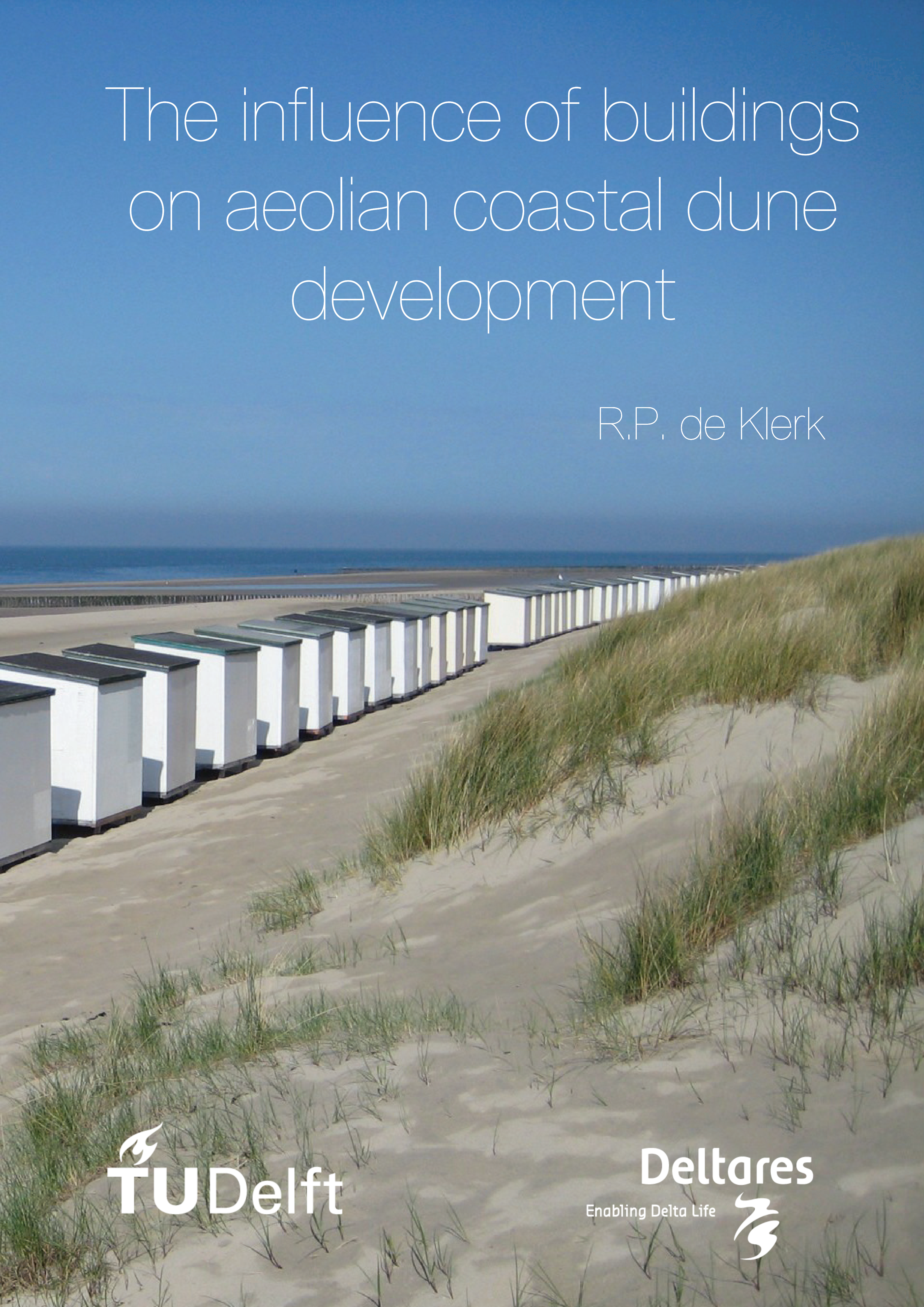
The influence of buildings on aeolian coastal dune development

R.P. de Klerk



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The influence of buildings on aeolian coastal dune development

by

R.P. de Klerk

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Preface

This thesis completes my master Hydraulic Engineering at Delft University of Technology. It was conducted at Deltares, an independent institute for applied research in the fields of water and subsurface. Their cooperation and support was of the utmost importance and is hereby gratefully acknowledged.

This research was an amazing experience, which certainly cannot be solely attributed to the interesting and highly topical subject that allowed me to research and be in the field, also performing drone measurements. Equally important were the people involved, and I would like to take this opportunity to thank them.

First of all, I would like to thank my entire thesis committee for their excellent and consistent guidance throughout this research project. Stefan Aarninkhof, thank you for your clever early insights that helped me to remain objective during the process. Sierd de Vries, thank you for your sincere interest in the subject, and sharing your expertise advise during our meetings, where we would sketch and exchange applicable theories on a chalkboard. Marieke Eleveld, thank you for your remarks on remote sensing and your enthusiasm, which really motivated me. Marjan Duiveman, thank you for your fruitful insights from a dune management perspective, which truly contributed to the use case of the project. Joost den Bieman, thank you for your clever guidance as a mentor throughout my research and letting me ask any - occasionally naive - questions. Bart van Westen, thank you for your contagious enthusiasm that made me also dive into the physics governing the development of coastal dunes. Thank you both, Joost and Bart, for your time and outstanding advice during (and outside) our Thursday afternoon talks.

Furthermore, I would like to thank Petra Damsma for her guidance as a 'silent' committee member, and her advice that made me look past coastal dunes as merely a defence against flooding. I would like to thank Stéphanie IJff for her insights on the ecology of dunes and what biodiversity really entails. Pascal van der Berg thank you for the fantastic site visit and sharing remarkable observations and expertise of your years of experience in the field. Thank you Pieter van der Gaag for your clear instructions on how to perform UAV measurements. Jaco and Alexandra, thank you for joining me on the road trip to Sint Maartenszee, and assisting with the measurements.

Last but not least, I would like to thank my fellow graduate students at Deltares and my friends and family for distracting me from my work at times I needed it!

R.P. de Klerk
Delft, October 24, 2019

Abstract

Coastal dunes are an essential component of the Dutch landscape and provide safety against flooding of the hinterland. Additionally, they offer recreation, nature conservation and a supply of drinking water. The safety standards of dunes are based on a minimum dune volume that is required to resist the load of design storm conditions. Considering scenarios with future sea level rise and increasing storms related to climate change sustainable dune development is desired. Combining the functionalities of the coastal zone in a sustainable way is key. Recreation is one of these functionalities, and is facilitated by placing buildings on the beach in front of the dune. This research refers to these structures as beach buildings.

The influence of beach buildings on coastal dune development is still largely unknown, and it could pose a risk to the functionalities coastal dunes provide. The objectives of this research are covered by the main research question: *What is the influence of specific types of beach buildings on aeolian coastal dune development and what are suitable dune management measures?*

This study uses high resolution LiDAR elevation measurements taken with an UAV of two case areas in the Netherlands to investigate the influence of beach buildings on aeolian coastal dune development. Measurements are made of two stretches of beach located in Julianadorp and Sint Maartenszee, where various beach building types are present. Different dune regions are classified based on the presence of building types. The elevation data is discretized in grids that are placed adjacent to the dune foot along these classified regions. Elevation changes and cross-profile evolution of the dunes within these regions make it possible to consistently analyse differences in dune development with quantitative parameters.

The dune area adjacent to beach buildings is mainly static. It therefore seems unfair to compare small-scale dune behaviour in the vicinity of beach buildings to dynamic dune development. A conceptual model is composed as a framework to correlate vegetation growth and changes in the dune profile to future dune development related to dynamic and static dune states and to isolate the effect of beach buildings.

Beach buildings only influence aeolian sediment transport locally, their effect on dune volumes therefore seems limited to local sedimentation patterns in their leeward side. Validity of this is given that the building dimensions and the distance from the dune foot remain proportional relative to the dune, and the distance between consecutive buildings are sufficiently large for unhindered sediment transport to occur. Larger individual beach buildings can even increase the yearly average volume change relative to the reference dune due to the reach of sedimentation patterns further landward.

The relocation of sediment for construction and maintenance purposes, on the other hand, can have serious consequences on dune volumes. In extreme cases the consequent relocation of sediment deposited by aeolian transport adjacent to permanent placed buildings restricts progradation of the dune foot, and the dune consequently steepens and blocks sediment transport further landward. In addition, the creation of a sand banquet can cause a loss of dune volume comparable to the amount of sediment that is relocated.

Foredunes behind consecutive and seasonally placed beach buildings are found to be densely vegetated, resulting in a more static dune state landward. The stabilization to a static dune is an import component in the effect beach buildings induce on coastal dune development. Possible explanations could be that optimal sedimentation rates prevail, and the physical presence of the structure provides sheltering against salt spray and high wind speeds. The dune fence can therefore be used as tool to regulate the cross-shore position and therefore the stabilizing effect of seasonal placed beach buildings.

The outcomes provide promising steps towards understanding the influence of beach buildings, it is recommended to perform a comparable study with distinct conditions, validate the hypothesis that the yearly sediment flux adjacent to buildings remains unchanged and further investigate the relation between vegetation vigour and the presence of beach buildings.

Contents

Nomenclature

Abbreviations

BCL	Basal Coastline
CFD	Computational Fluid Dynamics
DEM	Digital Elevation Model
DG	Direct Georeferencing
DTM	Digital Terrain Model
EU	European Union
GCP	Ground Control Point
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HHNK	Hoogheemraadschap Hollands Noorderkwartier (Dutch regional waterboard)
JarKus	Yearly coastal measurements (Jaarlijkse Kustmetingen)
LiDAR	Laser Imaging Detection And Ranging
MCL	Momentary Coast Line
NAP	Amsterdam Ordnance Datum (Normaal Amsterdams Peil)
RTK	Real Time Kinematic
UAV	Unmanned Aerial Vehicle (e.g. drone)

Symbols

α	Dune slope	$^\circ$
β	Angle with the dominant wind direction	$^\circ$
c	Passage width	m
d	Distance to the dune foot	m
H_{max}	Maximum dune height	m
l	Building length	m
$\sigma_{\Delta Z_b}$	Alongshore variability of the bed level change	m
ΔV	Average alongshore volume change	m^3/m
ΔV_c	Average alongshore volume that is relocated for maintenance and construction purposes	m^3/m
w	Building width	m
X_{df}	Distance landward from the dune foot	m
$X_{Z_{b,o}}$	Landward distance from the dune foot where the bed level does not change	m
Y_i	Alongshore distance of the subregion	m
Z_b	Bed level height	m
ΔZ_b	Bed level change	m

1
Introduction

1.1. Context

Coastal dunes are an essential component of the Dutch landscape. They provide a variety of functional goals such as the defence against flooding, recreational purposes, nature conservation and a supply of drinking water (A.V. de Groot et al., 2001). Historically, the main role for the dunes to play was the safety against flooding in the Netherlands. In 1990 the Dutch Government decided to keep the coastline in its current position, to ensure safety against flooding and preservation of the dunes. Of the approximately 350km long Dutch coast 254km is protected by dunes (Hillen and Roelse, 1995).

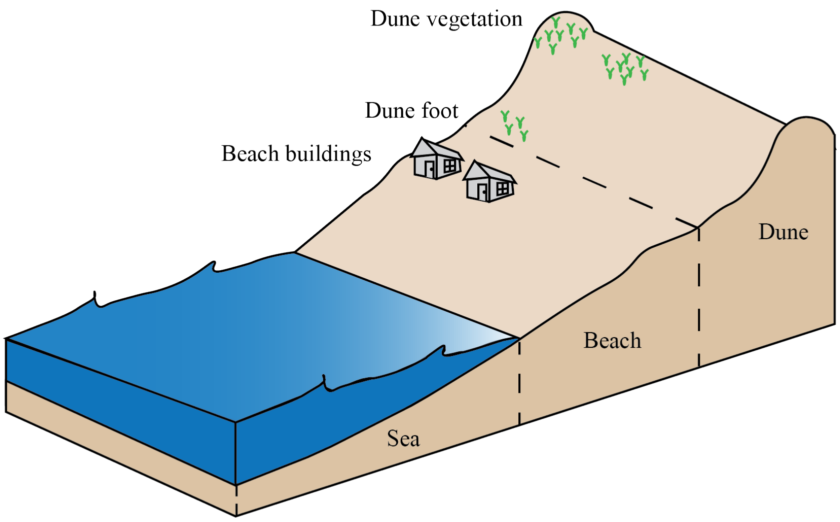


Figure 1.1: Schematization of a coastal dune with the presence of beach buildings

The safety standards for dunes against flooding are based on a minimum dune volume to be able to resist the load of design storm conditions. A reference for the coastline has been defined as the Momentary Coast Line (MCL) for each 250 m wide section along the Dutch coast protected by dunes against flooding. The position of the coastline in 1990 is set as the minimum state of the coastline, and is referred to as the Basal Coast Line. To maintain the minimum position of the MCL a yearly increase in dune volume is required to cope with storms and future sea level rise.

The ability of dunes to grow through aeolian sediment transport, is mainly accredited to their morphological character and allowance for vegetation growth (Psuty, 2004). Aeolian sediment transport is the transportation of sand particles induced by wind stresses that are exerted on an erodible surface (Bagnold, 1937). Dune development is directly related to vegetation growth due to positive feedback to sand burial by aeolian transport. Dune grasses require a certain rate of aeolian transport to thrive, on the other hand excessive sedimentation rates increase the risk of vegetation to become irrevocably buried (Nolet et al., 2018).

Key for future dune development is combining the functionalities of the coastal zone in a sustainable way. One of these functionalities consists of recreation within the coastal zone, and is partly facilitated by placing buildings on the beach. Buildings placed on the beach are from now on referred to as beach buildings and an example of typical placement is schematised in figure 1.1.

The presence of beach buildings could influence the aeolian sediment transport towards the dunes, and therefore have an impact on dune volumes in their vicinity. The physical presence of beach buildings causes spatial variation in local wind patterns that could influence aeolian sediment transport towards the subsequent dune. It is therefore crucial to regard the effect of beach buildings on aeolian sediment transport.

