Process-based support for supply limitations on the aeolian erosion probability: From AeoLiS to DUBEVEG

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Preface

With this thesis I conclude the Master of Science in Water Engineering and Management at the University of Twente, which wouldn't have been accomplished without the help and support of my great family, friends and thesis advisors.

First, I would like to thank Kathelijne and Daan for being my supervisors at the UT. They both helped me reason and understand the topic, which wasn't easy all the time. Daan, as my daily advisor, was always willing to listen to my questions and give me substantial feedback, which I deeply appreciate. Despite being in different cities, he made every skype meeting possible. Also, I would like to thanks Filipe who helped me understand DUBEVEG and answered any doubt I had about the model.

In addition, I would like to thank Deltares for allowing me to work in their facilities under the supervision of Joost and Bart. Both made sure I had someone to approach in case I had any question. I am really thankful to my daily supervisor Bart. He dedicated a lot of time to help me develop a proper methodology and made sure I was never left with any doubt. His great feedback and support made guided me throughout the whole project.

Special thanks to my friends who supported me during the whole process (even if we were in different cities or different countries). They always made sure I stayed motivated and that I had something to look forward to on my free days.

And finally, I am the most grateful to my parents who always kept me going and whom I deeply admire. Every achievement I have made was because of them, and I can't thank them enough for their unconditional support.

Andrea Flores, 2020

Abstract

Coastal dunes are the first flood defense in line against the sea (Keijsers et al., 2016), are used for recreation, provide drinking water storage and form an ecological niche in which plants are adapted to extreme conditions (Nordstrom and Puleo, 2012). The wind is the main driver for dune development, which acts through aeolian sediment transport. However, wind-driven sediment transport has been shown to reach limiting conditions due to sediment properties, moisture and beach geometry (de Vries et al., 2012). Therefore, Hoonhout and Vries (2016) developed AeoLiS: a process-based model which simulates aeolian sediment transport and includes the influence of soil moisture and beach armouring as supply-limited conditions. Nevertheless, AeoLiS is not capable of simulating long-term morphological development with reasonable computational demand. On the other hand, DUBEVEG (Keijsers et al., 2016) is a probabilistic cellular automata model which simulates the morphological evolution of a beach-dune system. However, it does not account explicitly for supply-limited conditions.

This thesis was developed to give the probability of erosion "P_e" in DUBEVEG (one of the key parameters in the model) a process-based support to include soil moisture and beach armouring as supply-limited conditions, from AeoLiS. The project was divided in three parts which are described below, together with their results.

The "Morphological influence due to DUBEVEG's parameters" section consists of the determination of the adequate key parameter in DUBEVEG to support supply-limited conditions, which was concluded to be the probability of erosion P_e. P_e determines the number of cells (representing a volume of sediment) that will be eroded from the bed based on the environmental conditions. It relates the potential and actual sediment supply for transport.

The section "Process-based support for a cellular automata model" describes the steps taken in order to obtain a process-based P_e from AeoLiS to DUBEVEG. This was done by simulating the sediment that was transported by aeolian forces from a single cell. This sediment flux accounted for the change in bed elevation, which was converted to a yearly probability of erosion. The latter was done by out-casting the situations that would lead to depositional effects from surrounding cells, on the single cell evaluated.

The last section "Sensitivity analysis of environmental conditions" includes a deeper understanding of the obtained P_e from AeoLiS and how this is influenced by the two

supply-limited conditions assessed. This was done by varying the environmental conditions that affect the supply-limited conditions over the cross-shore. It was concluded that the influence of the supply-limited conditions on the cross-shore can be divided based on an intertidal area (which presents a dominant supply-limitation by soil moisture and presents hydraulic mixing), a supratidal area (which depicts the influence of soil moisture, hydraulic-mixing, sediment sorting and armouring, all together) and a dry area (which has a dominant supply-limitation due to beach armouring).

Contents

1 Introduction

1.1 Background

1.1.1 Coastal environments

Coastal environments are the narrow transition areas that connect terrestrial and marine environments (Crossland, 2005), they provide a wide variety of regulating, provisioning, supporting and cultural services for humans (MEA, 2005). From the world's major cities, 60% are located in coastal zones and from the world's population, 40% lives within 100km of a coastal zone (Nicholls et al., 2007).

According to Wong and Sallenge (2014) coastal environments consist of both natural and human systems (See Figure 1.2). The natural systems include coastal features and ecosystems such as rocky coasts, beaches, barriers and sand dunes, estuaries and lagoons, deltas, river mouths, wetlands, and coral reefs. These elements help define the seaward and landward boundaries of the coast. The human systems include the built environment (e.g., settlements, water, drainage, as well as transportation infrastructure and networks) and human activities (e.g., tourism, aquaculture, fisheries). The human and natural systems form a tightly coupled socio-ecological system (Berkes and Folke, 1998; Hopkins et al., 2012).

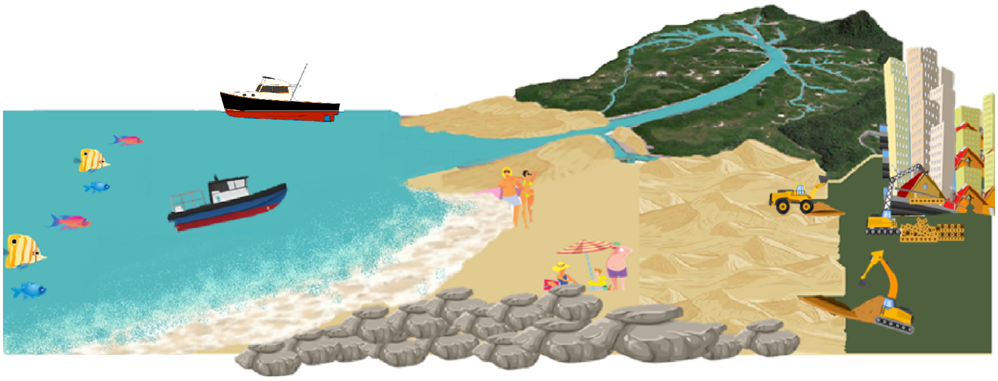


Figure 1.1: Human interaction with coastal environments

1.1.2 Coastal dune development

One of the important assets that form in coastal environments are dunes. In many parts of the world, coastal dunes are the first flood defence in line against the sea, including in the Netherlands (Keijsers et al., 2016). In addition, dunes are used for recreation, provide drinking water storage and form an ecological niche in which plants are adapted to extreme conditions (Nordstrom and Puleo, 2012).

The main criterion for dune development is sand supply. The availability of sand on the beach serves as sediment supply which allows erosion and deposition caused by aeolian processes in coastal environments. According to Zhang et al. (2015) sediment supply in coastal dunes is mainly derived from the narrow strip of beach that lies between the low tide level and the vegetation limit on the back-shore. This area is called the intertidal zone, and it is kept free of vegetation by wave action and water level fluctuations. Aeolian processes transport sand landward from this strip and initial deposition takes place, primarily due to the presence of vegetation but also as a result of the topographic effects (Nickling and Davidson-Arnott, 1990). In coastal environments dune development is enhanced by moisture because it supports plant growth and thus, deposition of the eroded sediment.

1.1.3 Dunes and climate change

The climatic crisis the world faces today constitutes just one among many human-caused threats coastal environments are facing (Wong and Sallenge, 2014). According to Buishand et al. (2010) Dutch climate scenarios include sea level rise, increased temperatures, increased yearly precipitation, stronger wind variation, etc. Flooding in coastal areas has led to discussions on whether extreme rainfall occurs more often along the coast than it is assumed in present-day hydrologic design practices. In addition, temperatures are expected to increase by 1.3 to 3.7°C. These conditions represent an adaptation challenge for coastal dunes that need to cope with their rate of change or face the risk of disappearing (See Figure 1.2).

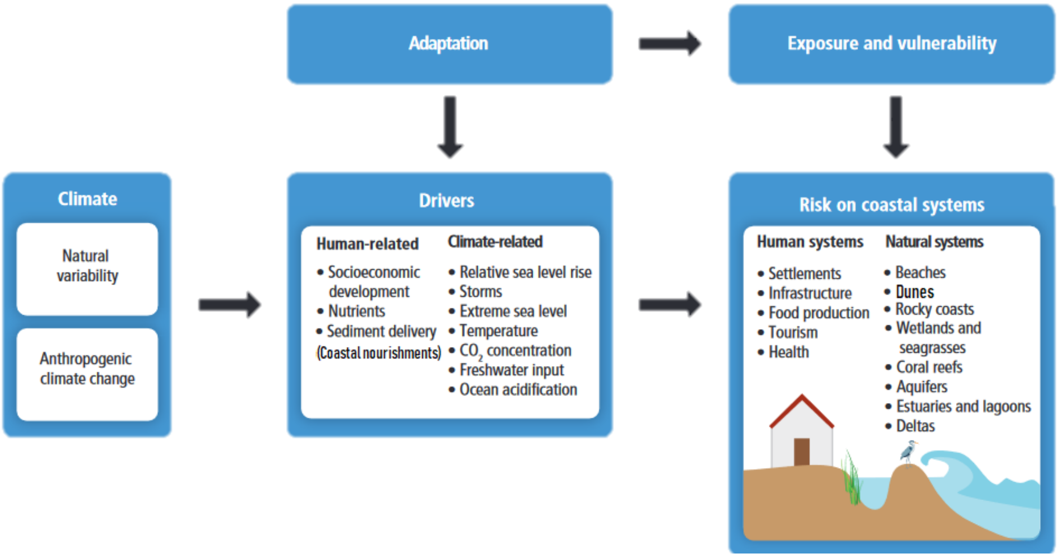


Figure 1.2: Climate, just as anthropogenic or natural variability, affects both climate and human related drivers (i.e., any climate-induced factor that directly or indirectly causes a change). Risk on coastal systems is the outcome of integrating drivers' associated hazards, exposure, and vulnerability. Adaptation options can be implemented either to modify the hazards or exposure and vulnerability, or both. (Adapted from Wong and Sallenge (2014)).

1.1.4 Aeolian sediment transport and supply-limited conditions

Sand that is transported landwards from the beach and back-shore by aeolian processes is the principal sediment input to coastal sand dunes (Zhang et al., 2015). Thus, the prediction of sediment transport rates is important for the assessment of dune development and depends on the available sediment supply (Nickling and Davidson-Arnott, 1990).

The bed surface properties influence aeolian sediment transport by changing the sediment transport capacity and/or the sediment availability (Kocurek and Lancaster, 1999). According to Hoonhout and Vries (2016) bed surface properties found in coastal environments include: soil moisture, shells, strand-lines, beach armouring, rainfall, salt crust, bed slope, vegetation, groundwater and human interventions.

Hoonhout and Vries (2016) also mentions that sediment transport models generally incorporate the effects of the bed properties that influence aeolian sediment transport capacity and availability through a single parameter: the velocity threshold. Hoonhout and Vries (2016) state that "This approach appears to be a critical limitation in existing aeolian sediment transport models for simulation of real-world cases with spatio temporal variations in bed surface properties". Hoonhout and Vries (2016) adds that " Sherman et al. (1997) and Sherman and Li (2012) summarized the performance of eight aeolian sediment transport models compared to field measurements on a sandy beach. All the models systematically over-predict the measured aeolian sediment transport rates, which is in agreement with other coastal field studies (Aagaard, 2014; Bauer et al., 2009; Jackson and Cooper, 1999; Lynch and Coop, 2008)."

The effect of supply-limited conditions on the coast determines how and if dune development will occur. This makes supply-limited conditions an important feature for assessing sediment transport, and therefore dune development (de Vries et al., 2014).

1.2 Numerical models related to coastal environments

Numerical modelling serves as a tool to understand the behaviour of systems based on their mathematical description. By simulating possible outcomes of undesired situations that present a risk for the population (e.g. floods), numerical models are able to decrease uncertainty and enhance action to prevent natural disasters.

There are several numerical models related to coastal environments. Each assesses different aspects of coastal dynamics and with a different approach. This thesis focused on two numerical models: DUBEVEG (Keijsers et al., 2016) and AeoLiS(Hoonhout and Vries, 2016). The former is a cellular automata model that simulates beach-dune system dynamics with a probabilistic approach. The latter is a model with a process-based approach that simulates sediment transport in coastal environments where supply-limited conditions (namely soil moisture and beach armouring) are represented. These models are described below.

1.2.1 DUBEVEG

The DUBEVEG model (DUne, BEach and VEGetation, (Keijsers et al., 2016)) is based on previous models proposed by Werner (1995) and Baas (2002). This model is a morphodynamic model that simulates beach-dune system dynamics, including the effects aeolian sediment transport, groundwater influence, biotic processes related to vegetation and hydrodynamic sediment input and erosion in a probabilistic rule-based approach (Silva et al., 2018).

The rules defined in the model control the probability of sand slabs being eroded, transported and deposited over a cellular grid domain. According to Silva et al. (2018), the rules are intended to represent complex processes by capturing the essential interaction between factors and variables that are important for dune development in coastal areas (See Figure 1.3). Small-scale interactions and feedback processes tend to result in emergent large-scale patterns and trends (Baas, 2002, 2007).

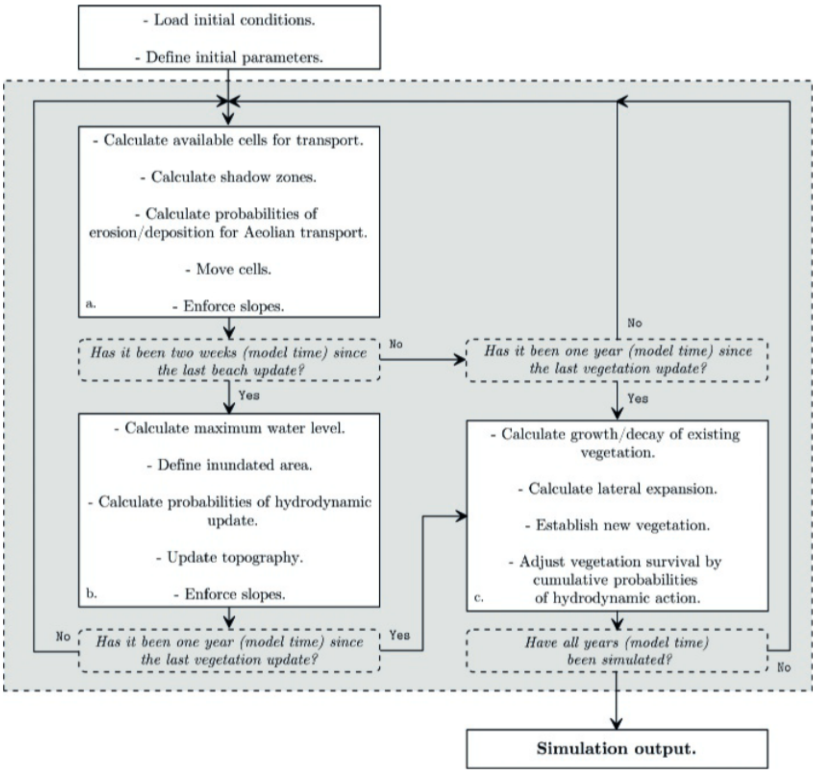


Figure 1.3: DUBUEVEG model outline, highlighting the aeolian module (a.), the hydrodynamic module (b.) and the vegetation module (c.) with the main processes and possible interaction scenarios. (Galiforni Silva et al., 2019; Silva et al., 2018)

Model advantages

Using a cellular automata model like DUBEVEG comes with certain advantages. These include the fact that it compounds several coastal processes in one, which affect a defined scenario and lead to a morphological change. It does it with a simplified approach which gives results with a low computational demand. Thus, DUBEVEG makes assessing large-scale processes like morphological change accessible in a matter of hours.

DUBEVEG was calibrated for Dutch coastal scenarios by (Keijsers et al., 2016), which makes it a useful tool to assess the morphological evolution of a beach-dune system that include conditions similar to Dutch scenarios. The Dutch cases evaluated include supply-limited conditions, which means that the morphological results account implicitly for them.

Model limitations

The main limitation of DUBEVEG is that it misses the explicit description of the processes it accounts for. This makes the generic applicability of the calibrated model limited to beaches with similar environmental conditions only. Hence, predictive skills for deviating condition are uncertain. Also, the model does not include a realistic time-variant and multi-directional wind.

1.2.2 AeoLiS

AeoLiS (Hoonhout and Vries, 2016) is a process-based model which quantifies aeolian sediment transport under supply-limiting conditions.

According to Hoonhout and Vries (2016) "AeoLiS is the first aeolian sediment transport model that simulates spatio-temporal variations in bed surface properties and sediment availability. AeoLiS is a generalization of existing modeling concepts for aeolian sediment transport that include the influence of bed surface properties and limitations in sediment availability, like the shear velocity threshold and critical fetch, and is compatible with these concepts. The model uses an advection scheme following de Vries et al. (2014) and a bed composition module that discretizes the bed in horizontal grid cells and vertical bed layers to account for spatial variations in bed surface properties".

Advantages

The most outstanding advantage of AeoLiS (Hoonhout and Vries, 2016) is that it simulates temporal variations in sediment availability, instead of parameterizing them, which is done through its bed composition module. Thus, it reduces the need for complex spatio-temporal parameterizations and consequently calibration. In addition, it includes soil moisture (described by its relation to the velocity threshold and combined with the inclusion of water level elevation, wave run-up, infiltration and evaporation) , the influence of sediment sorting and beach armoring and the reversed process of hydraulic mixing, as supply-limited conditions on aeolian sediment transport.

Due to its process-based approach, AeoLiS includes the possibility of accounting quantitatively for all of the processes and parameters that are defined in it, per cell and per time-step.

Model limitations

The model is capable of representing several coastal processes. However, AeoLiS (Hoonhout and Vries, 2016) does not include rainfall, groundwater nor salt influence as supply-limiting factor. In addition, it accounts for the erosion and deposition per time-step in a compound manner, which is included as "net entrainment". Thus, it doesn't quantify explicitly the individual erosion or deposition experienced per time-step. Another limitation of the model is the high computational demand for long-term simulations.

1.2.3 Research gap

According to Sherman and Li (2012) and Bauer et al. (1996) there is a gap of generic models that are able to predict the capability of aeolian sediment transport rates on beaches in non-specific cases. In addition, de Vries et al. (2014) located a gap in the implementation of supply limited-conditions in numerical models, which do not set an explicit limit to the erodible sediment available.

The DUBEVEG model in its current state, fails to fill in the two gaps just mentioned because it was calibrated in a non-generic Dutch case and it accounts for aeolian sediment transport and supply-limited conditions in a compound and implicit manner. In order to fill in this gap, this thesis is aimed to include supply-limited conditions with a more explicit approach in DUBEVEG .

