The potential of dune vegetation during storm conditions

Assessing the applicability of XBeach in dune rehabilitation projects

E.J. Heineke

THE POTENTIAL OF DUNE VEGETATION DURING STORM CONDITIONS

by

Esther Heineke

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Delft University of Technology

Supervisors: Prof. dr. ir. S. G. J. Aarninkhof
Ir. O. Nieuwenhuis
Ir. T. Leijnse
Ir. B. Van Westen
Prof dr. ir. A. J. H. M. Reniers

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ABSTRACT

Coastal protection is required to keep coastal areas protected during storm conditions. Coastal dunes are a natural defense against flooding and erosion from the sea against storms. Many insights have been obtained regarding the positive effects of coastal dune vegetation on dune formation and growth in the past. Several recent studies have demonstrated the ability of both aboveground and belowground dune vegetation to reduce dune erosion during storms.

However, the impacts of dune vegetation during collision regime storm conditions are not taken into consideration in morphological numerical modeling. Consequently, it is unclear how to evaluate vegetation impacts during design assessments. Therefore, the goal of this research is to investigate the potential effect of dune vegetation on dune erosion during collision regime storm conditions and subsequently link this with dune rehabilitation projects. This research is divided into two parts.

In Part I, the capability of the numerical model XBeach to simulate the potential effects of dune vegetation during the collision regime is investigated. Four vegetation approaches are identified in the model, which could possibly represent different dune vegetation effects. Using beach-dune profiles and erosion volumes obtained from two wave flume experiments, the performance and sensitivity of the vegetation approaches are tested in XBeach. Thereby, a distinction is made between the effect of aboveground vegetation: hydrodynamic altering and belowground vegetation: soil stabilization. The model results show that XBeach is capable of simulating dune erosion with vegetation during collision regime storm conditions. This can be primarily attributed to the increase of the critical slope in the avalanching module. This approach represents the soil stabilization effects of belowground vegetation. The application of the root model was added for even better simulations. This approach accounts for the additional root cohesion provided by belowground vegetation by increasing the critical velocity for sediment pickup. The values to be used for both vegetation approaches could not be defined systematically yet due to the small number of experiments assessed and little research found in the literature. It is recommended to obtain more information about the effect of dune vegetation on the stabilizing effects and the critical slope for avalanching. The application of a higher roughness value and the vegetation module, which both represent aboveground vegetation by altering the hydrodynamics, have shown to contribute insignificantly to erosion reduction in the examined cases.

In Part II, the belowground soil stabilization approaches are applied in a case study to give a first indication of the applicability of XBeach at large-scale and in dune rehabilitation projects. An XBeach model of Beira, Mozambique was set up. A higher critical slope demonstrated profile evolution and erosion reduction in line with observations in the literature. During wave impact, the avalanching module is the most suitable approach to account for the erosion-reducing effect of belowground vegetation. The root model appears to be a more appropriate strategy for accounting for belowground vegetation during milder conditions and shorter storm duration. It was proven that XBeach has very good potential to evaluate the effectiveness of dune vegetation in the design phase. The case study illustrates that vegetation will significantly increase the erosion resistance of the flood dunes. The dunes with vegetation can handle an additional 20-30 centimeters design water level or 0.5-0.8 meter storm wave height without breaching compared to the same dune without vegetation. The design with vegetation has shown to be more robust. However,

the approaches are based on different assumptions and limitations and therefore the results should be considered carefully. It is strongly advised to conduct more research in this relatively new study area.

This study investigates and proposes a method for quantifying the advantages of vegetation on dune erosion reduction. The relevance and added value of mature and robust dune vegetation for a resilient coastal dune system and protection against erosion and floods are confirmed. As a result, the incorporation of vegetation in dune rehabilitation projects is promoted.

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LIST OF ACRONYMS

1D	One-dimensional
A	Aboveground vegetation
AB	Both above- and belowground vegetation
AMF	Arbuscalur Mycorrhizal Funghi
B	Belowground vegetation
BSS	Brier Skill Score
CGI	Coastal Green Infrastructure
CPP	Coastal Protection Project
RHDHV	Royal HaskoningDHV
MHW	Mean High Water
MLW	Mean Low Water
MSL	Mean Sea Level
VF	Vegetation Factor
WiBo	Witteveen+Bos

1 INTRODUCTION

1.1 BACKGROUND

Vegetation in coastal dunes has the potential to reduce erosion and flood risk. Firstly, vegetation stimulates the growth and formation of natural dunes with a flood protection function. Secondly, the presence of vegetation in dunes has been shown to significantly reduce dune erosion during storm conditions.

Due to climate change and human activities, an increasing number of dune systems are degrading. Those dune systems need rehabilitation to fulfill their flood protection function during storm conditions. Vegetation is often recommended for implementation in dune rehabilitation projects. Firstly to enhance the erosion resistance of a dune system and secondly to reduce the chance of breaching by erosion during storm events.

Nonetheless, the potential effect of vegetation is often not taken into account during dune rehabilitation projects. There are several reasons for this. Firstly, it is relatively a new research area compared to the effect of vegetation on the formation of dunes. Consequently, there is a scarcity of quantitative data on the role of vegetation in erosion and flood protection. In addition, in numerical models of beach and dune morphodynamics, the role of vegetation under the collision regime is not taken into account. At the moment, it is unclear whether numerical models could accurately reproduce the potential effects. No calculation methods are available to assess dunes with vegetation during dune rehabilitation projects.

1.2 RESEARCH OBJECTIVE AND QUESTIONS

The objective of this research is to investigate the potential effect of dune vegetation on dune erosion during collision regime storm conditions and link this effect with dune rehabilitation projects. The research is divided into two sections:

- Simulate the potential impact of dune vegetation during collision storm regime conditions in the numerical model XBeach
- Apply the potential impact of dune vegetation during collision storm regime conditions to a large scale case study

To achieve the goal of this research, the following sub-questions are defined:

1. What are the important processes and effects of dunes and dune vegetation during collision storm conditions and how could this be quantified?
2. Is the numerical model XBeach capable of simulating the effects of vegetation during the collision regime?
    - Which different approaches could be identified to represent vegetation processes in the numerical model XBeach?
    - What is the sensitivity of the identified vegetation approaches and their parameters in XBeach?

3. How could the knowledge regarding dune vegetation during storm conditions be applied in real dune rehabilitation projects?
    - What is the effect and sensitivity of associated processes of dune vegetation considering different dimensions, wave heights, and storm durations in XBeach?
    - What could be the effect of mature, healthy belowground vegetation concerning future climate?

1.3 STARTING POINTS

Considering the complexity of this subject, as well as the restricted time allowed for completing a Master's Thesis, this research has some starting points which are summarized below.

- Study area is the dune area.
- The one-dimensional (1D) representation of dunes is considered.
- Focus is on cross-shore direction, the longshore direction and variations are neglected.
- Conditions studied are storm conditions, with a focus on the collision regime.
- Emphasis is on the effect of vegetation on the morphological response of dunes. This refers to the evolution of the dune profile and dune erosion volume.
- Vegetation considered is full-grown, mature vegetation.
- No biological, chemical, or physical activity related to dunes and vegetation is accounted for.

1.4 REPORT OUTLINE

This report is build-up of two parts, within a total of 10 different Chapters:

Chapter 2: gives background information and a literature review
Chapter 3: explains the methods used for Part I
Chapter 4: gives the results of Part I
Chapter 5: gives the interpretation of the results of Part I
Chapter 6: gives the methods used for Part II
Chapter 7: gives the results of Part II
Chapter 8: gives the interpretation of the results of Part II
Chapter 9: gives an overall discussion of this research
Chapter 10: gives overall conclusions and recommendations
Appendices: give extra information

2 LITERATURE REVIEW

2.1 INTRODUCTION

This chapter serves two purposes. Firstly, it provides a theoretical foundation to understand the concepts used in this report. Secondly, it gives an overview of current knowledge about dunes and vegetation during storm conditions. It is assumed that the reader has some basic knowledge about important concepts in coastal engineering. For more in-depth information is referred to the book Coastal Dynamics (Bosboom and Stive [2021]).

Section 2.2 provides an overview of the (coastal) terminology used in this report, paying extra attention to processes during storm conditions. In section 2.3 the potential effects of dune vegetation on dune erosion are outlined. A recap of previous studies and a first quantification considering dune vegetation during storm conditions is given in section 2.4. . Section 2.5 provides information about the current state and the implementation of vegetation in (numerical) modeling during dune design assessments.

2.2 COASTAL TERMINOLOGY

To get a full understanding of the concepts treated in this thesis, this section provides an overview of the (coastal) terminology used in this report. This terminology involves a description of the coastal zone, important hydrodynamic processes, sediment transport, storm impact regimes, and natural and artificial dune restoration.

2.2.1 Coastal zone

In this research, the area of interest is the dune area. The dune area is a part of the beach-dune system and also part of a broader area: the nearshore area. Figure 2.1 shows a visualization of a typical nearshore area. The beach consists of the backshore and the foreshore. The backshore extends from the dune foot to the mean high water (MHW) line. The zone between the MHW line and the mean low water (MLW) line is known as the foreshore. The nearshore is the part of the profile located seaward of the MLW line.

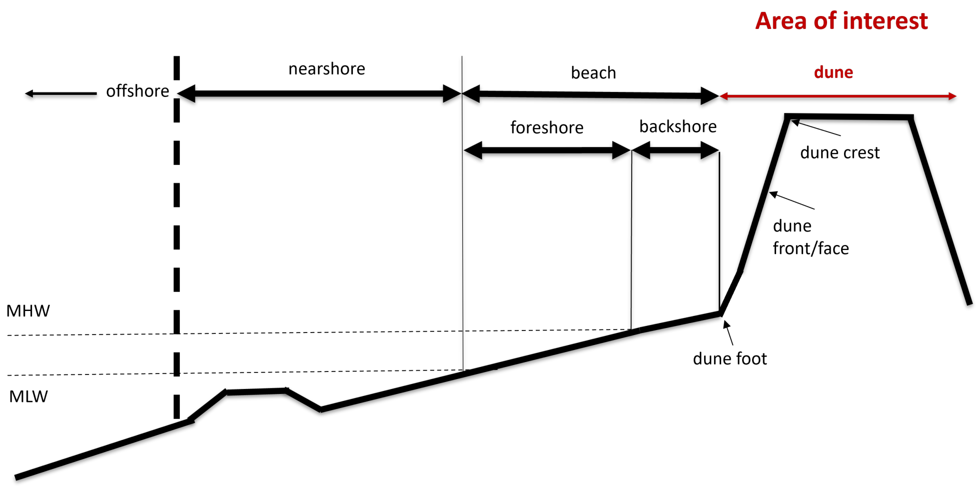


Figure 2.1: Definition of nearshore areas

DUNES Dunes are the result of complex interactions between wind, waves, sand, and vegetation (Puijenbroek [2017]). The focus of this thesis is on foredunes. For simplicity, these types are referred to as dunes from here on. Foredunes are the dunes closest to the shoreline. Therefore, they are significantly influenced by hydrodynamics and wind. Figure 2.2 captures a foredune and the key forces and processes that occur. The occurring natural processes together with human interaction determine the morphology and subsequently resistance of dunes during storm conditions.

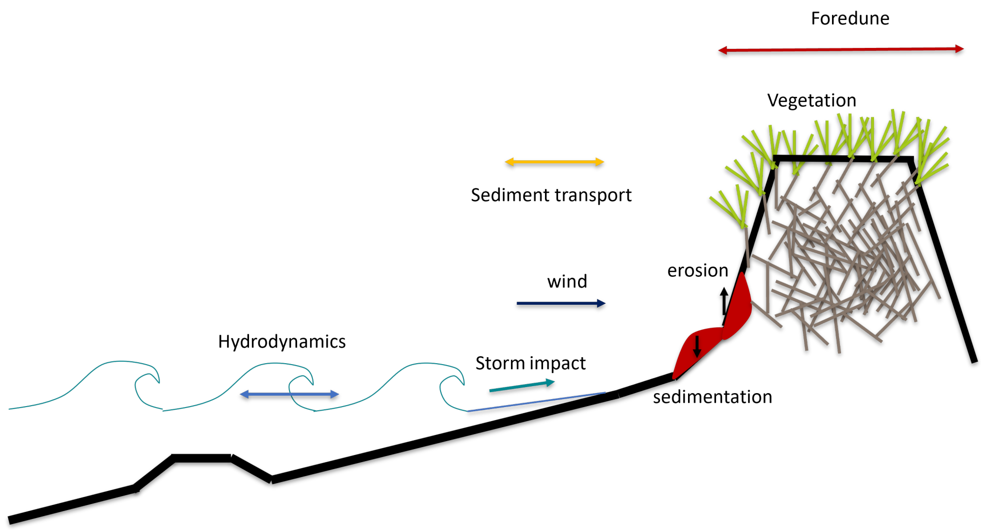


Figure 2.2: Overview dune, vegetation and important processes in dunes

2.2.2 Hydrodynamics

The morphology of the above-mentioned beach-dune area is largely determined by hydrodynamics. Waves approach the coastline and interact with the coastal zone. During storms, the mean water level rises, and strong winds produce larger waves. 6 main nearshore processes are identified which influence the dune erosion and morphology during storm conditions. 4 main processes are adapted from van Rijn [2009] and for a complete understanding, an explanation of nearshore currents and tide is added:

- Wave impact
- Long waves
- Turbulence
- Nearshore currents
- Avalanching
- Tide (meterological and astronomical)

During storms, the above-mentioned processes occur most of the time combined.

WAVE IMPACT The erosion volume of the dune is related to the force in the wave uprush (Fisher et al. [1987]). During an uprush, a large quantity of water runs up the beach face. This water exerts high shear stresses on the bed, is decelerated at a small distance, and hits the dune face. The force exerted by the water on the dune relates to the volume change. The profile of the beach affects this force and so also affects the volume change. On a mild beach slope, the force and so the dune erosion is smaller than when the dune face is connected to a steep slope.

LONG WAVES During storms, long waves dominate the inner surf and swash zone on sandy beaches and are thus critical for dune erosion. In the shoaling zone, different waves in a wave group can interact with each other and create a bound infragravity wave also known as a bound long wave (de Bakker et al. [2015]). This results in a variation of the mean sea level: a rise at the smallest waves in the wave group and a dip with the largest waves. When the waves break, the group structure disappears and the bounded long wave is free.
The infragravity waves have a relatively large wave period. They grow in amplitude towards the shore and as a result, the long wave energy near the dune face could be larger than that of short waves (van Thiel de Vries et al. [2008]).

TURBULENCE Turbulence could enhance the stirring up of sediment, bringing and keeping sediment of the dune in suspension. van Thiel de Vries et al. [2008] observed in his experiment that the region close to the dune is the location where high sediment concentrations were observed. Large-scale turbulence is created by nearshore processes such as breaking waves, rollers, and reflections from the dune. This turbulence penetrates from the top of the wave to the bed. Consequently, sediment from the bed is picked up and kept in suspension. The more sediment in suspension, the more likely erosion takes place.

NEARSHORE CURRENTS The sediment stirred up and brought into suspension by turbulence could be transported away by nearshore currents. A distinction can be made between cross-shore and longshore currents. Longshore currents move parallel to shore and cross-shore currents act perpendicular to the beach. Since in this research, only one-dimensional situations are considered and the longshore effects are assumed to be small during storm conditions, these are neglected. Cross-shore currents emerge under breaking waves. This wave-induced cross-shore mean current dominates water movements during storm conditions and so possibly sediment movement on the nearshore. The mean flow is also called undertow (Bosboom and Stive [2021]).

AVALANCHING Avalanching is an important erosion mechanism during the collision regime. When the dune face is moist and undercutting occurs, this might happen. It can occur in a variety of ways (Erikson [2007]. In the case of waves attacking the dune face, sediment at this location is wetted and so the weight of this associated sediment increases. Since the angle of repose is supposed to be smaller for wet sediment, sliding and avalanching could occur (Palmsten and Holman [2011a]).

ASTRONOMICAL AND METEOROLOGICAL TIDE The tide alters the section of a coastline profile that is influenced by waves. When the tide is high, waves may travel further inland, affecting the dunes. The dunes may not be impacted during low tide. Tide consists of an astronomical and meteorological tide. The gravitational pulls of the sun and moon create the astronomical tide. The meteorological tide is also called storm surge. It is a sea-level rise due to low atmospheric pressure and high wind speeds during extreme weather conditions. The wavelength and period are slightly shorter than those of tide, but they can cause severe flooding because a direct interaction between dunes and waves could take place. The tide plays also a role in the formation and growth of dunes because the length of the intertidal zone determines how much sediment can be transported by the wind into the dunes.

2.2.3 Sediment transport

The link between hydrodynamic forcing and the morphological response of the beach-dune system yields the transport of sediment. Sediment transport is defined as the movement of sediment particles over a well-defined plane over time as a result of shear pressures on the sand particles (Bosboom and Stive [2021]. The movement of sediment particles depends on the characteristics of the transported material (e.g., grain size, fall velocity). Erosion takes place when the net sediment balance is negative: more sediment is going out than coming in. This can be observed in the cross-shore direction or the longshore direction. When more sediment is coming in than going out, it is referred to as sedimentation or deposition. Two main transport mechanisms can be defined: aeolian and hydrodynamic transport. Aeolian sediment transport is the sediment transported by wind. This contributes to the formation and growth of dunes. The transfer of sediment by wind will not be discussed in detail, yet it is an essential process in dunes. Hydrodynamic sediment transport is the sediment initiated and transported by hydrodynamic forces. (Bosboom and Stive [2021])

HYDRODYNAMIC SEDIMENT TRANSPORT This report deals with hydrodynamic sediment transport at the dune location. Waves (gravity waves, infragravity waves) and currents (undertow) could enable sediment transport. The current related transport is often assumed to be larger than the wave-related part. The waves generally stir the sediment. The main mechanisms of transport are suspended transport and bedload transport. Bedload transport is almost exclusively determined by the bed shear stress acting on the sediment particles, resulting in rolling, sliding, and jumping sediment. Suspended transport takes place above the bed load layer when turbulence velocities are greater than the submerged weight.

2.2.4 Storm impact regimes

The potential impact of dune vegetation during the collision regime is studied in this research. The collision regime is defined by Sallenger (Sallenger A.H. [2000]). Sallenger divided storm impact into different regimes to show the different impacts of storms on the removal of sand from dunes. Storm impact regimes are based on dune dimensions (resistance) and water level elevation extremes (load). Depending on the wave energy, storm duration and wave run-up height relative to dune elevation, erosion of the system can occur in a swash regime, collision regime, overwash, or breaching regimes (Sallenger A.H. [2000]). The parameters used to define the

Sallenger impact regime are described below, and a definition sketch is shown in Figure 2.3.

- R_{low} is the elevation of the seaward limit of swash. Stockdon et al. [2006] defined R_{low} as the sum of meteorological tide, astronomical tide and wave setup.
- R_{high} (runup limit) is the highest elevation of the landward margin of swash. This measure includes the combined effects of astronomical tides, storm surge, set-up and and the 2% exceedance level for vertical wave run-up.
- D_{low} is the elevation of the dune toe.
- D_{high} denotes the height of the first line of beach defenses (i.e., beach berm or dune crest).

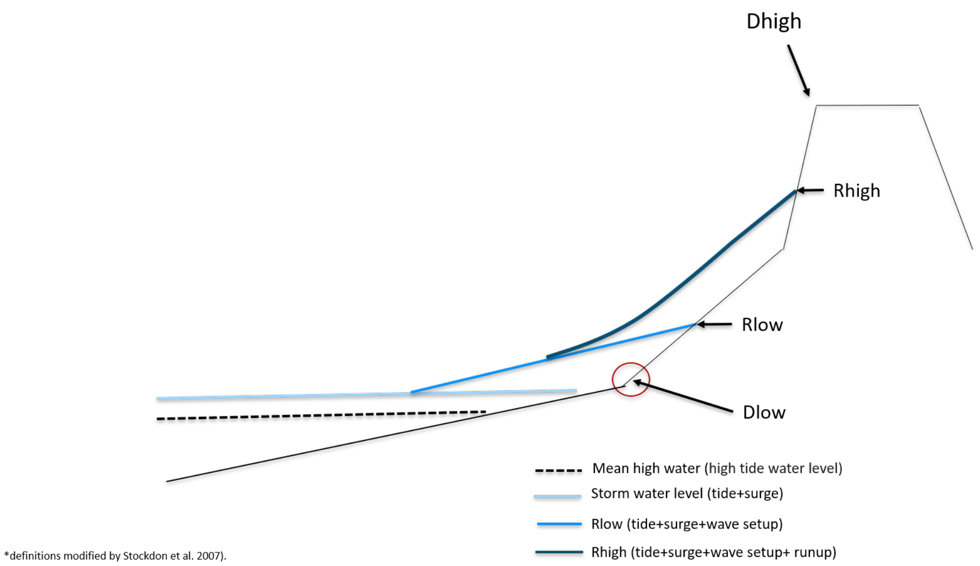


Figure 2.3: Definition sketch of parameters used to define Sallenger impact regime

The erosion mechanisms during the different regimes are described in the following paragraphs and illustrated in Figure 2.4.

SWASH $R_{high} < D_{low}$ During the swash regime, the maximum runup is lower than dune foot. In the swash regime, only the beach is affected by hydrodynamics. Storm redistributes sand cross-shore but only on the beach and the water does not reach dunes. The conditions could be accretive, building up the beach. Sand is redistributed on the beach. This regime normally results in bar and berm flattening.

COLLISION $D_{low} < R_{high} < D_{high}$ In the collision regime, the wave runup is above the dune foot and below the dune crest. The beach is flooded and waves can penetrate to the dune face and collide with the dune face. Especially large bores attack the dune and sediment can be taken from the dune front and placed on the beach itself. Between the shoreface, beach, and the front of the dunes, sand is re-distributed on the cross-shore. After a storm sand can either return to the dune or is transported away due to an alongshore gradient in transport or an offshore sink of sediment. When water takes away sediment from the dune foot, a dry scarp surface could arise. This might result in slumping. A dune scarp will retreat to a point where the dune may be breached if the load during the collision regime is significant. This leads to the loss of flood protection function.

In the collision regime, several mechanisms can affect dune erosion. This is divided into two stages: the swash/runup stage and the direct wave impact stage. Swash is caused by broken waves rushing up the beach and reaching the dune. These propagate through the swash zone as bores. These waves tend to have relatively long periods. The swash impacts the dune toe, partially eroding the sediment, and then returns to take it away. The swash impacts the dune toe, partially eroding the sediment, and then returns to take it away. Because part of the wave energy has been dissipated in the breaking process and along the beach slope before reaching the dune, the swash has less power than the broken wave that has formed the swash. Wave impact is when waves impinge on the dune and carry more energy with them. This only takes place during big storm surges. Therefore, erosion due to wave impact takes place less frequently. In both stages, different mechanisms will influence the erosion of dunes (Maximiliano-Cordova et al. [2019]; Charbonneau et al. [2017]).

OVERWASH $R_{high} < D_{high} R_{low} < D_{high}$ The third regime is the overwash, in which the wave runup is above the dune crest and the wave rundown is below the dune crest. The mean water level is lower than the dune crest, so overflow happens occasionally. In cases where the hinterland behind the dune is lower, the overflowing water can take substantial sediment to the back of the dune. Sediment is no longer conserved to the seaward side of the dune but deposited behind the crest. This results in a smoother profile than in the collision regime and it could result in dune scouring and channel incision.

INUNDATION $R_{high} > D_{low}$ If the water level increases further, water starts overflowing permanently. The wave rundown is above the crest, and this is called the inundation. Significant amounts of water flow over the dune row, a lot of sand is transported landward of the first dune row. In case the dune row is the only line of defense, this can result in inundation and flooding of the hinterland. If inundation persists, breaching takes place and the top of the island can be eroded even below the mean sea level.

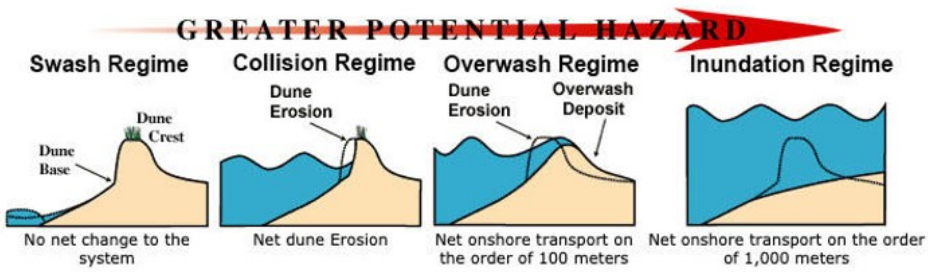


Figure 2.4: Sketch of storm impact regimes and erosion processes (source: USGS [2020])

2.2.5 Natural and artificial dune restoration

This study considers a dune rehabilitation project intending to use dunes to defend inland from flooding. As a result, it is critical to understand the natural evolution of a dune profile, as well as the artificial dune profile determination during dune rehabilitation efforts.

SUMMER AND WINTER PROFILES Coastal dune systems are naturally dynamic. After a storm, dunes are generally able to restore themselves. This can be explained by the so-called summer and winter beach and dune profiles. These profiles are illustrated in Figure 2.5. During storm conditions, high and long waves cause erosion of the dunes and beaches. Sediment is taken from the dune and deposited at the location where waves are breaking. The cross-shore profile after storm conditions is characterized by a narrow beach and a steep dune profile. In the Northern Hemisphere, most storms occur in winter. That is why a storm profile is also called a winter profile. The lower and shorter waves during summer conditions cause sand to move back towards the beach and dunes, restoring the profile.

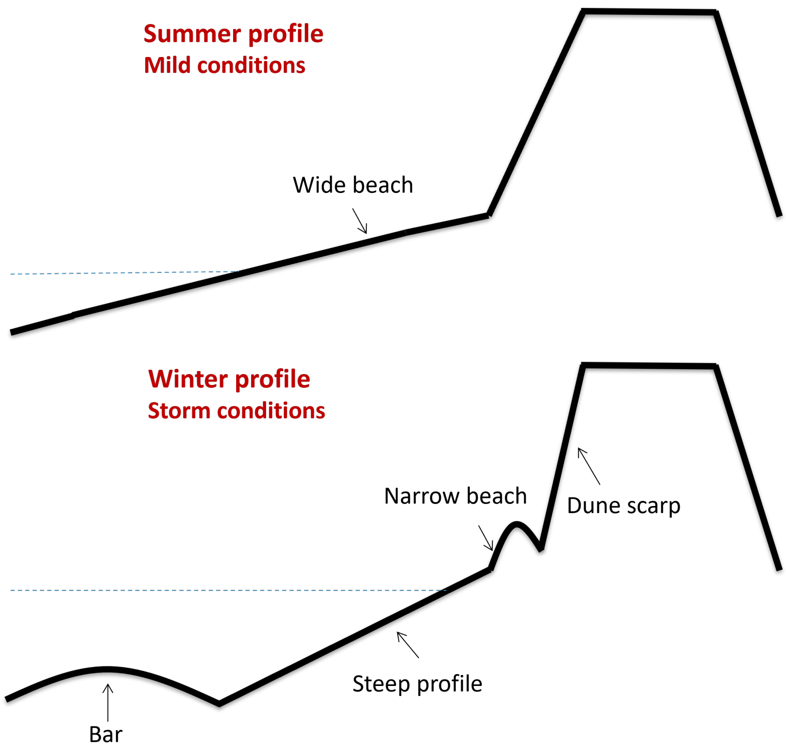


Figure 2.5: Visualisation of summer and winter (storm) profile.

MINIMUM SAFETY PROFILE IN DUNE DESIGN To serve the flood protection function and prevent breaching, a minimum safety profile must remain after a storm. The ENW [2007] describes the requirements of a minimum safety profile, which is used in dune rehabilitation projects in the Netherlands. This profile is the least amount of 'dune' that should fit in the post-storm profile. The calculation of the storm erosion profile is displayed in Figure 2.7. The requirements of a post-storm profile and thus minimum safety profile are depicted in Figure 2.6. The traditional way is displayed on the left, while an alternative method is presented on the right. A minimum dune height, a minimum dune width, and the dune's landward slope are all factors to consider. Because dune profiles can take on a variety of shapes, the profile with the aforementioned requirements is not always suitable. As a result, an alternative method was developed. The starting point of this method is that a too-small dune height is compensated for by a larger dune width. The volume per meter should be the same as the traditional minimum safety profile's volume per meter. On the right side of Figure 2.6, this is displayed.

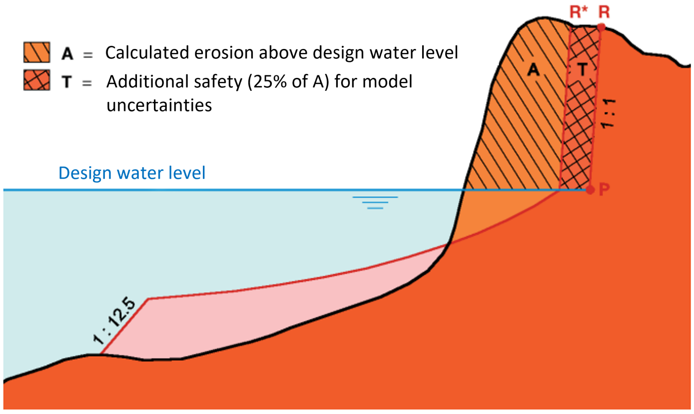


Figure 2.6: Calculation storm erosion profile (source: ENW [2007])

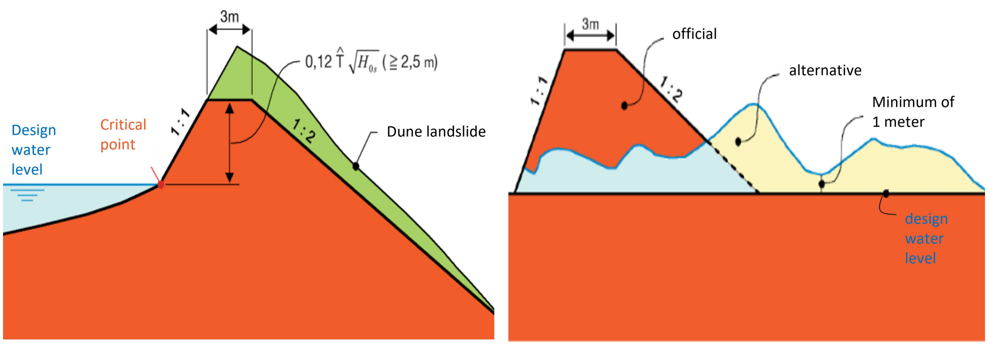


Figure 2.7: Definition of minimum standard safety profile (right) and minimum alternative safety profile (left). (source: ENW [2007])

2.3 IMPACT OF VEGETATION ON DUNE EROSION

In this section, the impact of vegetation on dune erosion is described. First, basic information about vegetation in the dune area is discussed. Hereafter the primary and secondary effects and processes concerning dunes and vegetation during storm conditions are described. The final paragraph proposes how a storm develops in combination with the response of a vegetated dune.

2.3.1 Dune vegetation

This thesis focuses on dune vegetation. Different types of dune vegetation exist. The type of species and number of species on dunes are site-specific. The reason is that the soil composition and climate (such as aeolian transport, wave inundation, salt spray, and wind stress) have a significant impact in determining whether species may survive (Bosboom and Stive [2021]).

VEGETATION ZONE The nearshore-beach-dune can be divided into different zones regarding vegetation.Tinkley [1985] described four major zones of foredune vegetation around the world. These zones can occur across typical coastal dune systems where rainfall is sufficiently high and the shoreline sufficiently stable or prograding. In this thesis, only zone I and II are considered. Figure 2.8 (McLachlan [1991]) indicates that the vegetation considered has a low vegetation cover and canopy height, but a high salt tolerance and tolerance to sand movement.

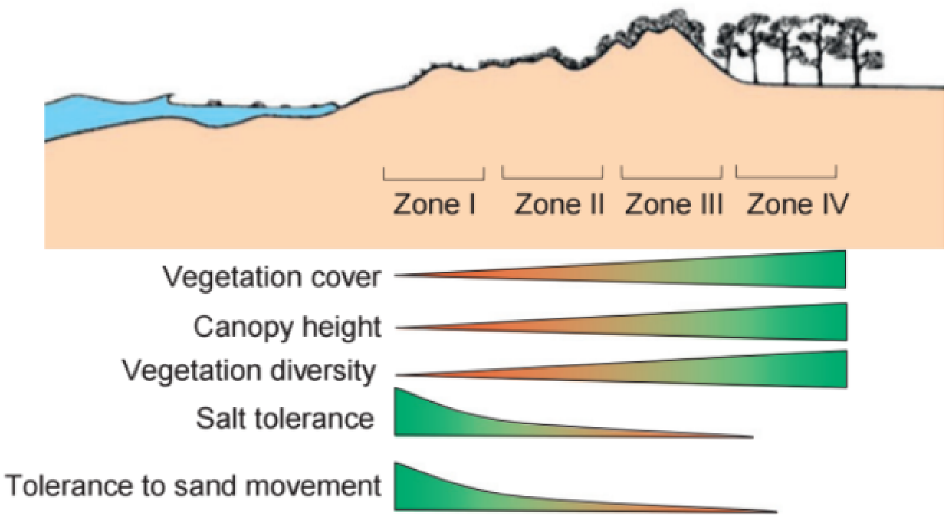


Figure 2.8: Vegetation zones (source: McLachlan [1991])

VEGETATION COMPONENTS The structure of dune vegetation depends on the type. However, the main distinction is made between above- and belowground vegetation components (Charbonneau et al. [2016]). This is displayed in Figure 2.9. With aboveground vegetation (A), we refer to the part of plants above the surface (stems and leaves). With belowground vegetation (B), we refer to the part of the plant below the surface (root network and biomass). They both have a different influence on dunes during hydrodynamic forcing and wind forcing, as will be discussed later.

The allocation of above- and belowground vegetation varies between species (Poorter and Nagel [2000]). It is important to pay attention to these differences since this could have implications for the potential dune growth and erosion resistance.

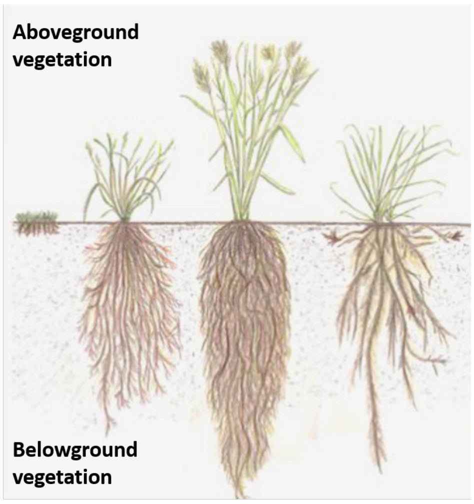


Figure 2.9: Belowground and aboveground allocation for different vegetation types (adapted from: Massachussets [2013])

2.3.2 Primary vegetation processes

The presence of vegetation on dunes affects dune erosion and the evolution of the dune during collision regime storm conditions. The main processes associated with aboveground vegetation are related to hydrodynamic interaction. Belowground vegetation is associated with soil stabilization. The following paragraphs describe the mechanisms involved with hydrodynamic interaction and soil stabilization. It must be noted that different processes are classified under the same denominator. The reason for this is that the exact physical causal role that vegetation plays in dune erosion resistance has not been established yet.

HYDRODYNAMIC INTERACTION The aboveground part of vegetation could interact with the hydrodynamics and so affect dune erosion. As mentioned above, the exact processes related to aboveground vegetation and hydrodynamics are poorly understood. Yet, the influence of vegetation on erosion in other ecosystems (e.g. marsh, creek, mangrove, and terrestrial) has been documented in the literature. Vegetation in these other ecosystems has been shown to extract energy from the flow through (viscous and form) drag and turbulent dissipation. Consequently, this results in smaller wave energy, a smaller wave height, smaller current magnitudes, smaller water level, decreasing wave runup, and overtopping (Blackmar et al. [2014]; Nepf and Koch [1999]). These interactions and effects are visualized in Figure 2.10.

SOIL STABILIZATION The belowground part of vegetation does interact with the soil. Thereby it affects dune resistance and consequently the erosion process. Roots themselves could change the physical properties of dunes and alter the composition of sediment Vannoppen et al. [2015]. Plant-induced sedimentary changes could increase the cohesion between grains and increase the effective diameter (Feagin et al. [2015]). Thereby roots anchor the soil and form a binding network within soil layers, aggregating the soil mass. Furthermore, Arbuscalur Mycorrhizal Funghi (AMF) and roots may create symbiotic relationships. AMF are microbial communities found inside and around the root systems of plants that aid in the binding of sand grains together by enhancing soil aggregation and shear strength.

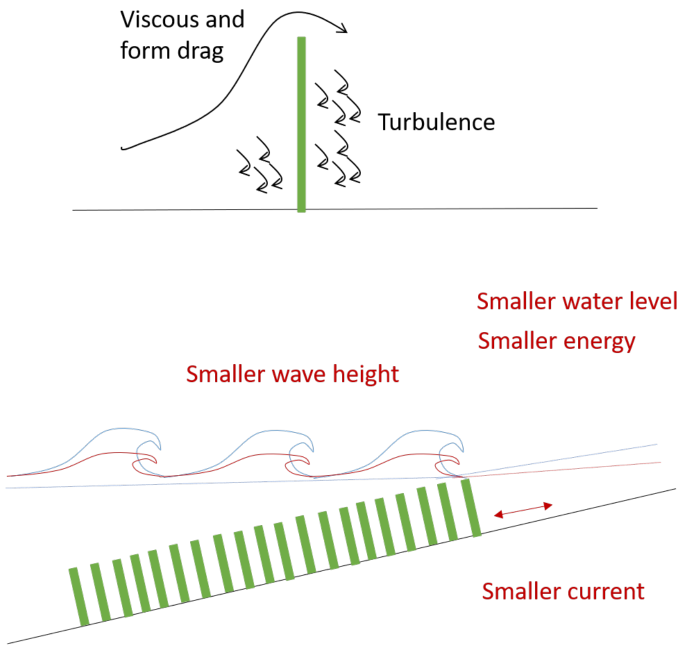


Figure 2.10: Interaction vegetation with hydrodynamics observed in other ecosystems than coastal dunes (Adapted from: Arkema et al. [2017])

2.3.3 Secondary vegetation processes

The processes and effects that could be divided into hydrodynamic interaction and soil stabilization were described in the previous subsection. Other important processes, which play an even more complex role in dune erosion are uprooting, destruction, and over strengthening.

UPROOTING Uprooting is another essential and complex process that occurs during storms. It affects hydrodynamic alteration, soil stabilization and the morphological response of dunes and vegetation. The impact of the waves could result in the mobilization of sediment and subsequently in the uprooting of the belowground vegetation. Aboveground vegetation might transport wave energy into the substrate via the stems, causing belowground plants to uproot (Figlus et al. [2014]). Uprooting could result in the loosening of sediment, more sediment mobilization, and so more erosion. This uprooted vegetation could be carried away by the water or be deposited on the dune. However, the uprooted vegetation could also result in a reduction of dune erosion. When either aboveground or belowground biomass is deposited at the dune, it could reduce velocities.

BURYING Vegetation could capture sediment particles, resulting in burying of vegetation itself. Avalanching may also cause plants to be buried. This phenomena might cause roughness to decrease and near-bed velocities and erosion rates to increase.

DESTRUCTION A third process is the destruction of vegetation. Environmental factors connected with storms, such as excessive precipitation, floods, high saline concentrations, accretion, and erosion could lead to death or destruction of vegetation. The impact of storms on vegetation is determined by the storm's spatial and temporal size, intensity, storm clusters, and species-specific responses of plants in distinct dune environments. The destruction of vegetation affects the subsequent foredune recovery.

The degree of scarping is affected by vegetation, but the degree of scarping also affects vegetation destruction. Following the studies of Hesp [2002] and Hesp and Martínez [2007], the degree of scarping is characterized by the erosion volume. Because of salt intolerance or inability to thrive in the swash zone, small scarping (10 % reduction in dune volume) might result in a slightly plant loss or death. Larger scarping (20%/40% volumetric loss) results in the dieback of plants on the scarp frontline due to the impacts of salt spray, burial, and slumping. A volumetric loss greater than 40% may result in foredune destabilization, resulting in devastating effects of the dune development and on the vegetation population. Plants with deep root systems may be able to withstand avalanching and collapsing by remaining rooted.

OVERSTRENGHTENING Overstrengthening, or too much stabilization, is a last critical process. This is associated with the whole beach-dune sediment system. Rapid storm erosion of dunes is required for the functioning of the beach-dune system and the exchange in sediment (Vellinga [1978]). The planting of vegetation could lead to problems as Dolan 1972 has seen on the Outer Banks of North Carolina. They noticed that artificial dunes were unable to release enough sand during storms, resulting in a steepening of the nearshore profile. This resulted in a catastrophic collapse of the system. (Carter and Stone [1989]).

2.3.4 Theoretical morphological development during storm conditions

To understand the effect of vegetation during the collision regime and link it to flood resilience, a conceptual model of the collision regime over time concerning erosion volumes has been set up for this research. This is visualized in Figure 2.11. It is assumed that vegetation reduces erosion volumes both by aboveground and belowground vegetation. Effects like the destruction of vegetation are not taken into account in this simple conceptual model.

The response of a dune during the collision regime could be divided into two phases. The potential effects of above- and belowground vegetation during these phases are described. As far as the researcher knows, mainly the erosion reduction described in Phase I leads to slightly larger flood resilience. What appears to be happening in Phase II is not well understood yet.

PHASE I When a storm arises, the swash regime takes place which is followed up by the collision regime. The predominant erosion of the dune is caused by hydrodynamic forces at this point. Swash flow or direct wave impact might both the cause of dune erosion (phase I). When vegetation is present, it is expected that the sediment pickup will be reduced, due to both aboveground and belowground components of vegetation. The aboveground vegetation increases friction, resulting in a smaller run-up and less picking up of sediment. The consequence of this is a smaller rate of erosion at the beginning of the collision regime (phase I). The belowground component of vegetation ensures soil stabilization due to a higher cohesion and shear strength, resulting in less sediment pickup and a higher critical angle. The retention of sediment and the postponement of slumping due to the possibility of a larger slope prolongs the duration of Phase I.

PHASE II When sediment has been taken from the dune, the dune steepens. This is also called scarping. The scarping continues till a critical dune slope. When the critical dune slope is reached, avalanching has a large contribution to dune erosion volume (phase II). The steep slope and the subsequent sudden avalanching could result in a fast erosion rate in a short time. When roots are well entrenched, however, the erosion volume rate may still be reduced than for the case without vegetation.

When the storm progresses further, or the dune crest height and/or width has been decreased, the regime could switch to the overwash regime. This is not within the scope of this research.

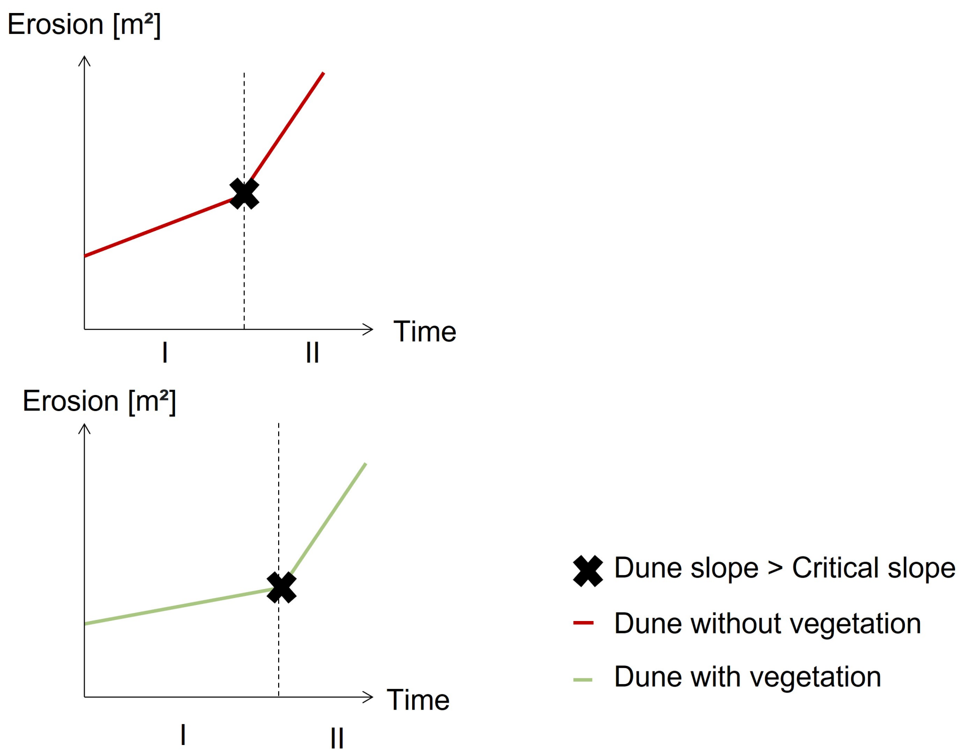


Figure 2.11: Concept of collision regime over time in relation to erosion volume- and dune vegetation

2.4 PREVIOUS PHYSICAL EXPERIMENTS OF VEGETATION IMPACT

Recently, a growing number of studies considered the effect of dune vegetation during storm conditions. In this section, studies concerning the collision regime are discussed. Some studies focused on the effect of the beach-dune morphology and conditions, others specifically addressed different vegetation species, characteristics, and allocation, while some explored the processes and interpretation of the observations. A distinction can be made between case and field studies and laboratory and wave flume experiment studies.

