Towards a coupled morphodynamic model of the nearshore zone and the beach at the Sand Engine
Combining waves, tide, morphodynamics and aeolian sediment transport into a process-based model

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TOWARDS A COUPLED MORPHODYNAMIC MODEL OF THE NEARSHORE ZONE AND THE BEACH AT THE SAND ENGINE

COMBINING WAVES, TIDE, MORPHODYNAMICS AND AEOLIAN SEDIMENT TRANSPORT INTO A PROCESS-BASED MODEL

by

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Morphodynamic models are widespread in coastal engineering practice and indispensable to predict the effectiveness of (large-scale) sandy interventions. These models enable quantification of the effects on enhanced safety against flooding and on environmental impact over time, based on physical processes such as hydrodynamics and sediment transport.

The Sand Engine is a mega-scale nourishment pilot along the Dutch coast with a substantial sub-aerial surface and significant aeolian sediment transport, which highlights the need to integrate aeolian sediment transport and dry beach changes in current morphodynamic models. An explicit objective of the Sand Engine emphasizes this need: its dune area should increase by natural processes in the coming years, a process linked to aeolian sediment transport. In order to accurately model the morphological evolution of the Sand Engine, a model incorporating both morphodynamics and aeolian sediment transport is preferable. However, morphodynamics and aeolian sediment transport interact and the dynamics of the bathymetry and the water line cause the physical interface between sub-aerial and sub-aqueous processes to be highly variable both in space and time, making it complex to model the (lower) beach and the nearshore zone. Current morphodynamic models such as Delft3D Flexible Mesh (FM) only take into account hydrodynamic forces as drivers for sediment transport and do not resolve bed changes on the dry beach. Vice versa aeolian sediment transport models as AeoLiS do not include hydrodynamics and subaqueous sediment transport. Recent developments in model couplings allow implementing the interaction between morphodynamics and aeolian sediment transport.

This study provides the first steps towards a fully coupled model. A technical framework for a two-way coupled model is presented, combining AeoLiS and Delft3D FM as components in one model in which sub-aqueous and sub-aerial sediment transport interact. The model components exchange information such as bed levels, water levels and wave heights with each other on flexible intervals during the computation. An accurate interpolation scheme allows for the use of different computational grids per component. A proof-of-concept demonstrates the technical functioning of this framework. As the morphology module of Delft3D FM is not yet fully developed, a workaround is made in this thesis using a one-way coupled model, using the sub-aqueous morphological changes from a Delft3D (structured) simulation. Hence, hydrodynamics and accompanying morphological changes do influence the aeolian sediment transport, but the sub-aqueous morphological change is not altered by aeolian sediment transport. Once the Delft3D FM morphology module is released, the technical framework allows for a two-way online coupled model. Delft3D (structured) misses the developed coupling interface and could not be used for the computation of hydrodynamics.

A demonstration of the one-way coupled model is presented for the Sand Engine. The morphological development of the nourishment is simulated for the first five years after completion and the model results are generally in agreement with observations. The sub-aqueous part of the total bed change is not altered in this model approach in comparison with uncoupled models, as a consequence of the one-way coupling. The added value of the coupled model so-far over uncoupled models is the ability to predict aeolian sediment transport in a highly dynamic coastal environment. Considering the total Sand Engine area, the coupled approach results in a slight increase of the Brier Skill Score from 0.21 to 0.24. The decrease of the difference between modeled and measured net sediment loss at the Sand Engine due to the net aeolian induced erosion is 30% less in an uncoupled AeoLiS model. The coupling enables sediment mixing by waves which increases aeolian induced erosion in the intertidal area, which is in agreement with measurements. Furthermore, an attempt has been made to simulate dune growth at the Sand Engine. However, the observed alongshore variability is not reproduced by the model and the coupled model model in its current state is not adequate to model dune growth. The occurrence of artificial water in the dune area locally lowers aeolian sediment transport which makes the result uninterpretable.

As the provided coupling is a pragmatic first step, several recommendations are stated to improve the coupled model such as the realization of a two-way coupled model and the improvement of the dune growth simulation. This thesis advocates that the provided model framework can be a base for a coupled model, which allows coupling with other models to include more relevant processes, and can be a suitable tool in practical applications, especially for the areas where aeolian sediment transport is significant (e.g. beach nourishments).
This thesis is submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering at Delft University of Technology. The research was carried out at Deltares.

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INTRODUCTION

Morphodynamic models are important in coastal engineering practice for multiple reasons. For (large-scale) sandy interventions, morphodynamic models are commonly used to predict the effectiveness of the proposed solution. Based on physical processes, like hydrodynamics and sediment transport, the development in time of such an intervention can be assessed. Quantitative predictions need to be made to judge the resulting enhanced safety and environmental impact. Morphodynamic models are also used to investigate coastal systems by examining the relative importance and impact of the various types of forcing.

Aeolian sediment transport processes are usually neglected in morphodynamic models, which is the case in e.g. Delft3D and XBeach. Generally the resulting erosion and accretion because of wind is (assumed to be) an order of magnitude smaller than its aqueous equivalent. The simplification to ignore wind blown sediment is not always justified, especially on longer timescales (multiple years) and for more complex geometries of (sub-aerial) nourishments. Furthermore, aeolian processes at the coast are believed to be the main driver for dune growth. However, modeling aeolian sediment transport at the beach is difficult, typically due to the large variety of sediment availability limitations such as moisture, non-erodible shells or vegetation.

In 2011, the mega-nourishment the Sand Engine was placed near the coast of Kijkduin [Stive et al., 2013]. The Sand Engine was designed with the concept of Building with Nature in mind [Ecoshape, 2014]: natural processes should force the nourished sediment to spread out along the coast in the upcoming years. As the nourishment consist of large volumes of sediment above sea level, it is also prone to wind. In the Environmental Impact Assessment of the Sand Engine, an intended dune area growth of 33 ha was quantified based on a simple empirical relation [Mulder and Tonnon, 2011]. The measurements of the first 5 years of evolution of the Sand Engine show a more complicated case. Dune growth varies along the Sand Engine and the growth rates are less than expected [Taal et al., 2016], although sediment transport towards the dunes is about 14 m$^3$/m/year [Hoonhout and de Vries, 2017]. Both hydrodynamics and aeolian processes influence sediment transport at the Sand Engine. The Sand Engine shows that both hydrodynamics and aeolian processes influence sediment transport. Wind blows sediment over the beach into and from the dunes and the intertidal area. Also interaction between aeolian sediment transport and the hydrodynamics is relevant, which causes that the intertidal area acts as an aeolian sediment supply [Hoonhout and de Vries, 2017]. Water features in the form of a dune lake and lagoon trap sediment transported by wind, thereby changing the sediment transport towards the dunes and the resulting sub-aqueous accretion changes basin properties and thus hydrodynamics.

Attempts are made to model sediment transport at the Sand Engine, however no model includes both wind and water processes. The hydrodynamic morphological model Delft3D was used to investigate the (sub-aqueous) processes at the Sand Engine [Luijendijk et al., 2017]. Hydrodynamic forces are taken into account as drivers for sediment transport, bed changes on the dry beach are not taken into account. The comparison of the Delft3D hindcast and measured bed level change in Figures 1.1a and 1.1b reveals that the morphological change is least reproduced as it comes to high areas, the dune lake and lagoon. An aeolian sediment transport hindcast of the Sand Engine was performed with AeoLiS [Hoonhout, 2017], a recently developed process-based aeolian sediment transport model which is able to take sediment availability into account. The simulation result, presented in Figure 1.1a, shows that AeoLiS performs best in the regions which are least represented in the Delft3D model, i.e. the dry beach, dune lake and lagoon.
The Sand Engine shows that there is a need to integrate aeolian sediment transport in current morphodynamic models. Mega-nourishments founded on a Building with Nature approach like the Sand Engine, incorporating a substantial subaerial surface area, are expected to be used more often to mitigate erosion problems in coastal zones. As a (mega-) nourishment is a costly investment it is important to have accurate tools to assess its effectiveness in the design phase.

The superposition of results from Delft3D and AeoLiS, shown in Figure 1.1a, is already closer to the observations than the individual results, even though this approach neglects all interaction between hydrodynamic processes and aeolian processes. A next step would be to integrate the processes of the models, so the hydrodynamic model influences the aeolian sediment transport model and vice versa. Software interfaces are developed, which provide the opportunity to interact with a model during its computation, an example of such an interface is BMI [Peckham et al., 2013]. Therewith, it becomes possible to couple models, so the computations of different models influence each other. Recently, BMI is implemented in the AeoLiS model and in the morphodynamic model Delft3D Flexible Mesh (FM), the intended successor of Delft3D, but is not implemented in Delft3D itself.

1.1. PROBLEM DEFINITION
Recent developments for model couplings allows implementing interaction between morphodynamics and aeolian sediment transport. Current morphodynamic models such as Delft3D FM only take into account hydrodynamic forces as drivers for sediment transport and lack direct information on dune growth. Vice versa aeolian sediment transport models as AeoLiS do not include hydrodynamics. The Sand Engine pilot highlights the need to integrate aeolian sediment transport in current morphodynamic models. The observations of the Sand Engine show the development in the first five years after its completion and especially the observed dune growth does not match its expectations.

However, combining an aeolian sediment transport model with a current morphodynamic model is not straightforward. Models are engineering tools based on assumptions dedicated to its intended goal which might be violated by the other model. The inclusion of extra information in a coupled model system needs to be handled correctly, the bookkeeping must be proper and even then the result should be carefully interpreted.

1.2. OBJECTIVE AND RESEARCH QUESTIONS
1.2.1. OBJECTIVE
The objective of this thesis is to develop a framework for an integrated process-based morphodynamic model including both sub-aqueous morphodynamics and aeolian sediment transport plus the interaction between...
these processes. The purpose of this model is to explain the morphological evolution and dune growth variability at the Sand Engine and to be able to improve predictions on dune growth in the design phase of mega-nourishments. This research provides the first steps towards a coupled model system by investigating which processes need to be coupled, providing a technical framework and demonstrate whether such a coupled model adds value over uncoupled models.

1.2.2. RESEARCH QUESTIONS

MAIN QUESTION
Does the inclusion of both sub-aqueous morphodynamics and aeolian sediment transport and their interaction in one coupled model improve predictions on coastal evolution and is this model able to simulate the first years of morphological evolution and dune growth variability at the Sand Engine?

SUBQUESTIONS
1. Which (interaction between) sub-aqueous morphodynamics and aeolian sediment transport processes shape the Sand Engine, and should therefore not be neglected in (coupled) modeling of the Sand Engine?
2. How can we combine different model characteristics of the existing morphodynamic and aeolian sediment transport models, Delft3D FM and AeoLiS, in order to create an operational coupled model structure which embodies this interaction?
3. Is such a coupled model of added value over uncoupled models, by decreasing the differences between observations and model results of the first years of the morphological evolution at the Sand Engine and by explaining the observed dune growth variability?

1.3. APPROACH

In order to find the answers on the research questions the following approach is chosen.

• A literature study on the Sand Engine, morphodynamics, aeolian sediment transport, model coupling and dune dynamics will be carried out. Subquestion 1 will be answered by analyses of the physical processes involved.

• Next, the coupling is addressed. This step comes back on research subquestion 2 on the models Delft3D FM and AeoLiS. The available coupling techniques will be briefly discussed. The outcome of the literature research on the physical processes and technical coupling considerations come together as a design of an online coupled model framework. To show that the model framework works accordingly to its expectations, a proof-of-concept will be presented.

• The added value of the model questioned in 3 will be addressed by comparing the results of a hindcast of the Sand Engine of a coupled model with measurements and with the results of an uncoupled model. By evaluating the result of the coupled model with an uncoupled model, the differences are investigated. Aeolian processes and overall morphological development will be addressed.

1.4. OUTLINE

This thesis is structured in line with the previously mentioned approach.
Chapter 1 states the introduction to this research and sets the objective and approach.
Chapter 2 treats the physical processes involved at, and the results of current uncoupled models of, the Sand Engine.
Chapter 3 describes the designed coupled model framework, presenting the technical structure.
Chapter 4 shows a proof-of-concept case of the coupled model framework. This chapter functions to demonstrate the functioning of the technical structure step-by-step.
Chapter 5 shows the use of the coupling framework, and an uncoupled model, to model the Sand Engine and compares the results with measurements.
Chapter 6 provides discussion on the coupling and the results.
Chapter 7 states the conclusions and recommendations.
1.5. **DELF3D DEFINITIONS**

**Delft3D** is a morphodynamic model, including different modules: hydrodynamics (Delft3D-FLOW), waves (Delft3D-WAVES) and sediment transport (Delft3D-MOR). Other modules could be included but this thesis solely refers to these three.

**Delft3D Flexible Mesh (Delft3D FM)** is the successor of Delft3D and also includes different modules: hydrodynamics (D-Flow Flexible Mesh / D-Flow FM), waves (D-Waves) and sediment transport (D-Morphology). A complication is that both hydrodynamics and morphology use the same computational model core: also called D-Flow Flexible Mesh (D-Flow FM) in which the calculation of sediment transport is optional.

The term **D-Flow FM** refers in this thesis to the model core, so D-Flow FM calculates hydrodynamics and if desired also sediment transport.

The waves module (D-Waves) is referred to as **SWAN**, by the name of the model core.
Chapter 2

COMPREHENDING THE EVOLUTION OF THE SAND ENGINE

2.1. INTRODUCTION
This chapter aims to find (the relations between) the processes which shape the Sand Engine to include these in a coupled model. In order to answer this, knowledge on the Sand Engine is needed. The Sand Engine and its predictions are described in Section 2.2. Next, observations of the Sand Engine are discussed regarding the overall morphological development, aeolian sediment transport and dune growth in Section 2.3. Furthermore, the uncoupled state-of-the art models of the Sand Engine are discussed in Section 2.4. Therewith conclusions on the importance of processes and model aspects can be drawn and finally the implications for the coupled model are presented in Section 2.5.

2.2. THE SAND ENGINE
The pilot project Sand Engine is a mega-nourishment at the Delfland coast, see Figure 2.1 for its location, and its construction finished in November 2011. A hook-shaped peninsula and water features, a lagoon and dune lake, were created using 21 million $m^3$ of sandy sediments, aerial pictures of the Sand Engine are presented in Figure 2.2a. Directly after completion, the Sand Engine protruded about 1 km into the sea, is approximately 2 km wide and the average height is +3.5 m NAP [Stive et al., 2013]. It is expected that the sediment will spread along the Delfland coast due to natural processes. The Sand Engine should reinforce the beach and the dunes and protect the hinterland in the years to come.

Several morphological studies were carried out to predict the development of the Sand Engine. As described in [Mulder and Tonnon, 2011], the morphodynamic model Delft3D [Lesser et al., 2004] was used, supplemented with a wave module, SWAN [Booij et al., 1999], and using Transport2004 [Van Rijn et al., 2004] as sediment transport model. As aeolian processes are not included in the modeling suite, dune development was predicted based on empirical relations between dune foot location and beach area [de Vriend and Roelvink, 1989] and the assumption that the dune profile remains constant as it shifts in the horizontal. Based on model predictions, it is expected that the Sand Engine will spread out in the coming 20 years and the dune area will increase with 33 ha, Figure 2.3 shows the predicted morphological evolution.

Figure 2.1: Location of the Sand Engine. (From [Hoonhout and de Vries, 2017])
2. Comprehending the evolution of the Sand Engine

Figure 2.2: Aerial pictures of the Sand Engine.

(a) Aerial picture of the Sand Engine just after completion in 2011. (From [Ecoshape, 2011])

(b) Aerial picture of the Sand Engine in 2015. (From [Taal et al., 2016])

Figure 2.3: Predictions of the Sand Engine evolution. Upper left the initial model bathymetry; The other plots show the prediction 3, 5, 10, 15, and 20 years after construction. Blue colors indicate sub-aqueous zones; yellow-to-brown colors show the sub-aerial beach; and green colors indicate the intertidal area between high and low water. (From [Stive et al., 2013])

Figure 2.4: Measured Sand Engine bathymetry changes 2011 - 2016. The left plots show the survey data of JETSKI measurements from 2011 and 2016. The colors are likewise Figure 2.3. The rightmost plot shows the erosion and accretion, computed by the difference of the measurements. Blue colors indicate erosion, red indicates accretion.
2.3. Observations

2.3.1. Overall Morphological Development

After construction, various measurement surveys were performed to observe the evolution of the Sand Engine. de Schipper et al. [2016] describe the morphological changes of the first 18 months and Taal et al. [2016] describe the first four years of the Monitoring and Evaluation Programme. They state the shoreline of the peninsula retreats, its associated sediment losses are mostly balanced by accretion of adjacent coastlines and dunes. The sand of the Sand Engine continues to diffuse along the coast as the head further erodes and adjacent coast accretes, see the erosion-accretion pattern in Figure 2.4. More surveys and computed erosion and accretion are shown in Appendix F. A sandy spit has formed at the point of the Sand Engine and extended in North-Eastern direction over the years. This resulted in an elongation of the channel that connects the lagoon to the sea. The dune lake accreted due to wind-blown sediment. The lagoon accreted as well because of the aeolian sediment transport, but sediment is also supplied via the channel. At the southern side of the Sand Engine sediment was deposited leading to a broader beach, sometimes interrupted by runnels. The head of the Sand Engine eroded and after storms a scarp has been observed. Over the first five years, the Sand Engine changed from a bell-shape into a more triangular shape.