The hypothesis is that AeoLiS (Hoonhout and Vries, 2016) as a process-based model which is able to calculate the influence of soil moisture and beach armouring on sediment supply explicitly, can help fill-in the gap by supporting these two supply-limited conditions in DUBEVEG.

1.3 Scope of the project

The main goal of this thesis is to fill-in the knowledge gap in DUBEVEG to include supply-limited conditions more explicitly. The project scope covers the support of soil moisture content and beach armouring as supply-limited conditions, using AeoLiS.

Following the scope of the project, below the objective and three research questions are presented.

1.3.1 Objective

Apply the model AeoLiS to include soil moisture and beach armouring as supply-limited conditions in DUBEVEG, by supporting one of its key parameters.

1.3.2 Research Questions

1. How does the variation of two key parameters, namely the probability of erosion and deposition (P_e and P_d), affect the nature and magnitude of the morphological change in DUBEVEG?

   The objective of RQ1 is to assess the impact of P_e and P_d over the patterns on the bed created over time in DUBEVEG, in order to determine the key parameter most adequate to extend and support supply-limited conditions.

2. How can the chosen key parameter in DUBEVEG be supported with AeoLiS to include soil moisture and beach armouring as supply-limited conditions, and what is the resultant P_e?

   The objective of RQ2 is to develop the steps to obtain P_e values that include soil moisture and beach armouring as supply-limited conditions from AeoLiS, so they can be related to the probabilistic model DUBEVEG.

3. How does the variation of coastal environmental conditions affect supply limitations and P_e [%]?

   The objective of RQ3 is to determine the influence that the variation of coastal environmental conditions have on soil moisture and beach armouring as supply-limited conditions and on P_e [%].

Outline

Followed by this introduction, the theoretical background is presented. It describes the concepts and two numerical models related to coastal dune development, that are of interest for this thesis. Afterwards, the methodology to determine a probability of erosion from AeoLiS (including soil moisture content and beach armouring as supply-limited conditions) is described. Subsequently, the results obtained based on the methodology are presented and discussed. Finally, the conclusions for the overall project are stated. Due to simplicity, abbreviations referring to the probability of erosion 'P_e' and the probability of deposition 'P_d' will be used.

2 Theoretical Background

This section includes a description of dune development through the influence of aeolian sediment transport and concepts that are relevant for this thesis. Afterwards, a description of soil moisture and beach armouring as supply-limited conditions is included. It finalizes with a technical characterization of the two numerical models that were used to reach the objective presented in the section 1.3.

2.1 Aeolian sediment transport for coastal dune development

A dune is a hill of sand which can form in sandy environments like deserts or on the coast (National Geographic, 2020). The evolution of coastal dunes depends on sediment supply, beach morphology, vegetation effectiveness, climatic variables such as wind climate, sea level and wave conditions (Short and Hesp, 1982). Through aeolian sediment transport, the wind force is the main driver of dune development.

Aeolian sediment transport is when the wind (as a forcing factor) initiates the sand particles to move when a certain threshold is exceeded (wind velocity threshold u_{th} Du Pont (2015); Puijenbroek (2017)). This is the result of the shear stress $u*$ which is created when aeolian forces blow on the bed. According to Bagnold (1935) if the shear stress can get the sediment entrained depends on if it is greater than the particles wind velocity threshold u_{th}, which depends on the characteristics of the sediment on the bed, and the bed itself. If this is the case, then the sediment on the bed gets eroded. After some time and depending on the environment's characteristics, the sediment gets deposited. This erosive and depositional behaviour reshapes the beach and creates bed patterns, including dunes (See Figure 2.1).

Figure 2.1: Aeolian sediment transport for dune formation

2.1.1 Aeolian erosion and deposition

The fluctuations of the wind and its relation to the morphology can either erode or deposit the sediment, creating a spatial variation along the coast (Keijsers et al., 2014). Based on the principle of sediment continuity, winds are erosional if transport rate (or wind shear velocity) increases downwind; deposition occurs when transport rates decrease in the direction of transport, and sediment bypass occurs when there is no change in transport rates (Lancaster, 2014).

Aeolian erosion in coastal environments is the action of the wind removing sediment (sand) from the top layer of a beach. Erosion by wind involves two linked processes: abrasion (mechanical wearing of coherent materials, including playa crusts and clods created by tillage) and deflation (removal of loose material) (Lancaster, 2014).

The process of the eroded sediment getting put back on the bed is called deposition. Deposition of the eroded sediment on the beach is enhanced by vegetation, which accumulates sediment and forms dunes.

2.1.2 Shear stress and wind velocity threshold

When there is wind on a coastal environment, this force creates a shear stress ($u*$) on the bed which results in sediment being picked up and transported. The shear stress is determined by the relation of the wind force and the height at which this force is exerted on the bed (Bagnold, 1935).

The minimum wind velocity required to move grains is called wind velocity threshold u_{th}. Bagnold (1935) defined the velocity threshold u_{th} relating the air and the particle's densities, with gravity and the particle's diameter and friction. The bigger the grain size, the higher the threshold, meaning that grains need a stronger wind force to get transported. Once the particle's u_{th} has been reached, stationary particles begin to roll or slide (surface creep), or hop (saltation) downwind because of the direct pressure of the wind (Nickling and Davidson-Arnott, 1990).

The velocity threshold can be affected by factors like soil-moisture and non-erodible elements on the bed. They have an increasing effect on the u_{th} which means they imply supply-limitation for aeolian sediment transport.

2.1.3 Sediment sorting

The bed is composed of sediment which varies in grain-sizes and composition. This causes the smaller grain fractions on the bed to get entrained before the big ones, due to the difference in velocity threshold u_{th} (Hoonhout and Vries, 2016). Therefore, the sediment on the bed starts to get sorted and non-erodible roughness elements emerge on the top layer. Sediment sorting leads to beach armouring, which restricts erosion because the presence of non-erodible elements partitions the shear stress on the bed (resulting in a reduced stress to entrain sediments) and larger fractions shelter the smaller grains which results in an increase of wind velocity threshold (Nickling and Davidson-Arnott, 1990).

2.2 Supply-limited conditions

Supply-limited conditions are environmental characteristics which limit the availability of sediment supply. According to Nickling W.G. (2009) most natural eroding surfaces tend to be supply-limited. The total sediment transport rate is controlled by the ability of the surface to supply grains to the air stream, often resulting in lower total transport rates than would be predicted by most theoretical or empirical models for a given wind speed (Hoonhout and Vries, 2016).

There are several supply-limiting conditions that affect aeolian sediment transport. These include rainfall, ground-water level, vegetation, shells, strand-lines, salt crusts, bed slopes, soil moisture, sediment armouring (non-erodible elements) and anthropogenic disturbance (Hoonhout and Vries, 2016). Nevertheless, the scope of this thesis focuses on soil moisture and sediment armouring. The spatio-temporal influence of these two supply-limited conditions is described next (See Figure 2.2).

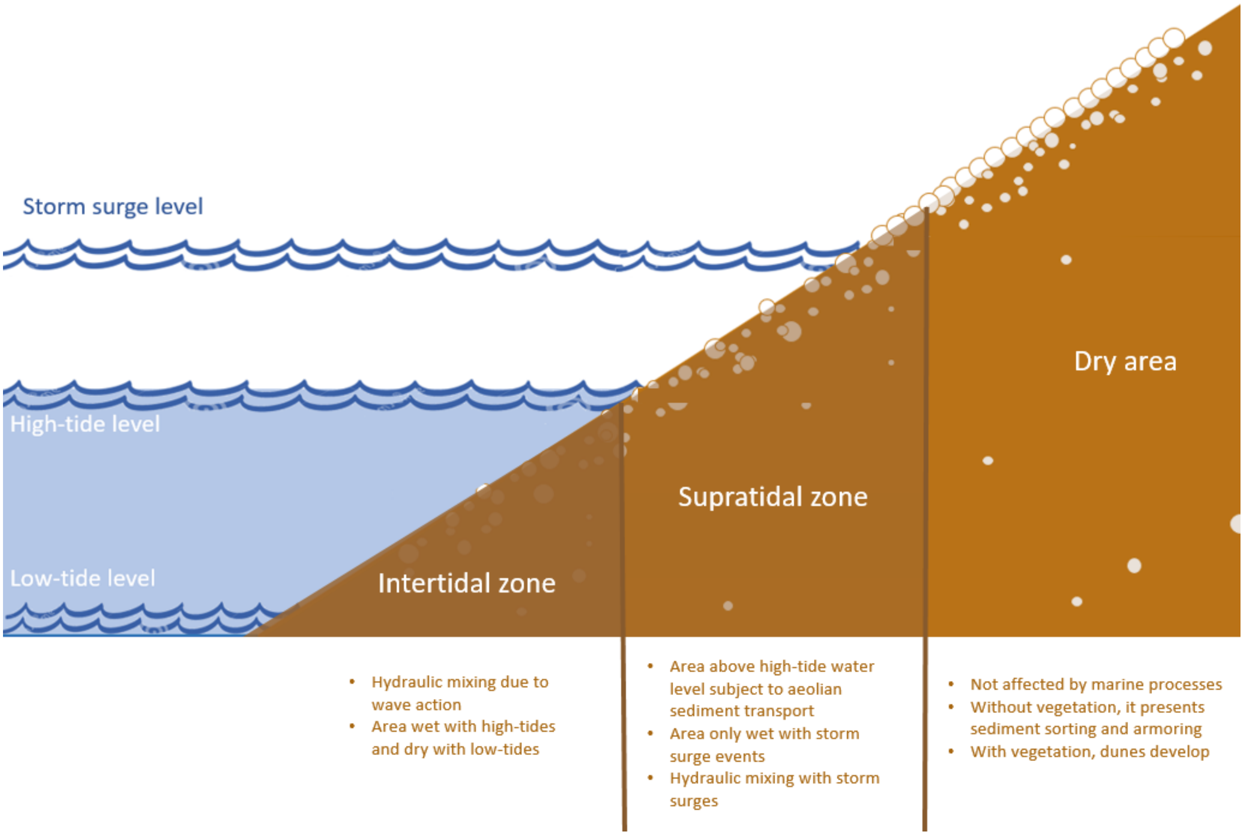


Figure 2.2: Supply-limiting conditions over the cross-shore

2.2.1 Soil moisture

Marine processes, like the tidal cycle and storm surges, affect sediment transport. Tides flood part of the beach and increase soil moisture. The soil moisture content is defined by the level of saturation of the sediment. When soil moisture is sufficiently high, it limits or even nullifies aeolian sediment transport. This is due to the increase in the wind velocity threshold u_{th}. Thus, the tidal influence on the coast reduces the sediment transport.

The tidal range varies over spring and neap cycles, which defines a difference in water levels between high and low tides. The entire covered area is called intertidal zone (See Figure 2.2). With low tides, the sand dries up and sediment is available for transport and with high tides the intertidal zone gets inundated, thus the aeolian sediment transport decreases significantly.

In addition, soil moisture is also affected by storm surge events. These are events that come with an abnormal rise in sea water level during a storm. It is measured as the height of the water above the normal predicted astronomical tide. The area that gets flooded with storm surges is represented by the supratidal zone (See Figure 2.2).

Following Belly et al. (1964), the influence of soil moisture on the velocity u_{th} is described by eq. 2.2.1, where W is the soil moisture content. This results in a dimensionless factor which is added to the wind velocity threshold u_{th} calculation (See Figure 2.3).

$$1.8 + 0.6 \quad log_{10} \quad W \tag{2.2.1}$$

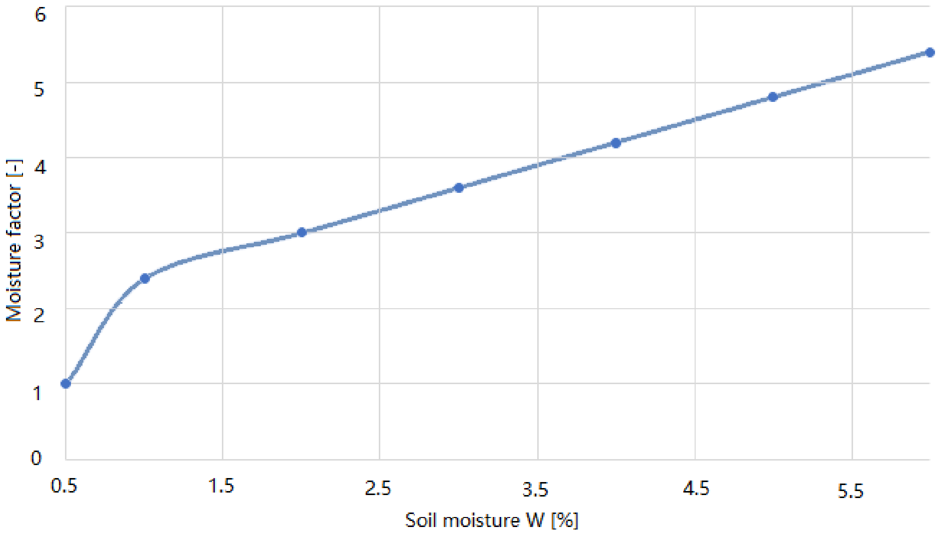


Figure 2.3: Soil moisture factor that results from eq. 2.2.1 with varying soil moisture content

2.2.2 Armouring and hydraulic mixing

As a result of sediment sorting which develops on the dry zone and during the non-flooded periods on the cross-shore, beach armouring occurs (See Figure 2.2). Beach armouring represents the process where large grains and shells emerge from the bed. This results on a top-layer of coarser elements which partition the shear stress and shelter smaller particles on the sub-layers, preventing their erosion. Thus, limits sediment supply.

Figure 2.4: Armouring as result of sediment sorting: top layer composed of non-erodible elements (Picture taken by Marli Miller, 2010)

Sediment armouring can be undone by hydraulic mixing (Hoonhout and Vries, 2016). This occurs if the area where sediment sorting happened is affected by waves. Waves mix the upper layer of the bed, breaking beach armouring and replenishing the sediment. Hydraulic mixing happens due to the continuous activity of tidal currents and waves and usually affects the intertidal area (Bauer et al., 1996). However, it can also occur further into the shore during storm surge events (See Figure 2.2).

2.3 Technical description of DUBEVEG and AeoLiS

The scope for this project defines the use of two numerical models. The first one is DUBEVEG, a probabilistic model that simulates a morphological change based on the interaction of dune-beach systems. The second one is AeoLiS (Hoonhout and Vries, 2016), which simulates aeolian sediment transport and includes soil moisture and beach armouring as supply-limited conditions. Below, the technical description (of interest to stay within the limits of the scope of the project) of both models is included.

2.3.1 DUBEVEG

DUBEVEG (DUne, BEach and VEGetation, Keijsers et al. (2016)) is a cellular automata model that simulates beach-dune development, through a probabilistic approach.

Aeolian module

DUBEVEG includes an aeolian, a hydrodynamic and a vegetation module. The core module of the model (in which this thesis focused) is the aeolian module.

The aeolian module works by stochastically picking individual slabs which are displaced over the domain. When a slab is picked-up in the cellular automata model, it represents a volume of sand being eroded in reality. This process is based on a probability of erosion $\mathrm{P_e}$. Then, the slab gets transported a distance L (Silva et al., 2018). The distance L, which represents how far a slab can go before getting deposited is dominated by $\mathrm{P_d}$.

$\mathbf{P_e}$ and $\mathbf{P_d}$ in DUBEVEG

DUBEVEG includes a probability of erosion and deposition (P_e and P_d). These probabilities are input predefined by the user. They represent the chance of a slab to be eroded or deposited, and are in a range of 0 to 1. A 0 value means no probability of getting eroded nor deposited. A value of 1 on the other hand, means 100% chance of a slab to be eroded or deposited.

The $\mathrm{P_e}$ and $\mathrm{P_d}$ are defined according to the conditions of the surrounding, taking into account the vegetation cover and the groundwater level. A higher value of vegetation cover would translate into a higher $\mathrm{P_d}$ and a lower $\mathrm{P_e}$. A higher value for the groundwater level would translate to a lower $\mathrm{P_e}$, thus limiting the sediment supply. Figure 2.5 represents the slab movement process in DUBEVE based on P_e and P_d.

Two types of slab erosion and deposition probabilities can be defined in DUBEVEG, depending on the state of the slab: vegetated or not (bare). When calibrating DUBEVEG, Keijsers et al. (2016) suggested a $\mathrm{P_e}$ value of 0.5 for a bare cell, representing a chance of 50% of a cell to be eroded. This to account for the supply-limiting conditions or the lack of wind that may exist in coastal environments. Regarding vegetated slabs, the erosion of sand is virtually zero once vegetation exceeds 15-50% of the slab cover (Buckley, 1987; Kuriyama et al., 2005; Lancaster and Baas, 1998; Wasson and Nanninga, 1986).

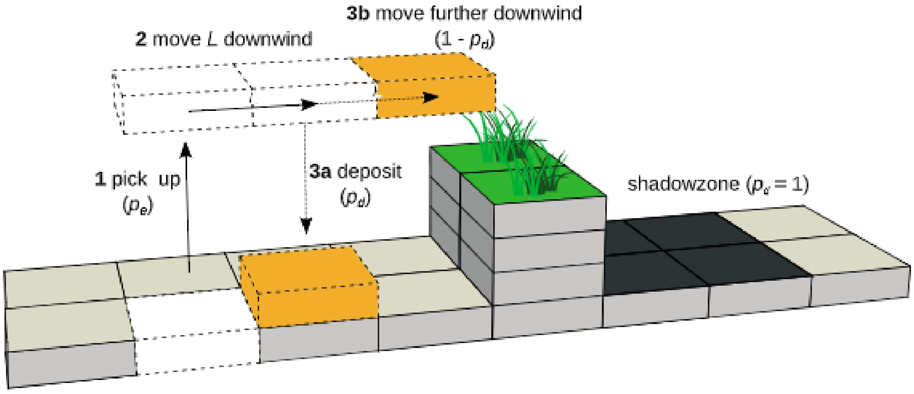


Figure 2.5: Process of slab movement with pickup in DUBEVEG (Keijsers et al., 2016)

Potential aeolian transport equation

$$Q = H_\mathrm{s} * L * \frac{P_\mathrm{e}}{P_\mathrm{d}} * n \tag{2.3.1}$$

The potential aeolian transport per meter along shore [Q in $m^3/m/y$] in DUBEVEG can be defined by eq. 2.3.1, which includes a probability ratio that relates the probability of erosion and deposition [$\frac{P_e}{P_d}$]. These P_e and P_d have a dominant behaviour on the output of the model because of its probabilistic approach. In addition, it relates the slab height [H_s in m] to a bed-related elevation. The length of the slab represents the hop length [L in m] a cell can advance per iteration, before it gets deposited. It also includes a parameter n, which represents the number of iterations that the module goes through over one year.