2.4.1 Case and field studies

Different case and field studies addressed the role of vegetation during the collision regime. The study of Lindell et al. [2017] analyzed Angelholm Beach in South Sweden and showed that wave and wind erosion increased due to the removal of vegetation. Dune front erosion during storms increased 2-4 times compared to dunes including vegetation. Charbonneau et al. [2017] quantified coastal dune erosion from Hurricane Sandy and documented a species-specific effect on collision erosion. This study highlights the importance of vegetation for dune stability and management and points out the importance of the type of vegetation. A recent field study in Mexico of Maximiliano-Cordova et al. [2021] showed that vegetation was negatively correlated with erosion during the collision regime. However, just one out of three sites revealed this correlation. This demonstrates how the protective role of vegetation varies depending on the species and location.

2.4.2 Shear strength and wave flume experiments

SHEAR STRENGTH Several laboratory experiments have been carried out to assess the effect of vegetation on dune resilience. (Figlus et al. [2014]) tested substrate shear of dune vegetation to investigate the resistance of vegetated dunes against erosion. The tests with dune vegetation exhibited an increase in the overall shear strength of a soil. The data of Ajedegba et al. [2019] also indicate a higher shear strength for dunes with vegetation. Furthermore, the root density of dune vegetation demonstrated a positive correlation with in-situ shear strength. Carter and Stone [1989] demonstrated a forty-fold increase in shear strength for dry loose sand (10-20 kN/m^2) to consolidated dune soils with vegetation (4-550 kN/m^2).

WAVE FLUME EXPERIMENTS Wave flume experiments that assessed the role of dune vegetation are depicted in Figure 2.12. In contrast to this study, the majority of the experiments focused on multiple storm conditions. It is worth noting that each of these studies had its own setup and research objective. The arrow between different experiments indicates the same experiment, published by different authors.

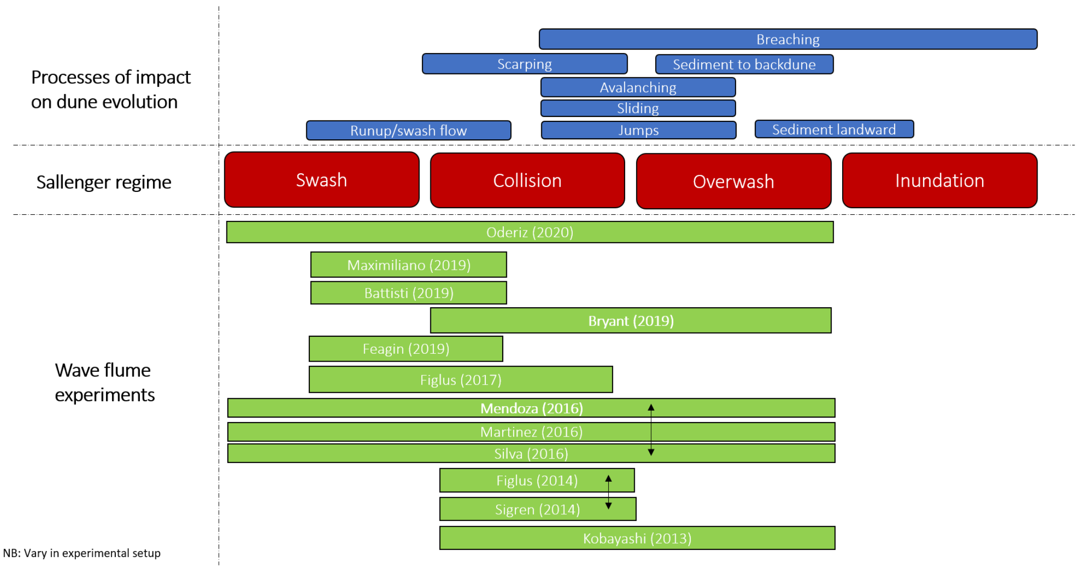


Figure 2.12: Overview small scale wave flume experiments and link with Sallenger regime and processes of impact on dune evolution. The arrow between different experiments indicates the same experiment, published by different authors.

Three wave flume experiments focused explicitly on vegetation during runup, without waves directly hitting the dune. Feagin et al. [2019] made a distinction between below- and aboveground vegetation. By dampening wave swash and run-up bores, the aboveground biomass prevented erosion. Belowground biomass initially enhanced erosion until excavation enabled them to also attenuate waves and reduce erosion. Also, Maximiliano-Cordova et al. [2019] focused on erosion during swash flow, but now for three different beach dune species. The efficiency of plant cover in slowing erosion varied depending on the plant architecture. The goal of de Battisti and Griffin [2020] was to investigate the impact of three widespread pioneer foredune species on erosion resistance and to separate the contributions of three different below-ground compartments (roots, rhizomes, and buried shoots). One of the most noteworthy discoveries is that all three species studied prevented erosion. The most important individual belowground plant compartment contribution came from buried roots, which drive sediment stabilization.

Four studies have looked at the impact of waves directly hitting the dune in combination with dune vegetation. Kobayashi [2013] conducted wave flume experiments with woody plants, represented by buried dowels. The goal was to investigate the effects of woody plants on dune erosion and overwash with irregular waves impinging on a dune. The wide vegetation covering the fore slope reduced erosion of the fore slope as well as the overtopping and overwash rates. Furthermore, the reduced wave overtopping resulted in an increase in offshore sand transport from the eroded dune. An explanation for this could be the smaller overtopping rate and so a higher undertow current. Figlus et al. [2014] studied the role of vegetation in dune erosion resiliency, where the seaward facing slope of the dune covered with real vegetation (Sporobolus Virginicus) was subjected to attacking waves. They focused on the development of the beach profile and dune scarp retreat in time. The maturity and plant density were varied. A vegetated dune resulted in an erosion reduction of 33% and a 30% lower dune scarp retreat rate compared to a nonvegetated dune. This research also suggests that plant age has a significant impact on erosion rate. In comparison to the previously stated research, Bryant et al. [2019] tested the erosion-reducing potential of below-ground biomass and aboveground biomass, both in isolation and in combination to quantify the dominant mechanisms contributed by vegetation structure to dune response. Wooden dowels represented the aboveground vegetation and coconut husk fibers the belowground vegetation. Overall, the results showed that vegetation biomass, regardless of form, reduces the degree of erosion sustained during collision and overwash. When comparing the isolated biomass, the isolated belowground biomass provided much more dune resilience than the isolated aboveground biomass. However, as compared to the bare control dune, the combination of above and belowground biomass resulted in the least amount of dune material loss.

Real dune vegetation was used in the wave flume experiments of Martinez et al. [2016], Silva et al. [2016] and Mendoza et al. [2017]. In the setup, they varied with profile (berm/no berm), wave conditions (mild/moderate/intense) and plant densities (none/low/medium/high). The trials revealed that vegetation reduces the amount of eroded dune and the speed of dune scarp retreat. Regardless of the wave conditions or the morphology of the beach-dune profile, the study found that vegetated dunes eroded less than dunes without vegetation. The volume eroded had no direct link with the density of plant cover. Figlus et al. [2017] conducted wave flume experiments with wave bursts imposed on the dune. Four different types of vegetation were considered with varying above- and belowground biomass and different root size distributions. In addition, the plant maturity was tested. The main goal of this research was to explore which aspects of vegetation and which physical processes are linked to larger erosion resistance. The research showed that both the aboveground and belowground portions of vegetation are relevant in dune protective capabilities and wave-induced erosion resistance. In the swash zone flow, the aboveground plant structure is the key factor linked to erosion reduction. A larger plant surface area resulted in a decreased turbulent kinetic energy. Furthermore, fine roots are key determinants of erosion reduction, likely making dune systems less prone to slumping and collapsing by an increase in shear strength. Odériz et al. [2020] conducted wave flume experiments targeting to impose swash, collision, and overwash conditions. Different densities of real vegetation were used. It has been observed that when vegetation was at forwarding positions on the dune, it decreased run-up and increased reflected energy. Energy was transferred to low-frequency bands. Vegetation has shown to reduce the eroded volume on the exposed dune face. This study also suggests that dune vegetation can dissipate waves and provide protection during the initial swash and collision stages of a storm.

Recently, Feagin [2021] conducted a large-scale lab experiment to identify the role of vegetation during wave impact. Contrary to the above-mentioned studies, they found evidence that a vegetated dune with above- and belowground biomass erodes more quickly and results in a much larger scarp than the dune without vegetation. Two dunes of 70 meters and 4.5 meters tall were constructed. Vegetation was planted on one profile for almost 6 months while leaving the other bare. They were hit with nearshore waves up to 1.5 m in height. The profile geometries, sedimentary properties, and hydrodynamics were all constructed in the same way. Vegetation was initially retarded and attenuated wave runup. However, it was also found that the vegetated dune resulted in larger reflected energy and larger moisture levels in the soil of the dune earlier in time. The observations can be explained by water hitting the vegetation, being stopped, retarded, and attenuated to go further behind the vegetation. The reflected water goes down the stems and the roots, resulting in saturation in front of vegetation. The pressure at the top of the soil is higher than at the bottom, resulting in collapsing of the dune. This starts with micro slope features. Because of these failures, the slopes get steeper, resulting in even more reflection and scour. For a dune without vegetation, water runs further up the dune, going up and down without interruption. This results in a more dispersed and partially saturated dune and so a smaller erosion rate.

2.4.3 Vegetation Factor

For a first indication of the potential effect of vegetation on dune erosion volumes, a Vegetation Factor (VF) is calculated for the collision regime based on existing data obtained by wave flume experiments and case studies. This factor differs from the Factor of Safety (FoS) defined in the study of Feagin et al. [2019]. In their study, the FoS was defined as erosion without vegetation divided by erosion with vegetation.

The Vegetation Factor [-] is defined as follows: the amount of erosion in the experiment with vegetation divided by the the amount of erosion for the experiment without vegetation:

$$VF = \frac{erosion\ with\ vegetation}{erosion\ without\ vegetation}$$

Appendix B contains the evaluated experiments and its main conditions for calculating the vegetation factor. The average VF during the collision regime and swash flow on the dune is 0.62 and the average VF for direct wave impact is 0.65. A VF of 0.65 means an erosion reduction of 35% for a vegetated dune. Histograms of the calculated vegetation factors are given in Figure 2.13 and 2.14. High outliers for the vegetation factor (below 0.5) are attributed to cases with above- and belowground vegetation and a high plant cover (Martinez-Cordova). For the available data, one trial showed a small increase of vegetation in the presence of vegetation (Silva, 2016) and therefore a VF > 1.

It must be noted that the conditions and available data differ and that more data was available for wave impact compared to the wave runup. Furthermore, the Vegetation Factor cannot be calculated for several studies due to a lack of data.

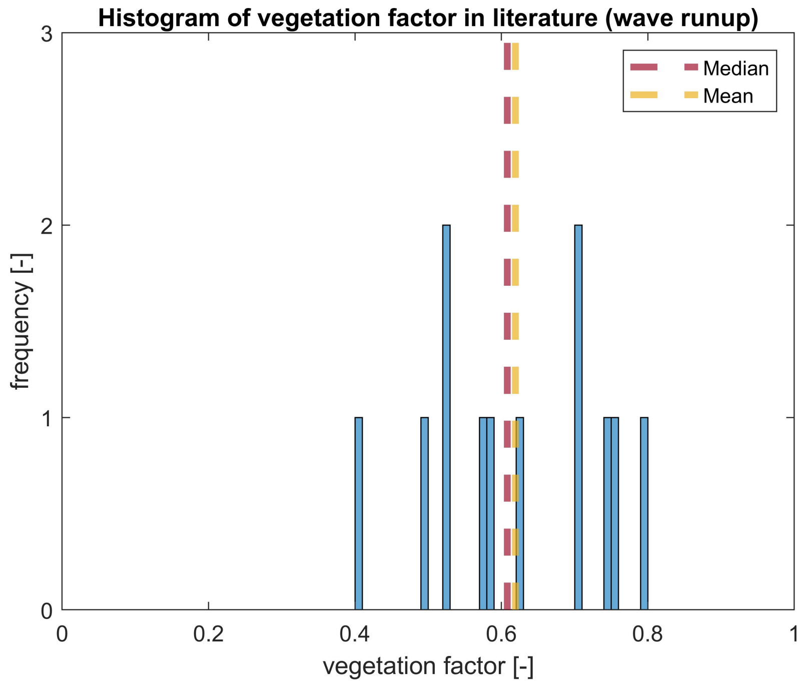


Figure 2.13: Histogram of calculated vegetation factors (runup). Frequency is the amount of studies with the certain vegetation factor found in literature.

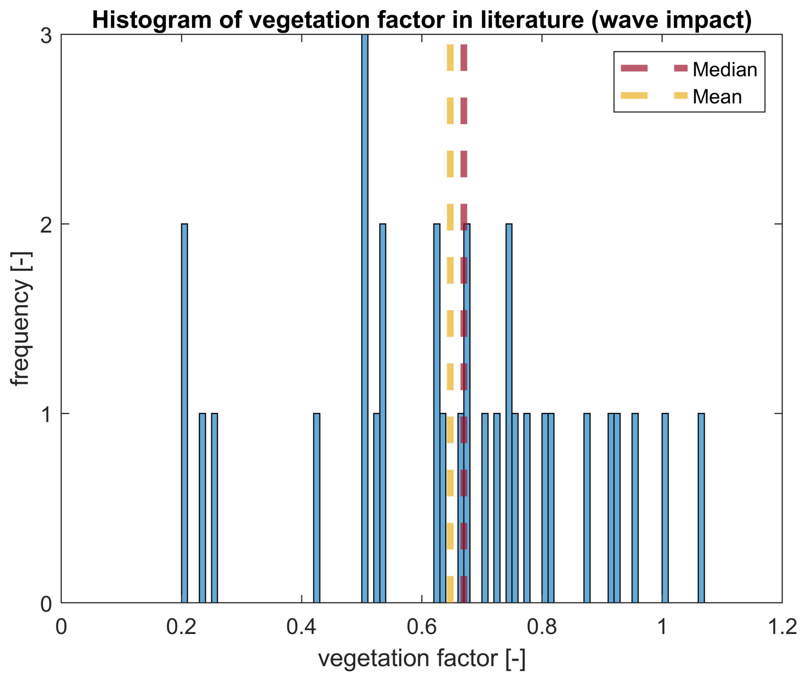


Figure 2.14: Histogram of calculated vegetation factors (wave impact). Frequency is the number of studies with the corresponding vegetation factor found in the literature.

2.5 PREVIOUS (NUMERICAL) MODELING OF VEGETATION IMPACT

For the evaluation of dune erosion during storm conditions, different methods are used. The goal of this research is to use a numerical model to investigate the impacts of vegetation on dune rehabilitation projects. Therefore, the previous (numerical) modeling of vegetation impact is examined in this section. There are two sorts of models described. The wave impact technique comes first, followed by the process-based model. For both types, the implementation of vegetation effects is discussed.

WAVE IMPACT MODEL The wave impact model is an analytical method. The eroded volume of a dune face can be calculated using the wave impact model. The force from waves impacting the dune is considered to be proportional to the weight of eroded material. Therefore, dune erosion volume is a function of the incident hydrodynamic wave momentum (Fisher et al. [1987]). An analytical solution has the advantage of simplifying the governing physical principles. Furthermore, it is useful if there is only a limited amount of data available.

With regard to vegetation, Ajedegba et al. [2019] developed an analytical wave impact model with the implementation of the contribution of vegetation roots to dune erosion volume reduction during the collision regime. The analytical solution included a resistance coefficient derived from direct field measurements of dune shear strength and root density at South Padre Island, Texas, USA. The analytical formulation with an additional resistance coefficient is shown in equation 2.1. The added resistance coefficient is the ratio of in-situ shear strength of bare dunes (τ_b) to the shear strength of vegetated dunes (τ_r). A range of values was proposed for this parameter, based on the assessment of different vegetation species: 0.2 - 0.8. This resistance coefficient equals the Vegetation Factor from section 2.4.3 and suggests 0.2-0.8 smaller erosion volumes for vegetated dunes in the tested area. The findings of this study lead to a method for quantifying the advantages of vegetation in erosion control. This was validated by comparing the results with field measurements.

$$\Delta V_{Er} = 4C_s \frac{\tau_b}{\tau_r}(R_u - z)^2 \frac{t}{T} \tag{2.1}$$

In equation 2.1, ΔV_{Er} is the eroded volume, C_s is a function of C_e, which in turn is an empirical coefficient related to wave height and speed. R_u is the run-up height which can be calculated with different empirical formulas, z is the dune toe elevation, t is the duration of the storm, and T is the wave period. For more confidence in this approach, more validation by field testing and data collection is needed. Generally, the added shear stress due to roots can be predicted well by the root diameter. Root tensile strength decreases with increasing root diameter which has been shown by several studies in the past (Operstein and Frydman [2000]; Bischetti et al. [2005]). An abundant smaller diameter and a finer root system can be more beneficial than a single taproot root system.

PROCESS BASED MODEL Process-based models like XBeach, Delft3D, MIKE21, and CSHORE compute the geomorphological feedbacks between storms. Compared to the analytical solution described above, they are computationally expensive, and demand high-resolution digital elevation and nearshore bathymetry data. This data is frequently missing or has low temporal precision, making these models challenging to use.

Due to the various processes, vegetation implementations, and the increased use of this model in dune design projects, the process-based model XBeach is employed in this study.

Several studies (e.g. de Vet et al. [2015]; Passeri et al. [2018]) have proven the functioning of applying different bed friction coefficients at vegetated sections in XBeach. They obtained good results by incorporating initial roughness maps based on land cover classification maps to prescribe spatially varying Manning roughness values. In addition, van der Lugt et al. [2019] created a dynamic roughness module that changes the bed friction coefficient because of burying and erosion in vegetated regions. During the erosion process, vegetation can uproot. This could result in a reduction of bed roughness, thereby increasing near-bed velocities and erosion rates. Vice versa, if a vegetated dune gets buried in sediment, the vegetation height decreases, reducing roughness. This approach is validated for two cases van der Lugt et al. [2019], where the predicted erosion and deposition volumes and dune-crest lowering were well predicted. The dissipation of energy induced by vegetation is incorporated into the vegetation module. By using this module, short waves, long waves, and mean flow are affected (van Rooijen et al. [2015]; van Rooijen et al. [2016]). This implementation was tested using lab experiments with submerged model kelp vegetation carried out by Kansy (1999). The above-mentioned vegetation implementations are validated for overwash conditions. Little attention is paid to modeling the effect of dune vegetation during collision conditions, especially the effect of belowground vegetation. Recently, the studies of Schweiger and Schuettrumpf [2021b] and Schweiger and Schuettrumpf [2021a] focused on the effect of belowground vegetation on dune erosion by implementing a novel root model. This root model relates the increased cohesion provided by roots to the critical velocity which is needed to pick up sediment.

2.6 SUMMARY

This chapter covers the theory that is required to comprehend this study. It includes information about the coastal zone, hydrodynamics, and sediment movement during storms, as well as the influence of storms on dunes.

The mechanisms affecting dune vegetation during collision regime storm conditions are described. The main processes taking place can be categorized into hydrodynamic interaction and soil stabilization. Aboveground vegetation mainly results in hydrodynamic interaction, affecting the load on the dune. Belowground vegetation stabilizes the soil, which affects the resistance of the dune. Both vegetation components have been shown to affect erosion volumes and erosion rates during the collision regime. The majority of the existing research found that erosion volume has decreased in the presence of vegetation.

The collision regime can be divided into swash flow and direct wave impact. During swash flow, both the aboveground portions and belowground portions appear to be important. The interaction of the aboveground portions with hydrodynamics could result in a higher roughness, the attenuation of swash, a reduction in energy, a lower runup, and affecting reflection. Belowground portions change the physical properties of the dunes and alter the composition of sediment, aggregating the soil, and resulting in smaller sediment mobility. During wave impact, mainly slumping and avalanching cause dune erosion. The relevance of belowground vegetation is expected to increase during this process. This is attributable to the fact that roots may be able to survive collapse while still being rooted. Belowground portions change the physical properties of the dunes and alter the composition of sediment, aggregating the soil, resulting in more cohesion, larger shear strength, and subsequently higher critical angles.

The analytical wave impact model and the numerical model XBeach both seek ways to include vegetation as a factor in determining dune erosion volumes. However, they have not been validated for collision cases or in a large number of situations. Therefore, the approaches with vegetation are not used in dune design projects yet.

Part I

SIMULATING PHYSICAL DUNE EROSION EXPERIMENTS WITH XBEACH

3 METHOD PART I

3.1 INTRODUCTION

This chapter explains the methods used to reach the main objective of Part I of this thesis: simulate the potential impact of dune vegetation during collision storm regime conditions in the numerical model XBeach. This includes the collection, selection, and review of data, the tools used in this research, the steps followed, and the reasoning behind it. The background of the data and tools used are critical for evaluating the reliability and validity of this research.

Section 3.2 contains a description of the two experiments that were utilized. Section 3.3 describes information about the numerical model XBeach. A detailed discussion of four vegetation approaches is given. These vegetation approaches are being tested to determine if they can properly represent potential vegetation effects. The XBeach setup, calibration processes, and approach for the sensitivity analysis are also covered in this section. In section 3.4, the evaluation methods for the simulations are discussed. A summary of the steps followed is given in 3.5.

3.2 SELECTED EXPERIMENTS

To examine the ability of XBeach to simulate the effect of vegetation during the collision regime, data from two small-scale physical model wave flume studies are used: Bryant et al. [2019] and Mendoza et al. [2017]. The choice for both experiments is the data availability (Bryant [2021];Oderiz [2022]). In addition, Bryant et al. [2019] isolated different components of vegetation in his experiment. This enabled the quantification of the different components and therefore the different associated processes. Both laboratory studies used a scaled-beach dune system. From now on, these experiments will be referred to as the Bryant experiment and the Mendoza experiment.

3.2.1 Selected cases

The experiments of Bryant and Mendoza differ in setup and within the experiments, various boundary conditions were imposed. In this research, three boundary conditions are chosen to examine: called the Deep Collision (DC) test of Bryant, the first Shallow Collision condition (SC1) of Bryant, and the medium storm condition test with high vegetation density cover of Mendoza. These tests were chosen since for these three cases, the collision regime was observed. Furthermore, a large difference in erosion volume between cases with and without vegetation was noted. Figure 3.1 illustrates the cases selected. The same terminology that was used in previous studies will be employed in this research. In summary: two main experiments (Bryant and Mendoza) are used in this study. This includes in total three different hydrodynamic conditions. Two hydrodynamic conditions belong to the Bryant experiment (DC and SC1) and one to the Mendoza experiment (AS2). First, the cases without (3 in total) vegetation are calibrated. These settings are used as a basis to calibrate the vegetation cases (7 in total). The hydrodynamic conditions

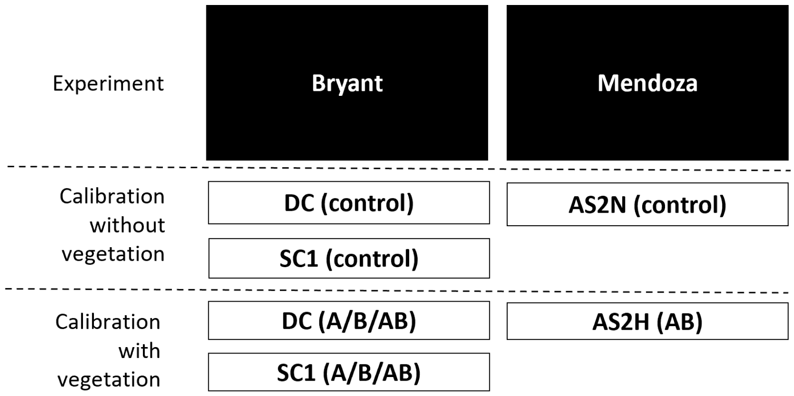


Figure 3.1: Illustration and names of experiments and cases used. In total 10 cases were considered. Control = no vegetation, A = aboveground vegetation, B = belowground vegetation, AB = above- and belowground vegetation

imposed are summarized in Table 3.1 and the results in terms of eroded volume and reduction are summarized in Figure 3.2. The DC case of Bryant has the largest absolute erosion volumes in both vegetated and not vegetated cases. It shows also the largest relative erosion reduction in presence of vegetation.

Table 3.1: Hydrodynamic conditions assessed experiments

	SWL [cm]	H_{m0} [cm]	T_p [s]	No. of bursts	Duration of wave burst [s]
Bryant DC	5	4.3	3.69	3	1200
Bryant SC1	0	7.4	3.69	3	1200
Mendoza AS2	5	10	1.56	1	900

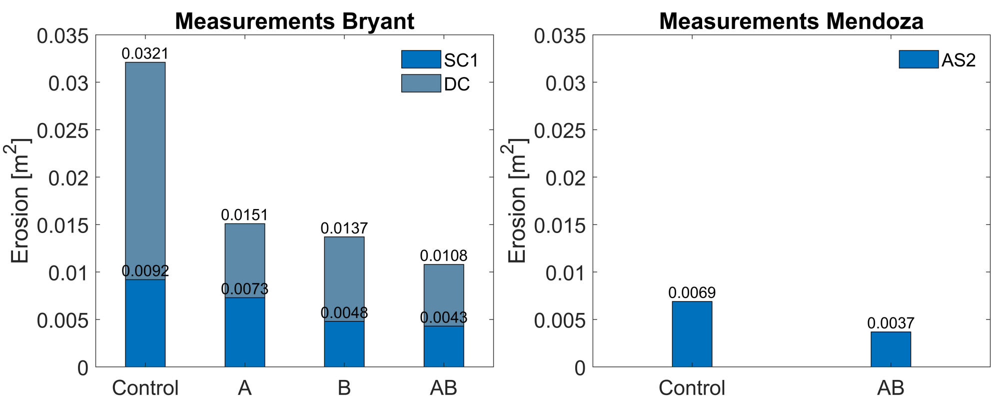


Figure 3.2: Results erosion volumes assessed experiments. Left the Bryant cases and right the Mendoza case.

3.2.2 Description Bryant experiment (DC and SC1 cases)

A short description of the Bryant experiment regarding the implementation of vegetation and relevant results are outlined. It is of great importance to know how vegetation is implemented in the experiments because different parts of vegetation affect different processes and the way vegetation is implemented could have implications for the outcomes and interpretation. In Appendix D a detailed description of the physical wave flume experiment is given.

The goal of this physical experiment was to quantify the engineering services dune vegetation provides in reducing erosion of dunes during scaled storm conditions by applying four different vegetation covers: no vegetation (control), aboveground (A), belowground (B), and above- and belowground together (AB). An illustration of the vegetation covers is displayed in Figure 3.3. The maximum erosion reduction was achieved by above and belowground vegetation, followed by isolated belowground vegetation, and lastly isolated aboveground vegetation.

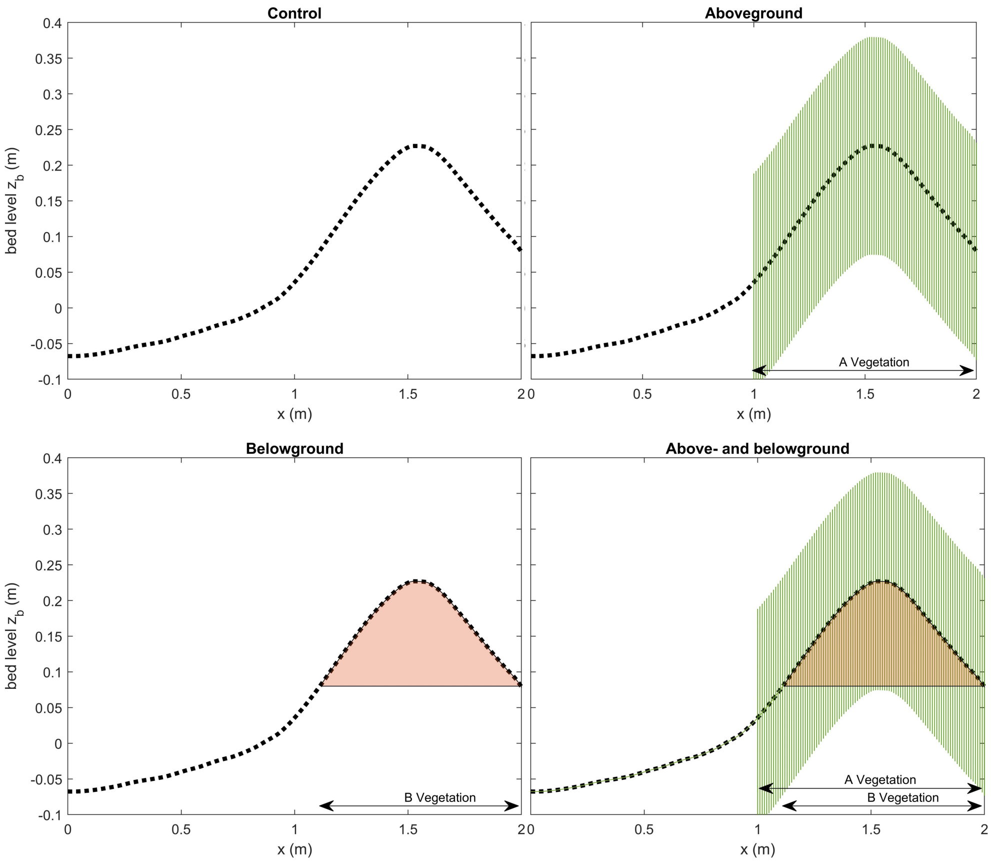


Figure 3.3: Illustration vegetation covers and dune profile Bryant experiment. The dunes without vegetation (also called control)

HYDRODYNAMIC INTERACTION (A) In this experiment, isolated aboveground vegetation (A) was represented by an array of wooden dowels on the cross-shore section of $1 < x < 2$ meter. The wooden dowels were based on dune vegetation samples with a diameter of 3.175 millimeters and a target density of 158 $stems/m^2$. The dowels were 15.25 centimeters incorporated into the surface and extend 15.25 centimeters above the surface. The dowels have been put down in a staggered grid with a spacing of 8 centimeters.

The A vegetation cover resulted in a reduction of eroded volume between 20-52 %, depending on the hydrodynamic conditions (Table 3.2). The upper picture in Figure 3.4 shows the incorporation of the wooden dowels in the physical experiment.

SOIL STABILIZATION (B) Natural coconut husk fibers were used to imitate belowground vegetation on the $1.15 < x < 2$ meter cross-shore section. The belowground mass density was calculated using measured belowground biomass from 12 different dune plant species (Feagin et al. [2019]). 300 grams of coir with 0.126 m^3 of dry sand were mixed, resulting in a laboratory belowground biomass density of 2380 m^3. This was mixed with sand from the dune using a mixer.

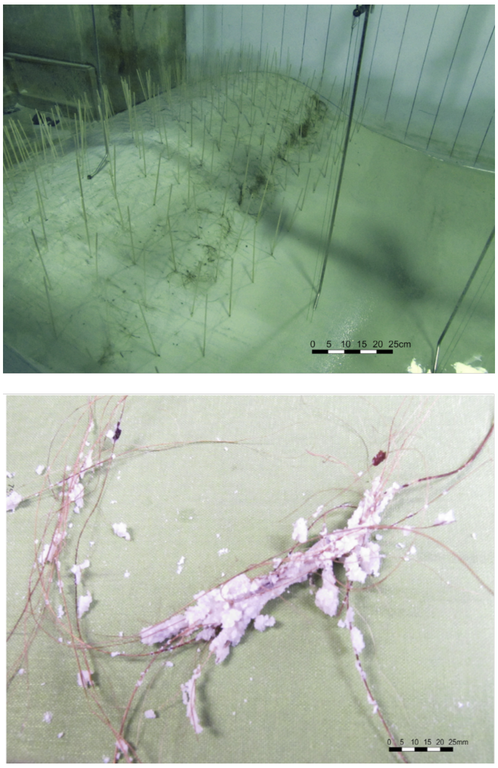


Figure 3.4: Above: wooden dowels Below: Sediment binding with coir fibers. Source: Bryant et al. [2019]

The B vegetation cover resulted in a large erosion reduction: varying between 47-57 %, depending on conditions (Table 3.2). Furthermore, the switch to the overwash regime was prevented. The lower picture in Figure 3.4 shows the sediment binding with coir fibers.

HYDRODYNAMIC INTERACTION AND SOIL STABILIZATION (AB) Both wooden dowels and coconut husk fiber were applied for the representation of both above and belowground vegetation.

The AB vegetation cover resulted in the largest erosion reduction: varying between 53-66%, depending on conditions (Table 3.2).

Table 3.2: Erosion volumes and reduction in erosion Bryant experiments

		Control	A	B	AB
Bryant DC	Erosion volume [m^3/m]	0.0321	0.0151	0.0137	0.0108
	Deviation erosion [%]	X	-52	-57	-66
Bryant SC1	Erosion volume [m^3/m]	0.0092	0.0073	0.0048	0.0043
	Deviation erosion [%]	X	-20	-47	-53

3.2.3 Description Mendoza experiment (AS2 case)

A brief summary of the Mendoza experiment with reference to the application of vegetation is provided, as well as important outcomes. The main focus of the Mendoza experiment was whether vegetation alters the response of beach–dune systems to storm-induced waves. 14 trials were conducted, which varied in hydrodynamic conditions and vegetation covers. The hydrodynamic condition with medium storm intensity which resulted in collision regime storm conditions and the highest vegetation cover is considered. The application of vegetation and the key findings of this case are described below.

HYDRODYNAMIC INTERACTION AND SOIL STABILIZATION (AB) In the experiment of Mendoza, real Ipomoea pes-caprae was used. These are creeping, dune-forming plants that are found in tropical and subtropical areas all over the world. They are typically the first to populate coastlines. Individual plants from the coast at the Veracruz field station were used to replicate the plants. Once the plants had grown robust enough to make the journey, they were taken to the laboratory. Vegetation was placed from the dune toe till the section where the slope turns horizontal on the lee side. The applied rooting depth was 10-20 centimeters and the plant height was 10 centimeters or lower. For the case considered, a plant density of 18 $branches/m^2$ was used. To set this parameter as close as possible, the surface of the dune was divided into 15 cm squares and the plants were distributed randomly in the squares until the desired coverage was reached. Figure 3.5 shows a picture of the dune with vegetation.

For the considered trial, the presence of plant cover resulted in a reduction of erosion volume of 46% (Table 3.3). The major morphological consequence of dune vegetation was to slow down erosion time. No direct relationship between the density of vegetation cover and the volume eroded was obtained.

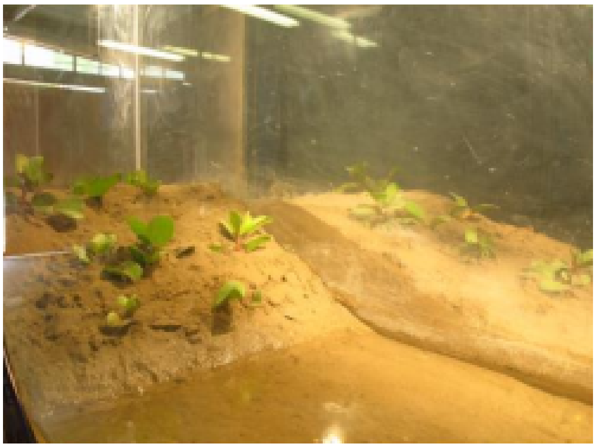


Figure 3.5: Ipomoea pes-caprae in Mendoza experiment. Source: Mendoza et al. [2017]

Table 3.3: Erosion volumes and reduction in erosion Mendoza experiment

		Control	A	B	AB
Mendoza AS2	Erosion volume [m^3/m]	0.0069	X	X	0.0037
	Deviation erosion [%]	X	X	X	-46

3.3 NUMERICAL MODELLING

In Part I, the numerical model XBeach is being used to simulate the potential impact of dune vegetation during collision regime storm conditions. The choice for the XBeach model in this research is first because XBeach is being used increasingly to define the minimum profile a dune needs to fulfill the flood protection function in dune rehabilitation projects. Secondly, different vegetation approaches were identified which could potentially be used to represent dune vegetation effects (section 2.4). The vegetation approaches are outlined in the following section.

3.3.1 Vegetation approaches XBeach

A general description of the XBeach model is given in Appendix C. In this subsection, the four vegetation approaches assessed in this research are further outlined.

- Roughness approach
- Vegetation module
- Root model
- Avalanching module

The link between the main processes, the description of the module and the approach in XBeach is summarized in Table 3.4.

Table 3.4: Identified vegetation approaches XBeach

Main Process	Description	Approach XBeach
Hydrodynamic interaction	Reduction flow velocity	Roughness approach (Constant)
	Reduction flow velocity + Effect erosion/sedimentation in time	Roughness approach (Dynamic)
	Short wave energy dissipation Attenuation long waves	Vegetation module (Short waves) Vegetation module (Mean flow & Long waves)
Soil stabilization	Increase in critical velocity and sediment pickup	Root model (Constant)
	Increase in critical velocity and sediment pickup +Effect erosion/sedimentation in time	Root model (Dynamic)
	Higher critical angle	Avalanching module

ROUGHNESS APPROACH Vegetation allows for a reduction in flow velocity. In turn, sediment transport and so erosion is affected by changes in flow velocity. The reduction of flow velocities due to vegetation is accounted for by the roughness approach. The presence of vegetation could be incorporated into the description of the bed friction coefficient (c_f). The bed friction coefficient can be defined using different formulations (Chezy: *Che*, Manning: n) and affects the bed friction and subsequently the bed shear stress (τ_b), which is associated with the mean flow and long waves. By applying larger bed friction coefficients (n) at vegetated sections, the spatial effect of vegetation on velocities is incorporated. This approach is called the constant roughness approach.

$$\tau_{bx}^{E} = c_f \rho u_E \sqrt{1.16 u_{rms}^2 + (u_E + v_E)^2} \tag{3.1}$$

$$c_f = \sqrt{\frac{g n^2}{h^{\frac{1}{12}}}} \tag{3.2}$$

In addition to the constant roughness approach, van der Lugt et al. [2019] created a dynamic roughness module that changes the bed friction coefficient because of burying and erosion in vegetated regions. During the erosion process, vegetation can uproot. This could result in a reduction of bed roughness, thereby increasing near-bed velocities and erosion rates. Vice versa, if a vegetated dune gets buried in sediment, the vegetation height decreases, reducing roughness. In formulation 3.3, n_0 is the initial Manning roughness for vegetation, n_{sand} the Manning roughness for bare sand, $\Delta z(t)$ the cumulative erosion/deposition. Two extra parameters have to be defined: the critical erosion depth *(droot)* and the critical deposition depth *(dstem)*.

$$n(t) = \begin{cases} n_{sand} + (n_0 - n_{sand}) \cdot min\left(max\left(0, \frac{dstem + \Delta z(t)}{dstem}\right), 1\right), & -dstem \leq \Delta z(t) < 0 \\ n_{sand} + (n_0 - n_{sand}) \cdot min\left(max\left(0, \frac{droot + \Delta z(t)}{droot}\right), 1\right), & \Delta z(t) \geq 0 \end{cases} \tag{3.3}$$

Table 3.5: Basic overview roughness approach

	Constant	Dynamic
Parameters	n	n, droot, dstem
Typical application	Vegetation presence	
Validation dune vegetation	Mostly used for overwash regime	Validated for overwash regime

VEGETATION MODULE The dissipation of energy induced by vegetation is incorporated into the vegetation module. By using this module, short waves, long waves and mean flow are affected. First, the implementation of short wave dissipation in XBeach is explained, hereafter the effect on the mean flow.

The short-wave dissipation in presence of vegetation in XBeach is incorporated with a specific algorithm van Rooijen et al. [2016], which quantifies the dissipation caused by vegetation into the wave dissipation term, using the approach of Mendez and Losada [2004], modified by Suzuki et al. [2012]. The dissipation is calculated as a function of the local wave height and several vegetation parameters. This wave dissipation term (*Dv)* is added to the short wave energy balance (Appendix C). Equation 3.4 is without the implementation of vegetation layers (*nv*) since this is most desirable for modeling mangrove species.

$$D_v = \frac{1}{2\sqrt{\pi}}\rho C_D b N \left(\frac{kg}{2\sigma}\right)^3 \frac{(sinh^3 k\alpha h - sinh^3 k\alpha h) + 3(sinhk - sinhk\alpha h))}{3kcosh^3 kh} H_{rms}^3 \quad (3.4)$$

b is the vegetation stem diameter, N is the vegetation density and α is the relative vegetation height (a/h), where a is the vegetation height and h the water depth. C_D is a bulk drag coefficient (van Rooijen et al. [2016]) that includes all phenomena contributing to the drag: pressure differences, skin friction, plant swaying, attenuation of orbital motion and interaction between individual waves in dense vegetation fields. This implementation is tested using lab experiments with submerged model kelp vegetation carried out by Kansy (1999).

The presence of vegetation within the area of wave propagation or wave breaking may not only result in short wave dissipation but also damping of infragravity waves and/or mean flow. The onshore-directed plant-induced force acting on the column in presence of vegetation is formulated with a Morison type equation in XBeach (Dalrymple et al. [1984]). The plant swaying motion and inertial forces are neglected and this drag force is directly added to the momentum equations (Appendix C). To take into account the velocity due to mean flow and infragravity waves, the Eulerian velocity (u^E) is used.
Along with the short wave dissipation by vegetation, this formulation is tested using lab experiments with submerged model kelp vegetation carries out by Kansy (1999).

$$F_{veg}(t) = \int_{\alpha,h}^{\alpha,h} \frac{1}{2}\rho C_D bvNu^L(t)|u^L(t)|dz \quad (3.5)$$

Table 3.6: Basic overview vegetation module

	Short waves	Long waves and/or mean flow
Parameters	Cd, b, N, a, n	
Typical application	Aquatic vegetation (vegetation with presence of waves, mangrove forests, kelp vegetation, salt marshes, etc.)	
Validation dune vegetation	Not yet validated. Approach is used by Fernandez-Montblanc (2020) to assess effect of dune vegetation on erosion and flooding. This model seems to overestimate the reduction of the erosion induced by vegetation	

ROOT MODEL Schweiger and Schuettrumpf [2021a] has included the influence of belowground (land-based) biomass on decreasing dune erosion volumes into the XBeach code. They extended XBeach's code with a root model based on the widely used slope stability analysis developed by Wu et al. [2011]. The main concept is to raise the critical velocity (u_{cr}) for erosion attributed to higher root cohesion provided by belowground biomass until cumulative erosion exceeds a user-defined constant rooting depth (*zroot*). The critical velocity is raised as long as the cumulative erosion is less than the rooting depth. The belowground biomass and its effect are removed when the cumulative erosion exceeds the rooting depth. All roots break fully and simultaneously and hence the tensile strength of all roots is mobilized at the same time when a shear failure occurs. The critical velocity is calculated with equation 3.6. This critical velocity defines the equilibrium sediment concentration, which is used as an input in the advection-diffusion equation, controlling sediment transport (Appendix C.

$$u_{cr,total} = u_{cr} + \underbrace{rcc(t) * \sqrt{\frac{1}{\rho} * C_r}}_{u_{cr,root} = \text{additional critical velocity due to root cohesion}} < \Delta zb(t) < 0 \quad (3.6)$$

The additional root cohesion (C_r) is represented as follows, where t_r is the root tensile strength [kN/m2] and RAR is the root area ratio defined as the fraction of soil cross-sectional area occupied by roots per unit area (De Baets et al., 2007).

$$C_r = 1.2 * RAR * t_r \quad (3.7)$$

1 ρ * C_r (root cohesion) is normalized by 1 to be able to calibrate the model only by varying the root cohesion coefficient (*rcc*). Consequently, a *rcc* of 1 is equal to an increase of u_{cr} by $u_{cr,root}$ = 1 m/s. Figure 3.6 shows the proposed relation between vegetation characteristics and the *rcc* value in the root model.

