Simulating Barrier Island Evolution

Coupling Process-Based Models

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Preface

This thesis report completes the Master of Science program in Civil Engineering at the Faculty of Civil Engineering and Geosciences at Delft University of Technology, The Netherlands. The thesis work was completed at Deltares and the USGS Coastal and Marine Science Center in Saint Petersburg, Florida.

Firstly, I would like to thank my supervisors at Deltares, Jaap van Thiel de Vries, Fedor Baart and Ap van Dongeren, for their advice and assistance with daily problems. Furthermore, my thanks go out to the rest of my graduation committee, Marcel Stive and Joep Storms, for their useful suggestions and insight during our meetings. Also, I would like to thank Nathaniel, Joe, Kara, Dave, Hillary and the other colleagues at the USGS, their hospitality guaranteed a terrific stay in Saint Petersburg.

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Summary

Barrier islands are important features in the coastal zone, among others because they shelter the mainland behind them from waves and storm surge. Thus, the degradation of barrier islands can pose a threat to coastal safety. Hence, there is a societal demand for understanding and predicting barrier island evolution. High energy events, such as storms and hurricanes, play an important part in this evolution, with hydraulic sediment transport causing large and rapid changes in morphology. In the periods between these events, (partial) barrier island recovery takes place, largely driven by the effect of aeolian sediment transport on longer timescales. Hence, when predicting the morphological development of barrier islands, both hydraulic and aeolian sediment transport need to be taken into account. Also, both the event timescale of hours to days, and the recovery timescale of weeks to months need to be resolved. Currently, no single numerical model exists that simulates both hydraulic and aeolian sediment transport, though there are models that resolve either one or the other separately. So, to resolve both at the same time, two models will have to be coupled.

The above leads to the two objectives of this thesis; firstly, constructing a coupling between a hydraulic and an aeolian sediment transport model, and analyze physical and numerical aspects of the model interaction. For this purpose the models XBeach and Dune are selected. The coupling is created using the Earth System Modelling Framework (ESMF). The second objective is confirmation of the predictive skill of the coupled model system for the evolution of a real world barrier island. Assateague Island (Maryland, United States of America) is selected as the study site for a hindcast, and a combination of model skill score and bias is used to represent the predictive capabilities of the coupled model.

From a process point of view, undertow, long wave flow, and increased turbulence due to wave breaking have a significant effect on the sediment transport during storms, and all are represented within the XBeach model. Aeolian transport is less important during storms, because the sand supply is limited by submergence and moisture content. During recovery periods, aeolian sediment transport does play an important role in transporting the sediment towards the beach and dunes, where it is often trapped by vegetation. The lower wave height during these periods allows for a relatively larger influence of short wave asymmetry and skewness, that can lead to hydraulic sediment transport towards the shoreline, creating a sediment supply for the beach and dune recovery. This makes the foreshore zone an interface between hydraulic and aeolian processes.

The coupling between XBeach and Dune allows the models to exchange information after every communal timestep, thus creating a dynamic interaction between the two models. This is only necessary when simulating recovery periods, for the influence of aeolian transport during storms is assumed to be negligible. The structure of the ESMF makes it possible to couple multiple models together, requiring only a few adaptations to the structure of the sub-model codes. This also provides the flexibility to add new or replace old models with relative ease.

To confirm the predictive skill of this coupled XBeach-Dune model, a hindcast of approximately six months of morphological development of Assateague Island will be performed. To this end, storms are distinguished from recovery periods, and are simulated in chronological order, the former with XBeach, the latter with the XBeach-Dune coupled model. The simulations lead to negative skill scores because of a significant overestimation of storm induced erosion. Even
when using an overwash sediment transport limiter to reduce the erosion during storms, the skill scores remain negative.

It can be concluded that the first thesis objective has been fulfilled, since a model coupling between XBeach and Dune has been constructed. Although a hindcast was performed, this could not confirm the predictive skill of the coupled XBeach-Dune model, so the second thesis objective was not completed.
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$\Delta V_{dune}$ Volume change in the vegetated dune [m$^3$]

$\Delta V_{foreshore}$ Volume change in the foreshore zone [m$^3$]

$D_{HIGH}$ Height of the dune crest [m]

$D_{LOW}$ Vertical position of the dune toe [m]

$dz_b$ Bed level change [m]

$H_s$ Significant wave height [m]

$R_{HIGH}$ Maximum vertical level of storm surge, wave setup and swash [m]

$R_{LOW}$ Vertical level below which the beach is continually submerged [m]

$u_{wind}$ Wind velocity [ms$^{-1}$]

$z_b$ Bed level elevation [m]

$z_{s,shoreline}$ Water level at the shoreline [m]

$z_s$ Water level [m]
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1 Introduction

1.1 Background
During the last two decades, both the general public and governments around the world have become more aware of the occurrence of global climate change causing, among others, sea level rise and increase in storm intensity and frequency. While there still is discussion about the causes of climate change and the rate of sea level rise, there is consensus about the fact that the mean sea level is rising.

With many of the world’s largest cities located in the coastal zone, a very large number of people are potentially affected by a rise in sea level threatening coastal safety. One aspect of this threat is the degradation of barrier islands that are sheltering the mainland coast behind it from wave attack. Besides being affected by sea level rise, barrier coasts are also susceptible to high energy events such as storms and hurricanes.

The problem that arises when trying to understand the evolution of barrier islands is that storms, recovery and sea level rise operate on completely different timescales. It is often difficult to fathom the interaction between two phenomena with different timescales, but they are present nonetheless; one of the consequences of sea level rise is that the combined wave setup and storm surge levels will reach higher, so waves can attack higher parts of the dunes.

The models simulating the effect of storms, recovery and sea level rise also operate on different timescales, which makes it difficult to simulate all phenomena in one model. To overcome this problem, different models, capable of simulating the phenomena and accompanying physical processes separately, can be coupled together, forming a coupled model.

This new coupled model should be able to handle both short timescales, simulating extreme events, and longer timescales, simulating calmer average conditions combined with long term trends (such as the change in mean sea level). The hydrodynamics and concurrent morphological changes are resolved by XBeach for both timescales, whereas the aeolian transport of sediment is resolved by Dune.

The coupling of these models, and thus the coupling of these different processes and timescales, opens up a vast number of modelling opportunities. For this thesis, the focus will be on a real world barrier island, named Assateague, where most of the processes represented in the coupled model are relevant. The simulations will feature both short term factors like storms and hurricanes as well as the longer term processes associated with barrier island recovery.

1.2 Problem description
In process-based coastal modelling, the focus is mostly on simulating a limited number of relevant processes occurring on one collective timescale. However, when looking at the physical processes dominating the evolution of barrier islands, it becomes apparent that the relevant physical processes operate on different timescales. Also, there is feedback between these processes, which necessitates simulating these processes simultaneously.

An approach to simulating the morphological development of barrier islands, is to resolve the associated relevant processes and their interaction, by creating a coupling between different
1.3 Objective
The problem description indicates the need for creating a coupling between different numerical models. After creation, it is important to gage the predictive skill of this new coupled model. Hence, the objective of this thesis is twofold:

1. Constructing a coupling between a hydraulic and an aeolian sediment transport model and analyze physical and numerical aspects of the model interaction.
2. Confirmation of the predictive skill of the coupled model system for the evolution of a real world barrier island.

1.4 Methodology
Below a description of each phase in the thesis can be found.

Literature study  Prior to the coupling itself, a literature study will be completed, focusing on the relevant physical processes related to barrier islands, taking place during the different timescales of storms, recovery and sea level rise. Also the interactions occurring between the different timescales will be explored.

Model coupling  The model coupling will be created in the Earth System Modelling Framework (ESMF [Hill et al. (2004)]), a software tool suite used for development of various earth science modelling applications. Earth science models usually represent physical domains and their governing processes, which can be coupled together within the ESMF to simulate phenomena that span several of these domains. In this thesis, ESMF will be used to couple the XBeach and Dune models.

Sub-model sensitivity  By performing sub-model test simulations, in which parameter settings are varied, a suitable parameter set for the coupled model is obtained.

Model confirmation  Eventually, a hindcast will be set up with real world data from Assateague Island, on the border between Maryland and Virginia, USA. This phase has been carried out in St. Petersburg, Florida, visiting the local USGS (United States Geological Survey) office for their expertise on Assateague Island.

Simulation results  The simulation results will be presented, analyzed and discussed. At this point the predictive skill of the coupled model can be calculated.

The above is followed by a discussion chapter and completed by a chapter containing conclusions and recommendations.
2 Literature study

In this chapter a review will be given of the available literature on the thesis subject.

2.1 Definitions in the coastal zone

In this thesis, the terminology from the Coastal Engineering Manual [U.S. Army Corps of Engineers (2002)] is used, the most relevant terms are depicted in figure 2.1 and are explained below.

![Diagram of coastal zone features](image)

Figure 2.1: Definitions used to describe features in the coastal zone, adapted from U.S. Army Corps of Engineers (2002).

The nearshore zone extends from the foreshore zone to water depths of about 20 m. Breaker bars are typical features found in the nearshore zone.

The foreshore zone is bounded by the mean low water (MLW) and mean high water (MHW) lines, and is also known as the intertidal zone. Under normal conditions, this zone alternates between being wet and dry, so it serves as the interactive interface between hydrodynamic and aeolian processes.

The backshore zone lies between the MHW line and the toe of the foredune. Together with the foreshore zone it forms the beach.

The foredune is the most seaward dune, located directly behind the backshore.

The back barrier lies landward of the foredune. It can contain different features, including dunes, dune ponds, supratidal marshes, vegetated barrier flats and washover fans.

The back barrier bay is located landward of the barrier island, and is connected to the sea by means of one or more tidal inlets. The character of the bay can vary, some contain intertidal salt marshes with tidal creeks, while others are completely submerged.

2.2 Sediment transport processes

When examining morphological change, it is important to grasp the underlying hydrodynamic and aeolian physical processes that cause sediment transport. In this research, the focus is on the cross-shore dimension, so the alongshore sediment transport processes will not be explored.