2.3.2 AeoLiS

AeoLiS (Hoonhout and Vries, 2016) is a process-based model that simulates aeolian sediment transport in situations where supply-limiting factors are important, like in coastal environments.

AeoLiS makes it possible to obtain several parameters related to aeolian transport like the moisture content [-], bed level above reference zb [m], instantaneous sediment flux q [kg/m/s], sediment entrainment [kg/m^2], wind velocity threshold u_{th} [m/s], wind velocity [m/s], shear stress $u*$ [m/s] and others, per defined time step.

Core processes in AeoLiS

AeoLiS implements the processes that affect aeolian sediment transport by taking into account the set of conditions that have an effect on them. A description of how AeoLiS implements some of the core processes, which are relevant for this research, is included below.

Sediment flux

The sediment flux accounts for the quantity of sand transported as a function of the shear stress exerted by the wind. AeoLiS represents it as a mass over meter per second q, which varies per grain-size and is calculated according to eq. 2.3.2. Where: $Cb = 1.5$ [-] is a constant to account for the grain-size distribution width, $D_n = 0.00025$ [m] is the reference grain-size and d_n is the mean size of the sediment being assessed, $\rho = 1.25$ [kg/m^3] is the air density and $g = 9.8$ [m/s^2] represents gravity.

$$q = Cb\frac{\rho}{g}\sqrt{\frac{d_n}{D_n}}(u *_R - u_{thW})^3 \tag{2.3.2}$$

Shear stress

Eq. 2.3.2 also considers the shear stress $u*$, which is calculated based on the law of the wall by Von Kárman eq. 2.3.3. Where: u_i is the velocity measured at hour i [m/s], k = 0.41 [-] is the Von Kárman constant, z = 10 [m] is the height of the wind measurement and z_0 [m] is the height at which the wind velocity approaches 0 [m/s].

$$u* = u_i(\frac{k}{ln(\frac{z}{z_0})}) \tag{2.3.3}$$

Roughness parameter

In addition, the shear stress $u*$ is modified based on the presence of roughness elements. It accounts for when due to sediment sorting, non-erodible elements appear on the top layer of the bed and shelter erodible elements.

As a result, there is partitioning of the shear stress. The definition of the roughness parameter as it is included in AeoLiS is described in eq. 2.3.4. Where: $m = 0.5$ [-] is a factor to account for the difference between the average and maximum shear stress, w_k^{bed} [-] is the weight on the bed of a grain size k, $\beta = 130$ [-] is the ratio between the drag coefficient of roughness elements and the bare surface and $\sigma_b = 4.2$ is the ratio between the basal area and frontal area of the roughness elements.

$$R = \sqrt{(1 - m \sum_{k=k_0}^{nk} w_k^{bed})(1 + \frac{m\beta}{\sigma_b} \sum_{k=k_0}^{nk} w_k^{bed})} \tag{2.3.4}$$

Wind velocity threshold

Eq. 2.3.2 also includes the velocity threshold u_{th}. It is the minimum wind velocity required to move a grain. It relates the density of a particle and the air's, to gravity and a particle's diameter and its friction. Following Bagnold (1935), the calculation of the velocity threshold is described in eq. 2.3.5. Where: A= 0.085 [-] is a constant based on grain size, $\sigma = 2650$ [kg/m^3] is the density of the grains, $\rho = 1.25$ [kg/m^3] is the density of the air, $g = 9.8$ [m/s^2] is gravity and dn_k [m] is the mean diameter of the grain being assessed[m].

$$u_{th} = A\sqrt{\frac{\sigma - \rho}{\rho} g dn_k} \tag{2.3.5}$$

The u_{th} velocity threshold in eq. 2.3.5 is influenced by the moisture content W[%]. The W moisture content is obtained according to Darcy's Law, which relates empirically the flow of liquid through a porous medium. Based on Belly et al. (1964) eq. 2.3.6 shows its calculation.

$$u_{thW} = A\sqrt{\frac{\sigma - \rho}{\rho} g dn_k} (1.8 + 0.6 log_{10} W) \tag{2.3.6}$$

3 Methodology

The method to assess the impact of P_e and P_d over the patterns created on the bed in DUBEVEG is described in this section. This was based on a sensitivity analysis of the effect that different values of P_e and P_d have throughout the simulation time on the topography. This is described in section 3.1 Morphological influence due to DUBEVEG's parameters.

After defining that the significant parameter for supporting supply-limitation in DUBEVEG was P_e (described in section 4), the methodology that was developed to obtain P_e [%] accounting for soil moisture and beach armouring as supply-limited conditions from AeoLiS is described. This is included in section 3.2 Process-based support for a cellular automata model.

Finally, a sensitivity analysis was made following the steps described in section 3.2, to determine the influence of varying environmental conditions on P_e [%]. The description of the cases which were analysed is included in section 3.3 Sensitivity analysis of environmental conditions.

3.1 Morphological influence due to DUBEVEG's parameters

The impact that two key parameters (P_e and P_d) had in the morphology in DUBEVEG was assessed. The objective was to determine the significance of both P_e and P_d, to select the most adequate parameter to be process-based supported to include soil moisture and beach armouring as supply-limited conditions.

As a first step, a base-case that was used as reference in DUBEVEG and AeoLiS was built-up. Afterwards, the base-case was simulated for 15 years in DUBEVEG. The output of interest is presented in Results, section 4.

3.1.1 Developing a base-case

A case scenario was developed to be used as the base-case for the simulations in DUBEVEG and AeoLiS. The base-case includes characteristics of the sand-flat De Hors, on Texel. Texel is the largest of the Wadden Sea islands in The Netherlands. Although the base-case is a simplification of a real Dutch-case, it is not the simplest because it includes supply-limiting conditions which vary in space and time.

Characteristics of the base-case

The base-case is composed of a flat beach with no initial along-shore variation and increasing bed level from water line to inland, which corresponds to a 1/143 mild-slope from water line to inland. The base-case has an area of 100x300 m^2, which correspond to the along-shore and the cross-shore distance, respectively.

The data set taken from Texel includes a predominant wind direction from south-west and a grain size that ranges from fine to medium, with D_{50} 210 μm. The wind data was taken from the Dutch Royal Meteorologic Institute for the closest location where data was available, Den Hoorn (Terschelling). It represents a mixed-energy wave-dominated inlet. The water level input series were based on tide gauges available at the harbour of Den Helder, close to the sand flat.

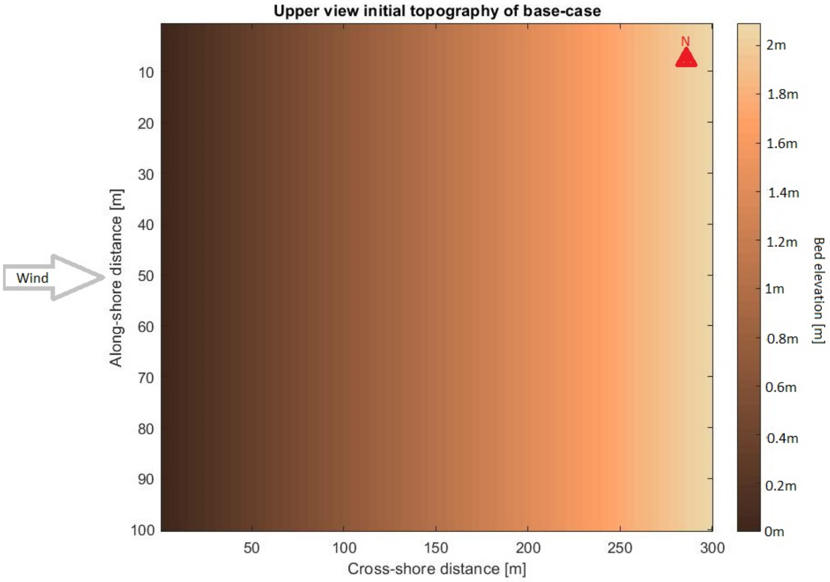


Figure 3.1: Base case initial topography

3.1.2 Base-case implementation in DUBEVEG

After defining the base-case, its implementation in DUBEVEG took place. In the simulations, the hydrodynamic module used as input the water levels from the harbour of Den Helder in 2018. It simulates a full neap-spring tide cycle. Thus, it gets updated after iterating for 2 weeks in simulation time.

Parameters used in DUBEVEG

The values chosen for the parameters in the simulations are included in Table 1. Most of the values used were calibrated by Keijsers et al. (2016), and defined for Dutch coasts.

Table 1: Values of the parameters used in DUBEVEG

Parameter	Description	Value	Units
n	Iterations per year	52	y^{-1}
H_s	Slab height	0.1	m
L	Cell width	1	m
wl	Reference water level	0	-
G	Groundwater depth factor	0.7	-
Fdiss	Wave dissipation factor	0.012	-
P_{eb} P_{ev}	Erosion probability of bare and vegetated cells	[0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 1]	-
P_{db} P_{dv}	Deposition probability of bare and vegetated cells	[0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 1]	-

In reality, groundwater affects dune development. This effect was tested in DUBEVEG by Galiforni Silva et al. (2019), who found that the model shows a threshold level on which groundwater starts to affect dune development. Based on the ranges presented on their paper, a 0.7 value was chosen as the groundwater depth factor. This would represent a situation where the groundwater level does have an influence on the sediment supply, yet it is not big enough to nullify it. The number of iterations per year refer to the aeolian module, which gets updated after iterating for 1 week in simulation time.

Based on the values from Table 1, 49 different cases were simulated. The only variation among them was the P_e and P_d defined per simulation (See Table 1). Each probability has two values. They are defined according to the state of the cell: vegetated or bare (not vegetated). Usually P_e is lower and P_d is higher if the cell is vegetated. However, the values for P_e and P_d for both vegetated (subscript v) and bare cells (subscript b) were assumed equal in the simulations. Therefore, the vegetation didn't influence the results.

The P_d is related in DUBEVEG to a distance L[m], which defines how far an eroded slab can move forward before being deposited (See steps 3a and 3bin figure 2.5). Bare cells are usually given a lower value for P_d, to include saltation on hard rock or moist surfaces. The default calibrated value in Keijsers et al. (2016) for the probability of deposition in DUBEVEG is $P_d = 0.1$. In this project, the values simulated for P_d represent a slab with a chance of 5%, 10%, 20%, 30%, 40%, 50% and 100% of being deposited.

In DUBEVEG, the default calibrated probability of erosion is $P_e = 0.5$. A value of 1 means a cell has a 100% chance of being eroded. The values used in the simulation represented a chance of being eroded of 5%, 10%, 20%, 30%, 40%, 50% and 100%.

The cases were simulated to represent 15 years of dune development. Because DUBEVEG is a probabilistic model and even by simulating the same conditions the obtained results will not be the identical, 5 replicates of each case were made. The output of this section (which is based on Research question 1) is included in Results section 4.

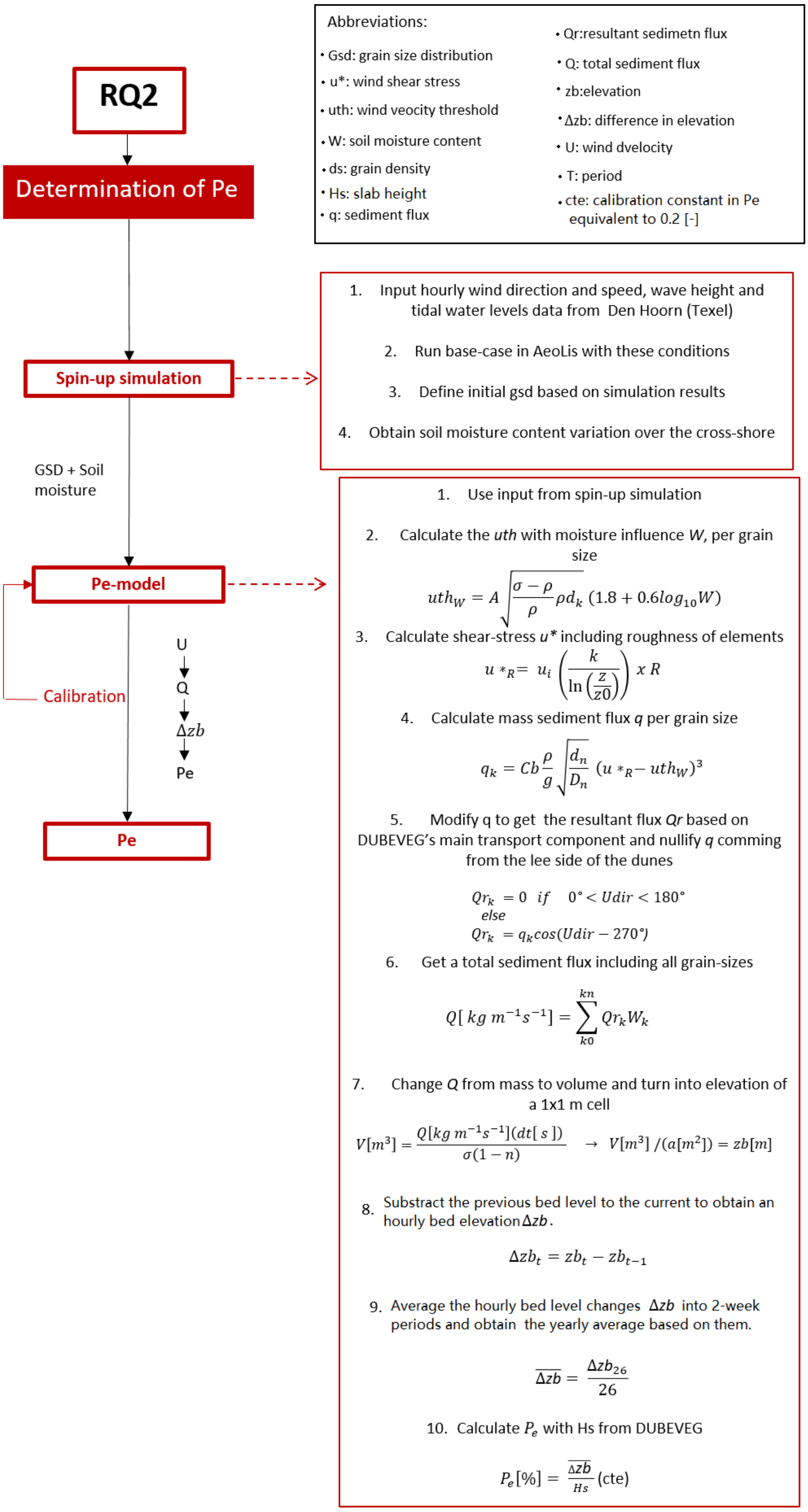
3.2 Process-based support for a cellular automata model

After defining that the probability of erosion P_e in DUBEVEG was the most adequate key parameter to be supported to include supply-limited conditions (described in section 4), the methodology described below was developed.

The method consisted in computing a yearly probability of erosion P_e based on the bed level change Δzb [m] of a single cell, by accounting for the equilibrium sediment flux over time. The erosion of a single cell with unlimited potential sediment-supply (available sediment supply before being affected by the environmental conditions) was simulated, as an isolated cell. This was done to prevent deposition from other cells into the single cell assessed, which would provide uncertainty when accounting for the bed level change Δzb [m] as the parameter to determine the erosion per time-step.

The influence that soil moisture and beach armouring have on the probability of erosion was of interest. However, beach armouring takes time to develop on the beach. In order to represent a case where the influence soil moisture and beach armouring was already formed, a spin-up simulation was undertaken. The output from the spin-up simulation was used to set up the Pe-model, where the bed level change Δzb [m] calculated per transect was converted into a P_e [%]. The Pe-model includes the core processes described in section 2.3.2 and the calculation of P_e [%]. Figure 3.2 describes the steps taken to solve Research question 2, regarding the process-based support for a cellular automata model.

Figure 3.2: Flow chart: Determination of Pe



Abbreviations:

- Gsd: grain size distribution
- u*: wind shear stress
- uth: wind veocity threshold
- W: soil moisture content
- ds: grain density
- Hs: slab height
- q: sediment flux
- Qr:resultant sedimetn flux
- Q: total sediment flux
- zb:elevation
- Δzb: difference in elevation
- U: wind dvelocity
- T: period
- cte: calibration constant in Pe equivalent to 0.2 [-]

1. Input hourly wind direction and speed, wave height and tidal water levels data from Den Hoorn (Texel)
2. Run base-case in AeoLis with these conditions
3. Define initial gsd based on simulation results
4. Obtain soil moisture content variation over the cross-shore

1. Use input from spin-up simulation
2. Calculate the *uth* with moisture influence *W*, per grain size

$$uth_W = A\sqrt{\frac{\sigma-\rho}{\rho}\rho d_k}\,(1.8+0.6log_{10}W)$$

3. Calculate shear-stress *u** including roughness of elements

$$u*_R = u_i\left(\frac{k}{\ln\left(\frac{z}{z0}\right)}\right)x\,R$$

4. Calculate mass sediment flux *q* per grain size

$$q_k = Cb\frac{\rho}{g}\sqrt{\frac{d_n}{D_n}}\,(u*_R - uth_W)^3$$

5. Modify q to get the resultant flux *Qr* based on DUBEVEG's main transport component and nullify *q* comming from the lee side of the dunes

$$Qr_k = 0 \quad if \quad 0° < Udir < 180°$$
$$else$$
$$Qr_k = q_k cos(Udir - 270°)$$

6. Get a total sediment flux including all grain-sizes

$$Q[\,kg\,m^{-1}s^{-1}] = \sum_{k0}^{kn} Qr_k W_k$$

7. Change *Q* from mass to volume and turn into elevation of a 1x1 m cell

$$V[m^3] = \frac{Q[kg\,m^{-1}s^{-1}](dt[\,s\,])}{\sigma(1-n)} \quad \rightarrow \quad V[m^3]\,/(a[m^2]) = zb[m]$$

8. Substract the previous bed level to the current to obtain an hourly bed elevation *Δzb*.

$$\Delta zb_t = zb_t - zb_{t-1}$$

9. Average the hourly bed level changes *Δzb* into 2-week periods and obtain the yearly average based on them.

$$\overline{\Delta zb} = \frac{\Delta zb_{26}}{26}$$

10. Calculate P_e with Hs from DUBEVEG

$$P_e[\%] = \frac{\overline{\Delta zb}}{Hs}(\text{cte})$$

3.2.1 Spin-up simulation set-up

In order to properly represent a case where beach armouring is formed, the spin-up simulation was made. The output of interest from the spin-up simulation was used to set up the Pe-model and it included: the grain-size distribution under the influence of beach armouring and the soil moisture content over time.