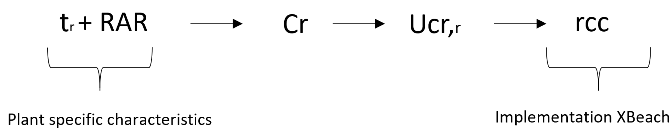


Figure 3.6: Relationship between vegetation characteristics and the rcc value in the root model

The value of *rcc* is steered by either the constant mode or the dynamic mode. The constant mode has a constant higher u_{Cr} due to the extra $u_{cr,root}$ in the region where roots are applied. The dynamic mode results in a lower $u_{cr,root}$ when erosion occurs. The differences are given in equation 3.8.

$$rcc(t) = \begin{cases} rcc_0 & constant \\ 0 + min\left(max\left(\frac{z_{root}+\Delta zb(t)}{z_{root}}, 0\right), 1\right) \cdot rcc_0, & dynamic \end{cases} \quad (3.8)$$

The additional root cohesion predicted by the Wu-Model should be seen as a proxy for an increased erosion resistance of the topsoil due to the presence of roots, namely the root model does not account for any biological, chemical, or physical processes that are inherent to plant roots. The root model validation presented by Schweiger and Schuettrumpf [2021b], only applies to the collision regime at small-scale due to the non-occurrence of dune overwash in all simulations.

Table 3.7: Basic overview root model

	Constant	Dynamic
Parameters	rcc	rcc, zroot
Typical application	Belowground biomass presence	
Validation dune vegetation	Validation collision regime small scale	

AVALANCHING As mentioned in the literature review, the maximum steepness of a dune might be affected by vegetation. The avalanching algorithm in XBeach accounts for the critical angle.

The sediment supply from the dune is simulated with a relatively simple tool in XBeach: an avalanche algorithm (van Thiel de Vries et al. [2008]). Figure 3.7 illustrates how this method works. The avalanche algorithm considers a wet and a dry zone, determined by a user-specified water depth (*hswitch*). For these zones, a critical wet slope (φ,cr_{wet} = *wetslp)* and a critical dry slope (φ,cr_{dry}= *dryslp)* should be defined. The critical wet slope to critical dry slope transition occurs at a user-specified water depth. When a critical slope is surpassed, material is exchanged between neighboring cells in the volume needed to return the slope to the critical slope. Equation 3.9 shows the implementation in XBeach.

$$\Delta z_b(t) = \begin{cases} min\left(\left(\frac{\delta z_b}{\delta x} - \phi_{cr,wet/dry}\right)\Delta x, \quad v_{av,max}\Delta t\right), \\ \frac{\delta z_b}{\delta x} > 0 \\ max\left(-\left(\frac{\delta z_b}{\delta x} - \phi_{cr,wet/dry}\right)\Delta x, \quad -v_{av,max}\Delta t\right), \\ \frac{\delta z_b}{\delta x} < 0 \end{cases} \tag{3.9}$$

Between the fat gray dashed-dotted and fat gray dashed line the bed level points are unstable (Figure 3.7). This means that the observed critical slope is higher than the defined critical slope ($\varphi > \varphi\ cr_{,wet}$). In the avalanching zone, there are three bed level points. The most seaward point avalanches first. Hereafter point two and hereafter point three (most far away from the sea). The black dashed line is the profile after avalanching. The new bed is not always stable, as can be observed. More avalanches may occur in the subsequent time step. For example, the first dry point steepens in this case, and might become unstable in the next time step ($\varphi > \varphi\ cr_{,dry}$). The critical wet slope is usually smaller than the critical dry slope because wet sand slides easier than dry sand.

Bottom update due to avalanching has been limited to a maximum avalanching transport rate to avoid the formation of significant shockwaves owing to rapid changes in bed level (*dzmax*). This value could also be specified (Van Thiel de Vries, 2009). It is important to note that the transition between wet and dry cells is not fixed at one specific bed level point, but is dependent on the sediment transport capacity of nearshore hydrodynamics and the *hswitch*.

Table 3.8: Basic overview avalanching module

	Standard
Parameters	wetslp ($\varphi\ cr_{,wet}$), dryslp ($\varphi\ cr_{,dry}$), hswitch, dzmax
Typical application	Standard implementation in XBeach model. Default settings for the wet and dry slope parameters in XBeach are based on field observations of post-storm dune slopes. It is greater than the angle of natural repose and can be interpreted as an average slope after dune erosion, with some areas having vertical slopes and others having slumped even more.
Validation dune vegetation	Not specific used for the representation of vegetation

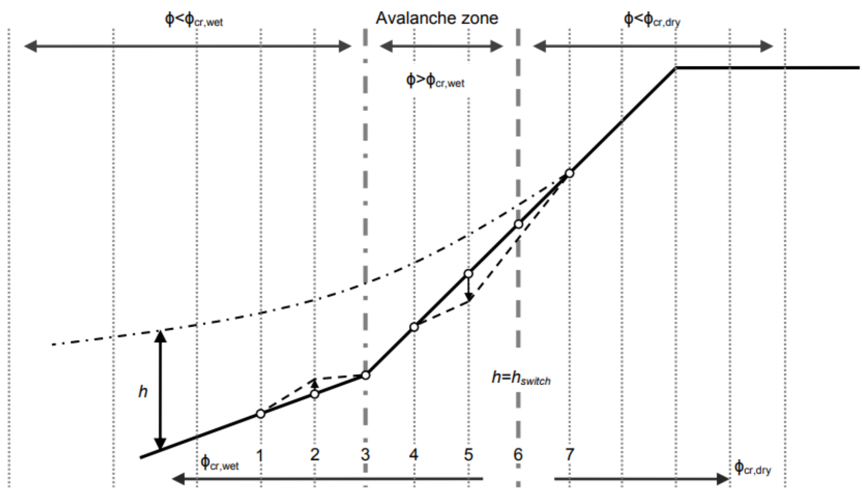


Figure 3.7: Illustration of the avalanching algorithm in XBeach. The solid line is the bed at t=start. The dashed black line is the bed when avalanching has taken place. The Black dashed-dotted line is the water surface. Vertical gray dotted, dashed and dashed-dotted lines are computational bed level points. Source: van Thiel de Vries et al. [2008]

3.3.2 XBeach basic model setup

Two different XBeach models were setup. The setup in XBeach for both experiment is discussed. The essential parameters are provided in Table 3.9.

Table 3.9: Essential parameters setup XBeach Bryant and Mendoza

Parameter	Description	Bryant	Mendoza
nx/ny	1D grid	487/2	1109/2
Δx_{max} / Δx_{min}	max/min cell size	1m/0.05m	0.25m/0.0008m
dtheta	wave bin size	180 degrees	180 degrees
zso	constant water level	0 m (SC1)/0.05 m (DC)	0.05 m
rhos	water density	1000 kg/m^3	1000 kg/m^3
front/back	seaward and coast boundary condition	wall/abs_1d	abs_1 d/abs_1d
left/right	lateral boundary condition	wall/wall	wall/wall
form	sediment transport formulation	vanthiel vanrijn	vanthiel vanrijn
depthscale	depthscale of labtest simulation, affects eps, hmin, hswitch and dzmax	15	20
wavemodel	timescale to resolve waves	surfbeat	surfbeat
wbctype	wave boundary condition type	parametric: jonswap with TMA = 1, gammsjp =3.3	parametric: jonswap with TMA = 1, gammsjp =3.3
morfac	morphological acceleration factor	1	1
D50	0.00015 m	0.00015 m	0.000142 m

BRYANT Schweiger and Schuettrumpf [2021b] built an XBeach set-up for the Bryant belowground experiment (B) in order to enhance the XBeach model's ability to forecast dune erosion in the presence of belowground biomass under various hydrodynamic circumstances. In the present research, the same setup is used (Figure 3.8). The model is one dimensional with a small grid size of 0.05 at the location of the waterline and a grid size of 1 meter more offshore (Δx_{min} / Δx_{max} = 0.05/1).

No morphological acceleration was applied to accelerate the simulation (morfac = 1). The default settings of XBeach were designed for prototyping scale. Since the physical experiment of Bryant was conducted at 1:15, the parameter *depthscale* has been adjusted to 15. This scales the model parameters *eps, hmin, hswitch and dzmax* related to sediment transport and morphodynamic processes (Brandenburg [2010]. A 1D absorbing weakly reflecting condition was applied on the back and a wall condition on the front, since the wavemaker could not absorb reflected waves (*front/back* = wall/abs_1d). The lateral boundaries were set to walls (*left/right* = wall).

The water level was set to 0 m reference height (0.3 m above the flat testing area) for the shallow collision conditions (SC1) and 0.05 m for the deep collision conditions (DC) over the entire length of the model including the section behind the dune (*tideloc* = 0). Because both were not included in the physical model setup, active reflection compensation (ARC = 0) and the formation of bound long waves (*order* = 1) was prevented. Waves have been simulated with irregular waves type JONSWAP. The conditions are summarized in Table 3.1.

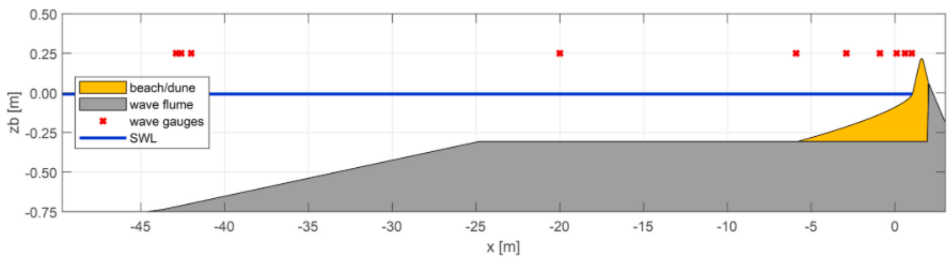


Figure 3.8: XBeach model set-up Bryant experiments. Data for profile evolution is available for $0 < x < 2$ m. Source: Schweiger and Schuettrumpf [2021a]

MENDOZA Also for the Mendoza experiment, a one-dimensional XBeach model was set up. The grid size was set to nx = 1109 cells with a variable mesh (Δx_{min} /Δx_{max} = 0.0.0008/0.25). Furthermore, a Manning roughness was applied with a value of 0.03 throughout the cross-section. The physical experiment of Mendoza was conducted at a 1:20 scale, so the parameter *depthscale* was adjusted to 20. This scales the model parameters *eps, hmin, hswitch and dzmax* related to sediment transport and morphodynamic processes (Brandenburg [2010]). Different from the Bryant setup, 1D absorbing weakly reflective conditions are imposed on both on- and offshore boundaries (front/back = abs_1d). A dynamic wave absorption system was installed on the wave generator, absorbing reflected waves.

The water level was set to 0.05 m, with as reference height the flat stretch at the back of the dune. The generation of bound long waves was restricted (order = 1). The lateral boundaries and the onshore boundary as walls (left/right = walls). Waves have been simulated with irregular waves type JONSWAP. 3.1 provides the hydrodynamic conditions imposed.

3.3.3 Procedure calibration and validation cases without and with vegetation

For both experiments, the cases without vegetation and with vegetation are calibrated. First, the procedure for the calibration of the nonvegetated dunes is outlined. The calibration strategy for the vegetated dunes is provided after that.

CASES WITHOUT VEGETATION The Bryant experiment is hydrodynamically and morphodynamically calibrated. The Mendoza experiment was not hydrodynamically calibrated, since this data was inaccessible. However, because this experiment is used as verification for the findings of the Bryant experiments, it is presumed that the absence of hydrodynamic calibration has no impact on the verification.

To hydrodynamically calibrate the Bryant model, the following approach is used: the simulations were conducted with the morphology switched off. The sea swell and infragravity waves from the raw wave data were split using generating a spectrum (Appendix F). The obtained high-frequency wave heights ($H_{rms,hf}$) from this data processing were compared with the time-averaged spatial output H_{mean} from the XBeach simulation. H_{mean} (simulated) represents the $H_{rms,hf}$ (measured) averaged over time interval. The hydrodynamic calibration is performed by systematically changing *gammax* (maximum ratio wave height to water depth), *alpha* (wave dissipation coefficient in roelvink formulation) , *n* (power in roelvink dissipation model), *delta* (fraction of wave height to add to water depth) and *gamma* (breaker parameter in Baldock or Roelvink formulation).
Regarding the morphodynamic calibration of the control cases without vegetation, the adjustment of *dryslp* (critical avalanching slope above water), *facua* (calibration factor time-averaged flows due to wave skewness and asymmetry), and *bermslope* (swash zone slope for (semi-) reflective beaches) has been applied.

CASES WITH VEGETATION The measured cases with vegetation are used to test the potential and performance of the four different vegetation approaches to represent the effect of vegetation in XBeach. In turn, these vegetation approaches are calibrated. The roughness and vegetation modules are tested to represent the aboveground vegetation and the associated hydrodynamic changing processes. The root model and the avalanching module account for soil stabilization and thus the belowground effect of vegetation. For the calibration of the vegetated cases, all possible combinations are illustrated in Figure 3.9.

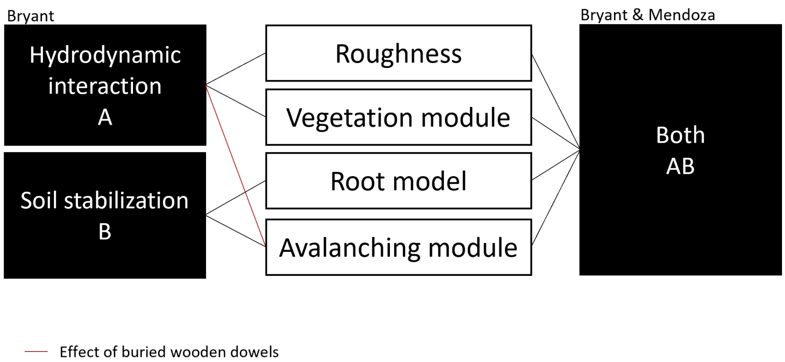


Figure 3.9: Overview combinations possible for calibration vegetation cases Bryant and Mendoza physical experiments

3.3.4 Procedure sensitivity analysis vegetation parameters

The approach for the sensitivity analysis and choice of parameters is presented. An overview of the parameters, standard settings in XBeach, common values for dune vegetation, values obtained from Bryant and Mendoza experiments, the range for the sensitivity analysis, and optional reference for parameter sensitivity are given in Figure 3.10.

Approach	Parameter	Description	Standard setting	Common values dune vegetation*	Values based on Bryant experiment (section 3.2)	Values based on Mendoza experiment (section 3.2)	Value range for sensitivity analysis	Reference for parameter sensitivity (DC/SC1/AS2)
Roughness	n [s/m ^1/3]	Manning roughness	X	0,04- 0,06	X	X	0,004 - 2	0,08/0,08/X
	droot [m]	Rooting depth	X	X	0,12	0,1-0,2	0,01 - 5	0,12/0,12/X
	dstem [m]	Stem height	X	0,09 – 0,77	0,1525	0,1	0,001525 - 15,25	0,1525/0,1525/X
Vegetation module	ah [m]	Height of vegetation section relative to the bed	X	0,09 – 0,77	0,1525	0,1	0,001525 - 15,25	0,1525/0,1525/X
	N [units/m2]	Density	X	5 – 20000	158	18	1,58 - 1580	158/158/X
	Cd [-]	Drag coefficient	X	X	X	X	0,5 - 3	1/1/X
	bv [m]	Stem diameter	X	0,002 – 0,007	0,003175	X	0,002 - 0,3	0,003175/0,003175/X
Root model	rcc [-]	Root cohesion coefficient	X	0-5	X	X	0-5	0,1/0,1/0,1
	zroot [m]	Rooting depth	X	0,01-20	0,12	0,1-0,2	0,01 - 5	0,5/0,5/0,5
Avalanching	wetslp [-]	critical slope wet cells	0,3	X	X	X	0,2-2	0,3/0,3/0,3
	dryslp [-]	critical slope dry cells	1	X	X	X	0,2-2	0,2/1/1,2
	dzmax [m/s/m]	Maximum bed level change due to avalanching	0,05	X	X	X	0-1	0,05/0,05/0,05
	hswitch [m]	Water depth at which is switched from wetslp to dryslp	0,1	X	X	X	0,01-1	0,1/0,1/0,1

*Sources: provided in text

Figure 3.10: List of parameters and range tested, common values for dune vegetation, values used in the physical experiments of Bryant and Mendoza

ROUGHNESS In this analysis, values between 0.004 and 2 are tested. Average values of Mannings roughness coefficient based on CORINE land cover data for scrub and/or herbaceous vegetation associations lies between 0.04 and 0.06, while a bare dune often has a value of 0.02 (Papaioannou et al. [2018]). The stem height (*dstem*) of dune vegetation assessed by Feagin et al. [2019] was between 0.09 and 0.77 meter. The analysed dstem varied between 0.05 and 1 meter. No specific values for rooting depth were found for dune vegetation. The rooting depth (*droot*) for the dynamic approach is varied between 0.05 and 5. To test the sensitivity, reference values were used:$n = 0.08$, $dstem = 0.1525$ and $droot = 0.12$.

VEGETATION MODULE The vegetation module has the most variables and it is important to consider realistic combinations of the density (N) and the vegetation diameter (b). A large variation in dune vegetation densities ($stems/m^2$) is reported (5-20000 $stems/m^2$) (Mendoza et al. [2017];Feagin et al. [2019];Fernández-Montblanc et al. [2020]). To test the sensitivity, a range of 1.58 - 1580 was applied. Dune vegetation diameters found in literature vary between 0.002 meter and 0.007 meter (Fernández-Montblanc et al. [2020]; Feagin et al. [2019]). A range of 0.002 and 0.3 is applied to test sensitivity. The vegetation height (a) is similar to the *dstem* in the dynamic roughness approach. Unfortunately, no values for dune vegetation were found in the literature for the drag coefficient (C_D). C_D is varied between 0.5 and 3. 3 is the largest recommended value in XBeach. To assess the sensitivity, the following values are used as reference $N = 158\ stems/m^2$, $a = 0.1525$ m, $b = 0.0003175$ m and $C_D = 1$.

ROOT MODEL The effect of the cohesion coefficient *rcc* on the sediment transport and subsequent profile is assessed with values between 0.05 and 5. This is based on equation 3.7, which describes the cohesion due to roots. The root area ratio (RAR) and tensile strength (t_r) are plant-specific. Critical velocities provided by roots are between 0-5 m/s for characteristics of dune vegetation, according to calculations of Schweiger and Schuettrumpf [2021a].

AVALANCHING The avalanching module has four variables: *wetslp*, *dryslp*, *dzmax* and *hswitch*. *wetslp* and *dryslp* are varied between 0.2 and 2, *dzmax* and *hswitch* between 0.01 and 1. The default values for the wet and dry slope limits in XBeach are based on typical post-storm dune slopes observed in the field (Roelvink et al. [2009]). It is greater than the angle of natural repose and must be viewed as an average slope following dune erosion, with some areas having vertical slopes and others having slumped even more. For reference, table 3.10 show the critical values in XBeach and the corresponding slope in degrees.

Table 3.10: Critical slopes in XBeach and the relation to degrees

critical slope XBeach [-]	0.2	0.5	1	1.5	2
angle [°]	11.3	26	45	56	63

3.4 EVALUATION METHOD

The evaluation of the simulation of the physical experiments within XBeach has been performed by different parameters, summarized in Figure E.1. The hydrodynamic evaluation of Bryant is performed for the two hydrodynamic conditions (DC and SC1) apart, by evaluating the Mean Error (ME) and a qualitative evaluation. The assessment of the hydrodynamic conditions apart from each other deviates from the study of Schweiger and Schuettrumpf [2021b], who tried to find one parameter which fitted all hydrodynamic conditions. The morphodynamic calibration for both experiments is done by evaluating the reduction erosion volume, the Brier Skill Score (BSS), and the Root Mean Square Error (RMSE). For the explanation and the formulations of these parameters is referred to Appendix E.

Table 3.11: Evaluation parameters

Evaluation	Parameter	Description	Ranges
Hydrodynamic	ME	Mean Error	0: perfect prediction
Morphodynamic	RMSE	Root Mean Squared Error	low value: good performance
Morphodynamic	BSS	Brier Skill Score	bad (< 0), poor (0–0.3), fair (0.3–0.6), good (0.6–0.8) (van Rijn et al., 2003)
Morphodynamic	X	Erosion volume	X

3.5 SUMMARY STEPS

This chapter covers the methods that are used for Part I of this study. Different steps are followed to answer the question whether the numerical model XBeach is capable of reproducing the effects of vegetation during the collision regime. These are visualized in Figure 3.11. First the physical wave flume experiments of Bryant and Mendoza, outlined in section 3.2, without vegetation are calibrated in the numerical XBeach model. On the Bryant calibrated cases without vegetation, four different vegetation approaches, discussed in section 3.3.1, are applied to test the performance and sensitivity of the approaches. The potential of these vegetation approaches to represent vegetation during collision regime storm conditions will be evaluated. Following that, the best matching settings in terms of eroded volume and profile evolution are applied by means of the evaluation parameters discussed in section 3.4. The best performing approaches are then applied on the vegetated Mendoza experiments for calibration and verification of the findings. Finally, a parameter sensitivity analysis is conducted. The approach and choices within this analysis are explained in 3.3.4.

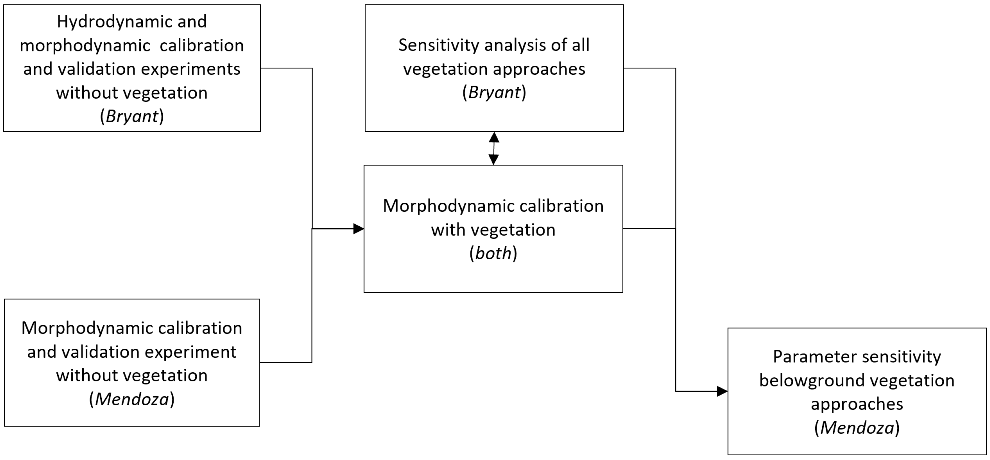


Figure 3.11: Overview steps followed part I

4 RESULTS PART I

4.1 INTRODUCTION

This chapter presents the results of the present performance of XBeach to simulate erosion of vegetated dunes during collision regime storm conditions. Four vegetation approaches were evaluated to see if they could adequately represent dune vegetation processes and impacts.

In section 4.2 the results of calibration and validation without vegetation are given for both Bryant and Mendoza experiments. The results of the XBeach calibration and validation for the cases including vegetation are presented in section 4.3. Section 4.4 provides a sensitivity analysis for the different vegetation approaches. All sections end with a short overview of the results. An overall summary of this chapter is given in section 4.5.

4.2 CALIBRATION AND VALIDATION CASES WITHOUT VEGETATION

A good calibration for the not vegetated cases allows for a good starting point regarding the assessment of the vegetation approaches. The final settings after hydrodynamically and morphologically calibrating the models are shown in Table 4.1. For information about the differences between the different cases (DC/SC1/AS2N) is referred to section 3.2.1 and Appendix D.

An overview of the final settings applied is given in Table 4.1.

Table 4.1: Calibration Bryant cases (DC and SC1) and Mendoza case (AS2) without vegetation

Parameter	Default	Value Bryant DC	Value Bryant SC1	Value Mendoza AS2
taper	100	0	0	default
n	10	default	default	default
alpha	1	default	default	default
gamma	0.55	default	default	default
delta	0	default	1	default
dryslp	1	0.2*	default	1.2
wetslp	0.3	default	default	default
swrunup	0	default	default	default
form	1	default	default	default
facua	0.1	0.35	0.35	0.35
bermslope	0.1	0.2	0.2	0.2
bermslopefac	15	20	20	20
turb	on	default	default	default

* to account for non-simulated runup and possible other processes which moisten the sediment at the duneface

4.2.1 Bryant

The calibrated and validated profile of the DC case show a good matching dune profile (BSS = 0.84) and a difference in reduction in eroded volume of only 3% percentage point (Figure 4.2). The final calibrated SC1 profile show a good matching dune profile (BSS =0.8) and a negligible underestimation of relative eroded volume (-1%) (Figure 4.3).

HYDRODYNAMIC CALIBRATION The hydrodynamic calibration has been conducted by changing the taper parameter to 0 for both cases. This resulted in the smallest Mean Error for the DC experiment. In the SC1 experiment, the delta was reduced to 0 in addition to the taper adjustment. Figure 4.1 shows the comparison of measured and simulated $H_{rms,hf}$ (sea-swell waves) for both cases. The fit is assumed to be good for this study. Especially the low wave height at the left of the wave flume has been simulated well. When the waves break, the accuracy becomes smaller. The model is sensitive for the moment of breaking of the wave. In general, good confidence in the model performance regarding hydrodynamics is obtained.

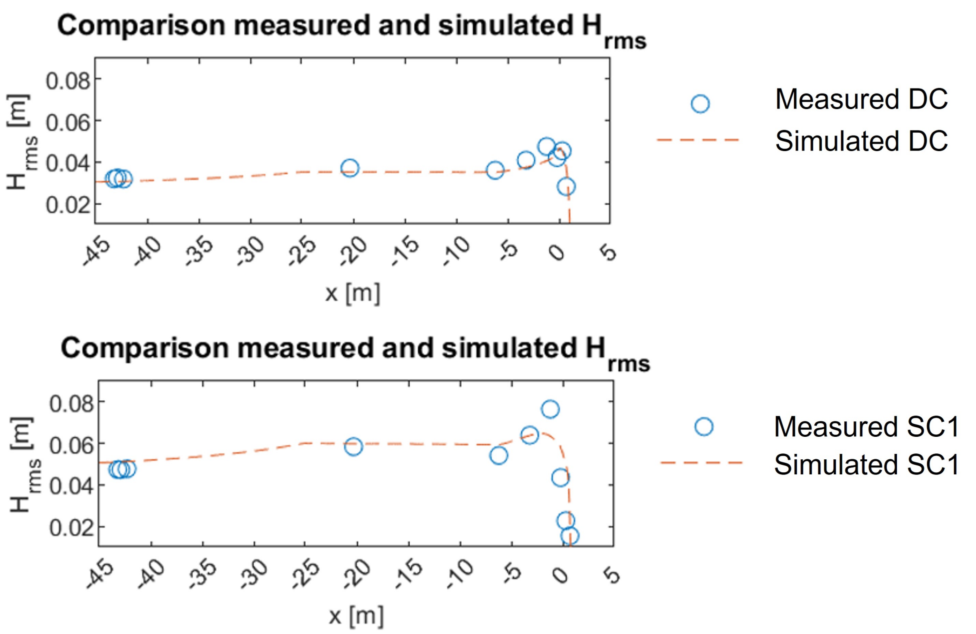


Figure 4.1: Hydrodynamic calibration Bryant DC (above) and SC1 (below) with the measured and simulated high-frequency wave height (sea-swell waves).

MORPHODYNAMIC CALIBRATION The profile change for the DC control experiment were simulated accurately by changing the parameters *bermslope* and *facua* and *dryslp*. Without this calibration, an underestimation of the final dune profile is observed (Figure 4.2). The overestimation of erosion might be caused by errors in the swash zone sediment motion modeling. This has been shown in other research as well (Berard et al. [2017] and Van Dongeren et al. [2009]). The parameters *bermslope* and *facua* were adjusted to account for two processes: berm growth and sediment transport onshore due to wave asymmetry. The *bermslope* module affects the sediment transport, berm growth, and profile slope. Complex nearshore processes are taken into account in a sediment transport correction calculation in this way. This module pushes the profile to a particular slope (van Dam [2019]). If the slope is smaller than the recommended slope, a strong local onshore transport of sediment will be provided. The parameter *facua* determines the effect of the waveform on the sediment transport, which is also important in the nearshore. *facua* has a wide range of values in literature and is frequently used to account for phenomena other than waveform. Examples include inaccuracies in other inputs such as high offshore water levels, wave heights, or bed roughness (Splinter and Palmsten [2012]).

Regarding the DC case, initially, no overwash was observed (Figure 4.2). An explanation for the underestimation of erosion and subsequent overwash could be the occurrence of the continuous undermining of the dune face in conjunction with deeper water resulting in alteration of pore pressure between sand grains. Palmsten and Holman [2011b] showed that this mechanism could affect dune survival. On top of that, inflow could make the boundary layer thinner, increasing shear stresses and so more erosion (Nielsen, 2008). Ultimately, a *dryslope* of 0.2 gave good results. This is around the value of *wetslope*. The influence of the wetted sand by the (not-simulated, but occurring) run-up and the subsequent avalanching process were incorporated by this adjustment. What exactly resulted in the missing overwash is unknown. It should be emphasized that in situations when waves directly impact a dune, the hydrodynamic and sediment transport conditions in the swash zone are highly complicated.

For the morphodynamic calibration of SC1, the same parameters were adjusted (*facua*, *bermslope*), resulting in a BSS of 0.79. The default value for the dry slope is preserved. This can be explained by the lower water level, resulting in no continuous undermining of the dune face and thus no indication of other processes affecting the erosion.

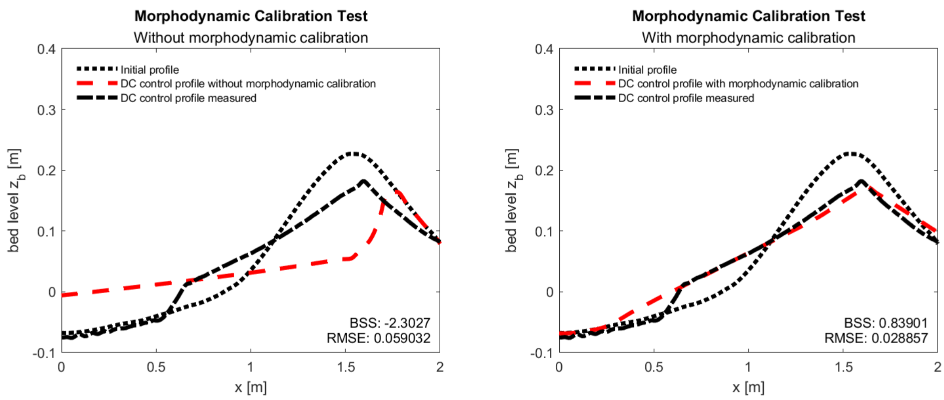


Figure 4.2: Profiles of Bryant DC simulation without morphodynamic calibration (left) and with morphodynamic calibration (right)

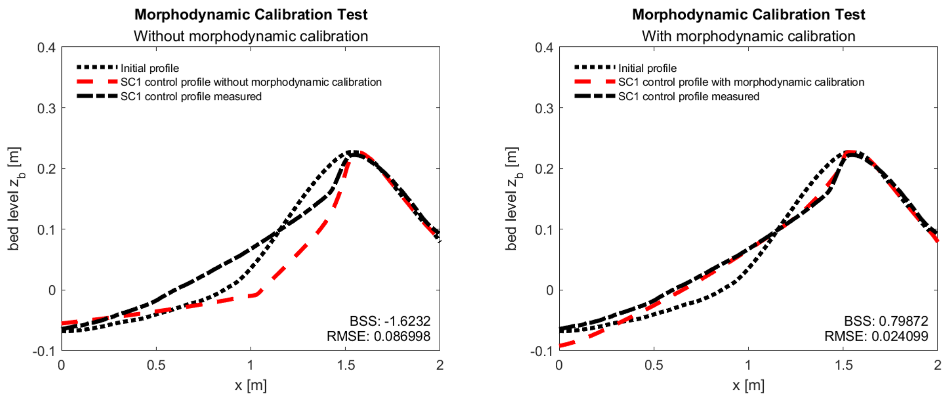


Figure 4.3: Profiles of Bryant SC1 simulation without morphodynamic calibration (left) and with morphodynamic calibration (right)

4.2.2 Mendoza

The Mendoza experiment is calibrated without vegetation to test and verify the Bryant case findings on a different experiment. The *facua* and *bermslope* parameters have been changed in the same way as the Bryant calibration. The final profile results in a similar simulated erosion as measured (0.0068 m^2 measured and 0.0069 m^2 simulated). The prediction of the model is less accurate than the initial profile. The AS2N control profile with morphodynamic calibration, on the other hand, is more comparable to the observed final profile than the initial.

Without calibration, erosion starts low at the dune and dune face. This is different from the experiment since in the experiment, the erosion is only at the top of the dune, and sediment is deposited at the dune toe and berm. The not-calibrated profile evolution of the Mendoza experiment coincides with the not-calibrated profiles of the Bryant experiments. The adjustment of *facua* and *bermslope* also results in better simulations regarding the eroded volume and the profile. No further changes in the setting have been applied. An extra uncertainty factor for this case is the missing of a hydrodynamic calibration.

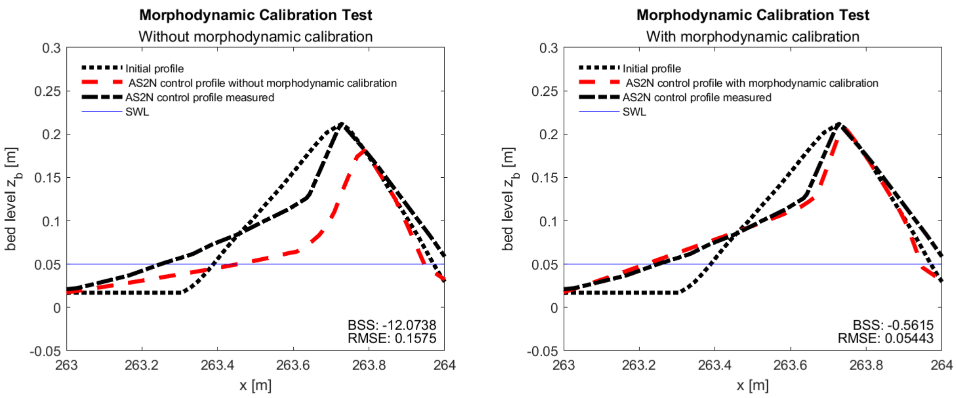


Figure 4.4: Profiles of Mendoza AS2N simulation without morphodynamic calibration (left) and with morphodynamic calibration (right)

4.2.3 Overview results cases without vegetation

The calibration of the control cases resulted in DC in a small overestimation. For the SC1 and AS2H in a small underestimation.

Table 4.2: Overview results simulation without vegetation

Case	Simulation eroded volume $[m3/m]$	Measured eroded volume $[m3/m]$	Difference simulation and measurement [%]	BSS	RMSE
DC Control	0.0330	0.0321	+3	0.84	0.013
SC1 Control	0.0085	0.0092	-8	0.80	0.024
AS2 Control	0.0068	0.0069	-1	-0.56	0.054

4.3 CALIBRATION AND VALIDATION CASES WITH VEGETATION

The findings of the calibration of the experiments with vegetation are presented in this section. The goal was to match the dune profiles and erosion volumes. This was done while considering the various processes that could occur in the experiments. The results presented include tables with final parameters and graphs with profile evolution and eroded volumes.

The choice of values for parameters and the combination of different vegetation approaches are explained in Appendix G and the final settings of the calibration parameters are listed in Table 4.3.

Table 4.3: Calibration Bryant cases (DC and SC1) and Mendoza case (AS2) with vegetation. In bold the changed parameters to account for vegetation.

	dryslp	wetslp	rcc
Default	1	0.3	X
DC Control	0.2*	0.3	X
SC1 Control	1	0.3	X
AS2 Control	1.2**	0.3	X
DC A	**0.5**	0.3	X
SC1 A	1	**0.4**	X
DC B	**0.5**	0.3	**0.05**
SC1 B	1	**0.5**	**0.05**
DC AB	**0.5**	0.3	**0.18**
SC1 AB	1	**0.5**	**0.08**
AS2 AB	1.2	**0.4**	**0.35**

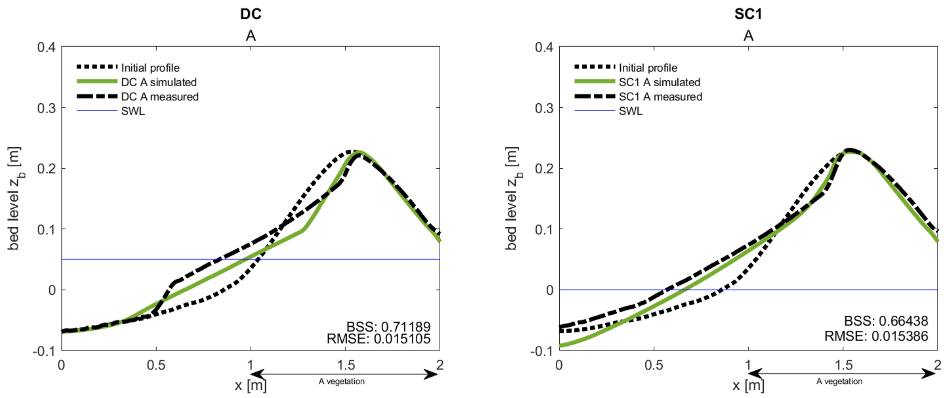
* to account for non-simulated runup and possible other processes which moisten the sediment at the duneface

** to account for initial steep slope

4.3.1 Bryant

HYDRODYNAMIC INTERACTION – ABOVEGROUND VEGETATION The predicted final profile (black dotted line) for the DC and SC1 condition is compared to the observed final profiles with vegetation (green line) in Figure 4.5. For the aboveground DC case, adjusting the dryslope to a higher value results in a well predicted profile and eroded volume. This is reflected by the BSS of 0.71 and the comparison of relative erosion volume reduction: the simulation with these setting lowers the erosion volume with 52% , where the measurements showed a reduction of 53%. The relative erosion reduction is slightly underestimated with 1 p.p. The simulated bed level at the water level is slightly lower than measured.

Applying a *wetslp* of 0.4 for the SC1 case does result in good outcomes: a BSS of 0.66 is achieved and a relative reduction of 20%, which equals the reduction in the measurements.

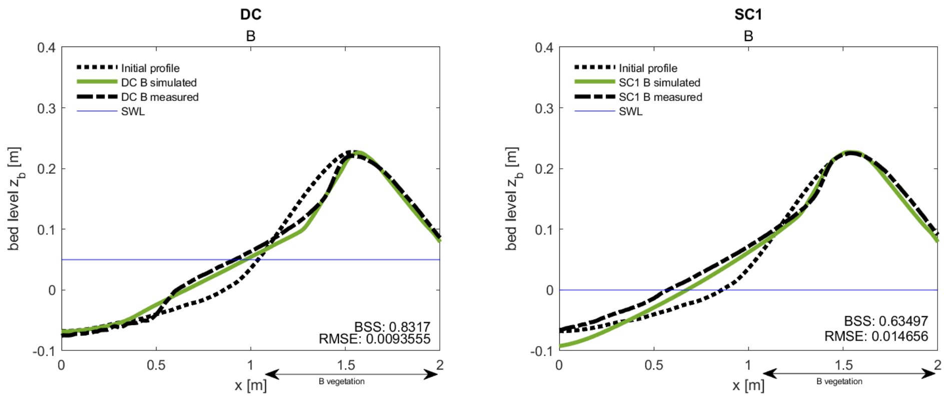


(a) A DC (b) A SC1

Figure 4.5: Profiles of Bryant DC (left) and SC1 (right) simulation with aboveground vegetation

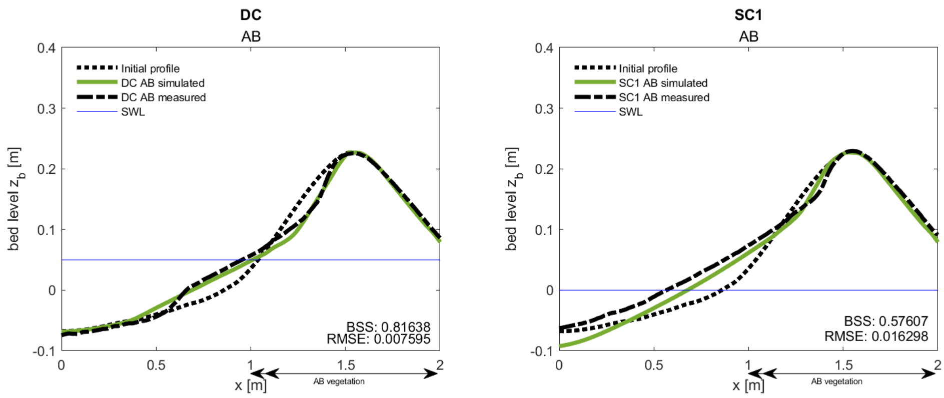
SOIL STABILIZATION – BELOWGROUND VEGETATION Adjusting the critical dry slope to a higher value (from 0.2 to 0.5) and using the constant root model with a *rcc* of 0.05, results in a well-predicted profile (BSS = 0.83) and eroded volume (54% reduction to control simulation, where the measurements showed a lowering of 57%) for the DC case. As shown on the left side of Figure 4.6, the absolute erosion of the simulation is larger. This is caused by the initial overestimation of the control simulation.
Applying a higher critical wet slope to the SC1 case results in erosion reduction and applying the root model with an increasing value of *rcc* results in erosion reduction. The combined values of *wetslp* = 0.5 and *rcc* = 0.05 results in the relative erosion reduction of 46 % compared to 47%. As a result, the relative eroded volume is underestimated by one percentage point.

HYDRODYNAMIC INTERACTION AND SOIL STABILIZATION – ABOVE AND BELOWGROUND VEGETATION Adjusting the critical wet slope and using the root model with the settings provided in Table 4.3 result in a good simulation for the DC case (BSS = 0.81). Also the reduction in eroded volume is both 66%.
Regarding the SC1 case, the profile is in medium agreement (BSS = 0.58). However, the erosion reduction is the same as measured: 53%.



(a) DC **(b)** SC1

Figure 4.6: Profiles of Bryant DC (left) and SC1 (right) simulation with belowground vegetation



(a) DC **(b)** SC1

Figure 4.7: Profiles of Bryant DC (left) and SC1 (right) simulation with above and belowground vegetation

4.3.2 Mendoza experiment

HYDRODYNAMIC INTERACTION AND SOIL STABILIZATION – ABOVE AND BELOWGROUND VEGETATION The *wetslp* was increased to 0.4 for the Mendoza experiment. A higher critical wet slope (e.g. 0.5) resulted in fact in a better reduction in erosion volume. However, then the simulated slope would be excessively steep, and the primary principle for the critical slope value change would be incorrect. Therefore, it was chosen to apply a *wetslp* of 0.4 and add the root model with a *rcc* of 0.35. This resulted in an erosion reduction of 46% which is also the same relative reduction as in the experiments for this case. The BSS, on the other hand, is low, which may be explained by the initial calibration mismatch for the situation without vegetation. (Figure 4.4). The simulated behavior (erosion volume and profile) with the calibration of vegetation, is consistent with the observed behavior in the measurements: A smaller dune erosion volume from the dune face, a similar slope in front of the dune, and a slightly smaller deposition at the beach.