In addition, relocation of sediment during construction and maintenance of beach buildings could affect dune volumes. The construction methods of larger beach buildings often require the relocation of sediment from the dune system to create a horizontal building ground. Occasionally, sediment is relocated for maintenance purposes to make the rear end of a pavilion accessible. Examples of mentioned interferences related to beach buildings are presented in figure 1.2.

(a) Relocation of sediment behind an individual pavilion

(b) Sediment patterns due to local influence on aeolian sediment transport by ribbon-development

Figure 1.2: Interferences induced by the maintenance and the physical presence of beach buildings

Beach buildings could influence the presence of dune vegetation, and therefore have an impact on future dune development. First off, buildings could have a direct effect on vegetation growth due to their physical presence in the vicinity of vegetation. Secondly, the vigorousness of dune vegetation is strongly dependent on sedimentation rates (Maun, 2009). Buildings could indirectly affect vegetation growth through an alteration in aeolian sediment transport rates.

The large variety of beach building types makes it particularly complex to generalize their effects on dune development. Beach buildings are typically encountered in a variety of configurations such as long rows of consecutive beach houses, small individual beach houses and large individual beach pavilions. There are several parameters that could have an impact on dune development such as height, length, width, surface area, placement seasonality, distance between consecutive buildings, and location from the dune foot.

In an exploratory research by Deltares (2014b) to quantify the effects of beach buildings on aeolian coastal dune development was concluded that the spatial resolution of the available Jarkus-data was too limited to significantly correlate trends in dune development to the presence of beach buildings. This was attributed to the three dimensional behaviour of dune morphology and the relatively small scale of buildings. In order to acquire data with higher resolution to reliably asses the influence of buildings on aeolian coastal dune development UAV-data has been gathered in two case areas in the Netherlands during the period 2015-2018. This data is used in this research.

1.2. Relevance

Coastal dunes provide protection against flooding of the hinterland for roughly 70% of the Dutch coast (A.V. de Groot et al., 2001). It is expected that the dunes are required to withstand increasing hydrodynamic loads related to climate change in the future. At the same time it is expected that beach buildings will emerge increasingly due to an increased demand for recreational activities within the coastal zone.

1.2.1. Climate change

A steady increase of the dune volume is desired to cope with future climate change induced sea level rise. A consequence of sea level rise is the retreat of coastlines that remain unprotected (Bruun, 1962; Ranasinghe et al., 2012). Recent research suggests that global average mean sea levels may rise at an accelerating rate attributed to climate change throughout the twenty-first century (Nicholls and Cazenave, 2010). It is expected that this has negative effects on the coastal sediment budget and consequently will lead to dune erosion. It is desired that dunes grow in height and volume to cope with the effects of sea level rise (Davidson-Arnott, 2005). The general expected response of a coastal profile to sea level rise is schematised in figure 1.3.

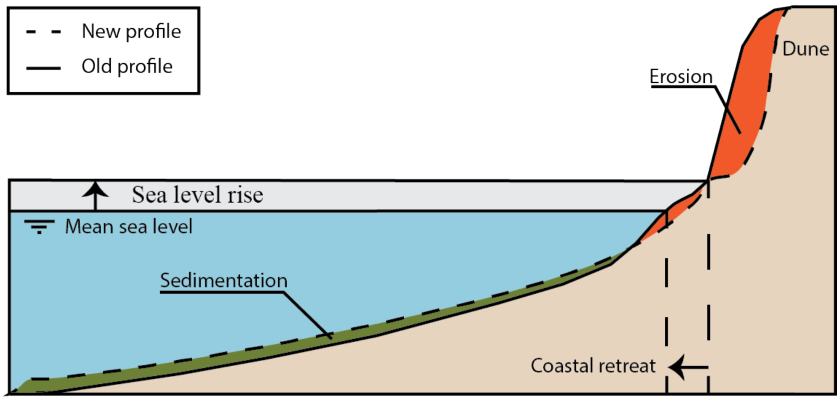


Figure 1.3: Schematization of the response of a coastal profile to sea level rise

Besides sea level rise it is predicted that storms will become more severe and will occur more frequently due to climate change related effects. Winter storms will become stronger and more north-westerly than usual, which results in an increase in frequency and severity of storm surges along the Dutch coast (Beniston et al., 2007). It is expected that these storms will increase dune erosion by wave attack. For the dunes to become resilient against future storms related to climate change a steady increase of dune volume and height is desired. The response of a coastal profile to a storm event is presented in figure 1.4.

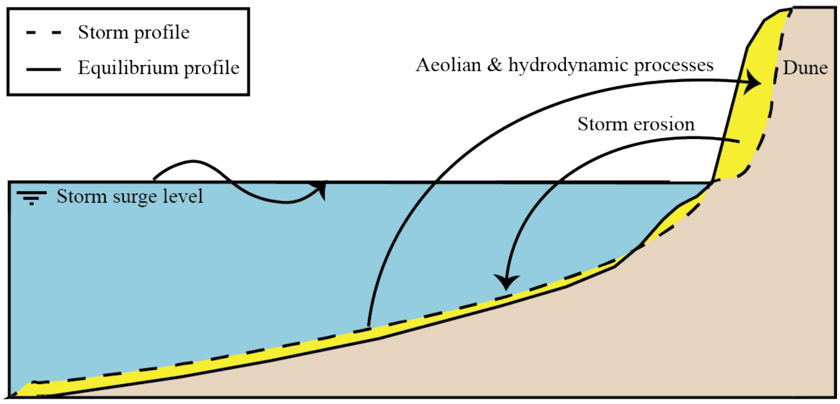


Figure 1.4: Schematization of the response of a coastal profile in equilibrium to a storm surge

To prevent potential backlog of resilience against future sea level rise and increasing hydrodynamic loads of dunes in the vicinity of beach buildings, it is crucial to gain more insight on the effect of beach buildings on coastal dune development.

1.2.2. Rising presence of beach buildings

The effect of beach buildings on coastal dune development is an increasing concern in the Netherlands, due to their rising presence. Recreational activities within the coastal zone are becoming increasingly popular, which is reflected by an increase in the presence of beach buildings along the Dutch coast. Research by Natuurmonumenten (2016) states that the amount of recreational objects that will be realized will increase threefold in the three years that follow the inventory in 2016 in comparison to the three years before. Beach buildings, bungalows, apartements, and hotels placed on the beach or 1.5 kilometeres of the outer dune are stated as recreational objects. An overview of recreational projects that are realised in the years 2016 - 2019 alone is presented in figure 1.5.

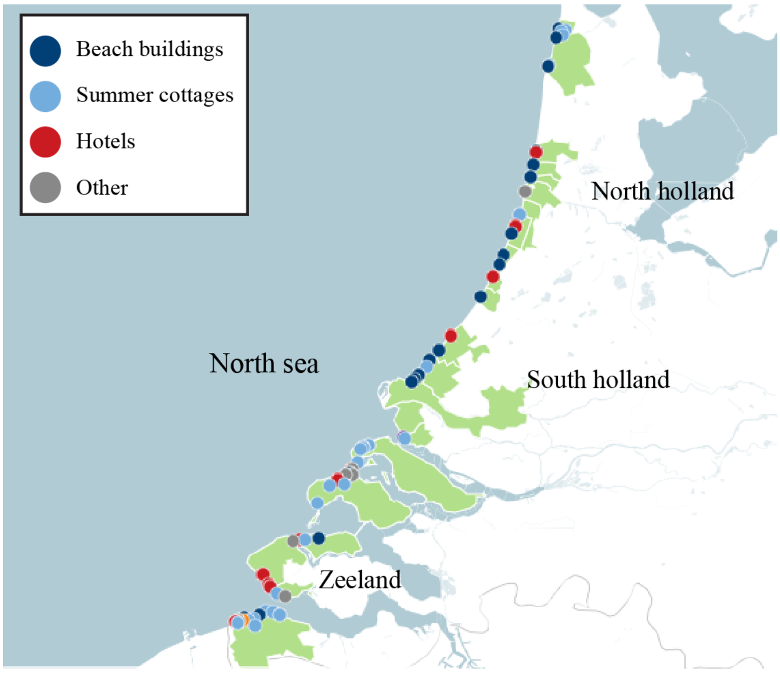


Figure 1.5: Overview of emerging recreational projects along the Dutch coast during 2016 - 2019, adopted from NRC (2016)

1.3. Objectives

The influence of beach buildings on coastal dune development is still largely unknown, and it could pose a risk to the functionalities coastal dunes provide. Coastal dune development is governed by complex interactions between physical and biological processes, and beach buildings come in a variety of dimensions and placement configurations. This makes it challenging to isolate the effects of beach buildings on coastal dune development. To effectively isolate the distinct effects of beach buildings on dune development a conceptual model is desired. Subsequently, more insight on the influence of beach buildings and how this relates to key processes can be gained by acquiring high resolution photographic and elevation data. New insights can be used as a foundation to compose effective dune management measures for future placement of beach buildings, to ensure sustainable dune development. The objectives of this research are translated to a comprehensive main research question:

> What is the influence of specific types of beach buildings on aeolian coastal dune development, and what are suitable dune management measures?

Three subquestions are identified that comprise the main research question:

1. *What is the difference in coastal dune development in areas with beach buildings present versus areas without, in terms of:*
   (a) Dune volume?
   (b) Vegetation development?
   (c) Dune state (characteristics)?
2. *What is the difference in effect on coastal dune development caused by different beach building characteristics, in terms of:*
   (a) Maintenance?
   (b) Construction?
   (c) Cross-shore positioning?
   (d) Dimensions, alongshore and local positioning?
3. *What are effective dune management measures to cope with the effect of beach buildings on coastal dune development?*

1.4. Thesis outline

This report starts with a literature review (chapter 2), in this chapter relevant processes that govern coastal dune development, previous research that studied the influence of beach buildings, and current dune management practices in the Netherlands are described. Afterwards, the research method to tackle the main objectives is presented in chapter 3. This chapter elaborates on the used data (section 3.1) and how it is used to quantify dune parameters that describe coastal dune development (section 3.2).

The results of this study are presented in chapter 4. First, the conceptual dune model (section 4.1) that separates static and dynamic dune development and functions as a framework to isolate the effect of beach buildings is introduced. In section 4.2 small-scale dune development that is described for a static and dynamic dune state is validated by the data and quantified dune parameters. Subsequently, section 4.3 applies beach buildings into the conceptual dune model and their influences on key processes is assessed based on observed and quantified differences with the reference dune. The results conclude with suitable dune management measures (chapter 5) that are composed based on the determined influence of beach buildings. The report finalizes with the discussion, recommendations, and conclusion in chapter 6, 7, and 8 respectively.

2
Literature Review

The literature review contains a thorough analysis of existing research on coastal dune development, the influence of beach buildings, and dune management policies. The results are used as a foundation of this research, knowledge gaps and relevant key processes are identified.

2.1. Coastal dune development

The development of coastal dunes is governed by complex interactions between physical and biological processes. This section elaborates on the key processes that govern coastal dune development. An overview of the relevant processes is presented in figure 2.1.

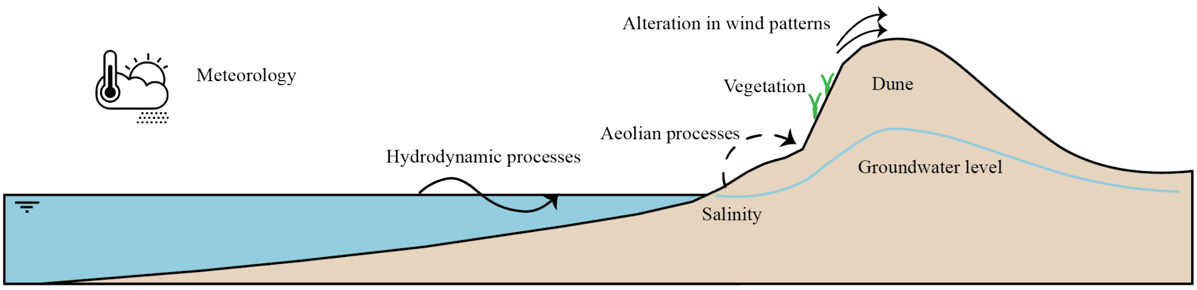


Figure 2.1: Overview relevant processes that govern coastal dune development

2.1.1. Aeolian sediment transport

Aeolian sediment transport is defined as the transport of sediment by the wind. This occurs as the wind exerts shear stress on an erodible bed and the velocity reaches a certain velocity threshold, which initiates the motion of sand particles (Bagnold, 1937). While observing sediment transport in the field and in wind tunnels Bagnold (1941) was the first to classify particle motion due to aeolian processes into three categories (figure 2.2):

- **Suspension**: referred to travelling sand particles that are relatively light, and therefore travel larger distances due to aeolian sediment transport.
- **Saltation**: relatively large particles that are too heavy to be in suspension and therefore 'bounce' on the surface following parabolic trajectories. Particles are rebounded from the surface by a landing particle, the rebounded particles have a large probability to be accelerated by the wind speed once again.
- **Creep**: this is referred to when the sand particles remain in near-continuous contact with the bed and they are 'rolled' along by the wind.

Aeolian sediment transport is considered as the driving force behind dune development. Sediment is transported from the beach towards the dunes.

There are three regimes that are typically considered as a limiting factor for the amount of sediment that is transported: the transport, fetch, and supply limited regimes. These distinct regimes are schematised in figure 2.3.

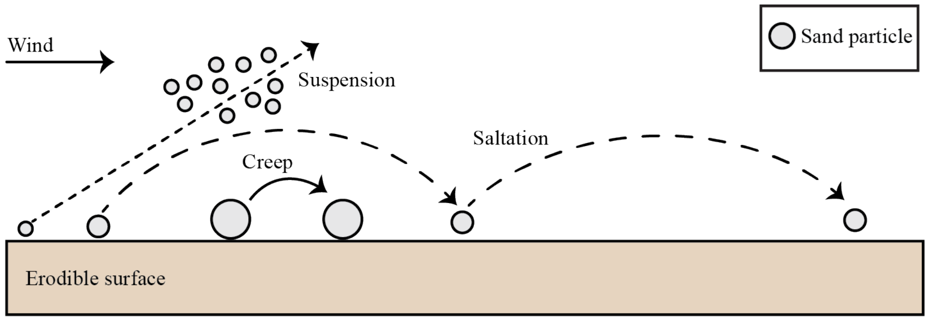


Figure 2.2: Distinct modes of aeolian sediment transport

First off, there is the transport limited regime, in this case the shear stress that the wind induces is the factor that determines the volume of sediment that is transported. This regime persists in open wide areas, where sediment availability is not a constraint, such as the desert.