2.2.1 Hydraulic sediment transport

Since the phenomena of interest are storm impact and recovery, the various processes resulting in sediment transport in the cross-shore direction are of particular interest. What follows is a description of the most relevant hydraulic sediment transport processes in the cross-shore direction, as described by Roelvink and Stive (1989).
Undertow is an offshore directed return flow. While the flow velocities in cross-shore direction have a depth averaged mean of zero, because of the balance between radiation stress and wave setup, this does not mean that there is no mass flux in the water column at all. The presence of waves creates an onshore directed mass flux above wave trough level, which is compensated for by the offshore directed undertow. Since sediment concentrations are usually highest near the bed, undertow causes sediment transport in seaward direction.

Long wave flow is caused by incoming wave groups, which are accompanied by a bound long wave. The spatial variation of the short wave amplitude in the wave group leads to a spatial variation in radiation stresses. This is in turn compensated by water level gradients, resulting in water level variations, effectively forming a long wave moving along with the wave group. This long wave is bound to the wave group by the modulating short wave amplitude forcing and is in anti phase with the envelope of the short wave amplitude. The presence of this bound long wave causes an orbital flow on the wave group scale. When the short waves start breaking, the forcing of the bound long wave disappears and the bound long wave is released. Due to the short wave envelope and the long wave being in anti phase with each other, the trough of the bound long wave coincides with the peak in the short wave amplitude, and vice versa, which causes higher sediment concentrations beneath the long wave trough compared to the crest. While the magnitude of the horizontal component of the long wave orbital velocity is similar, there is a net offshore directed transport due to the difference in sediment concentration. Note that this is only true for a long wave in anti phase with the wave group, so it does not hold after release of the long wave.

Short wave asymmetry is caused by the shoaling of waves in the nearshore zone, resulting in asymmetry around both the horizontal (skewness) and vertical axes (asymmetry). Skewness means that the wave crests get higher and narrower, while the troughs get flatter and wider. Consequently, the maximum onshore orbital velocity is higher than the maximum offshore velocity. Because sediment transport is proportional to an exponent of the water velocity, there is a net shoreward transport under skewed waves. Vertical asymmetry is the pitching forward of the waves, caused by the fact that the wave crest travels with a higher velocity than the wave trough (because wave celerity is related to water depth). This shape changes the vertical orbital velocities and accelerations.

Short wave breaking-induced turbulence causes the sediment on the bed to be stirred up, which increases the sediment concentration and subsequently increases the local transport.

Boundary layer streaming is a current in the turbulent boundary layer, close to the bed. It is caused by short wave asymmetry and horizontally non-homogeneous wave fields. Asymmetry in the orbital velocities leads to an asymmetry of the turbulence intensity in the boundary layer, which results in a nonzero wave-averaged stresses and a subsequent offshore directed flow. A horizontally non-homogeneous wave field leads to horizontal and vertical orbital velocities that are not exactly 90° out of phase, resulting in a wave-averaged net onshore flow. The streaming flow velocities are relatively low compared with the velocities of the wave orbital motions. However, under storm conditions with highly energetic, non-breaking waves, these processes can lead to a strong sheet-flow, washing away bedforms and generating a thin layer of moving, highly concentrated sediment. [Schretlen et al. (2008)]

2.2.2 Aeolian sediment transport
Sediment transport caused by wind can be divided into suspended transport and bed load transport, similar to hydrodynamic sediment transport. Under normal circumstances, only grains with
a diameter much smaller than typical for coastal sediment ($\leq 0.5 \text{ mm}$) are able to stay in suspension for longer periods of time. This means that suspended transport can be neglected for coastal applications.

Bed load transport starts with a number of grains being entrained by the wind. Momentum is transferred between the wind and the sand grains by means of drag forces, causing the grains to accelerate and move over a short distance. Once the grains impact the bed again, other grains are dislodged and are now available for entrainment by the wind. Because of the momentum transferred from the wind to the grains the wind decelerates, lessening the potential for entrainment of grains. Thus a feedback loop is created, which will result in an equilibrium, defined by a saturated density and corresponding mean velocity of the grains. This movement of grains by means of ‘jumping’ and subsequent impact is called saltation and is assumed to be the dominant mechanism for aeolian sediment transport in dune environments [Sauermann et al. (2001)].

2.3 Barrier islands

Barrier islands are elongated, narrow islands that shelter the back barrier bay and marshland coast behind from waves and storm surge. Because of the sheltering effect, relatively fragile features like intertidal salt marshes can flourish in the back barrier bay.

The character of both the barrier island itself and the bay behind are largely determined by the tidal range, the amount of wave energy and the supply of sand available. These differences in character can be captured in four main classes, defined by Leatherman (1979):

- **Microtidal transgressive** barrier islands are found along coastlines with a small tidal range, usually below $1.8 \text{ m}$ ($6 \text{ ft}$). The small tidal range means that the tidal forcing is relatively small compared to the wave forcing, resulting in a wave dominated system. Transgressive barriers have the tendency towards erosion, because of a deficiency in the sediment supply. This leads to elongated, narrow islands with only few tidal inlets. These islands generally do not have high dune ridges so they are especially vulnerable to storms, which is often confirmed by the presence of many washover fans.

- **Microtidal regressive** barrier islands are also wave-dominated features and have a history of accretion, demonstrated by multiple dune ridges. The presence of multiple dune ridges increases the stability of the island. Nonetheless, both trans- and regressive microtidal barriers are prone to overwash and breaching due to the small number of tidal inlets, which makes it hard to adjust to rapid changing water levels (for instance during a storm). Most storm-generated inlets are only temporary and disappear quickly after the storm, since the tidal motion is not strong enough to keep them open.

- **Mesotidal transgressive** barrier islands are located in places with a tidal range between $1.8 \text{ m}$ and $3.6 \text{ m}$ ($12 \text{ ft}$), so both tidal motion and wave action have significant influence shaping the island, creating a mixed energy environment. The larger tidal range means more tidal inlets and subsequently shorter barrier islands. Also it leads to more pronounced ebb- and flood-tidal deltas (see figure 2.2).

- **Mesotidal regressive** barrier islands again feature multiple dune ridges and they often have a typical drumstick shape. The bulges at both ends of the island are more morphologically active, either accretionary or erosive, than the more stable central part. As with most mesotidal barrier islands, the back barrier bays are often (partly) covered by intertidal salt marshes.

Coasts with tidal ranges larger than $3.6 \text{ m}$ (macrotidal regime) rarely feature fully developed permanent barrier islands, however some small, more temporary features could be present.
2.3.1 Event timescale - Storm impact

Barrier islands are significantly impacted by sporadic high energy events like storms and hurricanes, which have a timescale of hours to days. The impact of these events on barrier inlet systems can be divided into four successive regimes, as defined by Sallenger (2000). The variables used to differentiate between the regimes (see figure 2.3) are the vertical elevation of the toe of the foredune ridge, $D_{LOW}$, the height of its crest, $D_{HIGH}$, the vertical level below which the beach is always submerged, $R_{LOW}$ and the maximum level of the combination of storm surge, wave setup and swash height, $R_{HIGH}$.

I The swash regime is the condition where the storm surge and wave runup combined just reach the dune foot, so $R_{HIGH} \leq D_{LOW}$. This causes erosion of the beach, which is transported in an offshore direction. The sediment lost this way will (mostly) be transported to the foreshore again after the storm, during the recovery phase.

II The collision regime is only possible when a foredune ridge is present. In this case the combined storm surge and wave runup reach somewhere between the dune foot and the dune crest ($D_{LOW} < R_{HIGH} \leq D_{HIGH}$), causing waves to collide with the base of the dune, resulting in erosion of the foredune. Dunes eroded this way will not readily return during the recovery phase.

III The runup regime (also called the overwash regime) is characterized by wave runup overtopping the crest of the foredune (periodically exceeding the threshold $R_{HIGH} > D_{HIGH}$). The water from overtopping flows in a landward direction, initially at a high velocity (measured to exceed 2 $ms^{-1}$) but decelerating over distance. This flow transports sand eroded from the foredune, causing deposition on the back barrier, often in the form of washover fans. This mechanism effectively results in landward migration of the barrier island, called roll over.

IV The inundation regime defines the time period during a storm during which the water level
constantly exceeds the height of the foredunes ($R_{\text{LOW}} \geq D_{\text{HIGH}}$ for the whole duration of the inundation regime). This means (most of) the barrier island is now submerged and directly influenced by surf zone processes. This causes large amounts of sediment to be transported landward to the back barrier and back barrier bay, forming distinctive washover fans in the back barrier bay. The amount of sediment transported appears to be correlated to the water level gradient over the barrier island; the higher the seaside water level with respect to the bay side water level, the larger the sediment transport [Plant et al. (2011)].

**Figure 2.3:** Definition sketch of the variables defining the storm impact regimes, from Sal-lenger (2000).

Not all these regimes occur during every storm, smaller storms may only reach the collision regime. However, the thresholds between the different regimes are not stationary and can change during a storm, for instance the runup and inundation regimes are reached more easily if erosion in the collision regime causes the crest of the foredune ridge to be lowered. The redistribution of sediment during these regimes is shown in figure 2.4.

**Figure 2.4:** Sediment transport during the different regimes within a storm event.

From a process point of view, the high storm waves generate a strong undertow, which can transport a large amount of sediment in offshore direction. This transport is reinforced by long wave flow and increased turbulence due to wave breaking. Short wave asymmetry is also present, but its effects are overshadowed by the offshore sediment transport. Since a sheet-flow layer occurs
under non-breaking waves, sheet-flow does not have a significant effect landward of the breaker zone.

During the inundation regime, the whole island is submerged and can be influenced by hydraulic processes. Higher water levels move wave breaking closer to the island. Besides wave action, water flow over the island accounts for much of the transported sediment.

Although storms feature high wind velocities, de Vries et al. (2012) states that the amount of aeolian transport is severely limited, because the precipitation accompanying storms renders the sediment wet and non-erodible.

### 2.3.2 Intra-annual timescale - Barrier island recovery

Storms and hurricanes occur only sporadically and have a limited duration. Barrier islands are able to recover from the storm impact during the recovery period in between these events, with a typical timespan of weeks to months. In this period the tides, waves and wind will (partially) restore the storm induced erosion. The wave action will be considerably less and will mostly consist of locally generated wind waves and swell, both with limited wave height. The lower wave heights cause a delicate balance between on- and offshore sediment transport processes, and sand can potentially be transported landward. The bed shear stress caused by waves stirs up the sediment in the nearshore zone, which is transported towards the beach by the asymmetrical and skewed wave motions. The influence of the short wave asymmetry is larger because the asymmetric, shoaling waves can propagate further landward before they eventually break. The effect of long wave flow depends on whether the barrier experiences a lot of swell waves (arriving in wave groups).