Soil moisture was needed from the spin-up simulation to account for its influence as supply-limited condition because it varies over time and space. Also, the distribution of the grain-sizes on the bed affect aeolian erosion through sediment sorting and armouring. However, the latter takes years to develop in AeoLiS (Hoonhout and Vries, 2016) in order to fully nullify sediment transport and depends on bed grain composition. Thus, the interest of determine an initial simulation state including beach armouring supply-limitation from the spin-up simulation.

Some characteristics of the base-case were adapted so they could be included in the spin-up simulation. These are summarized in Table 2 and described below.

Table 2: Configuration set-up for determination of the initial grain-size distribution

Parameter	Description	Value	Units
Tdry	Adaptation time scale for soil drying	1800	s
bi	Bed interaction factor	0.1	-
dt	Time step	3600	s
nx	Cross-shore distance	300	m
ny	Along-shore distance	10	m
cell	cell size	1	m^2
Output-time	Output time	3600	s
Simulation time	Simulation time	31536000	s
Grain-size	Grain sizes	250 350 450 800	μm
Layer-thickness	Layer thickness	0.03	m
Grain-dist	Grain size distribution	0.40 0.30 0.20 0.10	-
nfraction	Number of fraction	4	-
nlayers	Number of layers	3	-
facDOD	Ratio between depth of disturbance and local wave height	0.3	-
process-bedupdate	Disable process for bed update	False	-

Adaptation time scale for drying

The default value didn't allow significant erosion to occur due to the constant wet periods. Therefore, this parameter in AeoLiS was decreased to allow more sediment transport in-between flood events on the cross-shore.

Bed interaction factor

The bed interaction factor describes the exchange of momentum between grain size fractions along the fetch distance. It describes whether impacting grains eject other grains from the bed or that they are rebounded due to fully elastic collisions with large, non-erodible elements. A low value for the bed interaction parameter would indicate a large number of rebounding grains,while a high value would indicate a low number of rebounding grains. Typically, the number of rebounded grains increases with an increasing number of non-erodible large elements in the bed. This parameter was adapted to only account for the weight of the grain fractions on the bed, without taking into account the grains in the air. Thus, keeping the focus on the grain-size distribution of the bed.

Number of bed layers

Three bed layers were simulated in AeoLiS, which correspond to the default value. This amount was unchanged because the grain-size distribution of interest was of the top-layer only and to save simulation time, which increases with the level of detail in the project.

Layer thickness

The thickness of the layers was chosen to be 3 cm. This parameter was increased from the default value so the simulation didn't run out of sediment (which occurred on the first trials for the spin-up simulation).

Depth of disturbance factor

The parameter facDOD represents the ratio between the depth of disturbance and the local wave height. It was increased so a larger part of the cross-shore depicted a clear influence of hydraulic mixing.

Tidal time series

The spin-up simulation in AeoLiS used hourly water levels from tide gauges located in Texel Noordzee, for the year of 2018. This data was obtained from Rijkswaterstaad waterinfo.

Increased bed slope

Due to the high water levels experienced in Texel in 2018, the original bed slope from the base-case was increased to 1/67. With this change, the cross-shore was divided in 3 zones: the intertidal, the supratidal and the dry zone. This was desired in order to assess the spatial variability of supply-limiting conditions on the cross-shore and their effect on P_e [%] (See Figure 2.2).

Modified grain-size distribution

The nominal grain-size which was included in the base-case as D_{50} 210 μm was replaced with a grain-size distribution that includes bigger grain fractions. The latter was changed to depict supply-limitation due to sediment sorting and armouring more efficiently, its definition is purely academic. The new composition has a grain-size distribution composed of: 40% of 250μm grains, 30% of 350μm grains, 20% of 450μm grains and 10% of 800μm grains (See table 2). It was assumed equally distributed along and across the area.

Unidirectional wind

The wind data was adapted to cope with the on-shore component of the sediment transport in DUBEVEG, by simulating a 1-D wind approach where the aeolian transport of sediment occurred from west to east. Therefore, the wind coming from 0 to 180 °in the nautical direction was nullified.

Modified beach width

The beach width was reduced to 10 m to speed-up the computational time, which didn't affect the simulation because there is no along-shore variation in the supply-limited conditions in AeoLiS and neither on the sediment transport calculated.

Bed update

The bed update process in AeoLiS was turned off to focus on the sorting of sediment.

3.2.2 Output of spin-up simulation

After simulating this case for 10 years in AeoLiS, the weight of the 4 grain-sizes simulated on the bed was obtained. Then an initial grain distribution which varies in space was defined. To assess the spatial variation of the bed composition, the cross-shore distance was divided in 10 transects of 30 m long each (Figure 3.3). Based on this division, the resulting average weight of the grain-sizes was accounted for. In addition, each transect represented a different grain-size distribution and soil moisture content. Therefore, each transect depicted a different supply-limited set of conditions (See Figure 3.3). These results are described in section 4.

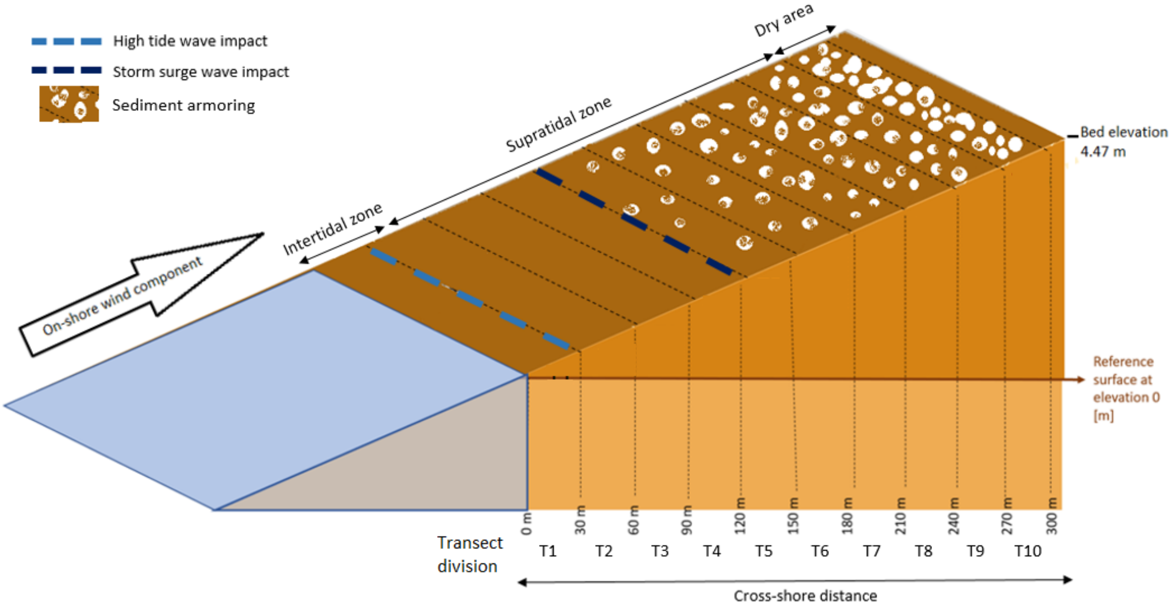


Figure 3.3: Cross-section division for obtainment of Pe

3.2.3 Determination of P_e

This section describes the Pe-model, which was used in order to obtain a process-based P_e including soil moisture and beach armouring as supply-limited conditions.

The Pe-model

The Pe-Model was set-up as a simplified version of AeoLiS that is able to calculate a sediment flux based on equations 2.4.2 to 2.4.6 described in section 2.3.2. Its objective is to calculate a P_e [%] based on the bed level change Δzb [m] in a single cell, accounting only for the erosion represented on that single cell as the sediment transport flux and without being influenced by deposition created by neighbour cells.

Due to the multiple wind directions that can be simulated in AeoLiS, deposition and erosion can occur from and into more than one direction. This behaviour was excluded by using the Pe-model, which allowed to account for the bed level change Δzb [m] as an indicator of the erosion presented in the single cell without influence of external deposition, per time-step. In addition, Aeolis includes an adaptation time scale parameter T [s] in the advection scheme. T [s] represents the amount of time it takes for the sediment to react to the wind force exerted on the bed. This parameter was also excluded from the Pe-model, in order to prevent the time between time-steps to not be enough to reach an equilibrium sediment transport. The latter would provide uncertainty to account for all the eroded sediment from the single cell in a time-step. Instead, the sediment flux calculated in the Pe-model represents the equilibrium sediment transport, which is the result of the direct erosive effect on one cell due to wind force.

The Pe-model also includes the influence of supply-limited conditions by using the output of the spin-up simulation in AeoLiS. The supply-limited conditions which are included are soil moisture (by tidal and wave influence) and sediment sorting resulting in armouring.

Pe-model set-up

The Pe-Model used as input the hourly time-series of the wind direction $Udir$ [rad], the wind velocity U [m/s], the moisture content W [%] and the grain size-distribution from the spin-up simulation.

It calculates the velocity threshold uth [m/s] per grain fraction including, the effect of the moisture content W [%] (eq. 2.3.6). Followed by this, the shear-stress $u*$ [m/s] is obtained. The appearance of non-erodible elements is accounted for with the implementation of the roughness as described in eq. 2.3.4.

Finally, it estimates the mass sediment flux q_k [kg/m/s] per grain-size (eq. 2.3.2), which represents the equilibrium sediment transport for one cell per time step.

After obtaining q_k [kg/m/s] per grain-size, it was modified to obtain a resultant flux Qr_k [kg/m/s] as described in eq. 3.2.1. Qr [kg/m/s] represents the on-shore component of the sediment transport in DUBEVEG. In the base-case in DUBEVEG, dunes are developed from west to east corresponding to the nautical wind direction of 270° azimuth bearings. In order to cope with DUBEVEG and only account for the sediment transport occurring from west to east in the Pe-model, the flux q [kg/m/s] coming from the lee side of the dunes was nullified (from 0 to 180° azimuth bearings).

$$Qr_k = 0 \quad if \quad 0° < Udir < 180° \quad else \quad Qr_k = q_k cos(Udir - 270°) \tag{3.2.1}$$

Subsequently, all Qr_k [kg/m/s] were summed up based on the grain fractions composition w_k, which is defined by the fractions weight. Lastly, the total sediment transport Q [kg/m/s] (eq. 3.2.2) was obtained. Where: Qr_k [kg/m/s] is the transformed sediment flux per grain-size k.

$$Q = \sum_{k_n}^{k_0} Qr_k w_k \tag{3.2.2}$$

Q [kg/m/s] was transformed into a volumetric measure V [m^3] according to eq. 3.2.3. Where: $\sigma = 2650$ [kg/m^3] is the grain density, the porosity is $n = 0.4$ [-] and the time-step is $dt = 3600$ [s], which accounts for 1 hour.

$$V = \frac{Q}{\sigma(1-n)}(dt) \tag{3.2.3}$$

Then, the bed level change Δzb [m] based on eq. 3.2.4 in one cell of area $a = 1$ [m^2] was computed, which represents the erosion that the single cell experienced per time-step.

$$\Delta zb_t = zb_t - zb_{t-1} \tag{3.2.4}$$

Finally, the hourly bed level changes Δzb [m] were summed and accounted for 2-week period in a year. The latter was done to represent the average erosion experienced once every spring-neap cycle. Thus, 26 values representing the erosion in a year were obtained.

These were averaged to calculate a yearly bed level change Δzb [m], and divided by the slab height Hs [m] in DUBEVEG which is 0.1 [m] to obtain P_e [%](eq. 3.2.5).

$$P_e[\%] = \frac{\Delta \bar{zb}}{H_s} \tag{3.2.5}$$

Calibration of P_e

The Pe-model uses input from AeoLiS (Hoonhout and Vries, 2016) which is capable of representing several coastal processes including soil moisture and beach armouring as supply-limited conditions. However, it does not include rainfall, groundwater nor salt influence as supply-limiting factors. Therefore, the Pe-model over predicts the sediment transport because it is based on the output of AeoLiS.

In order to account for the over prediction of sediment transport, a calibration of P_e [%] in the Pe-model was carried out. The calibration was implemented in the supratidal zone (Transect 4) to match the default $P_e = 50\%$ value in DUBEVEG (See Figure 3.3). This transect was chosen because it is influenced by all the supply-limited conditions of interest for this project. An assumption was made that this combination of conditions in the Pe-model represents best the compound processes as included in DUBEVEG (from the whole simulated area).

The result of the calibration was a calibration constant $cte = 0.2$ that accounts for 20% of the total sediment transport, adapting eq. 3.2.5 as follows.

$$P_e[\%] = cte\frac{\Delta \bar{zb}}{H_s} \tag{3.2.6}$$

3.3 Sensitivity analysis of environmental conditions

In reality, the probability of erosion is not a constant. It can vary in space and time, which is due to the continual influence of the time changing marine and aeolian processes that affect sediment supply. To assess the spatial variability of the obtained $P_e[\%]$ due to supply-limiting conditions, a sensitivity analysis was done by varying the environmental conditions to which the simulated cell was exposed to. This was done by following the steps described in section 3.2 and remaining with the same calibration constant $cte = 0.2$ in order to compare the impact of the new conditions to the already assessed case. The environmental conditions varied were:

- Increase of the tidal range: This situation included the same behaviour for the tidal range over time, but with doubled tidal range values compared to the originally obtained ones. This situation depicts an extreme and unrealistic water level increase and wave action, but shows the significant influence marine processes have on the coast.
- Decrease of the tidal range: This situation represents the same behaviour for the tidal range over time but with halved values compared to the original data. This effect represents an extreme scenario that comes with an overly-decreased influence of the marine processes on the cross-shore.
- Increase of the wind force: This situation depicts an increase of 50% in the wind force as it was originally obtained. This situation represents an extreme wind case scenario for strong storms.
- Decrease of the wind force: This situations includes a reduction of the wind force of 50%, which represents a beach with a very weak wind influence during the year.
- Sea Level rise (+1 m): Sea level rise is real-life situation which affects in present day sea water levels around the world. This situation was simulated by increasing 1 m the water levels, which surpasses reality. However, this extreme variation was done to clearly visualize its impact on the supply-limited conditions and on P_e.
- Nourished coast: Nowadays, several coasts are nourished with new sediment in order to gain land from the sea. This man-made realistic alteration comes with a wider varied range in grain-size distribution and with an increased compositions of big elements, like shells. In order to simulate a nourished beach, this case was represented in the spin-up simulation with an initial grain-size distribution composed of: 10% of 250μm grains, 20% of 350μm grains, 30% of 450μm grains and 40% of 800μm grains.

These environmental conditions were assessed in order to get a change in magnitude of soil moisture and sediment armouring and see their effect on P_e [%]. The results are included in section 4.3.

4 Results

In this section the results for the sensitivity analysis of DUBEVEG, regarding the morphological interaction of P_e and P_d are described. In addition, the results of the process-based support for P_e in a cellular automata model and sensitivity analysis when varying the environmental conditions are presented. The implications of the results are addressed in section 5, Discussion.

4.1 Morphological influence due to DUBEVEG's parameters

The results presented in this section describe the impact of two key parameters (P_e and P_d) in DUBEVEG over the morphological patterns created after 15 years of simulation, which accounts for the aggregated net change in DUBEVEG (the morphologic change on the initial state after the aeolian and marine processes affect the beach). The objective was to determine the significance of each parameter in DUBEVEG, to determine their suitability to support supply-limited conditions based on AeoLiS.

Forty-nine cases were assessed based on Table 1. The only difference among them was the combination of values representing P_e and P_d. Figure 4.1 depicts part of the results, whose evaluation is described below.

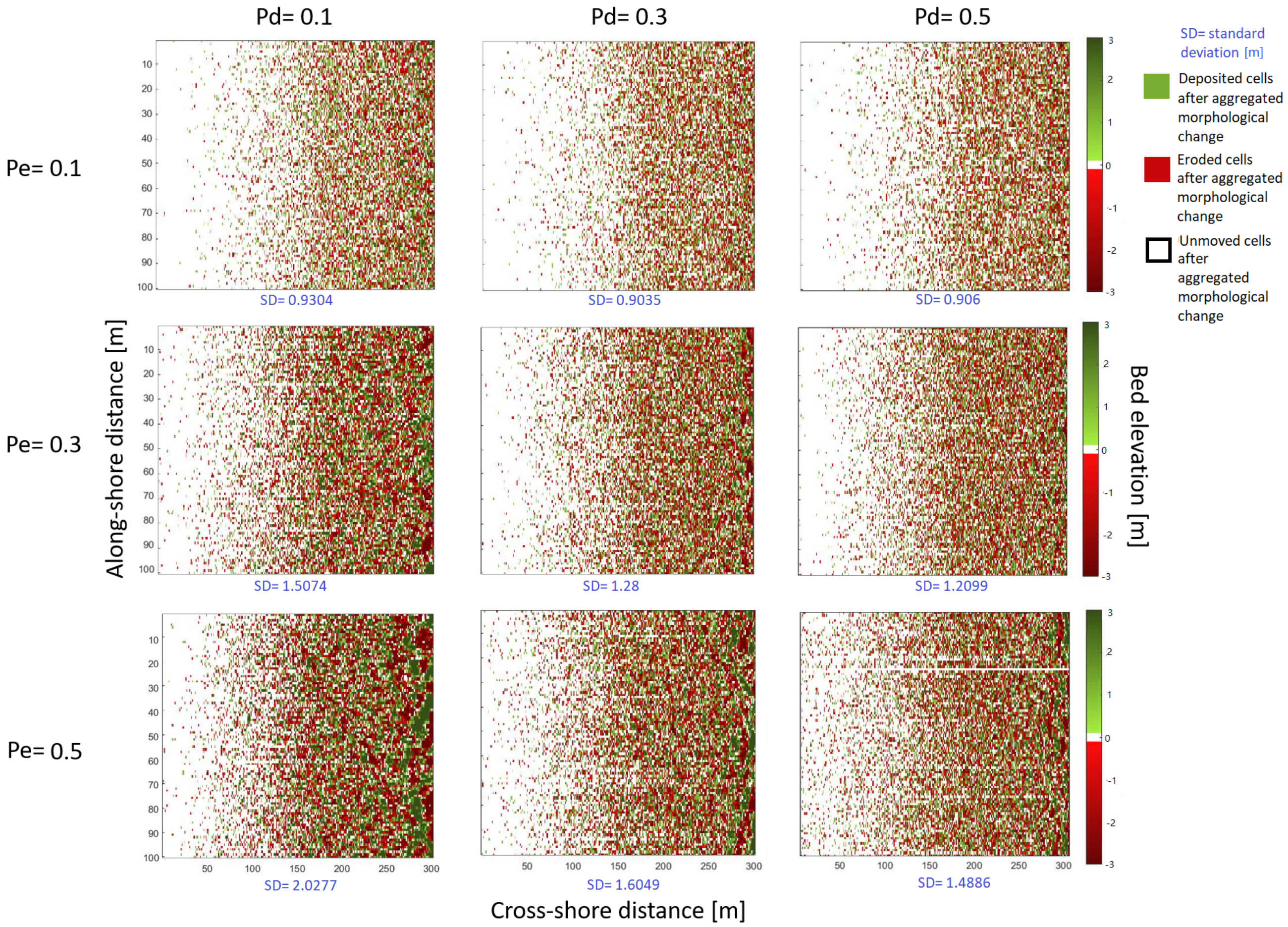


Figure 4.1: Bed patterns created with variation of Pe and Pd values in DUBEVEG

4.1.1 Morphological change based on the variation of P_e and P_d

When varying the probabilities in DUBEVEG, the resultant bed patterns after 15 years in simulation time showed higher, longer, wider and more dunes formed with larger values of P_e. The same increasing behaviour in the bed forms can be observed with a decrease in P_d. However, the change in the morphology when varying P_e was more significant.

