23h32 to March 25, 2001 00h22. For multiple simulations of this representative tide, the tidal signal is made cyclical by means of a harmonic analysis with 16 components after which all odd components are removed, analogue to the recommendations of Roelvink et al. (1998).

D.5 Morphology settings

In the Delft3D-Flow module, the sediment input can be defined. The total sediment input is subdivided into sediment fractions being either ‘sand’ (non-cohesive bed-load and suspended load transport), ‘mud’ (cohesive suspended load transport), or ‘bed-load’ (non-cohesive bed-load only). Different formulations can be assigned to these different types of sediment. Besides the distinction of sediment being cohesive or non-cohesive, also a distinction is made between bed load and suspended load transport (Figure D.3).
Bed load transport is defined as the transport of sediment particles close to the bed. These particles roll, slide and saltate in a thin layer (~ 0.01m) along the bed. Transport of sediment above this bed load layer is considered suspended load transport and is subject to influences of the water column. In Delft3D-Flow the height of the bed load layer is determined by a reference height as determined by Van Rijn (1993) based on the bed roughness. Bed load transport is calculated following a user defined transport formulation and suspended load transport uses the advection-diffusion equation. In this thesis, simulations for the sand-engine are generated using only non-cohesive (sand) sediment and both non-cohesive and cohesive (sand/mud) sediment.
D.6 Wave schematization

To determine the boundary conditions for the wave model, the boundary conditions have been derived from the larger wave model used during the EIA simulations of the sand-engine. For the wave model of the EIA simulations, datasets are used from two survey stations: survey station Noordwijk (MPN) and Europlatform (EUR). The wave data consist of the significant wave height ($H_s$), significant wave period ($T_{1/3}$), the wave propagation direction ($\theta_{\text{wave}}$), the wind velocity ($v_{\text{wind}}$), the wind direction ($\theta_{\text{wind}}$) and the water level set up for the period 1979-2001. The survey stations are presented in Figure D.4, together with the wave grids used for the EIA simulations in black, and the smaller wave grid in red.

![Model grids together with survey stations Europlatform (EUR) and Meetpost Noordwijk (MPN).](image)

EUR is located 35 km to the west of the most southwesterly located grid cell, in relative deep water (32m). MPN is located at the wave grid near the northern lateral boundary in relative shallow water (18m). Due to the location of the two survey stations with respect to the offshore boundary, both datasets are used to determine the boundary conditions. In Figure D.5 and D.6 the wave and wind data is presented, which is also described and elaborated in paragraph 2.2.2 and 2.2.3 (Tonnon et al., 2009).
By means of the water depth and the distances from the two survey stations to the offshore boundary of the wave grid, the representative wave climate is derived based on the weighted average of the wave and wind parameters of the two survey stations.

The wave data is clustered and classified into 10 wave height bins and 12 wave direction bins. The wave height bins read from 0.25 to 5.25m, with bin sizes of 0.5m, the wave direction bins reads from 0 to 360º with intervals of 15º. The waves with an incoming angle of 15º to 195º are not included, because these waves originate from offshore direction. The same derivation is applied for the wave period, wave direction, wind velocity, wind direction and wind set up. The resulting representative wave climate is given in Table D.1, while Figure D.7 visualizes the corresponding wave rose. Table D.1 presents the combined wave height and wave directions bins, given their probability of occurrence.
The wave climate from Table D.1 contains 116 different conditions. To reduce simulation time, this wave climate has been reduced to a set of 10 wave conditions, giving the same morphological development. The reduction method for a reduced wave climate is established by means of the software program OPTI (Mol, 2007). The parameters of each wave condition acts as a boundary condition applied at an entire lateral or offshore boundary, propagating into the model domain, see Appendix D.8 for an example.
The reduced wave climate contains six waves from the southwest direction and four from the northwest direction. Two wave conditions are dominant, regarding their probability of occurrence, wc29 and wc90. The sum of the weight factors is 0.53, which is significantly smaller than 1. This is because the reduced wave climate only considers morphological change due to wave action and does not take into account periods where wave action is absent, like in the summer seasons.

The wave data from Table D.2 presents the boundary conditions of the wave model during the EIA simulations. For the wave computations for the sand-engine in this thesis a smaller wave grid is used. The boundary conditions for this smaller wave grid have been derived by transforming the 10 individual wave conditions from Table D.2 with SWAN, to the borders of the smaller wave grid (in red in Figure D.4). These computations resulted into a reduced wave climate with 10 conditions for the smaller and more detailed wave model used in this thesis, presented in Table D.3. An example of a derivation for one wave condition is given in Appendix D.8.

<table>
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<tr>
<th>Condition</th>
<th>Hsign [m]</th>
<th>Tsign [s]</th>
<th>Θ golf [ºN]</th>
<th>Vwind [m/s]</th>
<th>Θ wind [ºN]</th>
<th>set up [m]</th>
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</table>

Table D.2 Reduced wave climate (Tonnon et al., 2009).

Table D.3 Derived wave climate from EIA boundary conditions.
D.7 Parameters Flow and Wave module

The majority of the parameters in the Delft3D simulations are set on their default value. The following list indicates the most important parameters that are used with the sand-engine simulations.