After the sediment is deposited in the foreshore zone during high tide, aeolian processes can transport this sediment further landward to the beach and (fore)dune ridges during low tide. This causes the dunes to grow and the total sediment volume of the barrier island to increase. Sand deposited in the back barrier bay is far less likely to be returned to the seaside beach of the barrier island, because there is less wave action in the sheltered bay. However, the sediment deposited on the back barrier itself in the form of overwash fans is highly mobile and easily transported by wind. The sediment is either deposited in vegetated areas or, in case of a serious lack of vegetation, migrating dune develop.

The transport of sediment during recovery periods is visualized in figure 2.5.

![Figure 2.5: Sediment transport during recovery periods.](image)

### 2.3.3 Decadal timescale - Effects of sea level rise

A rise in the mean sea level triggers a series of feedback loops between barrier island, back barrier bay and tidal inlets (see figure 2.6). An integral part in this is the ability of the back barrier bay to compensate for sea level rise by accretion. FitzGerald et al. (2006) suggest a conceptual model of the processes causing trapping of sand in tidal inlets and the long-term response of the barrier islands to this decreased sediment supply. This model assumes a mesotidal transgressive barrier coast featuring supratidal salt marshes, with a rate of sea level rise that exceeds the rate
of salt marsh accretion.

Figure 2.6: Stages of evolution of the barrier inlet system due to sea level rise, from FitzGerald et al. (2006).

The first stage consists of salt marshes being submerged and transformed into inter- and sub-tidal areas, for the rate of accretion of the salt marshes cannot match the rate of sea level rise. Because the salt marshes generally have quite a flat topography, this inundation adds a large volume to the tidal prism. This increased tidal prism causes stronger tidal currents which leads to scouring of the tidal creeks, an increase in the size of the tidal inlets and an increase in the equilibrium sediment volume of the ebb-tidal delta. Besides, the increase in submerged area in the back barrier bay provides an opportunity for newly formed flood-tidal deltas. The new sediment demand from the ebb-tidal delta is only partly met by the sediment from the scouring tidal creeks, so the remaining part will be supplied by the alongshore sediment transport. This extraction means a sudden gradient in alongshore sediment transport and can cause downdrift barrier island erosion.

In the second stage, the increase of the tidal prism, combined with the changes in bay and inlet dimensions, gives rise to a flood dominated system, with a bay importing bed load sediment. This regime instigates the growth of new flood tidal deltas and other shoals in the back barrier bay, further increasing the gradient in alongshore sediment transport and subsequent downdrift erosion, decreasing the size of the barrier islands. These thinner barrier islands are much more susceptible to breaching and during heavy storms new permanent tidal inlets can be created.

During the final stage, new tidal inlets are being formed and the thin barriers migrate landwards during heavy storms. When new inlets are created by barrier island breaching, the tidal volume passing through the existing large tidal inlets decreases. This causes the equilibrium sediment volume of the ebb-tidal delta to decrease, creating a temporary supply of sediment. Whether the barrier islands maintain the current state or disappear completely is dependent on the rate of sea
level rise.

2.4 Attemps to model coastal recovery and aeolian transport

While quite some research is put into understanding and predicting storm impact, barrier island recovery generally receives much less attention. One recent example of the contrary is the work of Pruis (2011), where both storms and recovery periods are simulated in a 1D profile model train. Similar to this thesis, XBeach (see section 3.1) is used to simulate storm impact. However, recovery is handled by an empirical profile recovery model, in which the post-storm profile recovers towards an equilibrium profile (assumed to be the initial profile). In this model approach, recovery is largely governed by the recovery time scale and the amount of sediment captured by vegetation. These two models are coupled serially, to be able to simulate a sequence of storms and recovery periods. Pruis indicates that the recovery model is especially sensitive to the recovery timescale, which, for some scenarios in his case study, necessitates assuming an unrealistically small recovery timescale. Nonetheless, he confirms the importance of the recovery process, by showing that simulating only storms underestimates the maximum island elevation by approximately 70 cm.

In contrast to the empirical approach of Pruis (2011), Muller (2011) tried to simulate the development of coastal dunes with the process-based aeolian transport model Dune (see section 3.1). To this end, Dune was adapted to be applied in the coastal environment. The capability of the model to make quantitative predictions was not investigated, due to lack of topographical data. However, Muller expects that the model will overestimate the amount of aeolian transport, since several supply limiting and transport processes present at beaches are not described in the model.
3 Model coupling

In this chapter, the physical background of the different numerical models and the details of the model coupling will be presented. In figure 3.1 the characteristic temporal and spatial scales of the models described in section 3.1 are depicted. The figure confirms the notion that coupling these models allows different timescales to interact with each other. This is not as much the case with spatial scales, as the model domain considered is approximately equal between the different models.

![Figure 3.1: Characteristic temporal and spatial scales of certain numerical models, from Baart et al. (2012).](image)

3.1 Description of sub-models

The models under consideration for use in the coupled model are summarized below.

3.1.1 XBeach

XBeach [Roelvink et al. (2009)] is a process-based storm impact model, written in Fortran. It has been created to resolve the time-varying effect on hydro- and morphodynamics caused by storms or hurricanes in the nearshore area. The most important processes represented by the model are dune erosion (including an avalanching mechanism for dune slumping), overwash and breaching. XBeach resolves 2DH (2D horizontal, averaged over depth) equations for wave action, flow, sediment transport and bed level change. It accounts for bound, free and refractively trapped infragravity waves. Grid options include rectilinear non-equidistant and curvilinear grids.

The computational routine of XBeach is depicted in figure 3.2a. The model input files define model settings, initial and boundary conditions. At the start of a new timestep the wave module is called, followed by the flow module. With the hydrodynamics obtained from these modules, the sediment transport (both suspended and bed load) is calculated. From the sediment transport the bed level changes are determined and slopes are checked for exceeding of the wet and dry critical slopes for stability. The steps are repeated until the entire simulation time is completed.
### 3.1.2 Dune

Dune [Kroy et al. (2002)] is a process-based aeolian sediment transport model, written in C++. The continuum saltation model for sand dunes described by Sauermann et al. (2001) together with an analytical description of the turbulent wind velocity field and the introduction of a separation bubble are capable of describing the morphological evolution of sand dunes found in the desert. Dune requires a rectilinear, equidistant grid. It calculates the wind shear stress on the sand surface and subsequently determines the sediment flux and bed level changes. When slopes become steeper than the angle of repose of the sediment, avalanching transport is instigated to flatten the slope.

Muller (2011) has adapted this original model to simulate sand dunes in a coastal environment, by including a tidal water level below which no erosion takes place and implemented the possibility for using a series of wind conditions from different directions as a boundary condition.

The computational routine of the modified Dune model can be seen in figure 3.2b. It is very similar to the XBeach one, only here the sediment transport is caused by wind shear, so the shear stress field over the bathymetry is calculated. Because the suspended transport is neglected, only the bed load (or saltation) transport is calculated. In addition to an avalanching algorithm, Dune has to take vegetation and non-erodible wet surfaces into account when updating the bed level. Again these steps are repeated until duration specified in the input files is completed.

![Diagram](image.png)

Figure 3.2: Schematic representation of the computational routines of both XBeach and Dune.
3.1.3 **Delft3D**

Delft3D [Lesser et al. (2004)] is a model suite composed of different modules, capable of simulating different processes like flow, tides, waves, stratification, morphology and transport of solvents in both 2DH and 3D.

3.2 **Model train**

The model train has to be able to simulate storm impact and recovery. XBeach itself has already been validated for simulating storm impact, so the first objective is to correctly represent the recovery phases.

3.2.1 **Resolving barrier island recovery**

From section 2.3.2 it becomes clear that mainly aeolian transport and short wave skewness and asymmetry are important processes during the recovery period. The former is captured by Dune, while the latter is incorporated in XBeach. Because XBeach is a depth and short wave averaged model, short wave asymmetry and its effect on sediment transport cannot be fully resolved, so the model uses a parameterization. Since wave groups are not expected to play an important role during recovery, they are assumed to be absent in recovery periods and XBeach is forced using a sequence stationary sea states (instead of the spectral wave group forcing that is applied during storms).

To allow for dynamic feedback between hydrodynamic processes and aeolian transport, XBeach and Dune have to be coupled, resolving both simultaneously. The resulting model train is depicted in figure 3.3a. The recovery period consists of weeks to months of relatively calm weather conditions, whereas the simulation of the storm event is relatively short. Because the net effect of aeolian transport is expected to be limited integrated over a storm (due to high water levels and the wetting of the sand by precipitation, see section 2.3.1), it is assumed acceptable to disregard aeolian transport during storms, resulting in a simplified model train (see figure 3.3b).

In the offline coupling between XBeach in storm and recovery simulations, only the bed level elevation (bathymetry) is exchanged between models. Because the models simulate storms and calm conditions respectively, different boundary conditions are being used and no hydrodynamic data has to be exchanged. The online coupling between Dune and XBeach also exchanges information about bed level change, although in this case both Dune and XBeach cause the bed level to change. The exchange of information between the models and the synchronization of time steps is taken care of within the ESMF coupling (as described in section 3.3).
3.2.2 Adding tidal basin evolution

When the recovery process can be simulated correctly, the following step is to take the tidal basin and the tidal inlets into account. As can be gathered from section 2.3.3, the dynamics of the tidal basin play an important role in the decadal evolution of the system of barrier islands, tidal inlets and the back barrier bay. To be able to correctly simulate the hydro- and morphodynamics of the tidal basin, including inlets and deltas, it becomes necessary to add a hydrodynamic model, capable of accurately resolving these on a longer timescale, to the coupled model. The most obvious candidate for this would be Delft3D. In the new model train, see figure 3.4a, Delft3D will resolve the recovery period, accounting for both barrier island recovery and tidal basin evolution. Thus when running the model train, XBeach and Delft3D will have to be coupled offline (serial), whereas Dune is running simultaneously with both XBeach and Delft3D, so there is an online coupling between them (parallel). In this case, the model train can again be simplified by resolving storms using only XBeach (see figure 3.4b).