This can observed in Figure 4.1, where as you go downwards (following the increase of P_e on the vertical axis) the cases show clusters of green and red cells. The green clusters represent cells piled together creating dune-like bed forms, which are accompanied by red clusters of cells that represent the eroded areas. It can be seen that as you increase P_e, more erosion of cells (representing sediment supply) create bigger change in the morphology obtained. Also, more deposition is observed, which comes along with the amount of cells that need to be deposited after being eroded. In addition, there is a decrease in the white spaces which represent the unchanged cell elevation after the aggregated simulation took place.

Quantitatively, the standard deviation which shows the difference between the initial morphologic state and the resultant morphologic profiles, depicts higher values with larger P_e (compared to the same increase in magnitude of P_d). This leads to a hypothesis of P_e having a dominant behaviour over P_d, in the shaping of the beach and the determination on the amount and size of formed dunes.

4.1.2 Morphological change based on different P_e and P_d values that result in the same P_e/P_d ratio

The diagonal of Figure 4.1 presents different P_e and P_d values that result in the same ratio of P_e/P_d. The $\frac{P_e}{P_d}$ ratio shows a relation between the eroded and deposited sediment in the potential aeolian transport equation (eq. 2.3.1). The differences observed in the resultant beach bed patterns created lead to the assumption that the result of the ratio is not as meaningful as the individual influence of P_e and P_d. The same resultant $\frac{P_e}{P_d}$ ratios give a final topography with more dunes formed with higher values of P_e. In addition, same resultant $\frac{P_e}{P_d}$ ratios give a significant different standard deviation, where the most changes that include highers and wider dunes formed are presented with larger P_e values. This strengthens the hypothesis of the dominant behaviour P_e has over P_d, on the morphologic change.

4.1.3 Physical meaning of the results

Physically in DUBEVEG, P_e represents the sediment supply available for transport and P_d the location where the sediment that was eroded will be deposited. This can be observed based on the behaviour of the dune development over time in the results.

The results at the most seaward area do not show bed forms due to the flattening influence of the marine processes. On the other hand, dunes are developed following the theoretical expansion of vegetation. This area corresponds to the most landward area on the base-case, thus dunes are depicted here. In addition, the hydrodynamic module does not have an erosive behaviour where dunes are formed. The intertidal area precedes where dunes are observed. This is where the majority of the sediment supply becomes available from, in theory. However, the results show white spots instead of erosion (red coloured spots) in the intertidal area because the sediment is often replenished.

P_e is directly related to the availability of sediment supplied for transport. With a higher probability of erosion, more cells are be available for transport (cells represent a volume of sediment). P_e controls sediment supply, although erosion of cells will only occur if after the hydrodynamic module kicks-in, the aeolian module is able to transport them. Meaning the actual transported cells depend on the effect the hydrodynamic module has on the picked-up cells, which then will have an impact on the sediment that will be deposited.

The sediment eroded needs to be deposited. This deposition is controlled by P_d. P_d determines how far the cell that was picked-up can reach before it is deposited. Meaning P_d distributes the eroded sediment, making it dependent on P_e.

4.1.4 Importance of P_e

The same effect is observed in the dunes formed with an increase of P_e than with a decrease in P_d. Nevertheless, P_e shows a dominant and stronger influence on the morphologic change over time on the beach. This is explained by P_e determining the available sediment for transport and P_d the determining the distribution of the eroded sediment.

P_e shows an implication for both the eroded and deposited sediment. Which is not the case of P_d. The results indicate that the physical representation of supply-limitation is linked to DUBEVEG's defined P_e. Thus, the thesis is further developed for the determination of P_e.

4.2 Process-based support for a cellular automata model

This section presents the results for the spin-up simulation and the Pe-model for the initial scenario as described from the methodology (Section 3.2).

The results from the spin-up simulation describe an initial grain-size distribution and a soil moisture content that vary over the cross-shore. The results from the Pe-model depict a P_e [%] that also varies over the cross-shore. This variation is based on the influence the input supply-limited conditions have on the coast. The results from the Pe-model describe the P_e [%] obtained from AeoLiS, as the methodology described.

In addition, the resultant P_e [%] from the cases where the environmental conditions varied are included.

4.2.1 Spin-up simulation results

From the spin-up simulation, two results were of interest: the final grain-size distribution and the soil moisture content. Both varied over the cross-shore, due to the spatial difference the supply-limited conditions had on the beach. The supply-limited conditions that were accounted for were beach armouring and soil moisture content.

Soil moisture content

The output from the spin-up simulation consisted of the hourly soil moisture content for the entire cross-shore, for 1 year. Its behaviour is controlled by the influence of the tidal cycle and wave action on the beach. In addition, wave action also has an influence on beach armouring. Its effect is discussed in section 'Initial grain-size distribution'.

Soil moisture on the beach limits sediment supply for transport by increasing the velocity threshold of the grains that compose the bed. The resultant soil moisture content from the spin-up simulation shows a decaying behaviour landwards. The moisture is higher close to the sea, due to greater influence of marine processes. The marine processes included are wave action and the tidal cycle. Their influence in reality decreases landwards due to the dissipation of energy, which is enhanced in the spin-up simulation with the increasing slope of the bed. This effect was intended in order to have a division of transects on the cross-shore with different influence of soil-moisture as supply-limited condition.

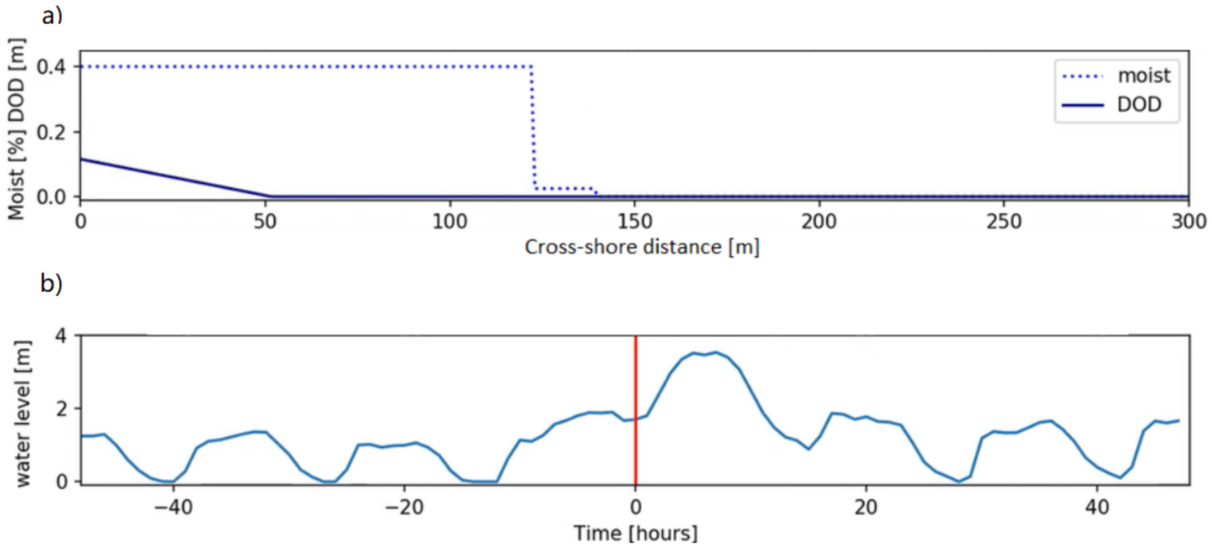


Figure 4.2: a) Example of the influence a water level of 2 m has on the cross-shore soil moisture and the cover of hydraulic mixing. Here, DOD is the depth of disturbance and moist is the moisture content. b) Shows the current 2 m water level in a water level time series of 96 hours

Figure 4.2 depicts as an example of the output of the spin-up simulation. It shows the instantaneous result for the tide and wave action influence on the cross-shore for a water level of 2 m. It can be noted that with tides and waves that result in a water level of 2 m, the soil moisture is significantly high until the cross-shore distance of 125 m. A soil moisture content of 40% is considered significantly high because it influences the velocity threshold of the grains in that saturated area, so that no aeolian transport can occur.

After a cross-shore distance of 125 m, Figure 4.2 presents a decrease that limits sediment-supply but does not nullify it. From the cross-shore distance 140 m on-wards, the beach is not affected by soil moisture as supply-limitation and can experience aeolian erosion.

Figure 4.2 includes a measure for DOD, which stands for 'depth of disturbance'. The depth of disturbance describes the relation between the wave height and the bed elevation on the cross-shore. If the bed elevation is smaller than the wave height, hydraulic mixing occurs. Thus, Figure 4.2 presents influence of hydraulic mixing up to 50 m on the cross-shore distance. Hydraulic mixing is the opposite process of beach armouring.

Initial grain-size distribution

In addition to the soil moisture content, a grain-size distribution was obtained from the spin-up simulation. The change over time of the grain-size distribution was assessed, based on the influence the environmental conditions. This was done by accounting for the weight of each sediment fraction after the simulation time. The aim was to detect the impact of sediment sorting, which leads to beach armouring as supply-limitation. In addition, hydraulic mixing (which undoes beach armouring) also altered the final grain-size distribution obtained.

Sediment sorting, beach armouring and hydraulic mixing all vary spatially and over time in AeoLiS. Which is the result of the variation of the environmental conditions that create them, in this case the marine and aeolian processes included. Beach armouring limits sediment supply by creating a top-layer made of non-erodible elements on the bed, which shelter smaller grains beneath from the erosive effect of the wind. Beach armouring can be undone if the area that presents it is reach by waves. Wave action causes hydraulic mixing on the top-layer of the bed, which in AeoLiS is represented by resetting the grain-size distribution with the initially defined one.

Based on how the grain-size distribution changed over time in the spin-up simulation, the initial grain-size distribution for the Pe-model was defined. It was chosen to represent a beach that includes beach armouring as supply-limited condition, after 10 years of influence in the simulation.

The initial grain-size distribution included grain-sizes of 250μm, 350μm, 450μm and 600μm. With a initial proportion of 40%, 30%, 20% and 10%, respectively. This academic grain distribution was equally distributed across and along the area.

Spatial variations over the cross-shore were observed in the grain-size distribution. The grain-size distribution obtained was averaged for every 30 m in the cross-shore distance, which defined the resultant grain-size defined per transect.

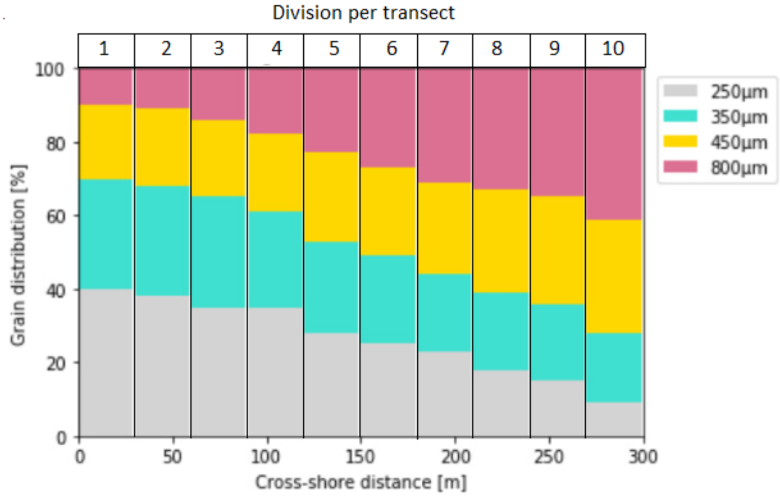


Figure 4.3: Initial grain-distribution for the Pe-model

As you go landwards in the base-case simulated in AeoLiS, the grain-size distribution presents an increase in content of the bigger grain-sizes and a decrease in the smaller ones. This is due to the increasing influence of sediment sorting and armouring, which is the strongest in the transects with less to no influence of marine processes, namely hydraulic mixing.

The first transects are in constant influence of hydraulic mixing due to wave action. This process undoes armouring and replenishes sediment. Figure 4.3 depicts the initial grain distribution as it was included in the Pe-model.

4.2.2 Pe-model results

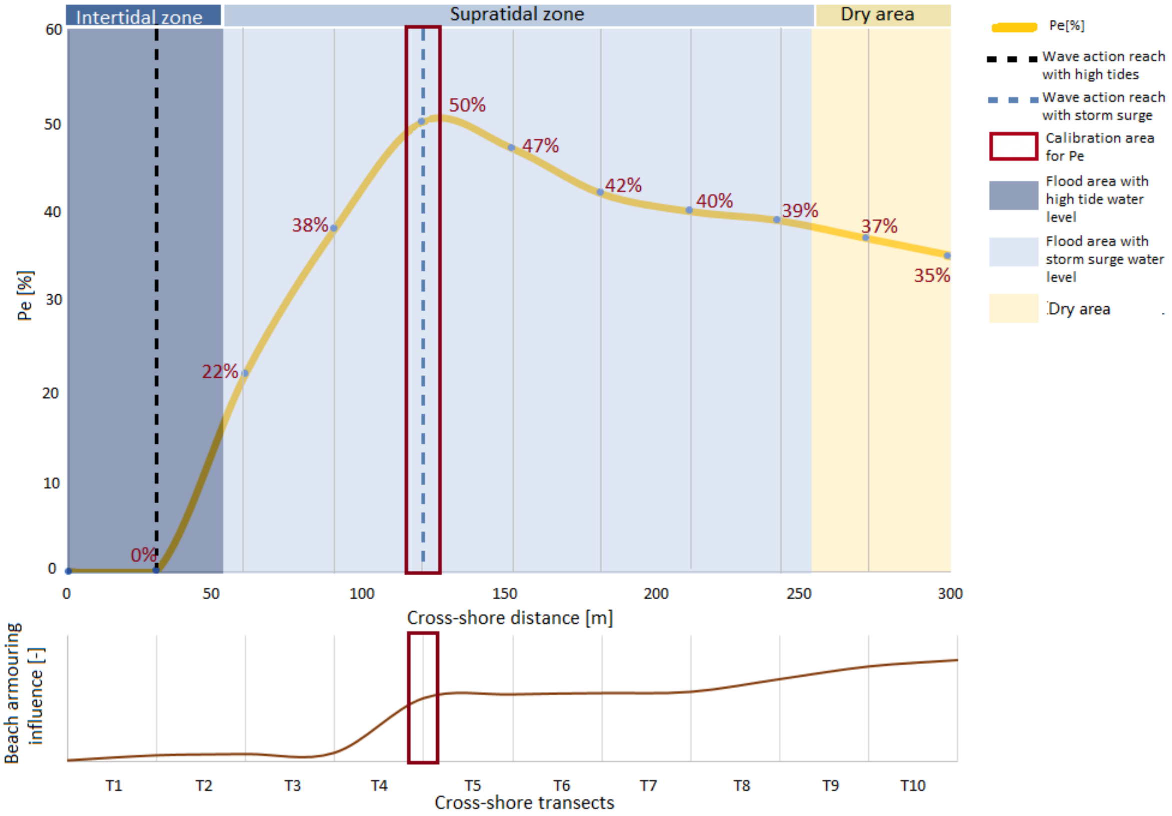


Figure 4.4: Variation of Pe[%] and beach armouring influence [-] over the cross-shore

The obtained P_e [%] from the Pe-model is depicted in Figure 4.4, where the influence of soil moisture content and sediment armouring over the cross-shore as supply-limited conditions can be observed. P_e [%] changes spatially and can be described based on the division of the 3 zones described in Figure 2.2 in section 2.2: the intertidal, supratidal and dry area.

Intertidal area

The intertidal area includes the transects closer to the sea, where marine processes dominate the resultant P_e [%] through the influence of soil moisture and hydraulic mixing. The behaviour of P_e [%] in the intertidal area is not linear, however it does not present big changes.

When the area is flooded due to the tidal influence, no aeolian erosion can occur. This is due to soil moisture which increases the wind velocity threshold and significantly reduces sediment supply. On the other hand, the little erosion this area presents is due to the short dry periods that come with low tides.

In the intertidal area there is barely any change in the grain-size distribution due to the strong influence of hydraulic mixing. In AeoliS, if the depth of disturbance of the waves is higher than the bed level, the grain-size distribution is reset to the initial one.

Supratidal area

The supratidal area presents the most variation in P_e [%] which is due to the combined influence of the marine processes during storm surges and aeolic processes: soil moisture, hydraulic mixture, sediment sorting and beach armouring.

In the supratidal area is where most of the aeolian erosion occurs, which happens when the area is dry and if the shear stress $u*$ is greater than uth. Soil moisture is present as supply limitation when the area is flooded during storm surges and shows a decaying behaviour landwards. Without soil moisture as supply-limiting condition, more sediment is available for transport. However, this area is subject to sediment sorting, which results in supply limitation due to beach armouring.

The peak value of P_e [%] is directly influenced by the the wave action during storm surges. This is due to the hydraulic mixing that takes place only where the depth of disturbance DOD is enough for the initial grain size distribution to be reset. On the latter area (which is not affected by the wave action during storm surges) there is no hydraulic mixing. Thus, overtime sediment sorting leads to beach armouring which is reflected in the decrease of the erosion presented.

Dry area

The last section of the cross-shore remains dry during the whole simulation because it is not influenced by the marine processes: flooding due to the tidal cycle, wave action nor storm surge effects. Therefore, the dry area is only influenced by aeolian processes resulting in sediment sorting when erosion takes place. Thus, it consist of only beach armouring as supply-limited condition in the Pe-model.