2.3.2. Aeolian Sediment Transport

Aeolian sand budgets at the Sand Engine of the first four years are described by Hoonhout and de Vries [2017]. They defined three different regions of the Sand Engine that are relevant and that are based on differences in measured behavior. Regions of erosion (1) and deposition (2) are distinct, but for a part of the sand engine it cannot be measured whether net aeolian driven volume change was positive or negative (3). During the years the exact location of these regions changes. A known source of sediment is the dry beach area, located mainly on the peninsula which is not influence by marine processes as it is located too high. Known deposition areas are the dune lake, lagoon and the dunes, where sediment accretes. The intertidal area is influenced by aeolian and marine processes, so it is unknown whether accreting or eroding aeolian processes dominate. Figure 2.5 shows the locations of the intertidal area in 2011 and 2015. Based on the volume balance of all the areas, it is advocated that the intertidal area is a sediment source, and in terms of volume supply even larger than the dry beach.

A clear link with hydrodynamic forcing is located in the intertidal area. Various beach properties are reasoned to limit aeolian sediment transport, like fetch length, moisture content, shell pavements, armouring and sorting. [Hoonhout and de Vries, 2016]. Without the tide, aeolian sediment transport would limit itself because of sediment sorting beach and armouring. Hydrodynamic processes undo these effects which makes the intertidal area a potential sediment source for aeolian sediment transport. During ebb, aeolian sediment transport in the intertidal area is possible as the sediment is located above the water level and prone to wind. As the finer sediment fractions are eroded more easily, sediment sorting or even beach armouring takes places, limiting the (aeolian) sediment supply. However as the tide rises, the (sorted) sediment becomes exposed to hydrodynamic processes like wave breaking and the top layer of the bed becomes mixed again. Therefore aeolian sediment supply is not (or less) limited when the water level drops and moisture content is sufficiently low in a new tidal cycle.

Contrarily to the sediment supply potential of the intertidal area, water surfaces trap sediment, considering aeolian sediment transport. Sediment could be blown into the sea where it sinks and is not transported any further by wind. At the Sand Engine sediment trapping water surfaces are present in the form of the sea, dune lake the lagoon. Another important sediment deposition location is the dunes where sediment settles due to the larger shear velocity because of the vegetation and due to a decrease in wind speed.
2. COMPREHENDING THE EVOLUTION OF THE SAND ENGINE

2.3.3. DUNE GROWTH

Dune growth along the Sand Engine from 2011 to 2015 shows spatial variation [Hoonhout and de Vries, 2017], especially westwards of the dune lake and the lagoon, see Figure 2.6 which shows the dune growth rates along the entire Delfland coast. On average a dune growth rate of $14 \text{ m}^3/\text{m}^3/\text{year}$ was found at the Sand Engine, which is less than the adjacent coasts. The lagoon and dune lake trap large amounts of sediment, on average $13 \text{ m}^3/\text{m}^3/\text{year}$. The prediction for dune growth used for the Environmental Impact Assessment of the Sand Engine, based on the empirical relation, was an increase of the dune area by 6.6 ha after 5 years and a 27.4 ha increase after 20 years, with an uncertainty bandwidth of a factor 2, [Mulder and Tonnon, 2011] and [Tonnon et al., 2009]. The wide beach area would imply a large increase of the dunes, however this is not observed. After 5 years only one ha of dune area increase is observed, [Taal et al., 2016]. A prediction for the dune volume increase was not given and is therefore hard to compare with recent measurements.
2.4. **STATE-OF-THE-ART UNCOPLED MODELING**

Besides the measurements, also models are able to inform on the processes at the Sand Engine. This section provides the main findings two state-of-the-art models, one ‘classical’ morphodynamic model and one aeolian sediment transport model.

2.4.1. **MORPHODYNAMIC MODEL**

Recently a Delft3D model was used to hindcast the first year of morphological change of the Sand Engine [Luijendijk et al., 2017]. The contributions of the modeled processes on the morphological response has been investigated. Wave forcing was the most important factor followed by the vertical tide, being responsible for respectively 75% and 17% of the eroded volumes. The contribution of other processes (horizontal tide, surge and wind) was of secondary order, being under 5%. Aeolian processes are not included in Delft3D and thus not investigated.

Improvements of the model result can be found when the model result is compared with measurements, see Figure 2.7. Especially the higher parts of the profile are not represented very well in the model and also the development at lagoon area is different compared to the measurements. The overall volume changes in the model and the general morphological evolution compare reasonably well. However according to the surveys of de Schipper et al. [2016] a sediment volume of about 0.5 M m$^3$ disappears out of the control area, which does not show up in the model results. This is likely due to aeolian sediment transport [Luijendijk et al., 2017] and alongshore redistribution [de Schipper et al., 2016]. Another result was that the model was sensitive to the setting of dry cell erosion, results in erosion of dry cells along the water line. Another important difference between model result and measurements is found at the the landward part of the peninsula Engine: the dry areas remain unchanged, whereas in reality erosion is observed.

2.4.2. **AEOLIAN SEDIMENT TRANSPORT MODEL**

Pioneering work on describing aeolian sediment transport is done by Bagnold [1937]. He designed a formula describing aeolian sediment transport. Instantaneous sediment transport rates are proportional to a cubic wind velocity above a certain velocity threshold. This relation was obtained with (dry) wind tunnel experiments. At the beach, the measured transport rates are found to be less than the rates predicted by Bagnold’s formula. Various beach properties are reasoned to limit transport, like fetch length, moisture content, shell pavements, armouring and sorting. [Hoonhout and de Vries, 2016].

The AeoLiS model by Hoonhout and de Vries [2016] is a extension of the process-based supply limitation model of de Vries et al. [2014]. A distinction is made between supply limiting factors as a result of the bed surface properties and transport limiting factors being mostly the wind forcing and grain diameter. By including different fractions, or even non-erodible elements, in the sediment composition, the model is able to simulate the processes of beach armouring and sorting. Also sediment supply in the intertidal area is conceptually included by introducing water level, wave energy, evaporation and infiltration input. Unfortunately no dune growth processes are included in the current version of AeoLiS. Deposition of sediment is included in the model, but vegetation growth and the effect of topography on the wind field is lacking.

Modeling aeolian sediment transport at the Sand Engine has been attempted with AeoLiS [Hoonhout, 2017]. Observed morphology was used as input and a simple approximation of the hydrodynamics was applied. The model did not solve bed change as this was implicitly included in the used morphological input, thereby excluding predictive capacity. The model results show that the total erosion and deposition volumes compare very well to the measurements of the Sand Engine described in [Hoonhout and de Vries, 2017], however the spatial distribution over the Sand Engine is different from the measurements. Dune accretion is overpredicted and filling of the dune lake and lagoon is underpredicted. However the importance of supply limitations is underlined, as without including these limitations the model predicts an overestimates the measured total sedimentation volumes with 400%.
2. COMPREHENDING THE EVOLUTION OF THE SAND ENGINE

Figure 2.7: Comparison of the bathymetry of the Sand Engine between the model results of Luijendijk and the measurements of De Schipper. (From [Luijendijk et al., 2017])

Figure 2.8: Comparison of bathymetry at the Sand Engine between measurements and AeoLiS model results. (From [Hoonhout, 2017])
2.5. **SUMMARY AND CONCLUSIONS**

In view of the morphological evolution of the Sand Engine, wave forcing and the vertical tide are the most important processes. These processes are included in the morphodynamic model Delft3D. The spreading of sand along the coast is, considering a larger scale, the most profound observation. Delft3D lacks sub-aerial processes and a sediment deficit between the model results and measurements is observed.

Aeolian sediment transport at the Sand Engine is governed by the availability of sediment. Dune growth needs aeolian sediment transport coming from the beach. This could be the reason why the dune growth at the Sand Engine is variable in space, because the lagoon and dune lake trap sediment. This also explains why dune growth rates at the Sand Engine are smaller than at the adjacent coast. The AeoLiS model includes the supply-limited transport and cross-shore aeolian sediment transport rates at the dunes are simulated. Modeling the increase of dune area is not possible as the current version of AeoLiS does not take enhanced sediment deposition in the dunes into account.

2.5.1. **IMPLICATIONS FOR COUPLED MODEL**

Interaction between aeolian sediment transport and hydrodynamics is located in the intertidal area. This area is subject to morphological change due to waves and currents and also aeolian driven sediment entrainment or deposition takes place. Hydrodynamics affect aeolian sediment transport on both small and large timescales. On an hourly timescale, especially the mixing of sediment by waves is important to undo armouring and the mixed sediment falls dry and becomes subject to wind because of the tide. Due to the dynamic bathymetry the shape of this intertidal area changes in time (order of months) and consequently the location of the source of aeolian transported sediment changes. The effect of aeolian sediment transport on hydrodynamics is relevant on larger timescales (years), and for morphodynamic models the transition between nearshore and the beach is a potentially important sediment sink. At the Sand Engine also the lowering of the bed level of the beach at the peninsula could lead to a breach of the beach towards the dune lake or lagoon.

This description of the concerned physics should now be transferred into the coupled model which is dealt with in the next chapter.
3

MODEL COUPLING

3.1. INTRODUCTION
This chapter explains the modeling approach used in this research. The two (sub-)models AeoLiS and Delft3D FM are coupled into one model. This chapter explains the general considerations of the coupling and presents the resulting coupled model. First the requirements of this model are listed in Section 3.2. Second the overview of the chosen coupled model approach is presented in Section 3.3. In Section 3.4 the coupled model framework is presented, this beholds a two-way coupling. To overcome issues with the morphology module of Delft3D FM, a workaround is created which results in a one-way coupling, this one-way model framework is presented in Section 3.5. One is referred to Appendix A for the technical implementation of the coupled model frameworks.

3.2. COUPLED MODEL REQUIREMENTS
Based on the theory in Chapter 2, the coupled model has to fulfill some requirements in order to represent the most important physics. The Sand Engine is a complex area which is highly dynamic as it varies considerably in space and time. To conform to the laws of nature mass conservation needs to be validated, especially because the models AeoLiS and Delft3D FM are under development and not all the implementations are fully tested. The geographical domain which is considered should cover the locations of the modeled processes. As the processes simulated by different models could occur on the same place because of the dynamic water line the domains should overlap to a great extend. However spatial overlap might be problematic when different morphological processes are not correctly separated in space. It could occur that the same sediment is transported a number of times by processes in different models while in reality this is only once.

This results in the following demands:

• The model needs to allow variation in time and space
• The coupling must be mass conservative
• The total domain area covers from offshore to the dune foot and the domains of the sub-models require a suitable minimum overlap
• The modeled processes in different sub-models should interact.
• The modeled processes should be separated in such a way that there is no 'double counting' of sediment transport.

1In addition to the previous chapters, the computational cores of Delft3D FM are explicitly mentioned, being the hydrodynamic model DFlow FM and the wave model SWAN. The other chapters imply the use of SWAN and DFlow FM within the Delft3D FM model. These computational cores are coupled, this existing coupling of DFlow FM and SWAN within Delft3D FM via a communication file is included in the model but is not elaborated any further as this is a well-established method.
3.3. OUTLINE OF COUPLED MODEL COMMUNICATION AND INTERACTION

This section provides an outline of communication between models within the coupled model. In short, this method is to use a controller environment to steer the models (AeoLiS, Delft3D FM) by means of the Basic Model Interface (BMI), which allows exchange of information on model variables.

3.3.1. CONCEPT OF COMMUNICATION BETWEEN THE MODELS

In order to couple the models their functionalities need to be extended to allow certain communication between them. The chosen method is to use a controller environment, abbreviated to controller in this thesis. The controller is responsible for the coupling: it steers the models and uses them like independent models. The controller calls a model to perform computations based on given input, but the model itself and its calculation method is not touched upon.

Other methods than the chosen one of using a controller could be: building a new model from scratch based on the computations of Delft3D FM and AeoLiS, or extensively adapting the current models in order establish communication while running. These are both very laborious procedures. By using a controller there is no need to waste time on (re)building the individual models nor can extra coding errors be introduced in the models. In addition, there is a very explicit description of the communication between the models. The downside of using a controller is that all the communication must be handled by the controller, the connection might be less efficient computationally wise and the information might be used incorrectly without noticing when communication between the models and controller is erroneous described.

A visual representation of the communication between the models and the controller is given in Figure 3.1. In a schematic way the following steps are taken:

- The controller starts the model runs by providing the initial conditions and boundary conditions.
- The models do their (separated) computations, they update variables by calculations, like hydrodynamics or sediment transport.
- The models have a certain output, containing the calculated variables, e.g. the bed levels.
- The controller reads the output of the models.
- If necessary the output is processed by the controller (e.g. interpolated).
- The controller gives new input to models (e.g. exchanged to the other model).
- These steps of model calculations and controller processing are looped until the end time of the models.
- Finally, the models deliver the output.

3.3.2. INTERACTION WITH THE MODELS: BMI

As described in the concept above, the sub-models need to be steered by the controller environment. The chosen method for this interaction is to use a controller environment. The controller is responsible for the coupling: it steers the models and uses them like independent models. The controller calls a model to perform computations based on given input, but the model itself and its calculation method is not touched upon.

First the need for this interface is stressed. Nowadays, a lot of hardware comes with plug-and-play technology, one can directly use it. Unfortunately this is not the case for software such as the models AeoLiS and Delft3D FM. However, attempts are made to standardize the handling of software to have a plug-and-play functionality. BMI is an example of such an attempt, designed by the Community Surface Dynamics Modeling System, both described in [Peckham et al., 2013]. Many alternatives are available, like ESMF [Hill et al., 2004], OMS [David et al., 2013] or openMI [Gregersen et al., 2007].

BMI (Basic Model Interface) is a software component interface. In this case the models are the software components, delivering certain functionalities like a morphodynamic computation. In order to explain what the interface means, an analogy is made with hardware in Peckham et al. [2013]. They state that an interface is like a port and it allows to interact by means of standardized capabilities. For the components, the interface consist of a set of methods or functions to be able to use their functionalities. By implementing the interface into a (software) component it becomes possible to interact with this component by standardized methods of the interface.
Implementing BMI does not change the models, it only allows to use their functionalities and model can still be run stand alone. This is a advantage of BMI over other alternatives. As BMI is designed to allow model coupling, its interface allows interaction with the models. According to Peckham et al. [2013] a standard pattern of three main parts is often encountered in models as they usually come in the following form: a set of variables or parameters is subjected to physical laws and changes (stepwise) in time. The three parts are initializing, updating and finalizing. BMI allows: to start the model (initialize), let the model do calculations (update) and finish the computation (finalize) and also read and/or change the used variables and parameters with get- and set-functions (called get- and put- functions in openMI literature). A more detailed description of the functions is described in the paper mentioned above.

Concluding, BMI is a set of methods and functions which are added to the models AeoLiS and Delft3D FM. Both AeoLiS and Delft3D FM are BMI-compliant. Hence, it is possible to use the functionalities of the models called from a different environment (being the controller). The amount of implemented functions differs between the computational cores. The most important difference is that get- and set-functionality has not been implemented in SWAN but it has been in AeoLiS and DFlow FM.

3.4. TWO-WAY COUPLED MODEL FRAMEWORK: DELFT3D FM - AEOLiS COUPLING

The previous sections describe the needs of this model and the general approach of coupling. This section describes the coupling of the sub-models AeoLiS and Delft3D FM into one. The technical implementation of this framework is provided in Appendix A.

The conceptual coupling of the models, being the most important processes and the interaction between them, is presented in Figure 3.2. After the start of the model, the input is processed towards initial and boundary conditions. Four physical processes are identified: wave phenomena, aeolian sediment transport, (tidal) hydrodynamics and sub-aqueous sediment transport. Waves influence the aeolian sediment transport and hydrodynamics. The hydrodynamics determine the sub-aqueous sediment transport and it influences the waves and the aeolian sediment transport. Together, the sub-aerial and sub-aqueous sediment transport determine the development of the bathymetry, which influences the waves, aeolian sediment transport and the hydrodynamics. Waves are modeled by SWAN, aeolian sediment transport by AeoLiS, and hydrodynamics and sub-aqueous sediment transport by DFlow FM. In Appendix B a brief description of the sub-models is presented, including the most important formula’s which are solved.

Three topics about this coupling are discussed in more detail. First the physics are addressed by specify-
3.4. **TWO-WAY COUPLED MODEL FRAMEWORK: DELFT3D FM - AEOLiS COUPLING**

3.4.1. **COUPLING OF VARIABLES**

There are three crucial variables identified which need to be exchanged between the models: bed level, water level and wave height. The bed level and its morphological development are considered as the output variable of primary interest. The water level determines to a great extent the processes which contribute to this morphological development. The wave height represents the amount of mixing of sediment. The formulas which are mentioned in this Section are explained in Appendix B. Besides these three variables mentioned above, there are other variables which need to be coupled for a correct current-wave interaction within Delft3D.

**BED LEVELS**

The predicted bed levels are the key output of the coupled model. They are the result of different morphological processes in both AEOLiS and DFlow FM. SWAN has no direct influence on the bed levels.

In AEOLiS, the computation of the bed levels is straightforward as the computed bed level difference directly originates from the sediment entrainment (sometimes called "pickup" in AEOLiS literature). Due to the wind, sediment erodes from the areas where the shear velocity threshold is low (e.g. a dry area with a lot of fine sediment) and accretes where the shear velocity threshold is high (e.g. in wet areas). The bed levels themselves do not influence this shear velocity threshold and therefore they do not influence sediment entrainment.

In DFlow FM there is a morphodynamic interaction between bed levels and the processes determining the sediment transport and therefore entrainment. The bed levels and water levels determine the water depth in the continuity equation, Formula B.1, and consequently velocities and related transport.