Second, the fetch limited regime, in this case the distance for the wind to reach saltation, the fetch length, is limited. For instance, in coastal areas where sediment is still moist from the change in tides and not available for transport. In this case there is a clear boundary from where sediment is available for transport, and if the length of the beach is limited compared to the fetch length, sediment transport is typically referred to as fetch limited (Jackson and Cooper, 1999).

Last, the supply limited regime. In coastal areas there are spatio-temporal variations in the bed surface properties caused by for example shells, variation of the ground water table induced by tidal differences, salt crusts, bed slopes, and vegetation (De Vries et al., 2014). These properties limit the sediment supply that is available for transport. Therefore, the spatio-temporal variations continuously affect the sediment supply.

In general larger beach widths, with a narrow slope result to larger sediment transport rates than steep narrow beaches with a steep slope. Beaches with larger beach width will therefore have relatively more dune growth by aeolian processes (Cohn et al., 2019).

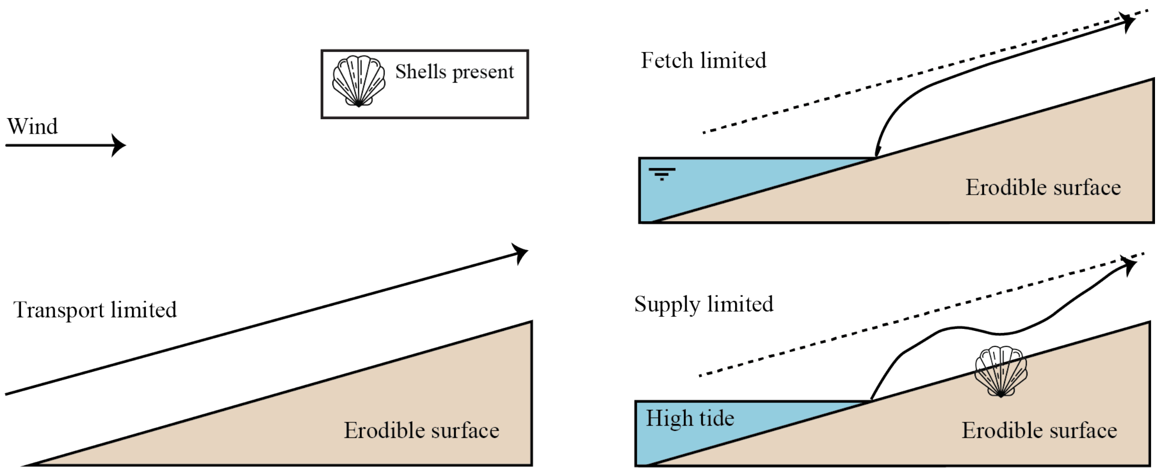


Figure 2.3: Distinct sediment transport limiters

The morphology of coastal dunes contain curvatures that interact with the wind and cause spatial variation in sediment transport by aeolian forces (Wiggs et al., 1996). The occurrence of spatial variation in wind fields, and therefore the sedimentation, is an essential process in the development of dunes. To illustrate this an example of an erodible hump with fictitious streamlines is presented in figure 2.4.

As the streamlines converge towards the top of the hump wind speeds accelerate and subsequently the shear stress on the erodible bed increases. This leads to an increase of the aeolian sediment transport. As the sediment transport increases over the hump the incoming sediment flux is lower than the outgoing flux. This causes erosion until the sediment transport reaches its maximum.

After the maximum shear stress is reached the streamlines diverge, which results in a decrease of the shear stress exerted on the erodible bed. Subsequently, the sediment transport decreases after reaching a maximum. The ingoing sediment flux becomes larger than the outgoing flux, this unbalanced flux results in sedimentation locally.

There is a spatial lag between the maximum shear stress and the maximum sediment transport rates (Claudin and Andreotti, 2006). This spatial lag is called the saturation length (L_{sat}). This is a consequence of an asymmetric velocity field. Additionally, the maximum shear stress is shifted upwind of the crest if the hump as illustrated in the figure.

Sudden changes in streamline curvature can cause secondary flow patterns such as lee flow separation and reversal. Aeolian literature often refers to these secondary flow patterns, but the exact impact of these turbulent flows on aeolian sediment transport rates is still poorly understood (Walker, 1999).

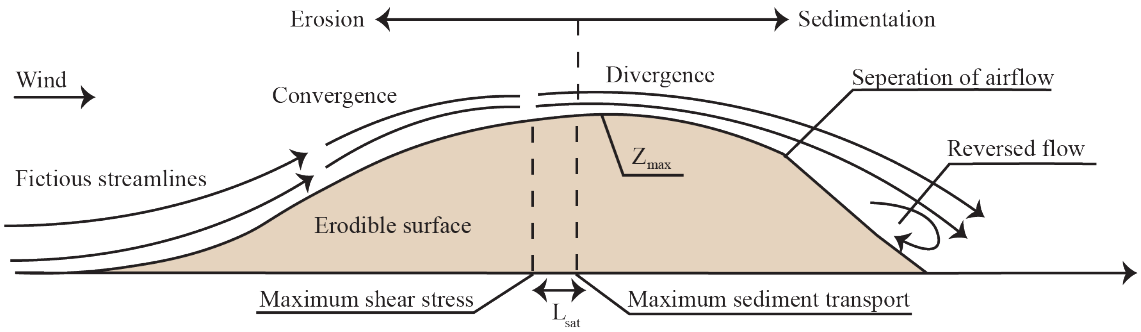


Figure 2.4: Erosion and deposition regimes due to spatial variation in streamline curvature, based on Walker (1999)

Beach buildings are non-erodible and capable of altering wind fields in their vicinity and therefore influence aeolian transport locally. How comparable objects to beach buildings alter wind fields are discussed in section 2.2.2.

2.1.2. Avalanching

Avalanching occurs when (dune) slopes become to steep and the surface is reset to the angle of repose. This can for example occur due to erosion by hydrodynamic processes or an increased amount of sedimentation that gradually steepens the slope.

The angle of repose deviates per sediment type, where the morphology of the particle plays an important role. Other external conditions such as the moisture content and the presence of solvents influence the angle of repose. The angle of repose for dry sand is 34°.

2.1.3. Vegetation

The presence of vegetation allows the dune to grow in height, and has a stabilizing effect on the dune. Sand is transported from the beach to the dunes by aeolian forces induced by onshore winds, and at the dunes it is trapped and fixed by vegetation. Sediment is trapped by vegetation because it functions as a roughness element and locally reduces shear stresses induced by the wind. (Raupach et al., 1993).

Dune grasses such as Marram grass (*Ammophila arenaria*) are able to establish themselves on dunes by germination of seedlings, lateral rhizome growth, and the plantation of culms (Van der Putten, 1990). Seedlings can be marine-dispersed, originate from local natural resources, or sowed by humans.

There are several biotic factors that are suggested to be the most important limiting factors for Marram grass and seedling survival (Maun, 1994; van der Putten et al., 1988). These biotic factors are nutrient deficiency, lack of moisture, extreme sand accretion, high wind stresses, soil salinity and salt spray. Sykes and Wilson (1988) state that Marram grass is tolerant of salt spray as an adult, but less tolerant when younger.

Marram grass is known for its tolerance and ability to thrive at certain sedimentation rates. Optimal burial rates for Marram grass are reported to be $0.31 m^2$ of deposition per growing season. A maximum tolerance to sand burial by Marram grass was suggested to be between 0.28 - 0.96 m^2 of sand per growing season by Van Puijenbroek et al. (2017). The explanation behind the positive relation between Marram grass and sedimentation is still heavily discussed by scientist, an extensive summary of these explanations is presented in Appendix A.

The tolerance of Marram grass to sand burial causes a positive feedback between vegetation growth and sand burial. This positive feedback mechanism is schematised in figure 2.5.

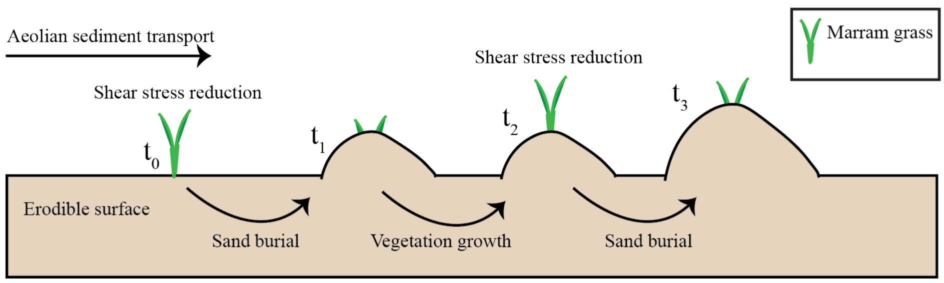


Figure 2.5: Mechanism behind positive feedback between vegetation growth and sedimentation

The presence of vegetation leads to alteration of local wind patterns and therefore alters sediment transport rates locally (Hesp et al., 2005). During onshore winds the wind is locally accelerated due to flow compression on the seaward slope of the dune. The presence of vegetation causes a counteracting force against the locally accelerated wind due to flow compression. At the vegetation there is a speed-up and in the canopy a slow-down.

2.1.4. Hydrodynamic processes

Hydrodynamic processes directly influence the coastal sediment budget by causing erosion and sedimentation in de nearshore region. Erosion of the coastal profile by hydrodynamic processes can be caused by extreme events, and sea level rise as described in section 1.1. Vegetation is affected as well during extreme events, due to erosion of the profile and increased salinity concentrations (Maun, 2009).

An important amount of the cross-shore sediment transport that facilitates beach recovery occurs in the swash zone (Elfrink and Baldock, 2002). Sediment is transported to the beach in calm conditions when low surge heights prevail. In this case bars present offshore as a result of an extreme event are transported back to beach during calm conditions. This sediment acts as a supply for aeolian sediment transport further landward to the dunes (Bosboom and Stive, 2012).

In the intertidal zone hydrodynamic and aeolian processes interact. Due to the swash induced moisture, salt intrusion, and the alteration in the groundwater table induced by the tide, the local aeolian sediment transport supply is reduced locally (De Vries et al., 2014).

Although hydrodynamic processes are mainly linked to dune erosion, new insights by Cohn et al. (2018) suggests that collisional wave impact is not unconditionally erosional. From an analysis of a morphological data set of a dissipative beach it is estimated that infragravity swash processes can contribute directly to dune growth.

2.1.5. Dynamic features

Dynamic features refer to dune components that are characteristic for dynamic dune behaviour and cause alongshore spatial variability in the cross-shore dune profile. These consist of foredunes and blowouts.

Foredunes are dune ridges which are formed by aeolian sediment transport from the beach. Foredunes typically form parallel to the shore and are generally classified in the two following types: embryo (incipient) dunes and established dunes.

- **Embryo dunes** are developing foredunes where pioneer plant communities are present. Often they are formed by sand deposition by aeolian transport and the sand is subsequently trapped by discrete humps of vegetation. The morphological development of embryo dunes is largely dependent on the plant density, distribution, height and cover, wind velocity and rates of aeolian sediment transport.

- **Established foredunes** develop from embryo dunes, they are often seen apart from embryo dunes by greater morphological complexity, height, width and age. The morphological development of established dunes largely depend on: sand supply, presence of vegetation species, rate of aeolian sand accretion and erosion, wind and wave conditions, degree of vegetation cover, significance of storm erosion, water level, and use by humans. The evolution from an incipient to an established foredune is presented in figure 2.6.

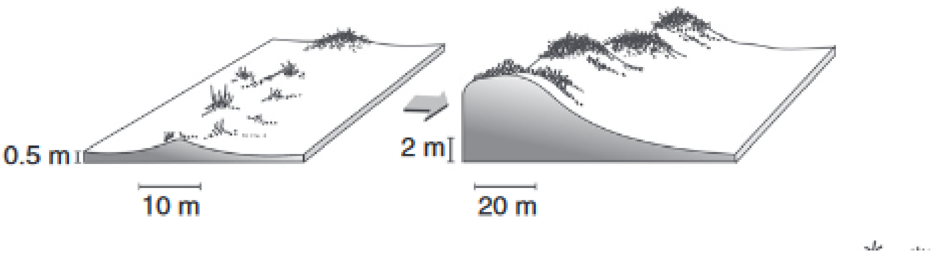


Figure 2.6: Evolution of the foredune, from incipient to established, adopted from Hesp and Walker (2013)

A blowout is a cup shaped scour formed by erosion and provides an erodible surface for sediment transport further landward. The morphology of a blowout is highly variable. There are two types of distinct blowouts. A semicircular blowout is relatively shallow shaped, and a trough blowout is often deeper and cup or bowl shaped (Hesp, 2002). These distinct types are presented in figure 2.7. Blowouts are generally initiated due to one or a combination of the following processes: wave erosion at the seaward dune, topographic acceleration of airflow over the dune crest, high velocity wind erosion, and human activities.

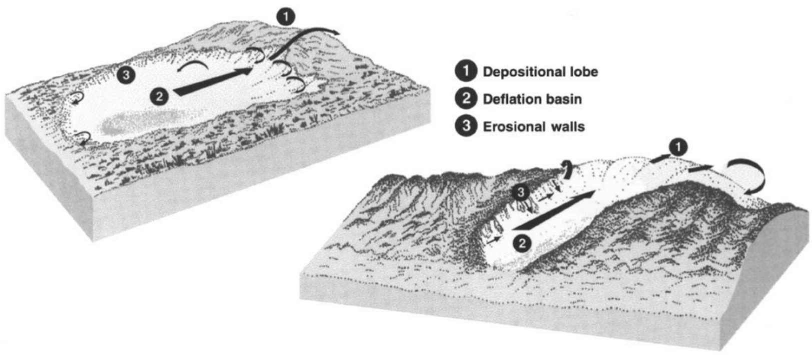


Figure 2.7: Types of blouwouts: semicircular and trough blowout, adopted from Hesp (2002)

2.2. Beach buildings

Existing research on the influence of beach buildings on aeolian sediment transport and dune development is still scarce. Significant research however is performed on the influence of buildings on wind patterns in general. This research defines beach buildings as buildings placed on the beach in front of the dune.