Regrettably, the adaptation of Delft3D for use within an ESMF coupling was not finished in time to be able to create an extended coupled model including Delft3D. Therefore, constructing a coupling between Dune and XBeach as depicted in figure 3.3b will be the focal point of this thesis.

3.3 Earth System Modelling Framework

The Earth System Modelling Framework (or ESMF) [Hill et al. (2004)] provides a generic structure for programming a coupling between different models. It looks to facilitate integrated multi-component modelling by providing a generic super- and infrastructure, made for use in earth science modelling efforts. This is an alternative approach to the conventional monolithic software development, where new functionality and processes are continually added to existing models, making for increasingly complex and inflexible model codes. This added flexibility enables adding new models to the coupling and replacing out of date models with state of the art ones, that are resolving the same processes. Also, under ESMF individual models can be further developed, independent of the other models they are coupled with.

The ESMF superstructure consists of three main classes: ESMF state class, gridded component class (GridComp) and coupler component class (CplComp). The ESMF states are used to communicate different kinds of data between the different components. A component uses one or more import states as input and subsequently produces one or more export states as output. A gridded component contains a user defined component (usually an individual numerical model like Dune or XBeach), that processes an import and an export state based on the same grid.
The CplComp handles the exchange of the different states between the GridComps, often by regridding data to different grids.

An example of this structure is depicted in figure 3.5. A general feature of all ESMF components is that they contain initialize, run and finalize routines. When running an ESMF application, an initialization call goes out from the application driver (AppDriver, the main program of the coupled model) to one or more of its parent GridComp (one subset of interacting models). In turn, the parent gridded component passes down the initialization call to all of its children, both gridded components (GridComp, the individual models) and coupler components (CplComp, handling the exchange of data between the models). The run and finalize calls are handled in a similar manner.

![ESMF superstructure of the coupled model](image)

The child gridded components are the separate computational models that have to be coupled. These models are rewritten to be compiled into libraries instead of executables. A library is a collection of functions and routines that can be called separately, without the need of running the entire executable. Furthermore the models need to be divided into initialize, run and finalize calls. The coupler component defines which data is exchanged between the models and determines a communal model timestep. The internal timestep of the individual models can either be equal to or smaller than the communal timestep (as long as there is model output available at the communal interval). The parent is also a gridded component, so if necessary it can itself function as a child to another parent gridded component or be coupled with another gridded component.
3.4 XBeach-Dune coupling

The model coupling allows for dynamic interaction between wind and water, with the goal of simulating post-storm recovery of beach and dunes. The coupled model 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. In principle, these processes operate independently from one another, one in the wet and the other in the dry environment. However, one of the similarities between them is that both cause a change in bed level and both are influenced by the same bathymetry. This means both models will have to exchange bed level information with one another. Seeing as they are separate physical processes, the resulting bed level changes of both models can be added up for each model grid cell at every communal timestep:

\[ dz_{b,\text{total}} = dz_{b,X\text{Beach}_i} + dz_{b,Dune_i} \]  

(3.1)

XBeach and Dune do not necessarily use the same grid, so the bed level change from XBeach has to be interpolated to the Dune grid, and vice versa. The total bed level change is applied to the bathymetry in both Dune and XBeach, to ensure that both individual models contain the same bathymetry. In terms of the ESMF superstructure, the export state leaving the XBeach GridComp contains the \(dz_{b,X\text{Beach}_i}\). This export state is input for the CplComp, regridding the \(dz_{b,X\text{Beach}_i}\) to the Dune grid. The export state from the CplComp again is input for the Dune GridComp, where the \(dz_{b,X\text{Beach}_i}\) is applied to the Dune bathymetry. The \(dz_{b,Dune_i}\) is handled the same. When the Dune and XBeach grids differ in extent (see figure 5.9b), there will only be interaction between the two models in the overlapping domain.

In addition to the bed level changes, the mean water level at the waterline is supplied to Dune by XBeach, to determine which part of the bathymetry is submerged and therefore non-erodible by wind. To calculate this mean water level, the water level of the wet grid cell closest to the shoreline is averaged in longshore direction.

\[ z_{s,\text{shoreline}_i} = \frac{1}{ny} \sum_{j=1}^{ny} z_{s,\text{shoreline}_i,j} \]  

(3.2)

Spatially, the interaction between the two models is primarily located within the intertidal zone, because it alternates between being sub- and emerged and being influenced by both hydrodynamic and aeolian processes. This means water level variations on a tidal timescale are essential for this interaction, so the models need to be coupled several times within one tidal cycle. Therefore, the communal coupled model timestep is set to one hour.

3.4.1 Model adjustments

For the models to correctly work together as a coupled model, some adjustments have to be made to the original model code. Firstly, the code of both models has to be modified to be able to compile the models as a library instead of an executable and to make it respond to the initialize, run and finalize calls, as stated in section 3.3. Besides that, the two models have to generate output at a certain communal time interval. To this end, part of the time management of the models is transferred to the coupler, imposing a communal time interval to both models. The communal time step as well as the total run time of the coupled model is specified in a separate input file and the values stated in the original model input files are ignored.
Furthermore, where XBeach includes the option to apply a morphological acceleration factor (or `morfac`), this option is not present in Dune, because its computational demand is significantly smaller. So in the coupled model, one would like to use the morphological factor present in XBeach, without implementing this option in Dune. Hence, the coupler program accounts for the `morfac` specified in the XBeach input when imposing a communal timestep, to ensure both models run parallel in morphological time.

An additional difference between the models is the definition and orientation of the model grid. In XBeach, wave directions are specified following the nautical convention (N is 0°, E is 90°), while wind directions in Dune are defined relative to the grid, without the possibility to include the orientation of the grid itself. Thus, to make the coupled model more generically applicable, a new wind input routine is implemented in Dune that is able to read nautical wind directions and requires a grid orientation angle, similar to XBeach.

As mentioned in section 3.1, both Dune and XBeach contain avalanching algorithms that are triggered when a certain critical slope is exceeded. When running the coupled model, there is a chance that a slope will avalanche in both models simultaneously, overestimating the effect on the bed level. Consequently, avalanching should be disabled in one of the models. As XBeach relies on the difference between the critical slopes for dry and wet sediment to achieve dune erosion, its avalanching algorithm cannot be disabled without greatly impacting the model results. Therefore, the avalanching algorithm in Dune is disabled.

With these adjustments, the new computational routine of the coupled model is depicted in figure 3.6.

**3.4.2 Future adjustments**

There are a number of additional adjustments to the coupled model that, while being desirable, are not strictly necessary. Given time limitations, these adjustments have not yet been implemented. First among these adjustments is making it possible for the coupled model to switch to different parameter settings during a simulation, allowing both storms and recovery periods in one single simulation instead of having to set up a series of subsequent ones (as is currently the case).

Secondly, it would reduce the computational time significantly if the coupled model would be parallelized, making use of the MPI (Message Passing Interface) functionality in XBeach and running the Dune module one a separate core. MPI allows the XBeach grid to be divided into parts that run on different cores, thus speeding up the total simulation.
Figure 3.6: Computational routine of the coupled model.
4 Sub-model sensitivity

The goal of this chapter is to obtain the right set of model parameter settings for the hindcast at Assateague Island, discussed in chapter 5. Because both models are going to be used in a situation they have not (often) been used in before (a recovery period), the right parameter settings are not known yet. Therefore, it is checked whether and how the important physical processes, defined in section 2.3, are incorporated in the models, and how sensitive the model results are to these processes.

4.1 Model parameters

4.1.1 Relevant XBeach parameters

From section 2.3.2 it becomes clear that short wave asymmetry and skewness can introduce a sediment transport mechanism that leads to deposition in the foreshore zone. Both the horizontal asymmetry (or wave skewness) and the vertical asymmetry are parameterized in XBeach, and can be tuned using the parameters \( \text{facSk} \) and \( \text{facAs} \) respectively. Both are dimensionless factors that govern the relative contribution of the horizontal or vertical asymmetry to the sediment advection velocity. To generate onshore transport, they can range from 0 to 1, with a default value of 0.1. When both parameters are set to the same value, the parameter \( \text{facua} \) can be used as a shortcut. For the time being, there seems to be no need to differentiate between the two asymmetry contributions, so only \( \text{facua} \) is specified.

XBeach can use both spectral wave group forcing and a stationary wave forcing, the former takes bound long waves into account, where the latter does not. During recovery periods, the hydrodynamic forcing is expected to mostly consist of locally generated wind waves, so bound long waves do not play a significant role. Thus, the stationary wave driver is used during recovery periods, with the additional advantage of being less computationally demanding than wave group forcing. During storms however, long waves do play an important role, as stated by van Thiel de Vries (2009). So in the storm simulations, the wave group forcing is used.

To reduce the required computational time in both recovery and storm simulations, a morphological acceleration factor (\( \text{morfac} \)) is used (as described by Lesser et al. (2004) and Roelvink (2006)). The recovery periods have a duration of weeks to months, so a high \( \text{morfac} \) is needed to keep the simulation time acceptable, therefore a value of 200 is used. In contrast, the storms only last for hours to days, so here a lower \( \text{morfac} \) of 10 is applied.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Default value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{morfac} )</td>
<td>Morphological acceleration factor</td>
<td>1</td>
</tr>
<tr>
<td>( \text{instat} )</td>
<td>Type of wave forcing</td>
<td>n.a.</td>
</tr>
<tr>
<td>( \text{facua} )</td>
<td>Short wave asymmetry factor</td>
<td>0.1</td>
</tr>
<tr>
<td>( \text{facSk} )</td>
<td>Wave skewness factor</td>
<td>( \text{facua} )</td>
</tr>
<tr>
<td>( \text{facAs} )</td>
<td>Vertical asymmetry factor</td>
<td>( \text{facua} )</td>
</tr>
<tr>
<td>( \text{smax} )</td>
<td>Overwash sediment transport limiter</td>
<td>-1</td>
</tr>
<tr>
<td>( \text{wetz} )</td>
<td>Indicates if a grid cell is wet (1) or dry (0)</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

All relevant XBeach parameters are summarized in table 4.1. Note that the parameter \( \text{smax} \) is not
used by default (no limit to sediment transport during overwash), which is indicated by the default value -1.

