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Process-based Modeling of Coastal Dune Development

M.Sc. Thesis

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Summary

A model that predicts sediment transport due to wind action can be valuable addition to hydrodynamic models to describe the long-term interaction between land and water. This thesis presents the application of an aeolian transport model [Sauermann et al., 2001, Kroy et al., 2002] as a tool for the evolution of coastal nourishments and dunes. The model was originally developed to describe important features and dynamics of typical desert dunes and was modified during this research to apply to sandy beaches and coastal nourishments.

Large parts of the densely populated areas in the Netherlands are located just behind the dunes. The hinterland safety in the Netherlands is guaranteed by making periodical safety assessments and keeping the 1990 coastline. In order to maintain this position, sand that is lost due to the erosive action of wind and waves has to be replaced artificially. To optimize long-term coastal management, large effort is made in the development of models to accurately predict coastal erosion and morphological behavior of nourishments. For this purpose process-based models like Delft3D can be used to asses the long-term development of nourishments. Although this model is widely used to simulate morphodynamic behavior of coastlines, processes related to the behavior of the dry beach and dunes are not included in this model. Modeling the influence of wind blown transport could improve predictions with respect to the sediment budget of the coastal zone.

The main objective of this thesis is to produce a numerical simulation of aeolian transport applied to the sand engine. The existing DUNE model of Sauerman (2001) will be used to investigate the influence of morphological shaping by wind. This study will try to investigate the driving processes in the model and adapt or extend the model application to the coastal system. A morphological analysis of the beach-dune system should therefore include the influence of aeolian transport. This need becomes more urgent when dealing with a type of ‘mega’ nourishment like the sand engine, because of the considerable portion of surface area above the water line.

Literature on aeolian transport contains a number of empirical formulas linking the transport rate to the shear stress velocity u_*, derived from the logarithmic wind profile. The most famous is derived by Bagnold (Bagnold, 1941). He assumed that the horizontal momentum of grains during saltation is transferred to the ground, dislodging new particles on impact.

For this research, the existing model of Sauermann (2001) is used (hereafter called DUNE model). This model predicts the evolution of desert dunes by combining several physical processes. First an analytical solution for air shear stress over smooth hills as proposed by Weng et al. (1991) is used to obtain a fast algorithm, since calculation of the turbulent wind field with the averaged Navier-Stokes equations would result in high simulation times. The next component is the saltation model for sand transport from Sauermann et al. (2001). This describes the relation between the wind shear stress and the transport rate. The advantage of this model is the inclusion of the saturation transients, which play an important role in the proper description of sand flux over arbitrary terrains. Correct modeling of the wake behind a dune, vegetation on the sand surface and the process of avalanching is dealt with in separate modules.

If we want to apply the DUNE model, it has to be determined if the various model assumptions hold in a sandy coastal environment. To make the model suitable for the Dutch coastal zone, changes had to be made to several program components. From literature, several processes can be identified that have to be included in a proper model of coastal aeolian transport as opposed to a desert environment. This study identified several important aspects that should be included in a correct model of aeolian sediment transport with morphologic feedback. Adjustments in the software were found necessary and intermediate results were reviewed. In the final modified model the following improvements are implemented.

- Variable water level.
- Boundary conditions mimicking an adjacent beach.
- Rotatable wind field.
- Coastal dune vegetation
- Variable shear velocity threshold.

An important feature of a beach is the presence of a water level. Which can vary with tidal movement and affects fetch and moisture content of the sand. Variable sediment conditions (as a result of moisture, shells etc.) where implemented. For a coastal engineering case it is also desirable to use actual wind data as input for the model. The vegetation module was already included in the model and could be used without major modification. A new type of influx at the boundary was defined, mimicking an adjacent beach.

The cases of the sand engine and Vlugtenbrug put these modifications to the test and evaluate the results. With the sand engine case the emphasis lies on the evolution of the shape due to aeolian processes. The Vlugtenburg profile represents an arbitrary beach profile, but also contains interesting features like vegetated dunes and a sandy dune valley.

Conclusions

The goal of this thesis was to apply an aeolian transport model to the sand engine. In the same period as this thesis, the sand engine was constructed. No quantative predictions for aeolian transport and dune evolution on the sand engine can be made yet. The transported volumes of sand are not reliable enough to make an accurate forecast of the evolution of the shape of the sand engine. Measured data from the sand engine would contribute significantly to the validation of this model. But model results do show that the processes of aeolian transport and morphologic feedback on the topography are captured. Combining this model with a hydraulic transport models like Delft3D or XBeach could provide more insight in the processes that act in the interface between the sea and the (high) beach. This need becomes more urgent when dealing with ‘mega’ nourishment like the sand engine, because of the considerable portion of surface area above the water line.

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This research is undertaken in order to obtain the degree of Master of Science at the Delft University of Technology at the faculty of Civil Engineering and Geosciences. This study has been carried out at Deltares from November 2010 to August 2011. This report describe my research into the application of an aeolian transport model applied to the Dutch coastal zone.

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1 Introduction

1.1 Context

1.1.1 Dutch coastal protection

The Dutch coast is about 350 kilometers in length, from which three quarters consists of sandy beaches and dunes. Large parts of the densely populated areas in the Netherlands are located just behind these dunes, and it would result in dramatic loss of life's and economic damages if these areas are flooded. Because of its important function, it is of great importance that the dunes are maintained especially in regions where the position and volume of dunes is limited.

In addition, the sandy coast represents other important functions in terms of natural values, recreation and attractiveness. The dunes also serve as a storage and filtering medium for drinking water. Because of this variety of functions, at several locations attempts are made to combine multiple functions without negative effects on the coastal defence function. In the last few centuries the dynamics of a sandy coast decreased due to stabilizing activities under the influence of strict management by Rijkswaterstaat and the water boards. Recently a more dynamic approach to coastal management is adopted [Mulder, 2000]. Examples of this are Groote Keten, De Kerf and the 'stuifdijk' on Schiermonnikoog where natural variability was restored without compromising flood protection.

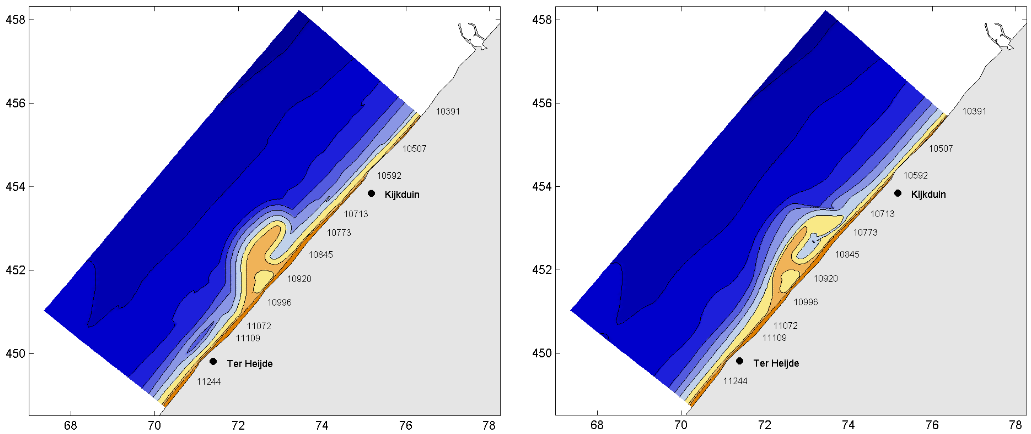
The hinterland safety is guaranteed by performing a safety assessment every 5 years. In addition, the long term safety is guaranteed by keeping the 1990 coastline. In order to maintain the position of the coastline, sand that is lost due to the erosive action of wind and waves has to be replaced artificially. On a larger scale, it is to be expected that sea level rises and land subsidence will increase. For this reason, there is a demand for future structural nourishment of the Dutch coast [Deltacommisie, 2008].

In order to optimize long-term coastal management there is a need to have a good understanding of the effectiveness of nourishments. A large effort is made in the development of models to accurately predict coastal erosion, and this effort is still ongoing. Apart from the hydrodynamic processes, the processes that affect the dry beach profile should also be understood. A morphological analysis of the beach-dune system should therefore include the influence of aeolian transport. This need becomes more urgent when dealing with a type of 'mega' nourishment like the sand engine, because of the considerable portion of surface area above the water line.

The sand engine is a nourishment project proposed by the province of Zuid Holland. At the moment, small periodical nourishments are carried out to protect the coast from structural erosion at weak points in the coastal defense. The province proposed that these nourishments can be carried out more efficiently. The sand engine is a mega nourishment that will be redistributed by natural forces to achieve a gradual build out of the Delfland coast. This nourishment will be larger than needed for the short term but will make many of the smaller interventions obsolete. A number of alternatives have been considered for the design profile of the sand engine. A Delft3D model was used in preliminary studies to predict the morphological effects of different alternatives in an objective way [Projectnota MER

Zandmotor, 2009]. The hooked-shaped peninsula was nominated for its high ecological and recreational qualities. Figure 1.1 presents the long-term development of the final alternative simulated by Delft3D. Although Delft3D is widely used to simulate morphological behavior of coastlines, processes related to the behavior of the dry beach and dunes are not included in this model.

Figure 1.1 Results from the Delft3D prediction, overview of initial bathymetry and after 5 years



The inclusion of an aeolian transport model should improve the quality of predictions on the effectiveness of mega nourishments. This study will focus on the aeolian processes on a sandy beach and making predictions with the use of a numerical model.

1.2 Objectives

1.2.1 Problem description

Because of its uniqueness in coastal engineering, the sand engine is carried out as a pilot project. Results from the sand engine will be used to develop experience with this scale of coastal nourishment. This makes the project an interesting research topic but also makes forecasting a challenge.

The present model of the sand engine based on Delft3D only takes in account the morphological changes caused by waves and flow. Although these hydrodynamic forces cause sediment transports that reshape the sand engine, the contribution of aeolian related sediment transports in the upper part of the sand body above sea level will also influence the evolution of the sand engine. The effect of aeolian transport can be considered locally (hotspots of accretion and erosion, formation of young dunes on top of the sand engine) or on a larger scale (supply of sand from the nourishment into the dune system). This makes aeolian transport an important factor to take into account with respect to the sediment budget of the coastal zone.

An important step is to develop a process based aeolian transport model to simulate the contribution of wind blown sediments. Presently aeolian sediment transport models are usually developed for areas like deserts. Modeling the effect of nourishments on dune morphology in a coastal system is still a unknown area. Due to time restrictions this study will not be able to review all the available models for aeolian transport. This thesis studies aeolian transport by attempting to produce a numerical simulation with an existing dune model (From this point called DUNE or dune model) that is presently in use for desert topographies. [Sauermann et al., 2001].

1.2.2 Goals

The main objective of this thesis is to produce a numerical simulation of aeolian transport applied to the sand engine. The existing DUNE model of Sauerman (2001) will be used to investigate the influence of morphological shaping by wind. This study will try to investigate the driving processes in the model and adapt or extend the model application to the coastal system.

1.3 Research Approach

1.3.1 Model

So far the aeolian transport model has been used to provide an understanding of important features of desert dunes like size, evolution and rate of motion. The model combines an analytical description of the turbulent wind velocity field above the dune with a continuum saltation model. The model also accounts for interaction with vegetated surfaces. The next section will elaborate on the steps that have to be carried out to reach the goal of this study.

1.3.2 Research steps

To make sure that the numerical simulation has a solid (physical) foundation, the processes controlling the sediment flux will be studied by means of a literature study in chapter 2. The result will be an overview of physical processes and their influence on the sediment transport model. Special attention will be given to aeolian processes in the Dutch coastal zone.

A second step is to investigate the model and identify which model assumptions and calculation methods are used. The DUNE model is not a product of the TU Delft or Deltares, and there is no prior experience with this software. Therefore the content and structure have to be examined in order to use it properly. Chapter 3 will present the model description, initial test cases and the insights and issues that arise from these test cases.

If we want to use the DUNE model, it has to be determined if the various model assumptions hold in a sandy coastal environment. In deserts, the model is successfully applied [Sauermann et al., 2003], but in our wet coastal system test cases have to be executed to explore its applicability. The result of the test runs are compared to existing situations, analytical solutions or other models. While doing this, coastal specific issues will come up and have to be accounted for in the model code. Modifications made to the software will be described in chapter 4.

The final validation and test cases will be presented in chapter 5. The case of the Sand Engine will be discussed and results will be analyzed. This includes generating input like the bathymetry but more important is to derive a limited set of wind conditions (directions and speeds) that drive the calculation. Because measured data of the sand engine does not exist yet, a second test case will be performed using the beach profile at Vlugtenburg.

The final chapter 6 deals with the discussion of the results followed by conclusions and recommendations.

2 Aeolian Transport

The coastal zone is a complex environment in which hydrodynamic, aeolian, human and biological processes continually influence the evolutionary behavior of the coastline. In this chapter some of the aeolian processes that are relevant to the coastal zone will be explained. This chapter starts with discussing the theoretical background behind the transport of sediment by wind. After a review of the general theory, the specific aeolian transport processes on a natural beach will be examined in more detail.

2.1 Introduction

Aeolian processes can be described as those which involve the entrainment and transport of sediment by wind. The study of aeolian transport is conducted in many different branches of research, including geology, ecology, agriculture and coastal engineering. Although there is considerable overlap, hydraulic engineers tend to concentrate on the mechanics of sand transport and practical measures aimed at stabilizing blowing sand, while geologists have focused on the classification and changes of large scale features and covering large time scales. [Pye and Tsoar, 1990]

A lot of the present research is build on R.A. Bagnold's standard work 'The Physics of Wind Blown Sand and Desert Dunes' [Bagnold, 1941]. He made major contributions to the understanding of the mechanics of aeolian transport and dune formation. Bagnold served in the Libyan desert as commander in the second world war. After this period he carried out a number of fundamental experimental studies on sand movement and summarized the results in his book.

Literature on aeolian transport contains a number of empirical formulas linking the transport rate to the wind (shear) velocity based on wind tunnel experiments. In the majority of these studies, the transport formula are derived from the logarithmic wind profile using the shear stress velocity u_*. The most famous is derived by Bagnold. He assumed that moving sediment transferred the horizontal speed from the jumps trough the air and transfers it on impact with the ground. The basic form of Bagnold's transport equation is:

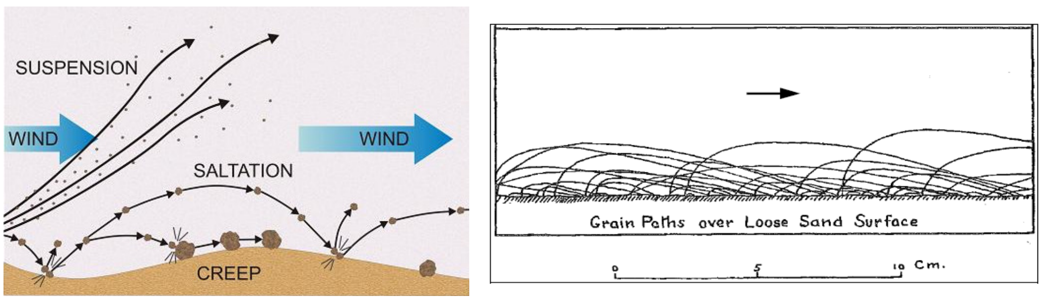
$$q = C_1 \sqrt{\frac{d}{D}} \frac{\rho}{g} u_*^3 \tag{2.1}$$

Where:
q = Sediment flux per unit width of lane per second
C_1 = Is Bagnold's empirical dimensionless coefficient (ranging from 1.5 for uniform sand to 2.8 for naturally graded sand with a wide range of grain sizes).
D = standard grain size used in the experiments/ (250 μm)

Wind shear velocity u_* is the most important input parameter for modeling aeolian transport rates. These aeolian processes depend on movement of individual grains as well as turbulent flow of air over the surface. Figure 2.1 depicts the three distinct modes of aeolian transport as identified by Bagnold: surface creep, saltation, and suspension. During surface creep, the sand grains move along the surface. During this movement they stay in contact with the bed.

The particle settling velocity is very small in relation to the component of the wind. Saltation occurs when the grains are lifted from the bed and are accelerated by the wind. When the particles impact with the surface, new grains are ejected. When the grains are transported over long distances it can be referred as suspension, particles are lifted from the surface and carried by the wind without having contact with the bed. Most of the sand transported by wind is transported by means of saltation.

Figure 2.1 The three distinct transport modes (left) and an illustration of the saltation process by Bagnold (right).



2.2 Background Aeolian Transport

2.2.1 Wind forcing

Looking at the mechanics that forces sediment into entrainment, it is important to have an insight in the shear stress of the air flow over a surface. To estimate the shear stress magnitude it is necessary to know if the flow regime is laminar or turbulent. In order to allow flow over a surface inertial, force has to overcome the viscous force. The Reynolds number Re gives the ratio between the inertial and viscous force and therefore is a good measure to distinguish between the laminar and turbulent regimes:

$$\mathrm{Re} = \frac{v \cdot L}{\nu} \tag{2.2}$$

Where L is a characteristic length which depends on the type of scale of flow (the height of the sand dunes can be used as a value for L), ν the kinematic fluid viscosity, a fluid property and a characteristic wind speed v. When Re is small, viscous effects are predominant and flow can be considered laminar whereas in situations where Re is large, the inertial effects are dominant and the flow can be regarded as turbulent. The critical Reynolds number at which flow becomes turbulent can be reached fairly easy with small roughness lengths and low wind velocity's. This turbulent flow is characterized by randomly directed and distributed fluctuations. Because the wind is never constant, eddy's can cause fluctuations in local wind speed. Therefore, the shear stresses of turbulent flow are much higher than of laminar flow. According to the mixing length theory developed by Prandtl (1935) turbulent shear stresses can be expressed as a product of the length scale and local velocity gradient squared in the form:

$$\tau_t = \eta \frac{\partial v}{\partial z} = \rho l^2 \left(\frac{dv}{dz} \right)^2 \tag{2.3}$$

Under the assumption that for flows near a wall the mixing length increases proportional to the distance from the wall $l = \kappa z$, equation 2.3 is solved by integrating over the height resulting in the well knows logarithmic velocity profile:

$$V_{(z)} = \frac{u_*}{\kappa} \ln \frac{z}{z_0} \tag{2.4}$$

The value of z_0 represents the roughness length, this is either the height of the roughness elements or the thickness of the laminar sub-layer. An increase in roughness length should result in a increase in surface shear stress. The shear stress velocity or friction velocity u_* is a measure for the shear stress τ rewritten units of velocity $u_* = \sqrt{\tau / \rho}$. The friction velocity has the advantage over the actual velocity being independent of the height of the velocity measurement.

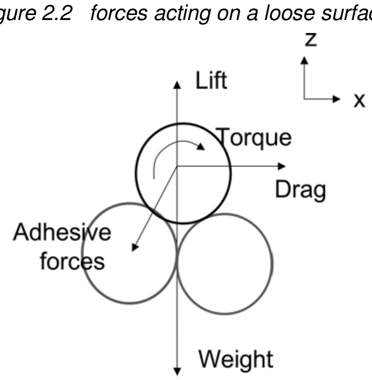
As aeolian transport occurs, sand grains extract momentum from the wind as they accelerate from rest and thereby changing the velocity profile near the bed. Bagnold observed this effect by comparing wind profile measurements of flow over a stable surface and flow during active sand movement. Whereas the velocity gradient measured over the stable surface converged at a point (z_0) just above the surface, the effects of the saltating sand caused the gradient to converge at a higher focal point. This means that the wind profile during sand movement deviates from that predicted by the logarithmic profile. Several other researches confirmed this effect and tried to find an applicable formulation for wind speed in the saltation layer (i.e. Chepil in 1945 and Belly in 1964). Owen (1964) modified the existing profile based on concepts of grain-borne shear stress and eddy viscosity.

The longer the trajectory of the grain, the longer it is exposed to the forces of the wind, and the more violently it hits the ground, ejecting new grains into the flow. When one grain hits the sand surface multiple grains can be dislodged by the impact. This is known as the splash or cascade process. The trajectory of a grain depends on whether the grain was entrained by the lift/drag forces of by impact from previous grains.

2.2.2 Entrainment threshold of grains

When the flow of air over a sand bed is gradually increased, a critical wind velocity is reached when grains start to move. This threshold wind velocity is known as the fluid threshold velocity defined by Bagnold. To calculate this equilibrium moment due to the shear stress at the threshold of grain movement, It is important to know when the combined lift and drag forces exceed the inertial forces of the grain bed.