2.2.1. Influence on dune development

Current research agrees that beach buildings can have a local impact the aeolian sediment transport towards the dunes (Deltares, 2014a; Onselen, 2018). Methods of existing research on the effect of beach buildings on dune development include the utilization of sediment traps, simulation of aeolian sediment transport with CFD, JarKus transects, and Google Earth images. The majority of these studies state that either or both the temporal and spatial scale of the measurements are a limitation to reliably asses the influence of beach buildings on coastal dune development. It is therefore often recommended to apply frequent monitoring and increase the spatial scale of future measurements. (Huisman, 2013; Deltares, 2014b).

Deltares (2013) made an inventorization of the available studies on the influence of beach buildings and concluded that available research is limited. The report suggests that the orientation towards the dominant wind direction seems to play an important role.

In another study by Deltares (2014a) the influence of beach buildings on coastal dune development in the location Spanjaards Duin was investigated with Google Earth images. The results were suggested to be preliminary because of the limited temporal frequency of the images. The study suggests that small single beach buildings only have a local effect on the morphology of the dune, and consecutive placed beach buildings seemed to have the largest impact on dune development as they work as a wall against aeolian sediment transport.

A follow-up study by Deltares (2013) concluded that creating a reliable Bayesian network that predicts the effects of beach building types on coastal dune development was not possible. The configurations of beach buildings was too large and available data too limited to calibrate the network. However, it was concluded that the initial chance for a positive trend in dune development along the case areas was 70% and that the conditional probability decreases when beach buildings are present.

Onselen (2018) analysed the effects of different construction types on aeolian sediment transport with CFD modelling. The study suggests that placing beach buildings on poles is the most effective way to promote unhindered aeolian sediment transport. A pole length of approximately 1.5m was deemed the most efficient, the extra beneficial effect on aeolian sediment transport by further enlarging the pole length was suggested to be negligible. The study by Onselen (2018) suggests that for optimal aeolian sediment transport rates towards the dunes, beach buildings should be placed as close to the dune foot as possible. This contradicts the findings of Deltares (2014a) that suggest a minimum distance of 5m from the dune foot. It should be noted that the findings of the research by Onselen (2018) are only based on the physical presence of beach buildings and their effect on aeolian sediment transport, and the relocation of sediment for construction and maintenance purposes is not considered.

In a study by Nordstrom and McCluskey (1985) the effect of buildings placed on the dune crest on aeolian sediment transport rates was investigated. Sand traps were used to measure the aeolian sediment transport with different scenarios with and without buildings. These measurements were performed for approximately a month and converted to annual sediment inputs with the help of local meteorological data. The study concluded that it was particularly important how the buildings were constructed and whether a sand fence was present or not. A significant decrease in sediment transport was reported when beach buildings were present. First off, it should be noted that converting monthly data to annual can cause serious errors keeping in mind that the direction of the wind variates over the year. Furthermore, sedimentation rates can differ at non-erodible objects relative to unsheltered beds during calm and storm conditions. Secondly, if aeolian sediment transport rates decrease at a faster rate or only during the first month of placement, results are exaggerated.

2.2.2. Airflow around buildings

Considerable research has been executed on interaction between buildings or objects and wind in general. The majority of these studies is executed for design guidelines with respect to wind loading or optimal pedestrian environments (Cook, 1986; Tominaga et al., 2008). Nevertheless, some of the used concepts can be useful to compose expected consequences of local airflow patterns induced by beach buildings on aeolian sediment transport in their vicinity.

Consider a non-erodible cube that is placed on an erodible surface, a shape that resembles the physical structure of a beach building. The airflow patterns that result from interaction with the wind and the cube are expected to be comparable to airflows around beach buildings. A schematization of the airflow around a cube is presented in figure 2.8.

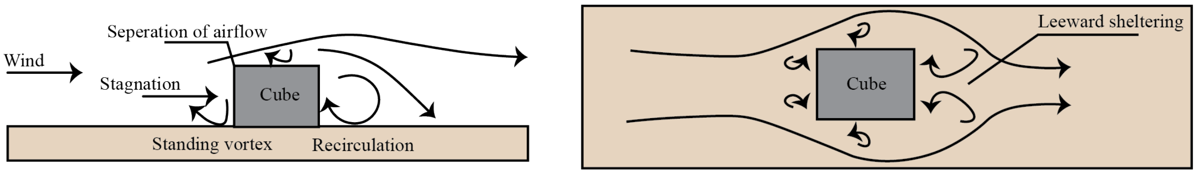


Figure 2.8: Airflow pattern around a cube

The alteration of the airflow directly after placement of the cube influences aeolian sediment transport in its vicinity. What the exact influence on aeolian sediment transport is unknown, because of the lack of understanding of the flow conditions in the vicinity of roughness elements (Wyatt and Nickiing, 1997). It is therefore not possible to make any conclusive statements about differences in sediment flux with the sheltering of the cube versus without.

It is proposed by Sutton and Neuman (2008) that under less energetic wind conditions non-erodible roughness elements increase the sediment flux, or decrease the wind velocity threshold at which aeolian sediment transport starts to occur. On the contrary, when large wind speeds prevail non-erodible roughness elements would suppress the sediment flux. This proposed relationship is schematised in figure 2.9.

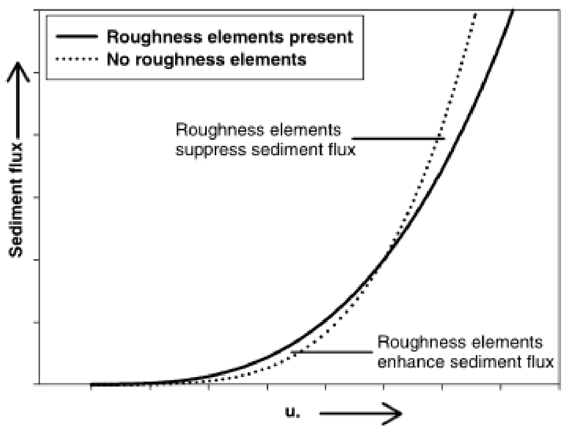


Figure 2.9: Proposed relationship between the shear velocity (u_*) and sediment flux, adopted from Sutton and Neuman (2008)

The passage width c determines the type of airflow and therefore the sediment flux between beach buildings. There are three types of air flow regimes between buildings, resistance, interaction, and isolated flow (Baskaran and Kashef, 1996; Blocken et al., 2007). These regimes are schematised in figure 2.10.

Flow resistance occurs when the passage width c is so small that the flow resistance between the passage leads to a reduction of the wind speed between beach buildings. It is expected that that this occurrence would lead to low amounts of sediment transport between consecutive buildings. Essentially, the buildings together form a blockade against aeolian sediment transport.

Interaction flow, this is the case when the passage width c is small enough for flow separation between the buildings to interact with one another and enforce aeolian forces. It is expected that this phenomenon increases aeolian sediment transport rates between consecutive buildings.

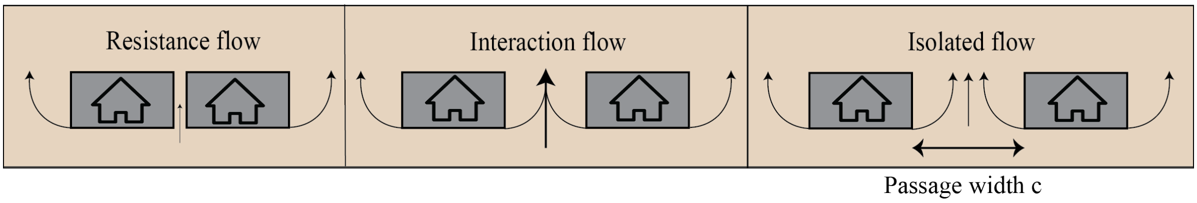


Figure 2.10: Schematization of flow regimes between buildings

Isolated flow is referred to when there is no interaction between separation flow between the buildings due to a sufficiently large passage width c. In this case the sediment transport rate is unaffected by the fact that the buildings are placed consecutively. In this case, they can be regarded as individual structures.

2.3. Dune management

The definition of coastal and dune management is reliant on our ideologies of the coastal zone and how we intend to use it. If we see the coast as a tool for socio-economic development, management will concentrate on building within the coast and protecting these structures. On the contrary, if we see the coast as a crucial part of our landscape, then management will largely concentrate on maintaining the authenticity of the dunes and the flora, fauna, and landscape as a whole within it (van der Meulen and Salman, 1996).

2.3.1. Dutch policy

The natural dynamic behaviour of foredunes in the Netherlands have been suppressed by coastal management in the past. The main focus was protecting the hinterland from floods, and suppressing the natural dynamics of dunes by planting vegetation, which resulted in static dunes, was a suitable way to achieve this (Arens et al., 2013).

The dense vegetation that prevails on a static dune in essence works as a barrier for sediment transport further landward, which results in a decrease of the biodiversity and prevents the back dune to grow in height (Arens and Wiersma, 1994). Due to the absence of sedimentation further landward other sediment intolerant vegetation species take over, and as a result a large part of the stabilized dunes suffer from intrusion of grasses and moss on the back dune.

During the 1980s more awareness for the consequence of a static dune system on the biodiversity arose, and subsequently more interest in the behaviour of dynamic dunes. The first studies emerged where observing the natural behaviour of dynamic dunes was of interest (Arens et al., 2013).

In 1990 a new approach to coastal erosion management ("Dynamic preservation of the coast") was adopted in the Netherlands, which changed from reactive to pro-active (Roeland and Piet, 1995). The main objectives of this approach is to preserve the safety against flooding, and enhance the natural values and functions in the coastal and dune area, through artificial nourishments. In order to cope with expected sea level rise in the future the required nourishment volume is expected to increase in the coming years (Deltares, 2012).

This had a positive effect on the coastal sediment budget, and in many areas this lead to an increase in the presence of embryo dunes (Arens et al., 2013), which is a fundamental difference to the more static landscape before 1990. The natural dynamics of coastal dunes, and the biodiversity that comes with it is therefore partially restored. Due to the revitalization of the aeolian processes, the coastline did become relatively stationary in comparison to static dune states, but in return the dunes are able to grow in height (Arens et al., 2013).

On this day nature managers believe that it is crucial to remobilize dunes to increase the biodiversity and allow the dune to grow in height (Martínez et al., 2008), subsequent studies that spectate the behaviour of restored dynamics dunes are occurring increasingly. A recent study by Ruessink et al. (2018) proved that by creating a dynamic dune state with the help of artificial blowouts in the Dutch National Park Zuid-Kennemerland, the yearly volume change to the back dunes increased with 26.5$m^3/year$ compared to the old static dune state.

2.3.2. Beach building placement policy

There is is a limitation of space on the beach to freely place beach buildings because of legal matters.

The emergency zone reaches up until ten meters landward of the high water line, and it is not permitted to build within this zone (Gemeente Texel, 2017). Coastal zone management in the case areas of interest divides the coastal area in the regions as depicted in figure 2.11. Relevant placement parameters are: angle with the dominant wind direction (β), Passage width (c), distance to the dune foot (d), length (l), and width (w).

The imaginary line that acts as a boundary between the emergency zone and the beach is based on the expected evolution of the high tide in the coming five years (HHNK, 2014). This part of the beach is reserved by the Dutch Rijkswaterstaat to maintain space for the movement of vehicles in the case of an emergency.

The imaginary boundary that separates the dune area from the beach is based on where the dune foot is predicted to be in five years, based on the evolution of the JarKus transects. In the dune region landward of this boundary it is not permitted to build.

In the region between the emergency zone and the defined dune foot it is allowed to place buildings on the beach when suitable permits are acquired, which are issued by regional water boards (HHNK, 2014). On average the regional waterboard HHNK maintains the following guideline: flexible towards beach building placement at areas the dunes are sufficiently safe against hydraulic loads, and strict towards beach building placement at areas where the adjacent dune is more prone to such loads (HHNK, 2014). Every five years the waterboard directs a new location for the placement of beach buildings, this period has been proved to be sufficient to predict future changes in the boundaries of the dune foot and the high water tide. The location is determined based on where the future influence of a beach building is acceptable to adjacent dune development (HHNK, 2013).
Amongst others beach building permits are issued by HHNK (2014) based on the following conditions:

- A permit for the placement of beach buildings is valid for 10 years, but the location of placement can be subject to changes based on the evolution of the dune foot, and the high water tide.
- Beach buildings are placed on stilts that have a separation distance of 3m. Stilts do not have to be removed during winter.
- Permanent beach buildings are allowed to have a maximum width of 50 metres along the beach
- Seasonal placed beach buildings are allowed to be present on the beach between 15 March and 15 Oktober.