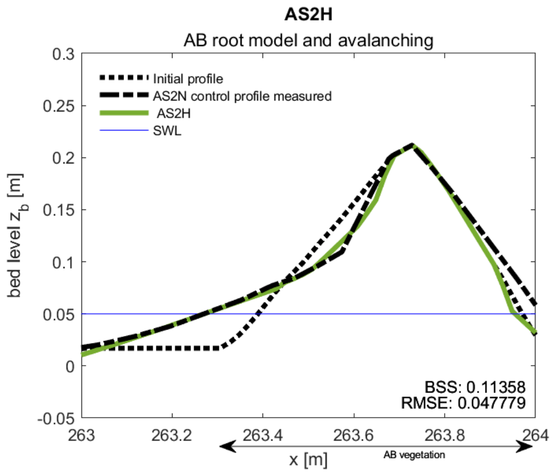


Figure 4.8: Profile of Mendoza AS2H with above and belowground vegetation

4.3.3 Overview results cases with vegetation

Table 4.4 shows an overview of the simulated reduction in eroded volume and the measured reduction eroded volume. The BSS and RMSE are also presented.

Table 4.4: Overview results simulations with vegetation

Vegetation	Simulation reduction eroded volume [%]	Measured reduction eroded volume [%]	Difference reduction simulation and measurement [p.p.]	BSS	RMSE
DC A	51	53	-2	0.79	0.015105
DC B	54	57	-3	0.83	0.0093555
DC AB	66	66	0	0.81	0.007595
SC1 A	20	21	-1	0.66	0.015386
SC1 B	48	46	+2	0.63	0.01 656
SC1 AB	53	53	0	0.58	0.57607
AS2 AB	46	46	0	0.11	0.047779

4.4 SENSITIVITY AND PERFORMANCE VEGETATION APPROACHES

A sensitivity analysis was carried out to acquire a better understanding of the performance of the various vegetation approaches. The procedure and the range of values applied are summarized in Figure 3.10. These values are applied on the calibrated control setup of Bryant DC and SC1 (both settings provided in Table 3.9 and 4.1). Regarding the Mendoza case, only the good performing vegetation approaches were assessed. The parameter sensitivity on dune erosion for every vegetation approach is displayed in box plots. It must be noted that the x axis values are not to scale. When the sensitivity analysis revealed a high sensitivity, the profile evolution is also provided and analysed.

4.4.1 Hydrodynamic interaction

The roughness approach and the vegetation module are considered to represent the impact of aboveground vegetation during storm conditions.

ROUGHNESS APPROACH The effect of vegetation on the velocity is accounted for using the roughness approach, where the Manning coefficient (n) is set to a higher value. A larger Manning coefficient aims to reduce the flow velocity and the sediment transport provided by the roughness of vegetation. The effect of the Manning coefficient showed to have a negligible effect on the simulation, independent of whether the constant or dynamic approach was applied or a larger applied width in the cross-section. In addition, the range of parameters used did not change the simulation outcome.

VEGETATION MODULE The vegetation module lowers the short waves, long waves, and mean flow, and so results in a decrease in sediment transport. This module is slightly sensitive for changes in drag coefficient (C_D), demonstrated in Figure 4.9. A larger C_D results in a slightly smaller erosion volume, with a maximum of 4% for the SC1 case. The effect of the vegetation module is negligible for the DC case.

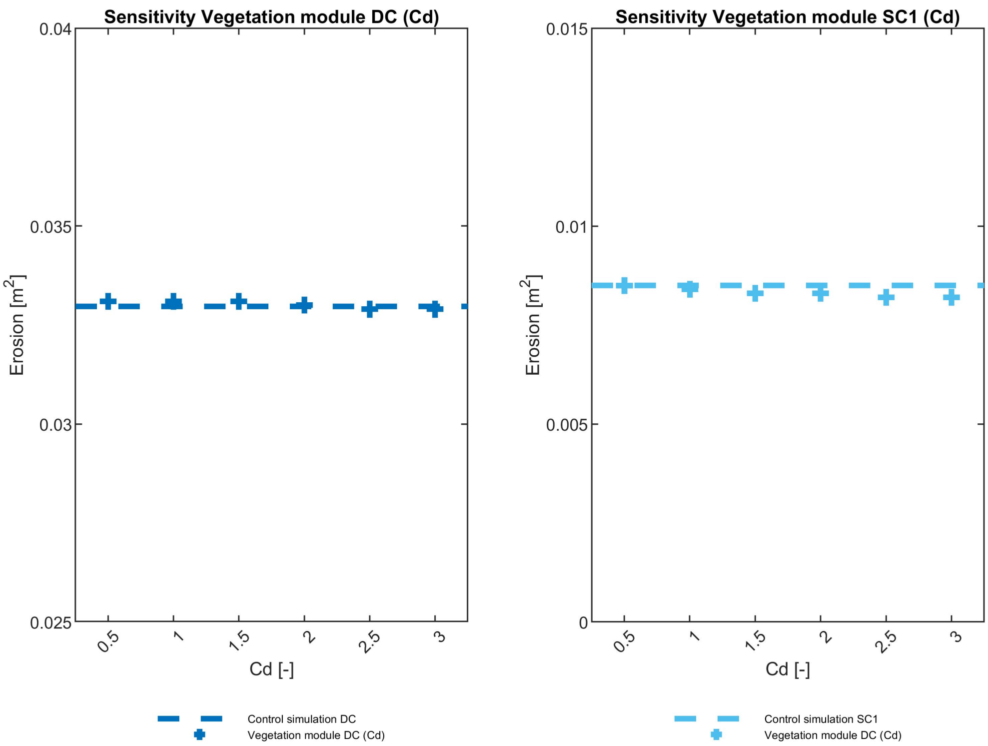


Figure 4.9: Sensitivity drag coefficient (C_D) parameter vegetation module for Bryant DC and SC1 case. A higher Cd results in a reduction in erosion volume. Note: the y axes are different.

Both Bryant cases are mildly sensitive for changes in density *(N)*, vegetation diameter (*bv*), and vegetation height relative to the bed (*a*). The sensitivity has been depicted for the SC1 case in Figure 4.10.

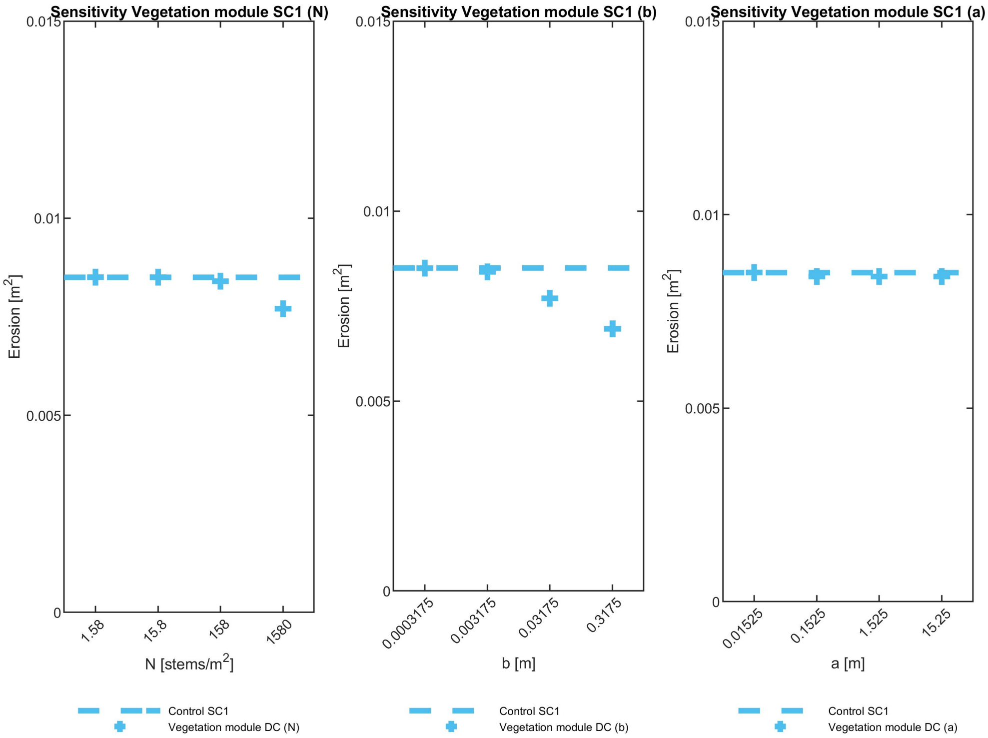


Figure 4.10: Sensitivity vegetation density (N), vegetation diameter (b) and vegetation height (a) parameters in the vegetation module for Bryant SC1 case. A higher N, b and a result in slightly less erosion.

In Figure 4.11 the bed profile change ($zb_0 - zb_{end}$), orbital flow velocity (u_{rms}), depth averaged flow velocity (u_e) and sediment concentration (cc_{tot}) for different simulations are illustrated. The blue line is the simulation with the settings of the simulation for the calibrated DC control. The green line includes the vegetation module with the reference values obtained from the Bryant experiment (N = 158 stems / m^2, a= 0.1525 m, b= 0.003175 m, C_D = 1). The first column shows the outcomes for t=1200 s, the second column for t=2400 s and the third column for t=3600 s. The vegetation approach has a direct impact on u_{rms} and u_e, as depicted by the graphs in rows 2 and 3. At the location of start of vegetation (x=1 for green line and x=0 for yellow line), there is directly a reduction in the near-bed short-wave orbital velocity. (u_{rms}) and the eulerian velociyy (u_e) seen, which results in a lower sediment concentration (cc_{tot}). This impacts indirectly the amount of sediment transport, and so the eroded volume.

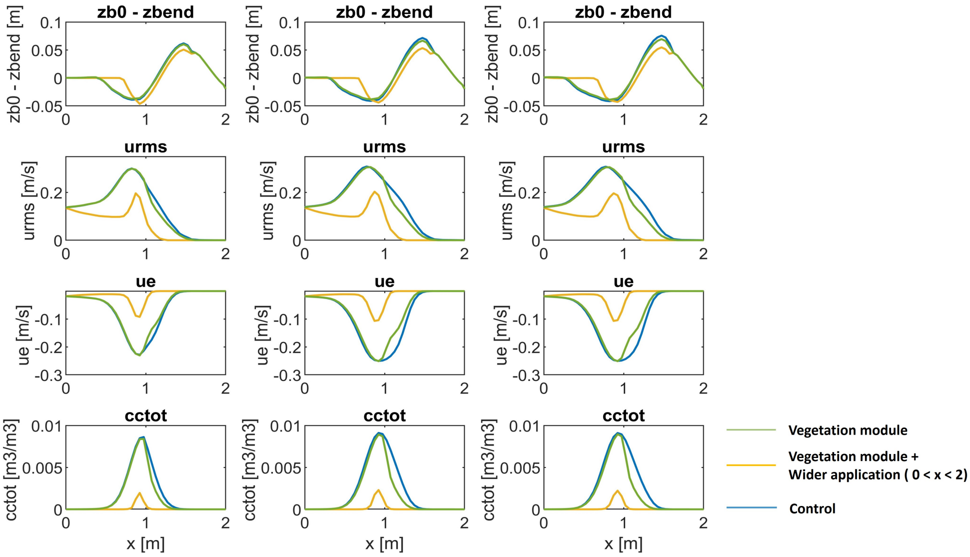


Figure 4.11: Vegetation module impacts the velocities, sediment concentration, and bed profile evolution. A wider vegetation width enhances this effect.

4.4.2 Soil stabilization (B)

The root model and the adjustment of the critical slope in the avalanching module are considered to represent the impact of belowground vegetation during storm conditions. Both the root model and adjustment of the avalanching module affect the simulation, which is further discussed in the following paragraphs.

ROOT MODEL The root model, which is a proxy for the effect of extra cohesion of vegetation and so ensures a larger velocity is needed for sediment transport, results in a reduction of erosion. The range of relative erosion reduction for the SC1 case is larger than the relative erosion reduction for the DC case. The erosion reduction for the SC1 case is between 0 - 32% and for the DC case between 0 - 7%. This is for a maximum root cohesion coefficient of 5 that has been assessed. However, for both cases, a maximum is reached for root cohesion values (*rcc*) above approximately 0.25. Figure 4.12 illustrates this.

In Figure 4.13, the effects of the values of the constant root approach and the applied width are further analyzed. The blue line represents the control case without the root model, and the green line the case with the application of the root model (*rcc* = 0.5). The root model directly impacts the sediment concentration (*cctot*). For the green line, there is no sediment concentration at the start of the vegetation section (from x=1.15 m), compared to the simulation without the root model (blue line). Consequently, this results in slightly less erosion at the top of the dune in comparison with the control. The use of a larger width does not result in significant changes in the sediment concentration. This is illustrated in Figure 4.13. When you zoom in on one of the lower plots, the *cctot* is somewhat diminished. This is displayed in the rightmost plot of Figure 4.13.

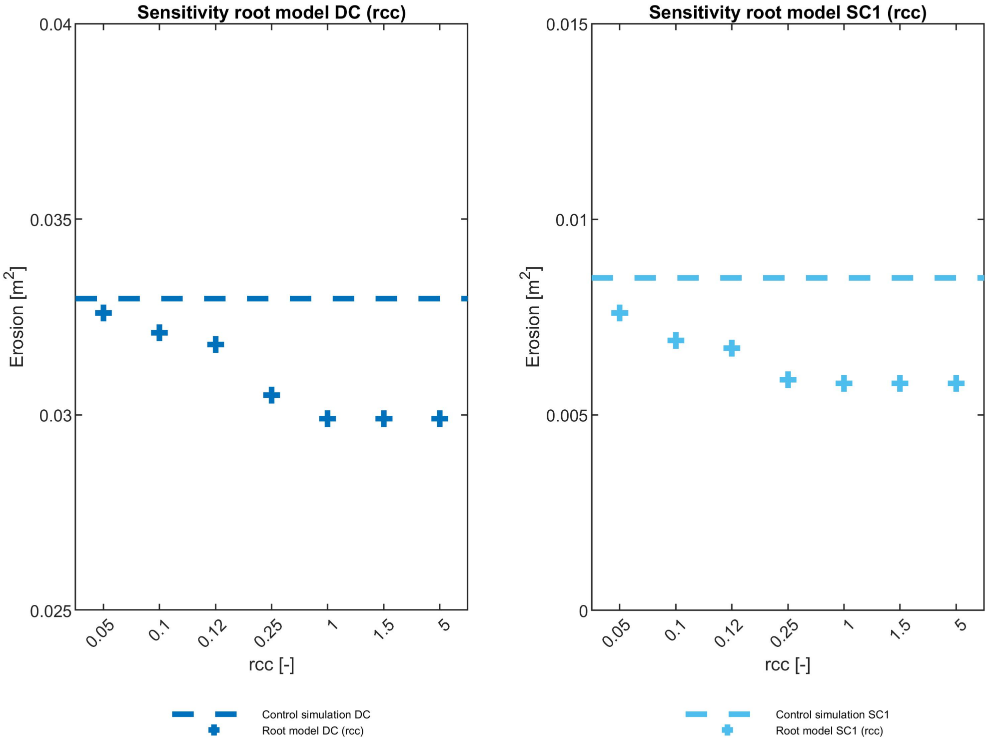


Figure 4.12: Sensitivity root cohesion coefficient (*rcc*) parameter constant root model for Bryant DC and SC1 case. A higher *rcc* results in a reduction in erosion volume to a certain extent. Note: the y axes are different

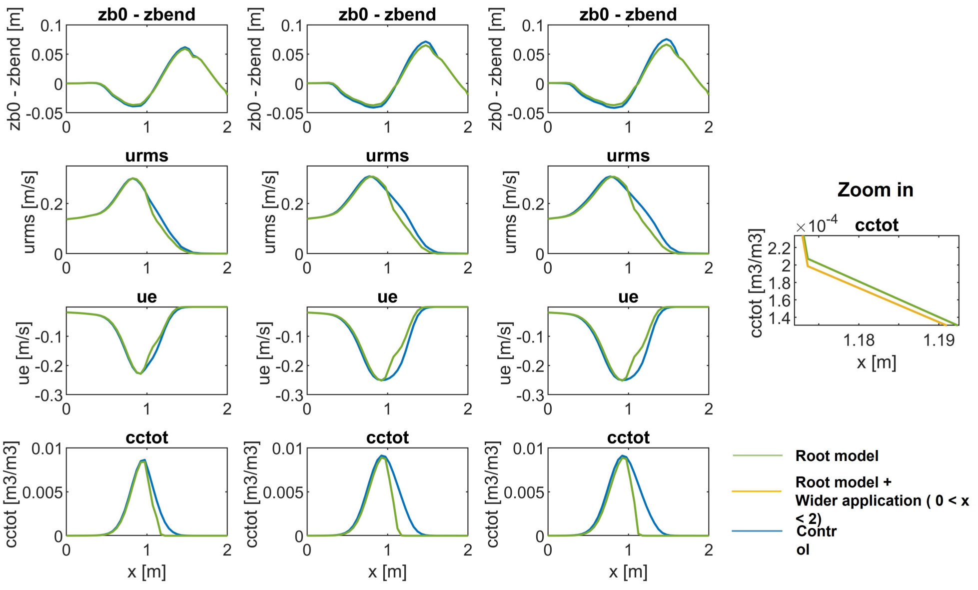


Figure 4.13: Root model impacts the sediment concentration and subsequently the velocities and bed profile. A wider application of the vegetation width demonstrates an insignificant effect (right zoom in the plot)

Applying the dynamic root model with a *rcc* of 0.1 and varying rooting depth (*zroot*) between 0.01 and 5 on the calibrated DC and SC1 control cases affects the erosion volumes. The erosion reduction effect reached a maximum for a *zroot* of approximately 0.5 meters (Figure 4.14). The effect of the rooting depth, and thus the effect of sedimentation/erosion of the dune and subsequently the vegetation effect can be analyzed by looking at the sediment concentration in Figure 4.15. The sediment concentration for both simulations (yellow and green lines) is lower than it would be without vegetation. The effect of vegetation remains constant throughout the simulation of the dynamic root model with a *zroot* of 5. The influence of roots does not vanish since the value of *zroot* is large. However, the second (t=2400 s) and third (t=3600 s) *cctot* graphs show the effect of the dynamic root model. In the first 1200 seconds the difference between the green and yellow line is small. Subsequent erosion affects the performance of the root model. This is visible in the bend in the second and third *cctot* graphs. For the small rooting depth (green), the effect vanishes due to erosion. The sediment concentration increases and so more sediment could be eroded. The profile differences are illustrated in the zoom-in graph on the right (Figure 4.15).

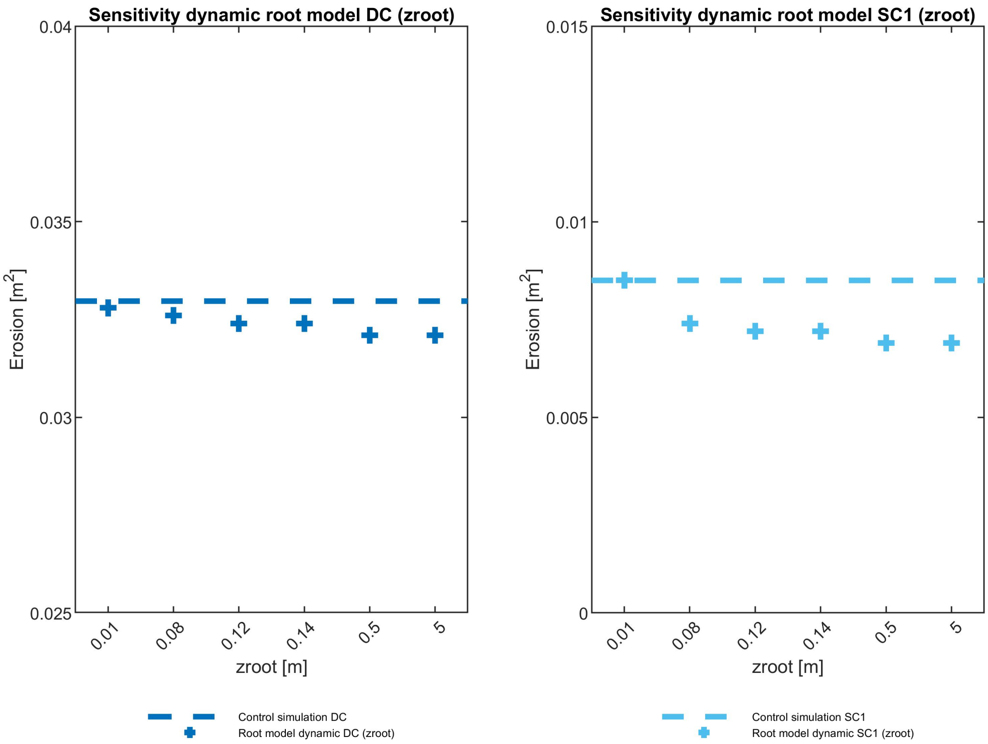


Figure 4.14: Sensitivity rooting depth parameter dynamic root model for Bryant DC and SC1 case. A higher zroot results in a reduction in erosion volume. Note: the y axes are different

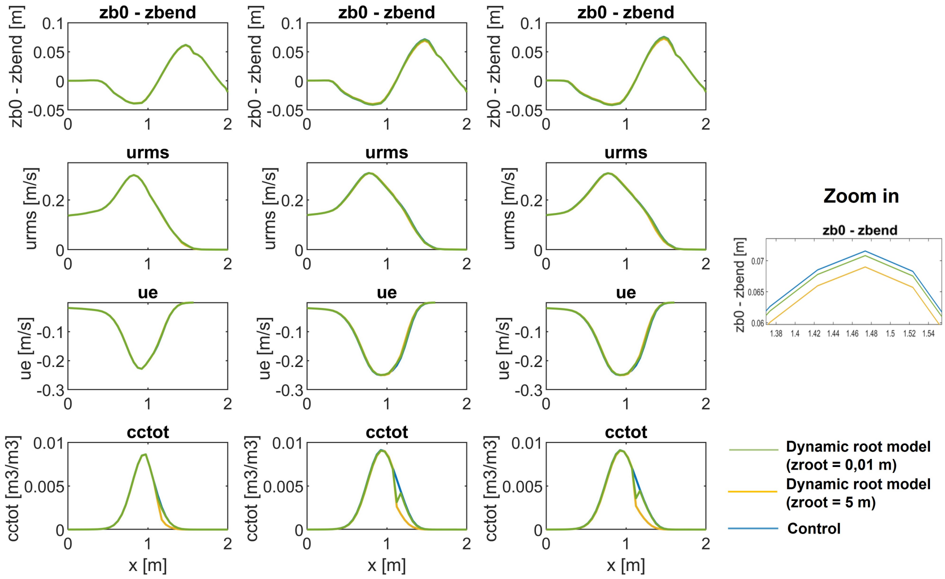


Figure 4.15: Dynamic root model takes into account deposition and erosion of the dune. The erosion of the dune in the dynamic root model. When erosion depth rooting depth (*zroot*), the effect of the root model decreases (yellow line).

AVALANCHING The avalanching module shows to have a relatively large effect on the magnitude of erosion of the dune and the profile evolution. It is the last step before bed update takes place, and accounts for the sediment transport when a certain critical angle is reached.

In general, a larger critical wet slope results in smaller erosion volumes and a larger occurring slope. Taking a look at Figure 4.16 and 4.21 on the left, a clear distinction can be made in the final profile and eroded volume between the two groups for the DC simulation. The first group includes the profiles with *wetslp* values between 0.3 and 0.8 and the second group includes values above 0.9. Group II has the largest critical wet slopes and shows an inclination between $1m < x < 1.2m$ at the location of transition between wet and dry cells. Group I has a smaller *wetslp* compared to group II, resulting in a smooth profile without a bend. This can be explained by the combination of values for the critical wet and dry slope.

Varying the critical wet slope for the SC1 case (Figure 4.16 and 4.21 on the right) result in a more natural profile and a smaller sensitivity for different values of *wetslp*. This behaviour is similar for the profiles of Mendoza, illustrated in Figure 4.17.

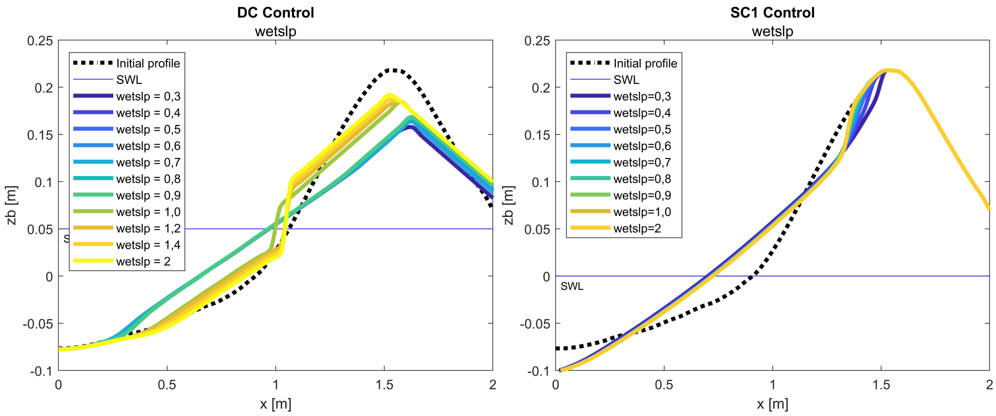


Figure 4.16: Profiles for different critical wet slope values in the avalanching module for Bryant DC case (left) and SC1 case (right). DC control has a constant *dryslp* of 0.2 which results in unnatural looking profiles. SC1 control has a constant *dryslp* of 1

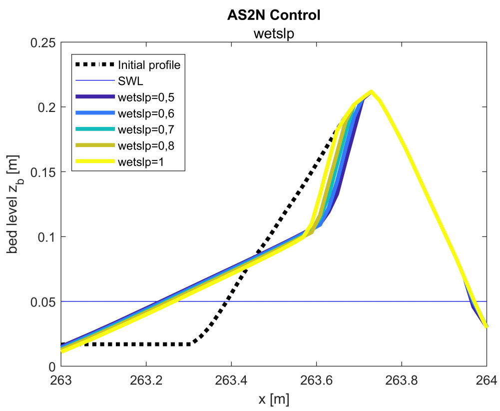


Figure 4.17: Profiles for different critical wet slope values in the avalanching module for Mendoza AS2N case. A constant *dryslp* of 1.2 was applied.

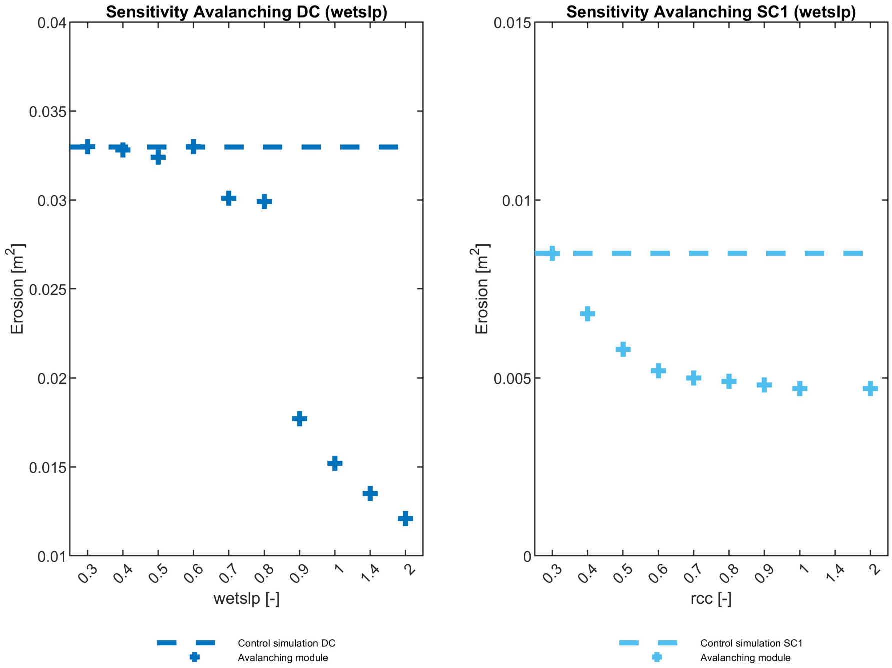


Figure 4.18: Sensitivity critical wet slope in the avalanching module for Bryant DC (left) and SC1 (right) case. A higher *wetslp* results in lower absolute erosion volumes. For the DC case, a jump can be observed between a *wetslp* of 0.9 and 1. A higher *wetslp* in the SC1 case results in a gradual erosion reduction. Note: the y-axes are different.

A decrease of critical dry slope results in a faster dune erosion rate, more dune erosion, and a smaller final slope from $1.3 < x < 1.6$ and a lower top for the DC case. Considering the sensitivity of the *dryslp* for the SC1 case, a low *dryslp* of 0.2 results in a fast avalanching of the dune. Small differences are shown for values between 0.4 and 2. The Mendoza case is slightly more sensitive to different values of the critical dry slope compared to the SC1 case, as indicated in Figure 4.20.

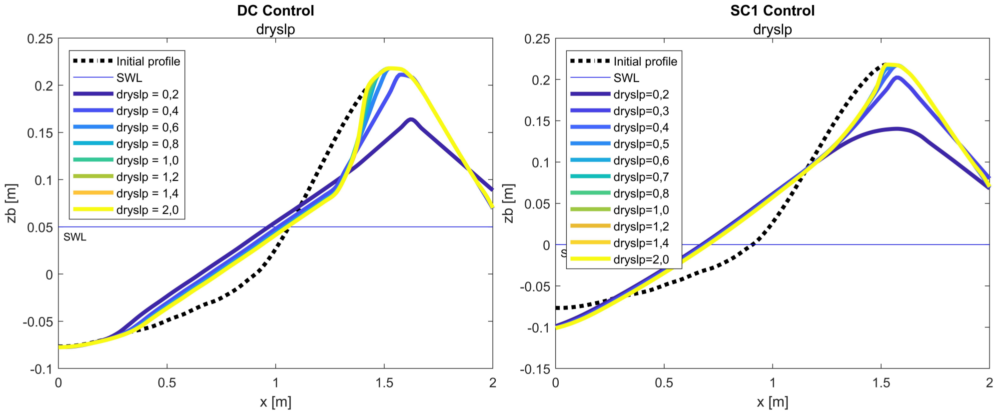


Figure 4.19: Profiles for different critical dry slope values in the avalanching module for Bryant DC case (left) and SC1 case (right). Both cases have a constant *wetslp* of 0.3

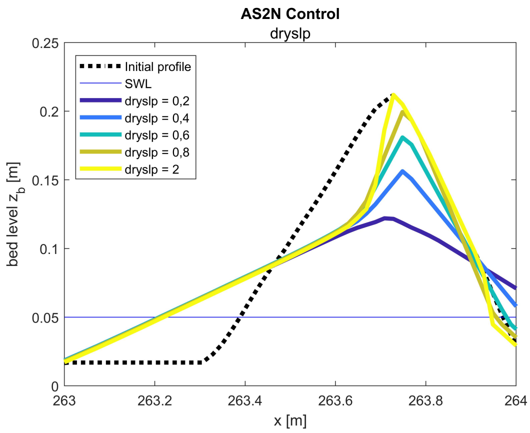


Figure 4.20: Profile for different critical dry slope values in the avalanching module for Mendoza AS2N. A constant *dryslp* of 1.2 was applied

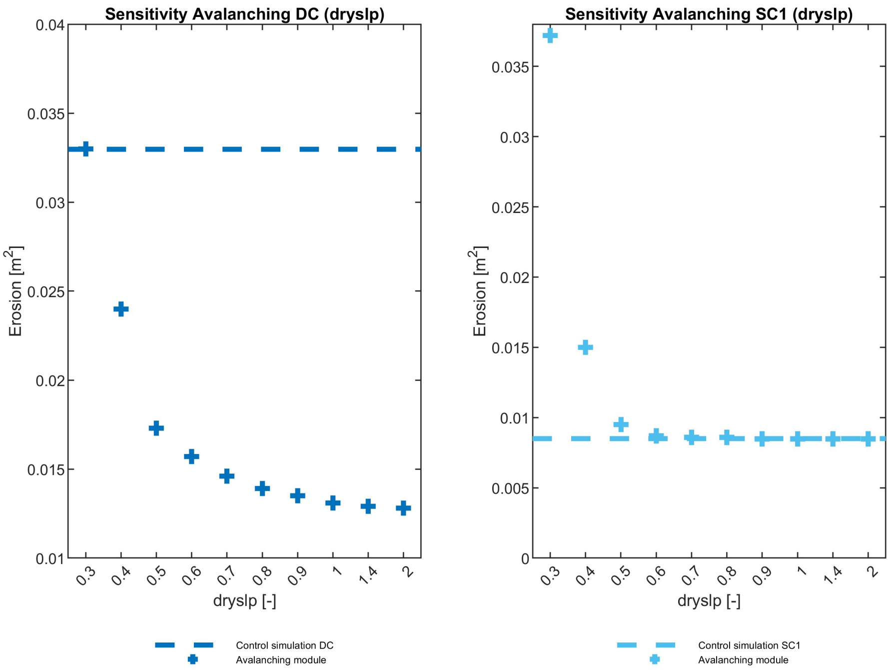


Figure 4.21: Sensitivity critical dry slope in the avalanching module for Bryant DC (left) and SC1 (right) case. The sensitivity pattern is similar. A higher *dryslp* results in a smaller absolute erosion volume. Note: the y axes are different

A larger *hswitch*, results in the DC case in more erosion. In the Bryant SC1 experiment and the Mendoza experiment, a larger *hswitch* results in less avalanching as displayed in Figure 4.22. The dune in the Mendoza experiment is the most sensitive for a different *hswitch*.

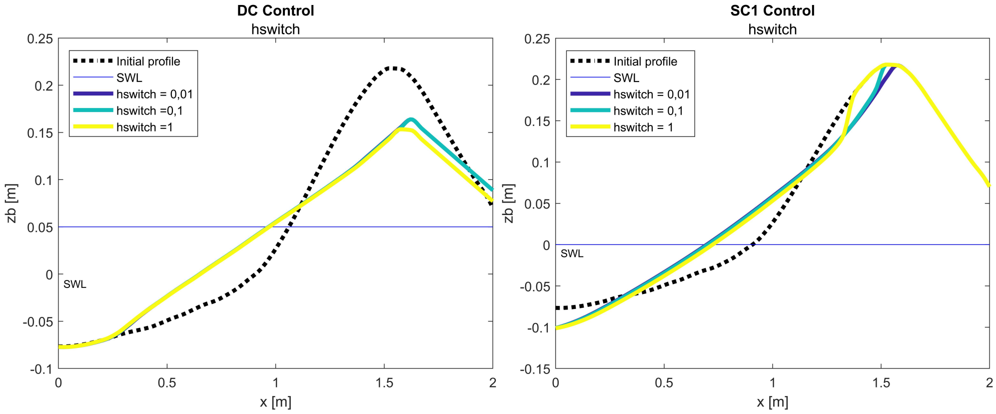


Figure 4.22: Profiles for different *hswitch* values in the avalanching module for Bryant DC case (left) and SC1 case (right).

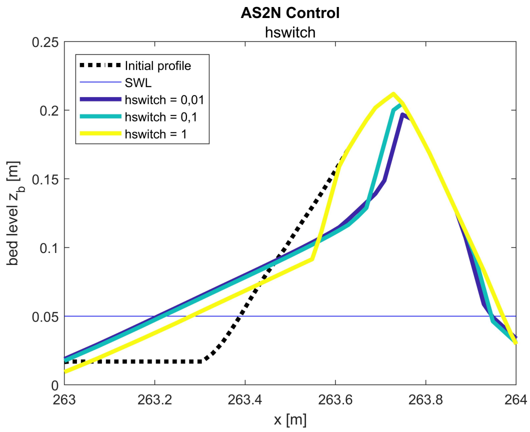


Figure 4.23: Profile for different *hswitch* values in the avalanching module for Mendoza AS2N.

4.4.3 Overview sensitivity analysis

An overview of the sensitivity analysis is given in Table 4.5.

Table 4.5: Main findings sensitivity analysis

Main process	Vegetation approach	Main findings parameters	Differences cases
Hydrodynamic interaction (A)	Roughness	Negligible effect both constant and dynamic mode and not sensitive	X
	Vegetation module	Medium level of sensitive for *Cd*, *N* and *bv*	Similar sensitivity patterns, different relative erosion reducing effect [%]
Soil stabilization (B)	Root model	Sensitive for value of *rcc* and *zroot*	Similar sensitivity patterns, different relative erosion reducing effect [%]
	Avalanching	Sensitive for values of *wetslp*, *dryslp* and *hswitch*	Similar sensitivity patterns, different relative erosion reducing effect [%]

4.5 SUMMARY

The cases with and without vegetation were simulated well in terms of reduction in eroded volume and profile evolution (BSS).

Regarding the vegetated cases, an increase of the critical slope in the avalanching module and the root model were applied. The roughness approach (both constant and dynamic) had an insignificant effect on the simulations and could therefore not be used as a representation of vegetation during the collision regime in the assessed cases. The vegetation module resulted in a small erosion reduction, but did not align with the erosion reduction measured in the experiments. Therefore, this module was also not used in the calibration.

The avalanching module is sensitive to the adjustment of the critical dry slope (*dryslp*), the critical wet (*wetslp*) slope, and the water at which is switched from *wetslp* to *dryslp* (*hswitch*). The constant root model is sensitive to the value of the root cohesion coefficient (*rcc*) till a certain point. In the dynamic root model, changes in *zroot* indicate differences in eroded volumes as well. The effect on the simulation and the performance of the approaches has also been shown to depend on the imposed hydrodynamic conditions and the initial setup of the model. This was observed by the differences in relative erosion reduction for different cases.

5 INTERPRETATION PART I

5.1 INTRODUCTION

The results of Part I are interpreted and further discussed below. First, the XBeach performance will be covered more in detail in section 5.2 , hereafter the sensitivity of the vegetation approaches is being discussed more in-depth (section 5.3).

5.2 XBEACH PERFORMANCE

5.2.1 Cases without vegetation (Control)

The results after the calibration for the cases with no vegetation (section 4.2) reveal that:

1. The control Bryant cases were simulated well in terms of relative erosion volume reduction and profile development (BSS) by the adjustment of *facua* and *bermslope*.
2. The Mendoza experiment was simulated well in terms of relative erosion volume, but the profiles scored low on the Brier Skill Score.

DISCUSSION FINDING 1 When calibrating a numerical model, it is important to think about the effects of the calibrated parameters and applied modules. When the calibration parameters are substantiated, simulations are more reliable. In the considered cases, without setting the *facua* to a higher value and switching on the bermslope module, all the simulations resulted in a large overestimation of erosion. The parameter *facua* accounts for onshore sediment transport as a result of wave asymmetry and the bermslope module is implemented to capture erosion processes at the waterline. The dynamic swash processes are complex and are not solved. In literature, the *facua* parameter is increased for different processes (Elsayed and Oumeraci [2017]), which is also the case for these simulations, since the exact process which causes the initial overestimation is uncertain. It is assumed that in all the simulations, adjusting these parameters mainly affect the profile at the region of the berm where no vegetation is present and not at the dune face itself. As a result, it has no consequence for the erosion/sedimentation at the vegetation location and therefore the evaluation of the vegetation approaches.

Regarding the initial overestimation of erosion in XBeach, there are a variety of probable explanations which are further addressed in Chapter 9:

- Absence of short wave reflection in the surfbeat mode
- Overestimation near-bed turbulence and underestimation of the slope above surge level, since XBeach default values are developed for larger scales (Brandenburg [2010]).

The absence of overwash in the DC case could be explained by an underestimation of wave run-up in surfbeat mode where short waves are not solved explicitly. This has been adressed in different studies (de Beer [2017]; Stockdon et al. [2014];Palmsten and Splinter [2016]). Attempts to induce overtopping/overwash and to reduce the dune retreat are done by applying the non-hydrostatic model (wavemodel= *nonh*), turning on *swrunup* and turning *turbulence* off (Brandenburg [2010]. Even though the model was already hydrodynamically calibrated, the hydrodynamic parameters were also adjusted (*gammax, alpha, n, delta and gamma*). These attempts did not result in overtopping and overwash as aimed for.

It is worth noting that the erosion observed is larger than the sedimentation in the Bryant experiments. One explanation for this could be the method used to determine the measured profiles. Following each wave burst, the bed level profiles of the beach-dune model were averaged alongshore to yield single profiles as a function of x. To eliminate edge effects along the flume walls, the alongshore profiles were averaged in 0.5 cm bins over a width somewhat smaller than the flume, roughly 1.4 m. This averaging might provide some unusual profiles. Another possible explanation is the use of a non-absorbing wave maker in the experiment. A reflection of the waves at the wave maker could result in small onshore sediment transport. Because mass is preserved in numerical models, a numerical model cannot accurately describe this without increasing the onshore sediment transport. In this research this has been done by the application of a higher facua and the bermslope module. However, during real storm conditions this is not likely to happen.

DISCUSSION FINDING 2 The profiles of the Mendoza experiment simulation profiles scored low on the Brier Skill Score. The prediction of the model is less accurate than the initial profile. The AS2N control profile with morphodynamic calibration, on the other hand, is more comparable to the observed final profile than the initial. Zingerle and Nurmi [2008] called this phenomenon the Double Penalty Effect: A high-resolution forecast of the same pattern as the observations but missing the observation area scores worse than a low-resolution forecast matching partly with the observation area. Without calibration, erosion starts low at the dune and dune face. This is different from the experiment since in the experiment, the erosion is only at the top of the dune, and sediment is deposited at the dune toe and berm. As a consequence, the Brier Skill Score cannot be used as the only evaluation method, which was also pointed out by Murphy, A.H, Epstein [1988]. The parameter has the restriction of not being able to characterize the direction of the migration of the bed level. It merely determines if the modeled bed level (at time t) is closer to the measured background level (at time t) than the starting bed level. If the modeled bed level migrates in the wrong direction but only by a tiny amount, the BSS will be higher than if the result is modeled in the right direction but substantially higher than observed. To distinguish position errors from amplitude errors, a qualitative evaluation is needed. Bosboom et al. [2014] and Bosboom et al. [2020] also found that the BSS could report a relative ranking of predictions not matching the intuitive judgment of experts. In turn, they suggested how to adjust calibration and validation procedures to be more in line with the judgment of morphology experts.

5.2.2 Cases with vegetation (A/B/AB)

The main findings regarding the simulation for the cases with vegetation are:

1. The vegetation approaches that mimic aboveground vegetation processes (roughness approach and vegetation module) alone are not capable of simulating the aboveground vegetation cases in terms of erosion reduction and BSS.

2. The vegetation approaches that mimic the belowground vegetation processes (avalanching module and root model) together are capable of simulating the vegetation cases in terms of erosion reduction and BSS.

   - The combination of the avalanching module and root model resulted in the best matches in terms of erosion reduction and BSS.

- The best combination of critical slope in the avalanching module and the root cohesion coefficient in the root model varies per situation.

DISCUSSION FINDING 1 Regarding point 1, it was found that the roughness approach and the vegetation module do not capture the reducing eroding effects that occur in reality. This might be the outcome of an initially incorrect hydrodynamic simulation in XBeach. When the hydrodynamics are simulated incorrectly in the first place, the subsequent impacts of the roughness approach and vegetation module on it cannot be accurately reproduced.

This finding also implies that these approaches, which influence flow velocities and wave propagation, are not the source of erosion reduction in the aboveground vegetation tests of Bryant. In turn, different processes are suggested to occur, which are not captured by these approaches. An example could be the impact of vegetation on turbulence. Previous research observed for example that plant structures in coastal wetlands can reduce erosion by impacting the turbulence (Nepf [1999]); Feagin et al. [2011]). Another process is an increased wave reflection on the vegetation, which could result in a lower run-up and subsequently lower sediment mobility and erosion. However, because the porosity of vegetation allows wave motion to pass through the voids, this effect is likely to be minor. This is especially the case in the experiments of Bryant and Mendoza assessed as clearly can be seen in Figure 3.4 and 3.5.