**WATER LEVELS**

The water level and accompanying shore water line are of major importance for the coastal processes. The water levels are the result of the computed hydrodynamics in DFlow FM and are transferred to AEOLiS and...
SWAN. The most profound physical property which is determined by the water level is whether a cell is wet or dry.

In AeoLiS the water levels are solely used for the distinction between wet and dry cells. The dry cells could erode because of wind forcing and the wet cells are set with a very high shear velocity threshold so erosion cannot take place. Related to the water level height, the moisture content of (dry) cells is computed which affects the shear velocity threshold. This shear velocity threshold determines the saturated concentration in Formula B.5.

In DFlow FM the water heights resulting from the water levels (and bed levels) are one of the primitive variables which are solved in the shallow water equations, Formula B.1. Hydrostatic waves travel through the domain and forces on the water column affect the depth-averaged currents for which the depths need to be known. A difficult aspect in DFlow FM is drying and flooding of cells. Positive water depths need to be guaranteed and the propagation of flood and ebb waves need to be accurate. Dry cells are taken out of the computation until they become wet again. Morphodynamic processes are computed only in the wet cells.

In SWAN the water depth influences the wave breaking process and the computed orbital velocities. Wave breaking is included as a wave action sink in the wave action balance, Formula B.4. The computed wave forces of SWAN are transferred to DFlow FM and included as hydrodynamic forcing resulting in water level set-up and set-down. This is included in the momentum equations, Formulas B.2 and B.3.

Both AeoLiS and DFlow make use of a water depth threshold to determine whether a cell is wet or dry. As DFlow FM alters water levels during the computation it is possible that an area temporarily becomes wet, e.g. the intertidal area, and during the lowering of the water level a wet cell becomes dry. If this is the case the water level will remain at the last computed value being smaller than the threshold. This can lead to an artificial thin film of water on dry cells. These values are exchanged to AeoLiS which could lead to an artificial decrease of aeolian sediment transport if this is not recognized as a fictitious water level. It is therefore important to set the water level threshold of AeoLiS larger than or equal to the threshold in DFlow FM.

**Wave Heights**

The existing coupling between DFlow FM and SWAN is crucial for modeling the current-wave interaction. Wave forces influence the currents (through radiation stresses) and vice versa the mean currents influence waves (changing wave propagation speed and mean direction and causing Doppler shift). The DFlow FM - SWAN coupling is a well-established method which is not elaborated on any further.

An important effect of waves is that the orbital velocities of waves stir up sediment and have a major impact on sediment transport. The mixing of sediment mixing also influences AeoLiS. The mixing of sediment changes the available mass in Formula B.5. By reworking sediment up to a certain depth, armoured layers are mixed with well mixed layers, which are able to erode further. The wave heights determine this mixing depth and therefore send to AeoLiS.

**3.4.2. Coupling in Time**

Coupling in time can roughly be divided in two cases: online and offline, both visualized in Figure 3.3. For offline coupled models the sub-models use the output of one as the input to the other. The processes involved are assumed to influence each other independently. As one sub-model is running, the other is not needed. During online coupling the sub-models are used at the same time using the same (coupled) information. After a certain interval information is exchanged between the sub-models so that the they both have the same input again. Based on physics in the intertidal area, there is chosen for an online coupling.

Although the morphological time scales of aeolian sedimentation processes and sub-aqueous processes considerably differ, online coupling is desired. To fulfill the demand of ‘no double counting’, equal bed and water levels in the sub-models are necessary in order to allow for an online coupling where morphological processes can act simultaneously.

The aeolian armouring process and sediment mixing are dependent on the instantaneous water line. As this is highly variable in time a tight coupling in time is desired, in the order of minutes to hours. Also it is a common engineering practice to couple DFlow FM and SWAN at an interval of 20 minutes. So it is then only a small step to include the morphological development in the coupling. The coupling to other models is also easier to realize if an online coupling is realized, which may become a welcome advantage in the future.

A visual representation of the exchange of information of variables in time is given in Figure 3.4 for the online coupling. A loop-wise procedure is developed and a loop looks as follows. It starts with an update of SWAN, determining the wave heights for AeoLiS and DFlow FM for the whole loop time (being 1200 seconds
3.4. **TWO-WAY COUPLED MODEL FRAMEWORK: DELFT3D FM - AEOLiS COUPLING**

Figure 3.3: Schematic of online and offline coupling.

In the example of the figure, AEOLiS does an update of (600 seconds) and DFlow FM does a number of updates so the total time equals the AEOLiS update (3*200 seconds). Then AEOLiS and DFlow FM exchange bed and water levels. AEOLiS gets a new water level from DFlow FM and the updated bed levels are combined. This procedure of updating AEOLiS and DFlow FM is repeated (once more), so at the end (1200 seconds) the new bed and water level is also input for the new SWAN update. This loop is now repeated until the end of the simulation.
Figure 3.4: Online coupling of the models. The arrows indicate transfer of updated variables. A white block indicate a model time step. The width of a block corresponds with the duration of one time step. Note the width of DFlow FM is schematized as they are much smaller in reality and the SWAN time step solves for one moment in time. The numbers indicate the amount of time steps taken used as input for the models. This amount is counted from the last update of the sub-model which stands higher in the 'hierarchy'. This is listed in the order SWAN, AeolIS, DFlow FM, based on the total time steps executed by a sub-model. The first AeolIS input is defined as 0.0.0.
3.5. ONE-WAY MODEL FRAMEWORK: A DELFT3D FM MORPHOLOGY WORKAROUND

A coupling between (sub-)models implies that the individual sub-models are of sufficient quality, as otherwise all other model-components will be negatively influenced by spurious outcome of a incorrect functioning sub-model. The morphology module of Delft3D FM is under development and during the execution of this research the output was of inadequate quality. It turned out to be necessary to use an alternative for the computed morphological change. Therefore a workaround was made in this thesis to overcome this problem. This section describes the resulting difference of the coupling set up.

SUBSTITUTE DELFT3D FM MORPHOLOGY BY DELFT3D MORPHOLOGY

Delft3D FM is supposed to simulate the same physics as Delft3D, including morphology, and Delft3D models already modeled the Sand Engine reasonably accurate, e.g. [Luijendijk et al., 2017]. Therefore it makes sense to fall back on the morphological results of Delft3D. However, Delft3D is not BMI-compliant and therefore could not be included within the coupled framework. A Delft3D simulation is performed including a forcing as similar as possible as in the coupled model. Intermediate bed levels of this simulation are used to determine the bed level difference in time, which are used as input in the coupled framework.

The bed level differences from Delft3D instead of bed level differences computed by Delft3D FM are transferred to the controller. The result is an one-way coupling, in Figure 3.6 the conceptual coupling is shown, including the use of Delft3D.

IMPLICATIONS ON THE COUPLING

The most important implication is that the suq-aqueous morphological change is now computed independently. The previous described two-way model framework was adapted accordingly. The fundamental difference is that in the two-way model framework sub-aqueous sediment transport influences aeolian sediment transport and the other way around aeolian sediment transport influences sub-aqueous sediment transport. In the one-way coupling sub-aqueous sediment transport still influences aeolian sediment transport, but aeolian transport does not influences sub-aqueous sediment transport. This difference is illustrated in Figure 3.7.

Figure 3.5: An example of complex grid configuration. The still water line of the Sand Engine is depicted in black. The yellow recti-linear grid represents a possible AeolLiS grid and the blue unstructured grid represents a possible DFlow FM grid.
Figure 3.6: Schematization of physical processes and the models representing them in the one-way coupling.

Figure 3.7: Two-way coupling versus one-way coupling.
3.6. **Summary**

The coupled model structure consists of the two sub-models AeolLiS and Delft3D FM which are steered by a controller for which BMI is used to interact with the models. The exchange of three variables is considered as essential to create a full-functioning morphodynamic model. These three variables are: bed levels, water levels and wave heights. To conform to the physical processes of the models as best as possible, an online model coupling is applied and variable exchange is highly frequent in time in the order of minutes to hours. As the fundamentally supported grid types differ between the sub-models, a complex mass-conservative interpolation method in space is developed.

Two different coupling frameworks are presented: a two-way coupling in which aeolian sediment transport and sub-aqueous sediment transport interact and an one-way coupling in which the sub-aqueous sediment transport is calculated independently. The latter is introduced as a pragmatic work-around to overcome problems with the morphology module of Delft3D FM.

A next step is to validate this coupled model. It needs to be shown that the designed model simulates the relevant processes from the previous chapter. The next chapter demonstrates the correct functioning of the proposed coupled model structure.
4.1. **INTRODUCTION**

In this chapter the model set up and preliminary results of a proof-of-concept case are presented to show that the coupled model works correctly. The complete outline of the proof-of-concept case is stated in Section 4.2. A relatively simple coast is simulated, for which the overall input for the model is presented in Section 4.3. The coupling of the models is enhanced in different steps from the individual uncoupled models towards the two-way coupled model. The steps are described in Section 4.4. The discussion about the results and conclusions are presented in Section 4.5 and 4.6.

4.2. **OUTLINE**

This section describes the goal and method of the proof-of-concept. The proof-of-concept is presented to give a quick insight in the functioning of the coupled model and to qualitatively demonstrate the physical effects. The set-up is based on a measured bathymetry but the boundary conditions are simplified for a clear result. This makes validation against data impossible, which is not a problem as this proof-of-concept is about the qualitative performance of the coupled model.

In order to show the functioning of the coupling, a step-wise increase in model complexity is applied. First the uncoupled models are used to create a benchmark after which these results are compared with coupled model results. There are two uncoupled models without exchange: an AeoLiS model and a Delft3D FM model. As the coupling between DFlow FM and SWAN within Delft3D FM is already well-established, Delft3D is referred to as uncoupled (to AeoLiS). The three coupled models are defined to increase the exchange of variables from Delft3D FM towards AeoLiS, the other way around bed level differences from AeoLiS are always passed on to Delft3D FM. In the first case the water levels are exchanged, which results in a time-varying water line in AeoLiS. Second, the wave heights are added to the exchange which causes sediment mixing in AeoLiS. Finally the morphological development computed by Delft3D FM is included and together with the AeoLiS morphological changes this results in the two-way coupled model.

4.3. **OVERALL MODEL SETUP**

This section gives a description of the overall model set up. The following aspects are discussed: bathymetry, computational domains, boundary conditions, sediment definitions and the time steps.

The area of interest is a narrow coastal strip, which is modelled in DFlow FM and AeoLiS, and a larger domain is set in SWAN. A schematic topview of the problem is presented in Figure 4.1a.

4.3.1. **BATHYMETRY**

The initial bathymetry in the AeoLiS and DFlow FM domain is an arbitrary cross-section at Vlugtenburg, shown in Figure 4.1b. For the SWAN domain, the bathymetry is an extension of the open boundaries of DFlow FM.

Some notable features of the profile are listed below.

- The fore-shore slope is approximately 1:100.
4.3. **Overall model setup**

(a) Model set-up used for the proof-of-concept.

(b) Bathymetry of the area of interest.

Figure 4.1: Proof-of-concept model set up.

- A near-shore bar is located at $x = 700$ m and a smaller one at $x = 830$ m.
- Around the intertidal zone the slope is approximately 1:15.
- In the intertidal zone a small bump is identified at $x = 910$ m.
- There is a topographic trough in the sub-aerial beach around $x = 1300$ m.

4.3.2. **DOMAINS & GRIDS**

The area of interest extends 100 m along-shore and approximately 1700 m cross-shore. In AeoLiS and DFlow FM this area is simulated on a equidistant rectilinear grid, with a cell size of 8.5 m by 10 m. In the cross-shore direction 196 cells are used for both AeoLiS and DFlow FM. In along-shore direction 10 cells are used for DFlow FM and 9 for AeoLiS. Note that in AeoLiS the bed level information is stored in the cell corners and in DFlow FM in the cell centers. So AeoLiS contains $197 \times 10$ bed level points and DFlow FM contains $196 \times 10$ bed level points. The extra column of bed level points is located at the land boundary side of the grid.

The SWAN grid equals the DFlow FM grid but it is extended. At the off-shore side it is extended by 10 cells of 50 m and at the lateral boundaries by 20 cells of 100 m at both sides. This results in a non-equidistant rectilinear grid of 206 $\times$ 50 cells.

4.3.3. **BOUNDARIES AND FORCING**

**AeoLiS**

At the offshore side a zero-transport boundary is imposed. At the lateral sides circular boundaries are used, implying an infinite wide beach. The onshore side is simulated using a Neumann boundary of a zero gradient.

**DFlow FM**

At the offshore side a sinusoidal time varying water level boundary is imposed with 1.7 m tidal range and a period of 745 minutes (a semi-diurnal tide). This roughly corresponds to the observed tidal signal at the Sand Engine. At the lateral sides Neumann boundaries of a zero gradient are used. The onshore side is a land boundary.

**SWAN**

The forcing of all the water boundaries is the same and contains a wave spectrum which is uniform in time. The spectrum characteristics are: a significant wave height of 1.5 m, a mean and peak wave direction of 22.5 degrees from the shore normal. The spreading coefficient is set to 4 which corresponds to wind-waves.

**WIND**

The wind forcing in all models is set constant at 10 m/s, directed shore normal, i.e. perpendicular towards the coast.
4.3.4. SEDIMENT AND MORPHOLOGY

AEOLiS

The definition of sediment which is used was taken from Hoonhout [2017]. A lognormal sediment definition is used for sand fractions supplemented with some shell fractions, see Figure 4.2. The layer thickness was set to 5 mm and 5 layers are used.

DFlow FM

A single fraction with a $d_{50}$ of 250 $\mu$m is used in DFlow FM. No morphological acceleration is applied.

4.3.5. TIME STEPS

The timestep of AeoLiS is set to 10 minutes. After each AeoLiS time step bed- and water levels are updated by DFlow FM. The boundaries in DFlow FM are updated every 12 seconds, during the runs DFlow FM used an average time step of 6.0 seconds. SWAN is updated every 20 minutes.

4.4. CASES

A few cases have been derived and a distinction between uncoupled (U) and coupled models (C) is made. The uncoupled models are the individual models AeoLiS and Delft3D FM. No exchange of variables exists between AeoLiS and DFlow FM. To evaluate the proof-of-concept there are coupled models in which exchange is present and an increasing number of processes is included.

4.4.1. UNCOUPLED MODELS

U1: AeoLiS-only Morphological development due to aeolian sediment transport around a constant water level.

U2: Delft3D FM-only Morphological development due to hydrodynamics forced by the tide and waves and resulting sediment transport.

4.4.2. COUPLED MODELS

C1: Aeolian sediment transport & hydrodynamics Morphological development solely due to aeolian sediment transport around a dynamic water level. Hydrodynamics include waves, but the sediment is not mixed by waves in AeoLiS. This beholds exchange of bed levels from AeoLiS and water levels from Delft3D FM.

C2: Aeolian sediment transport & hydrodynamics & wave mixing Morphological development due to aeolian sediment transport around a dynamic water level. Sediment is mixed by waves. This beholds exchange of bed levels from AeoLiS, water levels from DFlow FM and wave heights from SWAN.

C3: Two-way coupled Morphological development due to aeolian sediment transport around a dynamic water level and due to hydrodynamics forced by the tide and waves. Sediment is mixed by waves. Exchange of bed levels from AeoLiS, bed levels & water levels from DFlow FM and wave heights from SWAN.
4.5. RESULTS
In this section the results of the proof-of-concept cases are discussed and a link between the results and expectations is given. In Appendix D some extra results are presented on some technical performance of the coupling. It is shown that the coupling procedure costs only negligible extra computational time and the coupling also works for other grid definitions.

4.5.1. UNCOUPLED MODELS

U1 AeoLiS-only
The uncoupled cases show the individual model responses to the imposed forcing. In the AeoLiS model case U1, the fictive 10 m/s onshore-directed wind velocity quickly results in armouring of the bed. Although the wind velocity is relatively high the coarse fractions do not erode and cover the fines. Erosion starts above the water line and is limited to about 1 cm.

(a) Proof-of-concept AeoLiS-only initial profile.
(b) Proof-of-concept AeoLiS-only bed level differences.

Figure 4.3: Proof-of-concept AeoLiS-only, zoomed in around the water line

U2 Delft3D FM-only
The Delft3D FM only model case U2 shows a completely different result compared to the AeoLiS only case, as expected. The magnitude of the erosion and accretion is an order of magnitude larger compared with the AeoLiS result. Also the spatial distribution of erosion and deposition is completely different. A steepening of the profile occurs at the water line and a landward movement of the subtidal bar is observed. Above the mean water line no morphological development is visible. Although the most-landward located wet cell has a sufficient depth at high tide for morphology updates, it remains unchanged.

(a) Proof-of-concept Delft3D FM-only profile.
(b) Proof-of-concept Delft3D FM-only bed level differences.

Figure 4.4: Proof-of-concept Delft3D FM-only, zoomed in around the water line
4.5.2. **COUPLED MODELS**
The coupled cases of the proof-of-concept show the expected effects of the additional exchanged variables. The inclusion of sub-aqueous processes alters the aeolian sediment transport as seen in literature. The reverse effect of aeolian sediment transport on sub-aqueous processes is expected to be limited as the uncoupled results show a different order of magnitude of erosion. Therefore it makes sense to approach the performance from an aeolian perspective.

**C1 AEOLIAN SEDIMENT TRANSPORT & HYDRODYNAMICS**
By including the hydrodynamics and aeolian sediment transport as in case C1, a similar but seaward shifted erosion pattern develops compared to the uncoupled AeoLiS case. The water line, which acts as a zero-flux boundary, varies in time due to the sinusoidal tidal signal in DFlow FM. Therewith the most seaward located eroding cell is now shifted in offshore direction. The magnitude of the erosion stayed roughly the same as armouring still takes place, however due the time and space varying aeolian sediment transport this is a somewhat inconstant line, which is in line with other AeoLiS results [Hoonhout and de Vries, 2016].