4.1.2 Relevant Dune parameters

During recovery periods, sediment transported by wind is usually trapped in vegetated areas. Vegetation can be included in Dune by defining which grid cell contains vegetation, the height of the vegetation (which is specified per grid cell, so it can be varying throughout the model domain) and the concentration of the vegetation for the whole model. The relevant Dune parameters are summarized in table 4.2.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Default value</th>
</tr>
</thead>
<tbody>
<tr>
<td>veget</td>
<td>Vegetation height</td>
<td>0.5</td>
</tr>
<tr>
<td>concen</td>
<td>Vegetation concentration</td>
<td>0.5</td>
</tr>
</tbody>
</table>

4.2 Simulating recovery periods

To investigate the sensitivity of the models to the parameters mentioned in section 4.1, simple test models are created. In the case of XBeach, a cross-shore bathymetric profile from Assateague Island (the hindcast site, see section 5.1) is used to set up a 1D profile model. The model is configured to represent approximately 15 days of morphological evolution, using a representative tide. The model is run multiple times using stationary waves with varying heights and different values of facua. In Dune, a simple model is created using an alongshore uniform bathymetry (created from the same profile used in the 1D XBeach model). The location of the vegetation is fixed, and the model is run for different values of the vegetation height and concentration.

According to section 2.3.2, when simulating recovery periods XBeach needs to deposit sediment in the foreshore zone and Dune has to deposit sediment on the foredunes (and the back barrier). By varying the parameters described in section 4.1, the preferred model behaviour can be generated. To measure whether the models exhibit this behaviour, recovery indicators need to be defined. The first of which is the volume change in the foreshore zone. The foreshore zone is determined by looking at the wetz parameter from XBeach, which states whether a cell is wet or dry. By searching for the last wet cell (beginning at the seaward boundary) for every timestep and

![Figure 4.1: Both recovery indicators plotted against wave and vegetation height.](image-url)
subsequently looking for the maximum landward and seaward extent in the alongshore direction, the location of the foreshore zone is defined. The bed level changes of the cells within this zone are multiplied by the area of the cells to arrive at the change of sand volume, $\Delta V_{\text{foreshore}}$. This parameter is plotted against the wave height in figure 4.1a.

Figure 4.1a shows net deposition in the foreshore zone for the higher values of $\text{facua}$, with more deposition for higher waves (although it seems to stay constant from a wave height of 2 m). Low values of $\text{facua}$ lead to net erosion, indicating that this is indeed a parameter controlling the morphodynamic behaviour of XBeach in the foreshore zone. For the purpose of simulating recovery in XBeach, a high $\text{facua}$ of 1.0 seems suitable, since it generates the largest amount of deposition.

The second recovery parameter is the volume change within the vegetated dunes, $\Delta V_{\text{dune}}$. This is calculated by taking the bed level change in the cells which contain vegetation, multiply these with the area per cell and adding them all together. The resulting graph can be seen in figure 4.1b. As expected, the deposited volume increases for larger vegetation height and concentration. It seems that the deposition volume tends towards a maximum value (except for the simulation without vegetation). This maximum is already virtually reached for a concentration of $0.5 \text{ m}^{-2}$ and a vegetation height of 0.5 m, so these values will be used in the recovery simulations.

The parameter settings used for recovery simulations for both models are summarized in table 4.3

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Used value</th>
</tr>
</thead>
<tbody>
<tr>
<td>XBeach</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{morfac}$</td>
<td>Morphological acceleration factor</td>
<td>200</td>
</tr>
<tr>
<td>$\text{instat}$</td>
<td>Type of wave forcing</td>
<td>Stationary</td>
</tr>
<tr>
<td>$\text{facua}$</td>
<td>Short wave asymmetry factor</td>
<td>1.0</td>
</tr>
<tr>
<td>$\text{facSk}$</td>
<td>Wave skewness factor</td>
<td>1.0</td>
</tr>
<tr>
<td>$\text{facAs}$</td>
<td>Vertical asymmetry factor</td>
<td>1.0</td>
</tr>
<tr>
<td>Dune</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{veget}$</td>
<td>Vegetation height</td>
<td>0.5</td>
</tr>
<tr>
<td>$\text{concent}$</td>
<td>Vegetation concentration</td>
<td>0.5</td>
</tr>
</tbody>
</table>
4.3 Simulating storms

During storm simulations, the model is expected to erode the beach and foredunes. Infragravity waves play an important role in this erosion, so it is necessary to use spectral wave group forcing. Short wave asymmetry plays a far less significant role in storms than during recovery periods, so the standard value of 0.1 is used.

Table 4.4: XBeach parameter settings for storm simulations.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Used value</th>
</tr>
</thead>
<tbody>
<tr>
<td>XBeach</td>
<td>Morphological acceleration factor</td>
<td>10</td>
</tr>
<tr>
<td>morfac</td>
<td>Type of wave forcing</td>
<td>Wave group</td>
</tr>
<tr>
<td>instat</td>
<td>Short wave asymmetry factor</td>
<td>0.1</td>
</tr>
<tr>
<td>facua</td>
<td>Wave skewness factor</td>
<td>0.1</td>
</tr>
<tr>
<td>facAs</td>
<td>Vertical asymmetry factor</td>
<td>0.1</td>
</tr>
</tbody>
</table>
5 Model confirmation

In literature, a few different terms are used to describe the process of determining the trustworthiness of a numerical model, the most common being verification and validation. Oreskes et al. (1994) argue that neither is sufficient and suggest the use of the term confirmation. Hereby indicating that one can only search for confirming observations (observations that agree with the model results). A rise in both the amount and the diversity of the observations increases the probability that the model is not faulty. Henceforth, the term confirmation will be used. This chapter describes the study site, available data and model setup of the confirmation simulations.

5.1 Confirmation study site

As mentioned in section 1.4, Assateague Island will serve as the model confirmation site. It is a microtidal barrier (see section 2.3), located on the border between the states of Maryland and Virginia, on the Atlantic coast of the United States (see figure 5.2). Both Chincoteague Bay to the south and Sinepuxent Bay to the north are located landward of the island and both contain intertidal salt marshes and overwash fans. These bays are connected to the Atlantic Ocean by two tidal inlets, the northerly Ocean City inlet and the Chincoteague inlet to the south. Assateague Island is currently migrating landward, as can be seen from the offset to Fenwick island, north of the Ocean City inlet. Furthermore, the island is home to Assateague Island National Seashore (ASIS), a national park under management of the National Park Service.

![Aerial photograph of part of the study site after a northeaster (Nor’Ida) on December 4th 2009, taken by the USGS.](image)

The aerial photograph in figure 5.1 gives a good impression of the island; a partly vegetated foredune ridge, interspersed with either former overwash gullies or access pathways to the beach (less likely, because it is a more remote part of the island), a dirt track running over the length of
the island, the more heavily vegetated back barrier, incised by tidal gullies and eventually a salt marsh environment.

Figure 5.2: Map of Assateague Island, from www.teachoceanscience.net (2012).

5.1.1 Human intervention

The inlet at Ocean City was formed on August 23rd 1933, when the island was breached by a hurricane. Before the breach, Assateague and Fenwick island formed one continuous barrier island. The construction of jetties to keep the newly formed breach open, began in September of 1933 and was completed in 1935. These jetties interrupt the longshore sediment transport (oriented southward), causing erosion and accelerated landward migration at northern portion of Assateague Island. Since the creation of the inlet in 1933, the northern shoreline of the island has migrated westward over 350 m.

This ongoing erosive behaviour has instigated the ‘North End Restoration Project’, a two phase approach to counteract the degradation of northern Assateague Island. The first phase was executed in September of 2002 and consisted of a beach nourishment of 1.4 million m$^3$. The
nourishment was placed seaward of the mean high water (MHW) line, in order to create minimal disturbance to the barrier island habitat. The second phase of the project, consisting of biannual nearshore nourishments, was initiated in January of 2004 [ASIS (2006)].

5.2 Available data

5.2.1 Topographical data

The topography of Assateague Island is measured approximately annually by airborne LIDAR (light detection and ranging). This data is gridded with a resolution of 2.5 m in cross-shore and 10 m in alongshore direction. Bathymetric data is available on a coarser grid (with a resolution of 25 m), comprising from several different bathymetric surveys.

The earlier LIDAR surveys only contain a ‘first return’ signal, which means that the distance towards the first surface that reflects the light is registered. Because of this, vegetation has an effect on the measured bed level, when only the ‘first return’ signal is available. Most of the later measurements also have a ‘last return’ signal, registering the distance to the last surface reflecting the light, being the earth surface. This way, the vegetation can be filtered from the topography, leaving only a so called ‘bare earth’ topography. Furthermore, some of the measurements contain a large amount of noise within the model domain, so aren’t suitable to be compared to the model results.

Besides the topography, also the mean square of the difference between the data points and the resulting gridded bed level is computed for each grid cell. These differences are generally higher when the signal is obstructed by for instance vegetation. Therefore a high mean square value can be seen as an indication of the presence of vegetation.

5.2.2 Hydraulic and meteorological data

There are two permanent measurement devices close to Assateague Island: one is a tidal station just next to the Ocean City inlet (NW bay side), the other is an offshore wave buoy at about 37 km E-NE from the inlet. The tidal station measures water level elevation and standard meteorological data (including wind velocity and direction). The offshore wave buoy measures wave height and period (and sporadically wave direction), in addition to standard meteorological data.

For a range of wind directions, the wind speed measured at the tidal station is influenced significantly by the presence of structures in the vicinity (notice the anomaly in the N-NE of figure 5.3a). To compensate for this inaccuracy, the wind velocity measured at the offshore buoy is compared to the value measured at the tidal station in search for a consistent ratio between the two (this is only done for the directions that are undisturbed by structures). A new artificial dataset is constructed by multiplying the buoy data with the median value of the aforementioned ratio, which leads to a reasonably good result (see figure 5.3b).

For wave data at the offshore model boundary, the WIS (Wave Information Studies [U.S. Army Corps of Engineers (2010)]) database from USACE (US Army Corps of Engineers) is used. This database contains the results of simulated hindcasts for virtual wave gauges all along the US coastline. The wave rose for the gauge closest to the study site is depicted alongside the wind rose in figures 5.4a and 5.4b. There are almost no waves coming from westerly direction, which is to be expected because the island is located there. The highest waves seem to correspond with the highest wind speeds, coming from a NE direction. Besides that, a portion of the higher waves comes from a SE direction, and cannot be attributed to winds from that direction, so it is highly probable that these are swell waves instead of wind waves.
(a) Tidal station wind data, 2009 - 2011.