In addition to the interpretation above, another possible clarification could be given about finding 1. The erosion reducing effect of the imitation aboveground vegetation in the Bryant physical experiment (DC: 52% SC1: 20%) could not only be attributed to the top part of the wooden dowels. A part of the reducing effect could be caused by the dowels, which were incorporated for 0.1525 m into the dune. These buried wooden dowels could push particles aside, compressing and holding sediment and so increase sediment stability. Bardgett et al. [2014] also proposed that roots with a large diameter could increase sediment stability through this mechanism. According to this viewpoint, the influence of aboveground vegetation in the Bryant experiment may be smaller than previously reported.

Due to the limited quantity of information available regarding the specific physics taking place in the wave flume experiments with vegetation, it is difficult to pinpoint the specific cause of the erosion reduction and consequently, the minor erosion reducing effect of the aboveground vegetation approaches in XBeach.

DISCUSSION FINDING 2 The positive findings obtained by applying a larger critical slope in the avalanching module and the root model highlight the relevance of belowground vegetation for soil stabilization and erosion reduction. A larger occurring slope in presence of vegetation coincides with observations in wave flume experiment and in the field (Carter and Stone [1989]; Sigren et al. [2018], Armaroli et al. [2013]). The erosion reducing effect of roots during concentrated flow and thus sediment mobility (represented by the root model) has also been demonstrated by several studies considering loamy soils. In addition, Vannoppen et al. [2017] assessed the erosion reducing potential in sandy soils. This study revealed that when soil cohesiveness and sand concentration increased, erosion rates decreased exponentially.

The relationship between dune vegetation and the occurring critical angle of a dune has not been established yet. The critical angle of sediment depends on the properties of the soil. Belowground vegetation influences different soil properties, such as soil permeability, cohesion, organic matter, and aggregate stability (Vannoppen et al. [2015]). Roots are therefore argued to affect the critical angle.

Mainly the additional cohesion provided by roots is studied and related to the erosion reducing effect. Root diameter, architecture, length, and depth are examples of vegetation characteristics affecting soil cohesiveness, which in turn affects erosion volumes (Vannoppen et al. [2015]). Vegetation characteristics vary per vegetation type. The properties are proven to have a relationship with tensile strength and the root area ratio, and they may be utilized to compute the additional cohesion given by roots (De Baets et al. [2008] (equation 3.6 and 3.7) (equation 3.6 and 3.7).
The following vegetation properties have possibly a positive effect on cohesiveness and subsequent the critical slope, and the erosion reduction. These character traits are particularly prevalent in vegetation with fibrous roots.

- High root length density (total root length by soil volume)
- High root density (total roos mass by soil volume)
- High tensile strength
- High root area ratio (fraction of soil cross-sectional area occupied by roots per unit area)

Looking specifically at the final simulated and measured profiles, the simulated slope for the DC belowground cases of Bryant is steeper than the measured slope around $1.25 < x < 1.4$ (Figure 4.6). This could be explained as follows. Throughout the simulation, the model retains the same critical angle, which helps to understand this observation. In reality, erosion could result in the loss of sediment and the disappearance of belowground vegetation. In reality, erosion may cause sediment loss and the destruction of belowground vegetation. As a result, shear strength will be reduced, and the critical slope is reduced. An explanation for the absence of this behavior in the SC1 B case could be the smaller rate of erosion due to the smaller water level. This eroding and so reducing shear strength effect is expected to arise later in time.

For the vegetated DC cases, the critical dry slope in the avalanching module was increased, while for the SC1 case and the Mendoza AS2H case the critical wet slope was increased. This difference can be explained by the adjustment in settings for the cases without vegetation. For the DC case without vegetation, the dryslope was lowered. This was done to imitate the effects of a higher runup, and subsequently a similar critical angle for the wet cells as for the dry cells. In this sense, a higher dryslp is equivalent to a higher wetslp in the cases where the runup is simulated well. Unfortunately, this adjustment changes the avalanching module during the whole simulation. As a result, using the DC case to assess vegetation approaches is less accurate and the outcomes are less reliable compared to the other two cases. It also emphasizes the importance of a good initial calibration, when applying numerical models to a new situation.

To reach the reduction in eroded volume and a reasonable Brier Skill Score which evaluated the profile evolution after a storm, the critical slope in the avalanching module was adjusted and the root model was applied. For both approaches, no values to use were available. No relationship between the critical angle in presence of dune vegetation is available, and since coir fibers were used to imitate vegetation, no estimate could be made for the provided extra cohesion. Therefore, the critical slope was increased to the maximum slope observed and the root model was only applied as additional calibration. This was not based on vegetation characteristics. The values for the root cohesion coefficient (*rcc*) and critical angle differ per case. As a result the contribution of the root model also differed per case. A different set of calibration settings could produce identical results. There has not been any additional investigation into this The choices of the combination of the values for the SC1 case are given and explained in G.

For the cases with both above- and belowground vegetation, it was possible to add the vegetation module to account for the aboveground effects. Although the erosion reduction in these tests was probably caused by a combination of different processes, there has been chosen to only apply the belowground vegetation approaches. The reason for this is that the contribution of the different vegetation mechanisms to erosion reduction in these tests is unknown. The addition of an extra module with an uncertain parameter complicates the simulation. Only Bryant et al. [2019] has investigated the isolated contribution of the above- and belowground vegetation. However, for the case with both above and belowground vegetation, it remains unknown to which percentage the vegetation components attribute to the erosion reduction. Their study only demonstrated that the isolated belowground vegetation results in a larger erosion reducing effect compared to isolated aboveground vegetation.

5.3 SENSITIVITY VEGETATION APPROACHES

5.3.1 Hydrodynamic altering

The sensitivity analysis for the representation of aboveground vegetation during collision regime storm conditions shows that:

1. The constant and dynamic roughness approach has a negligible effect and is insensitive to the assessed simulations.
2. Parameters in the vegetation module show a small sensitivity for different values in the assessed simulations.

DISCUSSION FINDING 1 The negligible effect of the roughness approach on the eroded volume coincides with findings of Schweiger and Schuettrumpf [2021b] where this approach is applied to the Deltaflume test T04 in XBeach. Friction coefficients are better recognized for influencing hydrodynamics than for changing morphodynamics. In addition, this approach was shown to be mainly effective when overwash is present (Schambach et al. [2018]; Donnelly et al. [2009]). In the overwash regime, erosion is caused by the flow over the dune. The negligible effect in the present cases could be explained by the small velocities on the vegetated sections and the small width of vegetation on the dune.

DISCUSSION FINDING 2 The effect of the vegetation module is primarily determined by the value of the drag coefficient. This is as expected because this parameter is often used as a calibration parameter to minimize the difference between model outcomes and measurements. The drag coefficient is difficult to determine since it depends on biophysical characteristics and hydrodynamics. To the writer's knowledge, no specific values exist for dune vegetation. Data for the vegetation parameters are often scarce and highly dependent on the location and vegetation species. In addition, the vegetation properties can vary spatially. This makes it even more difficult to apply this module.

The combination of the vegetation density and the vegetation diameter in the vegetation module can also largely affect the simulation. However, these parameters are not intended to be changed, since they are based on physical properties obtained from the considered experiment.

5.3.2 Soil stabilization

The sensitivity analysis for the representation of belowground vegetation during collision regime storm conditions shows that:

1. The root model shows a sensitivity for values of rcc and zroot in the constant and dynamic model
2. The sensitivity of parameters in the avalanching module could be relatively large.

DISCUSSION FINDING 1 Especially for small values of *rcc*, between 0.01 and 0.25, the root model is very sensitive. For values above 0.25, the erosion reduction remains constant for both assessed cases. This can be explained by the calculation of the equilibrium concentration (C_{eq}). At a certain point, a larger critical velocity (as a result of a larger *rcc*), results in a larger equilibrium sediment concentration (Equation C.3). However, the maximum allowed sediment concentration (default C_{max} = 0.1 m3/m3) prevents the model for too large erosion values as given in Equation C.4. For values above approximately 0.25, the C_{max} is used instead of the calculated concentration, resulting in no changes in erosion when increasing the *rcc* further.

The effect of the root model depends on the values applied and the initial applied conditions. For the DC case, a root cohesion coefficient of 0.12 results for example in a relative erosion reduction of 7% and for the SC1 case of 21%. This could be explained by the higher runup and velocities simulated for the SC1 case. The root model could have a larger impact when the runup and velocities are higher, explaining the larger relative erosion reduction.

DISCUSSION FINDING 2 The avalanching module is very important in modeling the sediment transport from the dune during collision regime storm conditions. The sensitivity of the critical wet slope and the minimum water depth to consider cells as wet/dry have been pointed out by previous studies (Berard et al. [2017]).

The combination of values for *wetslp* and *dryslp* is important for the profile evolution. A higher critical wet slope compared to critical dry slope results in unnatural-looking profiles. This was observed for the sensitivity simulations of the SC1 case of Bryant (Figure 4.16 on the left). In the case of a low *dryslp* value combined with a high *wetslp* value, sediment could start to slump relatively early from the top of the dune compared to the lower part of the dune. When the sediment rolls down, it can abruptly hold a larger slope due to the larger value of wetslp at this location. This appears to be unnatural because wet sediment is often thought to have a lower critical slope than dry sediment. The transition between wet and dry cells can be observed when the critical slope between wet cells and dry cells is large. A sharp bend is simulated (left profiles shown in Figure 4.16 and 4.19).

It is also crucial to accurately simulate the water runup, because this, along with the value of the *hswitch*, decides whether a cell in XBeach is considered dry or wet.

The Mendoza simulation is more sensitive than Bryant SC1 for a varying critical dry slope. This can be attributed to the initial slope of the dry dune in the Mendoza simulation, which is at the start of the simulation already very steep. The initial dune settings are important to consider. When a dune is already very steep and the critical slopes are set low, the dune starts to erode immediately.

Whether the erosion reduces or increases by changing the *hswitch*, depends on the values chosen for the critical wet slope and critical dry slope. For the Bryant SC1 case a raise of the *hswitch* results in more avalanching, and for the Bryant DC and

Mendoza AS2N case it results in less avalanching. This can be explained by the combined values of the critical slopes. When the *hswitch* is raised to a higher value in the DC case, more cells are considered as dry. The low *dryslp* result in more dune avalanching. In the case of *wetslp* $<$ *dryslp* (SC1 and Mendoza case), a larger *hswitch* results in less avalanching, since a smaller amount of cells are considered as wet.

Part II

APPLICATION OF XBEACH TO CASE STUDY BEIRA

6 METHOD PART II

6.1 INTRODUCTION

This chapter explains the methods used to reach the main objective of Part II of this thesis: investigating the potential of vegetation during collision regime storm conditions on a large-scale dune using a case study. The consistency and sensitivity of the belowground vegetation approaches (validated in Part I) using actual dimensions and storm duration of Beira are examined. For this, it is important to acknowledge and point out the differences between small wave flume experiments and prototype dunes. More about this can be found in the discussion in Chapter 9.

A description of the selected case and study area is given in section 6.2 and in section 6.3 the XBeach model configuration is provided. The evaluation procedure for the consistency and the potential impact of vegetation in dune rehabilitation projects is shortly described in section 6.4. A summary of the steps followed is given in section 6.5.

For the following reasons, the potential effects of aboveground vegetation and subsequently the aboveground vegetation approaches are not considered in this section:

1. The application of the roughness approach has shown to have a minor impact on the velocities during the collision regime in the assessed cases (Part I).

2. The simulated profiles with the application of the vegetation module and vegetation settings based on the experiments did not correspond to the measured profiles. The vegetation module had a minor impact on wave dissipation and mean flow in the assessed cases. As a result, the feasibility of this approach to represent dune vegetation could not be verified (Part I).

3. It is assumed that cyclones in Beira are relatively large and devastating. Hesp and Martínez [2007] argued that the effect of aboveground vegetation could be insignificant when dune erosion volumes are relatively large. When for example a volumetric loss is greater than 40%, this may result in a devastating effect on the vegetation population. It is assumed that the belowground vegetation (roots) withstand these storms.

6.2 SELECTED CASE

The area of interest is Beira, Mozambique. Beira is located on Sofala Coast, next to the Mozambique Channel of the Indian ocean (Figure 6.1). The coast is exposed to storm surge risk due to cyclones. In addition, the city is vulnerable to sea-level rise, floods from intensive rainfall events, and coastal erosion. In this area, the initiative of a large Coastal Protection Project (CPP) is undertaken. This CPP aims to develop a strategy to protect Beira against sea hazards, flooding, and other climate-related disasters. The case of Beira was chosen as the study area since a dune rehabilitation design has been proposed. Royal HaskoningDHV (RHDHV) and Witteveen+Bos (WiBo) have provided data for this study.

DUNE VEGETATION POTENTIAL In the current dune design, implementation of vegetation is recommended. One reason for this is that during Cyclone Idai in 2019, there were no dune breaches in areas where vegetation was present. To confirm the potential of implementing dune vegetation as protection measure in this area, indicators of Conger and Chang [2019] are used. More information and an in-depth analysis can be found in Appendix H. This analysis suggests that Beira has a low vulnerability and a low protection. Based on this, it is recommended to focus on for example vegetation regeneration. The relevance of dune vegetation is thus highlighted.

Figure 6.1: Location of study area Beira in Mozambique. Adapted from: Cumbe et al. [2020].

6.2.1 Dune stretches study area

The study area is the East of Beira where dunes are present, as illustrated in Figure 6.2. Region 1 of this area has a shallow coast with beaches and dunes. This part is not well developed and has subsistence farming in the hinterland, destined for tourism. The coast is characterized by high dunes which serve as flood protection. The dune ridge has a few weak points that could flood in the current situation if water levels become too high. It is expected that during the next decades the dunes in this area will erode due to changing conditions (increase storminess, sea-level rise, increased tourism), resulting in a lowering of the top of the dunes, and a higher flood vulnerability. In region 2 of this area, a dune ridge was historically present along the entire coastline, vegetated with trees and low vegetation. The dunes have degraded at some locations. In addition, hard coastal structures like groynes and a sea wall is present.

Figure 6.2: Considered area of case study in Beira. Adapted from: RHDHV and WiBo [2021]

BOUNDARY CONDITIONS Different nearshore coastal profiles were measured in November 2020 and combined with LiDAR data and GEBCO data (Deltares [2021a]). The boundary conditions differ per location and therefore the designed dune dimensions and design conditions differ per location. The coast is wave-dominated and the beaches in the considered study area are exposed to relatively high wave action (compared to the rest of the coast). Most of the time nearshore significant wave heights (H_s) are smaller than 1.5 meters and values of 2 meters are only rarely exceeded. During extreme conditions, such as cyclone events, the waves nearshore may reach up to 3 to 3.5 meters. Waves approach relatively normal to the coast. Table 6.1 gives the minimum and maximum dune dimensions based on the current dune designs. The hydraulic conditions are also given (RHDHV and WiBo [2021]). The protection/design level of these dunes is 1/50 per year for the 2070 scenario. 10 % is added to account for uncertainties in the provided wave conditions. The 50-year water level plus 2/3 of the difference between the RP500 and RP50 is the design water level. This water level is typical practice for coastal safety estimates, and it accounts for variables such as storm duration.

The dominant vegetation found is Sporobolus Virginicus, Canavalea Rosea, and Ipomoea Pes-Caprae. These creepers are characterized by their high density of coverage, especially in consolidated sand deposits near shore. Table 6.2 lists essential vegetation traits (Feagin et al. [2019]; Fernández-Montblanc et al. [2020]).

Figure 6.3: Pictures of three types of vegetation present in Beira

Table 6.1: Summary Beira boundary conditions (adapted from: RHDHV and WiBo [2021]): 1/50 year for 2070

Parameter	**Study area**	**min./max. in Beira**
Backslope dune [-]	1:3	1:3/1:3
Dune width at crest [m]	21	3/54
Foreslope dune [-]	1:3	1:3/1:3
Dune height [+m MSL]	6.5	3.5/8.5
$Hs_{+10\%}$ [m]	2.7	0.5/3.4
$T_{+10\%}$ [s]	12.9	11.3/13.7
Design water level [m +MSL]	3.9	3/4
Full storm duration [hr]	30	30/30

Table 6.2: Overview vegetation characteristics Beira (Feagin et al. [2019])

Parameter	**Sporobolus Virginicus**	**Canavalea Rosae**	**Ipomoea Pes Caprae**
Height [m]	0.1 - 0.5	0.3	0.3 - 0.6
Width [m]	0.003	0.0025	0.005
Density [stems/m^2]	200 - 800	200 - 400	200 - 400
Tensile strength [kN/m^2]	X	X	6650 ± 2390
Root area ratio [%]	0.01 - 0.17	0.01 - 0.17	0.01 - 0.17

6.3 NUMERICAL MODELLING

In Part I, the numerical model XBeach was used to simulate physical wave flume experiments with the implementation of vegetation. In this part, XBeach is used to test the consistency and sensitivity of the belowground vegetation approaches on large spatial and temporal scale. In addition, the effect of different environmental conditions (storm duration, wave height and dune dimensions) is tested. The belowground vegetation approaches were already explained in Chapter 3.

6.3.1 XBeach Beira model setup

For the modelling of the Beira coast, a 1D XBeach model was set up. The essential XBeach model parameters and settings are given in Table 6.3. Royal HaskoningDHV and Witteveen+Bos provided an initial model setup. Only slight changes to the dimensions of the dune profile were made, to assess the rehabilitated dune. The number of grid cells in x and y direction are $nx = 468$ and $ny = 0$, respectively. The minimum grid spacing $\Delta x_{min} = 1$ at the waterline and the maximum grid spacing $\Delta x_{max} = 20$ more offshore. The default XBeach settings were used, with the exception of the nuhfac, bedfric, left/ right, single_dir, and thetamin. A constant Manning coefficient of 0.02 for sandy sediment is applied and the bed composition was considered constant in the computational domain. For the grain size, a D50 of 0.225 mm and a D90 of 0.338 mm are used.

Table 6.3: Essential XBeach model parameters and settings

Parameter	Value	Comment
nx/ny	468/0	1D
$\Delta x_{min}/\Delta x_{max}$	1/20	min. at waterline and max offshore
nuhfac	0	switch off viscosity switch for roller induced turbulent horizontal viscosity; will become default in new XBeach versions
bedfric	manning	standard bed friction n=0.02
left/right	wall/wall	used for 1D wave tank simulations
snells	1	used for 1D simulations; turn on snell's law for wave refraction
thetamin thetamax dtheta	-90/90/180	wave energy in one single bin

An illustration of the bathymetry and assessed dune dimensions are shown in Figure 6.4. The bathymetry extends for 2.5 kilometers until it reaches -10 m+MSL. From there, the slope is 1:50 to a depth of -15m+MSL. This is a standard practise in XBeach.

The hydraulic conditions imposed in the model are summarized in Table 6.1 under the heading 'Study Area'. Only the peak of the design storm is enforced to assess sensitivity of belowground vegetation approaches with different wave heights, dune dimensions and storm duration. For this purpose, a stable spectrum is imposed at the offshore boundary with a duration of 3600 seconds. For the evaluation of the consistency and the application in a dune rehabilitation project, a whole storm of 30 hours is considered.

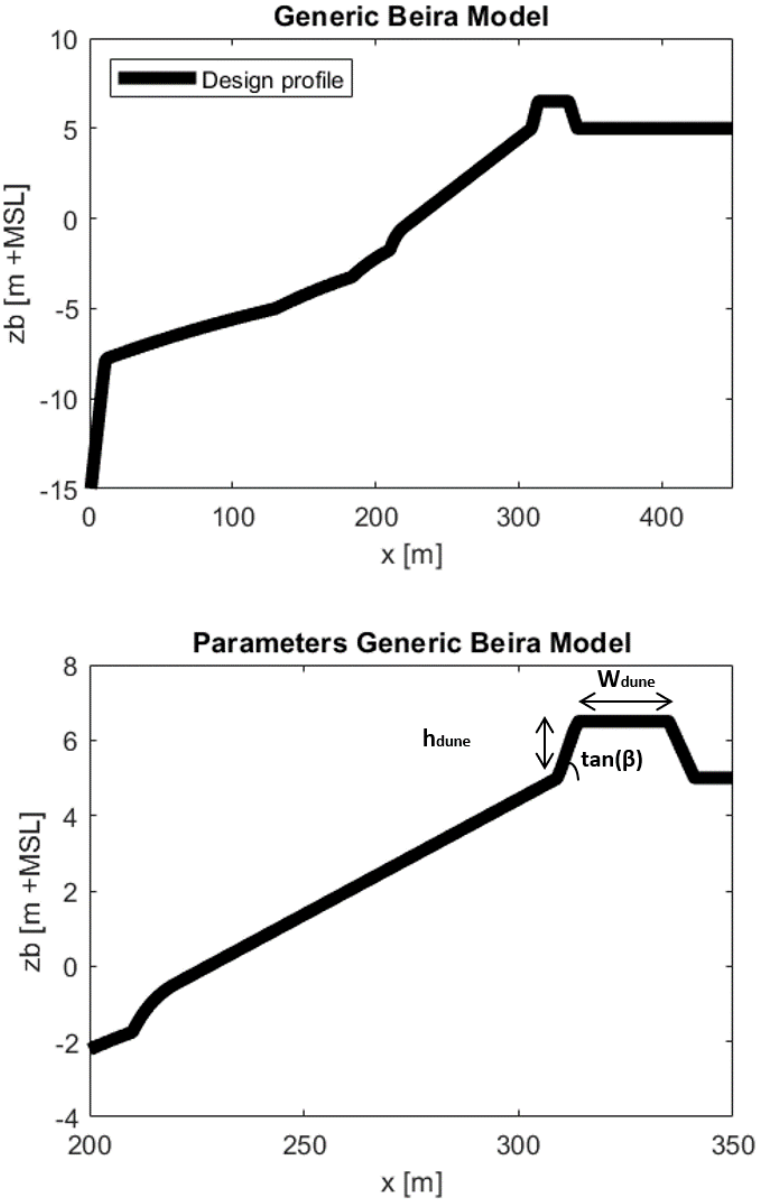


Figure 6.4: XBeach model set-up Beira coast. The lower figure illustrates the parameters varied to assess the sensitivity of the belowground vegetation approaches for different dune dimensions.

VEGETATION SETTINGS CONSISTENCY AND VERIFICATION To evaluate the consistency of the vegetation approaches on a large scale dune, values of u_{cr} for the vegetation present in Beira are calculated. This is done by using equation 3.7 and equation 3.6. The root area ratio (RAR) and the tensile strength (t_r) of the vegetation in Beira (from table 6.2) are used to calculate the potential cohesion provided by vegetation. The larger the RAR and t_r, the more erosion resistance is provided by the roots. This results in a maximum additional critical velocity $u_{cr,root}$ of 2.71 m/s. To test the consistency of the root model on the Beira dune, values between 0.05 and 2.7 are applied for the *rcc*, from the toe of the dune to the back of the dune. Regarding the critical wet slope, values between 0.5 and 2 are applied.

VEGETATION SETTINGS SENSITIVITY ENVIRONMENTAL CONDITIONS There is no systematic relationship between the critical slope and presence of vegetation, so the *wetslp* of 0.5 obtained from the simulations of the Bryant SC1 experiment is applied. A root cohesion coefficient (*rcc*) of 0.45 is applied.

Table 6.4: Belowground vegetation parameters and values

Vegetation approach	Parameter	Values consistency and verification large scale	Values sensitivity environmental conditions
Avalanching module	wetslp (-)	range: 0.5-2	0.5
Root model	rcc (-)	range: 0.05-2.7	0.45

6.4 EVALUATION METHODS

The evaluation of the application of the belowground vegetation approaches on large scale dunes and subsequently the potential impact in dune design has been performed by an assessment of the consistency and the potential use in dune rehabilitation projects.

6.4.1 Evaluation consistency and verification large scale

The consistency of the belowground vegetation approaches on large scale has been evaluated for two criteria: the profile evolution and the relative reduction in erosion volume. The profile evolution is evaluated using a qualitative comparison with the simulations of Part I. The reduction in erosion volume is compared using the application of the analytical wave impact approach including the effect of roots (Ajedegba et al. [2019]) and the reduction in eroded volume in the Bryant experiments assessed in Part I. The analytical wave impact approach relates the reduction in erosion volume with shear strength, as described in section 2.5. The effect of the higher shear strength due to roots is incorporated by a resistance coefficient: τ_b/τ_r, where τ_b is the shear strength of a bare dune and τ_r the shear strength of a vegetated dune.

6.4.2 Evaluation potential use in dune rehabilitation projects

To give insights into the potential effects of vegetation in dune rehabilitation projects, a dune design safety assessment has been done. It entails that there should be a minimum safety profile once a design storm has occurred. The requirements were outlined subsection 2.2.5 and illustrated in Figure 2.6. A full storm duration of 30 hours and a varying spectrum are applied. To give an indication of the effect of vegetation on future climate, firstly the water level has been raised in the simulation. The heightening of the water level continued, till the conditions did not fit the minimum safety profile or alternative profile determined for the profile without vegetation. Secondly, the wave heights were raised and the same procedure was followed as explained above.

Table 6.5: Belowground vegetation parameters and settings Beira used in dune design assessment

Vegetation approach	**Parameter**	**Values large scale dune design assessment**
Avalanching module	wetslp (-)	0.5

6.5 SUMMARY STEPS

The methods used in Part II of this research are covered in this chapter. Different steps are followed to assess the potential to use XBeach as a tool in large scale dune rehabilitation projects, including the potential effect of vegetation. The steps followed are visualized in Figure 6.5. First, the avalanching module and root model are applied on the large scale Beira dune with a full storm duration. The goal is to test the consistency of the effect on large scale dune dimensions and duration. Following that, the sensitivity of the belowground vegetation approaches with different environmental conditions is tested to give more insights in the applicability and effects of different dune dimensions and storm conditions. Finally, the potential effect of belowground vegetation in dune rehabilitation projects with regard to future climate was tested.

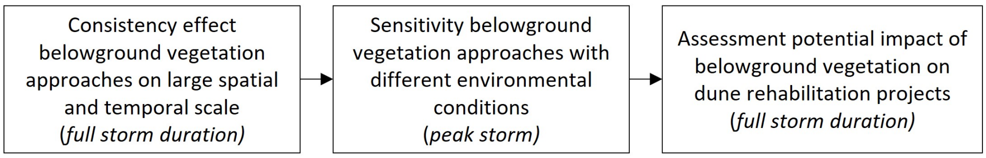


Figure 6.5: Overview steps followed part II

7 RESULTS PART II

7.1 INTRODUCTION

This chapter shows the results of the performance of the belowground vegetation approaches in XBeach on the coastline of Beira. This provides insight into the effect and sensitivity of belowground vegetation on large-scale dune dimensions and storm duration. In addition, the potential to use XBeach as a tool in dune rehabilitation projects is evaluated.

The findings of the consistency and subsequent verification tests with relation to erosion reduction and profile evolution on a large scale are reported in section 7.2. In section 7.3 the results of a sensitivity analysis concerning dune dimensions, wave height, and storm duration are given. The impact of vegetation in dune rehabilitation projects is presented in section 7.4.

7.2 CONSISTENCY AND VERIFICATION EROSION REDUCTION LARGE SCALE

In Part I, different insights have been obtained about the belowground vegetation approaches in XBeach for wave flume experiments. In this section, the Beira model verifies the profile evolution and relative erosion reduction with the implementation of vegetation on large-scale dune dimensions.

7.2.1 Profile evolution

The simulation without any belowground vegetation exhibits the largest retreat. The application of the smallest value of the root model (*rcc*=0.05) results in a negligible smaller retreat and erosion volumes, which cannot be observed in Figure 7.1. Increasing the value of *rcc* to 2.7, results in a slightly smaller retreat. The profile shape is similar to the case without vegetation. Sediment is deposited at the toe of the dune, resulting in a relatively high dune toe.

When a larger critical slope is applied, the crest of the dune is less retreated than when the root model is applied. The dune face is steeper, which results in limited deposition of sediment at the toe. This results in a lower elevation of the dune foot. When the two approaches are combined, the erosion mitigation is reinforced.

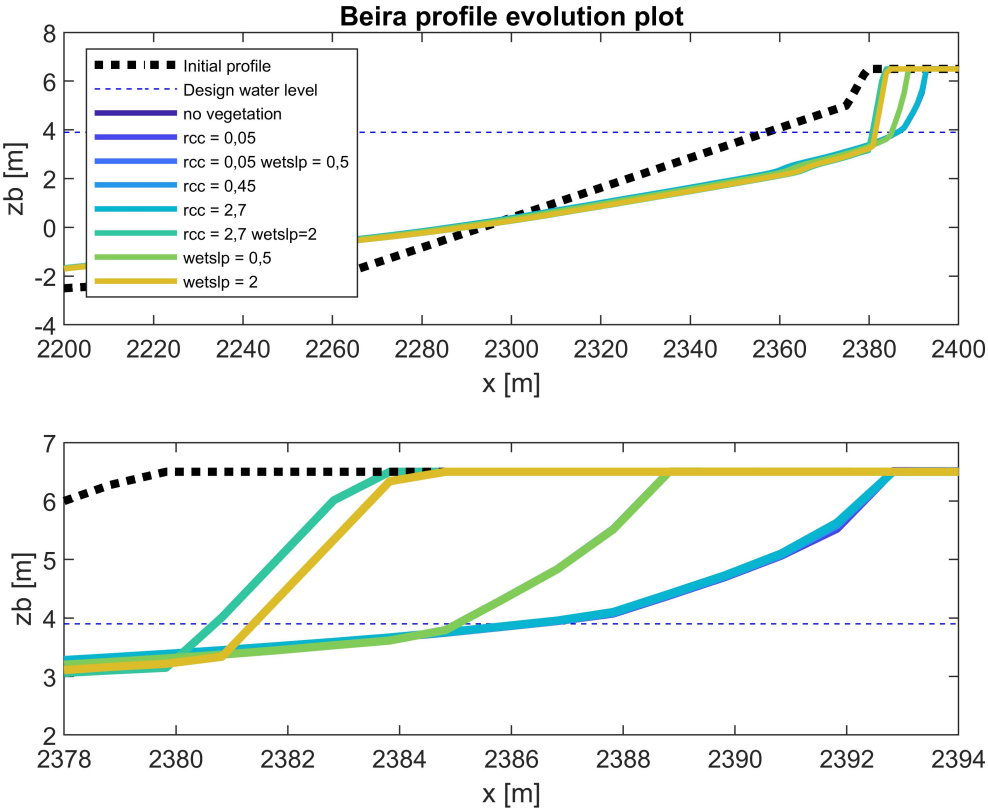


Figure 7.1: Illustration of profile evolution Beira model with the application of different vegetation approaches. Above plot shows the beach and dune and the lower plot a zoom in of the dune. The simulation without vegetation has the largest retreat and the simulation with both a higher critical angle (avalanching) and root model shows the smallest retreat and erosion volume.

7.2.2 Erosion volumes

Applying the Beira boundary conditions to the analytical approach without vegetation, similar erosion volumes are found as indicated in Table 7.1.

Table 7.1: Verification without vegetation analytical wave approach

Quantification method	Erosion without vegetation [m^3/m]
XBeach	43
Wave impact approach	45

Figure 7.2 shows that the application of a critical wetslope of 0.5 matches the erosion volumes for the wave impact approach with a resistance coefficient value (τ_b/τ_r) of 0.75. This falls in the range determined by Ajedegba et al. [2019] examining vegetation in South Padre. The erosion reduction for the Bryant belowground cases are also indicated in this figure. Increasing the critical wet slope till the maximum recommended value of 2, the erosion volume still falls within the range found by Ajedegba et al. [2019].

The application of a *rcc* with ranges between 0.05 and 2.7 results in all cases in a negligible erosion reduction. The effect of the different values is negligible and is therefore not added to Figure 7.2.

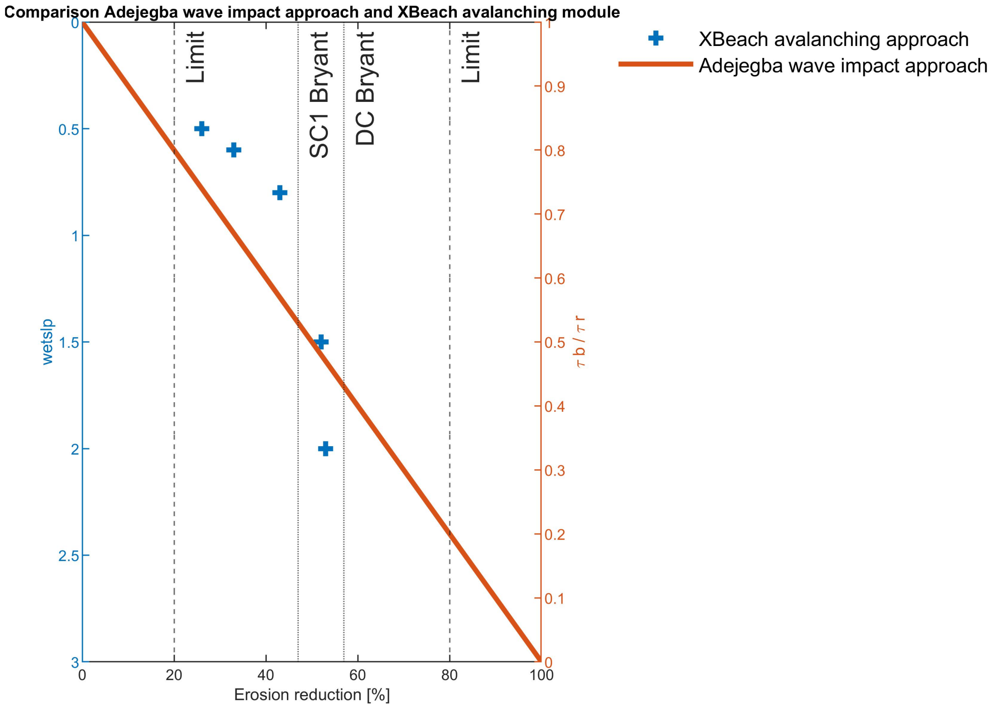


Figure 7.2: Correlation between the wave impact approach including roots and using XBeach including a higher critical slope in the avalanching module for Beira. Values of 0.5-2 for the wetslp fall within the limits of Adejegba. The erosion reduction values for the belowground Bryant cases are also indicated. The wave impact approach including roots shows a linear relationship, while the application of a larger wetslp indicates a nonlinear relationship.

7.3 SENSITIVITY LARGE SCALE BELOWGROUND VEGETATION APPROACHES

In the previous section, confidence is obtained in the erosion reducing effect of avalanching module alone and combined with the root model. In this section, the Beira model is used to assess and show the sensitivity of implementing the belowground approaches with a range of dune dimensions, a range of wave heights, and a range of storm duration. A critical wet slope of 0.5 is applied, which is a conservative option as illustrated in Figure 7.2. Furthermore, a *rcc* of 0.45 is applied. In contrast to the previous section, only the peak of a storm with a duration of 3600 seconds is employed.

7.3.1 Dimensions

Different beach and dune dimensions can be found along the coast in general and in Beira specifically. The Beira model is used to investigate whether different beach-dune geometries affect the amount of erosion reduction using the belowground vegetation approaches.

Applying a more gentle slope results in all cases in a larger erosion volume. The effect of the incorporation of a larger critical wet dune slope on dune erosion volumes varies depending on the dune slope. The larger the slope of the dune $(tan\beta)$, the larger the reducing effect of the avalanching module (Figure 7.3). A slope of 1/6 together with the avalanching module results in a relative erosion reduction of $\sim 5\%$ and a slope of 1/2 together with the avalanching module results in a $\sim 30\%$ relative reduction of erosion volume. By contrast, changes in the dune dimension have a negligible effect on the impact of the root model. The relative erosion reduction is all around $\sim$ 25%. The effect of the width (w_{dune}) and height (h_{dune}) of the dune on the erosion volume using the belowground vegetation approaches, result in the same relative erosion reduction and is therefore not illustrated.

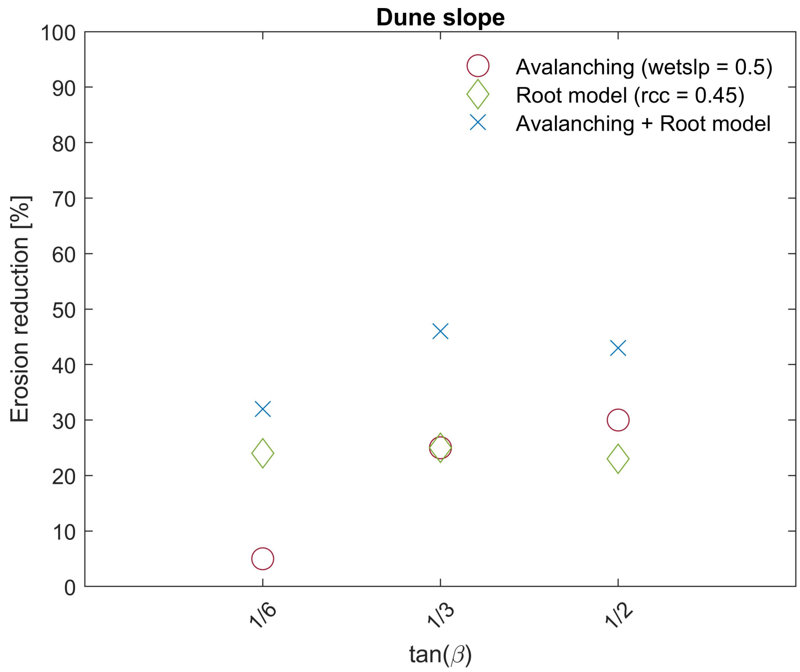


Figure 7.3: Reduction erosion volumes for dunes with the application of a higher critical angle in the avalanching module and the root model for dunes with different slopes (tan β). A smaller slope results in all cases in more erosion (not illustrated in this figure). The avalanching approach is sensitive to the dune slope. The erosion reduction is relatively larger for the steeper dune.

7.3.2 Hydraulic conditions

Different hydraulic conditions can be found along the coast in general and in Beira specifically, as presented in Table 6.1. The generic Beira model is used to investigate the sensitivity and applicability of the different belowground approaches during different hydraulic conditions, e.g. the wave height.

Both the separate and combined simulations are illustrated in Figure 7.4. Applying a larger critical wet slope in the avalanching module and a relatively small wave height ($1m < H < 2m$) shows to not affect the simulation. A slightly higher wave height ($2m < H < 4m$) results in the largest erosion reduction of around 30%. Increasing the wave height even more results in a slightly smaller erosion reduction. On contrary, the root model has the largest impact when the wave height is relatively small ($1m < H < 2m$). The impact decreases when the wave height becomes larger. Both approaches together reinforce each other.

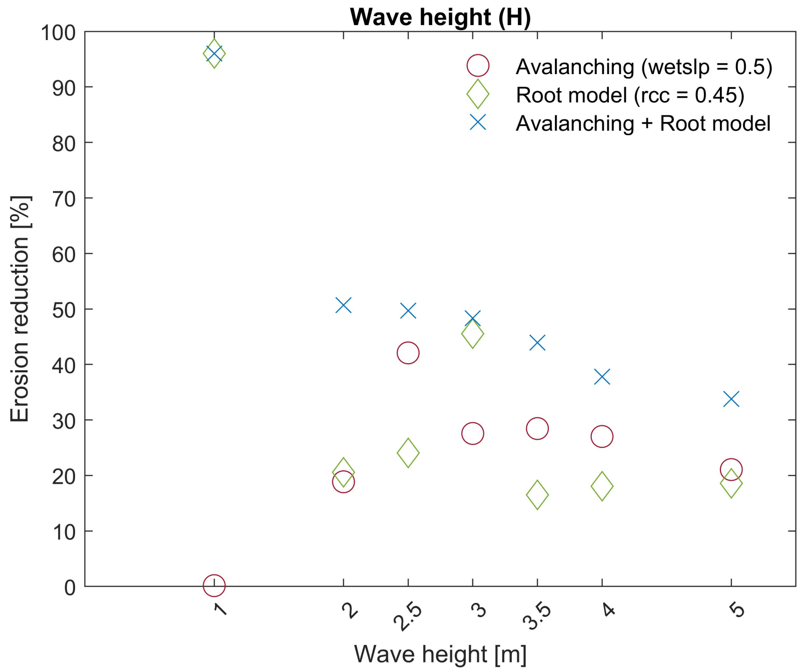


Figure 7.4: Reduction erosion volumes for dunes with the application of a higher critical angle in the avalanching module and the root model for dunes exposed to different wave heights. A higher wave height results in all cases in more erosion (not illustrated in this figure). Until a certain point, the impact of the avalanching module increases with rising wave height. Root model impact decreases with increasing wave height. Both approaches together reinforce each other.

7.3.3 Storm duration

The Beira model is used to check which tendency the model follows when simulating shorter and longer storm durations.

Both the separate approaches and the combined simulations are illustrated in Figure 7.5. The larger critical angle contributes in the first period of a storm for a small part in erosion reduction ($\sim$ 4%). At a certain moment in time, the erosion reduction reaches a steady-state ($\sim$ 22%). The root model contributes in the first part of a storm for a large part in erosion reduction ($\sim$ 44%), which decreases when the storm progresses ($\sim$ 0.5%).

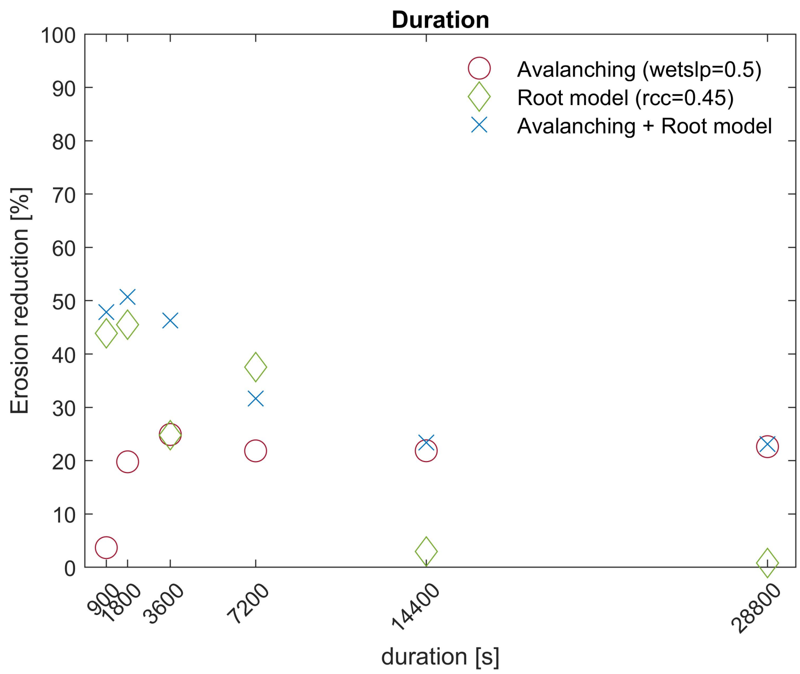


Figure 7.5: Reduction erosion volumes for dunes with the application of a higher critical angle in the avalanching module and the root model for dunes exposed to a different storm duration. A longer duration results in all cases in more erosion (not illustrated in this figure). Until a certain point, the impact of the avalanching module increases with rising wave height. Root model impact decreases with increasing wave height. Both approaches together reinforce each other.

7.4 IMPACT OF VEGETATION IN DUNE REHABILITATION PROJECTS

Using the knowledge of the increased strength of a dune by the implementation of vegetation, an assessment is done to test what larger storm a vegetated dune can withstand compared to a nonvegetated dune. Since a real storm in Beira has a large duration of 30 hours and in the previous sections was found that a larger duration indicated mainly the effect of a higher critical slope, only the avalanching module was applied.