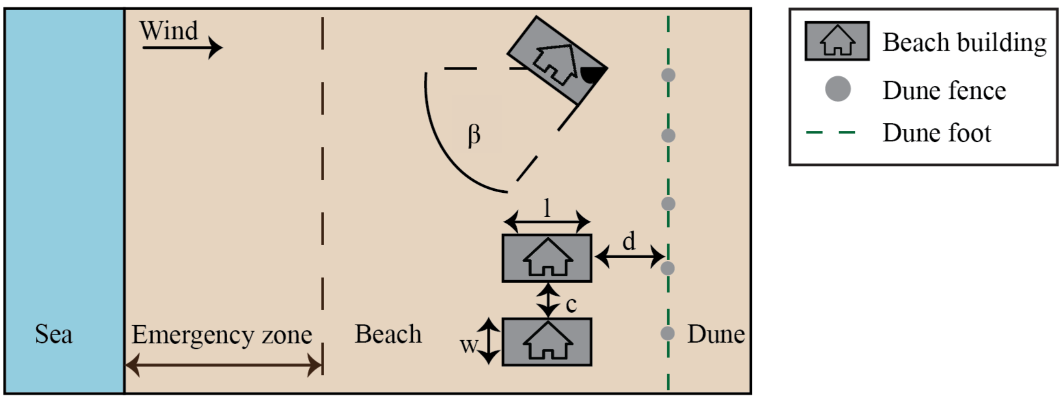


Figure 2.11: Schematization of typical placement of beach buildings

3
Method

High resolution bi-annual UAV elevation data of two case areas in the Netherlands with the presence of different beach building types is utilized to asses their influence on coastal dune development. Different dune subregions are classified based on the distinct building types that are present. Dune parameters that quantify coastal dune development within these subregions by utilizing the data are defined. A conceptual dune model (system framework) is composed to isolate the effects of beach buildings and validate the reliability of the dune parameters on a reference dynamic and static dune. Afterwards, the dune parameters of the subregions of the distinct beach buildings are quantified and visualized. The influence of beach buildings is identified by comparing quantifications and visual observations to the reference dune. Differences in dune parameters are physically related to key processes described in the conceptual dune model. Finally, dune management measures are composed accordingly. An overview of the research methodology is schematised in figure 3.1.

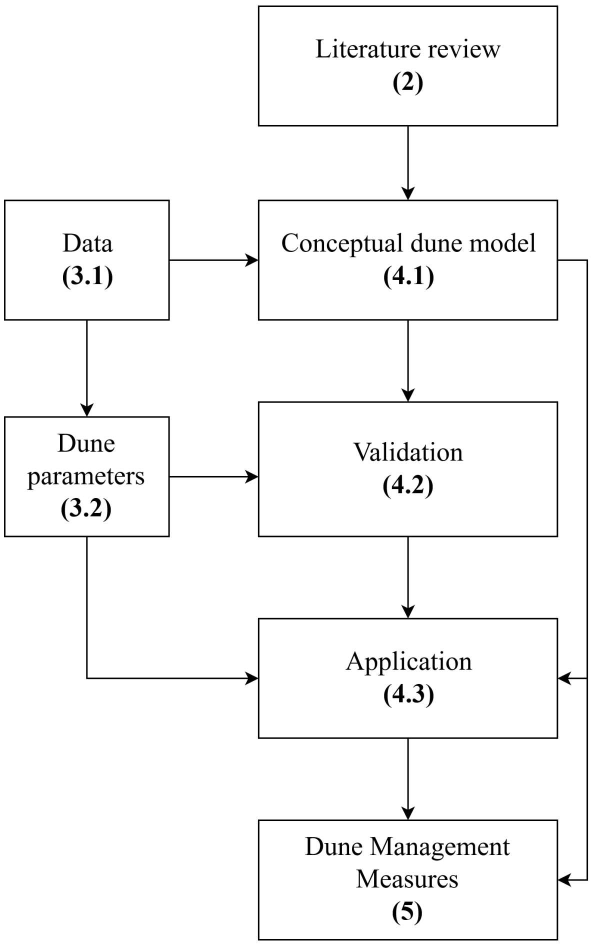


Figure 3.1: Method overview

3.1. Data

The data used for this research consists of an available dataset, UAV measurements and images taken in the process. The available dataset consists of high resolution UAV elevation and pictorial data of two case areas in the Netherlands, Julianadorp and Sint Maartenszee. Additional UAV measurements are performed to quantify short scale effects such as the relocation of sediment during the construction of beach buildings. Images taken during site visits are used to validate and emphasize derived concepts.

3.1.1. UAV Remote sensing

The data of this research consists of Digital Elevation Models (DEMs) generated with two types of UAV surveying methods, photogrammetry and LiDAR. Relevant theory on these methods is presented in this subsection. This research uses the term Unmanned Aerial Vehicle (UAV) to refer to a drone of any type.

Photogrammetry

Photogrammetry is a surveying method that is based on the processing of multiple overlapping images to elevation data. In this case the images are captured by an UAV that flies over a pre-determined measurement area with a constant speed. Ground Control Points (GCPs) are distributed over the measurement area and their geolocation is measured accurately. After orientating the images and marking the GCPs a dense point cloud can be generated through image processing software. Eventually, the DEMs can be generated through this dense point cloud. Photogrammetry can produce DEMs with very high resolutions, by Gonçalves and Henriques (2015) a vertical accuracy between 3.5 - 5 cm are reported for measurements in the coastal zone, with a 10 cm grid spacing.

The main disadvantage of photogrammetry is that it is unable to acquire reliable elevation data when vegetation is present. This is challenging due to the hindering of image matching by vegetation in various ways (Baltsavias et al., 2008; White et al., 2013).

LiDAR

Light detection and ranging (LiDAR) is a surveying method that provides vertical and horizontal information in the form of a high resolution elevation map, which eventually can be converted to a DEM. Laser pulses are emitted from the UAV and reflected light is measured with a sensor. The multiple recordings of a single UAV flight can be transformed to a three-dimensional dense georeferenced point cloud. The DEM can be extracted from this point cloud. The study by Doyle and Woodroffe (2018) demonstrates that LiDAR can be used to describe foredune morphology in considerable detail.

This research utilises LiDAR measurements to quantify dune parameters in vegetated areas. This is because unlike photogrammetry LiDAR has the ability to reach the ground even in forested areas (Lisein et al., 2013). The difference in measurement accuracy around vegetation is illustrated in figure 3.2.

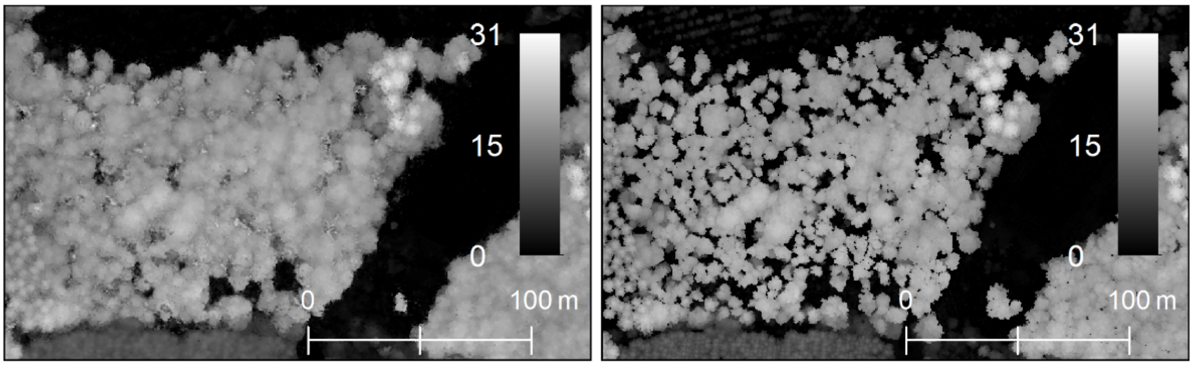


Figure 3.2: Left: photogrammetry DEM; right: LiDAR DEM; elevation scale is in [m]. Adopted from Lisein et al. (2013)

3.1.2. Dataset

The dataset consists of bi-annual UAV measurements in the coastal zone of Julianadorp and Sint Maartenszee. Within these case locations different types of beach buildings are present. The areas without beach buildings are classified as dynamic and static reference areas.

Characteristics

In Julianadorp and Sint Maartenszee seven UAV measurements are made by Shore (2017) in the period from 2015 - 2018. The measurement areas are chosen such that a wide variety of beach building types are present on the beach. Areas without buildings are included in the measurements to act as reference area. Each measurement consists of a DEM and an orthophoto. Orthophotos are generated identically for both surveying methods. An overview of the measurement characteristics is given in table 3.1.

Label	Surveying method	Date	Event
T0	Photogrammetry	September 2015	Before deconstruction seasonally placed buildings
T1	Photogrammetry	April 2016	After construction seasonally placed buildings
T2	Photogrammetry	September 2016	Before deconstruction seasonally placed buildings
T3	LiDAR	April 2017	After construction seasonally placed buildings
T4	LiDAR	September 2017	Before deconstruction seasonally placed buildings
T5	LiDAR	April 2018	After construction seasonally placed buildings
T6	LiDAR	September 2018	Before deconstruction seasonally placed buildings

Table 3.1: Overview measurement characteristics

Different surveying methods are used to acquire the measurements over time. The DEMs between September 2015 - 2016 are generated with photogrammetry. Hereafter, LiDAR is used to generate the DEMs. For both surveying methods distinct equipment is utilized, these are summarized in table 3.2.

Surveying method	UAV model type	Laser Scanner	Positioning system	Positioning accuracy
Photogrammetry	MD4-1000	-	DG (Applanix, 2019)	H: 0.5m; V:2.0m
LiDAR	DJI M600pro	AL3-32	RTK-GNSS (DJI, 2019)	H: 0.01m; V:0.02m

Table 3.2: Overview surveying equipment

An orthophoto is a large photograph of the case area with an uniform scale. The orthophotos are generated from the hundreds of overlapping images that an UAV takes of the measurement area. Orthophotos of Julianadorp and Sint Maartenszee are presented in figure 3.3 and 3.5. The DEMs of Julianadorp and Sint Maartenszee are presented in figure 3.4 and 3.6.

Figure 3.3: Orthophoto of Julianadorp (T6, September 2018)

The available DEMs have a pixel size of 10 cm, this is a high resolution compared to conventional data, like the JarKus transects. This high resolution is particularly valuable for this research, as the influence of beach buildings on coastal dune development has a relatively small scale. The orthophotos have a resolution of 2 cm and are used to couple bed level change to visual observations. The characteristics are summarized in table 3.3.

The respective locations of Julianadorp and Sint Maartenszee within the Netherlands are illustrated in figure 3.7.

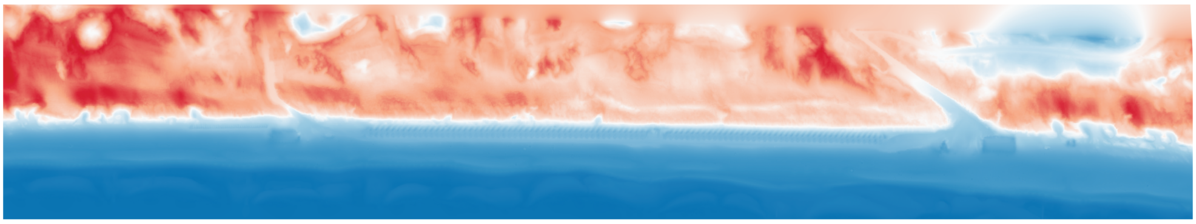


Figure 3.4: DEM of Julianadorp (T6, September 2018)

Figure 3.5: Orthophoto of Sint Maartenszee (T6, September 2018)

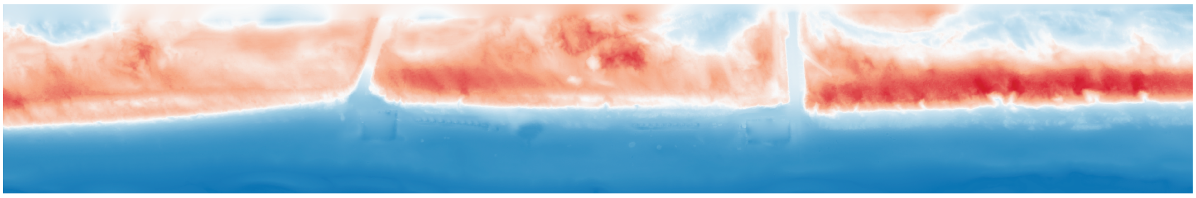


Figure 3.6: DEM of Sint Maartenszee (T6, September 2018)

Type	Pixel size	Measurement accuracy	Reference system
LiDAR DEM	10cm	2.5 cm	Amersfoort RD (EPSG:28992)
Orthophoto	2cm	-	Amersfoort RD (EPSG:28992)

Table 3.3: Characteristics of the DEMs and orthophotos

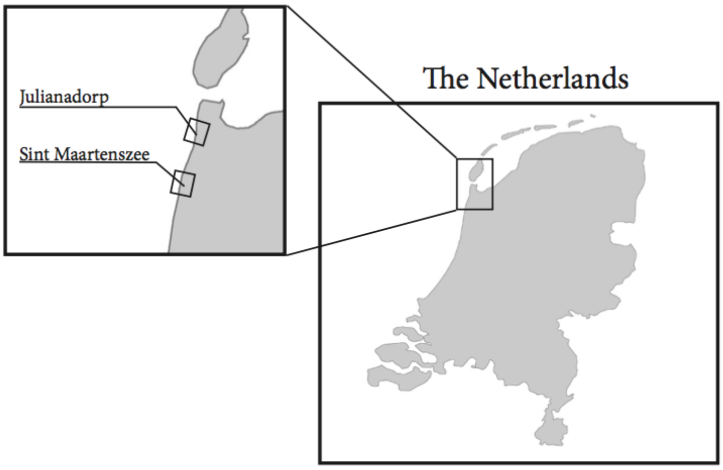


Figure 3.7: Location of the case areas in the Netherlands

Julianadorp

In the Julianadorp case area there are five subregions that can be classified with respect to beach building characteristics (figure 3.8):

(a) **Reference area south**: This subregion does not contain any beach buildings, it is classified as dynamic.

(b) **Small ribbon-development**: This subregion contains a row of consecutive placed small beach buildings, used as changing rooms. The beach buildings are placed on the beach seasonally and parallel to the dune foot.

(c) **Beach pavilion on sand**: This subregion has a larger beach pavilion present year round, it is placed directly on the sand north of a beach entrance.

(d) **Large ribbon-development**: This subregion contains a row of identical relatively large houses placed consecutively. The buildings are placed on the beach seasonally and with an angle in respect with the dune foot, and dominant wind direction.

(e) **Beach pavilion on stilts**: This subregion has a beach pavilion present year round, it is placed on stilts at the south of a beach entrance.