Figure 2.2 forces acting on a loose surface grain



Wind blowing over a horizontal granular sand bed exerts two types of forces on a sand grain. The force parallel to the wind direction is called the drag force. Acting vertically upwards is the lift force, this force results from the increase of pressure difference between bottom an top of the sand grain due to the wind speed over the grain (Bernoulli effect). Opposing these aerodynamic forces are the inertial forces, gravity and the interparticle cohesion. These are the forces that are related with the physical properties of the sand bed (figure 2.4). These forces at which grains can be entrained into the air are influenced by a number of factors, including humidity, grain size, presence of shells and packing.

Combining these forces exerted on grains will result in a measure of the ratio of the effectiveness wind shear stress and resisting forces like cohesion or gravity. Bagnold defined the critical shear stress velocity, u_{*_t} necessary to initiate movement as:

$$u_{*_t} = A \cdot \sqrt{d \cdot g \cdot (\rho_s - \rho) / \rho} \tag{2.5}$$

Where d is the grain diameter, ρ_s is the density of the sand grain. ρ is the density of the air and A is a proportionality coefficient. According to Bagnold, A is a constant (0.1 at the fluid threshold). Natural conditions on a beach are not constant over the area. So considering this approach for the shear stress velocity threshold as uniform across the beach does not take into account sediment properties and the state of the surroundings.

2.2.3 Transport equations

Expanding equation 2.1 by including the modified velocity profile accounting for the effect of the saltation layer on the wind flow results in:

$$q = C_2 \sqrt{\frac{d}{D}} \frac{\rho}{g} (u_* - u_{*_t})^3 \tag{2.6}$$

In this equation the shear stress velocity threshold value is included. C_2 is a different form of the dimensionless empirical coefficient. According to the studies of Bagnold the sediment flux per unit of width is proportional to the cube of the excess of wind velocity over the threshold value. Many other authors have developed sediment transport formula aimed at predicting mass transport of windblown sand. A short overview is given in table 2.1.

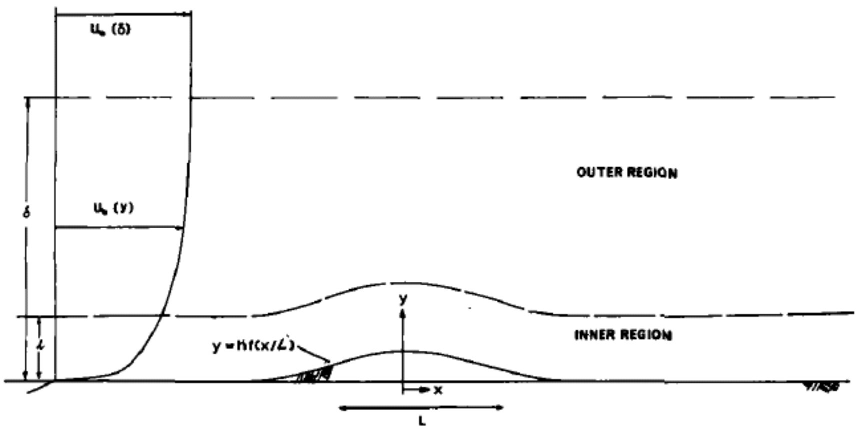
Table 2.1 Transport formula

Author	Formula
Kawamura (1951)	$q = C\frac{\rho}{g}(u_* + u_{*thr})^2(u_* - u_{*thr})$ $C = 2.78$
Zingg (1953)	$q = C\left(\frac{d}{D}\right)^{0.75}\frac{\rho}{g}u_*^3$ $C = 0.83$
Hsu (1971)	$q = C\ Fr^3 = C\left(\frac{u_*}{(\rho g)^{0.5}}\right)$
Lettau and Lettau (1977)	$q = C\sqrt{\frac{d}{D}}\frac{\rho}{g}(u_* - u_{*thr})u_*^2$ $C = 4.2$

When applying an empirical formula, it is important to have knowledge under what conditions they have been derived. Distinction can be made between those derived from wind tunnel studies (Bagnold, Zingg) and those derived from measurements of actual transport on field sites. (Hsu, Lettau and Lettau). Studies that have been performed using wind tunnel data have the advantage that certain phenomenon can be isolated and tested by using different conditions. They must however have scale inaccuracies because of the difficulties to incorporate the effects of large-scale turbulence. [Stam, 1994]

2.2.4 Smooth hills

Figure 2.3 Velocity profile over a smooth hill (source: Jackson and Hunt (1975))

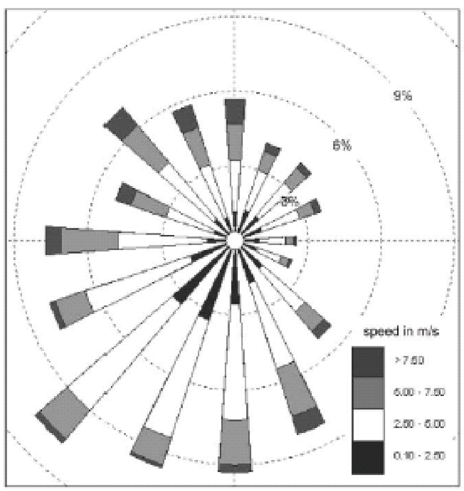


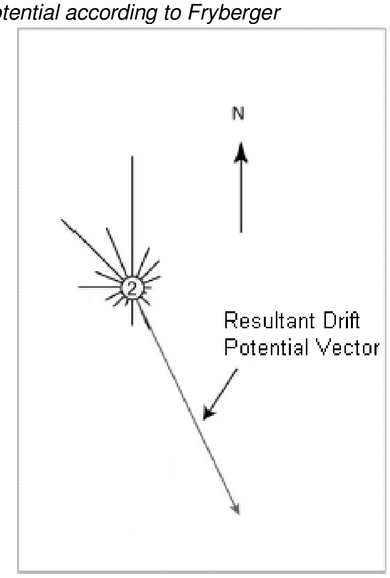
Surface shear stress is sensitive to changes in the surface elevation. Topographic obstacles like hills or dunes can perturbate the flow compared to air flow over a flat surface. Jackson and Hunt (1975) described the wind flow over a smooth 2D hill and Weng et al. (1991) extended the research for three dimensional hills. [Jackson and Hunt, 1975] [Weng at al., 1991]. The method that they used consists of dividing the flow over the hill into two parts, an inner region where shear stresses due to the perturbation affect the flow and an outer inviscid region. They presented an analytical solution that showed that the horizontal component of the speed of the wind flowing of a low hill at a certain point above the hill's surface is the sum of these two parts; the wind speed above level ground, plus a perturbation due to the presence of the hill.

2.2.5 Wind regime

The rate and direction of aeolian sand transport is strongly governed by the wind regime, i.e. the velocity distribution and directional variability. Following the suggestion of Bagnold, winds should be evaluated and defined in terms of their potential sand-moving effectiveness through the use of a suitable weighting equation applied to a standardized set of data. Provided that adequate wind data is available for a certain location, the velocity data and a sand transport rate equation can be used to approximate the regional sandflow resultants. Fryberger and Dean (1979) used this derivation to express the local wind regime into drift potentials, which are expressed numerically in vector units. Figure 2.2 shows an example in which a local wind climate is expressed in a drift potential according to the theory of Fryberger.

Figure 2.4 Transformation from an example windrose to a drift potential according to Fryberger





2.3 Characteristics on a beach

In the following section processes that influence transport of particles at the beach will be described. The emphasis will lie on transport across a natural beach as looking at theoretical phenomena derived from desert sites and wind tunnel tests could underestimate some contributions that are of importance in a coastal zone. An understanding of the physical characteristics of sand grains and the manner in which they influence aeolian transport is essential for correct interpretation of wind blown sand flux.

According to Gillette et al. (1996) and Bauer et al. (2006) several factors are related to the rate of transport over a cross section of a beach:

1 Saltation ‘cascade’. Grains that are dislodged near the leading edge of the sand sheet will impact the surface downwind and thereby dislodging a large number of grains, until an equilibrium rate of transport is achieved.
2 Aerodynamic feedback or Owen effect, increases the aerodynamic roughness. As more and more sediment is introduced into the saltation layer within the near-surface boundary layer, aerodynamic roughness increases (hence this increases the shear velocity)
3 The internal beach boundary layer changes with downwind distance, this is an additional factor separate from the influence of the Owen effect. As an internal boundary layer expands vertically with downwind distance, the near-surface wind speed decreases and the total shear is distributed across a thicker layer of atmosphere.
4 Soil resistance. Entrainment velocity changes over cross section (grain size, moisture, vegetation). This confirms that threshold entrainment velocity could change with downwind distance

2.3.1 Sediment size and properties

The movement of grains in any fluid is governed partly by the size, shape and density of the grains and partly by the properties of the fluid. In aeolian sand transport studies, grain-size is recognized as an important parameter. Bagnold (1941) found that quartz sand grains of size 0.08 mm are most readily transported by the wind, because the threshold friction velocity is at its minimum for this size; smaller grains require higher wind speeds, mainly because of stronger cohesion forces, and larger grains offer greater resistance due to their greater mass/surface ratios. [van der Wal, 1999]

Another conclusion made by Van der Wal during wind tunnel experiments is that large amounts of shell fragments considerably decreased the amount of sand blown off. Field observations confirmed that shell pavements can form within weeks, e.g. on the beach nourished in 1994 on the Wadden island of Texel. It may even be semi-persistent in areas that are not periodically flooded by the sea.

2.3.2 Moisture content

The concept of threshold velocity being dependent on moisture level is confirmed in studies that conducted wind tunnel tests. Literature also suggests the existence of a critical moisture content above which entrainment of sand is difficult and sediment transport is suppressed.

The increased cohesion forces are a result of the tensile forces between the water molecules and the sand grains. The capillary force at the contact points of grains and the adhesion (particle adsorption onto the surface of the grains). For small sediment sizes cohesive forces are significant but larger grains are considered to be cohesionless unless affected by moisture derived from an extern source like precipitation, tides or groundwater (e.g. due to the high moisture content of the lower part of a beach, the threshold velocity should be high in these regions).

Measurements on a natural beach were conducted by Svasek and Terwindt (1974). Despite the fact that their data showed a large amount of scatter. It was observed that once sand movement starts at some place, other downwind locations overcome the effects of a high moisture content and experience the beginning of sand transport. The effects of moisture content are overcome due to the presence of the impacting saltating grains. Local weather conditions can also play a dynamic role in controlling the transport of sand across a beach. At high wind velocities rain causes a decrease of the sand movement. However, directly after the rain, the sand movement increases again to almost the original level. Drying can even result in a temporary reduction of threshold wind velocity. [Davindson-Arnott, Bauer, 2009]

2.3.3 Vegetation

Vegetation has long been recognized as a major factor controlling coastal dune morphology (Figure 2.5). The interaction between vegetation cover, wind speed and supply of sediment from the shore is the controlling factor in the growth of coastal dune fields. Wolfe and Nickling (1993) concluded that vegetation effects sediment transport in several ways, vegetation extracts momentum from the wind field, the part of the surface that is covered with vegetation does not supply the system with sediment and the elements of the vegetation act as an obstacle for the saltation grains. Density of vegetation acts as a local wind shear stress reduction.

Figure 2.5 A vegetated 'dune'.

If the growth speed of the vegetation is slower the rate of deposition, the vegetation will be buried. On the other hand, deposition might stimulate vegetation growth because the plants have to adapt to the changing surface height.

Not only topographic features like vegetation are present on a beach but also obstacles ranging from washed up debris to structures like buildings.

2.3.4 Fetch effect

The fetch effect refers to the increase in aeolian transport with downwind distance from the zone of no transport. In the case of a beach this leading transport edge is the waterline. The maximum available fetch is determined by the angle of the incoming wind and the width of the beach. The distance from the leading transport edge and the point at which maximum transport capacity can be observed is called the critical fetch distance. If a beach is sufficiently wide or the wind approach angle is highly oblique, the maximum available fetch can exceed the critical fetch distance. In that case maximum transport occurs in the area near the upper beach and dunes. This implies that the rate of transport on a beach is not only dependent on typical ‘local’ factors at a spot (i.e. grain size, moisture content, wind speed) but also depend on fetch geometry (beach width, wind approach angle) [Bauer et al., 2009]

2.4 Concluding remarks: Aeolian transport in the coastal zone and modeling of wind blown sand

Accurate predictions of transport of sand by wind on a beach is only possible if the processes mentioned above are fully understood. However, due to the high complexity and variability it is hard to predict actual rates of transport. The transport equations mentioned earlier are derived for ‘ideal’ conditions. Sediment flux on a sandy beach with a moderate climate is often more complex than this. Transport of sediment can depend on a number of factors like moisture content, grain size sorting, details in topography and vegetation cover. Adding this to a coastal wind climate with non constant wind and a varying direction influencing the effective fetch length over a beach. This fetch distance is important for the saturation of the sand transport rate, because in a coastal zone the sand transported landwards by wind is the primary input of sediment into a dune system. The source of this sediment can only be found in the small range between the low tide level and the foredunes.

Applying a model suitable for modeling desert topographies should be done carefully. Assumptions valid for a desert with uniform sand conditions and stable governing climate may not automatically translate well to a beach. From a Dutch coastal engineering point of view there are specific demands for an aeolian transport model. If we want to make the model suitable for the Dutch coastal zone, changes have to be made to several components of the program.

Hydrodynamic forces are not specifically looked at in this study, interaction between ‘wet and dry’ is an important aspect. The beach and dunes are always threatened by hydrodynamic forces but wave and tide action also serves as the input of sediment in the lower beach area. Dunes erode when the waves are high and the water level is high, which is the case during a storm. During these storms, sand is transported from the dunes back to the beach. Interaction between hydrodynamics, storm events and dune growth by aeolian transport should be schematized using a model that can clearly distinguish storm driven dune erosion and aeolian dune growth. [Damsma, 2009]

3 The DUNE model

Numerical modeling of aeolian sediment transport can be a valuable tool for understanding and predicting morphological developments. In this chapter, a description will be made of the existing aeolean transport model made by Sauermann and Herrmann (Hereafter called DUNE). This model is applied with success in the investigation of different dunes in desert environments. For the purpose of this project, the model is applied in coastal areas and therefore the performance is reviewed.

3.1 Introduction

During the development of the DUNE model, Sauermann and Hermann aimed to model various dune types and environments with the same program. The DUNE model is a combination of three physical processes. First an analytical set of equations describe the turbulent wind field over a certain terrain. The next model component describes the saltation which leads to the evolution of a sand surface. Finally a model for avalanching that takes transport of sand due to gravity into account.

The analytical solution for air shear stress over smooth hills as proposed by Weng et al. (1991) is used to obtain a fast algorithm, since calculation of the turbulent wind field with the averaged Navier-Stokes equations would result in high simulation times. The saltation model for sand transport from Sauermann et al. (2001) describes the relation between the wind shear stress and the erosion rate. The advantage of this model is the inclusion of the saturation transients, which play an important role in the proper description of sand flux over arbitrary terrains. Correct modeling of the wake behind a dune and the process of avalanching is dealt with in separate modules.

The program is written in the C++ programming language. Resulting code in C++ is efficient, modular and standardized. The most important characteristic of C++ is the object-orientated approach. This allows the programmer to design applications with the emphasis on communication between objects rather than on a structured sequence of the code.

Model extensions

When the wind direction is not constant but periodically switches, different types of shapes like seif or longitudinal dunes can occur. The model has been extended in order to account for these bimodal winds by Parteli et al. (2008). They found that the resulting morphology depends strongly on wind direction and the characteristic duration of these conditions (figure 3.1). At a small angle between wind directions the typical barchans shape can be seen. Varying the angel between directions and their duration different dune forms can be replicated. [Parteli et al., 2008]

Using the same technique, dune formation on Mars was also studied. Finding giant saltation trajectories and a rather low threshold wind strength to sustain the transport [Almeida et al., 2008]. These observations provided evidence that dunes can be formed and move on the present Martian surface. However the wind velocity is seldom above the threshold for saltation motion. This paper found large resonance in the media.

More recently the model was adapted to incorporate the transition of a barchan dune into a parabolic dune due to vegetation growth [Duran and Herrmann, 2006]. They showed that vegetation growth can transform barchan dunes into parabolic dunes. As can be seen in fig 3.2, a longer parabolic dune emerges for a smaller vegetation growth rate. On the other hand, if vegetation strength is too high, inversion from a barchans to a parabolic dune does not occur. In this case the barchan keeps its shape.

Figure 3.1 Bimodal sand dunes on bedrock with varying angles between directions and characteristic duration (scaled) of these conditions [Parteli et al., 2008]. Long periods between alternating the wind condition leads to the top barchans shape. Using wind conditions that alternate more often lead to more longitudinal shapes

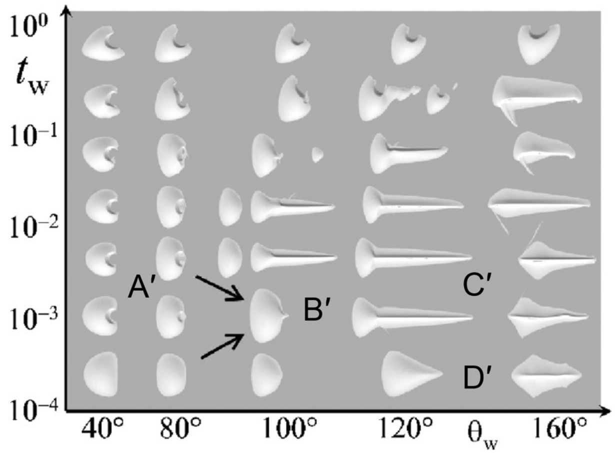
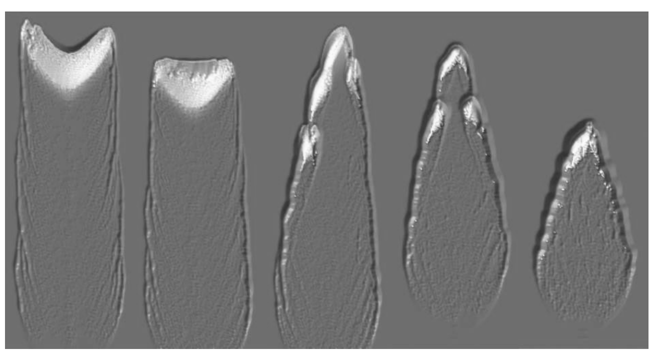


Figure 3.2 The transition (left to right) from a barchan shape into a parabolic dune shape under the influence of a relative weak vegetation cover. [Duran and Herrmann, 2006]



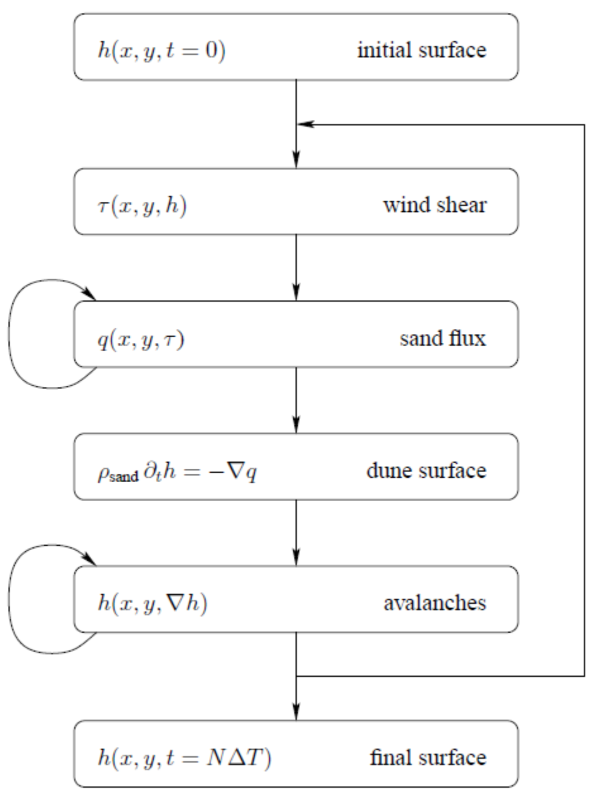
In the next section, there will be a short description on the basis of the model and governing equations. For a complete understanding of the model it is necessary to have an overview of the steps performed by the model and important components that are included. After that, several initial tests will be conducted. These test will be used to identify any structural difference between model application in a desert type environment and a coastal beach-dune system. The tests should reveal the components of the model that have to be adjusted to make the desired application possible.

3.2 Model description

For a full understanding of the model, this section describes the separate model steps. Figure 3.3 shows the principal structure of the model. The shear stress, sand flux, bed update and avalanching are calculated in successive order for the whole surface at every time step.