Table 7.2: Dune volumes after storm with taking vegetation effect into account and higher sea levels and wave heights

Imposed conditions	**Dune volume after storm** $[m^3/m]$
No vegetation (Safety profile)	**58**
With vegetation	67 (>58)
With vegetation + 0.1 m sea level	64 (>58)
With vegetation + 0.2 m sea level	59 (∼58)
With vegetation + 0.3 m sea level	56 (<58)
With vegetation + 0.5 m sea level	47 (<58)
With vegetation + 0.1 m wave height	65 (>58)
With vegetation + 0.2 m wave height	64 (>58)
With vegetation + 0.5 m wave height	60 (>58)
With vegetation + 0.8 m wave height	59 (∼58)
With vegetation + 1 m wave height	56 (<58)

Applying the same conditions to the profile with taking into account the effect of belowground vegetation, results in a profile which is larger than the minimum safety profile calculated for a dune without vegetation. The black profile in Figure

7.6 and Figure 7.7 is larger than the minimum safety profile (58 m^3/m) which is indicated with a red area.

SEA LEVEL Increasing the tide with steps of 0.1 meter, results in larger erosion volumes as expected. A higher water level between 0.2 and 0.3 meters still fits in the minimum safety profile. A water level of 0.5 meters higher than the initial water level results in overwash and larger erosion volume. With the inclusion of vegetation, this assessment indicates that the minimum safety profile for this stretch is obtained for an increased tide between 20 and 30 cm.

WAVE HEIGHT Increasing the wave height, results also in larger erosion volumes. Eventually, this evaluation suggests that vegetated dunes could withstand storms with a wave height between 0.5 and 0.8 meters higher than accounted for now.

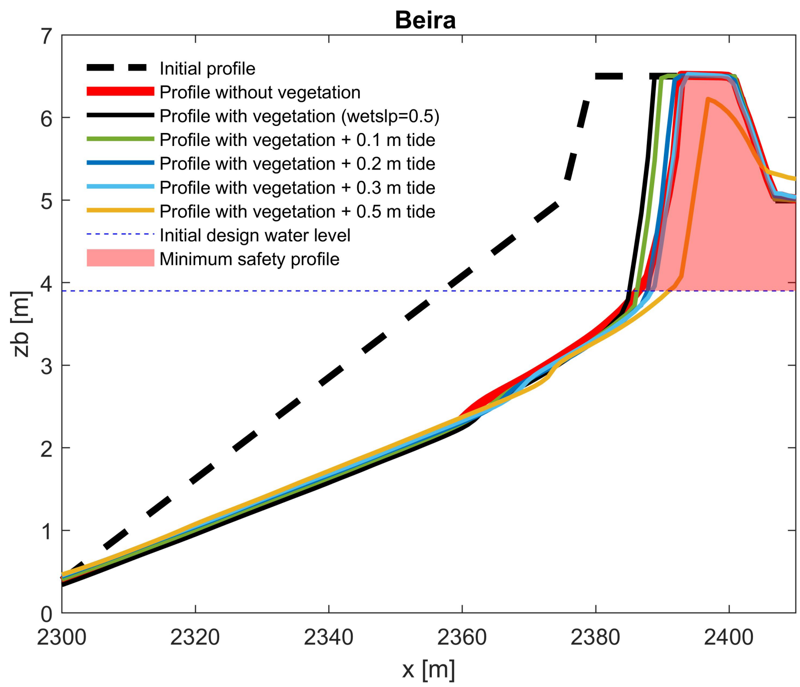


Figure 7.6: Effect of higher water level on erosion volumes for a dune with vegetation. Applying a higher critical angle representing vegetation could withstand a storm with a sea level rise of 0.2 - 0.3 meter higher than is accounted for now.

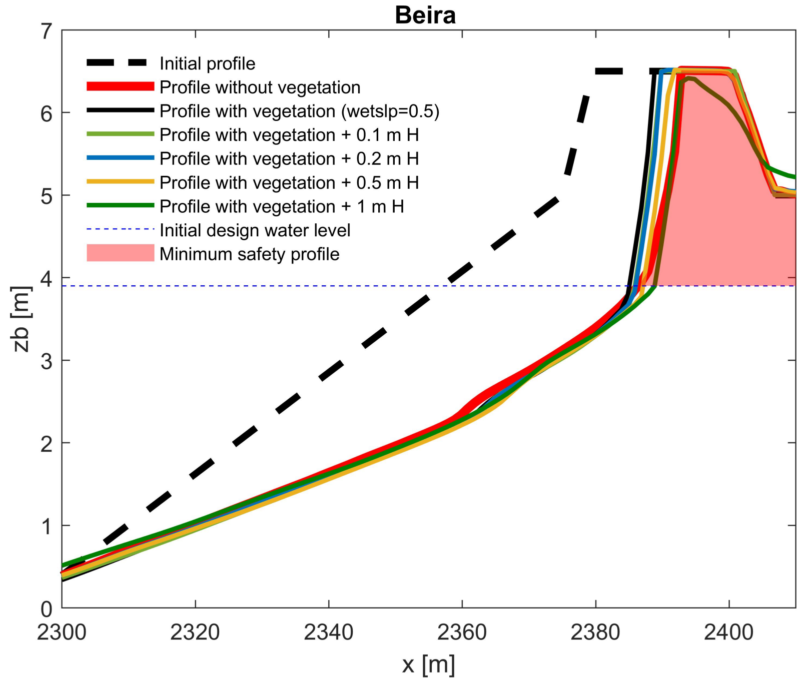


Figure 7.7: Effect of higher wave heights on erosion volumes for a dune with vegetation. Applying a higher critical angle representing vegetation could withstand storms with wave heights of 0.5 - 0.8 meters higher than is accounted for now.

7.5 SUMMARY

When the avalanching module is used on the Beira case with a larger critical slope to represent the erosion-reducing effect of vegetation, the profile evolution and relative erosion reduction are consistent with the findings of Part I, descriptions in the literature, and the analytical wave impact approach including roots. For a long storm duration together with large dune dimensions, the root model seems to have a negligible impact on the simulations.

The reduction in erosion volume with the use of the a higher critical wet slope in the avalanching module shows a sensitivity for the initial dune slope. In addition, the avalanching module shows a larger erosion reduction during direct wave impact, when relatively medium wave heights were forced. The root model is not sensitive to dune dimensions tested. In addition, this approach is more effective in reducing erosion when small wave heights are present and at the beginning of a storm.

The dune safety assessment with the application of belowground vegetation represented by a larger critical slope resulted in a smaller erosion volume. Regarding sea level, the dunes with vegetation could withstand a storm with a 20-30 centimeter higher water level than accounted for in the current design without vegetation. In terms of wave heights, it has been hypothesized that dunes with vegetation might endure a storm with 0.5 - 0.8 meter higher wave heights than currently considered.

8 INTERPRETATION PART II

8.1 INTRODUCTION

The analysis of XBeach in Chapter 7 has contributed in gaining a better understanding of the representation of belowground dune vegetation during storm conditions on a large scale. As a result, additional insight for using XBeach to evaluate vegetation in dune rehabilitation projects is obtained. The interpretations of the results are discussed in this chapter. The applicability of XBeach with vegetation on large-scale dunes is discussed in section 8.2 and the potential impact on dune rehabilitation projects is covered in section 8.3.

8.2 APPLICABILITY OF XBEACH WITH VEGETATION ON LARGE SCALE DUNES

8.2.1 Comparison and consistency large-scale

The results of the profile evolution and relative erosion reduction consistency (section 7.2) show that:

1. The application of higher critical wet slopes result in a consistent profile evolution and relative erosion reduction for the Beira dune on large temporal and spatial scale.

2. The application of the root model results in a negligible erosion reduction for the Beira dune on large temporal and spatial scale.

DISCUSSION FINDING 1 The consistency of profile evolution and reduction in eroded volume gives confidence in the approach to use a higher critical slope to represent belowground vegetation effects on large-scale dunes. The profile evolution with the application of the vegetation approaches is as expected and similar to the profiles observed in Part I and described in the literature. The application of a higher critical wet slope results in a smaller dune top retreat and a larger dune toe retreat. This is as expected, because the process of avalanching begins when a larger slope is attained. It is important to note that this steep slope may become unstable during actual storms. This can happen when for example vegetation is uprooted. As a consequence, the rate of erosion could increase. The strength provided by roots is presumed to be constant in this approach, therefore this is not taken into account.

There are some concerns about the reliability of findings from small-scale studies and the application of small-scale findings on large-scale dunes. On a small scale, erosion volumes appear to be smaller (Van Rijn [2013]; Brandenburg [2010]). This will be discussed more in depth in Chapter 9. Nonetheless, the erosion reduction with vegetation was comparable to that of the wave impact approach which included the effect of roots. This results in a higher confidence, because the wave impact approach has been validated for large-scale dunes in Texas. Since the focus of this research is on the erosion reduction due to vegetation, the absolute erosion volumes (and so the scaling effects) are less important.

The application of a critical wet slope between 0.5 and 2 on the Beira dune corresponds to resistance coefficients (τ_b/τ_r) between 0.75 and 0.5 using the wave impact approach including roots. When compared to resistance levels of Ajedegba et al. [2019] measured in the field, this is on the higher end of the spectrum (range 0.2-0.8). On top of that, the erosion reduction measured in the Bryant experiment was higher. Both findings suggest that also a greater critical wet slope might be used. It must be noted that the relationship between τ_b/τ_r and *wetslp* are not directly related. Nonetheless, they are both in some way related to the extra shear strength provided by roots.

DISCUSSION FINDING 2 The application of the root model results in a negligible erosion reduction for the Beira dune with a storm duration of 30 hours. This can be explained by the main erosion mechanism which occurs. Because the severity of the storm, the main cause of erosion is slumping. This is unaffected by the root model. A small difference in eroded volume for a *rcc* of 0.05 and 2.7 is obtained. This is consistent with the findings of Part I, which showed that the erosion reduction impact reached a peak for a certain *rcc*. From this, it can be concluded that equation 3.6 and 3.7 cannot be used for the determination of a value of *rcc*. Local vegetation characteristics can not be linked to the value applied for the root cohesion coefficient in the root model yet.

8.2.2 Sensitivity environmental conditions

The results of the sensitivity analysis concerning different dune dimensions, wave heights and storm duration (section 7.3) show that:

1. The erosion reduction of the belowground vegetation approaches in XBeach, when applying different dune dimensions, only show a sensitivity for dune slope in combination with the avalanching module.

2. The avalanching module is mainly effective in erosion reduction during medium wave heights and the root model during small wave heights.

3. At the beginning of a storm, the root model shows a large erosion reducing effect. When a storm progresses, the avalanching module is a more effective approach.

DISCUSSION FINDING 1 The effectiveness of the root model is not affected by the assessed dune slopes, dune widths or dune heights. With the applied settings, the dunes velocities on the vegetated section are apparently not affected. When lowering the dune more, it is expected that overwash takes place. In that case, the velocities are predicted to fluctuate, as will the effectiveness of the root model.

The avalanching module depends on the critical slope and therefore it was expected that this approach is sensitive for the initial dune slope (Figure 7.3). This makes sense because this module is determined by the slope. In addition, the larger critical angle caused by vegetation will become essential when the critical slope is reached.

DISCUSSION FINDING 2 The root model reduces the amount of sediment that is picked up by the flow by increasing the velocity which is needed to initiate sediment motion. Therefore this approach is most effective when the wave heights are relatively small and the flow is the main erosion mechanism (Figure 7.4).

When medium wave heights are imposed, direct wave impact the dunes and steeper slopes occur. This suggests that the application of a bigger critical wet slope under direct wave impact circumstances is the most effective when considering the erosion reducing effect in the presence of dune vegetation.

DISCUSSION FINDING 3 Finding 3 is consistent with the abovementioned finding (finding 2). The root model is mainly effective when small wave heights reach the coastline. This is mostly at the beginning of a storm, as indicated in Figure 7.5. Since storm hydrographs have usually a bell curve water level rise during storms, it is suggested that this also applies to the end of a storm. The actual effect of vegetation at the end of a storm depends on the profile development and the vegetation development during the storm. Additionally, this corresponds to the negligible erosion for *rcc* in Figure 7.1 where the storm duration was 30 hours.

As a storm progresses, dune erosion will steepen the dune face. When the critical angle is reached, avalanching takes place. This retreat due to avalanching continues till the slope of the dune does not cross the critical slope anymore. The slope of the dune remains steep due to the ongoing erosion, which explains why the relative reduction caused by a higher critical angle reaches more or less a steady-state (Figure 7.5). In reality this could be only the case when the provided strength by vegetation remains constant.

A reinforcing impact of combined approaches may be noticed almost at all times throughout a storm. Nonetheless, the combined effect is lower at t = 7200 seconds than when the root model is used alone (Figure 7.5). An explanation is that when using the root model, sediment is still deposited at the dune toe. This deposition could increase the volume of the dune. Subsequently, the reduction of eroded volume is higher, since more sediment is at the dune location. However, later this effect disappears. The deposited sediment is possibly carried offshore due to offshore sediment transport.

8.3 BENEFITS OF VEGETATION IN DUNE REHABILITATION PROJECTS

The results of section 7.4 indicate that vegetated dunes could withstand a sea-level rise of 0.2-0.3 meters and wave heights of 0.5-0.8 meter higher in 2050 than accounted for nowadays.

DISCUSSION FINDING When vegetation provides extra strength as indicated in different field studies and experiments, the storm a dune could withstand could be larger. As a consequence, future resilience will be increased. This is important when it comes to climate change and the higher sea levels and heavier storms that come with it.

The assessment demonstrates that XBeach is a useful tool to investigate and demonstrate the profit that could be obtained by the implementation of vegetation. In terms of improvement of design, the suggested higher sea level a dune could withstand results in an increase in design lifetime of approximately 15-22 years. This suggests that the non-vegetated dune could withstand a 1/50 storm expected in 2070, whereas the vegetated dune could withstand a storm with the same wave conditions in 2085-2092. This is based on the RCP8.5 sea level rise scenario with a median percentile and the locally downscaled value of Vousdoukas et al. [2018]. This scenario expects a gradual sea-level rise within 2100 a sea-level rise of 1 meter from 2010 on. For an illustration is referred to Appendix I. Another way of looking at the implementation of vegetation is that it could give more robustness to the design. This finding is interesting for consultant agencies during dune design and the decision-making in coastal protection strategies.

It is worth remembering that when a project is being realized, safety has to be ensured immediately. Vegetation growth needs time. After the implementation of vegetation, the potential resistance is not immediately present. As a result, the initial volumes should be maintained in designs. The amount of time it takes for dune vegetation to grow is determined by the vegetation type, as well as the surrounding environment. Growth rates depend on different factors such as CO_2, nutrients, temperature, rainfall, wind speed, and sediment supply. According to Baas and Nield [2007], the effectiveness of stabilizing species increases approximately by 0.05/year and pioneering species by 0.2/year. The effectiveness defined is conceptually equivalent to a plant coverage density. In turn, the aboveground vegetation growth is suggested to be correlated to belowground vegetation growth. To give an indication of vegetation growth, Barbier [2007] showed that an dune without vegetation (0% density) in France increased to a density of 80% after ten years for the dune vegetation species Ammophila Arenaria. Also, Wallén and Wallen [1980] showed an optimum of belowground biomass after 10 years for the same species.

The effect of vegetation on dune growth and thus resilience is not taken into account in this study. When vegetation captures sediment, dune growth is stimulated and dune height will increase over time. Additionally, it has been shown that dune building vegetation species are burial tolerant due to a high growing velocity. The growth is even stimulated in the case of sedimentation, due to changes in soil characteristics. This is a positive feedback. When dune height increases due to sediment deposition, higher waves are needed to overtop the dune and stronger waves are needed to pick sediment up from the dunes. When vegetation keeps growing, this process can continue. On top of that, van IJzendoorn et al. [2021] showed that sedimentation has outpaced sea level rise in the past on the Dutch coast. This phenomena might even lead to the bigger impact of vegetation in relation to the projected impact of sea level rise and climate change adaptation.

9 OVERALL DISCUSSION

9.1 INTRODUCTION

In Part I the potential impact of dune vegetation during collision regime storm conditions in the numerical XBeach was assessed using data of two wave flume experiments and in Part II the findings were further investigated and applied using a case study. Every research project has its own set of constraints and assumptions. In this chapter, the main limitations (section 9.2) of both parts are described. In section 9.3, a more in-depth reflection of the results and assumptions is provided. Figure 9.1 provides a sketch of the limitations involved in this research.

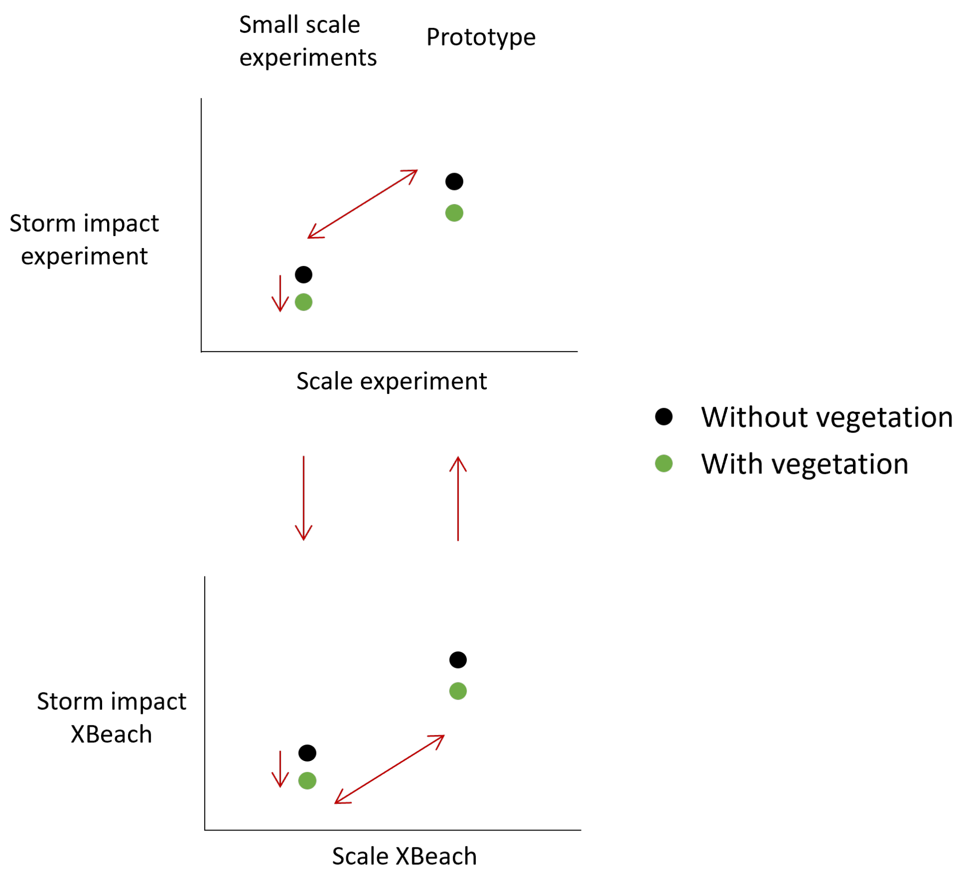


Figure 9.1: Sketch limitations in this research. Limitations are related to the starting points (not indicated in this figure), the physical experiments, the numerical modeling, different scales, and transposing knowledge between these factors as indicated with red arrows.

9.2 LIMITATIONS

The general limitations are divided into three categories: starting points, physical experiments, and numerical modeling. The most important points and consequences are discussed in detail in the in-depth reflection.

9.2.1 Starting points

The starting points of this research results in several limitations which should be taken into account when considering the implementation of vegetation in dune rehabilitation projects and the use of XBeach. The limitations and subsequent effects on the interpretation of the results are shortly pointed out in the bullet points below.

- This research concentrates on one-dimensional situations. Investigating vegetation in three-dimensional settings, could result for example in longshore instabilities and so in different outcomes.
- This research focuses on storm conditions, while the erosion and flood resilience of a dune also depends highly on the formation and growth of dunes during milder conditions. When vegetation allows for a growing of dune in volume, this will result in a larger erosion and flood resilience during storm conditions.
- This research focuses on the collision regime. A storm frequently goes through different regimes, each with its own set of erosion mechanisms and processes. Consequently, the impact of vegetation could be different.
- This research neglects structural cross-shore (e.g. sea-level rise) and longshore processes (e.g. longshore currents). Vegetation could also interact with these processes, which impacts the evolution of a dune.
- The considered vegetation is full-grown. Vegetation could be of any maturity, could have any density and so could have any strength. This impacts the potential effect vegetation has. In addition, vegetation may also be affected by other biological, chemical, and physical activities effects such as the moisture content, pH values, and amount of rainfall.

9.2.2 Physical experiments

The data of the two physical experiments assessed also bring limitations to the results, which will be pointed out briefly below.

- Only two experiments are used and it should be highlighted that this provides just a small sample of all possible dune erosion and vegetation scenarios. Recent research of for example Feagin [2021] observed an increase of erosion in the presence of vegetation.
- The dynamic similarity of all forces and the beach and dune shape were scaled in the physical experiments. However, scale effects are present in the trials which result in several limitations regarding reproducing the sediment dynamics. In this respect, it could be argued that the observed erosion and vegetation effects are different in large-scale conditions.
- Examples of shortcomings in the considered experiments concerning vegetation are:
  - Bryant used artificial vegetation with properties of real dune vegetation. Wooden dowels do not have the structural properties of flexible dune

vegetation; for this experiment is assumed that the dowels provide comparable blockage area, flow separation, and erosion patterns. This seems plausible, but the effect remains uncertain.

- Wooden dowels are incorporated in the sand. It is unknown whether this burying also influences the obtained results.
- Coir fibers, used as a representation of belowground vegetation, were not scaled to any plant root or biomass metrics. It is unclear whether coir fibers could represent belowground biomass.
- For the case of above- and belowground biomass together in the Bryant experiment, no attempt was made to directly link the fibers with the wooden dowels. In reality below and aboveground vegetation is connected.
- The transplanted plants were exposed to the new habitat for three days before the Mendoza trials. The results may be impacted since the scenario is not identical to the actual world.

9.2.3 Numerical modelling

The numerical model XBeach was used in Part I and Part II. It is important to know the uncertainties coming along with this model, as well as the approaches applied. These are listed below.

- XBeach generally simplifies reality to aid with the understanding of complicated processes. As a result, it is important to remember that models are just tools.
- Parameterization is used in several procedures in XBeach. Short wave breaking, onshore sediment movement, and dune avalanching are all examples of these processes. This can be done for computing efficiency. Another reason is that for many processes physical descriptions are uncertain. One drawback of parametric processes is that there is no physical basis for deviations from default values, especially when the model is applied to a different site.
- The vegetation approaches in XBeach that have been examined in this research have been validated for different storm conditions and types of vegetation in previous research. When it comes to dune vegetation and especially the interaction between dune vegetation and hydrodynamics during the collision regime, not much validation has been done. This results in no exact data for parameters such as rcc in the root model, C_D in the vegetation module and the critical angles for vegetation ($\varphi\ cr_{,wet}$ and $\varphi\ cr_{,dry}$) in the avalanching module.

9.3 IN-DEPTH REFLECTION

This section presents a reflection on this research and different assumptions done. It takes different points of view into account and helps the reader to consider biases. It emphasizes the need to carefully consider the outcomes. The in-depth reflection covers numerous topics, including contradictory studies, numerical modeling choices, and knowledge transfer from small- to large-scales.

9.3.1 Contradicting studies

Most research evidence supports the theory that vegetation reduces erosion volumes and rates, which was reflected by the Vegetation Factor in section 2.4.3. The evidence and information provided by these studies were used as a foundation for this research. However, there are several viewpoints on the impact of vegetation on dune erosion. As mentioned in the limitations, there is a limited amount of research addressing the effects of vegetation on dune erosion. In addition, the majority of the supporting researches consider small waves on short time scales.

varying effect of vegetation As explained in Chapter 2, Feagin [2021] conducted a massive lab experiment to identify the role of vegetation during extreme wave events. They found evidence that a vegetated dune with above- and belowground biomass erodes more quickly and results in a much larger scarp than the dune without vegetation. This was argued to be mainly a result of aboveground vegetation. This aboveground vegetation stopped the vegetation from running up the dune, resulting in a larger infiltration of water into the dune. As a result, there was early saturation over a narrow area, as well as faster and significant erosion and scarping.

As well as the findings of the Mendoza and Byrant experiments used in this research, the findings of Feagin [2021] could be disputed. It could be questioned whether the vegetation in the laboratory which was grown for 6 months is already fully grown and results in similar effects as vegetation that has grown in a real environment, with roots several meters deep. In addition, in this experiment, the increasing erosion was mainly assigned to the aboveground parts of vegetation. It is therefore interesting to test the effect of solely mature belowground vegetation for a large-scale dune.

Also, the study of Carter and Stone [1989] pointed the contradicting effects of vegetation out. They showed that the density and type of vegetation in combination with the occurring hydrodynamics impacting the dune result in variability in dune scarping in Magilligan, Northern Ireland. Dunes subjected to wave runup, swash bores, and different vegetation covers resulted in different slope failures. Similarly as assumed in this research, a dune with a relatively small vegetation density (approximately 1 plant / m^2) experiences more and a faster undercutting and erosion than a well-vegetated dune (4-6 plants / m^2). The strength of the well-vegetated dunes was frequently enough to keep the scarp in place. The time before failure appeared was related to the soil bulk density, depending on the shear strength of the dune slope and root development. However, other dunes with a different type of vegetation cover subjected to direct wave impact resulted in quick undercutting and collapsing of sediment and the roots.

Contradicting effects of vegetation during storm conditions were also observed in the field study of Maximiliano-Cordova et al. [2021]. They studied three different sites with different beach-dune morphology and dominant species. Only at one of the three sites, plant cover was negatively correlated with erosion during storm conditions. For the other sites, plant richness and overlap cover showed to not affect erosion.

In light of the studies used in this research and pointed out above, it may be stated that the protection provided by vegetation is mostly species, location, and storm-dependent. It is important to note that research on the overall impact of dune vegetation on dune erosion and the related processes is in progress and therefore could be contradictory.

destruction of aboveground vegetation In Part II, the effect of aboveground vegetation on dune erosion during the collision regime was neglected. The reason for the exclusion of aboveground vegetation was that the aboveground vegetation is hypothesized to be destroyed by storms with a long duration (Hesp and Martínez [2007]). However, different studies have observed a considerable impact of aboveground vegetation.

For example Odériz et al. [2020] and Bryant et al. [2019] both concluded that aboveground components of vegetation do protect a dune in both the initial swash and collision stages of a storm. Also, Miller et al. [2010] and Maximiliano-Cordova et al. [2021] discovered that beach and dune species are extremely resilient to storms.

Fernández-Montblanc et al. [2020] conducted a modeling study accounting for the effect of aboveground dune vegetation by the application of the vegetation module. They argued that aboveground dune vegetation results in wave energy dissipation and is a first-order component that can significantly minimize coastal flooding and erosion. The inclusion of vegetation increased the sediment retention between 22% - 82% compared to a dune without vegetation in a case study in Bellocchio (Italy, Northern Adriatic Sea). The validity of the findings of this study could be questioned since no data was available for model validation.

In conclusion, the exact impact of aboveground vegetation on dune erosion is debatable. It is crucial to keep this in mind.

9.3.2 Numerical modeling choices

By the application of a numerical model in Part I and II, different choices and assumptions are done in the setup and calibration. Some important points to consider are discussed below.

SURFBEAT INSTEAD OF NON-HYDROSTATIC MODELING For the simulation of hydrodynamics in XBeach, the surfbeat mode is applied in Part I and Part II. As a consequence, the effect of short wave reflection is not accounted for in the simulations. This, while the reflection of short waves could influence the simulations and thereby the morphodynamic response of the dune and beach. For example, when propagating and reflected waves collide, the consequence might be higher/lower waves, resulting in higher/lower wave impact and higher/lower sediment movement. Colliding incoming and outgoing waves could result in more turbulence and more sediment in suspension (van Gent et al. [2008]; van Thiel de Vries et al. [2008]; Van Rijn [2013]). Reflected waves could also result in a larger undertow and so more sediment transport (Martins et al. [2017]).

The absence of reflected short waves could contribute to the explanation of the initial mismatch of the experimental profiles and the simulation profiles for the control cases, where *facua* and *bermslope* had to be applied for obtaining good erosion volumes and profiles. The effect of the short wave reflection is assumed to be mainly important for the DC case where a reflection coefficient (Kr) of 0.57 was measured. For the SC1 case, this effect is probably smaller due to the smaller reflection coefficient (Kr = 0.38). The Mendoza case provided no data on reflection.

The use of the surfbeat mode in this research may be defended. Firstly, the main goal of this research was to compare dune erosion of vegetated and nonvegetated dunes and evaluate the representation of vegetation in XBeach. When for both vegetated and non-vegetated dunes the short wave reflection is not taken into account, it can be argued that this comparison can still be done. Especially since in the experiments of Bryant no differences in reflection are observed in the presence/absence of vegetation (Bryant [2022]). In addition, a link is established with actual dune rehabilitation efforts. The surfbeat mode is employed in the current determination of the dune volumes of Beira. In this regard, the representation of vegetation in this mode is primarily relevant. Furthermore, in the wave-resolving mode, much higher spatial resolution and associated smaller time steps are needed. This option is computationally far more costly than the surf-beat option.

NO SCALING OF TURBULENCE AND SEDIMENT TRANSPORT In the research of Brandenburg [2010], it was shown that small-scale experiments were modeled better by turning turbulence off and by calibration of the critical wet slope in the avalanching module in XBeach. It was hypothesized that XBeach overestimates turbulence since it could not scale turbulence well. In addition, it was observed that slopes were steeper for small-scale wave flume experiments. The simulated profiles in this study showed that the model underrates the slope above the surge level for small-scale experiments. In the cases of Bryant (SC1) and Mendoza in this research, the model does not underrate the slope above the surge level in the control simulations. Therefore a higher critical wet slope was not applied. Turbulence is also enabled, as it is possible that 100% turbulence exclusion is unrealistic.

When it comes to small-scale experiments and XBeach, it is crucial to be aware of the numerical modeling choices you make, the initial setup of the model and the possible scaling effects in small wave flume studies.

9.3.3 Transfer knowledge from small scale to large scale

For the representation of vegetation effects, the findings based on small-scale experiments of Part I are applied to a dune in Beira with real dimensions in Part II. This brings some limitations with it and it must be recognized that a one-to-one application of the same higher critical slope on the Beira dune based on findings of small-scale experiments should be carefully considered.

APPLICATION FINDINGS SMALL SCALE TO LARGE SCALE Small-scale physical models have significant constraints in recreating sediment dynamics since some characteristics or processes cannot be scaled. Scaling effects could be present, which was also pointed out in the studies of for example Van Rijn [2013] and Brandenburg [2010]. For example, the sediment itself can not be scaled. The reason is that the Reynolds criterion will not be met and cohesive forces will become dominant when using small sediment sizes (Brandenburg [2010]). Therefore, relatively large sediment sizes are applied in wave flume experiments. An important potential effect of this relatively large sediment size is a smaller sediment transport capacity. The transport capacity depends on the hydrodynamics (force) and characteristics of the dune (resistance). The rate between wave height and grain size is smaller in small wave flume experiments, and therefore the transport capacity of nearshore hydrodynamics is likely to decrease. In addition, the relatively larger sediment grain size used in small wave flumes result in relatively a larger roughness, a smaller run-up height, and therefore possibly smaller erosion volumes. Thirdly, coarser sand generates steeper slopes under the same wave stress, which results in a decreased sediment movement and steeper profiles than in nature (Brandenburg [2010]). For all aforementioned processes, it could be argued that the erosion in the small-scale wave flume experiments due to this phenomenon is slightly smaller than in large-scale conditions. This was also observed and pointed out in the study of Van Rijn [2013]. Unfortunately, a definite judgment on scale errors cannot be made due to a lack of data.

With respect to this research, erosion reduction in the presence of vegetation is considered. For both vegetated and not vegetated dunes in the experiments, the erosion might be underestimated compared to larger dimensions. It can be claimed that when comparing cases with and without vegetation, the erosion for both cases is underestimated, and therefore the possible effect of scale is less important.

As mentioned above, Brandenburg [2010] observed a difference in slope when using the same sediment size for different scales and used the critical wet slope in the avalanching module to account for this. This suggests that the critical wet slope obtained for a small-scale vegetated dune is not directly applicable to large-scale conditions. However, the critical wet slope in the small-scale control experiments of the Bryant SC1 case and Mendoza did not need to be modified from default values. It can therefore be argued that the higher slope for small-scale experiments observed by Brandenburg [2010] is not necessarily true for the Bryant and Mendoza experiments. In addition, the applicability of a higher critical wet slope on the Beira dune based on the slope obtained in Part II is supported by the comparison with the wave impact approach from Ajedegba et al. [2019]. This was validated for a large-scale dune.

It can be concluded that the scale effects do not influence the main finding that a higher critical slope could account for vegetation effects: reducing the erosion rate and volumes. The possible scaling effects must be considered when applying the same critical angle as applied in the small scale experiments.

9.3.4 Various management perspectives

STABILITY VERSUS MOBILITY The definition of dune rehabilitation in this research is the restoration of dunes from a damaged, to a less impaired or unimpaired state of overall function, to gain the greatest coastal protection benefits. Dune rehabilitation involves dune management. Different perspectives regarding dune management exist (Delgado-Fernandez et al. [2019]). Which perspective to follow depends on the main goal of intervening. From the flood protection perspective, the primary goal of a dune rehabilitation project is to increase the volume of material in the dune ridge to cope with dune erosion during design storms and hinder flooding Bosboom and Stive [2021]. As a result, the argument of creating stable dunes is employed in this thesis. Nonetheless, numerous perspectives on dune mobility exist to achieve optimal dunes. Allowing for mobile dunes is a concept that is gaining more attention (AP Grootjans [2002]) . The reason behind this is, that more thought is given to maintaining the natural functioning of the system and nature conservation. The state of mobile dunes and stable dunes is influenced by different environmental stress factors such as plantation Arens et al. [2007]. In this viewpoint, the implementation of vegetation by humans is not favorable.

Dune rehabilitation projects vary greatly in scale and complexity depending on the extent to which the existing dune system has been degraded and the environmental conditions. It is important to consider the goals of the intervention and the local conditions, before planting vegetation.

10 OVERALL CONCLUSIONS AND RECOMMENDATIONS

10.1 CONCLUSIONS

The objective of this research was to investigate the potential effects of dune vegetation during collision regime storm conditions and link this effect with dune rehabilitation projects. To reach this goal, several questions and subquestions were stated in Chapter 1. The research questions are answered in this section.

What are the important processes and effects of dunes and dune vegetation during collision storm conditions and how could this be quantified?

Collision regime storm conditions may occur when a storm elevates the water level. During these conditions, water reaches the dune. The dune could be affected by broken waves (swash bores) or impinging waves (wave impact), resulting in dune erosion. During the collision regime, vegetation mainly affects the dune erosion volume and erosion rate. Aboveground vegetation mostly causes hydrodynamic interaction, which affects the load on a dune. The main process related to belowground vegetation is soil stabilization. This affects the resistance of the dune.

In the presence of swash flow on a dune, both the aboveground portions and belowground portions appear to play an important role. The interaction of the aboveground portions with hydrodynamics could result in a higher roughness, wave swash and run-up bore attenuation, energy reduction, a change in wave reflection, and a lower run-up. The belowground portions change the physical properties of the dunes and alter the composition of the sediment. This is supposed to aggregate the soil, increase the shear strength, hold sediment together, increase the repose angle, and reduce sediment mobility. The importance of belowground vegetation is likely to increase during wave impact.

Dune erosion volumes during storm conditions could be calculated using different methods. A numerical model is an example. For a first indication of the effect of vegetation on dune erosion volumes, a Vegetation Factor (VF) is calculated. This is defined as the eroded volume of a vegetated dune divided by the eroded volume of a nonvegetated dune considering the same conditions. For the available data, vegetation during the collision regime provided on average a vegetation factor of 0.62 for wave swash erosion and a vegetation factor of 0.65 for erosion during wave impact. This suggests an average erosion reduction of approximately 35% for vegetated dunes.

Is the numerical model XBeach capable of simulating the effects of vegetation during the collision regime?

The XBeach model is capable of capturing the morphological effects of vegetation in terms of reduction in dune erosion volume and profile evolution. In XBeach, four different vegetation approaches were identified and tested to determine if they could accurately represent the potential effects of dune vegetation during the collision regime. The vegetation module in XBeach accounts for the short and long wave attenuation caused by aboveground vegetation and the roughness approach accounts for the reduction in flow velocity due to aboveground vegetation. The root model accounts for the additional root cohesion provided by belowground biomass by increasing the critical velocity for sediment pickup. Finally, the avalanching module allows sediment transport when a certain critical angle is exceeded. By increasing the critical angle, the influence of belowground biomass on the cohesion and subsequently occurring slope might be mimicked.

The effects of belowground vegetation were mimicked correctly by raising the critical slope in the avalanching module. The application of the root model was included for even better simulations. The sample size was insufficient to provide a quantitative suggestion for the critical slope to employ in the root model, along with which value for the root cohesion coefficient. Since the applied critical slope and the value for the root cohesion coefficient were set differently for different cases, no direct conclusions can be drawn from this. As far as the researcher knows, no systematic research has been done on the effect of dune vegetation on the critical angle. Therefore, no structural relationship has been found yet.

The application of an increased roughness or the application of the vegetation module could not represent the observed effects of aboveground vegetation. The roughness approach did not influence the simulations and has shown to be insensitive to changes in applied width or values during the collision regime for the assessed cases. The vegetation module is slightly sensitive to the imposed hydrodynamic conditions, as well as the applied width and drag coefficient value (C_D), vegetation diameter (b) and vegetation density (N). However, the simulations demonstrated that the erosion reduction using this approach was insignificant compared to the aboveground effects measured in the experiments.

How could the knowledge regarding dune vegetation during storm conditions be applied in real dune rehabilitation projects?

The consistency of erosion reduction for large-scale dimensions and duration using a higher critical slope, indicate that XBeach is a useful tool to investigate and demonstrate the profit that could be obtained by the implementation of belowground vegetation. This gives confidence in using a higher critical in XBeach to represent vegetation effects during dune design assessments. Considering dunes susceptible to collision regime storm conditions and direct wave impact, applying a larger critical slope might primarily be used to simulate the erosion reduction caused by belowground vegetation. The root model has shown to be more effective during milder wave conditions and short storm duration.

The case study of Beira indicates that dunes with a full-grown mature vegetation root system resulting in a higher critical angle, could withstand storms in 2070 with a higher sea-level rise of 20-30 centimeters or a 0.5-0.8 meter higher wave height than accounted for nowadays. In terms of improvement in dune rehabilitation projects, this can be related to the robustness of the current design. Also, the design lifetime could be increased. The suggested higher sea-level rise suggests for example an increase in design lifetime of approximately 15-22 years. While a non-vegetated dune might be able to resist a 1/50 storm in 2070, this research shows that a vegetated dune would be able to withstand a storm with similar wave conditions in 2085-2092. This is based on the RCP8.5 sea level rise scenario with a median percentile. This scenario expects a gradual sea-level rise with at the year 2100 1 meter sea-level rise from 2010 on.

10.2 RECOMMENDATIONS AND FUTURE WORK

Recommendations and future work that arise from this study are organized into four subcategories. The first set of recommendations relates to knowledge development using experiments and field studies. The second category concerns the use of the XBeach model in relation to vegetation. The third category advises on further XBeach development. The final category includes practical suggestions that could be used in dune design and rehabilitation strategies.

10.2.1 Experiments and field studies

To be able to make more conclusive and reliable statements regarding the effect of dune vegetation on dune erosion, more research should be done regarding the effect of vegetation during storm conditions. Based on this research, there should be focused on:

- Relationship between belowground vegetation, cohesion, shear strength, and subsequent critical slope (on large-scale).
- The interaction and effects of aboveground vegetation with hydrodynamics during different storm conditions (on large-scale).
- The effect of different types of vegetation and vegetation characteristics on dune erosion (on large-scale).
- The effect of local conditions on dune erosion volume in the presence of vegetation (on large-scale).
- Scale effects and comparison of findings in wave flume experiments and prototype scale.

10.2.2 XBeach application

Care should be taken by the application of the identified vegetation approaches in XBeach for the representation of dune vegetation during the collision regime. Key parameters in the assessed vegetation approaches, such as the critical wet slope (*wetslp*) and the root cohesion coefficient (*rcc*) are sensitive to different values and conditions. In addition, several limitations are involved in making use of small-scale experiments. However, some first suggestions regarding local conditions and values based on this research are given.

LOCAL CONDITIONS Since the impact of the applied critical angle and the root cohesion coefficient to account for vegetation differ per assessed case, it is important to consider local conditions when using these approaches. Local factors such as vegetation placement (which may vary depending on species), water level, and wave height determine which critical value should be raised (wet slope or dry slope). Furthermore, information about the local conditions could indicate to which value the critical angle and root cohesion coefficient could be increased. For a dune subjected to a small water level, and only vegetation at the top of the dune, it is recommended to heighten the critical dry slope. However, in the case of more extreme storm conditions, most of the time the critical wet slope is recommended to be raised for the representation of vegetation. This is due to the assumption that the vegetation section will become wet during storm conditions. Furthermore, the extent to which the critical slope must be raised depends on the extra strength the roots provide to the soil and hence on local conditions. It is important to set the critical wet slope not higher than a slope that occurs in reality.

Also, the local erosion mechanism and duration of a storm are important to consider. When a dune is subjected to slumping, often when storm duration is long, the avalanching module is more effective in reducing the erosion volumes provided by vegetation. When a dune is more subjected to wave swash and a shorter storm duration, the root model could be more effective.

PRELIMINARY RECOMMENDATION AVALANCHING MODULE Based on the assessed experiments, the critical wet slope could be raised from 0.3 to 0.4 - 0.5 when assessing dunes subjected to collision regime storm conditions. The XBeach manual recommends a maximum value of 2. However, as mentioned in the literature study, also much higher slopes are observed in real-life conditions.

10.2.3 XBeach development

XBeach has shown to be a good tool to examine the evolution of dunes during storm conditions and the capability of simulating vegetated dunes. Nonetheless, different suggestions regarding further XBeach development are done.

VALIDATION OF VEGETATION APPROACHES More modeling studies should be performed to ensure that the identified vegetation approaches are thoroughly validated. As a result, a more accurate recommendation for which dune vegetation values to employ in which situation may be made. Since this study is based on small-scale experiments, it is interesting to assess large-scale wave flume experiments in XBeach.

CRITICAL SLOPE FOR VEGETATED SECTION A new module or algorithm could be developed that allows the user to specify a different critical angle only for the vegetated portion. In addition, to account for the effect of erosion and subsequently the decrease of the effect of vegetation on the critical angle, one could argue to implement a dynamic approach, where a large critical slope which decreases with erosion depth. A proposal for the implementation of this is given in Appendix J.

PROCESS-BASED AVALANCHING A more processed-based model of dune slumping processes to incorporate the influence of vegetation and create even more realistic simulations of dune slumping could be developed. The resistance of the dunes might be included. For example, geotechnical characteristics representing the resisting strength of a dune described by Erikson [2007] could be applied. In addition, Carter [1980] provides an explanation and description of different types of dune failure for dunes with and without vegetation.

10.2.4 Practical recommendations

Based on this research, it is recommended to pay attention to the planting and growth of dune vegetation during dune rehabilitation projects. Firstly because it has the potential to reduce dune erosion volumes and retard dune erosion, which is important for flood and erosion protection. In addition, dune vegetation helps in dune formation and dune growth which also increases flood and erosion resilience.

For convenience, the strengths, weaknesses, challenges, and opportunities regarding the implementation of vegetation in dune rehabilitation projects are provided in Appendix K. The qualitative cost analysis provided can assist in determining costs when applying vegetation in a specific project. The information in this Appendix can be used as a resource about the practical application of vegetation in dune design.

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A SUMMARY PREVIOUS RESEARCH

A.1 INTRODUCTION

First an overview regarding researches which consider the effect of dune vegetation during storm conditions. For researches assigned with a *, the VF for the collision regime is calculated to give an idea of the size of this effect. An overview of calculated VF is finally shown. Hereafter, the researches and effects are described in words.