![Figure 4.5: Proof-of-concept Aeolian sediment transport morphology & hydrodynamics bed level differences.](image)

**C2 AEOLIAN SEDIMENT TRANSPORT & HYDRODYNAMICS & WAVE MIXING**
The addition of wave mixing to the coupled model in case C2 leads to enhanced erosion in the intertidal area. This is exactly in line with the expectation as the armouring due to aeolian sediment transport now is undone because of the wave action. The erosion above the high water line is now somewhat hampered, probably because the upwind increase of available sediment leads to less availability-limitations and a smaller cross-shore transport gradient.

![Figure 4.6: Proof-of-concept Aeolian sediment transport & hydrodynamics & wave mixing bed level differences.](image)
C3 TWO-WAY COUPLED

The two-way coupled case C3 builds on C2, by including the morphological development computed by DFlow FM. The enhanced aeolian sediment transport in the intertidal area leading to more pronounced erosion is clearly visible compared to the AeoLiS case U1. Enhanced erosion just below the low water line at x = 990 m is visible compared with the DFlow FM case U2.

![Figure 4.7: Proof-of-concept two-way coupled bed level differences. The uncoupled results (from Figures 4.3b and 4.4b) are also included.](image)

4.6. SUMMARY AND CONCLUSIONS

This section reviews the effects and reasons on the functioning of the coupling.

The proof-of-concept shows that the coupled model is not a simple superposition of two uncoupled models. The coupling has a considerable effect on the aeolian sediment transport, especially the sediment mixing by waves is of high impact. From a DFlow FM perspective, the effect of the coupling on sub-aqueous morphology is limited but not zero. The intertidal area is altered the most because of the coupling.

Still the influence of the individual models is clearly visible. The result in the dry domain in C3 is highly comparable to that of U1. Also the subtidal bathymetry changes of C3 and U2 almost perfectly align. This provides evidence that the coupling performs well.

The necessity to couple the three variables (bed levels, water levels, wave heights) is demonstrated in the proof-of-concept. As simulating morphological development is of key interest bed levels need to be exchanged. The proof-of-concept shows that AeoLiS is of lesser influence on the DFlow FM than vice versa. This aligns with the theory that aeolian processes cover larger time scales. The water level is important to AeoLiS to locate the zero-transport gradient and the exchange of wave heights induces extra available sediment in the intertidal area by limiting the armouring.

In Appendix D some extra results are presented on some technical performance of the coupling. It is shown that the coupling procedure costs only negligible extra computational time and the coupling also works for other grid definitions. Combined with results of this chapter it is concluded that the coupling works as expected. The model can be used for a real case, e.g. the Sand Engine, which is done in the next chapter.
5.1. **INTRODUCTION**

This chapter functions to investigate the performance of the coupled model. In this chapter, the model setup and results of the Sand Engine case are presented.

The Sand Engine is a complex coastal site and the one-way model framework was used, which is elaborated on in Section 5.2.

Next, the model setup is addressed in Section 5.3, the AeoLiS model is an adaptation of [Hoonhout, 2017]. The Delft3D FM setup (for hydrodynamics and wave mixing) and the Delft3D setup (for sub-aqueous morphology) are based on the Delft3D model of [Luijendijk et al., 2017].

A hindcast of five years of the evolution of the Sand Engine is performed with the one-way coupled model. First, the results are compared with measurements in Section 5.4. The primary interest is the morphological evolution, but the model performance on dune growth modeling is also addressed. The model results of the one-way coupled model of the Sand Engine are compared with measurements to investigate the model skill to compute morphological development quantified with the Brier Skill Score.

Second, the results are compared with an uncoupled model in Section 5.5. Because of the one-way approach, the sub-aqueous morphological development in the coupled model is not different from an uncoupled Delft3D model. In other words, considering the bed change, only the bed change induced by wind is altered. Therefore this comparison is made between the aeolian induced bed change of the coupled model and an uncoupled AeoLiS model.

5.2. **ONE-WAY COUPLED APPROACH**

The morphological evolution of the Sand Engine is very complex with large variations in space and time. This implies the need for a high-quality model. The morphology module of Delft3D FM is under development and during the execution of this research, the output was unfortunately not accurate enough. Therefore the results of the two-way coupled model (including morphology updates from DFlow FM) were of inadequate quality. In Appendix E, the first months of development of the Sand Engine according to the two-way model is included, on which this conclusion is based on. The workaround of an one-way model framework was presented in 3.5. The sub-aqueous morphological development is calculated independently, but the aeolian induced transports is still influenced by the sub-aqueous morphology, waves and hydrodynamics.

5.3. **MODEL SETUP**

This section describes the model setup. The one-way coupled model and the two-way coupled model have roughly the same setup, both are described in this section. Some modifications were made in the one-way coupled model to reduce computational costs.

The AeoLiS model is an adaptation of [Hoonhout, 2017]. The Delft3D FM setup (for hydrodynamics and wave mixing) and the Delft3D setup (for sub-aqueous morphology) are based on the Delft3D model of [Luijendijk et al., 2017]. The Delft3D FM setup is described for DFlow FM and SWAN. The Delft3D setup equals the Delft3D FM set up, unless stated else.
5.3. MODEL SETUP

5.3.1. BATHYMETRY
The initial bathymetry is based on the JETSKI data extended alongshore with NEMO measurements. The SWAN bathymetry is shown in Figure 5.1a. Both AeoLiS and DFLow FM use a linear interpolation from the data in Figure 5.1b. The part of the AeoLiS grid which is beyond the DFlow FM domain is an extension of the bathymetry at the edges of the DFlow FM domain.

5.3.2. DOMAINS & GRIDS
The area of interest is approximately 9.3 km along-shore and 3.9 km cross-shore.

First, the grids for the two-way coupled model are presented. SWAN uses nested grids, visualized in Figure 5.2a. In AeoLiS a part of this region is simulated on an equidistant rectilinear grid, with a cell size of 25 m by 25 m, resulting in 376 by 70 grid cells alongshore and cross-shore. The AeoLiS grid overlaps the DFlow FM grid but does not protrude as far offshore as no aeolian sediment transport is expected at sea. Compared to the DFlow FM onshore boundary the onshore of the AeoLiS grid is rotated in such a way it is parallel to the coastline around the Sand Engine. This is necessary to correctly use the circular lateral boundaries of AeoLiS as the beach width is now the same at both lateral boundaries. Figure 5.2b shows the overlap of both grids.

In DFlow FM a curvilinear grid is used. Grid cells differ in size from 36 m by 18 m for smallest cells near the lagoon up to 120 m by 100 m for the largest cells at the offshore corners.

The Delft3D model contains a larger domain for the hydrodynamic module. The entire Delfland coast is included in this domain.

Second, the grids in the one-way coupled model are addressed. The grids of AeoLiS and Delft3D FM are coarsened to reduce the computational time. As no morphodynamic interaction is present in Delft3D FM anymore, the lowering of the grid resolution is justified. AeoLiS grid cells are enlarged to 35 m by 35 m resulting, which roughly halves the amount of grid cells. The DFlow FM grid is coarsened by a factor 4 in
5. **Coupled model of the Sand Engine**

Figure 5.3: Waves, water levels and wind velocity forcing applied in the Sand Engine hindcast. The (instantaneous) wave heights are saved on a 48 hour interval, the water levels and wind velocities are saved on a 5 hour interval.

total: in x and y direction the grid cells are enlarged by a factor 2. In SWAN the most detailed grid was subject to the same coarsening as the DFlow FM grid. The intermediate sized SWAN grid was coarsened by a factor 2.25 in total, in x and y direction the grid cells are enlarged by a factor of 1.5.

### 5.3.3. Boundaries and Forcing

A five year hindcast is performed based on measured and computed forcings.

**AeoLiS**

At the offshore side a zero transport boundary is imposed. At the lateral sides circular boundaries are used, implying an infinite wide beach. The onshore side is simulated using a Neumann boundary of a zero transport gradient. The AeoLiS model uses measured wind velocities and directions obtained at Hoek van Holland. A constant wind field is implied over the whole AeoLiS domain.

**DFlow FM**

At the offshore side a time varying water level boundary is imposed. The water level boundaries is a superposition of the vertical tide and the measured surge. At the lateral sides Neumann boundaries with a non-zero gradient are used to simulate the horizontal tide, the gradient is based on the Kuststrookfijn model [Rijkswaterstaat and Deltares, 2009]. The onshore side is a land boundary. The DFlow FM and the SWAN model use measured wind velocities and directions obtained at Lichteiland Goeree (LEG). This offshore platform represents the wind at sea used to model wind wave interactions. A constant wind field is implied over the DFlow FM and is extended to the SWAN domains.

**SWAN**

SWAN is nested in three computational grids and the largest SWAN grid is forced with measured wave data of two offshore platforms: Europlatform (EUR) and IJmuiden munitie depot (IJM MSP). The Southern boundary uses EUR, the Northern uses IJM and the Western boundary partly uses EUR or IJM based on the distance the location of a point at the boundary to the platforms.

**Delft3D**

The same type of boundaries are applied as for the Delft3D FM setup, but the forcing is trimmed. To reduce computational costs, only moderate and high wave events are modeled, periods with offshore wave height smaller than one meter or offshore directed wave conditions are discard. Another distinction is that the Delft3D model uses a different nearshore wave model, for details one is referred to [Luijendijk et al., 2017].
5.3.4. SEDIMENT AND MORPHOLOGY

AEOLiS

The definition of sediment was taken from [Hoonhout, 2017]. A lognormal distributed sediment definition is used for sand fractions supplemented with lognormal distributed shell fractions, see Figures 5.4a and 5.4b. The layer thickness was set to 5 mm and 5 layers are used.

![Grain size distribution in AEOLiS and DFlow FM in two scales.](image)

5.3.5. TIME STEPS

The timestep of AEOLiS is set to 10 minutes. After each AEOLiS time step bed- and water levels are updated with DFlow FM. The water level boundary and Neumann boundaries in DFlow FM are updated every 12 seconds (user timestep), during the runs DFlow FM used an average time step of 6.0 seconds (computational timestep). In case of the two-way coupled model, SWAN is updated every 20 minutes after which wave information is updated in AEOLiS and DFlow FM. In the one-way coupled model, SWAN is updated every 60 minutes to reduce computational cost. Delft3D used a trimmed time series due to the reduction of low wave energy conditions and used a morphological acceleration of 5. The output from this computation was related to the ‘real’ time it represented. This resulted in an non-uniform interval at which Delft3D data was put in the coupled model.

5.4. RESULTS: COMPARISON OF COUPLED MODEL AND MEASUREMENTS

In this section the results of the Sand Engine case are presented. Two different aspects of the model output are discussed: the morphological change and the dune growth. The morphological change is output which both Delft3D and AEOLiS produce and is easily comparable with measured data. A large amount of measurements of the Sand Engine morphology is available which is used to validate the result. Dune growth is computed by AEOLiS. The dune area is less often measured than the bathymetry of Sand Engine. This study focuses on the five-year mean annual dune growth. Due to an unforeseen model error, a part of the results is meaningless. A certain band of alongshore dune growth results is unintentionally near-zero.

5.4.1. MORPHOLOGY

The computed morphological development is the main type of considered output. To evaluate the modeled result, a comparison is made with (bi)-monthly measurements of the JETSKI measurement campaign. Appendix F contains the results at all the dates of intermediate measurements.

The bed levels of the AEOLiS grid have been used to investigate the morphological change rather than the bed levels on the DFlow FM grid. As the AEOLiS output also includes information on aeolian sediment transport and dune growth on the same grid, this is more convenient to use.

First, a comparison of coupled model results and measurements is made for a qualitative judgment of the model performance. Then the origin of morphological changes is distinguished. This distinction is made between the two models computing bed updates: AEOLiS and / or Delft3D. A breakdown of the total bed level changes over the two models is made. Next, a spatial decomposition of the Sand Engine domain is
carried out and the measured and computed volume changes of the resulting areas are presented. Finally the performance of the model skill is assessed by means of the Brier Skill Score of the coupled model, as well as the AeoLiS and Delft3D contributions of the coupled model.

**Visual comparison with measurements**

This section presents only the start and end date of the measurements in Figure 5.5. By comparing the model result and the measured bathymetry changes the qualitative judgement of the model performance is that the model works reasonably well.

For most part the model works and the computed bathymetry roughly equals the observations. The Sand Engine spreads along the coast and the overall erosion patterns are similar. In the first year the spit develops. The lagoon entrance is elongated and narrowed over the years. The peninsula erodes and the adjacent coasts gradually increase in area forming a bell shaped Sand Engine. The eroding beach area and a filling of the lake and lagoon is observed and modeled.

Still, there is room for improvement. The model shows steepening of the profile around the water line, which is not measured. This is seen by the sub-aqueous erosion in the model result and the narrow of the light blue colored zone in the computed bathymetry. The observed subtidal bar is flattened out in the model, which can be explained by the 2DH computation and resulting depth averaged transport. The deeper part of the lagoon is twice as big in the model result as deposition inside of the lagoon away from the water line lacks. Also the landward movement of the lagoon channel in time is not included in the model. Another difference is the eroding zone of the peninsula. The measurements show that erosion has extended further landward than simulated in the model. Also the shape of this area is different, as the edges of the eroding area are more stretched along the coast in the observations. This shape-difference already emerges in the first years and stays relatively stable afterwards in both the model and the measurements.

**Origin of morphological change: AeoLiS vs Delft3D**

The objective of this thesis is to investigate the impact of the coupled model. As the result of the coupled model is due to the combination of models, it makes sense to look into the results of the individual models. The morphological development in the coupled model is a result of the combination of bed level differences in AeoLiS and Delft3D. The results of the coupled model at a certain location are therefore originated in AeoLiS, Delft3D or a combination of both. Combined the AeoLiS part and Delft3D part form the total bed level change, as depicted in Formula 5.1, in which \( \Delta z \) is the bed level change and the superscript denotes its origin. This defines three different bathymetry changes. Figure 5.6 shows the result of the three computed
5.4 RESULTS: COMPARISON OF COUPLED MODEL AND MEASUREMENTS

Figure 5.6: Computed bathymetry changes of the coupled model in the top panel. The mid panel and the bottom panel show the computed bathymetry changes by AeoLiS and Delft3D. In all panels the isobaths of -2m, +0m, +3m and +5m w.r.t NAP and a straight line marking the lagoon are depicted in grey.

The cumulative pickup of sediment registered by AeoLiS is presented, which is the aeolian sediment entrainment and is referred to as the AeoLiS part of the coupled model. The morphological simulation of Delft3D was a stand alone model run, so this part was unaltered in the coupled model.

The bed level changes computed by AeoLiS are mostly located landward of the water line, as expected. Deposition is observed in the lake and in the lagoon and erosion is concentrated along the water line, following the outerside of the spit. Besides some accretion around the water line, the sub-aqueous bathymetry is hardly affected by AeoLiS. Delft3D simulated morphological development, mostly under the still water line. The top of the peninsula erodes and accretion along the water line is located in the north and south. Steepening of the bathymetry in the north and south is visible by the sharp erosion and deposition gradient around the -2m isobath. An comprehended deposition in the deeper water near the spit is observed, especially during storm seasons. The beach, lake and a large part of the lagoon is unaltered by Delft3D.

Per location it is now possible to quantify the relative contribution of AeoLiS and Delft3D, shown in Figure 5.7. The percentage of the bed level difference due to a model is computed with Formulas 5.2 and 5.3. A remark on the depicted results: if the computed morphological approaches zero in both models, the formulas fail due to zero-division. The results are as expected. The initial beach area towards the land boundary is completely dominated by AeoLiS, including the dune lake and a large portion of the lagoon. The area from the +0m NAP isobath in 2016 towards the offshore boundary is completely controlled by Delft3D. Between the 2011 and 2016 isobath a small, but non-zero contribution of AeoLiS is seen. A strip around the 2016 isobath and the lagoon area show an equal contribution of AeoLiS and Delft3D, which indicates that multiple processes form these areas.

\[
\Delta_{z_{t ot al}} = \Delta_{z_{2b}}^{ALS} + \Delta_{z_{2b}}^{D3D} \\
\%_{ALS} = \frac{\Delta_{z_{2b}}^{ALS}}{\Delta_{z_{2b}}^{ALS} + \Delta_{z_{2b}}^{D3D}} \\
\%_{D3D} = \frac{\Delta_{z_{2b}}^{D3D}}{\Delta_{z_{2b}}^{ALS} + \Delta_{z_{2b}}^{D3D}}
\] (5.1) (5.2) (5.3)
5. Coupled model of the Sand Engine

Volume changes are accumulated over different areas of the Sand Engine to quantify and locate the sources of volume change.

The defined areas are based on the isobaths of the final simulation result, therefore the names can be deceptive because the location of e.g. the intertidal area will change in reality. The levels -2 m, +3 m and +5 m w.r.t NAP are used and the areas are the area of interest is located between x = -1500 m and x = 2500 m. The following areas are specified, they are visualized in Figure 5.8:

**The sub-aqueous area** Between the -2 m NAP isobath and the offshore boundary of the AeoLiS grid.

**The intertidal area** Between the -2 m NAP and +3 m NAP isobaths.

**The lake area** The dune lake within the +3 m NAP isobath.

**The lagoon area** Between the +3 m NAP isobath and one manually added line. The line is chosen in such way that the lagoon area is dominated by AeoLiS.