The influence of beach armouring is reflected on the decreased erosion. This is depicted in the resultant small composition of 250 and 350μm grain fractions and the large concentration of the 450 and 800μm grain fractions, which inhibit the erosion of the smaller grains on the layers from beneath the top-layer of the bed.

4.3 Sensitivity analysis of environmental conditions

Several environmental conditions were assessed, in order to get a change in magnitude of soil moisture and beach armouring (See section 3.3). In this section, the results of P_e [%] with varying magnitude of the supply-limited conditions are presented and compared to reference situation (the reference situation is the adapted base-case as it was implemented in AeoLiS, section 4.2.2).

4.3.1 Increased tidal range

The values in the tidal time series and the wave height series were doubled in order to theoretically simulate an increased tidal range. The results are described below.

Obtained P_e [%]

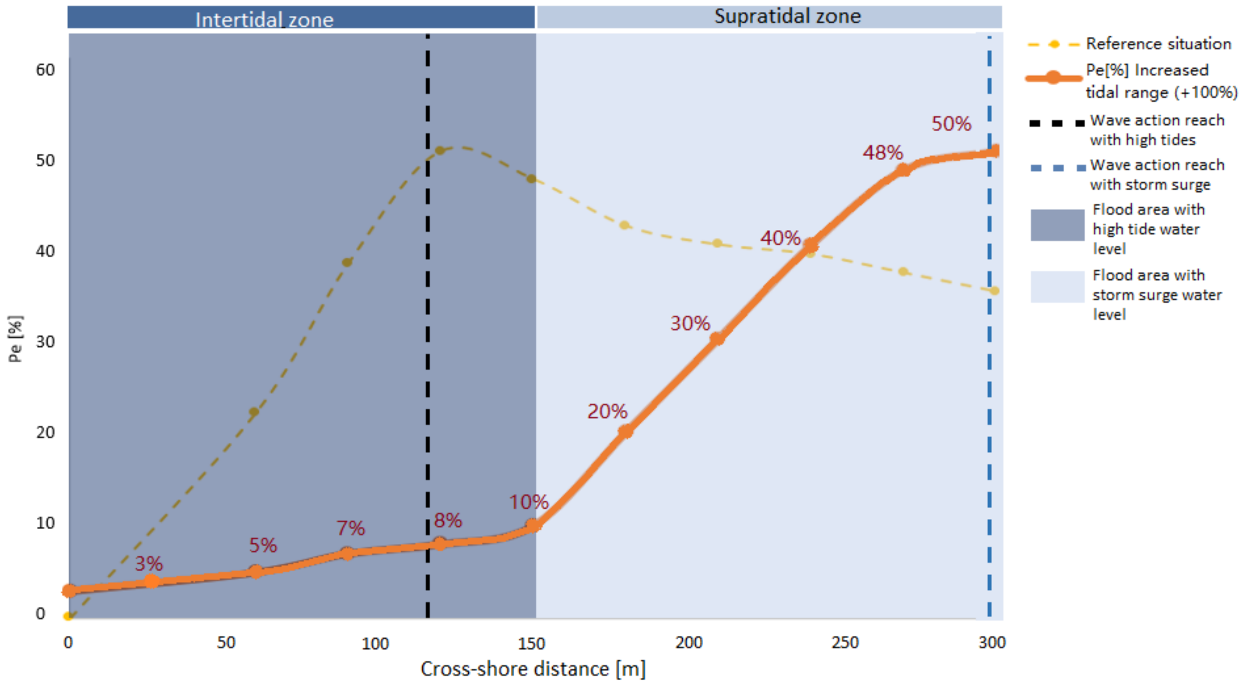


Figure 4.5: P_e spatial change with increased tidal range

From Figure 4.5 it can be observed that there is a lag in the behaviour of P_e [%] over the cross-shore. This change is due to the variation of the tidal range which increases the water levels and the wave action experienced on the beach.

Intertidal area

The increased tidal range case depicts an extended intertidal area that comes with a larger area getting flooded, which is due to the higher water levels experienced. Therefore, a decrease in P_e [%] compared to the reference situation is observed. In the intertidal area, soil moisture affects significantly the wind velocity threshold and acts as a dominant supply-limited condition. In addition, wave action covers a wider area, which results in frequent hydraulic mixing. This means that if sediment sorting leads to beach armouring during low tides, the latter will be undone by wave action. Thus, the grain-size distribution in the area doesn't vary greatly.

Supratidal area

The supratidal area in the increased tidal range shows a lag in space compared to the reference situation because of the extended intertidal area. This area is affected mostly by soil moisture as supply-limited condition, when storm surges flood it. During dry periods sediment sorting occurs, leading to beach armouring. However, storm surges come with extended wave action on the cross-shore, which undoes beach armouring. Therefore, P_e [%] shows an increase that is directly dependent on the decrease of soil moisture over the cross-shore.

Dry area

Due to the high influence of the marine processes, the whole cross-shore can be affected by soil moisture at any time. Therefore, it is never dry, which means it does not experience an area that is supply-limited purely by beach armouring.

4.3.2 Decreased tidal range

To theoretically simulate a decrease in the tidal range, the values in the tidal time series and the wave height series were halved. This led to a significant change decrease of P_e [%] over the cross-shore compared to the reference situation.

Obtained P_e [%]

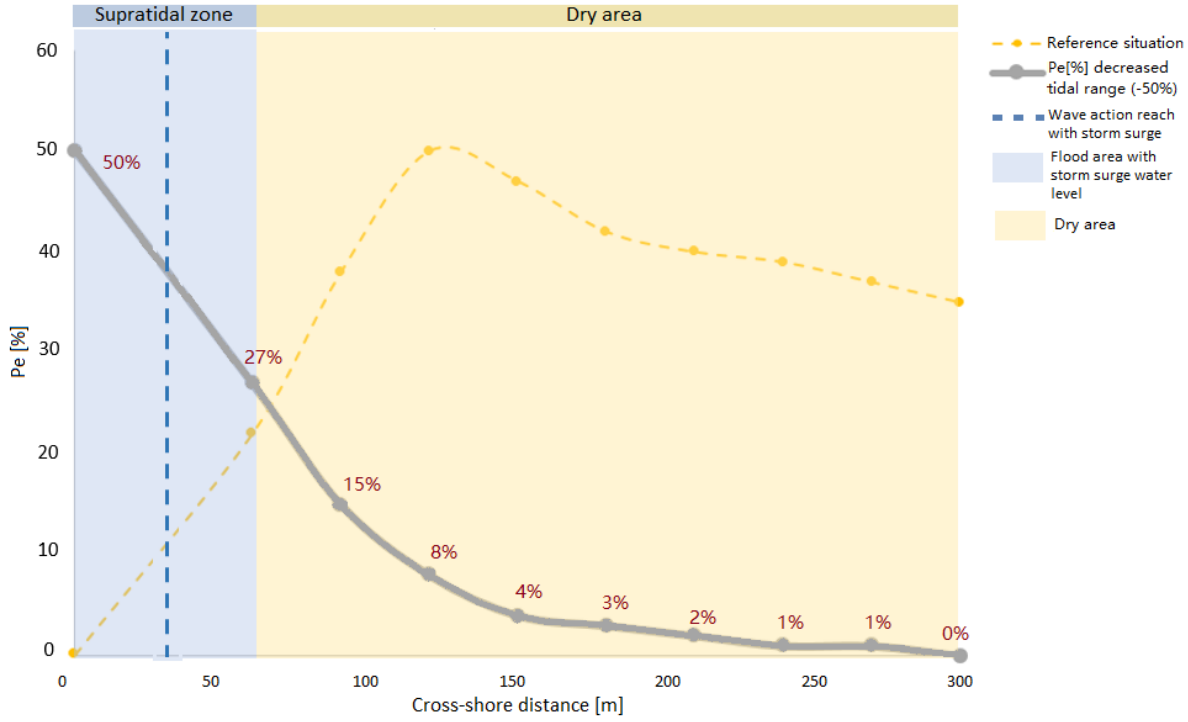


Figure 4.6: P_e spatial change with decreased tidal range

Sediment armouring occurs early on the cross-shore and is never undone by hydraulic mixing, which is due to the minimal impact of the marine processes in the simulation. As a result, the decreased tidal range depicts a decreasing P_e [%].

Intertidal area

The case with decreased tidal range depicts an unrealistic decrease in the water levels, which leads to an unrepresented intertidal area. This is due to the insignificant marine influence on the beach, where the water levels during the "regular tidal cycle" are not higher than the bed elevation.

Supratidal area

The decreased tidal range case depicts a very narrow supratidal area due to the low water levels. This area experiences aeolian erosion during the regular tide cycle, however it is restricted by soil moisture as supply-limited condition during storm surges. In addition, hydraulic mixing comes with the wave action from storm surges which accounts for the undoing of beach armouring in the first part of the shore. Therefore, there is sediment supply available for transport outside of storm surge events.

Dry area

The decreased tidal range case depicts a very extended zone with the characteristics of a dry area. The marine processes do not influence it, thus it experiences constant sediment sorting which results in a very wide area where beach armouring is formed. Due to the lack of hydraulic mixing, beach armouring in never undone which results in a visible decrease of P_e [%].

4.3.3 Stronger wind force

The values in the wind time series were increased by 50% of their initial magnitude in order to theoretically simulate an increased wind force. The resultant P_e [%] and grain-size distribution for this case is presented below.

Obtained grain-size distribution and P_e [%]

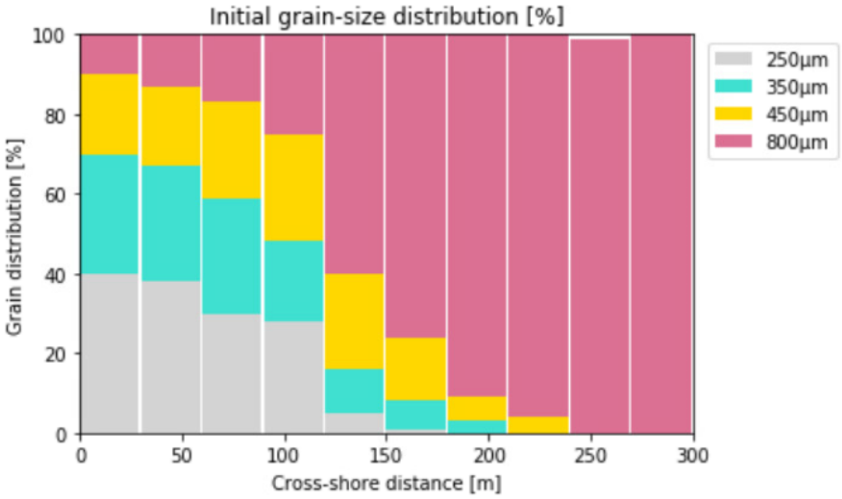


Figure 4.7: Initial grain-size distribution for increased wind force based on spin-up simulation

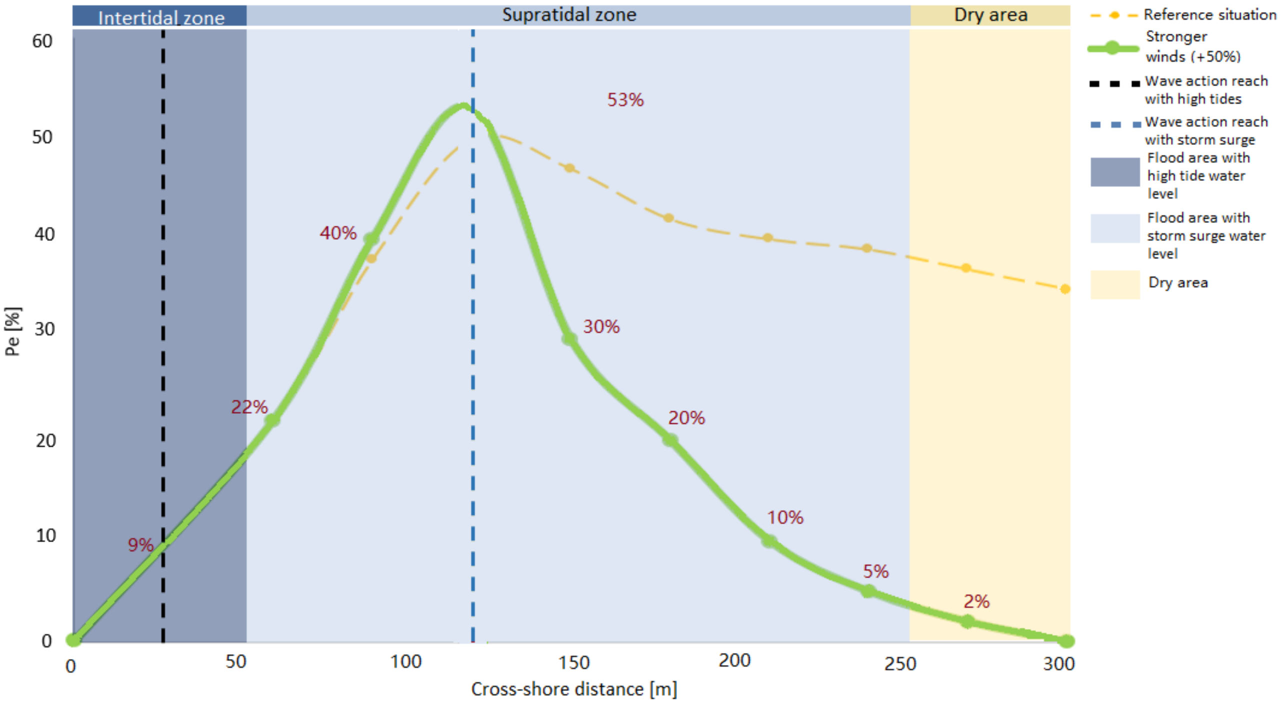


Figure 4.8: P_e spatial change with stronger wind force

The case that includes stronger wind depicts a rapid decrease in P_e [%]. This is due to the shear stress which comes with greater magnitude and produces sediment sorting at a faster rate. Thus, the appearance of non-erodible elements is accelerated and beach armouring becomes dominant as supply-limited conditions.

Intertidal area

The intertidal area for the stronger wind case presents a dominant supply-limitation by soil moisture. Even though there is hydraulic mixing in this area, it is subject to a slight change in the grain-size distribution. This is due to the increased erosion that is experienced with low tides, which results in sediment sorting at a minor scale (See Figure 4.7).

Supratidal area

The supratidal area depicts a strong influence of sediment sorting, which leads to the fast formation of beach armouring. Beach armouring is undone with storm surge events.

However, the wind is so strong that it leads to the appearance of non-erodible elements immediately after the area is dry. This results in very low values of P_e [%] which is controlled by beach armouring as supply-limited condition.

Dry area

In the dry area soil moisture has no influence as supply-limited condition. Due to the strong influence of the wind, which speeds sediment sorting, beach armouring plays an important role and limits sediment supply up to the point where erosion is minimal.

4.3.4 Decreased wind force

The values in the wind time series were decreased by 50% of their initial magnitude in order to theoretically simulate a decreased wind force. This variation shows a steady P_e [%] after the 100 m of the cross-shore.

Obtained grain-size distribution and P_e [%]

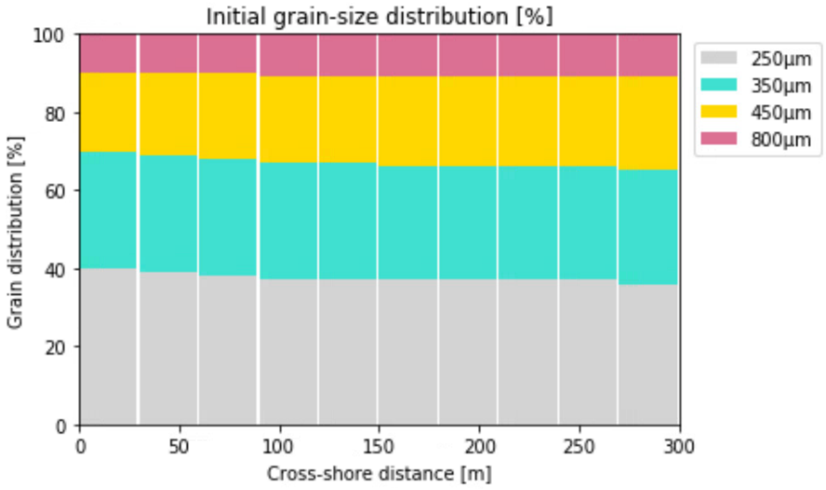


Figure 4.9: Initial grain-size distribution for decreased wind force based on spin-up simulation

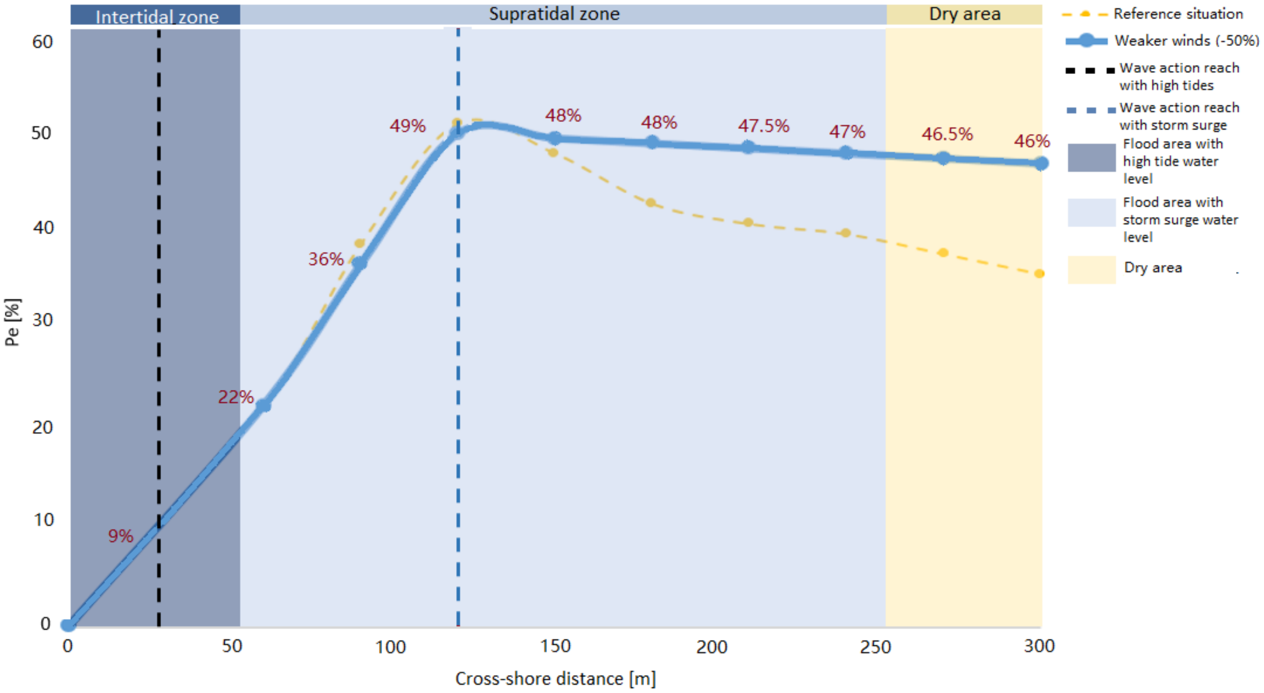


Figure 4.10: P_e spatial change with decreased wind force

The case with decreased wind produces less shear stress on the bed. Thus, sediment sorting occurs at a much slower rate compared to the reference situation, which gives a barely significant appearance of non-erodible elements on the bed. The result of this effect is a P_e [%] that decreases slowly due to a small impact of beach armouring as supply-limited condition.