The model starts with an initial profile h(x,y,t)=0, and checks if a separation bubble has to be added. This could be the case at the sharpe brink of a dune. With this concept a smooth surface is constructed to calculate the shear stress with an analytical formula based on a linear perturbation theory of Weng et al. (1991). The rate of wind speed increase with the log-height is represented by u_* (the shear stress velocity). The presence of a perturbation in the surface changes the wind shear stress, thereby influencing the entrainment of grains in the saltation layer. The result of the shear stress calculation is used as input for the solution of the sand transport equation. The local flux can now be used to compute the change in surface height for every position needed to update the surface profile. This is the only part of the calculation that is time dependent. If after this step the new surface profile now exceeds the angle of repose (±34°), avalanching will transport sand in the down slope direction. The steps are preformed n times until the final surface is reached.

Figure 3.3 overview of the full dune model.

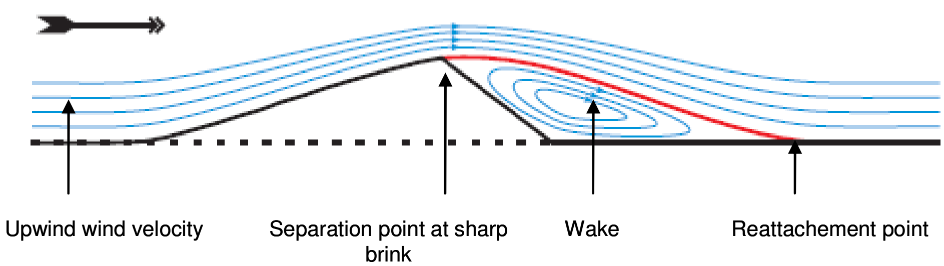


3.2.1 Shear stress calculation

First, the wind over the surface is calculated with the model of Weng et al., as detailed in the literature study. The presence of a dune or hill introduces a perturbation into the wind field. The research of Weng et al. resulted in a mathematical model using a two-dimensional transform of the terrain height. The calculation of the wind shear stress is used as input for the solution for the sand transport equation. Input for the shear stress calculation is the unperturbed upwind shear stress speed u_*. The model calculates the unperturbed upwind shear stress by $\overrightarrow{\tau_0} = u_*^2 \cdot \rho_{air}$.

All the assumptions made in the shear stress model work fine for smooth hill with gentle slopes. However, the approach that is used here does not account for flow separation at sharp brink lines of dunes. Instead of bending the streamlines around sharp edges, the brink of the dune is connected with the ground at the reattachment point. thereby creating an envelope that represents the lee side of the dune in which the wind and flux are set to zero. Figure 3.4 shows this surface formed by the separation streamlines from the point of flow separation to the point of re-attachment. The surface from a distance of approximately six times the height of the brink is called the separation bubble.

Figure 3.4 Seperation bubble (in red)



This combined envelope of topography and separation zone is applied in the shear stress computation. The algorithm developed by Weng et al. (1991) calculates the shear stress in Fourier space. The transformed components of the shear stress perturbation are calculated according to equation 3.1 and 3.1. $\tilde{\hat{\tau}}_x$ is the shear stress perturbation in wind direction, $\tilde{\hat{\tau}}_y$ denotes the lateral direction.

$$\tilde{\hat{\tau}}_x = \frac{\tilde{h}_s k_x^2}{|\vec{k}|} \frac{2}{U^2(l)} \left\{ -1 + \left(2\ln\frac{l}{z_0} + \frac{|\vec{k}|^2}{k_x^2} \right) \sigma \frac{K_1(2\sigma)}{K_0(2\sigma)} \right\} \tag{3.1}$$

And

$$\tilde{\hat{\tau}}_y = \frac{\tilde{h}_s k_x k_y}{|\vec{k}|} \frac{2}{U^2(l)} 2\sqrt{2}\sigma K_1\left(2\sqrt{2}\sigma\right) \tag{3.2}$$

$\hat{h}_s$ is the Fourier transformed separation bubble height (topography + separation zone) into Fourier two-dimensional space. $U(l)$ is the normalized vertical velocity profile at the height l. k_x and k_y are components of the wave vector $\vec{k}$ (the coordinates in Fourier space). z_0 is the aerodynamic roughness of the surface. K_0 and K_1 are modified Bessel functions. $\sigma = \sqrt{iLk_x z_0 / l}$ with L being a characteristic length scale given by ¼ the mean wavelength of the Fourier representation of the height profile.

After the Fourier components of the shear stress perturbation are transformed back to normal position space (x,y) the vector $\vec{\hat{\tau}} = \sqrt{\hat{\tau}_x + \hat{\tau}_y}$ can be inserted into the following equation leading to the local vector of the total shear stress,

$$\vec{\tau}_{tot} = \left|\vec{\tau}_0\right| \left(\vec{\tau}_0 \big/ \left|\vec{\tau}_0\right| + \vec{\hat{\tau}} \right) \tag{3.3}$$

Next the local shear velocity is computed by $u_* = \sqrt{\tau / \rho_{air}}$ which is applied in the sand flux computation.

3.2.2 Local sand transport

The second step in the model is the calculation of the sand flux. It is advided to consult the work of Sauermann et al. (2001) and Schwämmle (2002) for details on the complete derivation of the equation in the following paragraph. The sand bed can exchange grains with the moving saltation layer, the source term is represented by the erosion rate at any position (x,y). As the number of grains launched into saltation increases, the wind transfers more momentum to accelerate the grains, thus leading to a decrease of the wind strength within the saltation layer.

After a distance, the wind strength is just sufficient to sustain saltation and the flux achieves a maximum value. This distance is called the saturation length. The sand density and the grain velocity are calculated from the shear stress and are combined to compute the sand flux over a surface element q(x, y) = u(x, y)ρ (x, y). The time to reach the steady state sand flux over a new surface is shorter than the time scale of the surface evolution. Hence, the steady state is assumed to be reached instantaneously. By taking the interactions between the particles and the air into account, the following equation is obtained leading to the sand flux. The effective wind velocity is defined as

$$v_{eff} = \frac{u_{*t}}{\kappa} \left(\ln \frac{z_1}{z_0} + 2 \left[\sqrt{1 + \frac{z_1}{z_m} \left(\frac{u_*^2}{u_{*t}^2} - 1 \right)} - 1 \right] \right) \tag{3.4}$$

where u_{*t} is the threshold wind velocity, z_0 is the surface roughness in the absence of the saltating grains, z_m is the average saltation height and z_1 is the characteristic height, between z_0 and z_m, at which the wind velocity is computed. The grain velocity u is evaluated by solving the quadratic vector equation numerically:

$$\frac{3}{4}C_d\frac{\rho_{air}}{\rho_{grain}}d_{grain}^{-1}\left(\vec{v}_{eff}-\vec{u}\right)\left|\vec{v}_{eff}-\vec{u}\right|-\frac{g}{2\alpha}\frac{\vec{u}}{\left|\vec{u}\right|}\wedge-g\nabla h=0 \quad (3.5)$$

Where $\vec{v}_{eff}=v_{eff}\vec{u}_*/\left|\vec{u}_*\right|$ and C_d is the grain drag coefficient, d_{grain} and ρ_{grain} are the average diameter and the density of the grains and α is a dimensionless model parameter. Next the sand flux due to saltation is obtained by numerically solving the transport equation:

$$\frac{\partial}{\partial x}q=\frac{1}{l_s}q(1-\frac{q}{q_s}) \quad (3.6)$$

with

$$q_s=\frac{2\alpha}{g}\left|\vec{u}\right|\left(\left|\tau\right|-\tau_t\right) \quad (3.7) \quad \text{and} \quad l_s=\frac{2\alpha}{\gamma}\frac{\left|\vec{u}\right|^2}{g}\frac{\tau_t}{\tau-\tau_t} \quad (3.8)$$

Here g is the gravity acceleration, and γ is a dimensionless model parameters. A calculation of the saltation transport by the well known flux relations (Bagnold; Lettau and Lettau) would restrict the model to saturated sand flux, which is not the case for example at the foot of the windward side of a dune due to little sand supply.

The calculation of the sand flux over a dune surface leads to bed level changes by erosion and deposition of sand grains. The change in surface height can be computed from the conservation of mass:

$$\frac{\partial h}{\partial t}=\frac{1}{\rho_{sand}}\frac{\partial q}{\partial x} \quad (3.9)$$

Note that this equation is the only time dependent equation and thus defines the characteristic time scale of the model which is normally in the order of hours for every iteration.

3.2.3 Avalanching

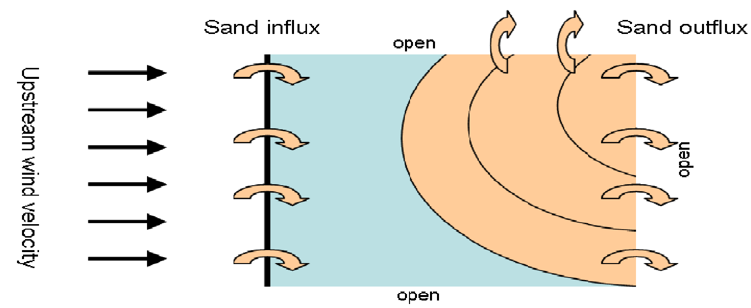
Surfaces with slopes that exceed the maximal stable angle of a sand surface, the so called angle of repose, undergo avalanches which slide down in down slope direction, so the unstable surface relaxes to a somewhat smaller angle. For the study of dune formation, two global properties are of interest. These are the sand transport downhill due to gravity and the maintenance of the angle of repose. To determine the new surface after the relaxation by avalanching, the model proposed by Bouchaud et al. (1994) is used. Like in the calculation of the sand flux the steady state of the avalanche model is assumed to be reached instantaneously.

3.2.4 Boundary conditions

Open boundary conditions

Boundary conditions are required to inform the interior of the numerical model about the world outside the model. Possible boundary conditions for DUNE are an open boundary or a periodic boundary The lateral and downwind boundaries are usually open which allows sand to move out the model domain (figure 3.4). The only true parameters that can be specified are the upwind shear stress velocity and the influx of sand trough the left/upwind boundary this additional parameter controls the sand influx q_{in} into the simulated dune field. It is set constant over the lateral direction at $x = 0$, but prescribing a certain influx at specific points along the edge is also possible.

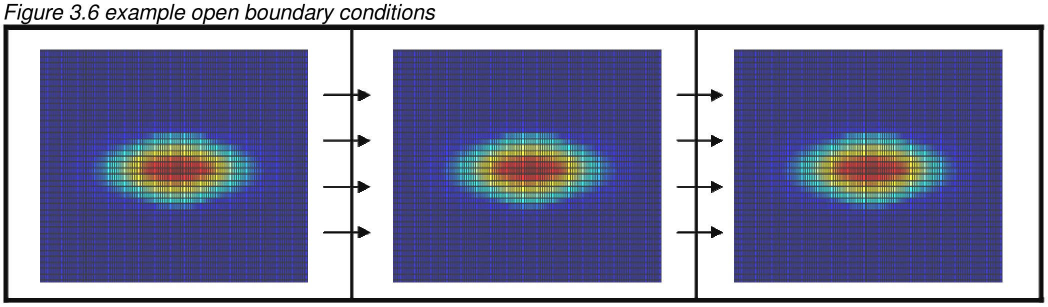
Figure 3.5 example open boundary conditions



Periodic boundary conditions

When the boundary conditions are defined as periodic, the separation bubble enters at the beginning of the dune field if it leaves the end. The sand influx is set equal to the outflux. The calculation of the stationary state of the avalanche model has to include periodic boundary effects as well. This condition simulates a larger dune field where sand lost from an upwind dune transfers into the model as an upwind boundary condition for the next dune (figure 3.6).

Figure 3.6 example open boundary conditions



3.2.5 Vegetation

Vegetation plays an important role in the stabilization and formation of coastal dunes. Dune vegetation is not only the key factor for dune stability, but also has recreational and ecological values. Duran (2006) extended the model to also include the vegetation growth. Including an approximation for the effect of vegetation on the sand flux should enable research on how the dune evolution is altered by the presence of vegetation. In the model vegetation is characterized by its local high h_v. This vegetation height can reach a maximum value H_v during a characteristic growth time t_g. The rate of growth of the plants should also be affected by the rate of sand surface change. This effect is introduced in the model by the following equation:

$$\frac{dh_v}{dt} = \frac{H_v - h_v}{t_g} - \left| \frac{\partial h}{\partial t} \right| \tag{3.10}$$

This equation expresses that if the accumulation of sand on the surface is sufficiently high, the growth rate of the vegetation can become negative and the plants die. Vegetation protects the surface via direct cover, trapping of particles and by extracting momentum from the main air flow. A part of the total shear stress will be acting on the vegetation, the remaining fraction acts on the sand grains. The component of the total shear stress that acts on the sand is described by:

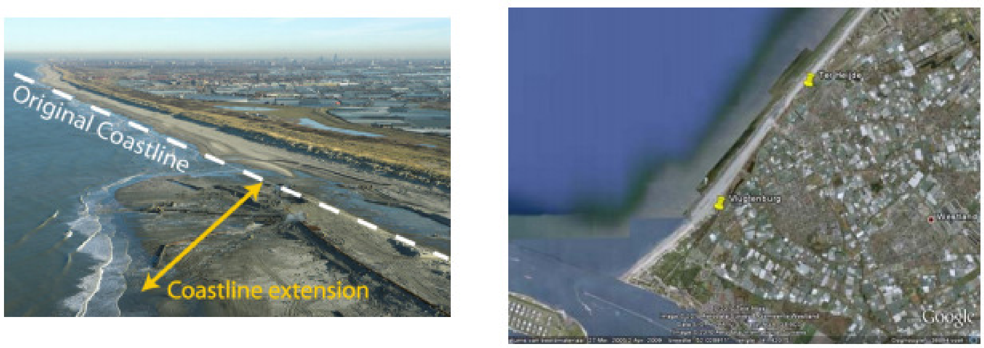
$$\tau_s = \frac{\tau}{(1 - m\rho_v)(1 + m\beta\lambda)} \tag{3.11}$$

Where τ is the total shear stress derived from the wind field, τ_s is the shear stress on the sand surface. To close the equation, the vegetation density is defined as $\rho_v = (h_v / H_v)^2$, m is a parameter for the non uniformity of the surface shear stress, β is the ratio of plant surface to surface drag and λ is defined as the frontal area density $\lambda = \rho_v / \sigma_{veg}$, where σ_{veg} is the ratio between width and height. The equation above represents a reduction of the shear stress acting on the sand grains containing interaction between vegetation and sand deposition. A decreased shear stress and thus the sand flux will result in sand deposition.

3.3 Initial test cases

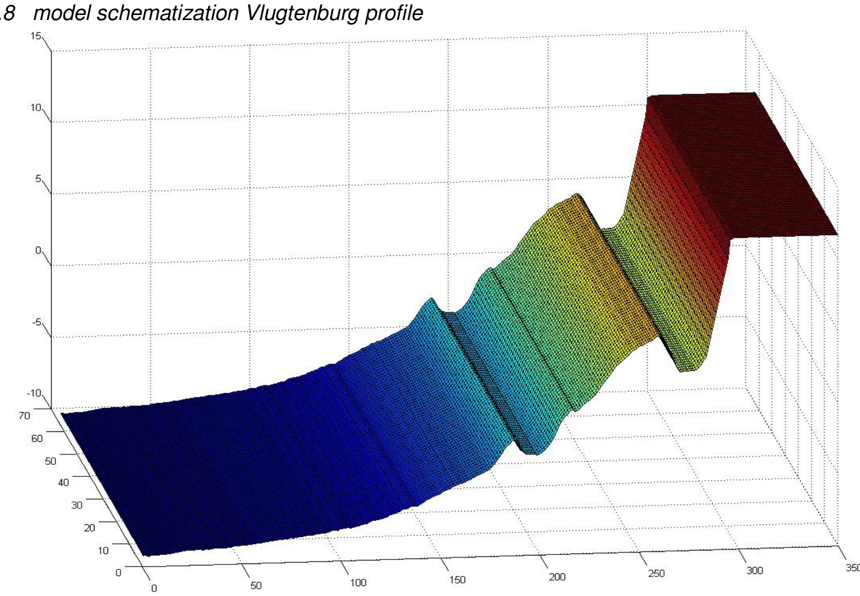
From a Dutch coastal engineering point of view there are different demands to an aeolian transport model. Although there are already good results with the modeling of dune formation in the desert and with theoretical shapes like a Gaussian hill, this coastal engineering application will concentrate on performing initial test cases with topographies that resemble or should resemble a beach including the foredunes. This is done to gain experience with the use of the model and to have an approach aimed towards identifying components of the model that have to be adapted to make it work for a beach-type topography i.e. the implementation of a water level or a typical coastal wind field. The bathymetry of the initial test case will be from a surface profile from a piece of the Holland coast called Vlugtenburg.

Figure 3.7 Vlugtenburg project location



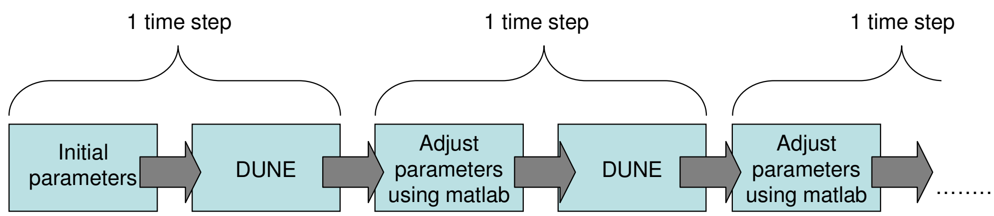
This beach is located at the southwest of the Holland coast, about 2 km northwards of the 'Noorderdam'. The beach of Vlugtenburg was extended seawards and a row of dune was artificially constructed as seen in figure 3.6. This profile was selected because of the proximity to the project site of the sand engine. It represents an arbitrary beach profile, but also contains interesting features like vegetated dunes and a sandy wet dune valley between the new and old foredune [De Vries et al., 2010]. For the simulations of the vegetation and sand input, a theoretical profile will be used in order to demonstrate the processes better.

Figure 3.8 model schematization Vlugtenburg profile



In the following section is shown how the model performs during these initial tests and what components have to be incorporated in the code. Despite the complexity of the code there is still a need to have some early indication of what the model is capable of. This is the reason that the first initial test will be conducted using matlab to manipulate the parameters externally while running the model i.e. pausing the model, change data like the water level to simulate a fluctuation tide, then continuing the model again (figure 3.8).

Figure 3.9 calculation steps



3.3.1 Approach

In the study of literature several processes where identified that have to be included in a proper model of coastal aeolian transport on a beach. The next test cases will deal with these specific processes, testing the assumptions made in the present state of the model. Due to the lack of experience with the model, these test are necessary to explore the applicable use of the software. The essential processes are implemented and the results are reviewed. These cases cover physical processes like tidal inundation of a beach, varying wind conditions, vegetation and supply of sediment. But also the numerical approximations for the artificial boundary conditions are evaluated.

The first test case will involve testing the model with a simulated water level. An important feature of a beach is the presence of a water level. This water level can vary with tidal movement. For a coastal engineering case it is also necessary to use actual wind data as input for the model. This next step is to explore the capabilities of the model to deal with such a variable wind climate. The boundary conditions are checked in the following model test. In the last tests the function of the vegetation module is explored and the influence of sand influx at the boundaries is checked.

This leads to the following model cases:

1 Tide
2 Wind field
3 Boundary conditions
4 Influx
5 Vegetation

3.3.2 Beach profile with a constant water level

Goals:

In DUNE a water level is not included. Instead a non erodible layer can be define at the height of the water surface by calculating the surface that that should be covered with water and laying the non erodible layer on top of it. As a result only the exposed 'dry' part is affected by the model. This method is used to asses the effect of a water level on a beach profile.

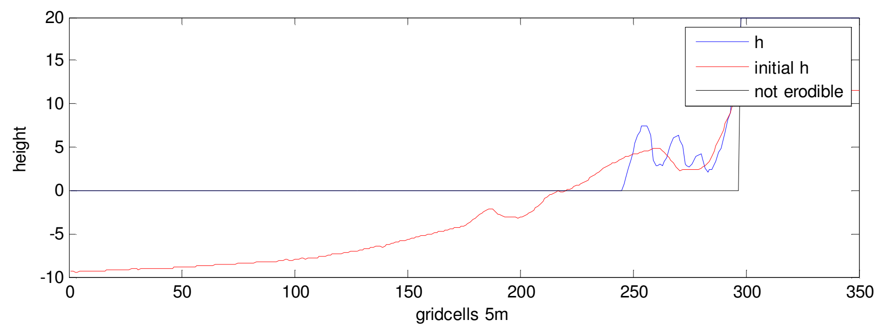
Set up:

As a start it is chosen to subject the existing beach profile of Vlugtenburg (figure 3.9) to a constant unidirectional onshore wind during roughly 200 days. An initial non-erodible surface is located at h=0, and represents the waterline. This test assumes no transport of sediment into the model at the upwind boundary. At the land boundary the surface is raised to form a ‘wall’ for trapping the sediment in the system.