**The dry beach area** Between the +3 m NAP and +5 m NAP isobaths.

**The dune area** Between the +5 m NAP isobath and a 100 m inwards defined line.

**The total area** Everything between the offshore boundary and the dune foot at the +5 m NAP isobath. As it known that AeoLiS lacks the process of deposition in the dune area, the area is not included in the total area.

In every region the volume changes are aggregated based on the measurements and the model results of the coupled model and the AeoLiS and Delft3D part, see Figure 5.9. Only the part of the areas that are covered by the measurements are taken into account.
5.4. Results: comparison of coupled model and measurements

Figure 5.9: Volume changes in time per area based on bathymetry changes and aeolian sediment pickup.

Considering the total area, a total sand volume of $1.641 \times 10^6 \text{ m}^3$ leaves the domain according to the measurements, whereas the coupled model simulates a sediment loss of $1.200 \times 10^6 \text{ m}^3$. If only a Delft3D simulation would be performed a $1.033 \times 10^6 \text{ m}^3$ loss is simulated. This is an improvement of 16% of the difference between model and measurements. The AeoLiS part of the coupled model leads to an extra loss of $0.167 \times 10^6 \text{ m}^3$ of sand. Investigating the development in time of the volume changes, a stepwise volume decrease is modeled. After two and a half years, the measurements and coupled model show roughly the same amount of sediment loss, but the measurement reached this by more severe erosion in the first year and relatively unchanged two years after. In the last two years the model and observations follow the same trend. One particular event stands out. At 5 December 2013 a big storm hit the Dutch coast, called the Sinterklaasstorm, which led to a enormous observed sediment loss.

The smaller areas shows other relations between model results and measurements, also included Figure 5.9. In the sub-aqueous area the AeoLiS contribution is negligible and only Delft3D is responsible for the coupled model result. Delft3D overestimates the volume loss of this area. This mismatch is found ever since the first storm season. A decreasing trend is not observed, or at least to a much lesser extent in the measurements.

Dune growth is computed by AeoLiS only and takes both the morphological development of the area as well as the aeolian sediment transport into account. The computation of dune growth due to the aeolian sediment transport is explained in the Section 5.4.2. Measurements are lacking in the considered JETSKI dataset. After a highly dynamic first year, a steady trend is obtained with a strong seasonal behavior.

In the dry beach area the model and measurements show a relatively large difference. The Delft3D model left this region unaltered, since the water line never reached this area. AeoLiS shows a steady decrease of the volume area in this area. In reality however a part of this region has been flooded and eroded. Clearly the Sinterklaasstorm can be seen and afterwards, the trend tends to be more erosive.

The lake is unaltered by Delft3D. Both the measurements and AeoLiS show an increasing trend, but the model under predicts this accretion, especially in the first year.

The intertidal area shows almost a spot on match until the first storm season, afterwards model and measurements take a different path. Delft3D dominates the total model result, but AeoLiS slightly contributes as well. AeoLiS erodes the intertidal, while Delft3D simulates accretion. During the first three years Delft3D computes an over prediction of the accretion, which especially developed during storm-seasons. The Sin-
terklaastorm shows the opposite effect in Delft3D compared to measurements. Instead of simulated accretion, erosion took place.

The development in the lagoon area compares well to that of the dune lake. Delft3D is negligible and AeoLiS underpredicts accretion. In this region the first year is represented reasonably well by the model and afterwards an accreting trend is simulated but weaker than the measurements show.

**Brier Skill Scores**

From [Luijendijk et al., 2017]: "The Brier Skill Score (BSS) is commonly used as a measure of morphodynamic model predictions. The BSS approach defined by [Sutherland et al., 2004] is adopted to evaluate the model skill, Formula 5.4: where MSE is the mean-squared error and \( MSE_{int} \) the MSE of the reference prediction for which the initial bed is taken (zero change reference model). Therefore, the BSS can be interpreted as the model added skill relative to a prediction that nothing changes. A prediction that is as good as the zero change reference prediction receives a score of 0 and a perfect prediction a score of 1. A value between 0 and 1 can be interpreted as the proportion of improvement over the reference prediction."

\[
\text{BSS} = 1 - \frac{\text{MSE}}{\text{MSE}_{\text{int}}} \tag{5.4}
\]

A BSS is calculated for the same regions as the volume changes are determined and besides the coupled model result the AeoLiS part and Delft3D part are scored, see Figure 5.10. The dune area is missing as no measured data is included for the reference prediction and the model does not include the process of dune accretion.

Considering the total area, the coupled model scores 0.24 after the 5 years simulation which is judged as ‘good’ according to the classification of Sutherland et al. [2004]. This is an improvement of the Delft3D stand alone result, which scored ‘reasonable’ with BSS of 0.17, or the AeoLiS part of the coupled model, which qualified as ‘poor’ with a 0.09 score. The combination is always better than one model alone, this indicates that the coupled model is a promising step in improving model results. Over time Delft3D improves the first two and a half years, to stay at a ‘reasonable’ level afterwards. The increase over time is explained due to the relative importance of processes on longer timescales like the gradual diffusion of sediment along the coast. The AeoLiS part of the model scored ‘poor’ the whole time, because aeolian sediment transport is of minor importance considering the whole area.
5.4. RESULTS: COMPARISON OF COUPLED MODEL AND MEASUREMENTS

The sub-aqueous area is Delft3D dominated, which is also reflected in the BSS. Delft3D scores already ‘good’ after the first 1.5 year and the scores steadily increase until the last year. The decrease can be attributed to the poorly understood accretion area in the deeper water of the domain, roughly at x = 1500 m. AeoLiS does not significantly contribute to the final overall score, but the first two years the coastline of the Sand Engine was partly located within the domain.

In the dry beach area the models perform ‘poor’ and no true model skill is observed, a zero-change prediction would score the same. In view of Delft3D this is exactly what happens, but AeoLiS simulates a part of the observed erosion and a non-zero score would be expected. It appears that AeoLiS lacks the ability to simulate the unordered spatial erosion pattern, but that is not the only reason explaining the poor performance. The volume changes in this area show that the the dry beach erodes significantly faster since the Sinterklaasstorm, this indicates that in reality the this part of the beach was influenced by marine processes from thereon, while it remained dry in the model. This explains the poor performance in the last years. The first years the erosion is not very profound and the skill score is then also very sensitive to noise in the measurements.

The lake is solely influenced by AeoLiS and a ‘reasonable’ skill is obtained, which is more or less constant after the first year. At the start of the simulation, the water level in the lake was at +0m NAP. The water level in the lake filled at some event of extreme high water levels whereby increasing the area which accreted. Besides the possible overprediction of these water levels, the lack of ground water seepage resulted that this elevated water level remained at a high level even after the water level offshore drops again. The observed water level in the lake was higher at the start of the simulation and lower at the end.

In the intertidal area a ‘good’ model result is shown, which improves over time. The intertidal area contains complex features like the spit and lagoon entrance. Also the processes around the water line are hard to model at the exact right location. The skill of Delft3D is continuously increasing after the first year. Also AeoLiS gives a reasonable result at the end of the simulation even though measurements show volume increase and AeoLiS decrease, indicating that the process of sediment pickup in the intertidal is wise to include.

The lagoon area shows ‘good’ model skill, originating from AeoLiS due to the choice of the area. As for the lake the volume change in this area is under predicted, but relatively less and a better performance is obtained. The pattern of accretion along the water line and slight erosion at the landward side are well represented. The decrease over time indicates that a long term process is lacking in the model. This could be the accretion of fines, supplied through the channel as the observation of the Sand Engine show a relatively high amount of fine sediments inside the lagoon. Also the assumption of a constant porosity does not hold in the lagoon, as higher porosities are measured than in the rest of the Sand Engine.

5.4.2. DUNE GROWTH

The dune growth rates differ along the Sand Engine in space and also in time. This section provides the results on simulated dune growth. Due to an unforeseen model error, part of the results between the alongshore distance is unintentionally near-zero and therefore meaningless. This is the case from -3100 m up to -2800 m, from 500 m up to 2200 m and from 3500 m up to 4200 m. The first year result is relatively unharmed as the distance is unintentionally near-zero and therefore meaningless. This is the case from -3100 m up to -2800 m, from 500 m up to 2200 m and from 3500 m up to 4200 m.

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Computing dune growth

Dune growth was computed by a summation of the aeolian sediment transport perpendicular to the orientation of the beach.

\[ Q = \frac{1}{T} \int \frac{q}{\rho_s(1-n)} dt \]  \hspace{1cm} (5.5)

In 5.5 the dune growth rate \( Q \left[ m^3/\text{m/year} \right] \) is the temporal averaged summed sediment flux towards the dune \( q \left[ kg/m/s \right] \), converted to mass by the density of the sediment \( \rho_s \left[ kg/m^3 \right] \) and the porosity \( n \left[ - \right] \).

\[ q = c * u_{10} * \cos(u_{dir} - \alpha) \]  \hspace{1cm} (5.6)

In 5.6 \( q \left[ kg/m/s \right] \) is the sediment flux towards the dune, \( c \left[ kg/m^2 \right] \) is the instantaneous sediment concentration integrated over the (saltation) height, \( u_{10} \left[ m/s \right] \) is the wind velocity, \( u_{dir} \left[ rad \right] \) is the Cartesian wind direction and \( \alpha \left[ rad \right] \) is the angle of the dune foot orientation.
Figure 5.11: Dune growth rates for periods of about a year at the line $y = -531$ m. Also the average dune growth rate over the total period is given.

**Model error**

The encountered problem was that the dune area unintentionally became wet, which directly resulted in an enormous drop in aeolian sediment transport. At the model boundaries it turned out to be difficult to match water levels and and bed levels. Once a DFlow FM boundary artificially turned wet, water kept flowing in. To avoid this problem another simulation was performed, in which water depth were put to zero by the controller for the area with $y < -500$. Also the lateral Neumann boundaries in DFlow FM were shortened and did not cover the +3 m area. This resulted at first in an improvement of the result, but after two years it still went wrong. The resulting dry and wet cell at the end of the original computation and after three years are displayed in Figure 5.12. The resulting dune growth of this altered simulation is displayed in Figure 5.13.

Note that the computation of volumes of the previous section is still useful. The accretion and erosion in the dune area is encountered in the volumes, besides the aeolian sediment transport. To the total computation of the volume it does not matter whether sediment settled in the bed, or that it is transported over the boundary.

Figure 5.12: Wet and dry cells.
5.5. RESULTS: COMPARISON OF COUPLED MODEL AND UNCOUPLED MODEL

To show the added value of the coupled model, also an uncoupled model simulated the Sand Engine. As the use of Delft3D implied an independent calculation of sub-aqueous morphodynamics only the aeolian sediment transport is considered truly coupled in this chapter. Therefore only the AeoLiS model is used in a stand-alone manner. No hydrodynamics are calculated in this stand-alone simulation and the water level remains at the initial level of zero. This section compares the stand-alone result with the AeoLiS part of the coupled model.

After the five year simulation, the uncoupled model clearly shows differences compared with the coupled model. In Figure 5.14 the resulting erosion and accretion due to aeolian sediment transport is displayed. The bathymetry development in the coupled model leads to change of location of the beach, like the widening of the northern and southern part of the beach. This lead to a difference of the location of erosion and accretion. The most notable difference of the uncoupled model is the lack of erosion along the water line. This is due to the lacking of sediment mixing due to waves in the intertidal area in the uncoupled model.

Another difference is the accretion pattern. In the uncoupled model the water line does not move so accretion is always roughly at the same location. In the coupled model the water level is highly dynamic, resulting in variation of the location where accretion takes places. The dune lake is a good example. In the coupled model, the dune lake filled up during a high water event enlarging the dune lake area and the accompanying accreting area. Whereas in the AeoLiS stand-alone run, the water level in lake remained stationary. Also parts of the beach show accretion in the coupled model because of beach lakes.

By aggregation the volume change over the areas, a further insight in the differences is shown, presented in Figure 5.15. A similar spatial decomposition was made as in Section 5.4.1. The areas are based on the isobaths in 2016. Eroding areas are the intertidal area and the dry beach and accretion is modeled in the lake, lagoon and dunes. The volume of accretion in the dune is computed by the summation of aeolian sediment transport as in Section 5.4.2 for the coupled model and is set equal to the sediment deficit in the uncoupled model.\(^1\) The accretion in the lake and lagoon are calculate by aggregation only the accreting part within the

---
\(^1\) The intermediate results of the uncoupled model were lost and aeolian transport could not be calculated.
area, the eroded volume was added to the dry beach erosion volume. The net result of the sub-aqueous areas was small $O(1.000 \, m^3)$ and was added to the intertidal areas in both cases.

Considering the total area, the sediment loss computed in the uncoupled AeoLiS model is $0.115 \times 10^6 \, m^3$. As the AeoLiS part of the coupled model resulted in a $0.115 \times 10^6 \, m^3$, 31% of the net aeolian induced erosion in the coupled model is caused by the coupling.

The biggest difference between the coupled and uncoupled model is the increased erosion in the intertidal zone with accompanying more accretion in the dunes in the coupled model. This is in line with the expectations as sediment supply is less limited. The dry beach area shows more or less equal results. In this area the wind and armouring of the bed are unhindered by marine processes. It indicates that this area only passes on sediment from the intertidal towards the dunes after armouring. The lake is slightly less accreted in the uncoupled model. This is mostly because of the smaller wet area. The water level in the lake is in the uncoupled model set to +0 NAP, which explains the small accreting volume. The total accretion in the lagoon is similar in both cases.

The result on the Brier Skill Scores at the end of the simulation for the areas is shown in Table 5.1. The BSS of the uncoupled AeoLiS model can directly be compared to the BSS of the AeoLiS part of the coupled model. To compare the AeoLiS result with the total coupled model, a superposition of the uncoupled AeoLiS result and the Delft3D result is presented. For the total area, the BSS increased from 0.21 to 0.24 indicating a slight increase of model skill. The intertidal area is the area that drives this improvement. The lake and the lagoon are better represented in the uncoupled model. The lake was filled with water during high water events in the coupled model whereby the accreting area became too large. In the lagoon the total volume change was roughly equal, but accretion and erosion were more concentrated in the uncoupled model. Especially the accretion at the seaward side of the lagoon was in better agreement with the observations. Possibly the increase in porosity and influx of fine marine sediment lead to extra accretion at this location, which happened to be at the constant water line of the uncoupled model.

Figure 5.14: Erosion and accretion induced by aeolian sediment transport. In the top plot the AeoLiS part of the coupled model is shown, in the bottom plot a stand-alone AeoLiS run is performed. In both panels the isobaths of -2m, +0m, +3m and +5m w.r.t NAP of the July 2016 bathymetry of the coupled model are shown.
5.6. SUMMARY AND CONCLUSIONS

A five year hindcast of the Sand Engine has been performed with the one-way coupled model framework. The morphology module of Delft3D FM was not accurate enough during the execution of this research and did not allow to use the two-way coupled model framework. Therefore the sub-aqueous morphological change was computed independently with Delft3D. Consequently, only the aeolian induced part of the total bed change was altered by this coupled model approach.

The inclusion of morphodynamics into the computation of aeolian sediment transport resulted in an additional sediment loss in the modeled area. The deficit between the Delft3D-only sediment loss and the measured sediment loss was decreased by 16%. The model skill of the coupled model was addressed and a score of 0.24 was obtained, which qualifies as ‘good’.

The aeolian sediment transport at the location of the dune foot was used to simulate dune growth. However, due to unintended wet cells a drop in aeolian sediment transport was encountered at some specific locations, resulting in an uninterpretable outcome. A modification of the model, by shortening the Neumann boundaries in DFlow FM plus the enforcement of dry cells in the dune area, did not solve this issue. It can be therefore concluded that the coupled model in its current state is not qualified to model dune growth.

By comparing the aeolian induced bed change of the coupled model with an uncoupled AeoLiS model the added value of the coupling is addressed. Roughly 30% of the net additional loss due to aeolian sediment transport was not computed in an uncoupled AeoLiS model. A superposition of uncoupled Delft3D and AeoLiS models gives an Brier Skill Score of 0.21. The slight increase in model skill and lowering of the sediment deficit between model and measurement is contributed to the increase of aeolian induced erosion in the intertidal area where wave mixing increase sediment availability. In specific regions the coupled model performed less than the uncoupled model did, partly linked to an exaggeration of the water surfaces in the coupled model.
6.1. **INTRODUCTION**
During the course of this research a few of topics of interest have come up which are open for discussion. To begin with, the coupling of the models is discussed in Section 6.2. Next, the Sand Engine case is treated in Section 6.3. The one-way coupling is discussed as well as the results of morphological development and dune growth. Subsequently, some perspective of the coupled model is presented in Section 6.4.

6.2. **MODEL COUPLING**
In order to progress, a simplification of processes is modeled and only a minimum of variables is coupled. The most important physics are tried to be captured, however it is unavoidable to neglect some of it. The designed coupling consists of an online exchange of three variables: bed levels, water levels and wave heights. This approach shows acceptable results, but it is possible to extend and thereby improve this coupling in future studies.

Especially the modeling of sediment can be more in-depth. This partly comes forth from the modeling choice of using a single representing sediment fraction \( D_{50} \) (and a standard \( D_{10} / D_{90} \) relation) in Delft3D FM. This removes the direct need to exchange mass of sediment fractions between AeoLiS and Delft3D FM. Still, the morphology module of Delft3D FM (and also of Delft3D) does some bookkeeping on (available) sediment mass in the bed and the water column. This can be coupled to the sediment bookkeeping of AeoLiS, favorably for multiple modeled sediment fractions.