(a) Reference area south

(b) Small ribbon-development

(c) Beach pavilion on sand

(d) Large ribbon-development

(e) Beach pavilion on stilts

Figure 3.8: Classified subregions at Julianadorp

Sint Maartenszee

In the case area Sint Maartenszee there are six regions that can be classified with respect to beach building characteristics (figure 3.9):

(a) **Reference areas north**: This subregion does not contain beach buildings, it is classified as static.

(b) **Beach pavilion North**: This subregion has a beach pavilion present seasonally, it is placed on stilts at the north entrance of the Sint Maartenszee beach.

(c) **Small ribbon-development**: This subregion contains a row of identical small beach buildings, they are placed consecutively and seasonally.

(d) **Beach pavilion Middle**: This subregion has a beach pavilion present seasonally, it is placed on stilts.

(e) **Beach pavilion South**: This subregion has a beach pavilion present year round, it is placed on stilts at south of a beach entrance.

(f) **Sand trapping fences**: This subregion contains sand trapping fences, their main purpose is to stimulate aeolian sediment deposits.

(a) Reference area North

(b) Beach pavilion North

(c) Small ribbon-development

(d) Beach pavilion Middle

(e) Beach pavilion South

(f) Fences placed to stimulate aeolian sediment deposit

Figure 3.9: Classified subregions in Sint Maartenszee

3.1.3. Measurements

High frequency UAV measurements

To measure the influence of the construction of seasonally placed beach buildings additional UAV measurements are made. The relocation of sediment during construction could have an abrupt significant impact on dune volumes. The available data is measured biannually and therefore it is not possible to extract these influences from the dataset. Therefore, additional measurements are made directly before and after the construction of seasonally placed small ribbon-development. Measurement characteristics of the high frequency measurements are summarized in table 3.4.

The extra measurements are made in Sint Maartenszee. Julianadorp is located in a military airspace, it is therefore not allowed to operate an UAV in this region, unlicensed. The measurement area is chosen such that all building types in Sint Maartenszee are included. An orthophoto of the measurement area is illustrated in figure 3.10.

Figure 3.10: Orthophoto just before construction of the small ribbon-development (T7, March 2019)

The DEMs are generated with photogrammetry. In this case photogrammetry is chosen over LiDAR for two reasons. First off, to map the relocation of sediment during construction it is only required to measure the elevation of sand pixels. DEMs generated by photogrammetry at the coastal zone without vegetation have been reported to be very accurate (Gonçalves and Henriques, 2015). Secondly, equipment is available to perform UAV measurements with photogrammetry.

The DEM and orthophotos are acquired with UAV measurements and photogrammetry in the following steps:

1. **Plan the UAV mission**, the path for the UAV is predetermined by mapping software (UcGS). A forward overlap of 85% and side overlap of 80% for the images is chosen, to obtain accurate image aligning. The measurement area is divided into three flights as the battery life of the UAV is limited. The flight plan is presented in figure 3.11 (a).

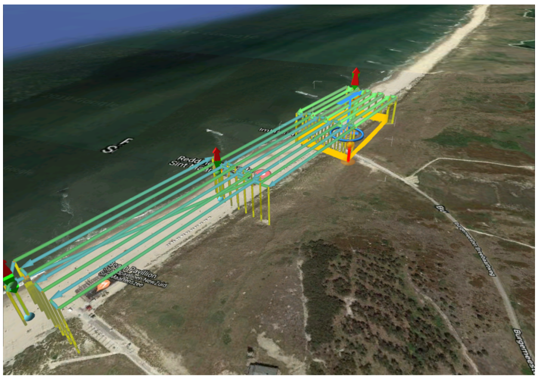
2. **Lay down and measure the Ground Control Points (GCPs)**, these are reference points that are distributed on the surface of the measurement area. The geolocation of the GCPs are measured with a GNSS receiver with an accuracy of 1.5 cm (Leica, 2019). In figure 3.11 (b) a photograph captured during a GCP measurement is presented.

3. **Fly the UAV**, the UAV mission can be executed when the surrounding is safe and environmental conditions are optimal to capture high resolution images. During the mission the UAV captures 581 images.

4. **Post-processing**, after the measurement is completed the images are handled with processing software (Agisoft). First the images are aligned based on the specific set image overlap. Subsequently, the GCPs are marked in the images and their measured geolocation is inserted. In figure 3.11 (c) a single UAV image is presented. Hereafter, the dense point cloud is generated by the processing software. Finally, from the dense point cloud the orthophoto and DEMs are generated. A 3D render from a dense point cloud of the measurement area is presented in figure 3.11 (d).

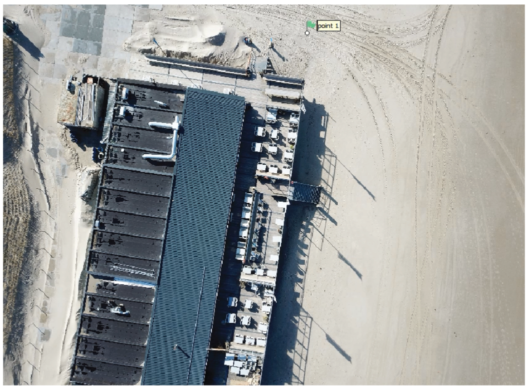
Site visits

Seasonally placed beach buildings are constructed in March, during this time a site visit is planned to investigate the amount of sediment that is relocated for construction. Images of the dune areas and beach buildings are taken to validate observations and concepts. Additionally, the dune manager of the case areas will state his insights gathered in the field over the years, during a site visit.

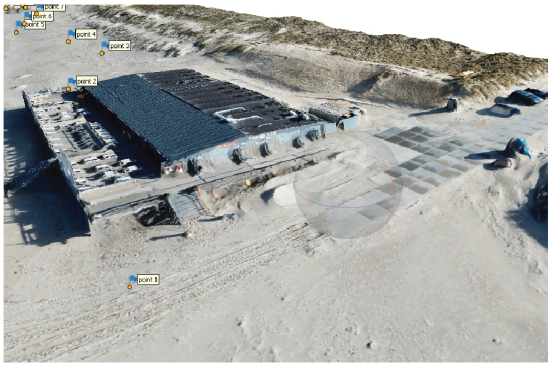


(a) Pre-determinend UAV flight plan

(b) Field measurement of a GCP



(c) Single UAV image



(d) 3D render from the dense point cloud

Figure 3.11: Phases in the UAV photogrammetry measuring process

Characteristic	Description
Surveying method	Photogrammetry
UAV model	DJI Maverick Pro
UAV positional accuracy	V:10cm, H:30cm
Measurement dates	T7 March, T8 May 2019
DEM accuracy	10cm (error of GCPs)

Table 3.4: High frequency measurement characteristics

The relocation of sediment

There are three types of interventions that could affect dune volumes as sediment is relocated from the coastal zone. These are subdivided in construction, maintenance, and usage.

- **Construction** - During the construction of beach buildings sediment can be relocated in order to create the proper placement conditions. The effect of construction is determined by performing high frequency measurements, and estimating relocation volumes during site visits.

- **Maintenance** - Deposits in the surroundings of beach buildings formed by aeolian sediment transport can block the functionalities of beach buildings. Eventually, sediment is relocated. The effect of maintenance is determined by observing relocation volumes from the DEMs and consulting the local dune manager during the site visit.

- **Beach use** - This refers to human activity coupled to usage of the beach buildings (e.g. cars, and pedestrians). The temporal and spatial scale of these occurrences is to small to define with the measurements or site visits.

3.2. Dune parameters

To quantify coastal dune development in the vicinity of beach buildings parameters are defined. The relative high resolution of the data facilitates the creation of new parameters with respect to conventional ones that are extracted from dune transects. First the data is processed to correctly isolate relevant elevation data that corresponds to the classified subregions. The definition of the parameters is based on characteristics relevant to coastal dune development.

3.2.1. Data processing

The LiDAR elevation data between April 2017 - September 2018 is used to quantify coastal dune development within the various subregions. The biannual photogrammetry measurements are excluded from the analysis due to their low accuracy in the regions with vegetation. Subtracting photogrammetry and LiDAR measurements proved to cause inaccurate results.

Per subregion a grid is created and aligned along the dune foot. The dune foot is defined as the contour line at NAP+4m. This height is often used as a reference height for the dune foot in the Netherlands (Deltares, 2016; HHNK, 2014). Additionally, it often corresponds with the contour line found directly behind beach buildings within the case areas. An example of two grids that represent subregions and are aligned along the dune foot are presented in figure 3.12.

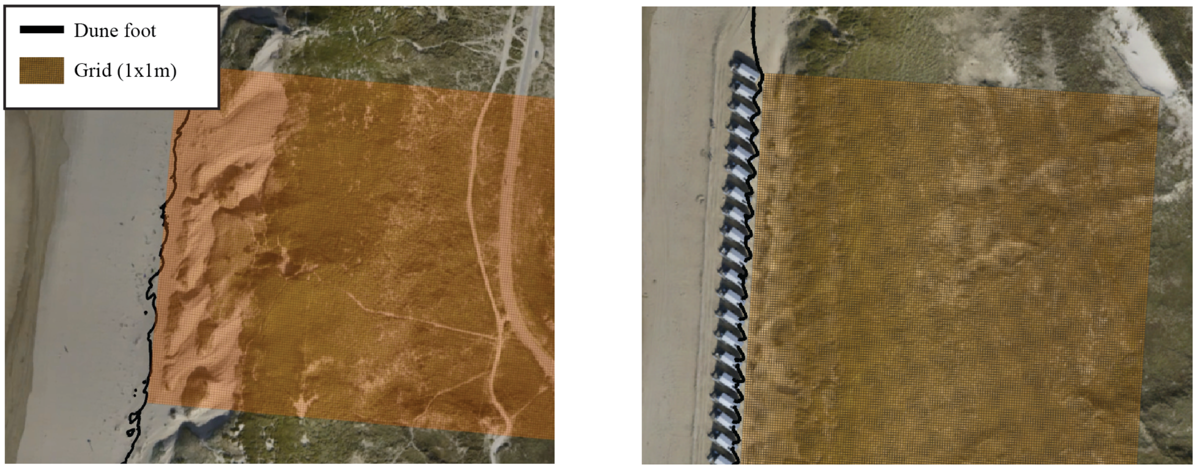


Figure 3.12: Grids aligned at the dune foot; left: dynamic dune region; right: large ribbon-development

The area of the grid is chosen such that it covers the full area of the dune behind the different beach building types. For example, the top boundary of the grid is located at the first building of the large ribbon-development and the end of the grid is placed at the last building.

The gridsize is set to 1x1m, which is convenient for different reasons. The scale of coastal dune development relevant to beach buildings is in the order of metres. The alongshore change in dune morphology, for example, is expressed in m^3/m. Also computational power is saved by lowering the original resolution of 1x1cm of the DEM, while preserving relevant accuracy.

The elevation data is discretized into the grids. This step facilitates the possibility to quantify coastal dune development per subregion in a concise way. An example of elevation data discretized in a grid created for the dynamic dune subregion is presented in figure 3.13

The heat map functions as an area of reference and introduces three parameters. The distance landward from the dune foot (X_{df}), the alongshore distance of the subregion (Y_i), and the bed level height (Z_b). By subtracting the elevation data of two consecutive time steps, the bed level change (ΔZ_b) can be obtained. Table 3.5 presents the parameters that act as a reference throughout this report.

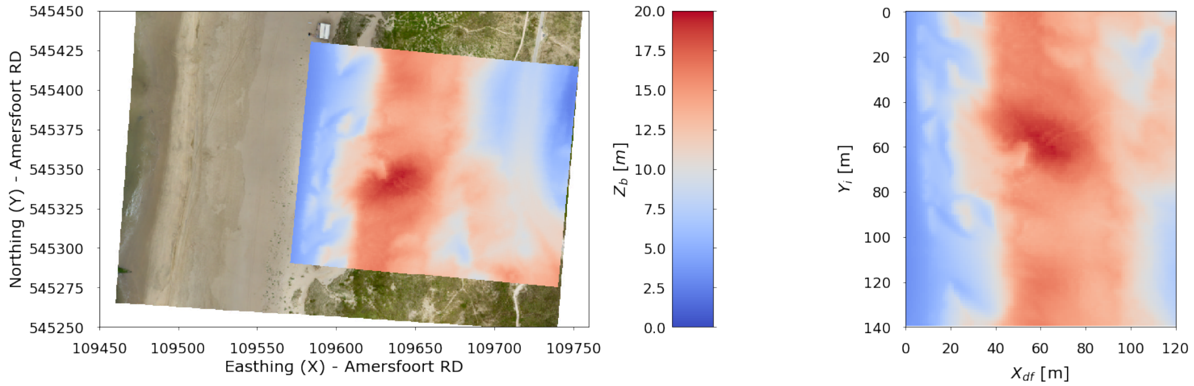


Figure 3.13: Elevation of the dynamic dune region discretized in grid; left: geographical projection; right: heat map

Parameter	Description
X_{df} $[m]$	Landward distance from the dune foot
Y_i $[m]$	Alongshore distance of the subregion
$Z_b{}^*$ $[m]$	Bed level height
$\Delta Z_b{}^*$ $[m]$	Bed level change

* $Z_{b,i}$ and $\Delta Z_{b,i}$ refer to one dune transect at the alongshore position Y_i

Table 3.5: Overview reference parameters

3.2.2. Quantification

Throughout this section the dynamic reference area illustrates how the dune parameters are quantified and visualized for the distinct subregions. An overview of the dune parameters and what they physically represent is schematised in figure 3.14. A summarizing table of the dune parameters that are quantified is presented in table 3.6.