Results:

After running the model to simulate 200 days the resulting profile in figure 3.10 shows erosion at the water line. The beach foot retracts a considerable distance.

Figure 3.10 cross shore profile



Discussion:
It is learned from this result that using a constant waterline leads to extreme erosion at the waterline. This is usually not observed at a natural beach. The primary cause of this is the lack of sediment input from the upwind direction. The wind has the potential to pick up sediment and when it reaches the intersection between the water level and the beach profile, it erodes the sand at that spot. This process causes the beach to retract. Because this model runs only account for the effect of aeolian transport the complicated interactions in the inter tidal area are not taken into account. Processes in this dry/wet area can supply sediment into the system preventing the extreme erosion.

3.3.3 Beach profile with changing tide

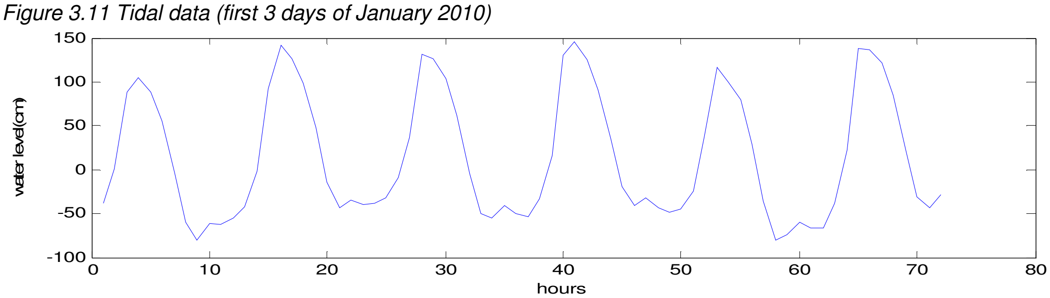
Goals:

In the previous test the water level height was constant in time. Using a variable water line should spread the erosion effect at the intersection between the water and the beach

Set up:

Changes due to the tide are done by varying the non erodible surface according to a sine function with frequency (twice a day) and amplitude (+/- 1 meter) or a changing water level from historical tide data (source: rijkswaterstaat 2010). The variation of the historical data (figure 3.11) is more scattered than a perfect sine function. This should lead to an even more realistic result.

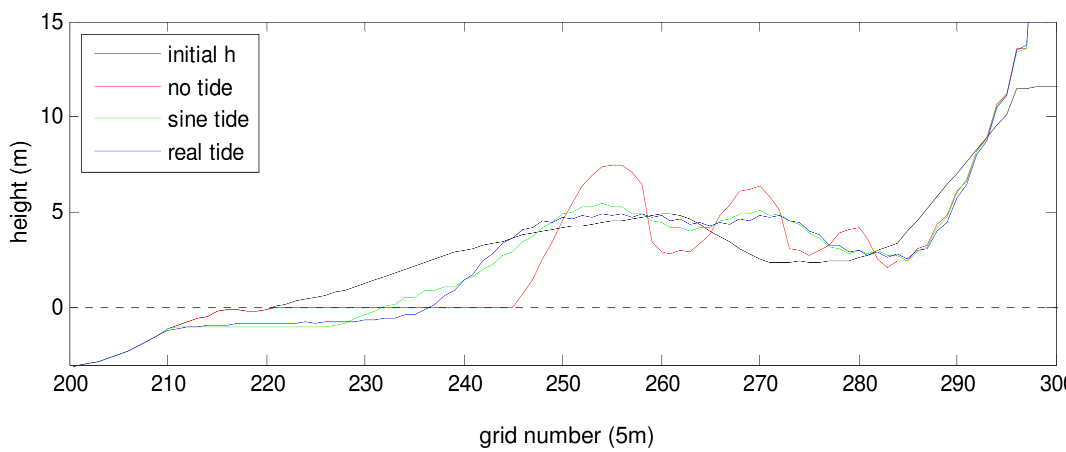
Figure 3.11 Tidal data (first 3 days of January 2010)



Results:

Using a variable water level in time leads to a less extreme looking end situation, as seen in figure 3.12. The erosion effect is spread out more in the inter tidal area (roughly between -1 nap and +1 nap).

Figure 3.12 cross shore profile



Discussion:

It can be concluded from these tests that it is important to include a varying water level, because this has a significant impact on beach topography. It is also important to note that the observed erosion is not a feature that is seen often at normal beaches. Maybe combining the wind model with a hydraulic model like Delft 3D can lead to a input in the inter tidal area. This lies outside the scope of this thesis. The input of sediment could be represented by sand that gets blown across the water and reaches the beach, or that the position of the inter tidal area remains stationary. (sediment removed by aeolian processes gets immediately replaced by swash action)

3.3.4 Beach profile with changing wind field

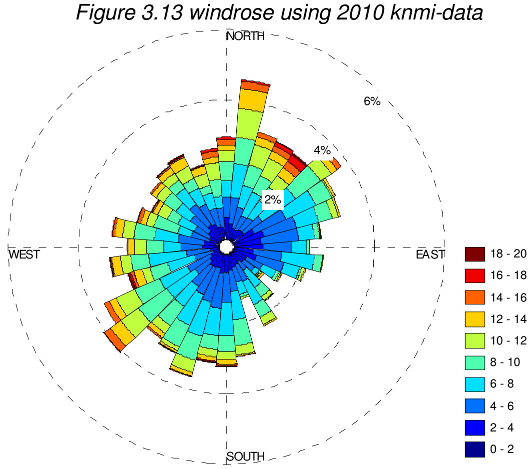
Goals:

The model in it's current state can handle different winds speeds and direction as demonstrated in Parteli et al. (2008). To have a more realistic representation of a situation with wind, we have to be able to incorporate a non constant wind field that can vary often between a wide range of conditions.

Set up:

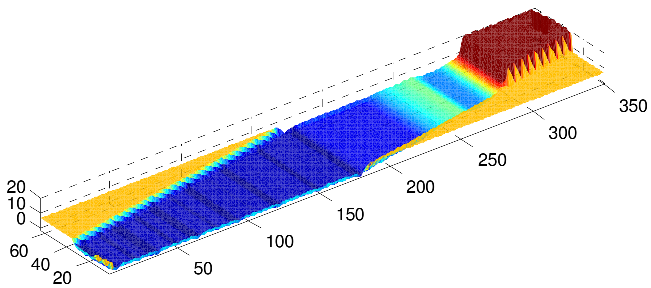
As a reference, the knmi-data of 2010 at Hoek van Holland is used (figure 3.13). Wind direction and speed is measured every hour. Model varabels for wind speed and duration are changed every hour.

Figure 3.13 windrose using 2010 knmi-data



Results:
When the model uses an other angle then zero, information in the corners of the model disappear. The areas at the corner in figure 3.14 have lost their information of the surface height.

Figure 3.14 model result with errors due to rotation



Discussion:

A problem arises when a non zero direction (angle) for the wind is chosen. From literature and review of the code it can be concluded that it is not the approach angle of the wind that rotates, instead the program rotates the simulation field, i.e. the whole system. So the parameter concerning with the wind direction represents the angle you rotate the field, keeping the actual wind direction constant. Problems with this approach arise at the edges of the model. Rotating a square grid around its center will lead to parts of the model falling outside the new model domain. When generating the output, the model rotates the surface back but loses information on the old surface area that fell outside the rotated grid.

3.3.5 Beach profile with changing wind field (2)

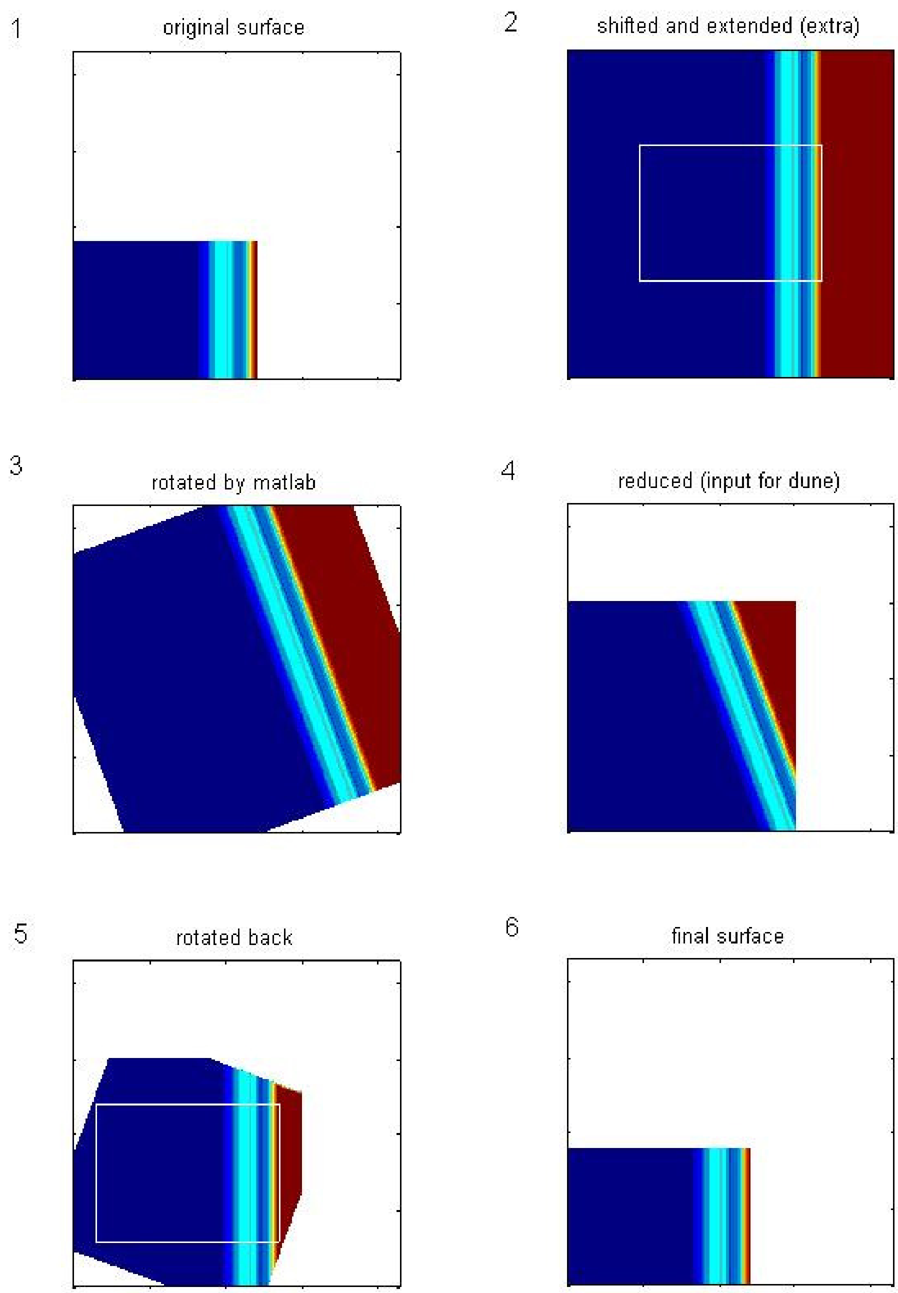
Goals:

At the moment, the model already runs using matlab to change variables like wind speed and tide level every hour. To implement the rotation of the whole matlab routine, the code has to include a section that rotates the (slightly larger) grid according to the wind direction at that point in time.

Set up:

Figure 3.15 sketches the steps performed to execute a rotation that does not result in loss of information at the edges. First the initial surface (1) is extended (2). This extended surface is rotated (3) ,this should also include the water level/non erodible surface). Next the rotated surface is reduced to a rectangular surface grid for input in the dune module (4). The model is run for the time associated with this wind condition. The model output is rotated back by the wind angle (5). Finally the rotated surface is reduced again to a rectangular surface grid resulting in a final surface with the same domain size as the original.

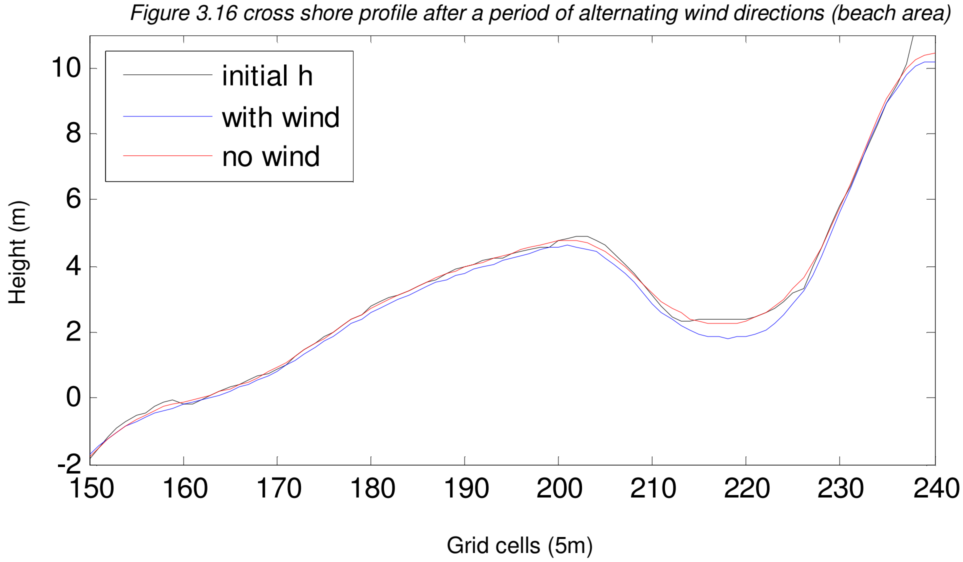
Figure 3.15 rotation steps.



Results

As observed in figure 3.16 the model does perform, but with a long computation time due to the large number of rotations. Smoothing of the surface can be observed, i.e. even when there is no wind forcing present, the surface profile still changes. It is also observed that the model does not conserve sediment, but loses sand.

Figure 3.16 cross shore profile after a period of alternating wind directions (beach area)



Discussion:

In this test case it became clear that a calculation with a changing wind direction every hour takes a lot of interpolation steps. Simulating a complete year will involve 8400 individual wind conditions. Information about the surface can be lost when the interpolation steps are performed too often, especially when the resulting errors of the same order of the surface level change due to the wind. In order to reduce the number of rotations, the wind climate should be reduced. This should reduce the computation time and numerical interpolation errors.

3.3.6 Reduced wind conditions

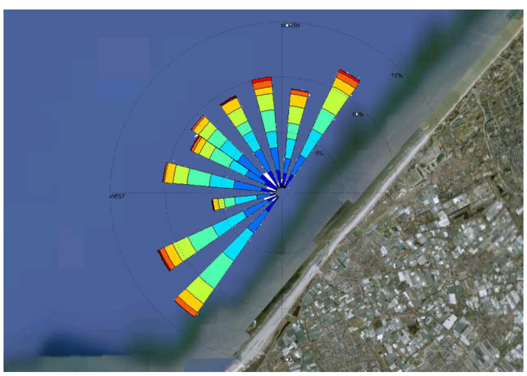
Goals

In the previous test case it became clear that a calculation with a changing wind direction every hour takes a lot of interpolation steps. Information about the surface can be lost when these steps are performed to often, especially when the resulting errors of the same order of magnitude as the surface level changes due to the wind.

Set up:

In order to reduce the number of rotations, some form of wind climate reduction has to be performed. This test case will use an onshore wind climate sorted by direction. So the first onshore direction is run with the hourly wind speed associated with this direction. After this the model rotates according to the second direction band and then runs for the associated number of wind hours.

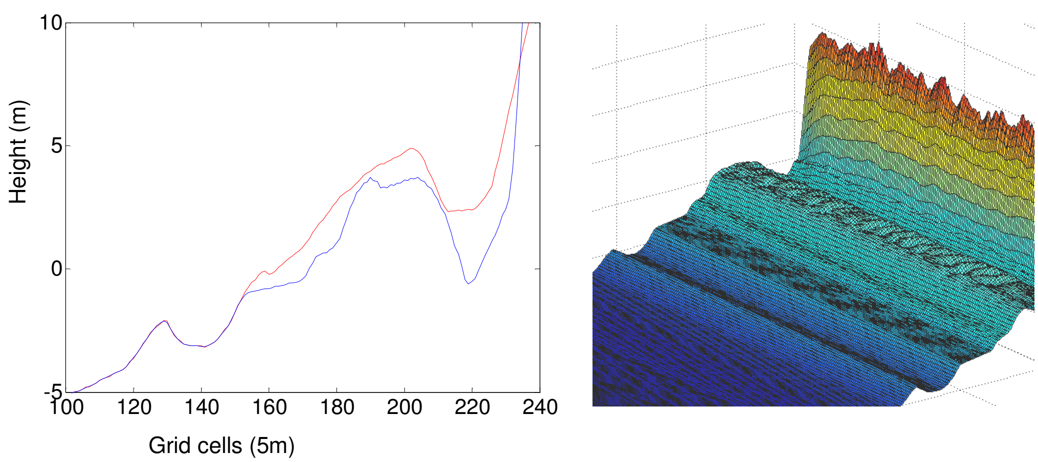
Figure 3.17 onshore wind rose and individual wind conditions.



Direction band	Avrg Dir	Direction band relative to the model	Number of individual wind hours:
0-18	9	59	436
18-36	27	77	554
Offshore wind directions			
216-234	225	-85	620
234-252	243	-67	555
252-270	261	-49	274
270-288	279	-31	481
288-306	297	-13	403
306-324	315	5	443
324-342	333	23	434
342-360	351	41	470
			4670 in total

Results:

Figure 3.18 cross section and overview



Discussion:

It is clearly visible in the model that there is a loss of sediment. The finale profile is much lower then the initial. It is expected that the model can not handle the rotating surface and keep track of the correct boundary conditions. It is also visible that orientation of the last wind direction can be seen in figure 3.18 (ripples directed in the wind). For the calculation of the sand engine the wind schematization can be more advanced, thereby reducing this effect.

In the next section more research will be done into the sand transport and shear stress at the boundaries.

3.3.7 Sand flux and shear on a rotated beach topography

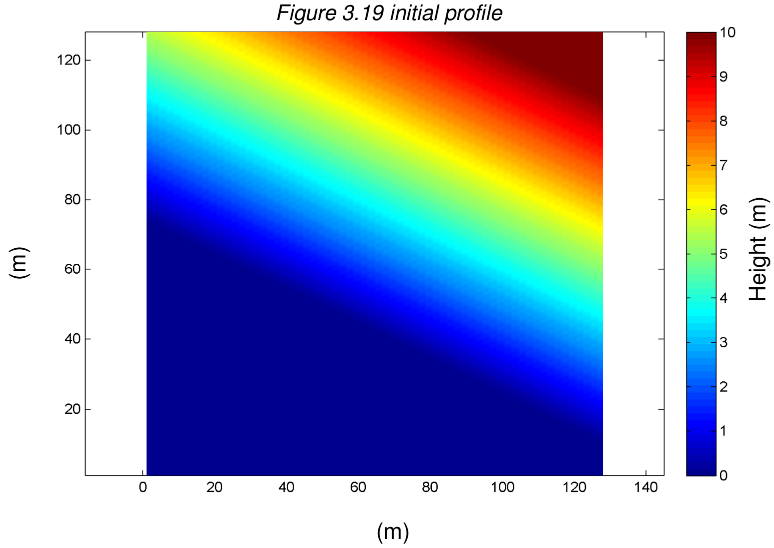
Goals:

In the previous model tests that used a rotated beach, it was observed that sand was lost in the model. To obtain a good insight in the sediment entering and leaving the model domain, it is necessary to look at the imposed boundary conditions. For testing the boundary conditions a sloped beach surface will be used. Because of the orientation of the surface, the sand surface runs up the upwind left boundary. A possible scenario in case of oblique wind directions.

Set up:

A simple 1:10 sloped profile will be used. This should lead to a uniform distribution of the shear stress and sand flux.