Examples of the evidence of the effectiveness of the use of vegetation for coastal protection with respect to coastal dunes

Year	Authors	Type of work	Regime	Results - storm conditions
2013	Kobayashi et al.*	Experimental/labaratory	collision/overwash	A wide vegetation cover reduced the erosion of the fore slope as well as the overtopping and overwash rates
2014	Sigren et al.*	Experimental/labaratory	collision	Erosion reduction of 33% , Rate of dune scarp decreased with of 30% . It has also been demonstrated that their roots contribute to strengthening the cohesiveness of the sand
2014	Figlus et al.*	Experimental/labaratory	collision	Erosion volume average reduction of 33% (regular wave test)
2015	Feagin et al.	Review		Dune scarp retreater at 30% slower rate in vegetated tests and formed a steeper slope (regular wave test). The more mature plants (5 weeks old) used in test V3 showed reduced dune erosion volumes up to approximately 8% (irregular wave test)
2016	Silva et al.*	Experimental/labaratory	swash/collision/overwash	Protective role of narrow dune helps to limited extent but enhanced by presence of vegetation. Wide dune more resistant, offers more protection to land behind and vegetation favours performance. Vegetation reduced height of scarp produced. Vegetation can reduce volume of material lost by dune especially for swash and collapse (wave attenuation is rarely linear), the above-ground plant parts slow wave uprush, and reduce wave overtopping and overwashing
2017	Mendoza et al.	Experimental/labaratory	swash/collision/overwash	Erosion regimes of collision and overwash were observed in the dune profiles with a berm, whereas swash and overwash regimes were observed when no berm was present. Retarding erosion time seems to be the most relevant morphological effect of the dune vegetation, which gives a slight, but relevant, contribution to the resilience and resistance of the beach profile. In turn, the wave breaking point is displaced seawards and bed velocities close to the shoreline are lower when vegetation is present, both of which explain the protective role of vegetation on the beach profile. deaccelerate the undertow close to the shoreline
2017	Figlus et al.	Experimental/labaratory	swash/collision	An increasing surface area of the aboveground plant structure resulted in a decreased turbulent kinetic energy in the swash zone, which was identified as a key factor linked to erosion reduction. With regard to belowground biomass, fine roots (D < 1 mm) were a key factor on the resultant dune erosion due to an increased shear strength and hence a less frequent occurrence of slumping and collapsing of the dune slope,. the above-ground plant parts slow wave uprush, and reduce wave overtopping and overwashing
2017	Lindell et al.*	Field data	collision	wave erosion greater for bare dunes than that on dunes where the vegetation remained
2017	Charbonneau	Field data	collision/overwash	the reduction of erosion by vegetation is species-specific
2019	Feagin et al.*	Experimental/labaratory	swash	Vegetation reduces run-up erosion More erosion back half BG treatments than AGBG Wave attenuation by aboveground biomass primary mechanism of reducing erosion Belowground biomass can increase erosion. Above-ground plant parts slow wave uprush, and reduce wave overtopping and overwashing
2019	Bryant et al.*	Experimental/labaratory	collision/overwash	For the collision regime, biomass reduced scarping of the dune face at lower water levels and delayed the onset of overtopping and transition to the overwash regime at deeper water levels. For the overwash regime, the presence of biomass reduced erosion of the dune's lee and stoss slope, and, in the case of the deeper water level, prevented the flattening of the entire dune form. Lowest percent loss of dune material and greatest decrease in sediment and water overwash 1) AG+BG 2) BG 3) AG
2020	De Battisti and Griffin*	Experimental/labaratory	swash	It has also been demonstrated that their roots contribute to strengthening the cohesiveness of the sand. Sediment loss reduction greatest ammophila 36%, Salsola 27%, Cakile 23% Overall, restoration projects employing different species that occupy different dune zones might provide better resistance against waves with respect to systems that employ only a single species (e.g. Ammophila) or those occupying the same zone. Buried shoots play a crucial role in sediment stabilization. Furthermore, we highlight that employing a coarse sediment can be deleterious for sediment stability and thus for achieving restoration goals in terms of coastal protection. their findings showed that the most important characteristic for reducing scarping was the total below-ground biomass. The greater the ratio of roots, rhizomes, and buried shoots to sediment below the surface, the greater the reduction in erosion.
2019	Maximilano-Cordova et al.*	Experimental/labaratory	swash	We found that erosion was reduced in dunes covered by plants, but such protection was species-specific, and the effectiveness of protection varied over time. Ipomoea was the most effective specie for protection. Differences between species and combinations of species were associated with their physical attributes such as growth form and plant architecture.
2020	Oderiz et al.*	Experimental/labaratory	swash/collision/overwash	The results showed that when vegetation was at forward positions on the dune, it decreased run-up, increased reflected energy and transferred it to low frequency bands, and reduced the eroded volume on the exposed dune face. When the vegetation was placed on the leeside of the dune, it retarded and prevented overwash, but not as efficiently as the internal rocky structure did. In summary, plants are better to dissipate waves and provide protection during the initial swash and collision stages of a storm, while a rock structure is better to prevent overwash and dune destruction during the final stages. spatial location of the plants on the dune affects the erosion patterns
2020	Davidson et al.	Review and projections	collision	the mass, density, and depth of the roots affect the erosion patterns
2021	Maximiliano-Cordova et al.	Field data	swash/collision/overwash	Erosion was reduced when the dunes were higher and, furthermore, plant cover was negatively correlated with erosion on these dunes.

Figure A.1: Overview studies that focused on the effect of dune vegetation during storm conditions. A * denotes that the VF was calculated for this study.

A.2 CASE, MODELLING AND FIELD STUDIES REGARDING DUNE VEGETATION

The outcomes of different case and field studies is summarized below. This strengthens the importance of coastal dune vegetation.
Sigren et al. [2018] conducted an analysis from Hurricane Ike to show the effects of coastal dune volume and vegetation on storm-induced property damage. For the west side of the storm, dune volume and vegetation were both substantially associated to less severe property damage. The findings of this study suggest that dunes might be an important component of coastal hazard mitigation techniques, as well as a unique potential for bioengineered, green infrastructure. Passeri et al. [2018] and Schambach et al. [2018] demonstrated with a model study that the presence of vegetation results in a reduction of overwash velocities, resulting in maintaining of sediment on the subaerial dune.
Godfrey and Godfrey [2020] acknowledged the role of salt-resistant plants in maintaining dunes and slowing overwash, and they suggested that overwash processes, beach preservation, dune vegetation and barrier island migrations were interrelated.Dahl [1983] analyzed pre- and posthurricane surveys to quantify the effects of vegetation on dune change following an overwash. Similar to the observations of Godfrey and Godfrey [2020], a greater quantity of sand was transported inland for the dunes without vegetation. Furthermore, Donnelly et al. [2009] qualitatively proved the significance of vegetation in decreasing dune erosion and overwash through field research. However, the contribution by vegetation was not quantified. The study of Lindell et al. [2017] analysed Angelholm Beach in South Sweden and showed that wave and wind erosion increase due to the removal of vegetation. Dune front erosion during storms increased 2-4 times compared to dunes including vegetation. Charbonneau et al. [2017] quantified coastal dune erosion from Hurricane Sandy and documented t a species-specific effect on collision erosion. Also Biel et al. [2019] studied and highlighted the dune resistance of specific species on collision erosion. A recent field study in Mexico of Maximiliano-Cordova et al. [2021] also showed that erosion was negatively correlated with erosion during the collision regime. However, this correlation was shown in 1 out of 3 sites. This shows that the protective role is species- and site-dependent. Ajedegba et al. [2019] established an analytical wave impact model that included the role of plant roots to the lowering of dune erosion volume during the collision regime. This approach takes the effect of extra strength provided by vegetation roots into account, which results in an erosion reduction between 1.25 and 5. This was validated by a case study regarding Hurricane Dolly in Mexico.

A.3 WAVE FLUME EXPERIMENTS REGARDING DUNE VEGETATION

Several wave flume experiments considering vegetation during storm conditions are summarized below. A division is made between experiments assessing specifically runup, wave impact or both.
In Figure A.2 the experiments which addressed the role of dune vegetation are shown, all with different set-ups and focus. The inundation regime is not described, since there is a possibility that during this regime waves are not longer the primary hydrodynamic force that affect the dune erosion Palmsten and Holman [2011a].

The general conclusion of all experiments, is that the existence of vegetation of dunes, results in a decrease in dune erosion. It was also emphasized that both above- and belowground biomass have a positive effect on the erosion resistance of

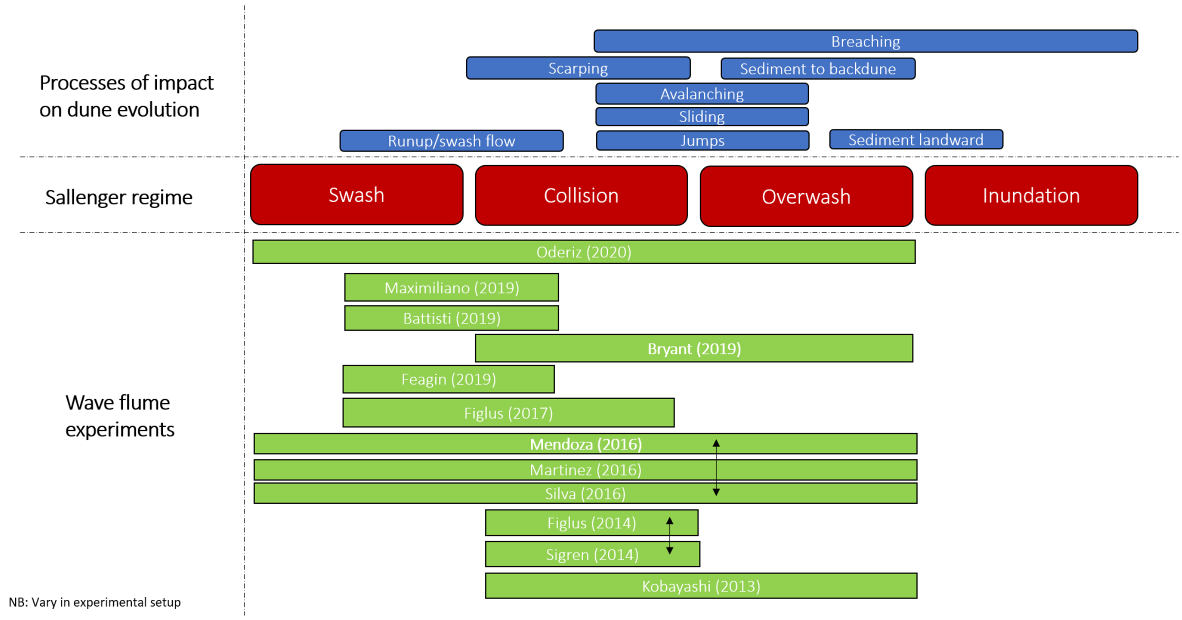


Figure A.2: Overview wave flume experiments and link with Sallenger regime and processes of impact on dunes

dunes.

COLLISION RUNUP de Battisti and Griffin [2020] sought to investigate the function of annual species in erosion resistance and to separate the contributions of 3 distinct below-ground compartments (roots, rhizomes, and buried shoots). The key results of this studies are the fact that all three species considered (both annual and perennial plants) reduce erosion and that the total belowground biomass mostly explained erosion resistance, compared to one compartment. The most important individual belowground plant compartment contribution came from buried roots, which drives sediment stabilization.

Maximiliano-Cordova et al. [2019] evaluated the erosion with swash flow considering three beach dune species. The results show that plant cover reduces erosion, the effectiveness depending on the plant architecture..

Feagin et al. [2019] conducted research with looking at the model wave run up effects at the initiation of a storm (prior to dune failure by collision). The length of the experiments were set accordingly.

COLLISION WAVE IMPACT AND OVERWASH Kobayashi [2013] did small wave flume experiments with woody plants, represented by buried dowels. The goal was to investigate the effects of woody plants on dune erosion and overwash with irregular waves impinging on a dune.The wide vegetation covering the foreslope reduced erosion of the foreslope as well as the overtopping and overwash rates. Furthermore, the reduced wave overtopping resulted in the increase of offshore sand transport from the eroded dune. An explanation for this could be the smaller overtopping rate and so a higher undertow current.

Figlus et al. [2014] studied the role of vegetation in dune erosion resiliency, where the seaward facing slope of the dune covered with the Sporobolus Virginicus was subjected to attacking waves. They focused on the development of the beach profile and dune scarp retreat in time. The maturity and plant density were varied. The addition of vegetation to the dunes resulted in a 33 percent reduction in erosion.

The rate of dune scarp retreat was 30 percent lower in the condition with plants compared to the one without plants.

Bryant et al. [2019] tested the erosion-reducing potential of below ground biomass and aboveground biomass, both in isolation and in combination with the goal to quantify the dominant mechanisms contributed by vegetation structure to dune response. Wooden dowels represented the vegetation, based on a data analysis of Feagin et al. [2019]. Overall, the results showed that vegetation biomass, regardless of form, reduces the degree of erosion sustained during collision and overwash. Looking at the isolated biomass, there was a much greater dune resistance afforded by the isolated belowground biomass compared to the isolated aboveground biomass. However, the combination of above and belowground biomass resulted in the lowest percent loss of dune material compared to the bare control dune.

SWASH, COLLISION AND OVERWASH Odériz et al. [2020] conducted wave flume experiments, with swash, collision and overwash conditions. Furthermore, different densities of real vegetation where used. The results showed that when vegetation was at forward positions on the dune, it decreased run-up, increased reflected energy and transferred it to low frequency bands, and reduced the eroded volume on the exposed dune face. When the vegetation was placed on the leeside of the dune, it retarded and prevented overwash. In summary, plants are better to dissipate waves and provide protection during the initial swash and collision stages of a storm.

Martinez et al. [2016],Silva et al. [2016] and Mendoza et al. [2017] conducted also wave flume experiments with real life vegetation (Sporobolus Virginicus) In the setup, they varied with profile (berm/no berm), wave conditions (mild/moderate/intense) and in plant densities (none/low/medium/high). The experiments exhibited the reducing effect of vegetation on the eroded dune volume and the rate of dune scarp retreat. The maturity of plant root system had a significant impact on the dune erosion. An older and denser dune reduced the total eroded dune volume by 8% for irregular waves and 30% for regular waves. In general, vegetated dunes eroded less than dunes without vegetation (regardless of the wave conditions and morphology of the beach-dune profile), although there was no direct relationship between the density of vegetation cover and the volume eroded.

Figlus et al. [2017] conducted wave flume experiments with wave bursts imposed on the dune. They considered four different types of vegetation with varying above- and belowground biomass and different root size distributions (P. Amarum, R. Phyllocephala, s. portulacastrum and S.Virginicus) and 5 different plant maturities. The main goal of this research was to explore which aspects of vegetation and which physical processes are linked to enhanced erosion resistance. The research showed that both the aboveground and belowground portions of vegetation are relevant in dune protective capabilities and wave induced erosion resistance. In the swash zone flow, the aboveground plant structure is the key factor linked to erosion reduction, In relation to this, a larger plant surface area resulted in a decrease turbulent kinetic energy (TKE). Furthermore, fine roots are key determinants of erosion reduction, likely making dune systems less prone for slumping and collapsing by an increase in shear strength.

B CALCULATION VEGETATION FACTOR

B.1 INTRODUCTION

This appendix provides the conditions and researches used for calculating the Vegetation Factors.

B.2 VEGETATION FACTOR SWASH / RUNUP

Based on wave flume studies – Swash flow/ runup

Citation	Vegetation type	More information vegetation	Wave height [m]	Period [s]	Duration [s]	VF [-]
De Battisti and Griffin (2020)	Ammophila	x				0,5882
De Battisti and Griffin (2020)	Salsola	x				0,7451
De Battisti and Griffin (2020)	Cakile	x				0,6275
Maximiliano (2019) -20 min	Ipomoea	AB vegetation	0,2	2,21	1200	0,5714
Maximiliano (2019)	Ipomoea	AB vegetation	0,2	2,21	2400	0,7
after 5 min	Ipomoea	AB vegetation				0,4
after 20 min	Ipomoea	AB vegetation				0,5263
after 40 min	Ipomoea	AB vegetation				0,7
Feagin (2019)	Different species	x	0,04	19,5	450	0,8
Feagin 2019	Different species	x	0,053	19,5	600	0,4926
Field data median, all species	/	A vegetation	/	/	/	0,7576
Field data median, all species	/	AB vegetation	/	/	/	0,5208
					mean	0,6078

Figure B.1: Information about the studies used to calculate the VF for the collision regime - Runup

B.3 VEGETATION FACTOR WAVE IMPACT

Collision regime - Vegetation Factor

Citation	Vegetation type	More information vegetation	More information storm	Wave height [m]	Period [s]	Duration [s or days]	VF [-]
Based on case studies / field studies							
Ajedegba (2018)	sea oats	B	Hurricane Dolly Mexico	7	10	36000	0,2
Ajedegba (2018)	railroad vines, gulf croton and camphor weed	B	Hurricane Dolly Mexico	?	?	?	0,8
Lindell et al. (2017)	Ammophila arenaria, Leymus arenarius,Rosa rugosa	x	Storm Egon Sweden	?	?	?	0,5
Lindell et al. (2017)	Ammophila arenaria, Leymus arenarius,Rosa rugosa	x	Storm Egon Sweden	?	?	?	0,25
Martinez-Cordova (2021)	Panicum amarum and Sporobolus virginicus	plant cover of 0.5 m2	Storm 12 Veracruz	4,5	9	3 days	0,875
Martinez-Cordova (2021)	Panicum amarum and Sporobolus virginicus	plant cover of 0.5 m2	Storm 12 Veracruz	4,5	9	3 days	0,75
Martinez-Cordova (2021)	Panicum amarum and Sporobolus virginicus	plant cover of 0.5 m2	Storm 12 Veracruz	4,5	9	3 days	0,625
Martinez-Cordova (2021)	Panicum amarum and Sporobolus virginicus	plant cover of 1.1 m2	Storm 12 Veracruz	4,5	9	3 days	0,5
Based on wave flume studies - Wave impact							
Figlus (2013) regular (same as Sigren, 2013)	Sporobolus Virginicus	x		0,05	0,7	3600	0,67
Figlus (2013) irregular	Sporobolus Virginicus	x		0,069	1,2	3600	0,92
Bryant (2019)	Wooden dowels and coconut fibers	A+B		0,074	3,69	3600	0,23529
Bryant (2019)	Wooden dowels and coconut fibers	A		0,074	3,69	3600	0,70588
Bryant (2019)	Wooden dowels and coconut fibers	B		0,074	3,69	3600	0,52941
Bryant (2019)	Wooden dowels and coconut fibers	A+B		0,043	3,69	3600	0,2
Bryant (2019)	Wooden dowels and coconut fibers	A		0,043	3,69	3600	0,5
Bryant (2019)	Wooden dowels and coconut fibers	B		0,043	3,69	3600	0,425
Silva (2016)	Ipomoea pes-caprae	high density		0,1	1,118	900	0,72131
Silva (2016)	Ipomoea pes-caprae	medium density		0,1	1,118	900	1,06557
Silva (2016)	Ipomoea pes-caprae	low density		0,1	1,118	900	1
Silva (2016)	Ipomoea pes-caprae	high density		0,1	1,5652	900	0,53435
Silva (2016)	Ipomoea pes-caprae	medium density		0,1	1,5652	900	0,74046
Silva (2016)	Ipomoea pes-caprae	low density		0,1	1,5652	900	0,53435
Silva (2016)	Ipomoea pes-caprae	high density		0,15	2,012	240	0,63043
Silva (2016)	Ipomoea pes-caprae	medium density		0,15	2,012	240	0,77536
Silva (2016)	Ipomoea pes-caprae	low density		0,15	2,012	240	0,81159
Silva (2016)	Ipomoea pes-caprae	high density		0,15	2,012	240	0,66176
Silva (2016)	Ipomoea pes-caprae	medium density		0,15	2,012	240	0,91176
Silva (2016)	Ipomoea pes-caprae	low density		0,15	2,012	240	0,67647
Figlus (2017)	P. Amarum, R.Phyllocephala, S. Portulacastrum, S.Virginicus	low mature		0,067	1,9	2520	0,95238
Figlus (2017)	P. Amarum, R.Phyllocephala, S. Portulacastrum, S.Virginicus	mature		0,067	1,9	2520	0,74074
Figlus (2017)	P. Amarum, R.Phyllocephala, S. Portulacastrum, S.Virginicus	optimal		0,067	1,9	2520	0,62893
						mean	**0,64745**

Figure B.2: Information about the studies used to calcule the vegetation factors for the collision regime - Wave impact

C GENERAL DESCRIPTION XBEACH

C.1 INTRODUCTION

A description of the XBeach model is given. First a general description of the XBeach model is given and hereafter the hydrodynamic options are described. The steps in the XBeach model are outlined, followed up by an overview of important equations in XBeach.

C.2 GENERAL DESCRIPTION MODEL

XBeach is used to simulate storm induced erosion. XBeach is an open source storm impact numerical model which involves hydrodynamic processes and morphodynamic processes. Short wave transformation, long wave transformation, wave induced setup, unstable currents, overwash, and inundation are all hydrodynamic processes that are involved. Considering the morphodynamic processes, bed load and suspended sediment transport, bed update and breaching are included. Furthermore, vegetation and hard structures can be incorporated. In diverse storm regimes, XBeach solves linked two-dimensional horizontal equations for wave propagation, flow, sediment transport, and bottom changes owing to time varying wave and flow boundary conditions.

C.3 HYDRODYNAMIC OPTIONS

Three wave modes are included: stationary, surfbeat and nonhydrostatic.

STATIONARY The stationary wave mode solves the wave-averaged equations but neglects infragravity waves. Wave-group variations are neglected. The stationary mode is useful for conditions where the incident waves are relatively small and/or short, and these motions would be small anyway. A typical application would be to model morphological changes during moderate wave conditions, often in combination with tides.

SURFBEAT The short wave fluctuations on the wave group scale, as well as the long waves connected with them, are resolved in the surfbeat mode (instationary). Steady currents and set-up as well as infragravity wave motions are included. When the focus is on swash zone processes rather than time-averaged currents and setup, the surfbeat mode is required. It is fully valid on dissipative beaches, where the short waves are mostly dissipated by the time they are near the shoreline. On intermediate beaches and during extreme events the swash motions are still predominantly in the infragravity band and so is the runup.

NON-HYDROSTATIC A combination of the non-linear shallow water equations is resolved in the non-hydrostatic mode, also known as wave-resolving mode. A pressure correction factor is used to allow the propagation and decay of individual waves. The depth-averaged flow due to waves and currents is computed. The depth averaged dynamic pressure is computed from the mean of the dynamic pressure at the surface and at the bed by assuming dynamic pressure at the surface to be zero and a linear change over depth. The short-wave action balance is no longer required. The main advantages of the non-hydrostatic mode are that the incident-band (short wave) runup and overwashing are included, which is especially important on steep slopes such as gravel beaches. Another advantage is that the wave asymmetry and skewness are resolved by the model and no approximate local model or empirical formulation is required for these terms. Finally, in cases where diffraction is a dominant process, wave-resolving modeling is needed as it is neglected in the short wave averaged mode.

C.4 STEPS XBEACH MODEL

The steps in the XBeach model are shown in Figure C.1. The main steps are shown in the boxes and other implementations are shown in the circles next to the boxes. Connectivity between different modules (arrows) and the most important output of steps (italic) are shown. The fat arrows indicate the main direction. The modules and other implementations will be discussed in depth below.

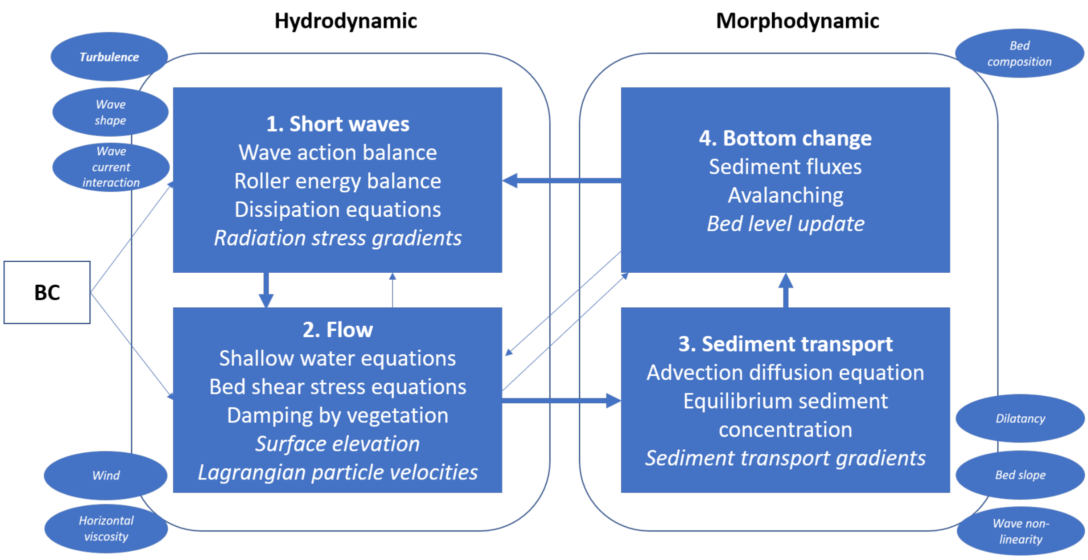


Figure C.1: Steps in XBeach including important equations, connectivity between steps (arrows) and output of steps (italic). Fat arrows indicate main direction steps and circles around modules other possible processes implemented

C.4.1 Short Waves

Short waves are calculated with a time-dependent wave-action balance on wave group time scale coupled to a roller energy balance.

$$\frac{\delta A}{\delta t} + \frac{\delta c_x A}{dx} = \frac{D_w + D_f + D_v}{\sigma} \tag{C.1}$$

The short wave action balance calculates the variation of the incident band wave envelope and wave energy dissipation. Wave-induced radiation stresses may be calculated utilizing the spatial distribution of wave action and hence wave energy (using linear wave theory). Variations in wave energy results in radiation stresses on wave group scales, thereby the forcing of long wave motions. The wave induced radiation stresses are an input to the depth-averaged shallow water equations. The roller energy balance accounts for the delay between the point where the waves start to break and the point where the wave set-up and longshore current start to build. Regarding the dissipation of wave energy, three short wave dissipation processes are accounted for: wave breaking, bottom friction and vegetation.

OTHER PROCESSES IMPLEMENTED Other processes included are the turbulence variance at the bed, non-linearity of waves which propagate from deep water onto beaches and the wave current interaction. The turbulence variance at the bed is used in the sediment transport module. The increasing non-linearity of waves propagating from deep water onto beaches is implemented in the wave shape. Two wave forms are implemented to take this non-linearity into account. The wave current interaction implies an exchange of energy, so after the start of the interaction both the waves and the mean flow are affected by each other. This feature is especially of importance in gullies and rip-currents (Reniers et al., 2007). In XBeach this is taken into account by correcting the wave number k with the use of Eikonal equations, which will have impact on the group and wave propagation speed.

C.4.2 Flow

The depth-averaged shallow water equations are used to solve the mean flow and the infragravity water level motions and velocities. (Mean setup, undertow, longshore currents, IG waves).

$$\frac{\partial u^L}{\partial t} + u^L \frac{\partial u^L}{\partial x} + v^L \frac{\partial u^L}{\partial y} - f\,v^L - \nu_h \left(\frac{\partial^2 u^L}{\partial x^2} + \frac{\partial^2 u^L}{\partial y^2} \right) = \frac{\tau_{sx}}{\rho h} - \frac{\tau_{bx}^E}{\rho h} - g \frac{\partial \eta}{\partial x} + \frac{F_x}{\rho h} + \frac{F_{v,x}}{\rho h}$$
$$\frac{\partial v^L}{\partial t} + u^L \frac{\partial v^L}{\partial x} + v^L \frac{\partial v^L}{\partial y} + f\,u^L - \nu_h \left(\frac{\partial^2 v^L}{\partial x^2} + \frac{\partial^2 v^L}{\partial y^2} \right) = \frac{\tau_{sy}}{\rho h} - \frac{\tau_{by}^E}{\rho h} - g \frac{\partial \eta}{\partial y} + \frac{F_y}{\rho h} + \frac{F_{v,y}}{\rho h}$$
$$\frac{\partial \eta}{\partial t} + \frac{\partial h u^L}{\partial x} + \frac{\partial h v^L}{\partial y} = 0$$

The wave groups are reducing in height near the beach because of wave breaking. There is a return current in the surfzone to compensate for the onshore mass transport. To account for the wave induced mass flux and subsequent return flow, the non-linear shallow water equations are formulated in a depth-averaged Generalized Lagrangian Mean formulation. This is calculated by dividing the distance a water particle travels in one wave period by the period itself. The depth-averaged Generalized Lagrangian Mean velocity is related to the Eulerian velocity (average velocity of a short wave obtained at a fixed place). The instantaneous velocities are directly resolved. In the shallow water equations, the effect of bed friction associated with mean currents and long waves is included by the bed shear stress. The bed shear stress is calculated with a formula developed by Ruessink. The dimensionless friction coefficient can be determined by five different formulations.

$$\tau_{bx}^E = c_f \rho u_E \sqrt{1.16 u_{rms}^2 + (u_E + v_E)^2} \tag{C.2}$$

OTHER PROCESSES IMPLEMENTED Other implementations in this module are the effect of wind and the calculation of horizontal viscosity to account for the exchange of horizontal momentum at spatial scales smaller than the computational grid size.

C.4.3 Sediment transport

The sediment transport is calculated by means of the advection-diffusion equation. The depth averaged sediment concentration C is calculated by a mismatch with

$$\frac{\partial hC}{\partial t}+\frac{\partial hCu^E}{\partial x}+\frac{\partial hCv^E}{\partial y}+\frac{\partial}{\partial x}\left[D_h h\frac{\partial C}{\partial x}\right]+\frac{\partial}{\partial y}\left[D_h h\frac{\partial C}{\partial y}\right]=\frac{hC_{eq}-hC}{T_s}$$

the equilibrium sediment concentration, which is the minimum value of the C_{eq} compared to the maximum allowed sediment concentration. The sediment concentration can be calculated with different formulae. One option is Soulsby and Van Rijn which combines suspended and bed load transport in one equation (equation **??**). A stands for the bed/suspended load coefficients and u_{cr} for the critical velocity. The critical velocity specifies the point at which depth averaged velocity sediment motion begins. The formulation of Soulsby-van Rijn is often used for storm conditions as there is a lot of suspended transport during these conditions. For mild conditions this is less accurate, as suspended and bed load may not be in similar direction. The actual sediment concentration is utilized to calculate sediment transport rates, which are then used as input for the bed-level update computation.

$$C_{eq}=max(min(C_{eq},\frac{1}{2}C_{max})+min(C_{eq},\frac{1}{2}C_{max}),0) \tag{C.3}$$

$$C_{eq,b/s}=\frac{A_{s,b/s}}{h}(\sqrt{v_{mg}^2+0.018\frac{u_{rms}^2}{C_d}}-u_{cr})^{2.4} \tag{C.4}$$

OTHER PROCESSES IMPLEMENTED The effect of dilatancy, the bed slope and wave non-linearity are also accounted for in XBeach. Dilatancy accounts for the influence of pore water on bed stability, effectively increasing the local critical Shields parameter and thereby reducing transport rates during high flow conditions.

C.4.4 Bottom change

Based on gradients in sediment transport (sediment fluxes), the bed levels can be calculated with the Exner equation (equation C.5).

$$\frac{dz_b}{dt}+\frac{f_{mor}}{(1-p)}\left(\frac{dq_x}{dx}+\frac{dq_y}{dy}\right)=0 \tag{C.5}$$

The process of avalanching reduces the cross-shore slope of the dunefront at locations that become wet during runup. This process is accounted for by updating the bed evolution and introduces a critical bed slope for both dry and wet area.

$$|\frac{dz_b}{dx}|>\phi_{cr} \tag{C.6}$$

Wet cells are assumed to be more prone to slumping than dry cells. Sediment between two adjacent cells is exchanged as long as the critical slope between these cells is exceeded. Bed level changes follows from lateral gradients in sediment transport.
The avalanching algorithm used by XBeach limits the areas submerged by water model grid cells to smaller slopes than for areas not submerged by water. This means that as waves collide with the dune face, the transition at the dune foot from

dry to wet sets off a chain reaction in the model that causes the dune to slump (Roelvink et al. [2009]).

OTHER PROCESSES IMPLEMENTED The effect of the bed composition is also implemented. This is of importance when there are different sediment fractions and sorting and armoring can take place.

C.5 OVERVIEW IMPORTANT EQUATIONS XBEACH

Short waves	**Wave action balance**	Time dependent version of wave action balance equation on wave group time scale	$\frac{\partial A}{\partial t}+\frac{\partial c_x A}{\partial x}+\frac{\partial c_y A}{\partial y}+\frac{\partial c_\theta A}{\partial \theta}=-\frac{D_w+D_f+D_v}{\sigma}$
	Roller energy balance **Dissipation equations**	Roller energy balance Wave breaking (Default: Roelvink2)	$\frac{\partial E_r}{\partial t}+\frac{\partial E_r c\cos\theta}{\partial x}+\frac{\partial E_r c\sin\theta}{\partial y}=D_w-D_r$ $\bar{D}_w=2\frac{\alpha}{T_{rep}}Q_b E_w\frac{H_{rms}}{h}$
		Bottom friction	$D_f=\frac{2}{3\pi}\rho f_w\left(\frac{\pi H_{rms}}{T_{m01}\sinh kh}\right)^3$
		Vegetation	$D_{v,i}=A_v\cdot\frac{\rho C_{D,i}b_{v,i}N_{v,i}}{2\sqrt{\pi}}\left(\frac{gk}{2\sigma}\right)^3 H_{rms}{}^3$, with $A_v=\frac{\left(\sinh^3 k\alpha_i h-\sinh^3 k\alpha_{i-1}h\right)+3\left(\sinh k\alpha_i h-\sinh k\alpha_{i-1}h\right)}{3k\cosh^3 kh}$
	Radiation stress gradients		$S_{xx,w}(x,y,t)=\int\left(\frac{c_g}{c}\left(1+\cos^2\theta\right)-\frac{1}{2}\right)S_w d\theta$
	Turbulence variance at bed	Default: bore averaged	$k_b=\frac{\overline{k_s}\cdot T_{rep}/T_{bore}}{\exp(h/L_{mix})-1}$
Flow	**Shallow water equations**	Depth-average shallow-water equations (GLM)	$\frac{\partial u^L}{\partial t}+u^L\frac{\partial u^L}{\partial x}+v^L\frac{\partial u^L}{\partial y}-fv^L-\nu_h\left(\frac{\partial^2 u^L}{\partial x^2}+\frac{\partial^2 u^L}{\partial y^2}\right)=\frac{\tau_{sx}}{\rho h}-\frac{\tau_{bx}^E}{\rho h}-g\frac{\partial\eta}{\partial x}+\frac{F_x}{\rho h}-\frac{F_{v,x}}{\rho h}$ $\frac{\partial v^L}{\partial t}+u^L\frac{\partial v^L}{\partial x}+v^L\frac{\partial v^L}{\partial y}+fu^L-\nu_h\left(\frac{\partial^2 v^L}{\partial x^2}+\frac{\partial^2 v^L}{\partial y^2}\right)=\frac{\tau_{sy}}{\rho h}-\frac{\tau_{by}^E}{\rho h}-g\frac{\partial\eta}{\partial y}+\frac{F_y}{\rho h}-\frac{F_{v,y}}{\rho h}$ $\frac{\partial\eta}{\partial t}+\frac{\partial hu^L}{\partial x}+\frac{\partial hv^L}{\partial y}=0$
	Bed shear stress equations	Bed shear stress approach according to Ruessink	$\tau_{bx}^E=c_f\rho u_E\sqrt{(1.16u_{rms})^2+(u_E+v_E)^2}$ $\tau_{by}^E=c_f\rho v_E\sqrt{(1.16u_{rms})^2+(u_E+v_E)^2}$
		Manning	$c_f=\frac{gn^2}{h^{1/3}}$
	Damping by vegetation	vegetation-induced time varying drag force	$F_v=F_D=\int_{-h}^{-h+h_{veg}}\frac{1}{2}\rho C_D b_v Nu\lvert u\rvert dz$
Sediment transport	**Transport formulation**	Depth-averaged advection diffusion equation	$\frac{\partial hC}{\partial t}+\frac{\partial hCu^E}{\partial x}+\frac{\partial hCv^E}{\partial y}+\frac{\partial}{\partial x}\left[D_h h\frac{\partial C}{\partial x}\right]+\frac{\partial}{\partial y}\left[D_h h\frac{\partial C}{\partial y}\right]=\frac{hC_{eq}-hC}{T_s}$
	Equilibrium sediment concentration	Comparison minimum value equilibrium concentration and maximum allowed	$C_{eq}=max\ (min\ (C_{eq,b},\frac{1}{2}C_{\max})+min\ (C_{eq,s},\frac{1}{2}C_{\max}),\ 0)$
	 General parameters	Equilibrium sediment concentration (Soulsby-Van Rijn) Velocity magnitude (long wave stirring turned on) Adjusted orbital velocity	$C_{eq,b}=\frac{A_{sb}}{h}\left(\sqrt{v_{mg}{}^2+0.018\frac{u_{rms,2}{}^2}{C_d}}-U_{cr}\right)^{2.4}$ $C_{eq,s}=\frac{A_{ss}}{h}\left(\sqrt{v_{mg}{}^2+0.018\frac{u_{rms,2}{}^2}{C_d}}-U_{cr}\right)^{2.4}$ $v_{mg}=\sqrt{\left(u^E\right)^2+\left(v^E\right)^2}$ $u_{rms,2}^2=u_{rms}^2+1.45k_b$
		Fall velocity	$w_s=\alpha_1\sqrt{\Delta gD_{50}}+\alpha_2\frac{\Delta gD_{50}^2}{\nu}$ $\alpha_1=1.06\tanh\left(0.016A^{0.50}\exp(-120/A)\right)$ $\alpha_2=0.055\tanh\left(12A^{-0.59}\exp(-0.0004A)\right)$
Bottom updating	**Due to sediment fluxes**	Exner equation	$\frac{\partial z_b}{\partial t}+\frac{f_{mor}}{(1-p)}\left(\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}\right)=0$
	Avalanching	Critical bed slope for both the dry and wet area	$\left\lvert\frac{\partial z_b}{\partial x}\right\rvert>m_{cr}$

D DESCRIPTION SELECTED WAVE FLUME EXPERIMENTS

D.1 INTRODUCTION

The wave flume experiments of Bryant and Mendoza are discussed.

D.2 SET-UP BRYANT EXPERIMENT

It is important to describe and understand the set-up in depth to understand the outcomes and use the input and results during the model phase.
The experiments were performed in a concrete flume at the U.S. Army Engineer Research and Development Center (dimensions: 63.4x1.5x1.5). The model setup is shown in Figure D.1, imposing a beach, a dune and an impermeable sloping wall. This beach-dune model was on 1:15 scale. The model was constructed with sand with a diameter D50 of 0.15 mm and the dune length was 1.13 m, dune height 49.8 cm relative to the floor, a foreslope of 1/2 and a backslope of 1/3.

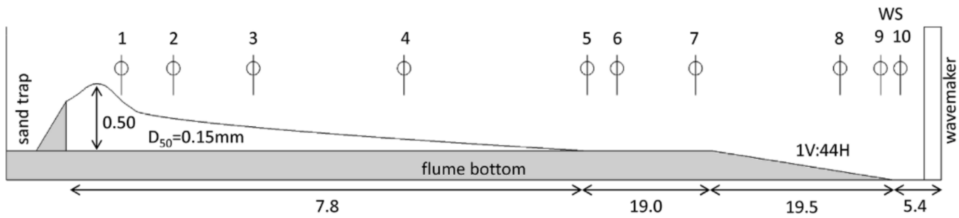


Figure D.1: Set-up wave flume experiment Bryant. Not to scale (source: Bryant et al. [2019])

In total, 5 different hydrodynamic conditions were applied, summarized in Table D.1. 2 water levels were modeled: 30 cm above the toe of the beach (S) and 35 cm above the toe of the beach (D). Irregular wave spectra based on a TMA shallow- water spectrum (gamma = 3.3) were generated in order to induce the collision (C) and overwash (O) regimes as defined by Sallenger (2000). A TMA spectrum is a modified JONSWAP spectrum to account for the waves coming in from deeper areas into an area where waves are much affected by limited water depth. The collision regime was targeted three times (SC1, SC2, DC) and the overwash regime two times (SO, DO). The target peak period (Tp) was based on measurement of Hurricane Sandy, taken at the US Army Field Research Facility in Duck, North Caroline. An average peak period of 14.3 s was measured, so a peak period of 3.69 was chosen for all hydrodynamic conditions, except SC2. For SC2 a Tp of 2 s was chosen to provide an extra condition. A model run consisted of three identical wave bursts. For the C-conditions, a duration of 1200 s was established and for the O-condition a duration of 400 s. Only for the DO conditions one wave burst was considered. Ten wave gauges (WG) were mounted along the flume, to measure the water surface elevation. Area LiDAR scans were used to measure the total change in dune profile, before and after wave runs.A single profile as a function of the x axis was created by averaging the LiDAR data alongshore.

Table D.1: Hydrodynamic conditions Bryant experiment

	SWL [cm]	H_{m0} [cm]	T_p ([s])	No. of bursts	Duration of wave burst [s]
SC1	30	7.4	3.69	3	1200
SC2	30	8.4	2.0	3	1200
SO	30	12.8	3.69	3	400
DC	35	4.3	3.69	3	1200
DO	35	13.2	3.69	1*	400

D.3 RESULTS BRYANT EXPERIMENT

D.3.1 General

During collision and overwash conditions, both above- and belowground plant features contributed to dune erosion and water and sediment overwash reduction. The above- and belowground vegetation cover resulted in the least change in volume at the vegetation section, hereafter the B vegetation cover and the A vegetation turned out to be the least effective. As the dune eroded, the storm impact regime transitioned in some cases slowly from collision to overwash. The inclusion of biomass delays this transition in storm impact regime, providing greater protection to coastal communities.

Since the collision regime is considered in this thesis, the SC1 and DC trials are the most interesting to test. The SC2 case is not considered due to the generally small observed erosion and the small deviations between the vegetation covers. The experimental set-up between DC and SC1 differs in waterlevel (SWL) and significant wave height (Hm0). The SWL of the SC1 test is 0.3 m above the toe of the dune compared to 0.35 cm and the Hm0 is 7.4 cm instead of 4.3 cm.

D.3.2 Deep Collision

All plant covers decreased erosion volume, maintained a high crest height, and prevented an overwash regime from arising. The quantity of erosion experienced varied depending on the biomass type, with the AB vegetation cover experiencing the least, followed by the B vegetation cover, and finally the A vegetation cover. Offshore sediment is brought to the coast. The crest of the control dune was eroded by roughly 5 cm, whereas the biomass-affected dunes kept their crest elevation and only experienced scarping of the dune face. Water overwash (13.6 kg) and sediment overwash (15 kg) occurred on the control dune . Only the aboveground vegetated experiment revealed sediment overwash: 3.6 kg, with a negligible amount of water overwash.

Examining the profiles, the final profile of DC exhibited a single beach slope of approximately 12 degrees leading from the dune to the submerged portion of the profile for all vegetation covers. The bar in front of the dune composes of sediment from the dune and from sediment offshore.