In this research, aeolian transported sediment was assumed to settle directly on the seafloor and lead to accretion by means of a bed level increase, while there is not touched upon the sediment composition. In reality sediment will gradually sink in the water column and settle on top of existing sediment in the bed. In the current coupled model the sediment concentration nor bed composition is changed. The DFlow FM morphology module incorporates other variables concerning sediment transport, like available sediment in the bed, bedload and suspended load. As many transport formulations exist in DFlow FM and the inclusion of suspended load and/or bedload varies, the coupling with aeolian sediment transport should be checked for each formula.

In addition to this improvement of the sediment exchange, the marine mixing process in AeoLiS can be computed by Delft3D FM. AeoLiS incorporates a rather simplified process by mixing the bed over the depth-of-disturbance, which is solely determined by the wave height and previous aeolian sediment transport while sub-aqueous sediment transport is neglected. The mixing of sediment by waves is a marine process and it would be a logical step to compute the mixing within a marine orientated model as Delft3D FM (or Delft3D).

6.3. **SAND ENGINE CASE**
6.3.1. **USE OF DELFT3D**
The need of using a Delft3D model to accurately simulate the morphological development in the Sand Engine case has a major impact on the coupled model. The seamlessly two-way coupled model framework presented in Chapter 3 was adapted to the one-way coupled structure. Half of the intended interaction between an aeolian sediment transport model and sub-aqueous morphodynamic model disappeared. The
aeolian sediment transport is still correctly influenced by changing hydrodynamics and its accompanying morphological change, but the computed sub-aqueous morphodynamics are not influenced by the aeolian sediment transport anymore. The result is that the improvement of aeolian sediment transport comes at a higher price. The hydrodynamics and waves are now twice computed, once for the morphological Delft3D model and another time by Delft3D FM in the coupled model. However the result of the one-way coupled model set up is still a considerable improvement over an uncoupled approach. Also the predictive capacity of the model is still intact. The models can run using only initial conditions and forcing, as no implied data assimilation is used. Therefore the validation against data remains possible.

In itself the chosen path of using an offline computation of the sub-aqueous morphological is not unsound. The different timescales of morphological activity allow accurate two-way modeling in a 'half online' coupled model. The morphological change due to aeolian sediment transport is relevant on a more monthly to yearly timescale. By using the one-way online coupled model approach (from the Sand Engine case) for a simulation of one year, its output can be used as new input for a second year. In this way Delft3D is offline coupled with the aeolian sediment transport. 'Half online' refers to the partial online coupling (of marine influence on aeolian sediment transport) and the partial offline coupling (of aeolian sediment transport on sub-aqueous morphology). This approach is an alternative to achieve an two-way coupling without the use of the morphology module of Delft3D FM. However, the double computation of hydrodynamics and waves makes that this is not the most favorable option.

6.3.2. MORPHOLOGICAL DEVELOPMENT

The computed morphological change shows satisfactory results. The good visual representation of the accretion and erosion patterns, together with the model skill show a competent model. However, this is mostly because of the good results from the Delft3D model, as the contribution of the aeolian sediment transport is smaller. Due to the usage of the independently computed Delft3D morphology, the added value of the coupling is now only in the improved aeolian sediment transport compared to a superposition of two uncoupled models. The fact remains that the inclusion of aeolian sediment transport into the morphological development is an notable achievement in itself, even besides the coupling. But the lack of improvement of the sub-aqueous part of the model is unfortunately undeniable. If the two-way coupled model would work as expected, than extra added value of the coupling would be expected. At the Sand Engine case, this would probably be most notable due to the change of bathymetry at the water line and the dry beach of the peninsula. Just above the water line extra erosion is computed by AeoLiS, which could possibly result in a fastened retreat of the water line. This could have impact on the dry cell erosion in Delft3D. The lowering of the peninsula could ultimately lead to a break through towards the dune lake and lagoon, presumably during a storm event. By including the aeolian sediment transport, this is expected to happen considerably sooner than in the uncoupled case. And, after periods of accretion in the dune lake and lagoon, the hydrodynamics in these basins are expected to significantly differ after such a breakthrough. The development of such a breakthrough and the forming of an extra tidal lagoon could significantly influence the long term development of the Sand Engine.

6.3.3. DUNE GROWTH MODELING

This research is another step towards the process-based modeling of dune growth. The aeolian sediment transport model of de Vries et al. [2014] was a basis to take supply limitations into account and the AeoLiS model by Hoonhout and de Vries [2016] introduces the use of sediment fractions and the provides the framework of handling of a spatiotemporal varying supply. The coupled model can be seen as a next step by including the computation of the spatiotemporal varying supply as a result of marine processes. The model calculates the a-priori unknown marine processes and make it an improvement of the prediction of the aeolian sediment transport.

Still dune growth modeling is far from perfect. At the beach the coupled model performs reasonably well considering the aeolian sediment transport, but the dune area appears to be too complicated to model. The coupled model shows it weakly reflects dune growth variability as observed at the Sand Engine. A small dip in aeolian sediment transport is modeled behind the dune lake, but the observed pattern of enhanced dune growth at the north and south of the Sand Engine is not represented in the model. Probably this could occur later as the widening of the beach area will serve as enhanced aeolian sediment source at the north and the south. In the coupled model approach this is expected to be a model challenge as the Delft3D model tends to steepen the profile around the water line. But by preventing the water to occur in the dune area it would be expected that the current model set up would still show some dune growth variability.
Also the distribution of accretion and erosion over the aeolian sediment budget areas is not completely in line with the measurements. This is not unexpected as a similar distribution of accretion and erosion is obtained in the results of Hoonhout [2017]. In here the bathymetry change was forced by measurements and simple assumptions were made on the hydrodynamics. This model also showed underestimation of deposition in the dune lake and the lagoon. However, one has to be very cautious by comparing these resulting volumes, as the budget areas are static in time in this thesis, while they are dynamic in Hoonhout [2017]. The fundamental dynamics of these areas make the latter approach preferable in future studies.

There are several improvements of the model possible. First, the artificial wet cells in the dune area need to be removed. The enforcement of a zero water depth by the controller did not have the desired effect as extra wet cells are created along the boundary of the forced area. This suggests that this is not right path to follow as the boundary of zero water depth can not be shifted seaward as the hydrodynamics would otherwise be effected. As the shortening of the Neumann boundaries was not tested without the enforcement, it can not be concluded this would not solve the problem and additional simulation could provide a conclusion on this measure.

A subsequent step could be to extend the coupled model with a groundwater model, as the omitting of groundwater seepage appears to be of major effect on the aeolian sediment transport in the coupled model. The coupled model combines water levels from Delft3D FM and aeolian sediment transport in AeoLiS and the water surface traps aeolian transported sediment. When after a flooding the high water level drops, the water sometimes remains in small bowl-form bed forms and (little) basins are created. In reality the water level will drop further because of groundwater seepage, but in the coupled model, this water level drop is not captured and sediment is trapped in the basins afterwards.

Also other phenomena are relevant. Storm erosion is not yet observed directly behind the peninsula of the Sand Engine but eventually it will change the location of the dunes. Dune erosion is generally linked to marine processes during storms when waves reach the dunes due to surge. This process could be better simulated with a dedicated model such as XBeach [Roelvink et al., 2012]. Another relevant process at the dunes is that vegetation increases the shear velocity threshold in the dunes and thereby trapping sediment. Also the local wind field could play an important role. The height differences at the Sand Engine, and at dunes in general, of several meters are likely to influence the wind flow.

Besides the physical phenomena also some modeling aspects of the coupled are significant. A first is the marine sediment mixing and the relation to the depth of disturbance. But also the influence of threshold depth for wet cells and the exact representation of the water line could be examined further.

6.4. FUTURE EXPECTATIONS COUPLED MODELING

The ability of coupling models has a large potential. It allows to broaden the scope of process-based modeling. An increasing number of processes can be included to better reproduce the physics or to shift focus of the model.

Larger spatial domains can be included. A logical step would be to expand the model capacity towards the dune area. For now the coupled model is able to calculate morphological development up to the dune foot, where it is expected that sediment will settle into the dunes behind it. This model barrier could be pushed to the land sides of the dune. By doing so the coupled model is of more value by better evaluating the coastal safety in terms of dune area and volume growth. And not only the safety function can be treated in more depth by an addition to the coupled model. For example, ecological models could be coupled to incorporate also those findings in the evaluation of a coastal intervention.

Another model limitation which could be pushed is the one of simulated time. In its current set up the coupled model is a considerable improvement on the 1-5 year timescale by including aeolian sediment transport in a morphodynamic model. This could be extend to a 10-20 year timescale, which is more similar to the total lifespan of a mega-nourishment like the Sand Engine. The first necessary improvement would be inclusion of aeolian sediment transport in the sub-aqueous morphological computation, either by the two-way online coupled model framework with an accurate Delft3D FM morphology module, or by a 'half online' coupling and still using Delft3D. The brute-force approach, without the use of morphological acceleration, can be applied, only it would require a hardly acceptable longer computational time. A first suggestion to accelerate the computation is to discard conditions of a low wind velocity and and low wave conditions, as the results in this research show an event driven pattern.

However, there are also some disadvantages to coupled modeling and it is not advised to unlimitedly couple models. The first drawback is of course that all models use computational time. One has to consider
whether the extra included process is worth the costs, which is often hard to say beforehand. Especially when there is a large difference in computational time between models, this is relevant. Another problem is the calibration of a coupled model. It becomes hard to finetune a coupled model as the amount of parameters which can be adapted increases. Also the target of calibration could become unclear if the coupled model fits multiple purposes. This thesis used the calibration from the uncoupled sub-models and no extra calibration of the total coupled model is performed. But one can question whether two individually ‘perfect’ calibrated sub-models make up one perfect coupled model. The interaction between the models tends to oppose this statement. An example is the sensitivity of the Delft3D model in Luijendijk et al. [2017] to the dry cell erosion factor, which also incorporates enhanced sub-aqueous sediment transport at the waterline, just as the depth of disturbance of wave mixing does for enhanced aeolian sediment transport. Which parameter has to be calibrated first is than hard to choose. In addition, the (technical) structure of a coupled model could become very complex. This is hard to debug and this research recommends to create simple testcases to test the functioning of the coupling. A too complex structure also has the disadvantage that the modeler can’t keep track of the outcome of the model. It will be harder to get a ‘feeling’ for the model.

Ultimately, this thesis advocates that the coupling of models is the way to go, even though there are some possible hiccups. The coupled model framework is easily transferable to another location due to the generic and process-based set up. It will be most relevant in areas with considerable aeolian sediment transport. Sandy solutions like beach nourishments are a good example. The coupled model allows than to examine the coastal safety of more ‘exotic’ designs incorporating various water and features like lakes and lagoon. Alternatives for a nourishment could be tested on morphological development with more confidence. Also it could be investigated whether there are relevant design parameters for nourishments that we are not aware of yet, for example Hoonhout and de Vries [2017] suggests the investigation of the height of a sub-aerial (mega-)nourishment.
7.1. CONCLUSIONS

This section answers the research questions presented in Chapter 1. The main research question of this research is:

Does the inclusion of both sub-aqueous morphodynamics and aeolian sediment transport and their interaction in one coupled model improve predictions on coastal evolution and is this model able to simulate the first years of morphological evolution and dune growth variability at the Sand Engine?

This research shows that a coupled model including both sub-aqueous morphodynamics and aeolian sediment transport does indeed improve predictions on coastal evolution. The Sand Engine case shows that the model simulation captures the physical processes involved better and is in closer agreement with observations compared to current uncoupled models. The coupled model is not adequate to model dune growth variability, but it is believed that the coupled approach provides a step in the right direction. An elaboration of these statements is present by the conclusions on the research sub-questions.

7.1.1. INTERACTION OF PHYSICAL PROCESSES

Which (interaction between) sub-aqueous morphodynamics and aeolian sediment transport processes shape the Sand Engine, and should therefore not be neglected in (coupled) modeling of the Sand Engine?

- Hydrodynamics determine the availability of sediment for aeolian transport. Water surfaces limit the availability of sediment for aeolian transport, while waves mix sediment which increases the availability after events of high water, i.e. flood and surges.

- Sub-aqueous morphodynamics and aeolian sediment transport result in bathymetry changes in the same area. Aeolian sediment transport erodes the beach and especially the intertidal area, while it results in accretion in water features like a dune lake or lagoon. At the Sand Engine, the lowering of the bed level at beach of the peninsula could expedite a breach of the beach towards the dune lake or lagoon. Sub-aqueous morphological changes alters the location of the source of aeolian sediment transport.

7.1.2. CREATING A COUPLED MODEL

How can we combine different model characteristics of the existing morphodynamic and aeolian sediment transport models, Delft3D FM and AeolLiS, in order to create an operational coupled model structure which embodies this interaction?

- A technical framework for a coupled model is presented, combining AeolLiS and Delft3D FM. The model components exchange information such as bed levels, water levels and wave heights with each other on flexible intervals during the computation. An accurate interpolation scheme allows for use of different computational grids per component.
• A two-way coupled modeling framework is presented of which the technical functionality is demonstrated in a proof-of-concept.

The proof-of-concept shows that the coupled model is not a simple superposition of two uncoupled models. The coupling has a considerable effect on the aeolian sediment transport, especially the sediment mixing by waves can be of big impact. The necessity to couple the three variables (bed levels, water levels, wave heights) is demonstrated in the proof-of-concept.

• An one-way online coupled model is presented which can be used to simulate complex morphological development. As a consequence of the one-way coupling, only the aeolian induced part of the total bed change is altered in this model approach compared to uncoupled models.

The morphology module of Delft3D FM is not yet fully developed. In this a workaround was applied by using another morphodynamic model (in this case structured Delft3D) to simulate the sub-aqueous morphological development at the Sand Engine, which runs independently of the designed model framework. Because of this approach hydrodynamics and accompanying morphological changes do influence the aeolian sediment transport. The other way around aeolian sediment transport is not used to update sub-aqueous morphological change. As Delft3D is not BMI-compliant, only its uncoupled model output can be implemented in the coupled model as a Delft3D computation cannot be altered whiles it is running.

7.1.3. Added Value of Coupling
Is such a coupled model of added value over uncoupled models, by decreasing the differences between observations and model results of the first years of the morphological evolution at the Sand Engine and by explaining the observed dune growth variability?

• The added value of the coupled model is demonstrated at the Sand Engine area by modeling aeolian sediment transport, showing a slight increase of model skill and a decreased sediment deficit between measurements and model results.

Considering the total area, the model skill qualified as 'good' with a Brier Skill Score of 0.24, whereas a superposition of uncoupled models scores 0.21. The mismatch between the model and the measurements of volume leaving the domain decreased with 16% by including aeolian sediment transport. The net aeolian induced erosion is 30 % less in an uncoupled AeoLiS model, because the coupled model incorporates the mixing of sediment by waves which increases aeolian induced erosion in the intertidal area.

• The coupled model model in its current state is not adequate to model dune growth.

Modeled cross-shore aeolian sediment transport rates are of the same order as the observed dune growth rates at the Sand Engine, but are overestimated. Due to unintended wet cells, a drop in aeolian sediment transport was encountered at some specific locations, resulting in uninterpretable outcome, but the potential of modeling dune growth by evaluating aeolian sediment transport at the dune foot with a model coupling AeoLiS and Delft3D FM still stands.

7.2. Recommendations
As the provided coupling is a pragmatic first step, recommendations are stated on the use of the two-way coupling on improving or extending the coupled model.

7.2.1. Using the Two-Way Coupling
• Validate the claim that the addition of aeolian sediment transport adds value to the (sub-aqueous) morphodynamics by using a two-way coupled model.

The use of beforehand computed morphological changes by Delft3D has the disadvantage that aeolian sediment transport does not influence these morphological changes. At the considered time scale of 5 years this will be of some impact and is therefore a debatable simplification. At larger timescales it is expected to be of even more influence, e.g. by changing the position of the coastline and by changing basin properties of the lagoon due to aeolian deposits, but this claim is now unsupported by process-based modeling research.
• Use DFlow FM to model (sub-aqueous) morphodynamics, when this is fully developed to create a two-way coupling.

In addition to the benefit of a two-way coupling, this eliminates the double calculation of the hydrodynamics. In the one-way coupled model the hydrodynamics is computed twice, first by Delft3D for the morphological changes and a second time by Delft3D FM to couple with AeoLiS. An alternative for developing the Delft3D FM morphology module is to create an offline two-way coupled model with Delft3D. The different timescales of aeolian sediment transport and (sub-aqueous) morphodynamics permit a decoupling of the processes, but this does not eliminate the double calculation of the hydrodynamics.

7.2.2. IMPROVING THE COUPLING OF THE MODELS

• Eliminate fictitious saturation of computational cells in the dune area to be able to investigate the model capabilities in simulating dune growth.

The current model setup is incapable of modeling spatial varying dune growth, and during this research it seemed not possible to judge whether the coupling of the two models, AeoLiS and Delft3D FM, could successfully simulate dune growth. However, this research provides the insight that the brute enforcement of dry areas in the controller is unwanted as it puts restrictions on the modeled physics (e.g. during high surges large water level gradients could occur at the edge of enforced dry area) and the results in this report still show fictitious wet cells. Since the model boundaries contain many (implicit) model assumptions, these assumptions could easily be violated in the coupling. The shortening of the Neumann boundaries in DFlow FM without an enforced dry area could therefore be the way to go.

• Extend the model coupling by connecting the interpretation of sediment between AeoLiS and Delft3D. Sediment bookkeeping in Delft3D FM is now not touched upon in this thesis and the coupling can be extended by exchanging more variables, especially in the morphological module of Delft3D FM such as available sediment in the bed, bedload and suspended load. Although this is not directly needed as aeolian deposits are relatively small, a better-kept coupling is still possible. In addition, it is advised to use multiple sediment fractions in Delft3D FM which equal the sediment fractions defined in AeoLiS, so the sediment mixing can be modeled in a process-based manner.