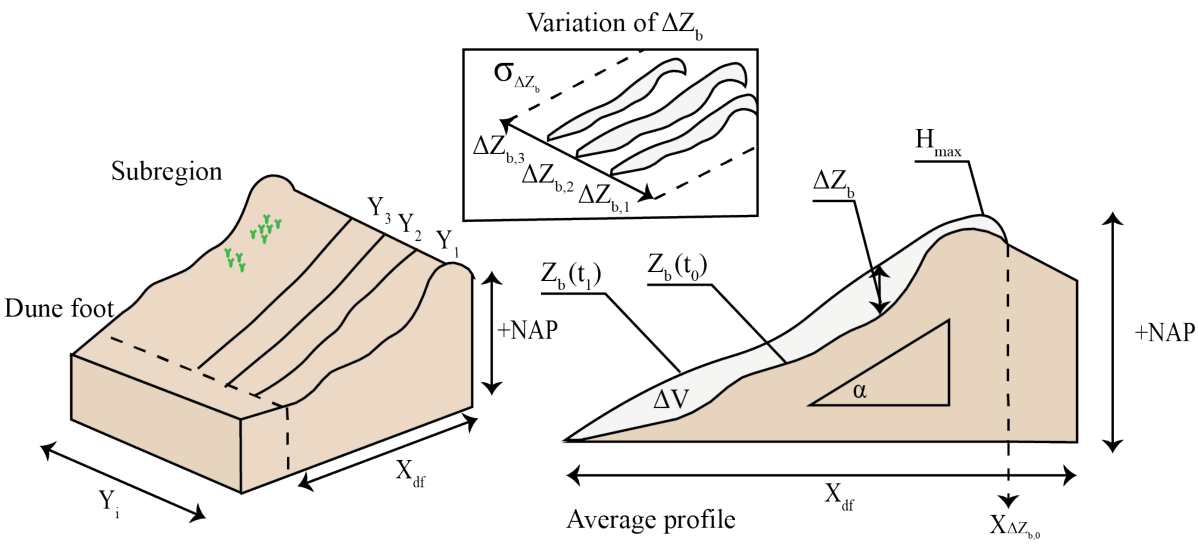


Figure 3.14: Concept dune parameters

Dune profile

Differences between the dune profile of the subregions is of interest to identify differences in coastal dune development. Parameters are extracted from the dune profile that quantify coastal dune development are

Dune parameter	Description
$X_{Z_{b,o}}$ $[m]$	Landward distance from the dune foot where the bed level does not change
H_{max} $[m]$	Maximum dune height
α [°]	Dune slope
$\sigma_{\Delta Z_b}$ $[m]$	Alongshore variability of the bed level change
ΔV $[m^3/m]$	Average alongshore volume change
$\Delta V_c{}^a$ $[m^3/m]$	Average alongshore volume that is relocated for maintenance and construction purposes

Table 3.6: Overview quantifiable dune parameters

the dune slope (α), and the maximum dune height (H_{max}).

The bed level (Z_b) of a subregion is visualized over the cross-section. The bed level (Z_b) represents the average of the alongshore bed level transects ($Z_{b,i}$), this concept is visualized in figure 3.15. To put in perspective: the JarKus data are based on one transect every 200 - 250m.

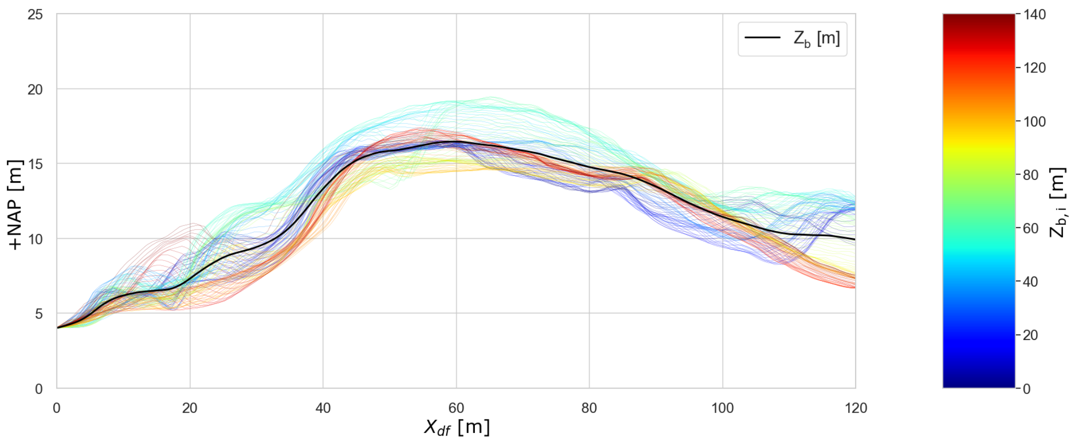


Figure 3.15: Multiple alongshore transects of the bed level, example dynamic dune

The dune slope (α) is defined as the slope between NAP + 6.5 - 9.5m of the bed level (Z_b) on September 2018. This range is chosen after an iteration process to find the most characteristic dune slope for the dune profile of the classified subregions.

The maximum dune height (H_{max}) is defined as the maximum height of the bed level (Z_b) on September 2018. The bed level (Z_b) of September 2018 is used as this is the latest measurement of the series and possible effects within the full measurement period are captured. Throughout the report the bed levels (Z_b), the maximum dune height (H_{max}) and the dune slope (α) are visualized identical to figure 3.16.

The bed levels (Z_b) of the different time steps visualize the evolution of the dune profile. In this case it can be observed that the dune crest between X_{df}= 40 - 80m is gradually growing in height. More insights on differences in coastal dune development between reference areas and distinct beach building types can be made by comparing the evolution of the cross-shore profile, dune slope (α), and maximum average dune height (H_{max}) between the classified subregions.

Bed level change

Differences in the bed level change (ΔZ_b) provide insight on sediment transport volumes and their distribution within a subregion. The bed level change (ΔZ_b) facilitates the quantification of the following dune parameters: the average alongshore volume change (ΔV), alongshore variability of the bed level change ($\sigma_{\Delta Z_b}$),

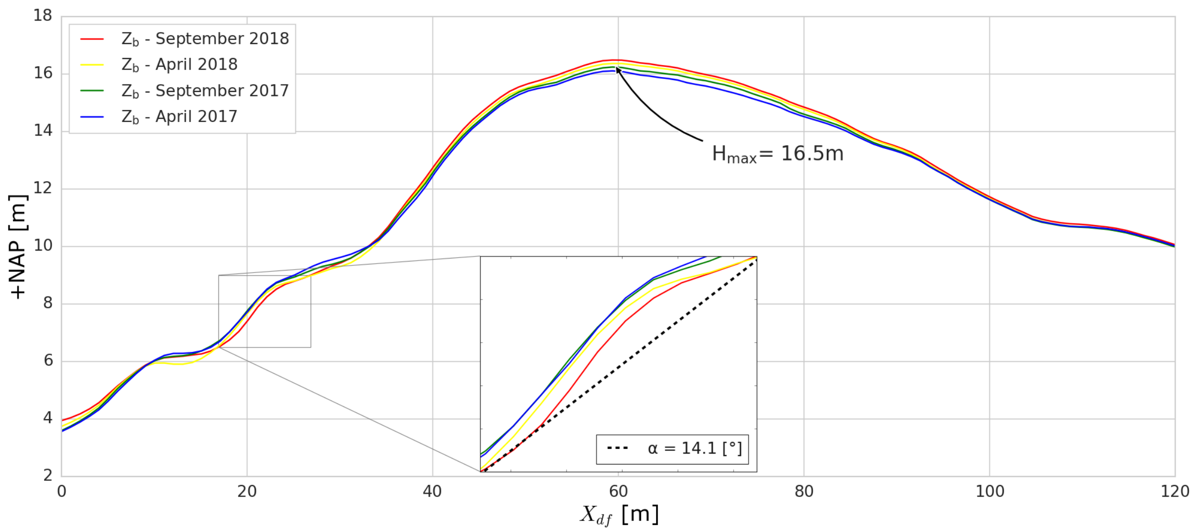


Figure 3.16: Concept visualization dune cross-section, example dynamic dune

and the landward distance from the dune foot where the bed level does not change ($X_{Z_{b,0}}$).

This research considers the bed level change (ΔZ_b) between September 2017 - 2018 of the LiDAR measurements. It is chosen not to consider seasonal differences in sedimentation rates, as the variation between vegetation height and density is large between the summer and winter, and subtracting acquired bed levels proved to result in degraded results.

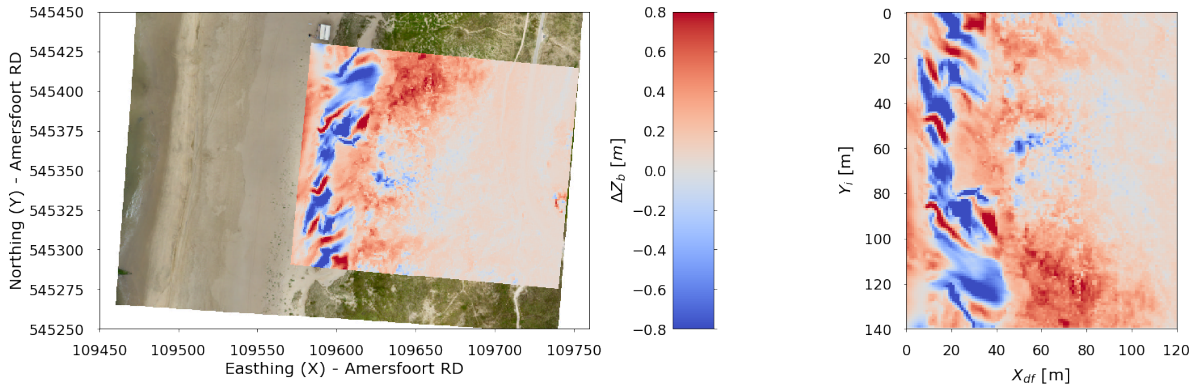


Figure 3.17: Bed level change September 2017 - 2018 of the dynamic dune case; left: geographical projection; right: heat map of the elevation data

The geographical projection of the yearly sedimentation patterns combined with visual observations from the orthophotos provide insight in variability of the sedimentation and the features that induce this. The bed level change of the dynamic dune subregion is presented in figure 3.17

The bed level change (ΔZ_b) of a subregion can be visualized over the cross-section. The bed level change (ΔZ_b) represents the average of the alongshore bed level change transects ($\Delta Z_{b,i}$). This concept is visualized in figure 3.18.

The average alongshore volume change (ΔV) is defined as the total bed level change averaged over the alongshore length ($Y_{i,max}$) of a subregion. At this point there is no general definition for the dune volume. In previous research the dune volume is based on the evolution of transects of dune profiles, provided by JarKuS data (Vries et al., 2012). This research bases its definition of the volume change on conventional methods applied on dune profile transects.

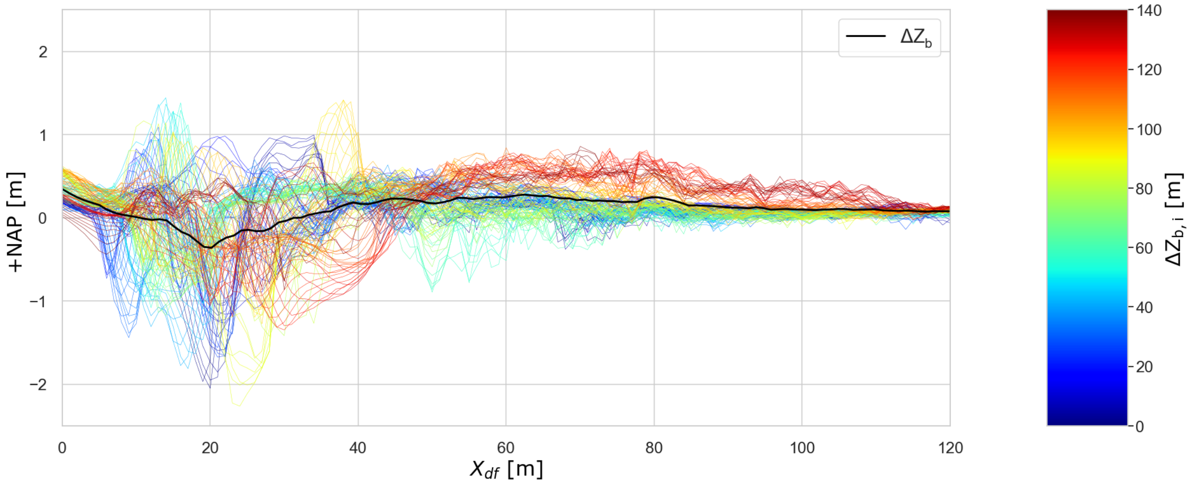


Figure 3.18: Multiple alongshore transects of the bed level change of September 2017 - 2018, example dynamic dune

The alongshore variability of the bed level change ($\sigma_{\Delta Z_b}$) provides insight on how sedimentation is distributed alongshore. The alongshore variability of the bed level change ($\sigma_{\Delta Z_b}$) is defined as the sum of twice the standard deviation (2σ) of the cross-shore sedimentation of the first 80 metres behind the dune foot, averaged cross-shore ($X_{df} = 80$). A range of 80 metres is chosen because the elevation data of most of the subregions reaches up until 80 metres cross-shore. It is expected that a low alongshore variability of the bed level change indicates that dense vegetation is present that captures aeolian sediment transport and limits spatial variability in sedimentation. Throughout the report the bed level change (ΔZ_b) is visualized identical to figure 3.19.

The interval illustrates 95% of the variation ($\Delta Z_b \pm 2\sigma$) of the bed level change. This visualization facilitates the possibility to asses the alongshore variability of the bed level change over the cross-section and confirm the features that induce this. The relatively small interval of 95% of the variation of the bed level change between $X_{df} = 0-5m$ represents a developing embryo dune for instance.