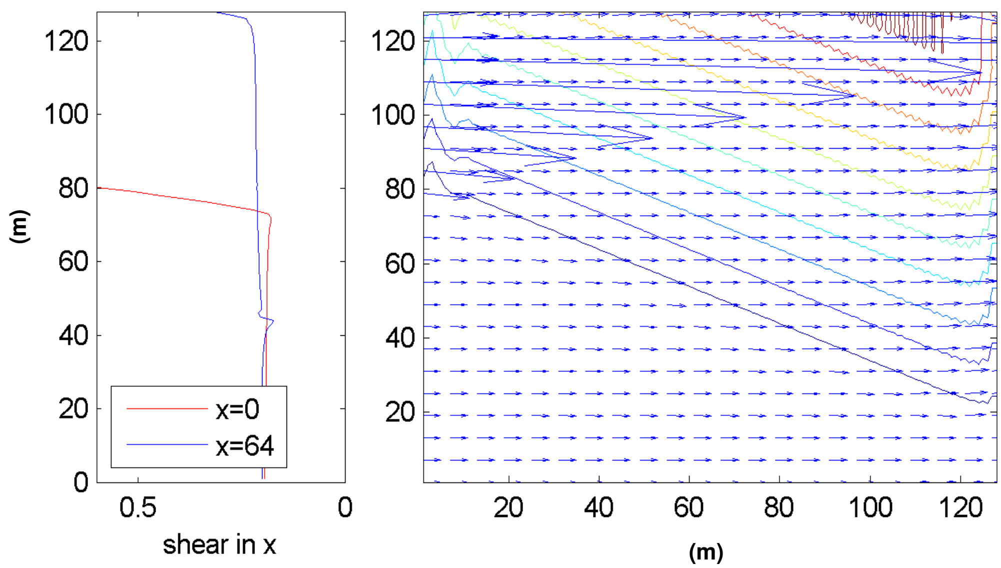
Figure 3.19 initial profile



Results:

At the upwind boundary high spikes in the local shear stress occur (order of magnitude 10x larger with respect to other locations). Figure 3.20 shows this effect. This in turn has an effect on the local sandflux.

Figure 3.20 plan view of the resulting shear stress on the surface and the upwind boundary



.
Discussion:

The section of the model that calculates the shear stress on the surface uses Fourier transformations. The program uses the Fourier transform of the terrain height. The algorithm for the analytical solution is then used to compute the Fourier Transform (FT) of the shear stress field. In the last stage the Fourier transforms are inverted back to calculate actual flow variables at the required points. No numerical iterations are involved.

The model seems to have difficulties with a non smooth surface profile at the boundaries. The model may see the elevated profile at the boundary as a sudden increase in surface height. Problems could occur when using the FT of the surface profile $\hat{h}_s$ to compute the local shear stress at every point. As is the case with Fourier approximations, the profile will not be the exact shape as prescribed in the initial bathymetry. Especially at the points where the surface is discontinuous. When the model uses certain boundary conditions, the model grid is extended outward to allow for the FT to begin far enough from the model area. The array is padded with zeros to form a larger one, putting the dune far enough from the boundary to be unaffected by the periodicity implied by the FT. Choosing the area that the model uses for the FT larger than the original area can only be done if the perturbations in the surface are gentle enough. If we want to use the rotated beach profile, the model should be extended outward and provide for a smooth (continuous) approach.

Deltares

3.3.8 Boundary flux test on generic profile

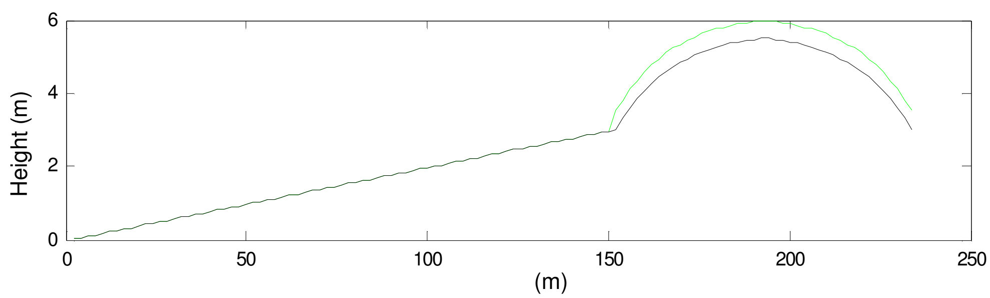
Goals:

In this test we will use a more synthetic profile to gain insight in factors like vegetation and influx of sand trough the upwind boundary.

Set up:

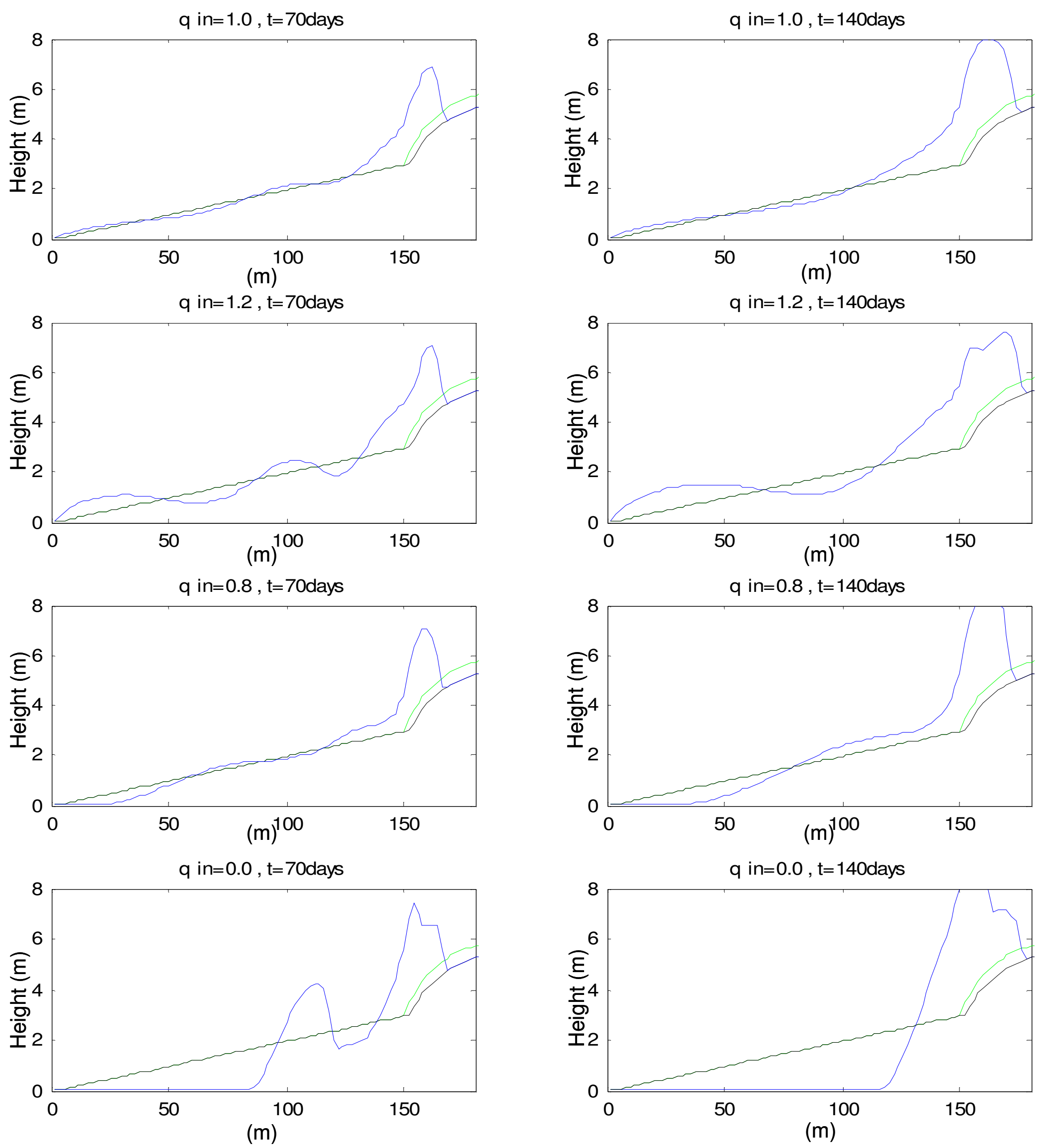
The initial profile is a beach-dune type situation. Beach slope 1/50:, beach width: 150m. The dune area can be initialized with vegetation.

Figure 3.21 custom beach-dune type profile



The input of sand trough the upwind side of the model can be controlled by adjusting the parameter q_in in the input file. Sand influx equal to 1 means saturated flux at the entrance, the program automatically calculates the saturated flux $q_s(u_*)$ for the wind shear stress u_*, and puts q_in = $q_s(u_*)$ at x = 0. So lowering this parameter should result in a input of sand lower than the saturated value causing local erosion. Increasing it should lead to the opposite, local accretion at the entrance of the model.

Figure 3.22 Development of the cross shore profile with a varing input of sand at the upwind boundary. Black is the initial surface, blue is the new sand surface and green is the location of vegetation



When the input flux is lower then the saturated value, erosion in the first part of the model takes place (figure 3.23). The opposite occurs when the boundary flux is higher then the saturated value.

3.3.9 Vegetation test on generic profile

Goals:

The interaction between vegetation cover and supply of sediment from the shore is the controlling factor in the growth of coastal dunes (apart from wind speed). In this test case the vegetation module is explored.

Set up:

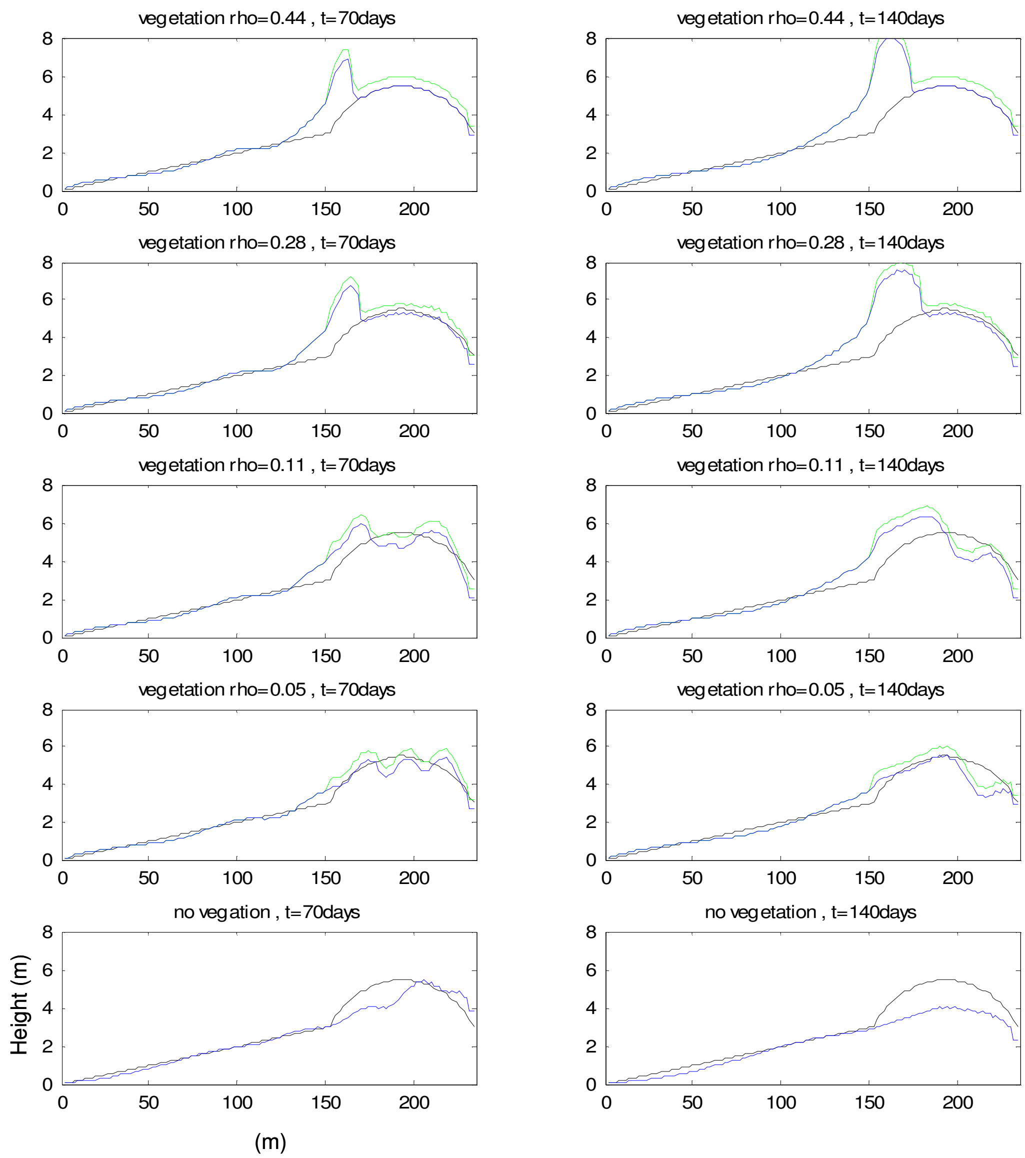
The initial profile is the beach-dune type situation. Beach slope 1/50:, beach width: 150m. The dune area will be initialized with vegetation. The vegetation acts as roughness that absorbs a part of the momentum transferred to the soil by wind. Increasing the spreading of the vegetation should decrease the local effect of sheltering, thus lowering the shear stress..Several vegetation parameters can be altered to influence the behavior of the module (Maximum height, growth time concentration and root size). In these tests, only the density of the vegetation will be varied, therefore influencing the degree that the shear stress is lowered. Sediment influx at the upwind boundary is assumed to be saturated.

In the first test the position of the vegetation is kept constant restricting it to the dune area. The second model test allows the vegetation to grow on all surfaces above a certain level (+3 m NAP).

Results:

Figure 3.24 demonstrates that high vegetation density can lower the local shear stress to zero, causing accumulation of sand.

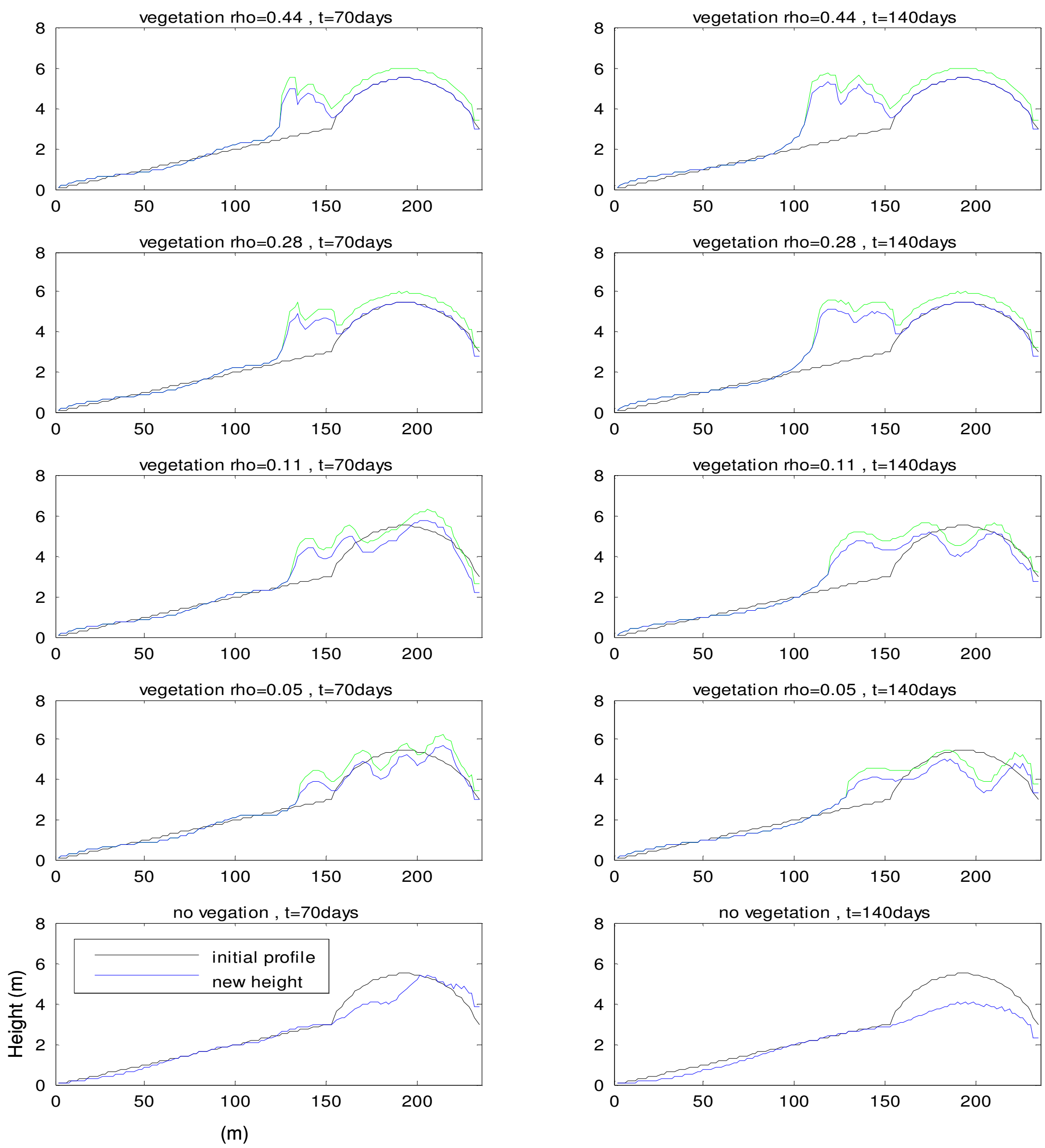
Figure 3.23 Development of the cross shore profile with a varying density of vegetation. Black is the initial surface, blue is the new sand surface and green is the location of vegetation



Results:

In figure 3.24 the position of the vegetation is not static. Vegetation is allowed to grow at any point above the +3m line. This should represent a natural plant covered dune developing in seaward direction.

Figure 3.24 Development of the cross shore profile with a varying density of vegetation. Vegetation is allows to grow at all surfaces above +3 m . Black is the initial surface, blue is the new sand surface and green is the location of vegetation.



3.4 Conclusions on initial model testing

In this chapter the setup of the DUNE model was explained. Details on the assumption for the shear stress, saltation and physical processes like avalanching and the separation bubble are made more clear. The initial test cases served as a learning process for the handling of the model and to spot problems in the model while simulating a beach-dune system.

In this part of the report the model was manipulated by using it embedded in a matlab-script. When problems arise (like the shear stress at the boundary problem) it is necessary to look deeper into the c++ code of the model. The next chapter will try to address these problems and attempt to find a implementation of a solution for this problem.

The literature on the model and the initial test cases combine lead to a number of issues that will be addressed in the next part of the study. The issues that will be looked at are:

- Tide
- Boundary
- Wind
- Shear velocity threshold
- Vegetation

4 Model modification and tests

This chapter will try to give an overview of the issues that were identified using literature and the initial test cases. The specific problems will be addressed, the implemented measure will be described and the results will be evaluated.

4.1 Approach of model issues

From literature and preliminary tests a few important issues regarding the dune model can be identified. The issues that will be looked at are:

- **Tide** – Because the field of application of the model is primarily deserts, no water level of tide is included. This has to be implemented in the code.
- **Boundary conditions** – When wind direction is quite oblique, sand transported form the adjacent beach cannot be simulated. The current model only accepts an input of sand trough the complete upwind side of the model.
- **Wind field** – The model can handle different wind directions, but this has only been used in situations where the wind field is fairly constant (unidirectional or bimodal wind). Incorporation of a frequently changing wind field has to be done carefully as to avoid loss of information inside the model domain.
- **Shear velocity threshold** – At a beach, several factors like weather conditions, armoring and sediment properties can have a bigger effect on the speed at which grains are entrained in the air. If possible this has to be incorporated into a formulae for the threshold value.
- **Vegetation** – Vegetation is present in the model, tests have to be performed to assess the behavior and effect.

4.2 Model modifications

In the previous part of the report, the model was manipulated by using it inside a matlab-script. The results contribute greatly to the knowledge about the model. If problems arise (like the shear stress at the boundary problem) it is necessary to look deeper into the c++ code of the model. This is the only way to discover unwanted effects on the results.