7.2.3. EXTENDING THE COUPLED MODEL

• Extend the model with options to accelerate the morphological updating to reduce computational time, similar to MORFAC in Delft3D. This allows upscaling of the considered timescale which can become more in line with the timescale of dune growth.

The current implementation only allows a brute-force simulation (MORFAC=1). DFlow FM (or Delft3D) has the ability of enhancing simulated morphological change. For AeoLiS such a procedure is not developed and the simulation of the armouring process is hard to accelerate. Ultimately an integrated morphological acceleration should be possible. As a start, periods of small wind velocities and low wave energy could be discarded.

• Extend the coupled model to simulate dune area growth by including extra phenomena like ground water, storm erosion, vegetation and a non-uniform wind field.

The expected increase of dune area is an important characteristic in the Environmental Impact Assessment of the Sand Engine. After the model can reproduce the dune growth in terms of cross-shore volumes, this next step can be taken. Modeling the increase of dune area is not yet possible as the current version of the coupled model does not take enhanced sediment deposition in the dunes into account. By incorporating some assumptions (or coupling to other models) on the vegetation, storm erosion and the morphodynamic updating of the wind field, large steps are taken towards modeling dune area increase. Also the omitting of groundwater seepage appears to be of major effect on the aeolian sediment transport in the coupled model.
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The technical implementation of the coupled model is addressed by describing the structure of the components and the links between them. First the structure is presented, second the links between them are addressed in the same way as the algorithm is implemented. Finally an overview of the exchange of variables between the models is included.

A visual representation of the structure of coupled model, is presented in Figure A.1. As described in the overview of the model it consists of the input, output, controller and sub-models. The controller is the beating heart of the coupled model by steering the sub-models. Additionally the communication file between DFlow FM and SWAN is explicitly mentioned because of its essential role in the coupled model. The conventional coupling between DFlow FM and SWAN is carried out via this file and several variables including wave heights, water levels, velocities etc. Deltares [2016b] provides additional information about this. In the designed coupled model, this well-established exchange and an additional exchange of information is executed via the communication file. Finally output is delivered by the sub-models, being most notably the computed bathymetry by the models. However more output can be requested: e.g. on hydrodynamics in DFlow FM, wave fields in SWAN or aeolian sediment transport in AeoLiS.

Likewise as for the model overview the model steps are discussed. All the components are linked as shown in Figure A.1. These links are called upon one at a time in the designed algorithm. Although all components and links are portrayed, it can be hard to comprehend how a certain variable goes from one sub-model to another. Therefore an extra overview of the coupling of variables is presented in Table A.1. In a schematic way the algorithm takes the following steps:

0. The controller is provided with the initial conditions and boundary conditions and complementary settings. The controller initializes the sub-models based on this information. In case of the one-way coupling, the bed level differences calculated by Delft3D are also treated as input for the controller.

1. The SWAN model is called to do an update with the initial input from the controller. Water level and bed level updates are read from the communication file, see link 11.

2. After a SWAN update, renewed wave variables are updated in the communication file, this is part of the well-established DFlow FM - SWAN coupling.

3. After a SWAN update, new wave height information for AeoLiS is read by the controller.

4. The AeoLiS model is called to do an update with the input from the controller. The combined bed level difference from AeoLiS and DFlow FM of the previous update is provided. The same procedure is applied to water level differences. Wave heights from the SWAN are also provided. If the output writing interval is reached, output is provided, see link 12.

5. After an AeoLiS update, renewed bed levels (and water levels) are read by the controller.
Figure A.1: Technical implementation of the information loop in the coupled model framework showing the links between all the components.

6. The DFlow FM model is called to do an update with input from the controller. The combined bed level difference from AeoLiS and DFlow FM of the previous update is provided. To perform the update, also information is read from the communication file, see link 7. If the output writing interval is reached, output is provided, see link 12.

7. Bed level differences and water level differences from DFlow FM are read by the controller.

8. Wave information in the communication file is read by DFlow FM, this is part of the well-established DFlow FM - SWAN coupling. Links 4 up to 8 are now repeated until the SWAN update interval is reached.

9. After a DFlow FM update has reached the SWAN update interval, information is written in the communication file, this is part of the well-established DFlow FM - SWAN coupling. This includes among others the updated water levels by DFlow FM.

10. Updated bed levels by the combination of AeoLiS and DFlow FM updates are written in the communication file.

11. SWAN reads the communication file and information to do a next SWAN update is provided. Links 1 up to 11 are now repeated until the end of the simulation.

12. Output is written at a certain interval by AeoLiS and DFlow FM. At the end of the computations, the controller finalizes the model and some meta-information on computational time is provided.
Table A.1: Variable coupling overview. The variables (bed levels, water levels and wave heights) are exchanged from model A towards model B via links from A.1. The method of this exchange is described above. The gray method is an artificial extra exchange, due to the definition of the water depth in DFlow FM (the water level minus the bed level) so if AeoLiS lowers the bed level, the water level should lower as well.
This appendix provides a brief description of the (sub-)models: Delft3D FM and AeolSiS. Two computational cores of Delft3D FM are described, DFlow FM accounting for hydrodynamics and sediment transport, and SWAN accounting for waves.

B.1. Delft3D FM

B.1.1. DFlow FM

To simulate hydrodynamics and (sub-aqueous) morphological development DFlow FM (Flexible Mesh) is used in Delft3D FM, which is developed at Deltares, [Deltares, 2016a]. The equations which are solved in the 2DH computation are based on the depth averaged shallow water equations, derived from the Navier-Stokes equations: Formulas B.1, B.2 and B.3. Important assumptions in DFlow FM are the hydrostatic pressure assumption, Reynolds averaging and the Boussinesq approximation lead to the simplified formulations.

\[
\frac{dh}{dt} + \frac{dU h}{dx} + \frac{dV h}{dy} = Q \tag{B.1}
\]

\[
\frac{\delta u}{\delta t} + u \frac{\delta u}{\delta t} + v \frac{\delta u}{\delta y} + w \frac{\delta u}{\delta z} - fu = -\frac{1}{\rho_0} \frac{\delta P}{\delta x} + \frac{\delta}{\delta z} (\nu \frac{\delta u}{\delta z}) + M_x \tag{B.2}
\]

\[
\frac{\delta v}{\delta t} + u \frac{\delta v}{\delta t} + v \frac{\delta v}{\delta y} + w \frac{\delta v}{\delta z} + fu = -\frac{1}{\rho_0} \frac{\delta P}{\delta y} + \frac{\delta}{\delta z} (\nu \frac{\delta v}{\delta z}) + M_y \tag{B.3}
\]

In Formula B.1 the following variables are used: \( h \) is the water depth, \( U \) and \( V \) are depth averaged velocities in x- and y-direction, \( Q \) is representing the contributions per unit area due to the discharge or withdrawal of water, precipitation and evaporation. In Formulas B.2 and B.3 the following variables are used: \( u \) and \( v \) are the flow velocity in x- and y-direction, \( f \) is the Coriolis parameter, \( \delta P/\delta x \) and \( \delta P/\delta y \) represent the pressure gradients, \( F_x \) and \( F_y \) represent the unbalance of horizontal Reynolds stresses, \( \nu \) is the vertical eddy viscosity coefficient, \( M_x \) and \( M_y \) represent the contributions due to external sources or sinks of momentum (external forces by hydraulic structures, discharge or withdrawal of water, wave stresses, etc.).

Morphological development is simulated in within DFlow FM. This module is still under development. Multiple formulations based on the type of transport can be used to simulate erosion and deposition. For the schematization of 'sand' transport, representing non-cohesive bedload transport and suspended load transport, by default the Van Rijn approach is followed [van Rijn, 1993].

A characteristic feature of DFlow FM is the use of an unstructured grid, which allows for a flexible choice of grid points in DFlow FM, hence its name. A staggered grid is used, so water levels and velocities are not stored at the same place. Instead, the water levels are stored at the grid centers, in DFlow FM called flownodes, and velocities at grid centers, called flowlinks, respectively.

The numerical implementation is based on a finite volume solver, the continuity equation Formula B.1 is solved implicitly for all points. Time integration is done explicitly for part of the advection term, resulting in a time step limitation by the flow Courant number. The resulting limited time step is varying in time and is automatically set during the computation.
**B.1.2. SWAN**

SWAN, Simulating Waves Nearshore, is used to simulate the evolution of random, short-crested, wind-generated waves [Booij et al., 1999], developed at Delft University of Technology (The Netherlands) [The SWAN team, 2016]. Several wave propagation processes like refraction and shoaling are included, as well as the wave generation and dissipation processes like wind generation and wave breaking. SWAN solves the spectral wave action balance equation B.4 in an iterative manner.

\[
\frac{\delta}{\delta t} N + \frac{\delta}{\delta x} c_x N + \frac{\delta}{\delta y} c_y N + \frac{\delta}{\delta \sigma} c_\sigma N + \frac{\delta}{\delta \theta} c_\theta N = \frac{S}{\sigma} \tag{B.4}
\]

In formula B.4 the following variables are used: \( N \) is the action density, \( \sigma \) represents frequencies, \( \theta \) is the propagation direction, the different \( c \)'s are the propagation velocities in different directions and spectral space, \( S_{tot} \) is the source/sink term that represents all physical processes which generate, dissipate and redistribute wave energy.

A dynamic interaction between SWAN and DFlow FM is well-established, simulating effects of waves on currents (wave forces in the momentum balance) and vice versa (set-up, current refraction). Communication with DFlow FM is executed via a so-called communication file [Deltares, 2016b]. There is no BMI get- and set-functionality is implemented in SWAN, but by using the communication file to change the variables this is not necessary.

To allow an easy coupling with DFow FM, the D-Waves module developed by Deltares is used [Deltares, 2016b]. SWAN is the model core, D-Waves allows interaction with the model. Functionalities like interpolation and communication with DFlow FM are added to the SWAN model in D-Waves. In this thesis the name SWAN will be used, although BMI is implemented in D-Waves.

**B.2. AEOLiS**

The AeoLiS model by Hoonhout and de Vries [2016] is a recently developed model, based on the process-based supply limitation model of de Vries et al. [2014]. A distinction is made between supply limiting factors as a result of the bed surface properties and maximal transport limiting factors being mostly the wind forcing. Also sediment supply in the intertidal area is conceptually included by introducing water level, wave energy, evaporation and infiltration input. The transport equation which is solved, is a 2DH advection equation for transport by wind, see Formula B.5.

\[
\frac{\delta c}{\delta t} + u_{z,x} \frac{\delta c}{\delta x} + u_{z,y} \frac{\delta c}{\delta y} = \min \left( \frac{\delta m_a}{\delta t}, \frac{c_{sat} - c}{T} \right) \tag{B.5}
\]

In Formula B.5 the following variables are used: \( c \) [kg/m\(^2\)] is the sediment mass per unit area in the air, \( c_{sat} \) [kg/m\(^2\)] is the maximum sediment mass in the air that is reached in case of saturation, \( m_a \) is available sediment in the bed [kg/m\(^2\)], \( u_{z,x} \) and \( u_{z,y} \) are the x- and y-component of the wind velocity [m/s] at height \( z \) [m], \( T \) [s] is an adaptation time scale, \( t \) [s] denotes time and \( x \) [m] and \( y \) [m] denote cross-shore and alongshore distances.

The bed is build up of several layers all containing multiple sediment fractions. By including different fractions, or even non-erodible elements, in the sediment composition, the model is able to simulate the processes of beach armouring and sorting.

The numerical set up is based on a first order upwind method in space and implicit Euler in time. Other schemes like central discretization in space and the \( \theta \)-method are implemented but not extensively tested and therefore not used in this report.
This chapter describes the methods used for spatial coupling. As the computational grids of the used models might be defined on different points in space, choices have to be made when information is exchanged. As an example two small grids are defined in Figure C.1. If information is available in one grid, the question arises how this information should be transferred to the other model.

Different methods of spatial coupling are developed to cope with the different characteristics of the exchanged information. In this thesis three variables are identified as crucial to couple the models. These three variables are bed levels, water levels and wave heights. The existing coupling of wave information between DFlow FM and SWAN is not touched upon in this thesis and the wave heights are already transferred to the DFlow FM grid by the established method of the DFlow-Waves coupling. Therefore only the spatial coupling between the AeoLiS grid and DFlow FM grid is elaborated.

The main consideration in the chosen methods is that the area around one grid point which the point should represent (the grid cell) is taken into account. This is used as a weight to determine the relative importance of adjacent grid points, so in general a point representing a larger area is more important than a point representing a smaller area.

An important encountered problem is the effect of smoothening of information when it travels back and forth between to grids. Especially near steep gradients this can be problematic, see also the example in Figure C.2. An unwanted effect of this smoothing is that e.g. bed levels are changed even if there is no transport of sediment calculated by the model. Therefore it is chosen to exchange the differences instead of the direct values of parameters. As long the models compute a change of zero there will be no information exchanged.

The structure of this appendix is as follows. First the used definitions are stated. The second section treats the bed level differences and the used method of the weighted aggregation and weighted interpolation. The section on coupling water levels continues on this weighted methods and extends this with a correction to prevent water level drops at the boundaries. Then the coupling of wave heights is briefly treated as it is likewise the coupling of water levels. Finally the technical implementation is discussed.

Figure C.1: In the top figure an example of overlapping grids: an AeoLiS grid and a DFlow FM grid. In the lower left panel show a case in which the values on the DFlow FM grid are known and the values on the AeoLiS grid need to be determined. At the right the opposite case is presented in which DFlow FM values are unknown.
Figure C.2: Smoothing as a result of repeated interpolation on an illustrative 1D grid. In the upper figure three values are known on the yellow AeoLiS grid points. Linear interpolation towards the intermediate DFlow FM grid points shown in the middle figure is straightforward. When these values are then used for interpolation back to the AeoLiS grid, the value of the cell in the middle is artificially higher than it was as starting point.

C.1. DEFINITIONS

C.1.1. GRID DEFINITIONS

Grid  The spatial decomposition of a 2D surface constructed by points and lines to represent the surface in a discrete manner.

Coarse grid  The grid containing large grid cells, so the grid cells which represent the largest area.

Fine grid  The grid containing small grid cells, so the grid cells which represent the smallest area.

Largest grid  The grid covering the largest total area.

Smallest grid  The grid covering the smallest total area.

Grid point  A point of the computational grid. DFlow FM uses a staggered grid and in this chapter the grid point solely refers to the water level points. AeoLiS does not use a staggered grid, therefore the grid point is unambiguous.

Representing area  The area around a grid point which is represented by this point. DFlow FM uses a staggered grid and the grid cells described in the manual [Deltares, 2014], are chosen as the representing areas. In AeoLiS there is no predefined grid cell, so the Voronoi cells are used. A Voronoi decomposition divides an area and a set of points within this area into regions based on the smallest distance to the points.

Grid cell  The combination of a grid point and its accompanying representing area. Grid cells of a single model (AeoLiS or DFlow FM) never overlap.

Sending grid  The grid for which information is available, which has to be send to the receiving grid.

Receiving grid  The grid for which information has to be calculated based on the information on the sending grid.
C. COUPLING IN SPACE

C.2. COUPLING BED LEVELS DIFFERENCES

The most important restriction of the spatial coupling is that this should be mass conservative. This is achieved by volume conservation as a constant density of the bed is assumed in both AeoLiS and DFlow FM. The sum of all bed level differences times the area in grid A should equal that of grid B. As the grids and corresponding areas are constant over time only bed heights need to be correct. The considered area of a grid point is the representing area.

The first step to ensure mass conservation is to exchange bed level differences. As the accompanying areas are known and invariable this represents the changes of the amount of mass. By doing so, control is gained over the amount of exchanged mass and no extra smoothing occurs.

Step two to ensure mass conservation is to use the overlap of both grids as measure of the exchange. All grid cells of the sending grid which overlap with grid cells from the receiving grid should be considered in the coupling. Grid cells of the sending grid which do not overlap the receiving grid are not exchanged. Grid cells of the sending grid which only partially overlap the receiving grid should only exchange a part of the amount of mass. Therefore the change of mass in the sending grid equals the change of mass in the receiving grid if and only if the sending grid is completely within the receiving grid.

The exchanged bed level differences now directly represent mass fluxes as it is the product of height difference times area time (times a constant density). And by basing it on the overlapping area of two grid cells, this now is the exchanged mass between these two cells. This procedure is repeated over all cells which overlap, so a sending cell can send to multiple receiving cells and vice versa a receiving cell can receive from multiple sending cells. A the end a summation of the received height differences (= received mass) will result in the total received mass of a receiving cell.

This stepwise procedure can be visualized in Figure C.3 and is summarized as follows:

- Decompose the receiving grid cells into polygons based on the sending grid.
- Weight the polygons resulting from the decomposition based total area of receiving grid cell. The sum of all weights within one receiving grid cells equals one.
- Multiply the values of the bed level differences with the weights. These products represent the exchanged mass from the sending cells to the receiving grid cells.
- Sum the products of the polygons per receiving grid cell.
C.3. COUPLING WATER LEVEL DIFFERENCES

The coupling of water levels is much alike the coupling of bed levels as mass should be conserved. However, at the boundaries problems could occur. As the grid cells will not perfectly overlap in the most likely case that the grids are different, there will be receiving grid cells that only partly overlap the sending grid and partly overlap empty space. In the case of coupling bed level differences they are treated as a region with a zero flux. For water levels this results in unwanted water level drops at the boundary. Therefore it is chosen to extrapolate the values if a receiving grid cell is only partly covered by the sending cells, so a continuous water level height is created. This is achieved by basing the weights on the covered area of the cell instead of the whole cell.