Table D.2: Erosion volumes Bryant DC

Experiment	Erosion volume [m3/m]	Deviation control [%]
Control	0.0321	X
A	0.0151	-52
B	0.0137	-57
AB	0.0108	-66

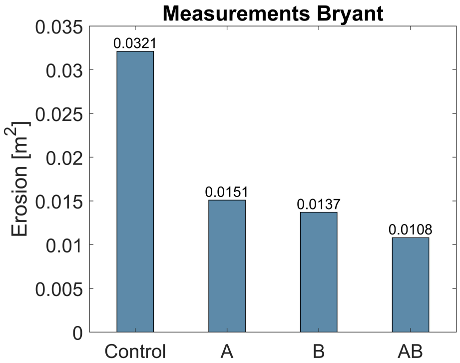


Figure D.2: DC Bryant measurements

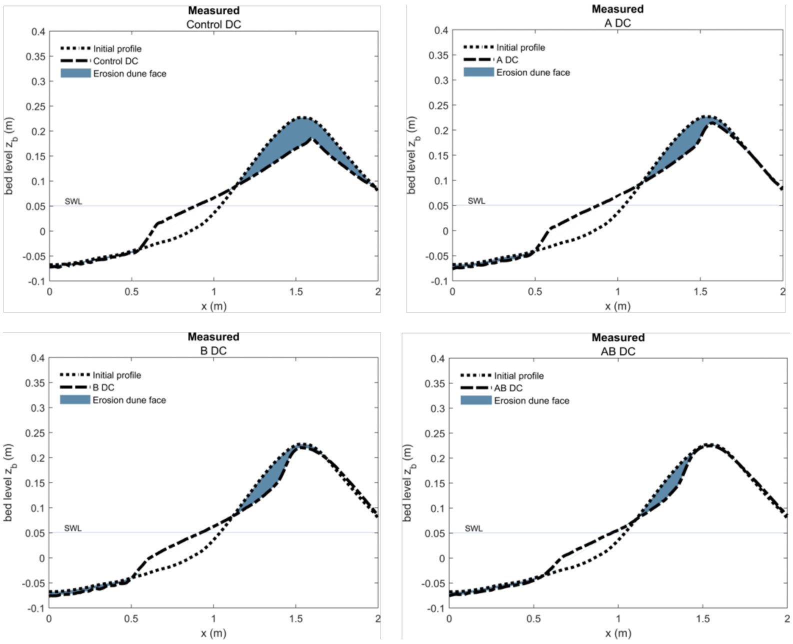


Figure D.3: Profile evolution Bryant DC

D.3.3 Shallow Collision

Also for the SC1 condition, the eroded volume reduces and the dune crest height remains higher , independent of cover type. The amount of erosion relative to the control varied, depending on the presence and type of biomass. The A vegetation cover had the smallest impact on dune erosion volume, whereas the B and AB vegetation covers retained a slightly higher elevation and more dune volume compared to the control. The erosion volume of the duneface is for the AB case slightly larger than for the B case, but the dune volume above zb=0.8 m, stays larger for the AB case. No sediment and water overwash has been observed in the experiment.

The final profile all show a slightly steeper area at the top of the dune. The nearshore beach is flattened to a slope of approximately 12 degrees.

D.3.4 Comparison SC1 and DC

In the DC tests, sediment was deposited offshore to form a small bar, while in the SC1 case the material was brought to the nearshore beach. DC has a much higher erosion volume, which can be explained by a high water level and the continuous undermining of the duneface.

Table D.3: Erosion volumes Bryant SC1

Experiment	Erosion volume [m3/m]	Deviation control [%]
Control	0.0092	X
A	0.0073	-20
B	0.0048	-47
AB	0.0043	-53

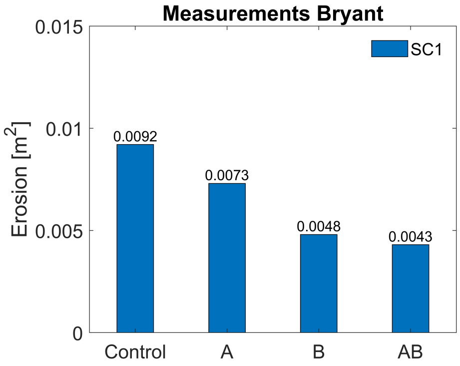


Figure D.4: Eroded volume SC1 Bryant measurements

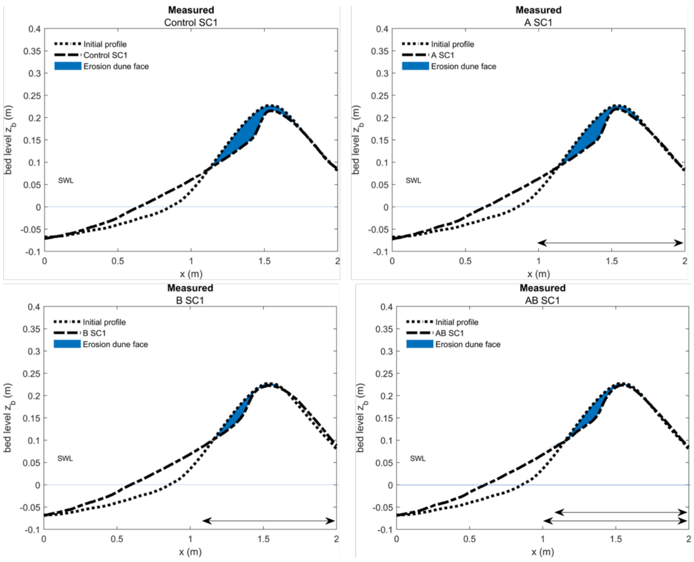


Figure D.5: Profile evolution Bryant SC1

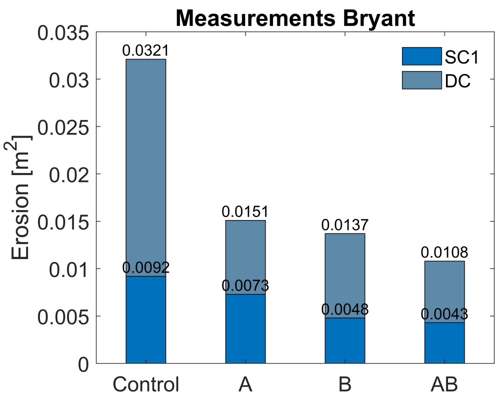


Figure D.6: DC and SC1 comparison eroded volumes

D.4 SET-UP MENDOZA EXPERIMENT

It is important to describe and understand the set-up in depth to understand the outcomes and use the input and results during the model phase.
The physical experiment was conducted in a 0.8 m wide, 1.2 m high and 37 m long wave flume (Engineering Institute of the National Autonomous University of Mexico). Model setup shows a 1:20 model, constructed with sand from Veracruz. The diameter of this sand was D50 0.142mm, containing 6% of fine material, a uniformity coefficient of 1.42 and specific gravity of 2.7. The model setup is shown in

Figure D.7 , The setup consists of a submerged profile, a horizontal berm and a dune. The submerged part of profile A had a gentle slope (1/32) from the bottom of the flume to a depth of 8.5 cm below the still water level, a second slope of 1/7 began at coordinate 26.75 m, 2 cm above the SWL. From there, a horizontal berm, 35 cm long, extended to the toe of the berm where the dune face rose to 22 cm above the SWL, with a 1/2.25 slope. The back of the dune had a 1/1.36 slope which descended again, to reach the SWL, giving a total dune base width of 75 cm. Behind the dune a horizontal section of 1.2 m was left. A vertical impermeable wall is place behind the profile. This profile is similar to the profile of Kobayashi et al, 2009;

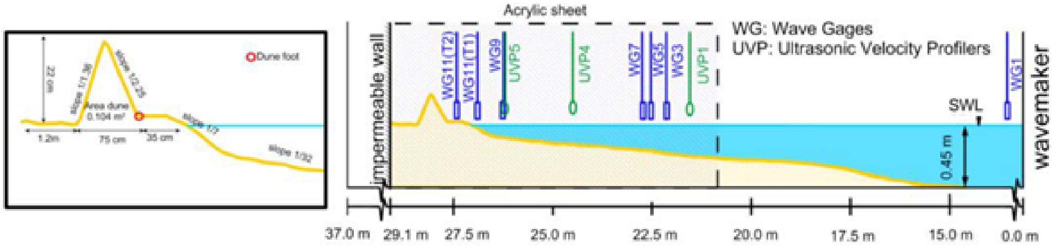


Figure D.7: Set-up wave flume experiment Mendoza. Not to scale (source: Mendoza et al. [2017])

Three wave conditions are applied, S1 S2 and S3, with the first two having a duration of 900 s and the last one of 240 s. The SWL for all these conditions was set on 0.45 m, with a storm surge of 0.05 m. The wave trains consist of irregular waves generated from a jonswap spectrum with gamma = 3.3. In the beginning of an experiment and in order to saturate the dune, three minutes of a mild wave train (Hs=5 cm m and Tp=1.0 s) were generated; if any significant deformation of the beach-dune system was found after these waves, the model was repaired.
All conditions are applied to a non vegetated dune, a dune with low plant density, medium plant density and high plant density.

During the experiment, 11 wave gauges recorded the free water surface elevation. Furthermore, 3 Ultra Velocity Profilers recorded the velocity profiles and the evolution of the profile morphodynamics was measured with a laser total station.

Table D.4: Hydrodynamic conditions Mendoza experiment

	SWL [cm]	H_{m0} [cm]	T_p [s]	Duration of wave burst [s]
AS1	45	10	1.1	900
AS2	45	10	1.5	900
AS3	45	15	2.0	240

D.5 RESULTS MENDOZA EXPERIMENT

D.5.1 General

Vegetation reduced net erosion on the dune face, independent of the wave conditions, morphology of the beach-dune profile or the mode of erosion. The most important morphological consequence of dune vegetation appears to be delaying erosion time. This contributes to the beach profile's durability and resistance. Erosion of the dune face was reduced by vegetation, particularly with a strong storm, when Iribarren numbers were greater. When vegetation is present, the wave breaking point is moved seawards, and bed velocities near to the coastline are lower. Both of these factors contribute to vegetation's protective role. In the experiments with the highest wave conditions, vegetation on both profiles prevented overwash and hence dune degradation on the landward side.

Since the collision regime is considered in this thesis, the profile with the berm (A) is the most interesting to test.

D.5.2 AS2H

Erosion reduced in the presence of the plant with 46% and erosion was lowest in the test with a high vegetation cover. However, there was no direct relationship between the density of vegetation cover and the volume eroded.

The erosion was lower, the coastline retreat was lower, dune foot retreat was lower.

Table D.5: Erosion volumes Mendoza AS2

Experiment	Erosion volume [m3/m]	Deviation control [%]
Control (AS2N)	0.0069	X
AB (AS2H)	0.0037	-46

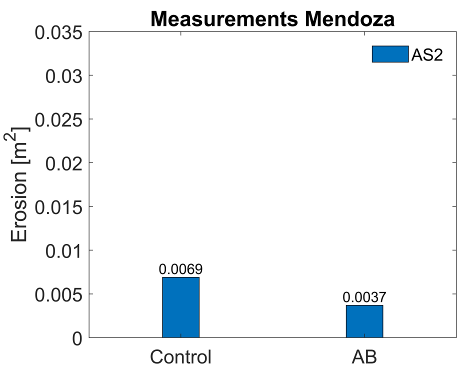


Figure D.8: AS2H Mendoza experiments

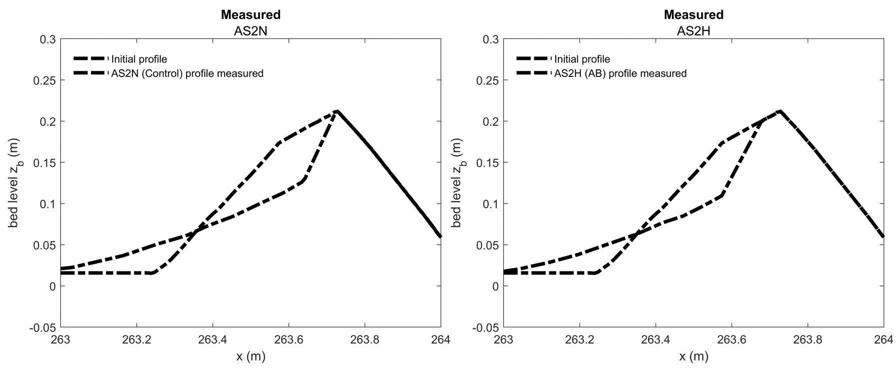


Figure D.9: Profile evolution Bryant AS2N (left) and AS2H (right)

E FORMULATIONS STATISTICAL PARAMETERS AND MORPHOLOGICAL INDICATORS

E.1 INTRODUCTION

In this Appendix an explanation and the formulations of the statistics used for the hydrodynamic and morphological calibration and validation are given.

E.2 MORPHOLOGY INDICATORS

Morphology indicators give insight in the storm impact on a beach dune profile (e.g. profile development, dune retreat, berm slope and erosion volume). In this research the erosion volume is used.

EROSION VOLUME The dune erosion volume is defined as the volume per running meter between the initial bed level and the bed level at a given time. The lower limit used is the toe of the dune.
The letters s, m, c, and v represent simulated, measured, control (without vegetation) and vegetation, respectively.

$$Volume\ Reduction_{\ s/m} = \frac{\Delta V_{s/m,v} - \Delta V_{s/m,c}}{\Delta V_{s/m,c}} * 100$$

$$Difference\ in\ reduction = Volume\ Reduction_s - Volume\ Reduction_m$$

E.3 MODEL PERFORMANCE STATISTICS

Model performance statistics are used to quantify the performance of model results. This is done by a comparison with the measured data. $n$is the amount of datapoints.

Table E.1: Model Performance Statistics

Parameter	Description	Ranges
ME	Mean Error	0: perfect prediction
RMSE	Root Mean Squared Error	low value: good performance
BSS	Brier Skill Score	bad (< 0), poor (0–0.3), fair (0.3–0.6), good (0.6–0.8) (van Rijn et al. [2003])

MEAN ERROR / BIAS The Mean Error (ME), sometimes called Bias is useful to quantify model performance for parameters such as wave heights or water levels. (Deltares, BOI, zandige keringen).

$$ME = \frac{1}{N} \sum_{i=1}^{N} = (H_{i,s} - H_{i,m})$$

RMSE Root Mean Square Error (RMSE) is the standard deviation of the residuals (prediction errors). Residuals are a measure of how far from the regression line data points are; RMSE is a measure of how spread out these residuals are. In other words, it tells you how concentrated the data is around the line of best fit. Root mean square error is commonly used in climatology, forecasting, and regression analysis to verify experimental results.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(zb_{i,s} - zb_{i,m})^2}$$

BRIER SKILL SCORE The statistical parameters Bier-Skill Score (BSS) is used to compare predicted and measured profile with the initial profile (van Rijn et al 2003). Many coastal modelling studies assessing bed level changes use this score. The Skill Score is an objective way for evaluating the performance of morphological models based on the relative error between prediction and observation in terms of observed profile changes. z is the elevation of the beach-dune profile and the subscript c stands for post-computed, m for post-measured and o for initial.

$$BSS = 1 - \frac{\sum_{i=1}^{N}(zb_{i,s} - zb_{i,m})^2}{\sum_{i=1}^{N}(zb_{i,0} - z_{i,m})^2}$$

F SPLITTING SEASWELL AND INFRAGRAVITY WAVES FROM A TIMESERIES

F.1 INTRODUCTION

For the splitting of sea-well waves and infragravity waves from the data from Bryant (2019). The function $comp_spec$ in Matlab is used to generate a spectrum. Hereafter the spectrum is splitted into a sea-well and infragravity part. The split in frequency assumed is fsplit = fpeak/2.

F.2 FREQUENCY SPECTRUM

On the ocean, short irregular waves are generated by local wind fields. In the physical experiment of Bryant, irregular waves are forced with a TMA shallow-water spectrum. This wave field consists of different wave components. One wave component is defined by a sine curve with a phase and amplitude. The wave components together are an irregular high frequency wave field. Since the TMA shallow-water spectrum generates high and low frequency waves, these are splitted for hydrodynamic calibration.

F.3 CODE FOR SPLITTING

```
zs = %water level timeseries
sfreq = sampling frequency (Hz)

[f,Snn,A,ff,Af] = comp_spec(zs,sfreq);

df = f(2)-f(1);

fsplit = 0.5/Tpeak;

m0hf= sum(Snn(f >= fsplit)*df);% short wave energy density variance

m0lf = sum(Snn(f <  fsplit)*df);%  long wave energy density variance

Hm0_hf = 4*sqrt(m0hf);% high freq / sea-swell significant wave height

Hm0_lf = 4*sqrt(m0lf); % low freq / infragravity significant wave
height

Hm0    = sqrt(Hm0_hf.^2+Hm0_lf.^2);
```

F.4 COMPUTATION OF SPECTRUM FUNCTION MATLAB

```
function [f,Snn,A,ff,Af] = comp_spec(zs,sfreq)
% Based on xb_get_spectrum.m (XBeach toolbox), by Bas Hoonhout & Robert
Mc Call
%
% % sampling freq in Hz!!
%
% AvR, feb 2013
%%
% initialize spectrum
[n m] = size(zs);

% required number of samples
nr = 2^(nextpow2(n));

% number of Welch repetitions
nw = ceil((n-nr)/(0.5*nr))+1;

if nr > n
    nr = n;
end
% allocate matrices
Snn     = zeros(floor(nr/2),m);

% compute spectrum
idxe    = round(linspace(nr,n,nw));
idxb    = idxe-nr+1;

T       = nr/sfreq;
df      = 1/T;
ff      = df*[0:1:round(nr/2) -1*floor(nr/2)+1:1:-1];
f       = ff(1:floor(nr/2));

for i = 1:m
    P   = squeeze(zs(:,i));

    for j = 1:nw
        Pj  = P(idxb(j):idxe(j));

        Q   = fft(Pj,[],1)/nr;
        V   = 2/df*abs(Q).^2;
        Snn(:,i) = Snn(:,i) + squeeze(V(1:floor(nr/2)))/nw; % variance
density spectrum

        % compute amplitude spectrum (following HOlthuijsen 2007)
        A(:,i) = sqrt(Snn(:,i)*df*2);
        Af(:,i) = sqrt(squeeze(V)/nw*df*2);
    end
 end
```

G CHOICE OF PARAMETER COMBINATIONS CALIBRATION

G.1 INTRODUCTION

The choice for the combination of values for the SC1 case is outlined.

G.2 CHOICE OF CALIBRATION COMBINATIONS DURING CALIBRATION

In general, for the hydrodynamic interaction the roughness and vegetation module are identified. The root model and the avalanching module account for soil stabilization and thus the belowground effect of vegetation. In this section, the choice of calibration combinations are explained for the SC1 case. All combinations possible are illustrated in Figure G.1.

Since both eroded volume and profile evolution were used for evaluation, here the reasoning for calibration is explained.the best combination and fit was chosen per case based on three criteria. The first criteria is the physical possibility: the presence of aboveground/belowground vegetation and possible vegetation processes and effects. The second criteria encloses the erosion volume reduction (matching relative erosion reduction compared to control. The final criteria is a reasonable BSS score (BSS > 0.6).

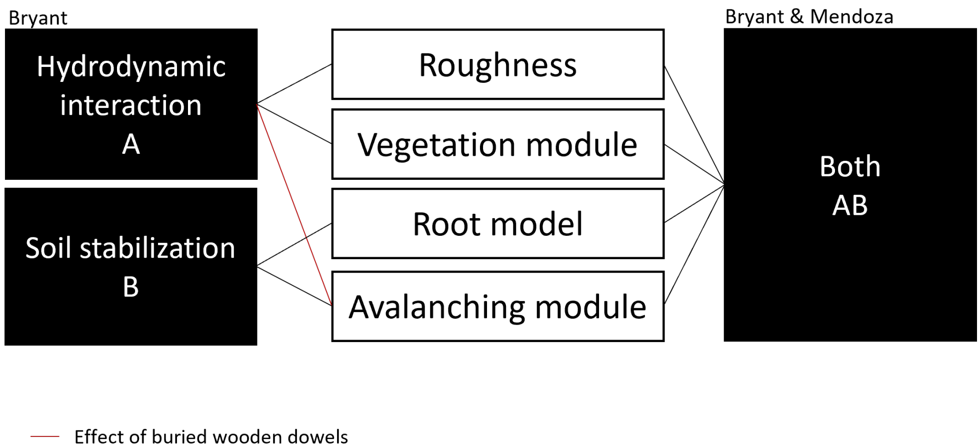


Figure G.1: Overview combinations possible for calibration vegetation cases Bryant and Mendoza physical experiments

G.2.1 Hydrodynamic interaction (A)

For the hydrodynamic interaction, the roughness and vegetation module are applied. However, the roughness module shows to have an insignificant effect and the vegetation module a maximum of 5% erosion reduction. This is insignificant, in comparison with 20% erosion reduction. Therefore, the avalanching module is applied, which accounts for the wooden dowels which could interact with the soil and sediment. The critical wet slope is increased, and both the BSS and erosion reduction are evaluated as shown in Figure G.2. A higher wetslope results in a lower BSS and a higher erosion reduction. Since a wetslope of 0.4 results in a perfect erosion reduction (0 p.p. difference) and a good BSS (0.6), this was chosen as value for calibration.

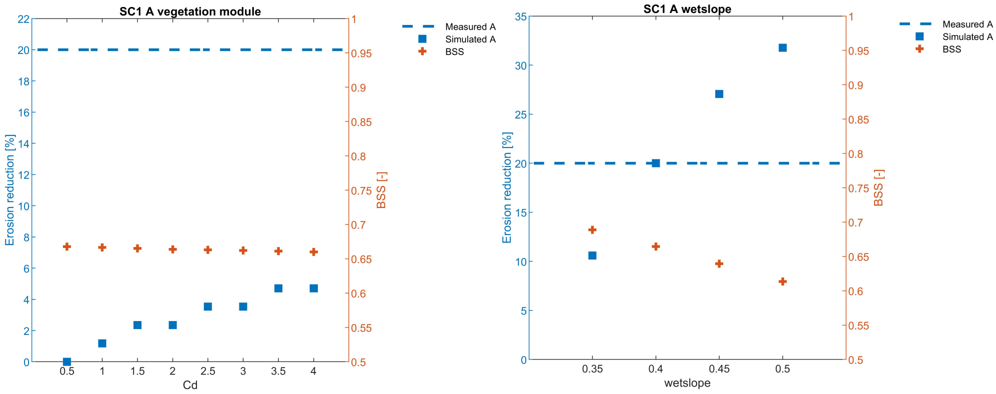


Figure G.2: SC1 A relation reduction in erosion, BSS and value of Cd for the vegetation module/value of wetslope of the avalanching module. A higher Cd and wetslope result in more erosion reduction and a lower BSS

G.2.2 Soil stabilization (B)

For the soil stabilization, the avalanching module and the root model are applied. To see the consequences, the critical wet slope and root model are applied separately first. Both the BSS and erosion reduction are evaluated. An increase in the wetslope results in a reduction of eroded volume, and a better match in relative reduction of erosion with the measurements. However, an increasing wetslope also results in a lower BSS (Figure G.3). Considering the profile, a wetslope higher than 0.5 results in too steep slopes. This is in direct conflict with the purpose of modifying the avalanching module. As a consequence, a wetslope of 0.5 is chosen as maximum, which results in an erosion reduction of 31%. However, the relative erosion reduction of the measured case is 47%. Therefore, also the root model is applied. Applying the root model alone results in a maximum erosion reduction of 32% (rcc=5), which is also lower than the 47% reduction seen in the measurements. Considering the BSS, a higher BSS is achieved for a lower rcc value. Since the root

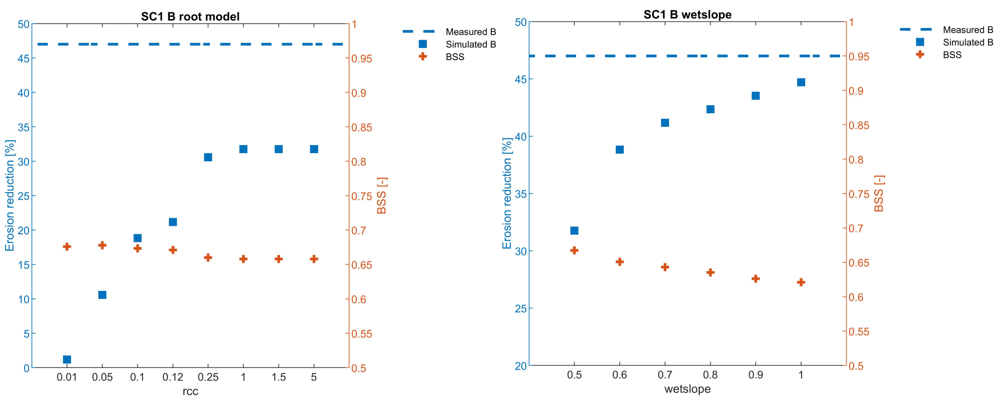


Figure G.3: SC1 relation reduction in erosion, BSS and value of rcc for the root model/value of wetslope of the avalanching module. A higher rcc and wetslope result in more erosion reduction and a lower BSS

model and higher critical wet slope in the avalanching module could reinforce eachother, finally a rcc of 0.05 and a wetslope of 0.5 resulted in an erosion reduction of 49%, which deviates 2 p.p. from the measurement.

G.2.3 Hydrodynamic interaction (A) Soil stabilization (B)

For the cases with aboveground and belowground vegetation, so with hydrodynamic interaction and soil stabilization, more combinations are possible. Since several modules require calibration, and the choice of values is uncertain, this is complicated. It was decided to solely use the root model and alter the wet critical slope for the sake of simplicity. A wetslope of 0.5 and a rcc of 0.08 result in an erosion reduction of 53% and a BSS of 0.58.

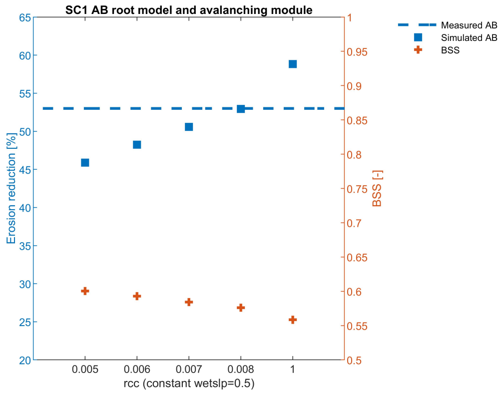


Figure G.4: SC1 relation reduction in erosion, BSS and value of rcc for the root model and a constant higher value of wetslope. A wetslope of 0.5 and an increasing wetslope results in more erosion reduction and a lower BSS

H ANALYSIS POTENTIAL COASTAL GREEN INFRASTRUCTURE

H.1 INTRODUCTION

The effect of vegetation is location depended. Therefore, it is interesting to assess the potential of a location to implement vegetation in dune design. A first indication for the Beira location is provided in this appendix.

H.2 INDICATORS

Conger and Chang [2019] developed indicators to identify the potential of Coastal Green Infrastructure (CGI). CGI is defined as natural or nature-based systems that provide coastal flood and erosion protection as well as multiple social, economic, and environmental benefits while considering its vulnerability to environmental conditions. The indicators of Conger can be used to categorize and assess the potential of dune vegetation in dune rehabilitation projects. Indicators for the coastal protection index are relief, coastal types, coastal vegetation, habitat zone, wave exposure, maximum wave height, maximum wave fetch, and coastal land use. Low protection and high protection examples are displayed in H.1. Indicators for the vulnerability index are relief, tidal range, habitat zone, sea-level change, erosion change, wave exposure, and coastal land use. A description of these indicators can be found in Figure H.2.

When a system has a low coastal green infrastructure vulnerability and high protection benefits, the potential to utilize vegetation (CGI) in beach-dune rehabilitation projects is considered high.

H.3 BEIRA

When the Conger and Chang [2019] criteria are applied to the Beira study area, the result is that Beira has a low protection potential as well as a low vulnerability. For an explanation of the calculation is referred to the paper of Conger and Chang [2019].

Because the CGI's vulnerability is minimal, it is recommended to explore ways to increase their CGI coastal protection benefits. To boost coastal protection, these communities might concentrate their efforts on activities such as coastal vegetation regeneration or the creation of new habitats in riparian regions. Where hard protection structures already exist, hybrid usage of CGI and adapting existing structures to allow for the production of new CGI can be investigated.

PROTECTION The relief in Beira is low, approximately 6-10 meters. This indicates a relatively low wave attenuation (2). The coastal type is moderate and is characterized by beaches and dunes (3), which provide moderate protection. Considering vegetation, dune vegetation is present (4). The habitat zone is on the higher tide

(4). The coast is exposed (1) and the fetch is also large (1). The coastal land use is mostly green for region 1 (5) and mixed green and gray for region 2 (3).

VULNERABILITY The relief in Beria scores a 4 for the vulnerability (6-10 meters). The tidal range is above 6 meters (1). The habitat zone is higher tide (2). The sea-level change is 21-40 cm/100 years (4). The erosion change is moderate (3). The coastal land use is mostly green for region 1 (5) and mixed green and gray for region 2 (3).

	Explanation	Low protection	High protection	Beira
Relief	Attenuation of waves on the coast. High relief improves wave attenuation.	Low relief	High relief	2
Coastal type	Attenuate waves by providing rough surfaces for the waves to go over.	Sand, gravel and mudflats Human-made	Estuaries, beaches, dunes, rocky beaches, rocky cliffs and platforms	3
Coastal vegetation	Waves are attenuated by the drag friction provided by the stems and leaves. Different forms of drag friction are available.	No vegetation Kelp forests	Sea grasses Marsh or dune vegetation Mixed vegetation	4
Habitat zone	The magnitude of the interaction between waves and coastal profile and vegetation. The habitat zone refers to the water depth in which the dominant CGI is located.	Sub-tidal Lower tide	Inter-tidal Higher tide Supra tidal	4
Wave exposure	Indicates frequency and intensity of wave action at the coast. Stress CGI is exposed to.	Exposed Semi-exposed	Semi-protected Protected Very-protected	2
Max wave height	Refers to one year's highest wave height. Coastal green infrastructure is more effective in dampening the energy of small (0-2 m) to moderate height waves (2-4 m).	High	Low	4
Max fetch	Refers to water surface area available for the wind to form waves. Small wave fetches and weak waves increase coastal protection benefits.	High	Low	1
Coastal land use	Reflects the intensity of the development at the coast. The greener land use, the more amount of space to migrate upland	Mostly gray	Mostly green	5
				21,9 = Very low protection

Figure H.1: CGI Protection indicators. A successful vegetation implementation is indicated by a high score for protection.

	Explanation	Low vulnerability	High vulnerability	Beira
Relief	Inundation risks throughout the coastal slope. Low relief indicates larger areas with a low elevation that is under inundation risk.	High relief	Low relief	4
Tidal range	Shows the zone of the coast that is frequently inundated. It impacts the habitat zone and sediment deposition zone at coasts.	High	Low	1
Habitat zone	Related to the zone CGIs are in the tidal range. CGIs at the lower tidal zones are more vulnerable to the changing conditions because the availability of the sediments throughout the tidal range is lower in the lower-tidal zones.	Supra-tidal	Sub-tidal	2
Sea level change (cm/100 years)	Changes in the water levels over the past 100 years. It includes sea-level rise and vertical land movement adjustments. The negative values indicate land uplift, thus a decrease in the sea levels, whereas the positive values indicate increases in the sea levels.	Land uplift	Increase sea levels	4
Erosion change (m/y)	Stability of coastlines. The positive values indicate accretion, therefore low CGI vulnerability whereas the negative values indicate coastal erosion, thus high vulnerability.	Accretion	Erosion	3
Wave exposure	Frequency and duration of inundation. High wave exposure can result in the loss of CGI due to tear stress, increases vulnerability	Very protected	Exposed	5
Coastal land use	Human development and activities at the coast can confine CGI to a small zone, affecting its ability to move and adapt to changing conditions. Green, less developed coastal areas provide more room for CGI to migrate upland, gray and densely developed coastal areas can create a coastal squeeze.	Mostly green	Mostly gray	1
				8,28 = Very low vulnerability

Figure H.2: CGI Vulnerability indicators. A successful vegetation implementation is indicated by a low score for vulnerability.

I VEGETATION DURING STORM CONDITIONS IN RELATION TO SEA LEVEL RISE

I.1 INTRODUCTION

In the current design for 2070, the effect of sea level rise was included. This was done by increasing the mean sea level with 0.52 m. When using the same scenario (RCP8.5 with median percentile), this assessment suggests that the implementation of vegetation could increase the design lifetime with approximately 15-20 years which is illustrated in Figure I.1.

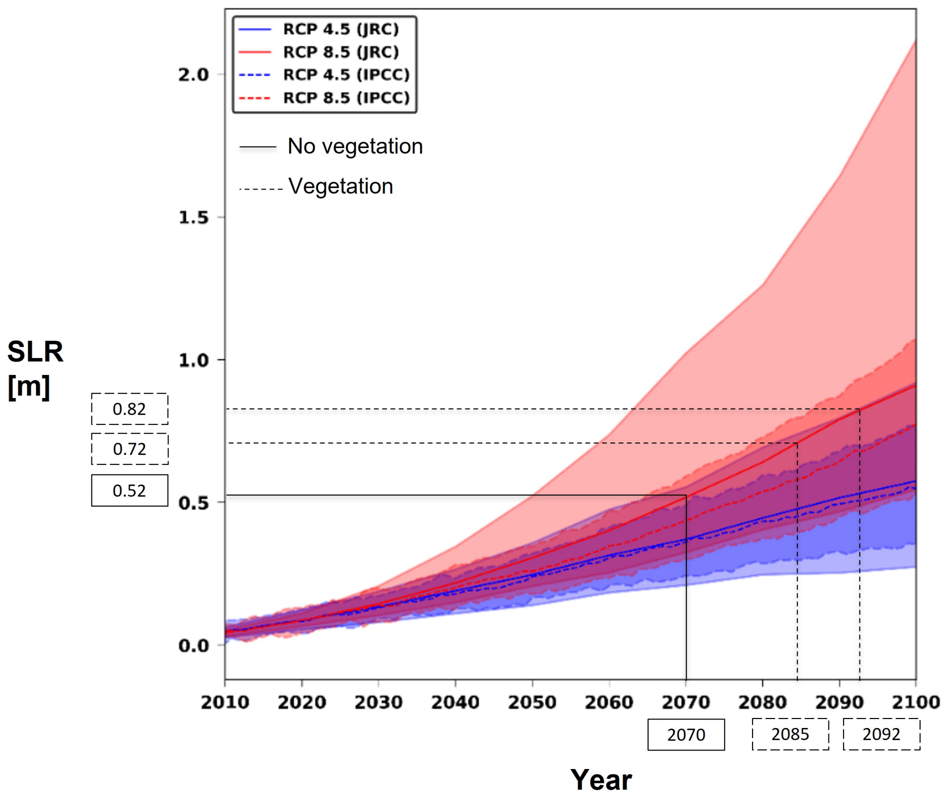


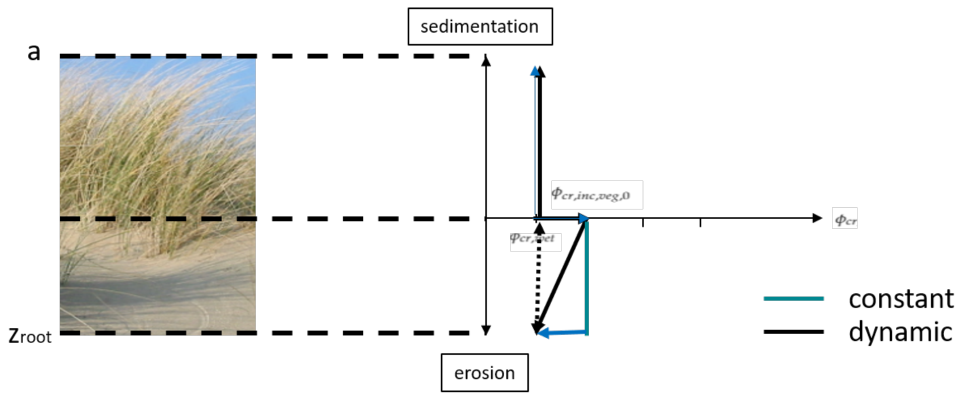
Figure I.1: Effect of vegetation on design life time (adapted from: Deltares [2021b] and Vousdoukas et al. [2018])

J RECOMMENDATION IMPLEMENTATION XBEACH

J.1 INTRODUCTION

In this Appendix, the recommended implementation of the critical slope for avalanching is decribed. Two approaches could be implemented

- Constant approach: constant assumed critical slope for places with vegetation
- Dynamic approach: dynamic critical slope due to removal of roots by erosion due



J.2 PROPOSED CODE

$\phi_{cr,wet}$ = critical wet slope without biomass
$\phi_{cr,dry}$ = critical dry slope without biomass
$\phi_{cr,inc,veg,dry}$ = critical dry slope with biomass
$\phi_{cr,inc,veg,wet}$ = critical wet slope with biomass
$\phi_{cr,inc,veg,,wet/dry,0}$ = critical slope with biomass at t=0 (specified in settings)
z_{root} = rooting depth
Δz = erosion/deposition depth (negative is erosion)
Constant change (for $z_{root} \leq \Delta z(t) < 0$):
$\phi_{cr,inc,veg,wet(t)} = \phi_{cr,inc,veg,wet,0}$
$\phi_{cr,inc,veg,dry(t)} = \phi_{cr,inc,veg,dry,0}$

Dynamic change in time (for $z_{root} \leq \Delta z(t) < 0$):

$$\phi_{cr,inc,veg}(t) = \phi_{cr,wet/dry} + (\phi_{cr,inc,veg,wet/dry,0} - \phi_{cr,wet/dry}) * min(max(0, \frac{z_{root} + \Delta z(t)}{z_{root}}), 1) \tag{J.1}$$

Constant and dynamic change for $\Delta z(t) \geq 0$:

$$\phi_{cr,inc,veg,wet/dry}(t) = \phi_{cr,wet/dry} \tag{J.2}$$

For example:
$\phi_{cr,wet}$ = 0.3
$\phi_{veg,extra}$ = 0.1
$\phi_{cr,inc,veg,0}$ = 0.4
z_{root} = 0.5 m
Δz = 0.4 m

$$\phi_{cr,inc,veg}(t) = 0.3 + (0.4 - 0.3) * 0.2 = 0.32 \tag{J.3}$$

K QUALITATIVE ANALYSIS VEGETATION IN REHABILITATION PROJECTS

K.1 INTRODUCTION

This appendix provides a qualitative evaluation of the use of vegetation in dune rehabilitation projects. When dune designers or managers need further information about vegetation in dune design, this can be a useful resource.

First, a strength-weaknesses-opportunities and challenges (SWOC) analysis is provided (section K.2). In section K.3, a simple qualitative cost analysis is given.

K.2 QUALITATIVE SWOC ANALYSIS

To evaluate a design with and without a so-called Strengths-Weaknesses-Opportunities and Challenges (SWOC) analysis has been performed on different defined classes. A SWOC analysis has shown to be a useful tool for discussing and identifying strengths, weaknesses, opportunities, and challenges related to an existing design. The strengths and weaknesses are about the internal design, and the opportunities and challenges are external attributes, which point out the environment and the future.

To provide a systematic evaluation, three classes are defined where attention is paid to the whole ecosystem. These classes (Table K.1) are a combination of three evaluation concepts: the Ecosystem Services (ESS), People Planet Profit (PPP), and the Society, Ecology, and Economy (SEE). The classes can be used to evaluate the values of different aspects of the ecosystem and allow comparing environmental and economic gain, profits, and losses. An overview of the SWOC analysis is provided in Figure K.1.

Table K.1: Three classes used for evaluation based on ESS, PPP, and SEE

Class	ESS	PPP	SEE
I	Provisioning services	Profit	Economy
II	Regulating services	Planet	Ecology
III	Cultural services	People	Societal

CLASS I Regarding class I, an advantage of the design with vegetation is the possibility of a larger resilience in the future. Partly due to the accretion of sediment in presence of vegetation, and partly due to the larger stability of the dune in presence of vegetation. Both effects could result in smaller quantities of nourishment volume needed in the future. Another strength is the increase in job opportunities. These job opportunities are related to planting the vegetation itself and maintaining the vegetation. A weakness is the insecurity of the extra strength of the dunes and subsequently the quantities of the nourishment. This makes it difficult to convince the client to invest in vegetation. An external opportunity is either the initiation or the revival of a nursery. This could result in job availability. Furthermore, sustainable measures could enhance tourism, which is positive for the economy. A rehabilitation with vegetation asks for monitoring and maintenance of the works, which implies high costs. The main strength of the design without taking vegetation into account is the large certainty of the design. The most important weakness of a design without vegetation is the possible growth of unwanted vegetation or even no vegetation. In the context of erosion and flood reduction, this is a missing opportunity.

CLASS II The rehabilitation of dunes affects for both cases the flood and erosion control. However, the implementation of vegetation in the design could result in a natural heightening and strengthening of the dune and so possibly a larger water safety. A weakness of the design could be too dense vegetation and geomorphological stabilization which could result in a rapid decline in ecological diversity and species richness. This could pose a threat to endangered and rare species (Howe et al. [2010]; Jones et al. [2010]).

CLASS III Regarding society, the implementation of vegetation could result in more knowledge of dunes and vegetation, a sense of place and recreation, and tourism.

	Class I: Provisioning ecosystem services / Economy / Profit		Clas II: Regulating services / Ecology / Planet		Class III: Cultural services / Societal / people	
	Rehabilitate without vegetation	**Rehabilitate with vegetation**	**Rehabilitate without vegetation**	**Rehabilitate with vegetation**	**Rehabilitate without vegetation**	**Rehabilitate with vegetation**
Strengths (design)	Certainty	Possibility of larger resilience in future climate (e.g. smaller quantities of nourishment volume needed in the future) Increased job opportuntities (maintaining vegetation, planting vegetation) Possibility of increased dune growth rate	More biodiversity and natural vegetation growth	Assisting the natural heightening of dune: larger flood control Assisting the natural strengthening of dune: larger flood and erosion control		Increase the knowledge and essence of vegetation and dunes Increase the sense of place Increase in recreation and tourism
Weaknesses (design)	Possible growth of unwanted vegetation or no vegetation	Insecurity of strength in dunes and so quantities of nourishment Confidence in extra strength vegetation and so convicing client		Too dense vegetation cover and geomorphological stabilization could result in a rapid decline in ecological diversity and species richness, and imposing a threat to rare or endangered species		
Opportunities (external) **Challenges (external)**		Revival of nursery Need for monitoring and maintenance of vegetation				Involve community Educate people to walk on paths

Figure K.1: Overview strengths, weaknesses, opportunities, and challenges for the implementation of vegetation in dune design

K.3 QUALITATIVE COST ANALYSIS

This section provides an overview of the extra costs of the implementation of vegetation in dune restoration. This analysis provides a qualitative description of the extra investments needed for the implementation of vegetation. It must be mentioned that is difficult to estimate the costs of the implementation of vegetation correctly. The real costs remain highly uncertain since it differs per location and scope of the project. Considering the costs at the project level, general factors for every alternative were divided by Hillen et al. [2010]. These categories of factors that determine costs are used to identify the extra costs.

1. Planning and engineering
2. Material costs
3. Labor costs
4. Costs for implementation in the environment
5. Costs for management and maintenance

PLANNING AND ENGINEERING Extra planning and engineering are needed regarding planting vegetation. Firstly, different type of vegetation needs to be evaluated, the type of planting needs to be selected and the real planting work needs to be planned. The best results are obtained by working together with local communities. These involved people could then educate other locals about the importance and functional nature of this work and generate support. Furthermore, the human action that threats the dunes and the vegetation such as beach driving, sand mining, and undesirable infrastructure development can be reduced.

MATERIAL COSTS Planting vegetation calls for extra material. The material costs consist of material to produce the vegetation itself, the protection measures, and the measures to grow the vegetation such as a nursery. Nursery development aimed to actively foster the natural recolonization of plants that will enable sand accretion and strengthening. Creepers such as Canavalia Rosea, Ipomoea pes-caprae, and Cyperus crassipes will naturally colonize the area. The municipality would need to actively engage in restoration by planting shrub plants mainly.

LABOR COSTS Planting plants is time-consuming; they have a finite lifespan and must be maintained on a regular basis. This includes, for example, replacing plants, putting fertilizer, replacing branches blown away, repair after vandalism. Also, the training of labor forces for building and maintaining the vegetation imposes costs.

COSTS FOR IMPLEMENTATION IN THE ENVIRONMENT No extra land is needed for implementation. However, when there is chosen to plant vegetation from a nursery nearby, required land for this nursery is needed. The required amount of land has to be obtained which could be a financially-legally challenging and costly task.

COSTS FOR MANAGEMENT AND MAINTENANCE For the management and maintenance of the vegetation, a responsible organization is needed. Therefore it is even more important to quantify the vegetation effects during storm conditions.

COLOPHON

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