4.2.1 Beach profile with changing tide

In the present model set up, the implementation of a varying water level is represented by evaluating the position of the non erodible surface using matlab and correct it every time step. The non erodible layer acts as cover on the submerged surface only exposing the 'dry' parts of the topography. In this way only the part of the beach that should be exposed to the wind is exposed. From a programming point of view it would be more efficient to try to implement a section in the model code that calculates this non erodible water level.

Implementation:

This function is incorporated in the software by inserting a section in the code that evaluates the water level every time step and superimposes a non erodible surface onto the sand that should be covered with water. The routine can handle a sine function as well as input from a water level file.

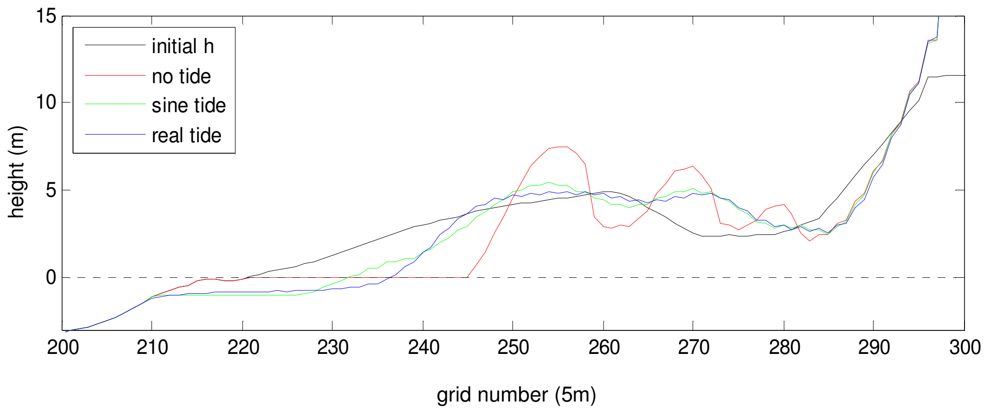
Set up

For the simulation of the tidal movements, actual historical data from Hoek van Holland area can be used. A periodic sine tide can also be implemented. For these initial tests using the sine tide of this data will suffice, but is it recommended to look at more statistical data as model input.

Results:

Results from the model runs with the non erodible layer calculated internally are comparable with the results found earlier in the initial tests using matlab.

Figure 4.1 beach cross section



Discussion:

Apparently it does not make much difference if the water level is calculated inside the model or externally. In future application a reduced wind climate is used. Using historical data would not take into account any correlation between water level and wind speeds i.e. a high (surge) water level and strong onshore wind.

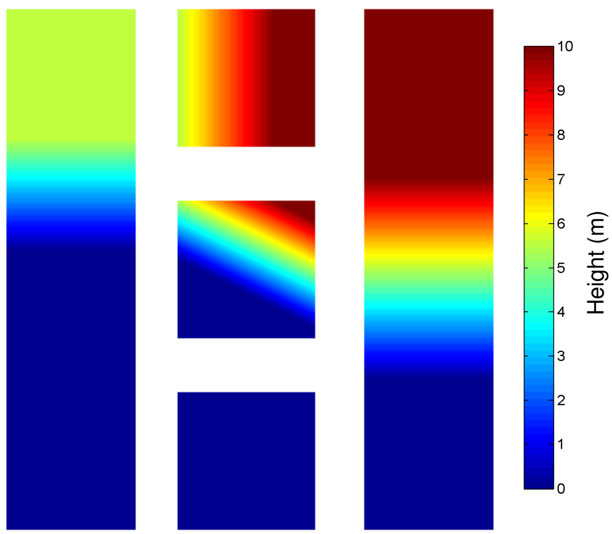
4.2.2 Sand flux and shear on a rotated beach topography

Initial test cases showed large deviations from the expected behavior at the edges of the model. Shear stress peaked at the edges and a lot of erosion could be seen at the boundaries of the model. (due to a potential capacity to pick up sediment but zero influx of sand) Previous

Implementation:

Using the extended model domain, but not letting the model fill the extended space with zero's, but extrapolate the edges.

Figure 4.2 Extended model domain. Middle square is the initial model domain, outside areas are extrapolated in the model (and not filled with zero)



Results

Figure 4.3 Shear stress inside the model and on the boundaries. Early in the run.

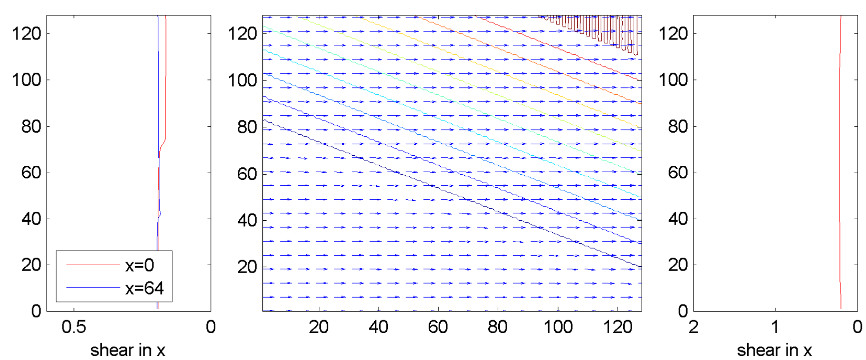
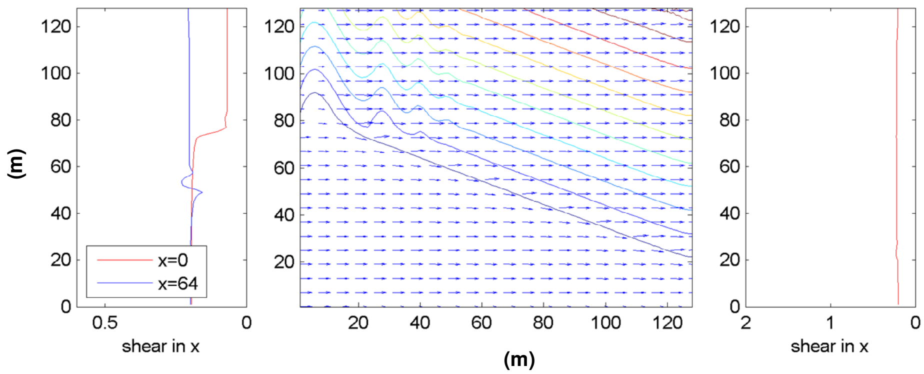


Figure 4.4 shear stress inside the model and on the boundaries. End of the run



There is no spike in shear stress at the boundary, this is a good result. Because of the lack of sediment coming into the system at x=0 a large area of scour moves trough the model.

Discussion:

When a constant input is set in the model, on the entire boundary at x=0 an influx of sediment is given. If we look at the theoretical beach profile, it is not possible to have an influx of sediment coming from the sea. A boundary condition has to be used that only gives a positive sediment influx when there is a beach on the upwind side. This influx of sand at the boundary has to be incorporated into the model. We can use a custom boundary condition that only inputs sand at the upper part of the model.

4.2.3 Custom boundary condition at the upwind side

Goal:

The previous chapter described the fix of the shear stress at the model boundaries. In this case there is still an error in local sediment influx at the edges. This is dealt with by programming a new type of boundary condition that checks if there is a sand surface present at the edge.

Modification:

When this is the case, the influx at the boundary at the ‘dry’ part is set as fully saturated, mimicking a infinitely long adjacent beach. When the surface height at the edge should be sea the influx is 0.

Results:

These results are quite good, showing no scour on the left edge of the model and only a minimal disturbance running trough the domain. The flux in x-direction seems to match the saturated flux in other locations (like the middle).

Figure 4.5 Sediment flux inside the model and on the boundaries. Beginning of the run.

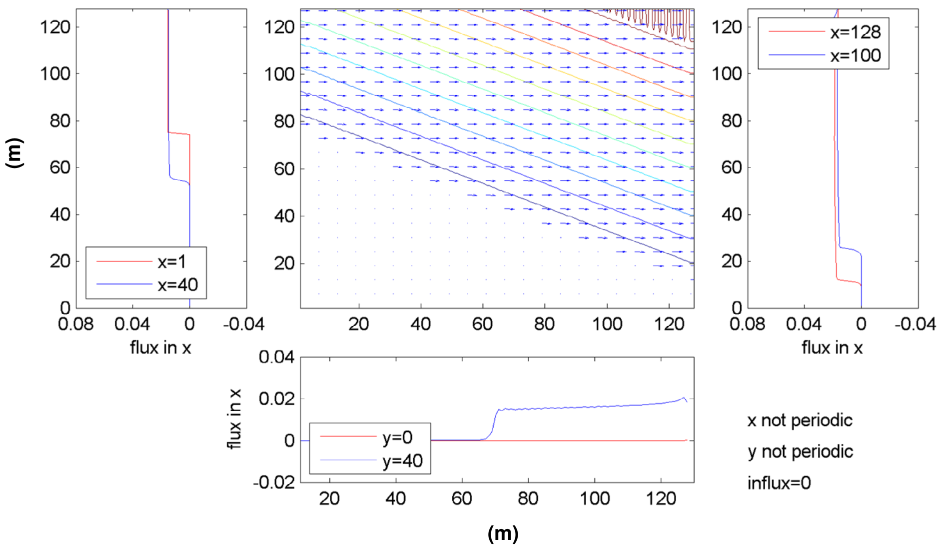
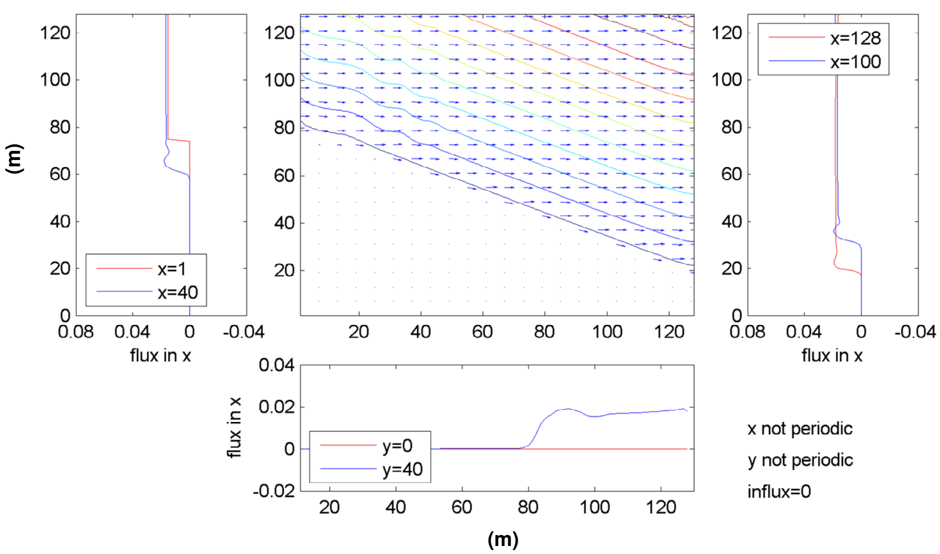


Figure 4.6 Sediment flux inside the model and on the boundaries. End of the run.



Discussion

When the wind direction is oblique enough, sediment originating form the adjacent beach can now be accounted for. Note that it is still assumed that no supply of sediment will come from the water-land interface.

4.2.4 Wind field

Goal:

In the previous section, a rotated beach topography was treated. The model in it's current state can handle different wind speeds and directions. To have a more realistic representation of a situation with wind, a non constant wind field has to be incorporated. Problems arise when the incoming wind direction is non zero. Information is lost on the edges as a consequence of rotating a square grid. In the initial test a script in matlab was used to perform the rotation. This was a time consuming procedure while the model is also able to rotate the topography. As it is preferable that most of the calculation takes place inside the model, changes in the code have to be made to use a (reduced) wind field as input, changing wind shear velocity and direction per time step or period, without stopping the model to adjust these parameters.

As a reference we can take the knmi-data of 2010 at Hoek van Holland. Wind direction and speed is measured every hour. Reducing the this data may lead to a more efficient model input.

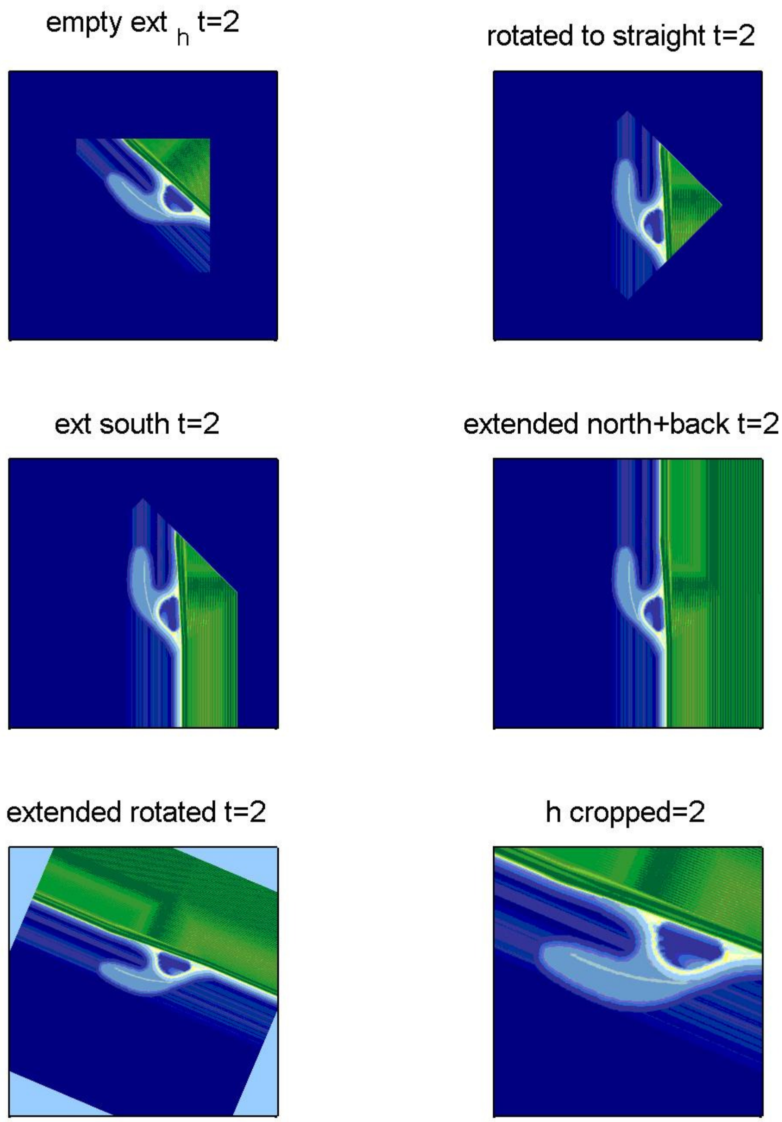
Modifications:

Changes in the code have to be made to use a (reduced) wind field as input, changing wind shear velocity and direction per time step or period, without stopping the model to adjust these parameters. Similar to the matlab script, a routine is written (figure 4.7) that first extrapolates the model, then uses the rotation function and finally crops the surface profile to the initial size. This should take care of the problems at the edges where information is lost.

The modifications in the code are:

- New rotation function that extrapolates the surface, does the rotation and than reduces the surface to the original size.
- Tide module that overwrites the non-erodable file according to a sine shaped tide.
- Stopped avalanching at the edges.
- New wind condition that can take a string of wind directions and speeds.

Figure 4.7 new rotation routine. First the model domain is enlarged, then it is rotated back to 0 degrees orientation. The surface is extrapolated north and southward. Finally, the topography is rotated and cropped back to the original model domain.



Results

Initial results from this rotation routine indicated that discontinuities at the corners are not present in this version of the model. The areas at the edges are still not suitable for exact analysis, but de edges will not influence the center area of interest.

4.2.5 Variable shear stress velocity threshold

Goal:

The original use of the model is to simulate the formation and migration of aeolian sand dunes. When the model is used as a tool to simulate desert topographies, it is justifiable to use uniform sand conditions across the model area and during the model duration. Any deviations from these ideal conditions that limit saltation could lead to an overestimated calculation of the changes in morphology. Implementation of a variable threshold value for the shear stress velocity could replicate the natural conditions on a beach.

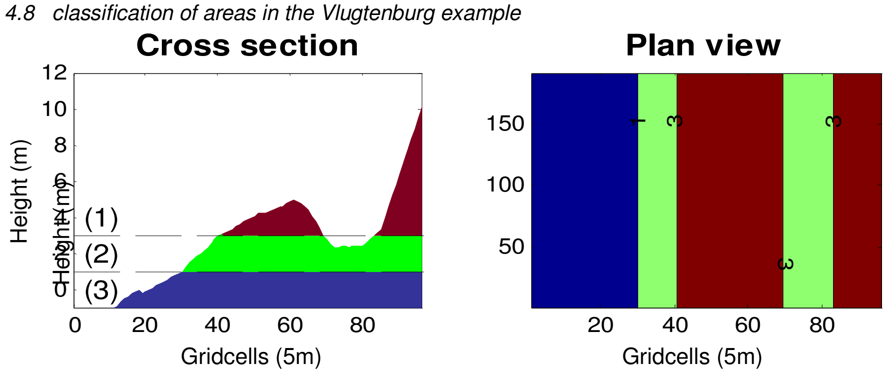
When the flow of air over a sand bed is gradually increased, there comes a critical wind velocity u_{*t} when grains begin to move. This value is used in the model to determine if the transport of sand is going to occur, if $u_* < u_{*_t}$, the time step is skipped without updating the surface profile. The value of u_{*t} is also a parameter in the transport formula. if $u_* >> u_{*_t}$ then the sand flux is large, if $u_* \approx u_{*_t}$ little transport of sand will be seen.

This thesis is not a study into all the different temporal and spatial factors that interact with the transport of sediment on a beach and the dune system. For the purpose of this thesis an attempt will be made to classify certain parts of the beach and assign a different velocity threshold to these sections.

Modification:

For the classification of distinct area's with a deviating value of grain threshold velocity it is proposed to use the height as a division between zones. The low lying inter tidal area is often immersed by the tide, but when the water level is residing, the sand still has a high moisture content. The intermediate area containing the part of the beach that is only inundated during high water levels is relatively dry, presence of shells could be important here.
The dune area is assumed to contain dry sand, mainly influenced by vegetation.

Figure 4.8 classification of areas in the Vlugtenburg example



(1) dry part of the dunes / Back beach (from 3m and upward)
(2) mid-beach area (from 1m till 3m)
(3) Inter tidal area / foreshore (from -1m till 1m in this example, take the appropriate tidal range)

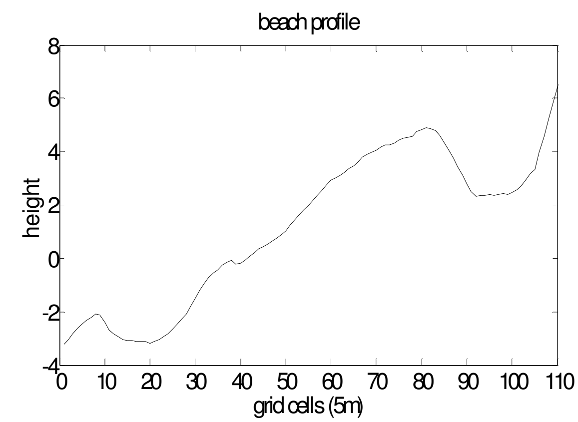
Approach:

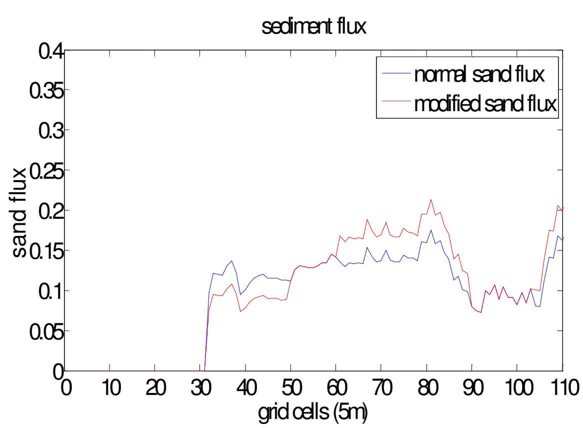
Assumptions could be made for the different conditions of the three beach sections. A very rough estimation is that the threshold in the wet inter tidal area is 10% higher than the mid-beach section. The dry dune area could have a 10% lower velocity threshold than the mid-beach section. The modifications in the code contain a part that classifies the topography according to height and than assigns a local velocity threshold value. When the total sand flux is calculated, the uniform value for u_{*t} should be replaced by this local value.

Results:

Figure 4.9 shows that at the specified locations (governed by profile height) the transport of sand is reduced or increased.