The stepwise procedure can be visualized in Figure C.4 and is summarized as follows:

- Decompose the receiving grid cells into polygons based on the sending grid.
- Weight the polygons resulting from the decomposition based total non-empty area of receiving grid cell. The sum of all weights within one receiving grid cells equals one.
- Multiply the values of the water level differences with the weights. These products represent the exchanged mass from the sending cells to the receiving grid cells.
- Sum the products of the polygons per receiving grid cell.

C.4. COUPLING WAVE HEIGHTS

The wave heights are coupled in a manner like the water levels differences, so with an extrapolation around the edge. But as wave heights don’t need strict conservation between the grids, the direct values are used instead of the differences.
C. COUPLED IN SPACE

Figure C.5: A visual representation of the coupling of water level differences as technically implemented. The result is the same as shown in Figure C.4, but now the same weights are used as in the coupling of bed level differences in Figure C.3 which are corrected.

C.5. TECHNICAL IMPLEMENTATION

The section elaborates on the technical implementation of the coupling method in the controller environment.

The exchanged variables are (at first) defined in the grid centers. By assigning a polygon made up by the grid cell corners, two arrays of polygons are created: one for the receiving grid of length \( m \) and one for the sending grid of length \( n \). A \( m \times n \) matrix \( M \) is constructed and for every index \((m, n)\) the overlapping area of polygon \( j \) of the sending grid and polygon \( i \) from the receiving grid is computed and divided by the area of the \( i^{th} \) polygon of the receiving grid.

The vector \( a \) of computed bed level differences of the sending grid is also of length \( n \) as there is an equal amount of grid points and polygons per grid. A matrix multiplication of \( Ma = b \) will give a vector \( b \) of length \( m \). This matrix multiplication combines the two last steps of the spatial coupling procedures. The vector \( b \) is now the resulting bed level differences of the receiving grid.

As there are two combinations of conversion, from AeoLiS to DFlow FM and from DFlow FM to AeoLiS, there are two matrices.

The method of coupling water levels differences and wave heights differs slightly from the coupling of bed level differences. Per receiving grid cell there must be determined to which extent it overlaps the combination of all sending grid cells. The reciprocal of the fraction of overlap is then used as a correction factor for this cell. So all corrections factors combined make up a vector \( c \) of length \( n \) and is added to the matrix multiplication by means of a Hadamard product (entrywise product): \((Ma) \circ c = b\).

Figure C.5 shows the procedure of the correction factors in a graphic way which end up exactly as described in the section on coupling water level differences.

C.5.1. REDUCTION OF COMPUTATIONAL TIME

To reduce the computational time of the spatial coupling several routines are implemented to fasten the code.

The most obvious reduction of computational effort is by calculating the weight matrices beforehand. As the grids are invariable in time the conversion between the grids is also invariable in time. As the variables are extensively exchanged in time a great number of computations is saved. A small example: a one year run and a 10 minute exchange interval implies \(365 \times 24 \times 6 \times 2 \approx 100,000\) exchanges for the bed levels only.

The construction of the weight matrices is accelerated by using the R-tree data structure, this structure is
described in [Guttman, 1984]. Although using pre-defined weight matrices reduces the effort of constructing these matrices only once at the beginning of the model run, still a comparison of $20,000 \times 20,000 = 400 \times 10^6$ possible cell overlaps needs to be evaluated. The use of bounding rectangles around the polygons accelerate this procedure from a about 6 hours into several minutes on a Core e5-2670 CPU machine (at 2.60 GHz).

Another reduction is obtained by using sparse matrices. The grids used for the Sand Engine consist of approximately 20,000 cells for DFlow and AeoLiS and the grid cell sizes are in the same order of magnitude. Due to the small differences in cell sizes all the amount of cells which overlap is usually limited to three or four cells, and at maximum perhaps ten cells. The resulting weight matrices are therefore filled for less than 0.05 %. The computational effort was the smallest when applying the Compressed Sparse Column (CSC) format. Other tested, but slower formats are: Dictionary of keys (DOK); List of lists (LIL); Coordinate list (COO); Compressed sparse row (CSR).

C.5.2. TEST CASE
This section shows a test case of the result of the spatial coupling procedure on a larger grid. The matrix multiplication and its result are discussed. Both the corrected and uncorrected procedure are addressed. At last the smoothing effect of repeated interpolation is demonstrated.

First the used grids are defined in Figure C.6.

The procedure of weighting and its result is visualized in Figure C.7. As starting points the smaller grid is uniformly set to a value of 1.0. If there would be no weighting the matrix multiplication will result in an aggregation of all the values in a receiving grid cell. This shows how the summing trait of the matrix multiplication is performed. By including the weights and performing a bed level procedure, the final result is obtained.

Figure C.8 illustrates the difference of the use of correction factors. The same input is used, so the smaller grid is everywhere defined to be one. The uncorrected procedure (for bed levels) is performed and shown. Also the correction factors are calculated. The multiplication of the uncorrected procedure result and the correction factors is the final result (as for water levels). This shows the extrapolating character of the corrected procedure.

Another example in Figure C.9 shows the need to use differences instead of direct values. Input is given using random values between 1.0 and 2.0 on the smaller grid. A corrected transformation to the larger grid is performed. This is then used as input for a transformation back to the fine grid. This shows that values on the smaller grid are smoothened and do not resemble the initial input anymore. The information of the individual cells on the smaller grid is lost and a lot of cells have the same values. This happens because they are dependent on the same cells of the larger grid.

C.6. DISCUSSION
The spatial coupling (interpolation) technique introduced in Appendix C is a powerful method and the concept could be applied in other morphodynamic coupled models. The use of area size around gridpoints allows to conserve mass while complex, unstructured grids are handled. There are however a few remarks. First of all is the currently designed version a fit-for-purpose technique. It is tailored for a staggered grid with grid cells and grid points (DFlow FM grid) and a rectilinear grid (AeoLiS). Modifications need to be made to allows for example two unstructured grids. Another important aspect is the boundary. When possible the advise is to align the boundaries of different models to avoid any discrepancies as numerical models are usually forced at the boundaries.
Figure C.6: Definition of the grids in the example. The upper panel shows the two used grids: a small, fine one in red and a large, coarse grid in blue. The middle panel shows the representing areas (or region of influence) of the grid points. In the bottom panel the names of points are defined.
Figure C.7: Transferring values from a coarse grid to a fine grid. The upper panel shows the input, defined of the fine grid. The middle panel shows the result of a summation of the values of the fine grid to the coarse grid, without the use of weighting factors. The bottom panel is the result of the spatial coupling procedure for bed level differences.
Figure C.8: Transferring values from a small fine grid to a large coarse grid. The fine grid is smaller than the coarse grid, therefore the use of correction factors is relevant. The upper panel is the input on the fine grid, identical to the top panel of Figure C.7. The second panel is the result of the spatial coupling procedure for bed level differences, so no correction factors are used. The third panel shows correction factors. The bottom panel is the result of the procedure for water level differences, so correction factors are used.
Figure C.9: Transferring random values from the coarse grid (top panel) to the fine grid using correction factors. The resulting values from the fine grid (middle panel) are then transferred back to the coarse grid (bottom panel). Smoothing is illustrated, which is prevented by using differences instead of direct values.
D.1. Computational time

A timer was added in the controlling environment to measure the computational time of the different elements in the coupled model. A subdivision of the computational time is given for the elements: AeolIS, DFlow FM, SWAN and the coupling. This subdivision is related to the proof-of-concept fully coupled case. Depending on the grids and model settings, a different subdivision will be obtained. To account for the grid size (e.g. SWAN uses a larger grid), the computational time is divided by the number of grid cells of the sub-models, resulting in the computational time per grid cell, see Figure D.1.

The total coupling is responsible for 17.1 percent of the total computational time (23.54 if the grid sizes are taken into account), but most of this (93 percent) is by writing in the communication file between SWAN and DFlow FM. This step, referred to as link 10 in Appendix Technical implementation, includes morphological change as a result of AeolIS to the SWAN computation. This is not strictly needed as the morphological change because of AeolIS is expected to be small between two SWAN computations. Besides, this step is avoidable by disclosing an extra variable in the BMI-implementation in DFlow FM. This thesis includes the com-file step to be as accurate as possible, but it is advised to check whether this is really necessary in other projects. Without this step, the coupling takes 1.3 percent of the total computational time, of which only 0.3 percent is because of the coupling of variables during the simulation. 1.0 percent point is because of the initialization and finalizing of the models and is referred to as the remainder in the plot.

Therefore, one can say that the extra computational effort of the coupling is relatively small.

(a) Including writing to DFlow FM - SWAN communication-file by the controller.

(b) Without writing to DFlow FM - SWAN communication-file by the controller.

Figure D.1: Division of computational time per grid cell in the proof-of-concept fully coupled case. The coupled model parts which are not directly related to the updating of the sub-models, and therefore link to the coupling of the models, are emphasized.
D.2. MASS CONSERVATION AND GRID DEFINITION

This section proves that the coupled model is mass conservative and the influence of moderately different grid is addressed in this section.

Three different grid compositions are used to simulate the proof-of-concept case with the fully coupled model, besides the one presented in Chapter D. In the case presented in Chapter D the AeoLiS and DFlow FM grids matched, see Figure D.2a. In the three other compositions the AeoLiS grid cells are twice as large in alongshore and cross-shore direction, so the covered area is quadrupled compared to the previous cases. These cases defines the grids in such a way that DFlow FM grid cell centers matched the AeoLiS grid points. This discards the need for a complex spatial interpolation. By increasing the AeoLiS grid cell size multiple DFlow FM grid cells are covered by one AeoLiS cell and sometimes an DFlow cell is covered by multiple AeoLiS cells. The three grid compositions differ in the placement of the AeoLiS grid relative to the DFlow FM grid. The first composition has the same origin as the original case. By doing so, some of the DFlow FM cells still perfectly match the AeoLiS cell, but other DFlow FM cells cover by multiple (two or four) AeoLiS grid cell, see Figure D.3a. The second composition shifts the grid from the first composition one grid cell in onshore direction. This results in the same coverage of AeoLiS cells and DFlow FM cells, but the perfectly matched cells are now different, see Figure D.4a. The last composition places the AeoLiS grid such that one AeoLiS grid cell exactly covers four DFlow FM cells. Each DFlow FM cell is now linked to only one AeoLiS cell, see Figure D.5a.

A cross-section of the bathymetry change is obtained for all four cases, at y = 200 \footnote{Only in the last case the AeoLiS grid does not have a cell at y = 200, so the cell at y = 210 is consulted}. A zoom-in around morphological most active zone is presented in all figures below.

In the case of equal grids, the bed level differences of the AeoLiS grid and the DFlow FM grid show a spot-on match, see Figure D.2b. Also the mass balance holds very well. The sediment that leaves the domain over the dune is 4.144 \text{m}^3/\text{m} (per meter along the dune landward boundary). The total accretion and erosion resulted in an total loss of volume of 2.742 \text{m}^3/\text{m}. This leaves a deficit of 1.402 \text{m}^3/\text{m}. However in the uncoupled DFlow FM simulation, exactly this amount of sediment was added to the profile. It is assumed that the same amount of sediment was added in this coupled simulation. This closes the mass balance. The amount of sediment in the air and in the water orders of magnitude smaller.

In Figure D.3b the bed level differences computed on the AeoLiS and the DFlow FM do not match any more, especially near steep gradients in the DFlow FM profile, the AeoLiS grid point is placed differently. This is because one AeoLiS cell, now receives information of 9 DFlow FM cells, which can be seen in the lower right corner of D.3a. The resulting total bed level difference in AeoLiS and DFlow FM are now -2.303 and -2.353 \text{m}^3/\text{m}. The resulting sediment difference between the two grids is therefor 0.050 \text{m}^3/\text{m}. As the morphological active profile has a length of at least 400 \text{m}, the average error is 0.125 mm, which is considered as accurate. The mass balance also holds. The sediment that travels out of the domain (3.711 \text{m}^3/\text{m}) and the estimated sediment coming in by DFlow FM (1.402 \text{m}^3/\text{m}) result in a total sediment deficit of 2.309 \text{m}^3/\text{m} which is observed as the total bed level difference in the grids.

The last two cases in Figures D.4b and D.5b show a similar result as the previous one. Small changes of the bed level differences can be observed, especially around x = 1050. This is where the aeolian sediment transport is the largest and the exact position of the water line might differ. Also the location of an AeoLiS grid point relative to the DFlow points determines the shape of the sedimentation peak. An interesting result is that in the last case the AeoLiS points are all located between two cells resulting that the bed level differences exactly match the average of the two adjacent DFlow FM points.

It is likely that the small differences in the cases of the larger AeoLiS grid the small deviations could partly be explained by non-uniform alongshore transport. The mass transport through the lateral boundaries of the cells is not taken into account in this analysis. Even without this, it is demonstrated that the coupling works in a mass conservative way, regardless of the cell size and position.
(b) Bed level change around the water line.

Figure D.2: Proof-of-concept grids equal.

Figure D.3: Proof-of-concept coarse AeoLiS grid, same origin.

Figure D.4: Proof-of-concept coarse AeoLiS grid, AeoLiS shifted one DFlow FM cell in x-direction.
(a) Grid definition. 

(b) Bed level change around the water line.

Figure D.5: Proof-of-concept coarse AeoLiS grid, AeoLiS shifted a half DFlow FM cell in x- and y-direction.
This appendix shows results of the morphological development of the Sand Engine from the coupled model. In this case DFlow FM computes morphological change of the first months, which unfortunately shows it is not ready for the complex area of the Sand Engine. Figure E.1 shows the computed morphological evolution, similar to Section 5.4.1 the origin of morphological change is split up in a AeoLiS part and a DFlow FM part.

- DFlow FM result does not show spreading of sediment along the coast.
- The spreading of the Sand Engine is key for an accurate computation.
- Ergo, the current version of the morphology module of DFlow FM is not fully developed and is not accurate enough of modeling the complex area of the Sand Engine.
- The coupled model needs another morphodynamic model to accurately simulate the morphological development at the Sand Engine.
Figure E.1: Computed bathymetry changes of the two-way coupled in the top panel. The mid panel and the bottom panel show the computed bathymetry changes by AeoLiS and DFlow FM. In all panels the isobaths of -2m, +0m, +3m and +5m w.r.t NAP and a straight line marking the lagoon are depicted in gray.
MEASURED AND MODELED MORPHOLOGICAL DEVELOPMENT AT THE SAND ENGINE

This appendix shows supplementary results of the morphological development in the Sand Engine case of Section 5.4.1. On the dates that a measurement is available also the computed data is extracted, so the measurements determine the temporal resolution of this appendix. The starting date is 03-08-2011 and the latest considered measurement is from 12-05-2016. The measured and computed bed levels at these dates and the intermediate dates are depicted in Section F. The resulting erosion and accretion since the first measurement are depicted in Section F.2. Also the morphological development between two consecutive data sets is presented, in Section F.3.

In Section 5.4.1 a distinction is made between the result of the coupled model and it building-blocks, being AeoLiS and Delft3D. Therefore the erosion accretion results of the last two sections are also breakdown in the parts of AeoLiS and Delft3D besides the measurements and the total coupled model. Likewise as in the mentioned chapter, the results on the AeoLiS grid are considered.
**F.1. Bed Levels**

This section shows the bed levels at the dates that a measurement is performed, both for the measurements as for the coupled model output.

**F.1.1. Measurements**

![Figure F.1: All available measured bed levels.](image-url)
Figure E2: Computed bed levels at the dates that measurements are available.
F.2. MORPHOLOGICAL DEVELOPMENT W.R.T. START

This section shows the morphological development with reference to the start date of the measurements 03-08-2011, i.e. the accretion and erosion since the completion of the Sand Engine. This is given for both the measurements and the coupled model output. Likewise as for Section 5.4.1, this is also presented for the contribution of the AeolLiS part and the Delft3D part of the coupled model.

F.2.1. MEASUREMENTS

Figure F.3: Measured erosion and accretion w.r.t. 03-08-2011.
F.2.2. COUPLED MODEL

Figure F.4: Modeled erosion and accretion w.r.t. 03-08-2011.
F.2.3. **AEOLiS PART OF COUPLED MODEL**

![Modeled erosion and accretion w.r.t. 03-08-2011 for the AEOLiS part of the coupled model.](image)

**Figure F.5:** Modeled erosion and accretion w.r.t. 03-08-2011 for the AEOLiS part of the coupled model.
F.2.4. DELFT3D PART OF COUPLED MODEL

Figure F.6: Modeled erosion and accretion w.r.t. 03-08-2011 for the Delft3D part of the coupled model.
F.3. MORPHOLOGICAL DEVELOPMENT W.R.T. PREVIOUS MEASUREMENT

This section shows the morphological development with reference to the date of the previous measurement, i.e. the accretion and erosion between two consecutive measurements. Identical to the previous section, this is given for both the measurements, the coupled model output, the AeoLiS part of the coupled model and the Delft3D part of the coupled model.

F.3.1. MEASUREMENTS

Figure F.7: Measured erosion and accretion w.r.t. previous measurement
F.3.2. Coupled model

![Modeled erosion accretion compared to previous measurement](image)

Figure F.8: Modeled erosion and accretion w.r.t. previous.
F.3.3. AEOLiS PART OF COUPLED MODEL

Figure F.9: Modeled erosion and accretion w.r.t. previous for the AEOLiS part of the coupled model.
**F.3.4. Delft3D part of coupled model**

Figure E10: Modeled erosion and accretion w.r.t. previous for the Delft3D part of the coupled model.