Intertidal area

The case with the decreased wind has a dominant supply-limitation by soil moisture in the intertidal area. This zone presents a minor decreased erosion, which is experienced during low tides due to the weaker wind force to which it is subject (compared to the reference situation).

Supratidal area

The supratidal area experiences reduced shear stress on the bed which slows down sediment sorting, so beach armouring takes longer to form. Thus, beach armouring barely limits sediment supply. In addition, since marine processes are only present with storm surges, soil moisture does not limit supply greatly. Therefore, the obtained P_e [%] is the result of the wind force that blows constantly but not too hard for sediment sorting to lead to significant beach armouring.

Dry area

The dry area remains unsaturated, which means soil moisture does not affect sediment supply. However, due to the weak winds simulated, sediment sorting is greatly slowed down. Therefore, the dry area barely presents beach armouring as supply-limited condition.

4.3.5 Sea Level rise (+1 m)

A sea level rise of 1 m was simulated, which resulted in the same behaviour of the marine processes but with more cover on the cross-shore. Therefore, P_e [%] changed over the cross-shore compared to the reference situation.

Obtained P_e [%]

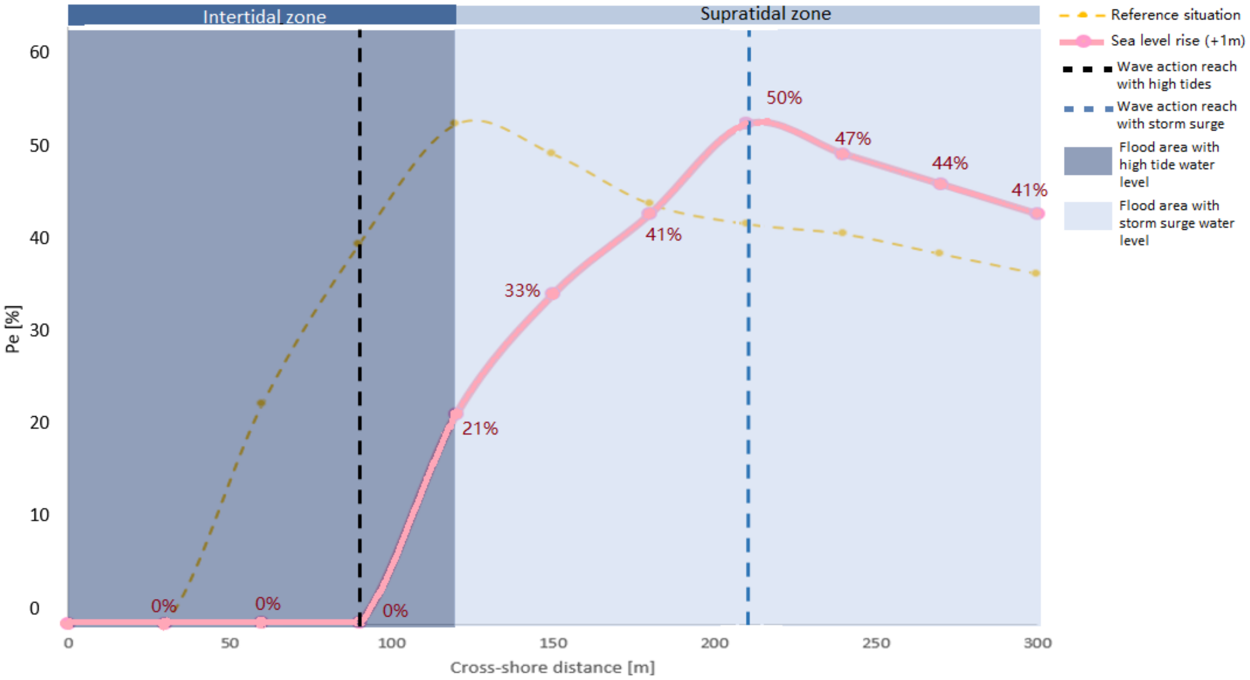


Figure 4.11: P_e spatial change based on SLR

The resultant P_e [%] for scenario with 1m sea level rise depicts the same behaviour as the reference situation, but lagged (See Figure 4.11). This lag can be explained due to the wider area that gets inundated with the regular tidal cycle. Marine processes have an important influence and dominate P_e [%].

Intertidal area

The intertidal area covers a wide area of the cross-shore and experiences soil moisture as the main supply-limited condition. This is due to the increased water levels that are experienced with 1 m of sea level rise. Because this area is constantly flooded, P_e [%] is significantly low in this area. In addition, the wave impact also affects a great part of the intertidal area. Thus, hydraulic mixing has a great influence by mixing the top-layer of the bed.

Supratidal area

The supratidal area is depicted further on the cross-shore (compared to the reference situation), which is due to the stronger influence that the marine processes have on the beach. In this area, both soil moisture and beach armouring play a role. Soil moisture is the dominant supply-limited condition in this area. On the other hand, due to the wider wave impact during storm surges, hydraulic mixing takes place. Therefore, beach armouring is undone and can only limit erosion for some time. Thus, the slight decrease in P_e [%] at the beginning at the supratidal area, which is becomes more pronounced were wave action doesn't affect.

Dry area

Due to the increased water levels, the beach does not include an area which stays dry through out the year. Therefore, this scenario does not include a supply-limitation purely based on beach armouring. If the beach was wider with the same slope or had a higher slope with higher bed elevation, then a dry area with supply limitation due to beach armouring would be developed.

4.3.6 Nourished sediment

Nourished coasts are man-influenced scenarios where usually sediment from the sea is taken and put on the shore, which results in a bed with varying grain-sizes. Nourished sediment usually include significant non-erodible elements (or elements with very high velocity threshold uth) such as shells and other coarse organic elements. The obtained P_e [%] and initial grain-size distribution used for this case are presented below.

Obtained grain-size distribution and P_e [%]

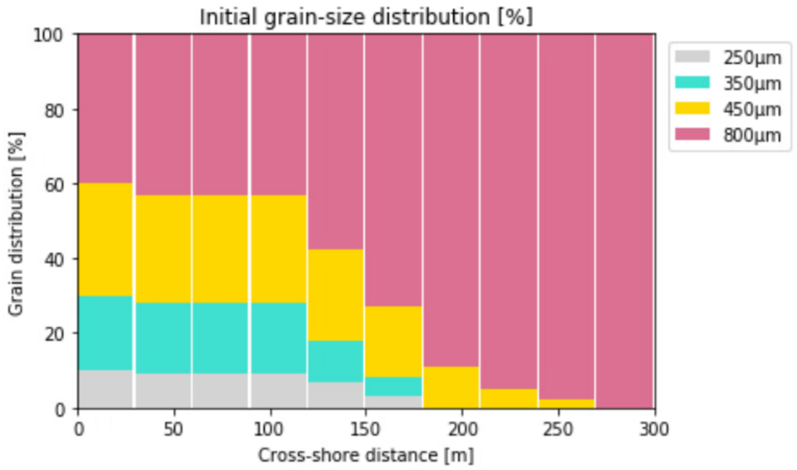


Figure 4.12: Initial grain-size distribution for the nourished sediment scenario

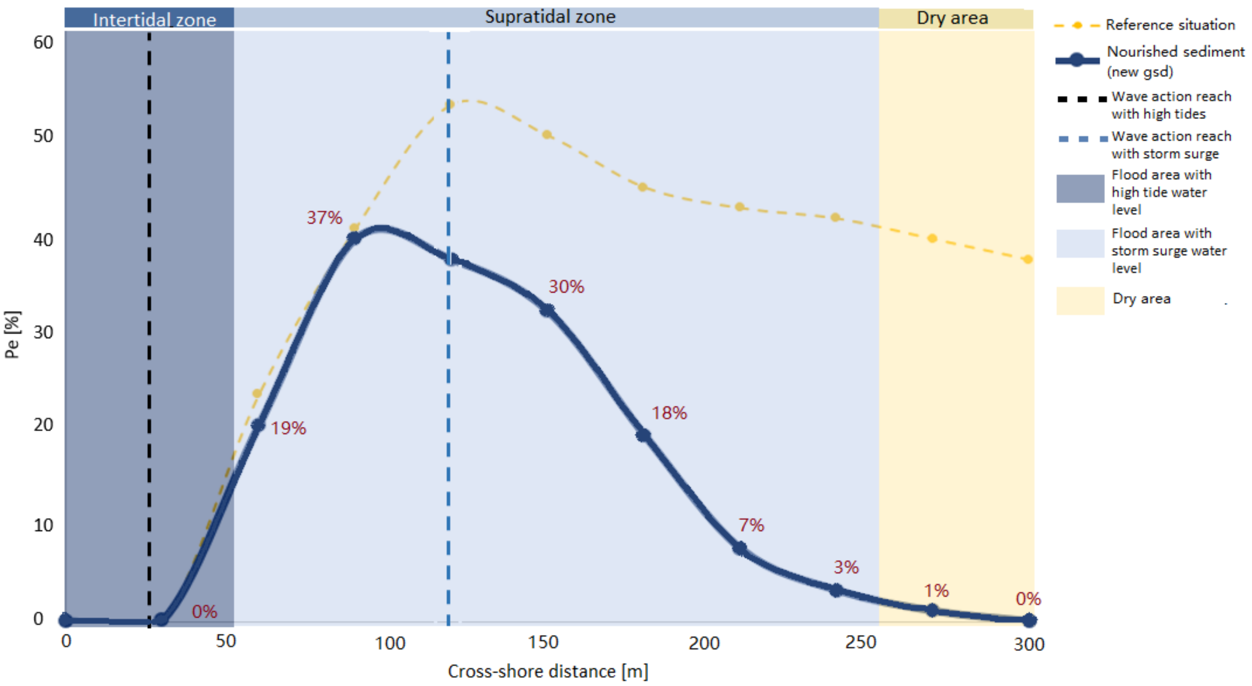


Figure 4.13: P_e spatial change based on nourished sediment

The obtained P_e [%] for the nourished sediment case presents a faster decrease compared to the reference situation, which is caused by the beach armouring that forms promptly on the cross-shore due to the initial high concentration of the big grains.

Intertidal area

The intertidal area in the nourished sediment scenario presents the same behaviour as the reference situation due to the same impact over the cross-shore of marine processes. Thus, the dominant supply-limited condition in this area is soil moisture.

P_e [%] is slightly reduced due to sediment sorting starting to lead in a small-scale to beach armouring with low tides. Hydraulic mixing plays an important role by constantly mixing and replenishing the sediment on the top-layer. The difference in erosion from the reference situation is due to the high concentration of big grain-sizes on the bed (See Figure 4.12).

Supratidal area

This dominance and the fast rate at which P_e [%] decays, is explained by the large amount of non-erodible elements which appear early on the cross-shore. During storm surges soil moisture increases the water level and saturates the sediment. These extreme events come with waves that compensate (on a small-scale) for the fast appearance of non-erodible elements by undoing beach armouring through hydraulic mixing. However, P_e [%] is still lower than the reference situation because the average grain-size distribution over the year consist on a greater portion of big grains on the top layer of the bed, which are harder to erode to do a higher wind velocity threshold uth.

Dry area

The dry area of the nourished sediment scenario depicts a complete supply limitation due to beach armouring. The latter appears early on the simulation and thus nullifies erosion of sediment. This is due to the increased wind velocity threshold of the bigger grain-sizes that appeared on the bed followed by sediment sorting.

5 Discussion

This section presents the discussion based on the analysis of the results. In addition they present the implications and the uncertainties that the assumptions made represent.

The discussion is divided in three parts, which include a section for DUBEVEG, AeoLiS and the result of joining both models.

5.1 DUBEVEG

Potential aeolian transport

In reality, the potential aeolian transport is the amount of sediment that is up for transportation due to the relation of the shear stress on the bed and the wind velocity threshold of the grains, without restriction on the availability of sediment. Nevertheless, for this projects its definition was considered as the sediment transport that would occur per m per year, if there are no bed forms, vegetation and taking into account the compound effect of the environmental conditions DUBEVEG includes. This definition was made to stay withing the scope of the project. However, it results in an over prediction of the sediment that can be eroded due to the diminished roughness on the bed (due to the missing bed forms ans vegetation). In addition, the potential aeolian transport represents a lower value than the actual available (for including a restriction for the available sediment supply). Thus, the importance of considering the correct definition.

Probabilities in DUBEVEG

The are four types of probabilities in DUBEVEG: probability of erosion of a bare cell, probability of erosion of a vegetated cell, probability of deposition of a bare cell and probability of deposition of a vegetated cell. They were reduced to two: a probability of erosion and a probability of deposition. Both probabilities were assumed equal for a bare and a vegetated cell to stay within the scope of the project, which doesn't include vegetation as supply-limited condition. In reality, dunes are formed under the presence of vegetation. This means means that the final bed patterns that resulted from the simulation were smaller, shorter and less than realistically speaking.

Assessment of P_e and P_d

The impact of P_e and P_d was evaluated after 15 years of morphological change, which represents a short period of time to represent a proper morphological change. However, the results are significant since they showed a trend which led to conclusion that P_e was the proper key parameter to focus on.

The impact of P_e and P_d observed was based on the aggregated behaviour of all the modules in DUBEVEG. This means that the initial P_e and P_d did not account for the final probability values that resulted in the morphological change observed. In reality and in the model, the probabilities change after being affected by the environmental conditions. Therefore, the impact of both probabilities as expected was based on the definition of the potential aeolian transport. This means the impact of the hydrodynamic processes was overlooked.

Importance of P_e

Based on previous literature about the model outline of DUBEVEG (Keijsers et al., 2016), the results obtained from the sensitivity analysis in Galiforni Silva et al. (2017) and the punctual conclusions from Van Dokkum (2019), P_e was expected to be the key parameter (over P_d) to include process-based supported supply-limited conditions . The results in section 4.1 corroborated the results from Van Dokkum (2019) and added the individual significance of the probabilities and showed a dominance of P_e (in accordance to Galiforni Silva et al. (2017)) over the bed patterns created. With bigger P_e values the dunes formed were longer, higher, more and were presented in a wider area of the beach, which is in accordance to Van Dokkum (2019).

The impact of P_e was as expected following its physical definition in DUBEVEG, that states it represents the potential sediment supply to be entrained for transport and it is characterized by the environmental conditions. However, in reality the environmental conditions are not included in the potential aeolian sediment supply but in the available sediment supply.

5.2 AeoLiS

Sediment transport

The main challenge encountered in Aeolis (Hoonhout and Vries, 2016) was to account for the erosion, which together with deposition, occurs in all cells and in all directions. This means their obtainment was not explicit. Therefore, a methodology was developed to account for the erosion based on the change of elevation in a single cell, which works if there is no deposition coming from neighbour cells in between time-steps and assuming all the eroded sediment comes from that same cell.

This scenario is not realistic because it described an isolated cell which is not influenced by any neighbour cells. In reality, there are no isolated cells in a beach. However, this made it possible to account for the experienced bed level change based on the erosion presented on the cell. The inclusion of surrounding cells in the scenario would add uncertainty to the results, due to possible external deposition that would alter the change in bed elevation of the cell whose erosion is evaluated.

In addition, the sediment transport flux was accounted for as the equilibrium sediment flux, where the adaptation time (the time it takes for the sediment on the bed to react and get eroded) was not taken into account. This resulted in a higher value for the total sediment flux over a year, which is directly related to the obtained P_e [%]. However, the sediment flux including the adaptation time was evaluated and the results did not account properly for the erosive behaviour when assessing a single cell. Therefore, the equilibrium sediment flux was preferred.

Wind direction

A unidirectional wind was simulated, which is not realistic and leads to an underestimation of the erosion that can occur in a cell. However, several authors (Kroy et al., 2002; Schatz and Herrmann, 2005) have spoken about the flow separation in the lee side of dunes which limits the region of recirculating flow behind the brink. This results in a flow velocity which is low compared to the velocity threshold. Therefore, this effect limits erosion coming from 0 to 180 °in the nautical direction as in was implemented in AeoLiS.

Calibration of P_e

Aeolis (Hoonhout and Vries, 2016) includes soil moisture and beach armouring as supply-limited conditions, which are the scope of the project. In reality, these are not the only supply-limited conditions on a coastal environment. Thus, the sediment transported calculated is overestimated.

To account for the overestimation of the sediment transported, the calibration of P_e [%] was based in DUBEVEG. It was assumed that the default $P_e = 0.5$ calibrated by Keijsers et al. (2016) corresponds to the P_e of the supratidal area, where all the supply-limited conditions assessed have an influence. Since two supply-limited conditions were accounted for in the Pe-model, this assessment only increases the applicability of DUBEVEG in scenarios with dominant soil moisture or beach armouring supply-limitation

5.3 DUBEVEG and AeoLiS

Contrasting nature of the models

The link between DUBEVEG and AeoLiS was not straight forward because of the difference in the nature of each model. The main differences between them are: the scale of the processes they simulate (DUBEVEG: large-scale morphological changes, AeoLiS: small-scale aeolian sediment transport), the time scale of the processes they simulate (DUBEVEG: represents morphologic changes of tens to hundreds of years, AeoLiS: simulates aeolian sediment transport for years but can't be calculated for time-steps bigger than 1 hour) and the approach of each model (DUBEVEG: probabilistic cellular automata model, AeoLiS: process-based numerical model). The major implication of the contrasting nature of the models was the development of an academic methodology which does not completely represent reality (See section 5.1 and 5.2).

Obtained P_e

The obtained P_e [%] from the Pe-model varies in time and space, which represents a realistic behaviour (Bauer et al., 2009). However, in DUBEVEG P_e is spatially homogeneous and does not vary in time. Therefore, the cross-shore was divided in transects where the obtained P_e [%] was averaged to depict a realistic cross-shore variation. In addition,

P_e [%] was obtained as the average of 26 two-week periods to match the hydrodynamic module update in DUBEVEG. The 2 week-periods simulate a complete neap-spring cycle, which is the main reason for the time variation of P_e due to the different environmental conditions presented per cycle.