Figure 4.9 vlugentburg profile and sediment flux





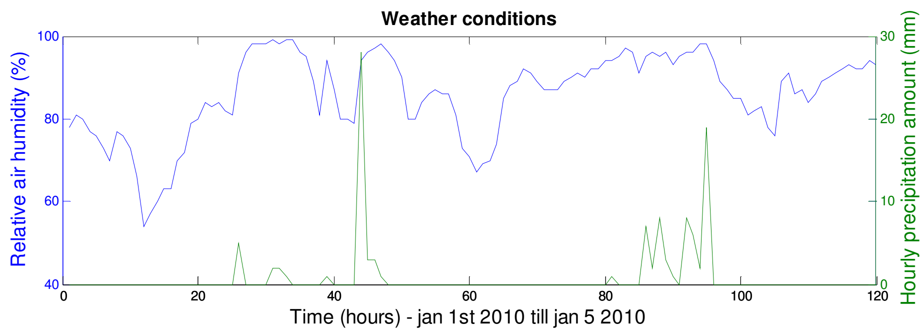
Discussion:

Implementation of the variable shear stress based on profile height does work. The assumptions made about the varied threshold value (+10% or -10%) are done for this study. Future studies should look at the ratio between shear stress threshold value and sand flux. (as seen in figure 4.9, this relation is not linear because the value is implemented in the transport formula).

Variations in time

Not only the spatial variation of the threshold could be significant, but also the variation of the conditions on the total beach area in time influences saltation (mainly weather conditions).

Figure 4.10 KNMI data, location Hoek van Holland



Although it is difficult to extract exact moments of wet event from the KNMI-data and the data seems limited, a rough estimation could be made for some periods of conditions that limit saltation. If these moments coincide with extreme wind conditions like storms, the effect could be significant. Implementing this feature requires an analysis of the weather data, which leads to the definition of periods in which the transport of sand is reduced or halted. During these periods the average value u_{*_t} can be increased to represent days with high sand moisture content.

4.2.6 Vegetation

The initial test cases on vegetation showed that the module functions as described in the literature. In this test case only the results on the beach cross section were analyzed. The behavior of vegetation should be reviewed in more complex cases. Several tests where conducted to monitor if the vegetation functions in a 2D case (i.e. if the vegetation could keep track of rotation). Results show that vegetation acts as it should, even when rotated surface profiles are used. Final conclusions on the2D vegetation case will be shown in the next chapter when the Vlugtenburg case is analyzed using the new adapted model.

4.3 Conclusions

The issues that differentiate a coastal aeolian model from the assumption made for a desert model where summarized in the beginning of this chapter. Attempt are made to implement changes in the C++ code that incorporate solutions to this issues. This chapter summarized most of the change done to the model during this study. Intermediate results were evaluated, but final conclusions on the effect that these (combined) changes have on the results of the model will be analyzed in the next chapter. That chapter will contain the test case of the Vlugtenburg model and the Sand Engine case.

5 Model cases

In the previous chapters, the issues with the present state of the model where identified. Subsequently several solutions where implemented in the model. This chapter presents the modified model using two test cases. The first test case will be the Vlugtenburg model including vegetation. The second case is that of the sand engine.

5.1 Introduction

The goal of this thesis is to produce a numerical simulation of aeolian transport for the sand engine project. Previous chapters presented the model and some of its limitations. In the final modelsetup the following modifications are implemented as described in the precious chapter:

- Variable water level
- Boundary condition mimicking an adjacent beach
- Rotatable wind field
- Variable shear velocity threshold

The following cases will put these modifications to the test and evaluate the results. Because this chapter will attempt to predict morphological changes, the input of the model has to be looked at in more detail. The most important input is the local wind data. To reduce computational time, the number of wind conditions have to be reduced, but it still has to replicate the conditions of the actual situation. Also vegetation will be implemented in the case of the Vlugtenburg example.

With the sand engine case the emphasis will lie on the evolution of the shape due to aeolian processes. Several calculations using Delft3D have been performed for the sand engine.

Figure 5.1 project overview of Vlugtenburg(left) and the sand engine (right)

5.2 Wind climate

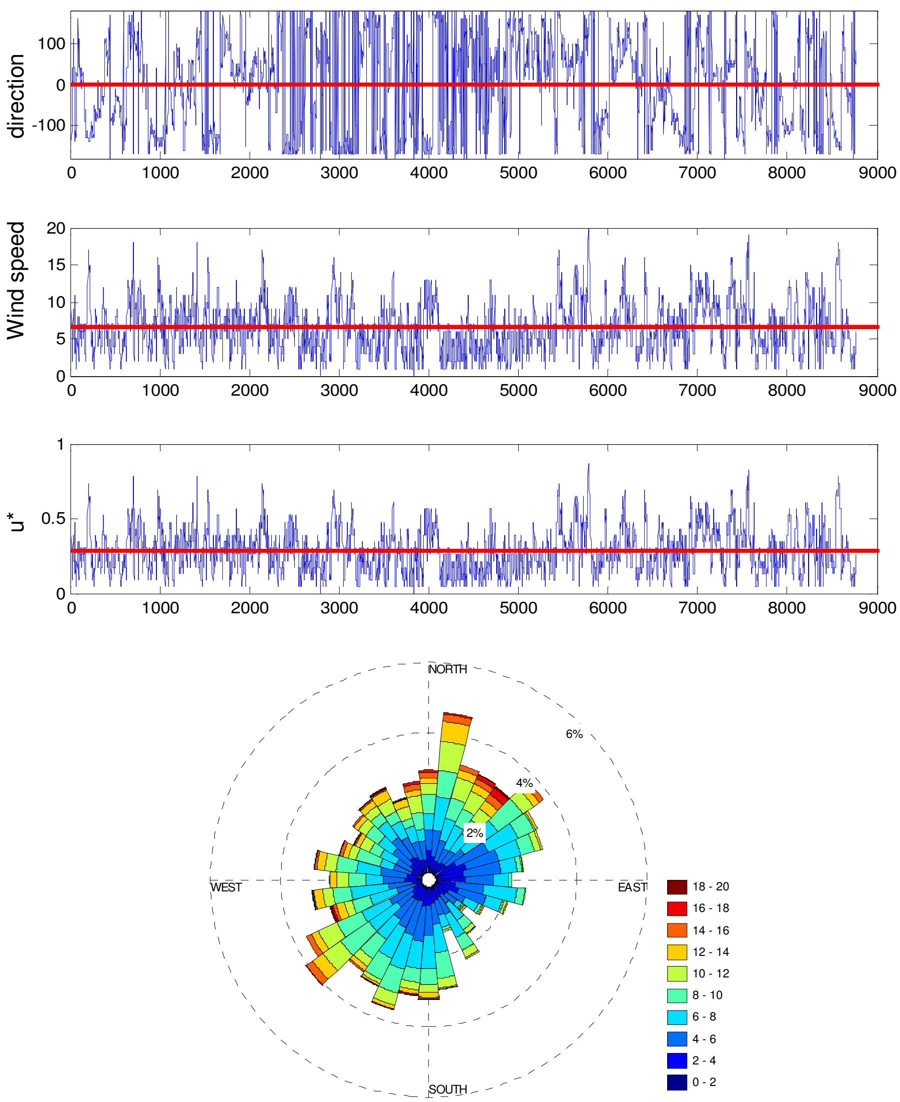
To have a realistic representation of a situation with wind, we need to be able to incorporate a varying wind speed and direction. As a reference we can take the metrological data of 2010 at Hoek van Holland gathered by the KNMI. Wind direction and speed is measured every hour.

Figure 5.2 2010 KNMI data at Hoek van Holland

Note on KMNI data

The measurements are done with an Cup-anemometer and vane on the Noorderhoofd jetty.

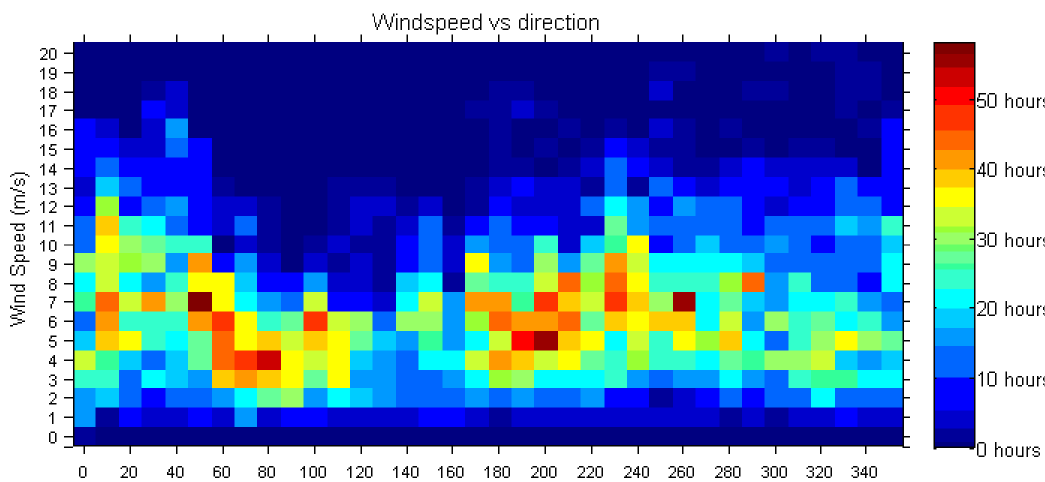
The data that is used is the hourly mean wind speed, maximum wind gusts are not taken into account. It is also possible to use the mean wind speed during the last 10 minutes of the observation interval.



5.2.1 Wind climate reduction

Calculating with a changing wind direction and speed every hour will result in a high computation time. In order to reduce the number of rotations, this test case will use a reduced wind climate. In the previous test cases the wind climate was schematized by using only onshore wind directions, a constant wind speed and an equal duration per direction. That wind climate was not an accurate representation of the local wind environment. The objective of this wind climate schematization is to define a wind climate consisting of a limited number of wind classes, which produce the same natural variability and transport rates as the full set of conditions.

Figure 5.3 full wind climate windspeed vs direction



For this study, the representative wind climate was derived from the KNMI-data of 2010 from the location Hoek van Holland. Figure 5.3 shows the full set of 8400 hours of wind data. For a more in depth analysis of the wind climate at a location on the Dutch coast it is advised to take a larger sample period spanning multiple years.

In order to reduce the number of conditions, a limit number of wind conditions have to be withdrawn from the total data. For this purpose, the wind data is dived into classes. the distribution of the wind speed represents calm conditions (1 m/s < u_wind < 4 m/s), light breeze (5 m/s < u_wind < 8 m/s), gentle breeze (9 m/s < u_wind < 12 m/s), moderate breeze (13 m/s < u_wind < 16m/s) and strong winds (17 m/s < u_wind < 20 m/s). This reduces the number of unique conditions.

Directional data of the wind also have to be divided into components. Representative wind directions are separated according to the concept of equal transport. Using this method each derived wind condition represents an equal amount of transport potential. The influence of each wind condition is thereby considered to be more evenly distributed in comparison to dividing it into bins of equal degrees.

If the wind climate is to be reduced even more, it can be argued that from this climate only the onshore directions have an influence on the transport of sand from the beach to the dunes. Also below a certain wind speed no transport will occur. This reduces the wind climate to an effective onshore wind climate.

First the total wind climate is converted into shear stress velocity u_*. Assuming that the sand flux scales with the cube of the shear velocity $q \propto \rho_{air} u_*^3$, the effective transport contribution of every direction bin can be determined. Adding the contributions of each direction bin lead to the total transport. The last step is to divide the total transport by the reduced number of direction bins. In this way each bin holds equal contribution to the total transport. This process is show in figure 5.4. Now that the width of the direction bins are determined, the average windspeed and direction per condition can be calculated. This results in the direction bands as seen in figure 5.5.

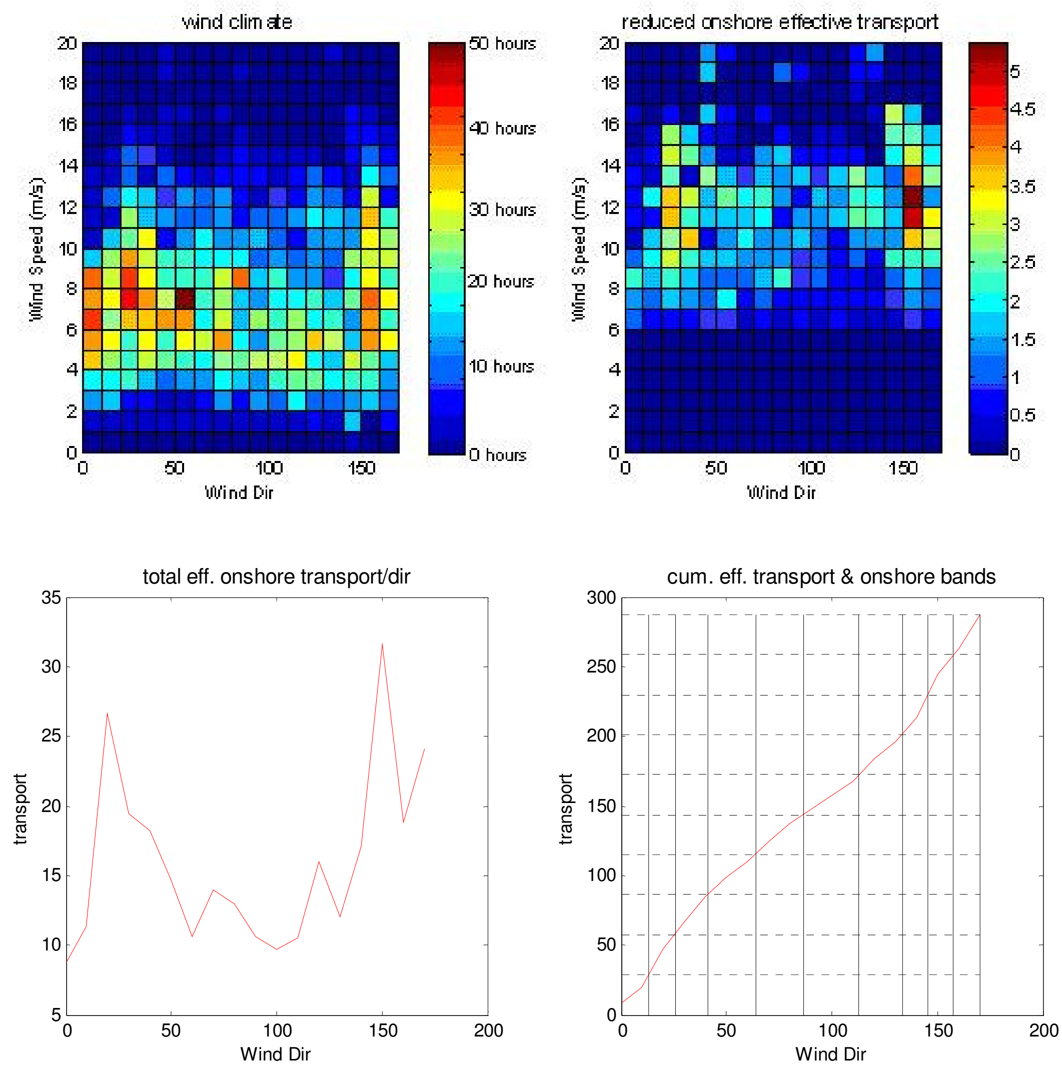
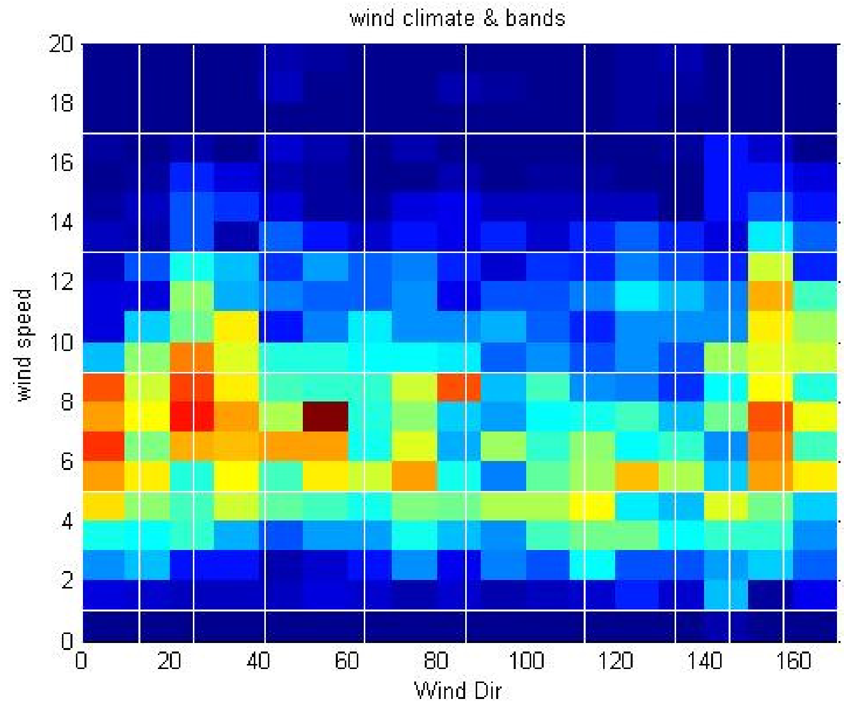


Figure 5.4Top left shows the onshore wind climate, top right is the effective onshore transport eliminating wind speed below the threshold value. Bottom left is the effective transport per directional bin. The last graph show the division of the wind direction bins into part of equal transport.

Figure 5.5 division of the directional bands



The order in which the model is forced by the conditions should not have an impact on the final topography. Inputting the wind conditions in a orderly manner will result in orientation of the topography towards the last wind condition. By choosing a random sequence (randomize the order of input) of the conditions this phenomenon should be prevented.

5.3 Sand engine case

Goals:

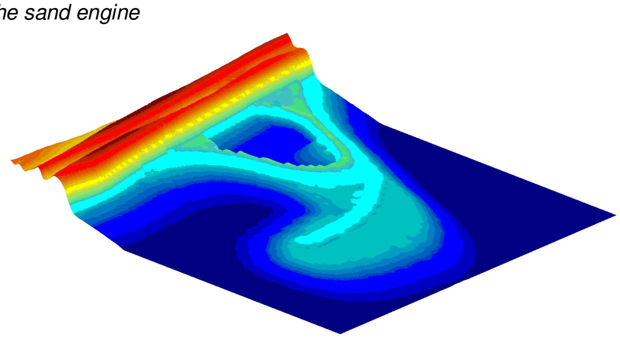
The reason that this study is performed is to improve forecasting abilities of coastal situations. By employing this wind model to the sand engine case or other mega nourishments, the applicability of the software for these type of simulation case can be assessed.

Set up:

For the MER study, several Delft3D calculations were performed with the sand engine bathymetry. This study will use the topography used in these calculations and turn it into input for the model.

The model will be simulated for 1 year, using the wind climate as derived earlier in this chapter. This wind climate reduction is needed to keep the calculation time low. Vegetation will not be present on the sand engine, at this moment no large area's of vegetation are present on the sand engine. Vegetation would however be present in the dune area's, but this case concentrates on the morphologic changes on the body of the sand engine. The simulated water level will be a simple sine shape, fluctuating between +1 NAP and – 1 NAP.

Figure 5.6 overview of the topography of the sand engine



Results:

Figure 5.7 Initial profile of the sand engine and cross section displaying surface levels at the beginning of the simulation, at half, and the end situation.