(b) Artificial nearshore dataset, constructed from offshore buoy data, 2009 - 2011.

Figure 5.3: Comparison between original and artificial wind roses, showing the directions the wind is coming from.

(a) Wind rose.

(b) Wave rose.

Figure 5.4: Wind and wave roses for the total study period (see section 5.2.3).
In figures 5.5a and 5.5a, again wind and wave roses are displayed, but now only for the storms during the study period (see section 5.3.1). The predominant storms are coming from a NE direction, which corresponds with the typical northeasters (large rotating storm systems, with winds coming from the NE) traveling along the US Atlantic coast. These northeastern winds seem to cause almost all of the storm waves.

(a) Storm wind rose.  
(b) Storm wave rose.  

Figure 5.5: Wind and wave roses for storm conditions during the study period.

5.2.3 Hindcast period
To be able to see if the coupled model can successfully resolve both storm and recovery, the simulation period should contain both. Furthermore, it should span two or more LIDAR surveys to be able to compare the measurements with the simulated morphological development. In this light, the period between the LIDAR surveys of September 15th 1997, April 3rd 1998 and October 1st 1999 is selected, see figures 5.7a to 5.7c respectively. It contains two northeasters hitting Assateague Island in late January and early February of 1998, about two months before the second LIDAR survey (see figure 5.6). Additionally, both LIDAR surveys contain relatively little noise and the chosen period avoids the nourishments of 2002 and onwards.

The actual morphological developments in this period are visualized in figures 5.7d and 5.7e, and the cumulative change in figure 5.7f. Note that the exact extent of the LIDAR surveys varies from year to year, and only points where both years contain data can be compared. When examining these developments, a few key features stand out. Firstly, from ’97 to ’98 (figure 5.7d) the face of the foredunes seems to be eroding and a bar is forming on the seaside beach. The dune erosion is more pronounced in the alongshore stretch between -600 m and -300 m, where the foredune is lowered considerably. The lower lying areas in between the dune crests of the foredune ridge show significant accretion, while elevation of the dune crests stays more or less constant. The pattern suggests that the accretion is the result of small overwash fans that only extend for about 100 m onto the barrier island. The back barrier, landward of the dirt track, looks to be eroding. However, this area is more densely vegetated (in 2009 anyway) as can be seen from the aerial photographs of the area (see figure 5.1) and it is expected to be less vulnerable to erosion by wind, making it more likely that (part) of that erosion is due to either a change in the vegetation or an inaccuracy in the measurements. Otherwise, it is hard to find a physical basis for severe erosion on that part of the island.
Figure 5.6: Significant wave height, water level and wind velocity during the study period. Storms are indicated by the darker markers, and the April 3rd 1998 LiDAR measurement is indicated by the dashed line.

Between '98 and '99 (figure 5.7e), there is accretion on the beach again and the sand deposited by overwash is mostly eroded again. The higher vegetated parts of the foredune ridge grow somewhat, as does the back barrier. The overwash deposits probably facilitate this accretion, by providing a source of relatively mobile sand. The total change over the two year period seems to result in a nett accretion of the beach and foredune areas and a nett erosion of the back barrier (figure 5.7f).
Figure 5.7: Bathymetries and bed level changes from LIDAR surveys taken in 1997, 1998 and 1999. (the Atlantic is on the left hand side).
5.3 Model setup

As mentioned in chapter 3.2, recovery periods are simulated by the coupled model, while storms are resolved using only XBeach (see figure 5.8a). Therefore the simulation period needs to be divided into storm and recovery simulations in a chronological sequence. In this section, the setup for both the coupled (Dune and XBeach) and the XBeach storm simulations are discussed. The model parameter settings used can be found in tables 4.3 and 4.4.

In addition to hindcast discussed above, both XBeach and Dune are used stand-alone to perform a hindcast of the complete study period as reference simulations. The results of these stand-alone hindcasts are discussed in appendix A.

5.3.1 Distinguishing storms from recovery periods

Since wave height plays an important part in the impact of storms on Assateague Island and an hourly record of the wave height is available, wave height seems a good parameter to distinguish between storms and recovery periods. To determine the threshold value for storms, a large number of simple 1D profile simulations is done for different wave heights and steepnesses. The absolute, cumulative change in volume of the beach profile for these different conditions is depicted in figure 5.8b. It can be seen that the change in volume increases dramatically from wave heights above approximately 3 m. Therefore 3 m will be used as a threshold value for storms, with the additional requirement that a single storm contains 10 or more successive data points that exceed the aforementioned threshold (which corresponds with approximately 10 hours). This additional requirement prevents existence of many very small storms of only several hours.

![Figure 5.8: The model train requires distinction between storms and recovery, made by applying a threshold wave height.](image)

5.3.2 Grids

Within the coupled model, XBeach and Dune use different but overlapping grids. The XBeach grid is non-equidistant, in contrast to the Dune grid, so the grid resolution can vary locally. The focus in this simulation is on cross-shore phenomena, so the resolution in cross-shore direction is higher (varying from 12 m offshore to 5 m on the beach and first dune ridge) than in the alongshore direction (20 m).

The XBeach grid extends further in offshore direction to allow for proper onshore wave propagation, shoaling and breaking, which is not needed in the Dune grid. Similarly, the bathymetry in the Dune grid is extended in alongshore direction to reduce the influence of errors introduced...
by the rotation of the bathymetry during the simulation. The overlap between both grids can be seen in figure 5.9b.

![Assateague Island bathymetry and XBeach (red) and Dune (black) grids partly overlapping.](image)

**Figure 5.9:** Assateague Island model domain and overlapping grids (UTM zone 18S, elevation w.r.t. NAVD88).

### 5.3.3 Initial and boundary conditions

#### 5.3.3.1 Bathymetry

For XBeach, the LIDAR survey of September 15th 1997 is taken as the initial bathymetry of the sequence of simulations. For the subsequent simulations, the resulting bathymetry from the previous simulation is used as initial bathymetry. Because Dune is not run during storms, there is no resulting bathymetry for the Dune grid after a storm, so the resulting XBeach bathymetry from the storm simulation is interpolated and extended to the Dune grid.

#### 5.3.3.2 Storms

During storms, the wave heights, periods and directions are taken from the WIS database at an hourly interval, and applied as spectral wave group forcing on the model boundary. At the same interval, water level information is taken from the Ocean City tidal gauge. During storm simulations, a morphological acceleration factor of 10 is used, to reduce the needed computational time.

#### 5.3.3.3 Recovery periods

During recovery periods, input reduction is used to reduce the computational demand of the simulation. The reduction is performed based on wind transport. As mentioned before, an hourly record of wind and wave measurements is available, and for every wind speed, the associated wind shear stress and subsequently the sediment transport is calculated. All wind conditions are collected into bins with directional and shear stress limits (see figure 5.10a). Simultaneously, wave height, period and direction that occur at the same time as the binned wind condition are added to the same bin. For each bin, the total cumulative transport is determined and a single representative shear stress value is determined per bin (see figure 5.10b), in such a way that the total transport per bin is the same. The mean values for wave height, direction, period and wind direction are assumed to be representative per bin.

The bins that do not contribute to the wind transport, either because they do not include any wind conditions, or because the wind speeds are too low to cause sediment transport (as is the case in the bottom row of figure 5.10b), are discarded, reducing the number of conditions to be simulated. The representative values for the wind shear stress, direction and duration form
the input for Dune. Similarly, the representative wave parameters are used as a sequence of stationary sea states, forcing the XBeach model.

Figure 5.10: Input reduction based on aeolian sediment transport. Note that white markers indicate representative direction and shear stress per bin.

Similar to the storm simulations, a morphological acceleration factor is used during recovery simulations. However, the Dune model currently lacks this feature, so this factor can only be applied in XBeach. Therefore, the coupling time interval is specified in morphological time instead of hydrodynamic time.

Because the recovery process takes place on a much larger timescale than a storm, the computational demand is significantly greater. To still be able to complete the simulation in an acceptable timeframe, a high morphological factor of 200 is used in recovery simulations. When applying such a large factor, there is a risk of greatly amplifying the effect of tidal currents on the morphological development. This happens because the tidal period gets smaller (inversely proportional with the morphological factor) while the tidal range stays constant, resulting in the same volume of water flowing in and out of the model in a significantly smaller time frame, increasing both velocities and their impact on morphology. To prevent this from occurring, the tidal period is increased again.
6 Simulation results

In this chapter, the results of the model simulations described in chapter 5 will be presented and discussed. Additionally, the influence and sensitivity of several model parameters is assessed.

6.1 Model performance indicators

When determining how well a numerical model performs while predicting morphological change, it is useful to define objective indicators of predictive skill and possible bias towards either erosion or accretion. The indicators used are identical to those used by McCall et al. (2010). For the mean square error (MSE) skill score, Murphy and Epstein (1989) define:

\[
\text{Forecast Skill} = 1 - \frac{\text{MSE(precision)}}{\text{MSE(reference)}} = 1 - \frac{\frac{1}{N} \sum_{i=1}^{N} (dz_{LIDAR,i} - dz_{simulated,i})^2}{\frac{1}{N} \sum_{i=1}^{N} (dz_{LIDAR,i})^2}
\]  

Here the mean square error of the simulated bed level change is normalized by the variance of the observed bed level change (the reference). This ratio is detracted from 1, to relate a skill score of 1 to perfect prediction. A skill score of 0 means that the model prediction performs equally well as prediction no bed level change at all. Thus, a negative skill score is worse than predicting no bed level change. The bias of a model prediction is defined as follows:

\[
\text{Bias} = \frac{1}{N} \sum_{i=1}^{N} (z_{simulated,i} - z_{LIDAR,i})
\]  

If the model predictions only include a random error, the mean value of this error, and thus the bias should be 0. However, when there is a consistent bias towards erosion or accretion present in the model results, the bias will be either negative or positive respectively.