Flow-module
- Timestep: 9 s (Courant number $\sigma < 10$)
- Horizontal eddy-diffusivity: 1.0 m$^2$/s
- Bed roughness: predictor (Van Rijn, 2007a)
- Bottom stress formulation due to wave forces: Van Rijn (2007a)
- Sediment transport formulation: TRANSPOR 2004 (Van Rijn, 2007a, b, and c)

Wave-module (SWAN)
- Wave interval (coupling with Flow): 24 minutes
- SWAN mode: third generation physics
- Wave-current interaction activated
- Depth-induced breaking, alpha, beta: Battjes and Jansen (1978), 1, 0.73
- Wave forces based on radiation stress
- Bottom friction formulation, coefficient: JONSWAP, 0.067
- White-capping, refraction and frequency shift activated

Sediment
- Type: sand
- Density: 2650 kg/m$^3$
- D50 median grain diameter sand: 215 µm
- Dry density: 1600 kg/m$^3$
- Initial sediment layer thickness: 15m

- Type: mud
- Reference density for hindered settling: 1600 kg/m$^3$
- Specific density: 2650 kg/m$^3$
- Dry bed density: 500 kg/m$^3$
- Settling velocity: 0.25 mm/s
- Critical bed shear stress for sedimentation: 1000 N/m$^2$
- Critical bed shear stress for erosion: 0.5 N/m$^2$
- Erosion parameter: 0.0001 kg/m$^2$/s
- Initial sediment layer thickness at bed: 0.96 m

Morphology
- Morphological scaling factor: 100
- Suspended transport factor: 1
- Bed-load transport factor: 1
- Wave-related suspended transport factor: 0.2
- Wave-related bed-load transport factor: 0.2
D.8 Derivation one wave condition, from the southwest

Figure D.x Derivation wave conditions for detailed wave grid, for one wave condition.

Figure D.x Derivation wave conditions for detailed wave grid, at the offshore boundary.
Appendix E

Model parameters XBeach
For the flow computations a Chezy coefficient of 60 is used, which is within reason for the sediment and morphology characteristics. The flow computations are performed up to a water depth of 1 cm.

The sediment transport computations are performed with the proposed characteristics for the design of the sand-engine. These characteristics are applied uniform throughout the model domain. Further default settings are used regarding sediment transport computations (Van Thiel de Vries, 2009).

Grid input
nx = 485
ny = 253
alfa = -43
xori = 66184.4507
yori = 448827.8165

Hydrodynamic simulation
tstart = 0
tintg = 1200
tintm = 3600
tintp = 600
tstop = 117000
CFL = 0.7

Sediment transport
rhos = 2650
D50 = 0.000250
D90 = 0.000375
rfb = 1

Morphological updating
morfac = 10
morstart = 1800
por = 0.4
dzmax = 0.17
Appendix F

Morphodynamic analysis sand-engine
Bathymetry development

Figure F.1 provides bottom contour lines of the annual morphological development near the sand engine for five years, without storms.

![Figure F.1: Morphological annual development of the sand-engine over the first five years.](image-url)
Figure F.2  Morphological annual development of the sand-engine over the first three years, including sedimentation erosion plots.
Figure F.3  Morphological annual development of the sand-engine in the fourth and fifth year, including sedimentation erosion plots.
Figure F.4  Morphological annual development of the sand-engine, visualized with MKL position plots indicating
the beach width.
Figure F.5  Dune foot position of the Delfland coast (2010) with sand-engine.

Figure F.6  Morphological annual development of the sand-engine over the first five years.
Figure F.7  Morphological annual development of the sand-engine over the first five years.
Figure F.8 Morphological annual development of the sand-engine over the first five years.
Figure F.9  Morphological annual development of the sand-engine over the first five years.

Figure F.10  Morphological annual development of the sand-engine over the first five years.

Figure F.11  Morphological annual development of the sand-engine over the first five years.
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Table F.1  Wave climate with adjusted weight factors representing the south westerly dominated wave climate from 1993.

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<th>Condition</th>
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<th>Tsign [s]</th>
<th>Θ golf [ºN]</th>
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<th>Θ wind [ºN]</th>
<th>set up [m]</th>
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Table F.2  Wave climate with adjusted weight factors representing the northerly dominated wave climate from 1996.
Figure F.13   Cross-sections at the lagoon of the sand-engine for different wave climates.
Figure F.14  Cross-sections at the lagoon and the tidal channel, indicating a siltation layer in the lagoon of the sand-engine.
Figure F.15  Cumulative erosion sedimentation plot between the bathymetry after 5 years of northern and southwestern dominated wave climates.
Figure F.16  Suspended sand matter in the tidal channel together with water level elevation and absolute velocity for southwest wave conditions.

Figure F.17  Suspended sand matter in the tidal channel together with water level elevation and absolute velocity for northwest wave conditions.
Appendix G

Morphodynamic analysis storm events at the sand-engine
Figure G.1  Wave characteristics during 1/20 and 1/100 year storm events.
Figure G.2  MKL position pre- and post 1/20 and 1/100 year storm events.

Figure G.3  Dune foot position pre- and post 1/20 and 1/100 year storm events.
Figure G.4  Series coupling of Delft3D and XBeach, with a storm event at 2.5 year.
Figure G.5  Indicators after five years, post 1/20 year storm event (at 2.5 years).

Figure G.6  Indicators after five years, post 1/100 year storm event (at 2.5 years).
Figure G.7  Indicators after five years, post annual 1/1 year storm events.
Figure G.8  Cross-sections middle sand-engine after 5 and 10 years.