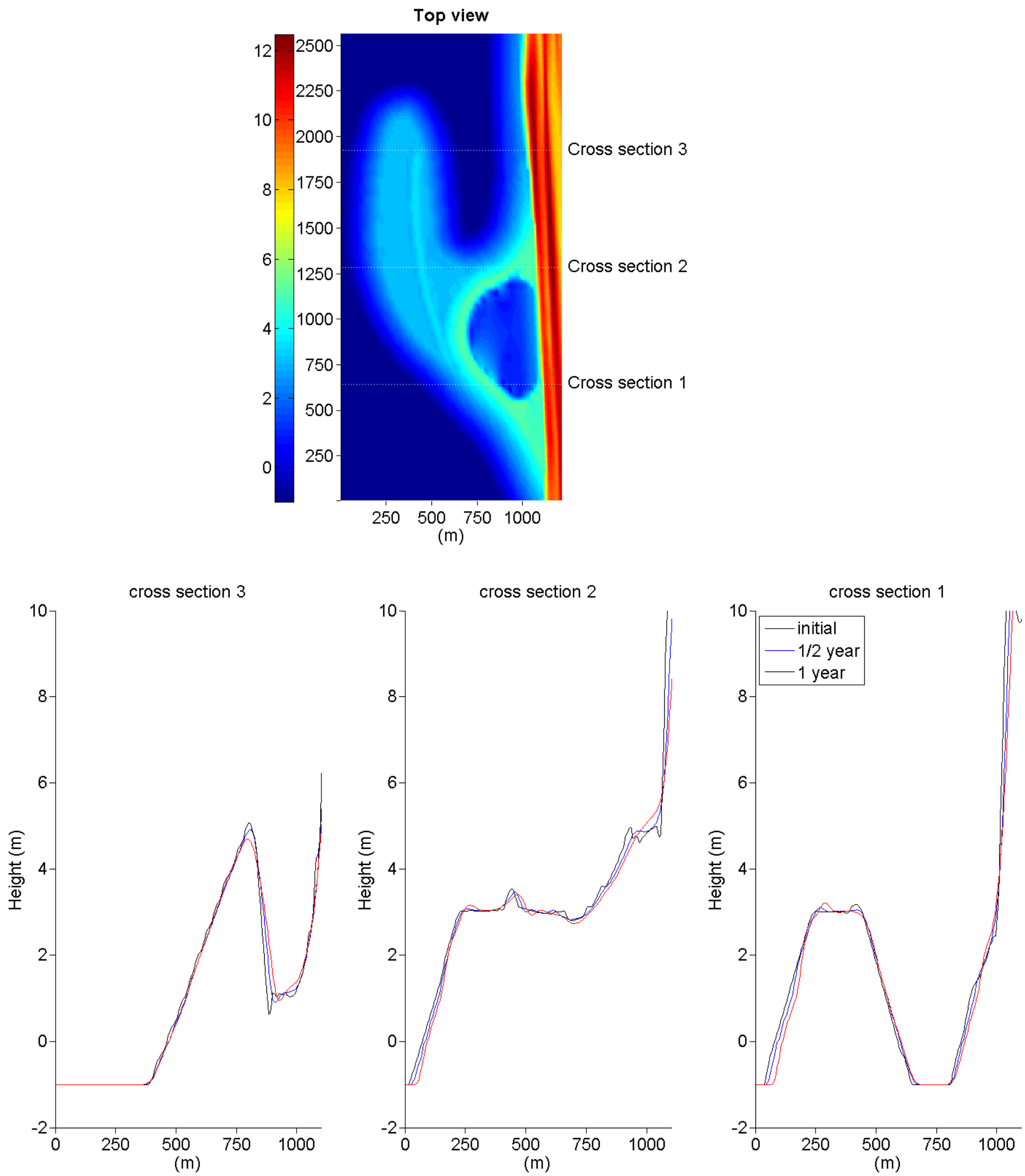


Figure 5.8 Sedimentation / Erosion plot

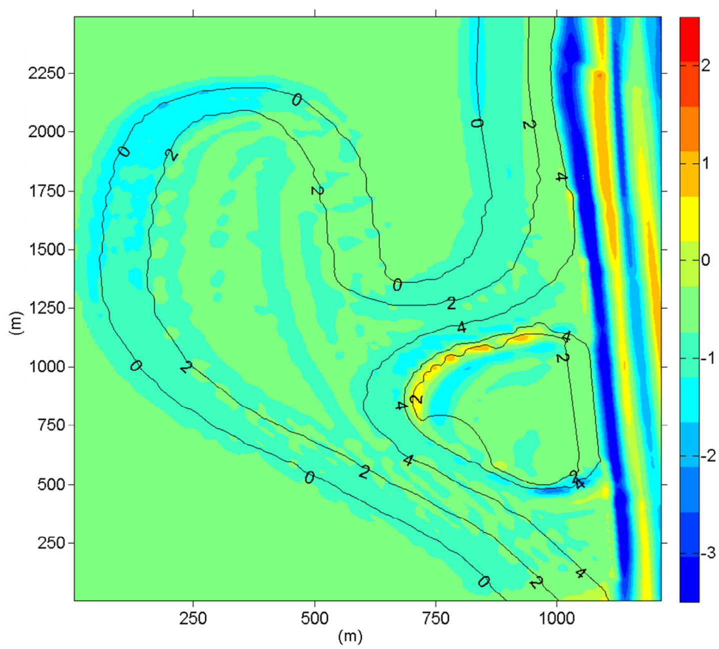
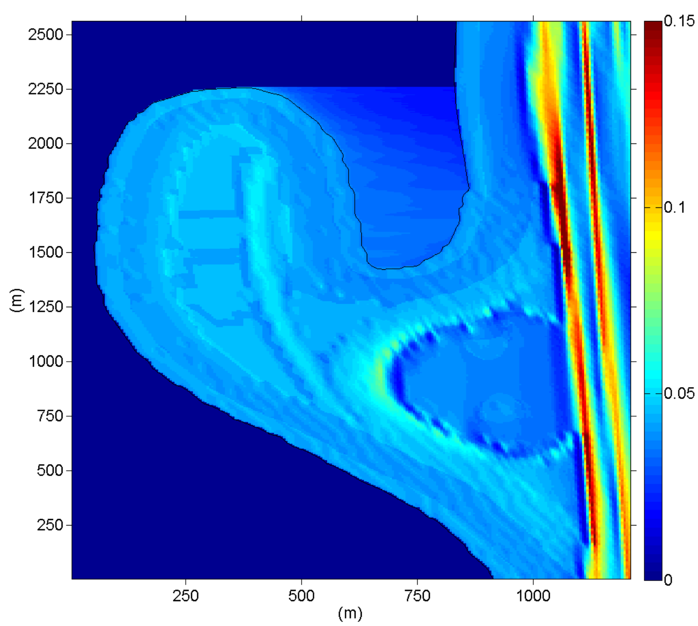


Figure 5.9 Sand flux under a straight incoming wind condition



Results:

As a general model result it is observed that no unexpected accumulation of sand is visible. The model seems to perform without mayor bugs. The morphological changes can be seen in figure 5.7 in three cross sections and in the sedimentation/erosion plot (figure 5.8)

Important morphological changes that are clearly visible is that the high ridges on the sand engine tend to migrate landward. The high ridge around the dune lake also migrates landward into the lake. A lot of morphologic variability can be seen in the dune area, but this will be ignored in this study.

As seen in the test cases where the tidal level was implemented, erosion in the inter tidal area takes place. This effect seems to be less in cross section 3

Discussion:

In general it can be concluded from the model that aeolian transport and the resulting morphologic feedback results in a lowering of the entire surface profile and landward migration of perturbing features like the ridges.

It is not yet feasible to give quantitative results on amount of sand transported and the morphologic changes that this results in. This is because the assumptions in the model are still mostly based on aeolian transport in a desert. As mentioned in the previous chapter, aeolian transport can be limited by sediment factors and weather conditions. So a desert model would tend to overestimate sediment flux on a beach, making it difficult to judge the simulated effective time of this sand engine case. Conditions allowing for moments of successful aeolian transport can be more scarce. In this case the model has simulated 1 year, as a result of these limiting conditions this might represent a longer period of effective transport in a coastal zone.

As seen in the test cases where the tidal level was implemented, erosion in the inter tidal area takes place. Because the model does not supply sediment in this zone, the sediment in that area is picked up and transported more landward. It would be very useful to implement an assumption for the interaction between wet and dry in this intersection between the water line and the beach profile. It should also be noted that the non-erodible surface does not act the same a water surface would. Sand falling on the layer does not sink, but gets blown across the layer (seen in figure 5.9).

Influence of vegetation on the sand engine or the dune area is not included in this model run.

5.4 Vlugtenburg case

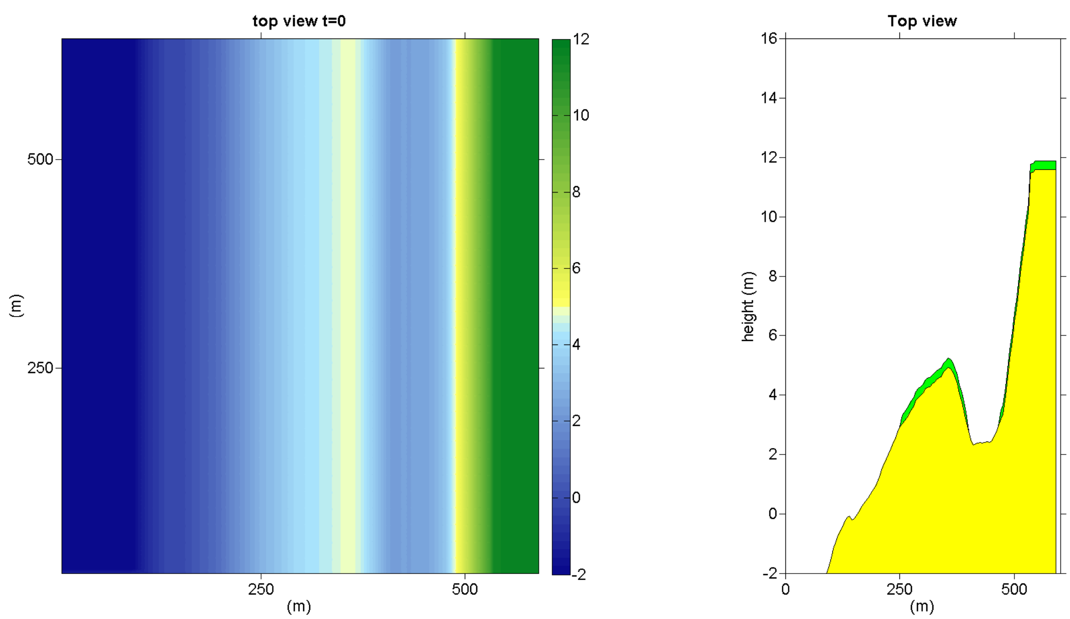
Goals:

The Vlugtenburg profile is used in earlier model tests. In this final model test the adapted model is used. The beach of Vlugtenburg was extended seawards and a row of dune was artificially constructed. This profile was selected, because of the proximity to the project site of the sand engine. It represents an arbitrary beach profile, but also contains interesting features like vegetated dunes and a sandy wet dune valley between the new and old foredune. The Vlugtenburg profile is useful, because it represents a beach-dune type situation.

Set up:

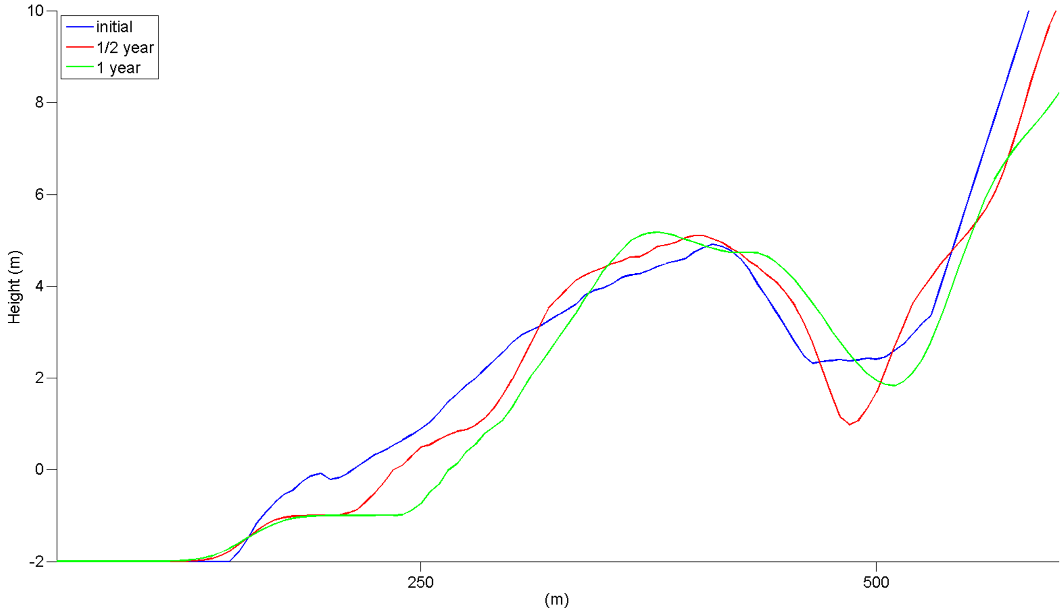
The model will be simulated for 1 year using the wind climate as derived earlier in this chapter. Vegetation will be assumed present at area's above +3m NAP. This position will be stationary, the vegetation is not allowed to spread out in this simulations. The simulated water level will be a simple sine shape, fluctuating between +1 NAP and – 1 NAP.

Figure 5.10 initial surface profile, including vegetation



Results:

Figure 5.11 surface levels at the beginning of the simulation, at half, and the end situation



No odd sand shapes are seen in the model output. The toe of the beach profile (between -2 and -1) is smoothed out slightly, this could point at numerical smoothing due to the large number of rotation steps. The rest of the model seems to be able to handle this type of simulation. The beach foot retracts a considerable distance. The central dune migrates slightly landward and the dune valley gets a bit deeper.

Discussion:

As seen in the test cases where the tidal level was implemented, erosion in the inter tidal area takes place. Because the model does not supply sediment in this zone, the sediment in that area is picked up and transported more landward. It would be very useful to implement an assumption for the interaction between wet and dry in this intersection between the water line and the beach profile. Vegetation cover is not dense enough to fixate the middle dune. However, the dune does not migrate far.

6 Conclusions and recommendations

In this chapter the main findings of this thesis are discussed. These findings are used to evaluate the performance of the model. The final conclusions will be provided and recommendations are given with respect to future applications of this model.

6.1 Introduction

This study investigates aeolian transport in the coastal zone by the development of a process-based model. The main objective was to simulate aeolian transport and the morphological feedback. Modeling effort is focused on applying a numerical process-based model on mega nourishment cases like the sand engine. An existing model (DUNE) was used to achieve this goal. This thesis discusses the theory behind this model and performed test cases to asses its applicability in the Dutch coastal zone. Lessons learned from these tests where translated into modifications to the software. Finally the adapted model was applied to the case of the sand engine. Ultimately, this leads to a general model that can be used to conduct research on the process of aeolian transport on a beach. This provides a useful tool for predicting the morphological development of mega nourishments on the short and long term.

6.2 DUNE Model

The DUNE model is based on three physical processes. First an analytical set of equations for wind shear stress over smooth hills as proposed by Weng et al. (1991) is used to obtain a fast algorithm. This describes the turbulent wind field over a certain terrain. The next model component describes the relation between the wind shear stress and the erosion rate. This accounts for the saltation which leads to the evolution of a sand surface. The advantage of this model is the inclusion of assumption in the wake behind a dune. Finally a model for avalanching is used that takes transport of sand due to gravity into account.

Modifications

This study identified several important aspects that should be included in a correct model of aeolian sediment transport with morphologic feedback. Adjustments in the software were found necessary and intermediate results were reviewed. In the final modified model the following improvements are implemented.

- Variable water level.
- Boundary conditions mimicking an adjacent beach.
- Rotatable wind field.
- Variable shear velocity threshold.

Finally, the modified model was applied to two cases, the sand engine and the Vlugtenburg profile. These results were used to asses the model performance.

6.3 Conclusions on the DUNE model

- The DUNE model is a computational efficient model and relatively easy to use.

Due to the model set up, combining efficient model components (i.e. the fast Fourier algorithm of Weng et al. (1991)) computation times are reasonable. An average (full) simulation takes in the order of hours to finish. The parameter file structure and the format of the in- and output files are easy to access.

- Processes that are important for the coastal zone are often not included.

The area of application of the DUNE model lies in desert environments. Aspects like a water level, variable surface conditions or a non uniform wind climate are not included in the model. This thesis identified these processes and implemented them in the software.

6.4 Findings on aeolian transport on a beach

From the literature and tests, the following conclusions are drawn:

Processes affecting profile

The final model profile is the result of morphological changes due to aeolian transport. Not only the rate of transport is important for the resulting profile, but also imposed conditions on the boundary or in the driving forces determine the outcome.

- Input of sediment in important for beach profile

Several cases show that varying the supply of sediment into the model domain is determining for the final shape. Sediment input in the lower part of the beach is difficult to model. In a coastal situation, we can expect that no supply of sediment will come from the water-land interface.

- The presence of a (varying) water level influences the amount of sediment transported on a beach.

The presence of a water level is not required in a model for a desert environment, but when modeling a beach it is important. Using a constant water level will result in concentrated erosion at the waterline. Implementing a fluctuating tidal level spreads this area out. Implementing a water level also limits the area of the beach that can be influenced by the wind. During high tide the beach area is smaller than during a low tide.

- The schematization of the wind climate is important for the final result.

Input reduction is necessary to keep the computation time acceptable. This is the reason why the number of wind conditions have to be reduced, but they should still produce the same transport rates as the full dataset. Simplifying the climate too much will result in average (moderate) conditions. This is not desirable, because extreme conditions have an significant impact on the transport rate. In this study the data of 1 year is used. Using large sample periods of wind data should lead to an better approximation of the annual conditions.

Processes limiting aeolian transport

The rate of transport may be physically correct in desert situations, as showed in several papers regarding the migration of barchan dunes. In a Dutch coastal situation the amount of sand transported yearly may be less due to limiting conditions. Factors that influence transport by wind on a beach where examined in chapter 2. Important factors were moisture content, water level and presence of vegetation. During the modeling attempts in the preceding chapters it was confirmed that the variability of these factors play an important role in the prediction of aeolian transport on a beach.

- Moisture content of the sand affects the transport across a beach. Variability of moisture content can be due to a residing water level, ground water level or precipitation.

Moisture derived from residing tide or high ground water level affects the threshold velocity. After wetting, moisture is retained by sand as a surface film increasing the cohesive forces between grains. Therefore effective periods of transport can be limited by weather conditions.

- Correct modeling of vegetation is important when forecasting dune growth. The interaction between vegetation cover and supply of sediment control coastal dune morphology.

While desert dune are scarcely vegetated, the coastline consists of stabilized vegetated dunes. The shape and rate of growth of these dunes are influenced by the vegetation cover. In situations where dunes are not controlled by people, different types of dune shapes can evolve due to the presence of vegetation. Initial test cases showed that varying vegetation properties leads to different deposition rates. An important goal of nourishments like the sand engine is to supply sand to the dune area. This emphasizes the need to have a complete understanding of vegetation properties.

6.5 Recommendations

To obtain a better understanding of modeling aeolian transport in the coastal zone, further research is required. Based on the findings of this thesis some recommendations follow.

Variable velocity threshold

Factors limiting aeolian transport on a beach are not accounted for in this model. This study addresses this problem by implementing a component in the model that makes it possible to vary the threshold value of shear stress velocity in space. Theoretically this threshold can represent surface conditions like moisture and shells. More research has to be done on the magnitude of these physical effects that limiting factor. These spatial varying parameters can later be used to improve the model

Vegetation

Further investigation is necessary to attain a representative value for the reducing capacity of standard vegetation found in the Dutch dune system. The properties of vegetation types like Maram grass should be translated into the parameters used in this model. Properties like plant density, growth speed, maximum height and aerodynamic roughness should be known

Tide

The model currently does not include a water table module or a possible implementation of tide. Something that should be studied in future programming attempts is the possibility of incorporating the presence of a water level. This includes the presence of an open water surface and an underground water table.

Code

The program is coded in C++, this is a relatively fast and efficient programming language. Converting the program from C++ to Fortran would improve the compatibility with existing Deltares models (which are usually written in Fortran), like XBeach and Delft3D. Because of this single language, it would be possible to have integration of different model components.

Coupling

A combination of numerical process-based models can provide insight into the distinct forces that act on a beach. Especially the interface between the sea and the beach is an import aspect in the coastal zone. Combining the use of a hydrodynamic model like Delft3D or XBeach with this aeolian model should provide more insight in the interaction between wet and dry parts of the profile. This is further discussed in the work of T. Pekkeriet. [Pekkeriet, 2011]

Wind climate

A more detailed study needs to be done for determining the average conditions at a beach site. In this study, the wind climate is approached by looking at data from 2010. Using a bigger dataset could lead to a more accurate description of the wind conditions.

6.6 Recommendations on the sand engine or future nourishments

The goal of this thesis was to apply an aeolian transport model to the sand engine. In the same period as this thesis, the sand engine was constructed. No quantative predictions for aeolian transport and dune evolution on the sand engine can be made yet. The transported volumes of sand are not reliable enough to make an accurate forecast of the evolution of the shape of the sand engine. Measured data from the sand engine would contribute significantly to the validation of this model. It is strongly recommended that measurements are conducted often.

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