6.2 Hindcast results

The resulting barrier island bathymetry of the morphological hindcast from September 15th 1997 to April 3rd 1998 is compared with the LIDAR measurements. The choice to only do a hindcast for the first part of the period suggested in section 5.2.3, is motivated by a combination of time constraints and required computational time.

Ideally, the resulting bathymetry in figure 6.1c should closely resemble the 1998 LIDAR measurement in figure 6.1b. However, as can be seen from figure 6.1f, they differ significantly from one another.

One of the more prominent differences is the overestimation of erosion in the numerical model; the bed level elevation of the beach is too low and there are several breaches in the foredune ridge on locations that have not breached in reality. Additionally, the assumed overwash fans...
Figure 6.1: Comparison between the LIDAR measurements and the 1998 hindcast bathymetry.
in figure 5.7d are not present here. When comparing the development of the back barrier, the erosion observed in figure 5.7d is not present in the simulation result. In fact, there is very little change of the back barrier at all (see figure 6.1e).

All in all it seems that either the storm erosion is overestimated and/or the accretion during the recovery periods is underestimated. To gain an insight in which is the case, the change of volume through time in certain zones of the barrier island is depicted in figure 6.2. The zones are defined as follows: the foreshore zone is between the MLW (Mean Low Water) and MHW (Mean High Water) lines, the dunes (and back shore) are from MHW line to the dirt track (at about 130 m cross-shore in figure 6.1c) and the back barrier is from the dirt track to the MLW line at the bay side of the barrier island.

![Volume changes of different barrier island zones.](image)

Similar to the small final bathymetrical change of the back barrier, the volume of the back barrier varies little over time. In contrast to the back barrier, both the dunes and the foreshore zone do experience significant changes in volume. In general, these zones respond strongly to storms (indicated in green), while there is relatively very little response during recovery periods. Most storms cause the dunes to decrease in volume, while the foreshore increases in volume. This is consistent with dune slumping and erosion during storms and thus can be expected. Notably, the first storms of both November 1997 and January 1998 do not conform to this pattern, which is apparently caused by nearshore erosion and bar formation respectively.

During the recovery periods in between the storms, there is no consistent increase in dune volume as would be expected. Mostly, there is little change and sometimes even a decrease in volume. Note that the decrease in dune volume during the first recovery period from September to October 1997 is due to the avalanching of steep slopes in the initial bathymetry.

The lack of accretion on the barrier island during recovery periods is substantiated by figures 6.3b...
and 6.3c, where the cumulative bed level change of all recovery periods is shown. The contributions of both XBeach and Dune in the coupled model are shown separately. The bed level change on the subaerial barrier island caused by Dune is evidently about an order of magnitude smaller than the erosion induced by storms (see figure 6.3a).

For a barrier island that is not rapidly degenerating, a balance between storm erosion and accretion during recovery periods is expected (over a sufficiently long time period). As can be seen from figures 6.3a to 6.3c, this is not the case. Since the study site is not rapidly degenerating, at least not within the study period, the storm erosion is overestimated, and the accretion during recovery periods is possibly underestimated.

Table 6.1: Skill and bias for different simulations.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Skill</th>
<th>Bias (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No change</td>
<td></td>
<td></td>
</tr>
<tr>
<td>'97 - '98</td>
<td>0</td>
<td>0.1119</td>
</tr>
<tr>
<td>'98 - '99</td>
<td>0</td>
<td>-0.0495</td>
</tr>
<tr>
<td>'97 - '99</td>
<td>0</td>
<td>0.0902</td>
</tr>
<tr>
<td>Hindcast</td>
<td></td>
<td></td>
</tr>
<tr>
<td>facua 1.0</td>
<td>-2.3706</td>
<td>-0.1980</td>
</tr>
<tr>
<td>facua 0.7</td>
<td>-2.2904</td>
<td>-0.1972</td>
</tr>
<tr>
<td>facua 0.3</td>
<td>-2.5846</td>
<td>-0.2184</td>
</tr>
<tr>
<td>Storms only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>smax 1.0</td>
<td>-0.3428</td>
<td>-0.0620</td>
</tr>
<tr>
<td>smax 0.8</td>
<td>-0.1130</td>
<td>-0.0262</td>
</tr>
<tr>
<td>smax 0.5</td>
<td>0.2204</td>
<td>0.0389</td>
</tr>
</tbody>
</table>
The poor performance is confirmed by a negative skill score (see table 6.1, facua 1.0). Also, the net overestimation of erosion is supported by the negative bias of the results. Both skill and bias are affirmed in figure 6.4. For a good skill score, most points have to be near the solid line (representing perfect agreement) or within one standard deviation away from it (indicated by the dashed lines). However, a large part of points are located outside these bounds, indicating a low skill score. While the highest density of points is located just above the solid line, indicating a slight underestimation of erosion or overestimation of erosion, most of the points furthest away from the solid line are located below it, in agreement with the negative bias.

![Figure 6.4: Measured versus simulated bed level change for every grid cell. The colorscale corresponds to the density of the points, the solid line represents perfect agreement and the dashed lines indicate the standard deviation of the measured bed level change.](image)

6.3 Hindcast sensitivity
Since there still is a significant difference between the model results and the measured development of Assateague Island, it should provide useful to look into the sensitivity of the coupled model to several calibration parameters, to obtain a better fit.

6.3.1 Recovery periods
Because the recovery periods are resolved using the coupled model, both XBeach and Dune model parameters can be used for calibration. Firstly, the hindcast has been performed for different values of the short wave assymetry parameter facua. The results shown in section 6.2 use the maximum facua of 1.0, for comparison the performance of lower values is depicted in figures 6.5a and 6.5b. These figures show small differences in morphological development, but the fit with the 1998 LIDAR measurement is not significantly better than using a facua of 1.0 (see table 6.1), since the skill scores are equally poor and the bias is similar.
Secondly, there are two Dune parameters that could increase the accretion of the barrier island, the vegetation layout and the wind speed. In figure 6.6a, the same vegetation layout and the unmodified wind speed as in section 6.2 are used, but now for a coupled model simulation of just the recovery periods, without storms in between. Little bed level change is happening, but it is spread across the whole island. When changing the vegetation layout based on the mean square difference (as described in section 5.2.1) to one based on aerial photographs, the amount of bed level change does not change much, but the spread over the island becomes less and it is constricted to the beach and foredune ridge (figure 6.6b). Only when using higher wind speeds (and the modified vegetation layout) does the bed level change actually increase (figure 6.6c).
6.3.2 Storms

To try and prevent an overestimation of storm induced erosion, the parameter $s_{\text{max}}$ is used, which specifies a maximum Shields value used in case of overwash, effectively limiting the sediment transport. It is usually set to values between 0.8 and 1.0 [McCall et al. (2010)]. All storms of the study period are simulated serially, without any recovery periods in between, for different values of $s_{\text{max}}$ (see figures 6.7a to 6.7c). In the simulations in section 6.2, no maximum Shields value was specified. The figures show that for a lower value of $s_{\text{max}}$, the overestimation of the storm induced erosions is reduced, with the lowest value of 0.5 performing best (see table 6.1), having a slightly positive skill score. However, the values that lie within the range suggested by McCall et al. (2010) result in negative skill scores. For all values of $s_{\text{max}}$, the bias is smaller than in the original simulations, which is to be expected when the storm induced erosion is reduced.

![Simulation results](image)

Figure 6.7: Difference between resulting simulated bed levels and 1998 LIDAR measurement for different values of $s_{\text{max}}$.

6.4 Conclusions

Summing up the foregoing, the case study shows that currently a hindcast by the coupled model performs poorly when compared to predicting no bed level change at all (see table 6.1). On the seaside of the island, the storm induced erosion is overestimated, while the morphological development of the back barrier is hardly present in the model. Varying the facua and vegetation parameters does not influence the end result by much, only specifying an $s_{\text{max}}$ leads to less storm induced erosion and a better skill score.

However, changing the $s_{\text{max}}$ does not improve simulation of the morphological developments of the back barrier. This suggests the possibility that one or more relevant processes are neglected in the coupled model, for instance bay side hydrodynamics or vegetation dynamics. Either way, the fact that the LIDAR data often does not capture the entire back barrier makes it hard to find out which physical process(es) instigate the bed level change of the back barrier.

Due to the absence of much of the physical processes that limit the availability of sediment for aeolian transport in the Dune model (moisture content and sediment armouring, among others), the transport simulated by the model is only equal to the transport capacity of the wind velocity.
Therefore, expectation would be for the aeolian transport to be overestimated, as suggested by Sauermann et al. (2001) and de Vries et al. (2012). Nonetheless, the total contribution of the aeolian transport in the coupled model is relatively small, as can be seen in figure 6.3c and there is no indication that this is indeed an overestimation. Additionally, since the Dune model has not been designed or confirmed for use in the coastal environment, it is not known if it can be used for quantitative predictions.
7 Discussion

This chapter looks to provide some critical reflection on the thesis, divided into three main subjects.

7.1 Simulating post-storm recovery

When trying to simulate recovery, there are two possible modelling approaches: an empirical approach or a process-based approach. In the work of Pruis (2011) an empirical model assuming recovery towards an equilibrium profile is used. The model behaviour is largely governed by a few calibration parameters, which increases the range of the possible model outcomes. The downside is that this makes the model less generic, because it requires extensive calibration when applied to a new situation.

This thesis tries to simulate post-storm recovery by resolving the relevant processes. The processes that are thought to dominate recovery (explored in section 2.3.2) are not included in one single numerical model, which necessitates the online coupling of two models. In general, a process-based approach requires a better physical understanding of the system, to be able to differentiate relevant from irrelevant processes. Additionally, creating a model coupling brings a set of difficulties to the table, as illustrated in section 7.2. Nonetheless, a process-based approach has the advantage of being more generically applicable, because the processes dominating a certain phenomenon stay the same. Also, the influence of individual processes can be isolated and investigated and additional processes can be added to the model. For these reasons, it seems worthwhile pursuing a coupled process-based model. However, the approach has yet to prove its merit in making quantitative predictions, so if that is the goal, currently the empirical approach will probably obtain better results after calibration.

Another difficulty with simulating barrier island recovery specifically is that the interaction between hydrodynamic and aeolian processes takes place in the foreshore zone, which is a fairly narrow zone that only spans several grid cells in a normal model grid. To gain more accuracy and dynamic interaction in this zone, the resolution of the model grid should be increased locally. This results in a larger computational demand, especially when simulating months or years of morphological development. Also, because Dune requires an equidistant, rectilinear grid, the resolution of the whole grid is increased.