The defined steps to obtain P_e show that (under the previously defined assumptions) it is possible to link the output of AeoLiS with DUBEVEG, and its implementation is expected to lead to a more accurate length and height of the bed patterns developed in DUBEVEG.

Sensitivity analysis of environmental conditions

In reality and in the results in section 4.3, P_e [%] varies in time and space because it is affected by supply-limited conditions, which are influenced by environmental conditions that change in magnitude and time of occurrence (tidal range, wave impact, wind direction and force). The extreme variation of the environmental conditions were extreme and unrealistic. However, the results presented in section 4 show the importance of the influence of each environmental condition assessed on supply-limitation by soil moisture and beach armouring, and how their magnitude can have a strong impact on the obtained P_e [%]. Their meaning is described below.

Increased tidal range

The increased tidal range scenario presented a P_e with lag in space (compared to the reference situation). This behaviour was anticipated due to the expansion of the marine processes on the beach that it represented. However, the results are not completely realistic because an increase of 50% on the current conditions is too extreme. However, this variation showed a realistic impact of soil moisture on the beach and a correct impact the hydraulic mixing, which maintain a low erosion over the simulation.

In addition, this increased tidal range would probably also come with increased wind forces which might increase the averaged P_e after the 10 years of simulation. However, this scenario was not assessed.

Decreased tidal range

This variation depicts a strong influence of beach armouring, which was expected due to the barely significant influence of the regular water level and wave action on the shore. However, this case shows a severe decrease in the tidal range which is not realistic nor expected in places where dunes are important as flood defenses.

In addition, P_e in Figure 4.6 shows a beach armouring completely formed and capable reducing the erosion at the minimum. This would only be the case is the beach is not influenced by other factors (e.g human intervention) during at least 10 years, which is hardly realistic. Therefore, P_e is underestimated.

Stronger wind force

The observed decreasing behavior of P_e was expected since we consider the 10 years of simulation to which the case was subject to. Thus, the results are showing a case where beach armouring is already formed and where it is able to prevent the erosion of the smaller grains on the layers from beneath. Nevertheless, the results are not completely realistic because the initial grain-size distribution was purely academic and the wind that was simulated showed an extreme wind scenario which is hard to be experience during the whole year (these strong winds were only experienced once or twice a year during very heavy storms).

In addition, this behavior corresponds only to the end of the simulation. On the other hand, the "expected" behavior where P_e increases greatly due to stronger wind, is experienced at the beginning of the simulation. This increase of P_e is experienced more explicitly in the first months of simulation where the 250, 350 and 450μm grains get easily eroded. The initial content of 800μm grain fractions on the bed was 10%, so until this bigger grain size was dominant on the top-layer of the bed (so before there was beach armouring), P_e was significantly higher. However, due to the accelerated sediment sorting which comes with the stronger wind, beach armouring became dominant early on the simulation (after the first storm surge). Therefore, the increased P_e came early on the simulation (when sediment sorting was occurring) and it quickly led to the appearance of beach armouring, which decreased the P_e from then on.

Weaker wind force

The resultant P_e shows a slight decrease from the peak on-wards, which was expected because of the lack of soil moisture beach armouring as supply-limited conditions. This means that the observed erosion is purely due to the wind, that even though is low, consists of no restrictions in sediment supply. Beach armouring is not present because the decreased wind did not allow for its formation by the end of the spin-up simulation. However, this doesn't necessarily mean that there will not be any beach armouring forming, but that under these wind conditions it will take longer to form (due to the slowed down sediment sorting). In addition, armouring could form faster under the same wind regime if the grain-size distribution was to include a larger composition of bigger-grain sizes. Thus, the resultant P_e is also influenced by the initial grain-size distribution.

Sea level rise (+1 m)

This case shows a very similar behaviour of P_e as the reference situation but lagged, which is in accordance to the expectations. This is because the magnitude of the marine processes is the same, but with a +1 m increase in the overall water levels. This case shows the increased importance of soil moisture as inhibitor of erosion with sea level rise. Although sea level rise is a problem that manifests in reality, a 1 m increase does not depict a realistic but an extreme case which would take more than 15 years to occur.

However, this case shows the dominant behaviour marine processes have on the beach with an increase in water level. Also, there would be no sediment supply for dune development and neither space for them to develop, putting dunes at risk.

Nourished sediment

The results depicted the heavy influence that big elements like shells have on supply-limitation, which decreases greatly the erosion by sheltering the smaller grains below the top-layer of the bed. The decrease of P_e came earlier on the cross-shore and on the simulation than expected (in space and time) in the area that experiences hydraulic mixing, where the decrease was still very significant. This can be explained by the fast formation of beach armouring, which happened even though sediment sorting occurred at the same rate as on the reference situation. Nevertheless, this case is hard to be experienced in reality because it used a non-typical initial grain-size distribution. It could only be encountered in scenarios where man has altered significantly the coastal environment with very coarse material.

6 Conclusions

The overall project resulted in the definition of steps to get a probability of erosion from AeoLiS that can be related in DUBEVEG. In addition, the importance of the obtained P_e and the significant change it had based on the influence of varying supply-limited conditions were determined.

The final conclusions are presented below, based on the resolution of the three research questions presented initially.

6.1 Research question 1

How does the variation of two key parameters, namely the probability of erosion and deposition (P_e and P_d), affect the nature and magnitude of the morphological change in DUBEVEG?

The results obtained showed that both P_e and P_d affect the resultant morphology in DUBEVEG. However, P_e showed to have a stronger influence in the bed patterns formed over time by taking the lead role in the definition of the height, length and number of dunes formed. A relation between the potential aeolian sediment supply and the actual aeolian sediment supply was found in P_e. Thus, P_e was determined to be the adequate key parameter to support supply-limited conditions due to the influence it has on sediment supply. P_d showed a dependent behaviour on P_e, because it determines the distribution of the eroded sediment.

The influence was identified when accounting for the aggregated results in DUBEVEG, which means that the conclusions regarding the behaviour of P_e and P_d were reached taking into account the hydrodynamic and aeolian modules. Nevertheless, the compound results depict a difference which was explained by the varying values used for P_e and P_d.

6.2 Research question 2

How can the chosen key parameter in DUBEVEG be supported with AeoLiS to include soil moisture and beach armouring as supply-limited conditions, and what is the resultant P_e?

A methodology was developed to enable the support of P_e in DUBEVEG form AeoLiS. The steps to determine a P_e [%] from AeoLiS consist on relating the change in bed elevation to the probability of erosion in a single cell. This relation is possible because all the factors that implied deposition on that cell were outcast. The latter was achieved by implementing a unidirectional wind and by accounting only for the eroded sediment coming from the single cell.

Finally, this methodology resulted in a single year value for P_e [%], which varies 10 times over a 300 m cross-shore. The spatial variation of P_e [%] was clearly defined by three areas: the intertidal, the supratidal and the dry area. These lasts experienced supply limitation of soil moisture and beach armouring in different magnitudes.

Consequently, the intertidal area resulted in a supply-limitation dominated by soil moisture. Soil moisture proved to have a significant decrease in P_e. However, it was usually accompanied by wave action which led to a slightly higher P_e over a year due to hydraulic mixing. The supratidal area was influenced by both supply-limited conditions assessed without dominance observed from either. This area depicted the peak P_e in all the situations assessed. Finally, the dry area was dominated by beach armouring as supply-limited condition. The latter showed a very important decrease in P_e which could lead to nullified erosion over time.

6.3 Research question 3

How does the variation of coastal environmental conditions affect supply limitations and P_e [%]?

Following the defined steps, a sensitivity analysis was made to determine the change of P_e [%] based on the influence the variation of the environmental conditions had on soil moisture and beach armouring and their decreasing effect on erosion. It was concluded that the impact of soil moisture and beach armouring on P_e [%] was very similar in all cases, but with a significant time or/and spatial change in the final, which depends on the environmental condition varied.

P_e [%] was observed to be heavily influenced by the tidal cycle. It comes with an increased wind velocity threshold for the sediment, which limits sediment supply due to soil moisture. In addition, the tidal cycle involves wave action which results in hydraulic mixing when the waves are higher than the bed elevation. P_e [%] is also strongly dependent on the grain-size distribution of the bed because it allows sediment sorting which leads to beach armouring. Beach armouring on the top-layer proved to decrease P_e [%] significantly, specially in areas which are less influenced by marine processes. However, it can be undone by hydraulic mixing caused by wave action.

7 Recommendations

This section includes a series of suggestions that would improve the final results of this thesis, as they were identified throughout the project. They also serve to point out a path to extend the research.

Related to the use of DUBEVEG:

- It is suggested to determine a more quantitative approach to compare the differences found with the variation of the probabilities. This to have more accurate results to determine impact of the varied probabilities.

Related to the use of AeoLiS:

- Look into the effect of the adaptation time scale T included in the advection scheme that defines the sediment transport in AeoLiS, and implement it to obtain a more realistic sediment flux.
- Try other wind approaches to include realistic wind behaviours and to improve the accuracy of the volume of sediment eroded.
- Work on the inclusion of characteristics that represent a realistic cases over a long period of time. This to include a non-academic grain-size distribution, a more accurate depth of disturbance ration between the bed elevation and the wave height and a sustained definition of the soil drying adaptation time scale.

General suggestions:

- It is suggested to expand further the applicability of DUBEVEG by including a wider range of supply-limited conditions.
- To determine the significance of including a P_e which can vary in time or/and space in DUBEVEG.
- To determine if the inclusion of a process-based supported P_d would further improve the obtained bed patterns in DUBEVEG.

References

T. Aagaard. Sediment supply to beaches: Cross-shore sand transport on the lower shoreface. *Geophys. Res. Earth Surf.*, 119:913–926, 2014.

Andreas C.W. Baas. Chaos, fractals and self-organization in coastal geomorphology: Simulating dune landscapes in vegetated environments. *Geomorphology*, 48(1-3):309–328, 2002.

Andreas C.W. Baas. Complex systems in aeolian geomorphology. *Geomorphology*, 91 (3-4):311–331, 2007.

R.A. Bagnold. The movement of desert sand. *Nature*, 135(3421):881–882, 1935.

R.A. Bagnold. Physical aspects of dry deserts. *Biology of Deserts*, pages 7–12, 1954.

B. O. Bauer and R. G. D. Davidson-Arnott. A general framework for modelling sediement supply to coastal dunes including wind angle, beach geometry, and fetch effects. *Geomorphology*, 49:89–108, 2003.

B. O. Bauer, R. G. D. Davidson-Arnott, P. A. Hesp, S. L. Namikas, J. Ollerhead, and I. J. Walk. Aeolian sediment transport on a beach:surface moisture, wind fetch, and mean transport. *Geomorphology*, 105:106–116, 2009.

B.O Bauer, R. Davidson-Arnott, K.F. Nordstrom, J. Ollerhead, and N.L. Jackson. Indeterminacy in aeolian sediment transport across beaches. *Journal of Coastal Research*, 12:641–653, 1996.

P. Belly, K. Abdel-Latif, and Coastal Engineering Research Center(U.S.). Sand movement by wind. *Technical memorandum: Coastal Engineering Research Center*, (1):320–349, 1964.

F. Berkes and C. Folke. Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience. *Cambridge University Press*, page 459, 1998.

R. Buckley. The effect of sparse vegetation on the transport of dune sand by wind. *Nature*, 325:426–428, 1987.

Adri Buishand, Rudmer Jilderda, and Janet Wijngaard. Regional differences in the extreme rainfall climatology in the Netherlands. KNMI, 2010.

Christopher Crossland, Dan Baird, Jean-Paul Ducrotoy, Han Lindeboom, Robert Buddemeier, William Dennison, Bruce Maxwell, Stephen Smith, and Dennis Swaney. The coastal zone — a domain of global interactions. pages 1–37, 03 2006.

Kremer H.H.-Lindeboom H.J. Marshall Crossland J.I. Le Tissier M.D.A. Crossland, C.J. Coastal fluxes in the antropocene: The land–ocean interactions in the coastal zone. *Springer-Verlag*, page 232, 2005.

Poppe De Boer. Intertidal sediments: composition and structure. *Intertidal Deposits: River Mouths, Tidal Flats and Coastal Lagoons*, pages 345–361, 01 1998.

S. de Vries, H.N. Southgate, W.Kanning, and R.Ranasingheac. Dune behavior and aeolian transport on decadal timescales. *Coastal Engineering*, 67:41–53, 2012.

S. de Vries, J.S.M. van Thiel de Vries, L.C. van Rijn, S.M. Arens, and R. Ranasinghe. Aeolian sediment transport in limited situations. *Aeolian Research*, pages 75–85, 2014.

S. C. Du Pont. Dune morphodynamics. *Comptes Rendus Physique*, 16:118–138, 2015.

Filipe Galiforni Silva, Kathelijne M. Wijnberg, Alma V. de Groot, and Suzanne J.M.H. Hulscher. On the importance of tidal inlet processes for coastal dune development. *Proceedings Coastal Dynamics*, pages 1131–1141, 2017.

Filipe Galiforni Silva, Kathelijne M. Wijnberg, Alma V. de Groot, and Suzanne J.M.H. Hulscher. The effects of beach width variability on coastal dune development at decadal scales. *Geomorphology*, 329:58–69, 2019.

Bas M. Hoonhout and Sierd de Vries. A process-based model for aeolian sediment transport and spatiotemporal varying sediment availability. *Journal of Geophysical Research: Earth Surface*, 121(8):1555–1575, 2016.

T.S. Hopkins, D. Bailly, R. Elmgren, G. Glegg, A. Sandberg, and J.G. Stottrup. A systems approach framework for the transition to sustainable development: potential value based on coastal experiments. *Ecology and Society*, 39:39, 2012.

D. W. T. Jackson and J. A. G. Cooper. Beach fetch distance and aeolian sediment transport. *Sedimentology*, 46:517–522, 1999.

JGS Keijsers, A Poortinga, MJPM Riksen, and J Maroulis. Spatio-temporal variability in accretion and erosion of coastal foredunes in the netherlands:regional climate and local topography. 2014.

J.G.S. Keijsers, A.V. de Groot, and M.J.P.M. Riksen. Modeling the biogeomorphic evolution of coastal dunes. *Journal of Geophysical Research Earth Surface*, pages 1–21, 2016.

G. Kocurek and N. Lancaster. Aeolian system sediment state: Theory and mojave desert kelso dune field example. *Sedimentology*, 46(3):505–515, 1999.

Klaus Kroy, Gerd Sauermann, and Hans J. Herrmann. Minimal model for sand dunes. *Physical Review Letters*, 88(5), 2002.

Y. Kuriyama, N. Mochizuki, and T. Nakashima. Influence of vegetation on aeolian sand transport rate from a backshore to a foredune at Hasaki, Japan. *Sedimentology*, 52(5): 1123–1132, 2005.

N Lancaster. Aeolian processes. *Earth Systems and Environmental Sciences*, 2014.

N. Lancaster and Andreas Baas. Influence of vegetation cover on sand transport by wind. *Earth Surface Processes Landforms*, 23:69–82, 1998.

D. W. T. Jackson Lynch, K. and J. A. G. Coop. Aeolian fetch distance and secondary airflow effects: The influence of micro-scalevariables on meso-scale foredune development. *Earth Surface Processes Landforms*, 33(7):991–1005, 2008.

MEA. Ecosystems and Human Well-Being: Synthesis. *Millennium Ecosystem Assessment*, page 137, 2005.

NG National Geographic. Dune. 03 2020. URL `https://www.nationalgeographic.org/encyclopedia/dune/`.

R.J. Nicholls, P.P. Wong, V. Burkett, J. Codignotto, J. Hay, R. Mc. Lean, and Y. Saito. Coastal systems and low-lying areas. *Climate Change 2007: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, pages 315–356, 2007.

W. Nickling and R. Davidson-Arnott. Aeolian sediment transport on beaches and coastal sand dunes. *Proceedings of the Symposium on Coastal Sand Dunes, National Research Council of Canada*, pages 1–35, 1990.

Neuman C.M. Nickling W.G. Aeolian sediment transport. *Geomorphology of Desert Environments*, pages 517–555, 2009.

K.F. Nordstrom and Jack A. Puleo. Effects of beach raking and sand fences on dune dimensions and morphology. *Geomorphology*, 179:106–115, 2012.

M. E. B. Puijenbroek. Dunes above and beyond. the interaction between ecological and geomorpholical process during early dune development. *Wageningen University, Wageningen, The Netherlands*, 2017.

V. Schatz and H. Herrmann. Flow separation in the lee of transverse dunes. 02 2005.

Douglas Sherman and Bailiang Li. Predicting aeolian sand transport rates: A reevaluation of models. *Aeolian Research*, 2012.

Douglas J. Sherman, Derek W. T. Jackson, Steven L. Namikas, and Jinkang Wang. Wind-blown sand on beaches: an evaluation of models. 1997.

A.P. Short and P.A. Hesp. Wave, Beach and Dune interactions in South Eastern Australia. *Marine Geology*, 48:259–284, 1982.

Filipe Galiforni Silva, Kathelijne M. Wijnberg, Alma V. de Groot, and Suzanne J.M.H. Hulscher. The influence of groundwater depth on coastal dune development at sand flats close to inlets. *Ocean Dynamics*, 68(7):885–897, 2018.

Jan Willem Van Dokkum. The applicability of the cellular automata model DUBEVEG on an anthropogenic shore. 2019.

Sierd Vries, Mitchell Harley, Matthieu De Schipper, and Gerben Ruessink. Dune growth due to aeolian sediment transport and the role of the beach and intertidal zone. 07 2015.

R. Wasson and P. Nanninga. Estimating wind transport of sand o vegetated surfaces. *Earth Surface Processes Landforms*, 11:505–514, 1986.

B. Werner. Eolian dunes: Computer simulations and attractor interpretation. *Geology*, 23(12):1107–1110, 1995.

I.J. Losada J.-P. Gattuso J. Hinkel A. Khattabi K.L. McInnes Y. Saito Wong, P.P. and A. Sallenge. Coastal systems and low-lying areas. *Climate Change 2014: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, pages 361–409, 2014.

Wenyan Zhang, Ralf Schneider, Jakob Kolb, Tim Teichmann, Joanna Dudzinska-Nowak, Jan Harff, and Till Hanebuth. Land–sea interaction and morphogenesis of coastal foredunes — a modeling case study from the southern baltic sea coast. *Coastal Engineering*, 99, 04 2015. doi: 10.1016/j.coastaleng.2015.03.005.