7.2 Model coupling

Creating an online model coupling has proven to be technically feasible. The difficulties encountered when coupling multiple computational models can be roughly divided into three categories: programming difficulties, numerical instabilities and physical process problems.

The use of a generic framework like ESMF to program the coupling prevents part of the programming difficulties by providing a clear superstructure and an extensive infrastructure for handling grids and exchanging information between models. ESMF, while written in C, also contains a Fortran wrapper. This, combined with a newly created C interface for XBeach solves any problems posed by the difference in programming languages between XBeach and Dune. Models that are already structured in initialize, run and finalize routines only need minimal adaptation before being ready to use within ESMF or another modelling framework, since most of them make use of similar routines. This should be a consideration when deciding on a model structure while
developing new models. For a comparison between different modelling frameworks (including ESMF), see Jagers (2010).

Numerical instabilities are mostly introduced by the fact that the coupled model not always confirms to the assumptions made in the individual models. The risk for these instabilities is most notably present when the extent of the model grids of the individual models differs (as is the case in section 5.3.2). Since many (implicit) model assumptions concern the model boundaries, these assumptions are easily violated when results from other models are applied. These numerical instabilities can be prevented by ensuring that the model assumptions are being met in the gridded or coupler component.

Part of the physical process problems can be detected in advance, for instance when a specific physical process is included in both models (in this case avalanching, see section 3.4.1). These problems can generally be resolved by adjusting the gridded components to not call certain parts of the original model code. However, many physical process problems are only discovered when trying to gage the predictive skill of the coupled model. Even though the individual models have reasonable skill scores, this can change when applying them in a coupled model to simulate a more complex system. Identifying the source of these problems is generally hard, since both the model as well as the physical system have increased in complexity.

The current state of the Dune-XBeach coupling is that both the programming difficulties and the numerical instabilities seem to be resolved. The poor skill scores from the hindcast in section 6.2 indicate that the coupled model still contains physical process problems.

7.3 Coupled Dune-XBeach model performance
Chapter 6 shows that the coupled model currently lacks the skill to make accurate quantitative predictions. Identifying what causes this is hard for different reasons; the occurrence of multiple events between measurements, the limited extent of the LIDAR measurements, the need to calibrate both models in the model coupled model and the fact that Dune has not been confirmed for use in coastal environments.

In the timespan between the LIDAR measurements, approximately six months, seven storms and eight recovery periods are defined (see figure 6.2). There was one other LIDAR measurement done within the study period, on February 9th 1998, but that contains so much noise it cannot be used. This means that only the cumulative effect of all these events can be compared, while for confirmation purposes one would prefer separate recovery periods and storms, with measurements in between.

Additionally, the lack of LIDAR data of the back barrier makes it difficult to analyze what is actually happening with the whole barrier island (see section 5.2.3). Insight into the natural evolution of the island is obviously very important when performing a hindcast, especially to be able to correctly calibrate both XBeach and Dune. This touches on another inherent added complexity of the coupled model, the need for calibrating two models simultaneously, instead of one. For this purpose it is necessary to still be able to analyze output from both models separately (as is done in figures 6.3b and 6.3c). This way it can be determined which of the two models is in need of calibration.

The lack of any sort of quantitative confirmation of the Dune model seriously hampers the potential progress of the coupled model. While a good predictive skill score for use of Dune as an individual model in the coastal zone would not guarantee the same for the coupled model, it is a
condition for a coupled model suitable for quantitative predictions.
8 Conclusions and recommendations

This chapter contains concluding remarks, looking back on the objectives of the thesis, and gives recommendations regarding future research.

8.1 Conclusions
For the concluding remarks, reference is made to the thesis objectives, presented in section 1.3, first of which is:

Constructing a coupling between a hydrodynamic and an aeolian sediment transport model and analyze physical and numerical aspects of the model interaction.

The coupling between XBeach and Dune was successfully programmed, making use of the generic structure of the Earth System Modelling Framework (ESMF), to allow for easy future expansion or replacement of existing components. ESMF has proven to be suitable for coupling these models, though there are other alternatives. Some adjustments to the original models were necessary to adhere to the model structure required by ESMF.

The second objective of this thesis is:

Confirmation of the predictive skill of the coupled model system for the evolution of a real world barrier island.

The predictive skill of the coupled model is tested by performing a six month hindcast of the morphological development of Assateague Island. The results show a negative skill score, meaning the simulation results are worse than predicting no erosion at all. Analysis of the results indicates that this is mostly caused by a significant overestimation of the beach and foredune erosion in the storm simulations. Therefore, a few model parameter values are varied in an effort to obtain a better skill. Only using a transport limiter for the overwash induced sediment transport significantly improves the prediction skill, although even then the resulting skill score is still negative (when staying within the range suggested by McCall et al. (2010)). Also, the expected overestimation of aeolian transport due to neglecting transport limiting effects cannot be confirmed by the model results.

8.2 Recommendations
Firstly, there are a number of recommendations concerning the Dune model. The current implementation of the shear stress module requires the x-axis of the model grid to be parallel to the wind direction, resulting in several rotation problems and numerical diffusion of bathymetric features. Therefore, it is recommended to adjust the module to remove the need for grid rotation. If this turns out not to be feasible, implementing a non-rotating administrative grid in Dune solves part of the problems. Subsequently, Dune will need to acquire some form of quantitative confirmation, specifically for use in a coastal environment.

Furthermore, there are several more adjustments to be made to the coupled model. One of them is enabling switching between different parameter settings within one simulation. This allows resolving a series of storms and recovery periods within one simulation instead of requiring multiple simulations, which will greatly improve the ease of use when simulating longer periods. An
impractical consequence of simulating long periods is long computational times. To reduce the required time, the coupled model should be parallelized, which enables subdividing the computational load between multiple computational cores. The Dune model could be run on one core, and the existing MPI support in XBeach could be used to run it on multiple cores (since XBeach has a greater computational demand than Dune).

As said before, the current implementation of the coupled model within ESMF allows for relatively easy inclusion of additional models. The most obvious addition is including Delft3D in the coupled model, to simulate the back barrier bay and tidal inlets, which might be more important when simulating a mesotidal barrier island. Another interesting possibility is to include a dynamic vegetation module to the coupling. Note that the predictive skill of the current Dune-XBeach coupled model should first be successfully confirmed before adding any new models.

Regarding the predictive skill of the Dune-XBeach coupled model, the ideal confirmation case study would preferably feature pre- and post-storm bed level measurements, so a single recovery period can be isolated, without any storm events. This way, just the effect of recovery can be simulated, without interference of storms. Additionally, using ‘bare earth’ topography instead of topography that still includes vegetation is highly advisable, since dense vegetation seems to introduce a significant topographical error. Furthermore, the extent of the measurements should be increased to include the back barrier, to get a more complete picture of the autonomous development of the whole barrier island. As for selecting a study site, it is probably best to stick to micro-tidal instead of meso-tidal barrier islands, since the tidal bay and inlets play a less important role there.

In summary, the process-based coupled model approach still seems promising from a theoretical standpoint, though the current hindcast attempts result in negative skill scores, presumably through overestimation of storm impact. This will have to be resolved before the XBeach-Dune model will be able to make (quantitative) predictions.


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Appendices
A Single model reference simulations

To obtain an understanding of the ability of current models to simulate barrier island evolution, the study period (described in section 5.2.3) is hindcasted using both XBeach and Dune separately as stand-alone models.

A.1 XBeach stand-alone

Using XBeach stand-alone, only the storms (see section 5.3.1 for the definition used) occurring during the study period are simulated, all recovery periods are neglected. This series of storms is simulated in chronological order. The model settings are identical to those described in section 4.3.

Figure A.1: Comparison between the LIDAR measurements and the 1999 XBeach stand-alone hindcast bathymetry.
The results of the XBeach stand-alone simulation are depicted in figure A.1. It can be seen that the storm induced erosion is severely overestimated. The resulting bed levels of the beach and foredune are far too low (see figure A.1f), and the foredune ridge breaches on several locations, sometimes accompanied by overwash fans. These breaches cannot be found in the LiDAR measurements. Additionally, the lowering of the back barrier is not captured by the model results. These discrepancies lead to a very low skill score of -10.6670 and a bias of -0.3478 m (see section 6.1 for the definitions of skill and bias).

The overestimation of storm induced erosion is similar to the observations in chapter 6, and might also be lessened by using the parameter $s_{max}$. However, even if $s_{max}$ is applied, no recovery of the barrier island will take place in between storms, so these simulations will not be able to predict accretion of beach and foredunes as is measured in figure A.1d.

A.2 Dune stand-alone

The stand-alone model runs with Dune will only simulate recovery, so all storms during the study period are neglected. Because the Dune model has a high computational efficiency, no form of input reduction is necessary, so the hourly wind measurements are directly inputted into the model.

Figure A.2 shows the results of the Dune stand-alone simulation. As can be seen from figure A.2c, the barrier island has practically disappeared. This is an artifact of the current implementation of changing wind directions in Dune. As mentioned in section 8.2, the shear stress module in Dune requires the x-axis to be parallel to the wind direction, which implies that the grid is not stationary in the case of varying wind directions. This means that the bathymetry needs to be interpolated to the new rotated grid every time the wind changes direction. Each interpolation introduces an interpolation error, generally leading to diffusion of large gradients (slopes) in the bathymetry. A small number of rotations will only affect small bed level details, but performing many more rotations eventually wipes out the whole bathymetry. Hence, no conclusion can be drawn about the ability of Dune as a stand-alone model to simulate recovery.

This problem can essentially be solved in two ways: either replacing the shear stress module or implementing an administrative non-rotating bathymetry. The new shear stress module should be able to calculate the shear stress for varying wind directions without rotating the grid, thus abolishing the interpolation errors. However, this may require quite some work, since the shear stress module is central to the Dune model. Therefore the other option, implementing an administrative grid, might be more feasible. The bed level changes calculated from the rotated bathymetry would be rotated back to the original orientation, and would be applied to the non-rotating administrative grid, thus lessening the interpolation errors.
Figure A.2: Comparison between the LIDAR measurements and the 1999 Dune stand-alone hindcast bathymetry.