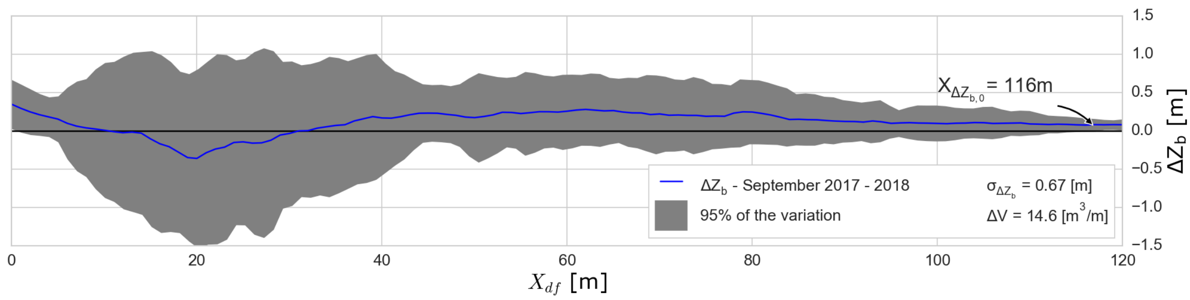


Figure 3.19: Visualization of the bed level change, example dynamic dune

The bed level change provides insight in how far sedimentation reaches landward from the dune foot, and how it is distributed over the cross-section. The cross-shore distance where the bed level does not change ($X_{Z_{b,o}}$) is defined as the location landward of the dune foot (X_{df}) where $\Delta Z_b < 0.05$m. A threshold of 0.05m is chosen as this is still within the cross-shore range of the bed level change of the dynamic dune, which has the largest distance of the dune foot where the bed level does not change ($X_{Z_{b,o}}$).

4
Results

First, the conceptual dune model that functions as a framework to isolate the effect of beach buildings is introduced. In section 4.2 small-scale dune development that is described for a static and dynamic dune state is validated by the data and quantified dune parameters. Subsequently, section 4.3 applies beach buildings into the conceptual dune model and their influences on key processes is assessed based on observed and quantified differences with the reference static dune.

4.1. Conceptual Dune Model

The conceptual dune model functions as a system framework and aims to describe dune development of dunes in progradation based on the dune state, it is schematised in figure 4.1.

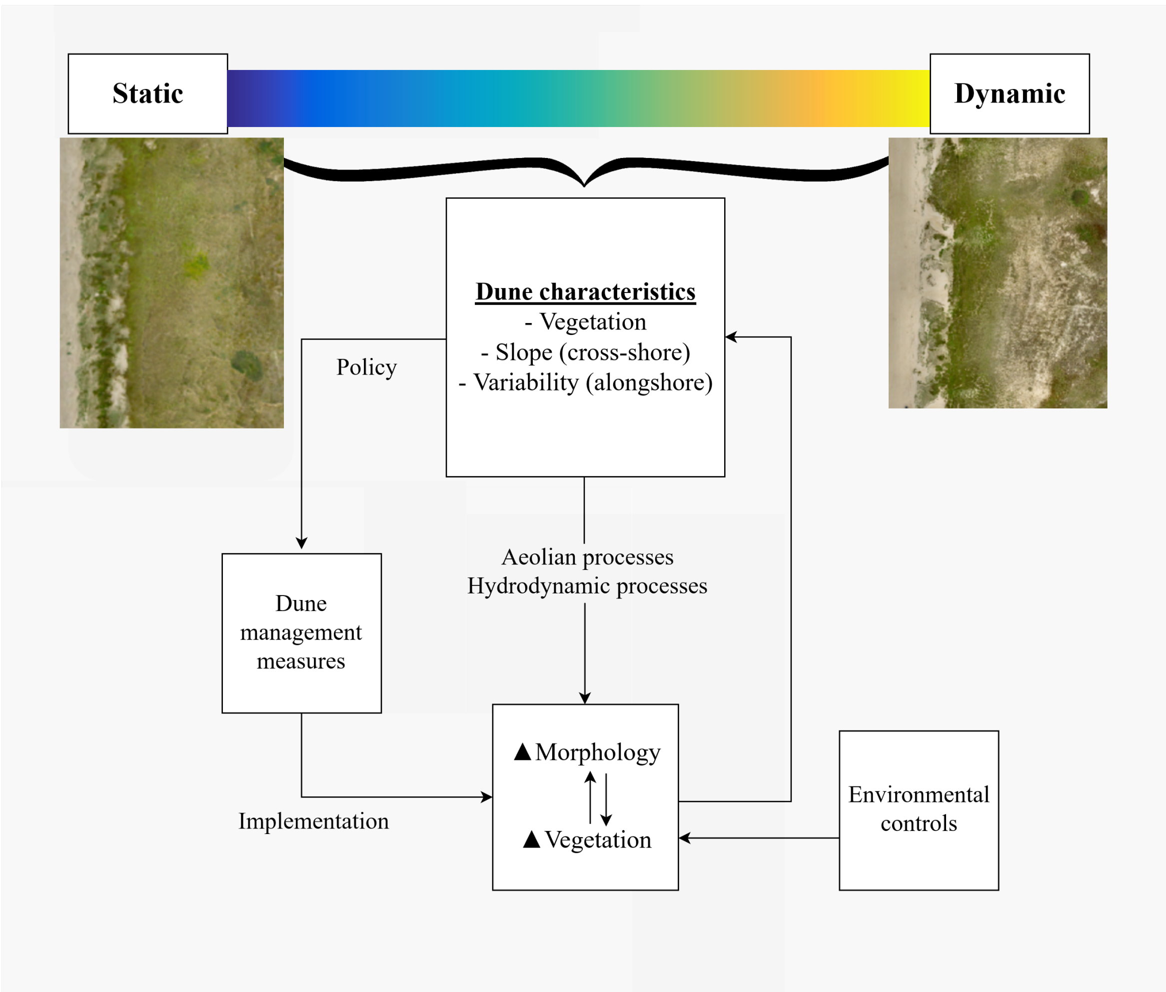


Figure 4.1: Conceptual dune model

4.1.1. Framework

This research separates two dune states with different characteristics in terms of vegetation growth, cross-shore slope and alongshore variability of the profile, which leads to distinct dune development. Interferences with the morphology or presence of vegetation of the dune has a consequence on these characteristics and therefore on future dune development.

Dune state (characteristics)

The dune state can be converted to a spectrum that determines the dune characteristics. On one end of the spectrum there is a fully static dune, which is characterized by the uniform presence of vegetation, low along-shore variability of the dune profile, and a steep dune slope. On the other end there is a dynamic dune that is characterized by its relatively gentle dune slope, large variability of the dune profile, and presence of vegetation. These distinct dune states and coupled future evolution of the dune profile is extensively elaborated later on in this section. The balance between events that stabilize towards a static dune or mobilize towards a dynamic dune are schematised in figure 4.2.

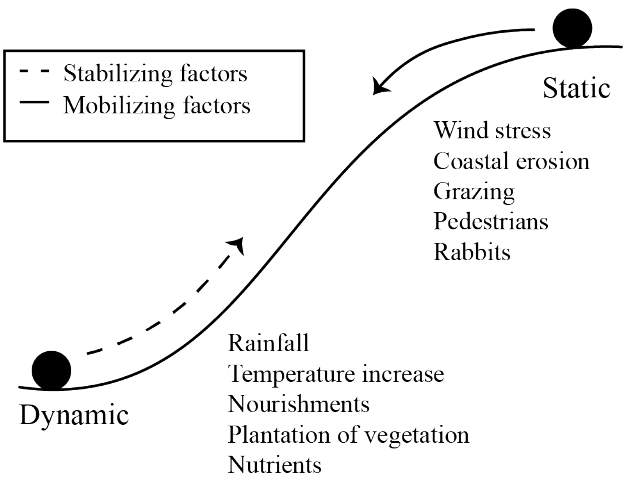


Figure 4.2: Balance between a static and dynamic dune state, based on Arens et al. (2013)

Dune controls

Dune controls refer to events or occurrences that have a sudden influence on the morphology or the presence of vegetation regardless of the dune state. They are further subdivided in two categories, induced by nature (environmental) or humans.

- **Dune management measures**, these type of measures refer to applications initiated by humans that influence the development of dune morphology or vegetation. Dune measures are often applied to gain a desirable dune development outcome based on local or national policy. Examples are: fences placed to stimulate sedimentation, plantation of vegetation, use of chemical binders, and the restoration of a breach in the foredune.
- **Environmental controls**, these refer to the occurrence of events initiated by nature that have a sudden large influence on the morphology or presence of vegetation. Examples of controls induced by nature are: grazing of wildlife, increase in temperature, nutrients, or soil humidity. Aeolian and hydrodynamic processes do not fall in this category.

Interaction between vegetation and morphology change

Different types of vegetation and their distribution on the dune can give insight on the potential to capture sediment. Marram grass is known for its ability to tolerate, and even experience enhanced growth due to burial by aeolian sediment transport (Maun, 2009). Most plant species are intolerant towards sand burial, like mosses, which are the first plant species to be eliminated.

Sand deposition is often said to be the leading stress factor to alter plant species diversity in dunes (Maun, 2009). Densely vegetated areas with Marram grass are found in locations where a recurring amount of sediment is deposited. While, a decline in sediment deposition causes the vitality of Marram grass to decline or even to die off. For over centuries the reason for this decline (increase) in vitality of Marram grass coupled with a decrease (increase) of sediment deposition has been debated by dune ecologists and is still not entirely known. An overview of different explanations is presented in Appendix A

The study by Van der Biest et al. (2017) showcases the importance of sedimentation on the presence of vegetation, and proves that the prevention of sedimentation further landward can transform the vegetation species present on the back dune. The location of the study area was the nature reserve *Westhoek* in Belgium, which used to be a dynamic dune field covered with Marram grass. However, in 1970 a dune revetment was constructed which resulted in a blockage of aeolian sediment transport. Van der Biest et al. (2017) stated that sediment transport was largely interrupted by the revetment. This resulted in a transformation of the types of vegetation that were observed in the area. An overview of this transformation in vegetation types is given in figure 4.3.

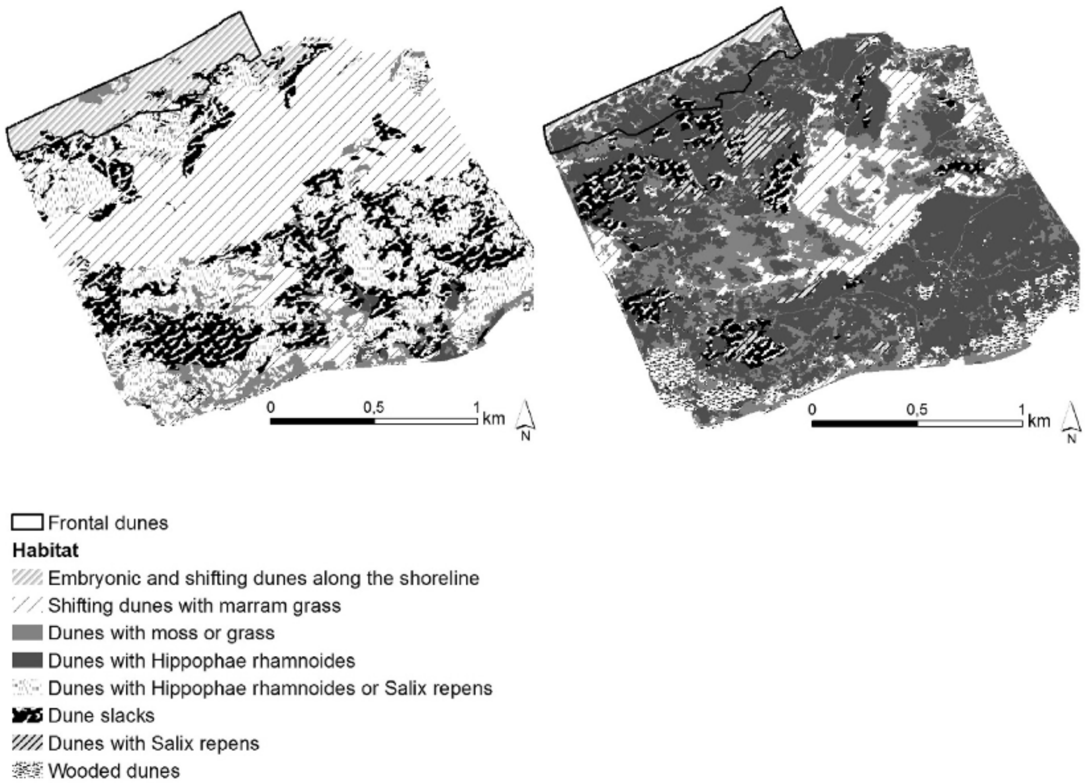


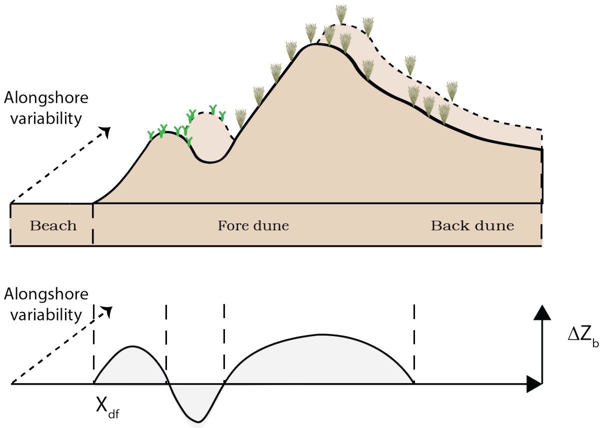
Figure 4.3: Vegetation transformation in Westhoek; left: dynamic scenario, right: static scenario after construction revetment; adopted from Van der Biest et al. (2017)

Beach buildings
Beach buildings can have a direct influence on the morphology, vegetation change, and the dune state. How they influence these characteristics is dependent on the type and placement of the beach building. Effects are identified and quantified in section 4.3.

4.1.2. Dynamic dune development

Dynamic dunes are in a natural dune state, recognized by their dynamic behaviour. Typical dynamic characteristics are a large variability of the vegetation density and dune morphology. A cause of this large variability is the presence of dynamic features, such as blowouts initiated by the wind or hydrodynamic loads. As blowouts are susceptible to erosion, sediment is able to reach further landward by aeolian sediment transport, consequently the transition to sediment intolerant vegetation species occurs further landward. Figure 4.4 (a) illustrates the dynamic subregion, and the presence of blowouts and the transition to other sand burial intolerant vegetation species, which can be observed with a yellow, greyish colour. Figure 4.4 (b) schematises a theoretical cross-section and coupled bed level change.

(a) Top view



(b) Illustration of variability of a dynamic dune

Figure 4.4: Dynamic dune subregion

The evolution of coastal (dynamic) dunes in a state of progradation have been discussed by scientist for a long time. Some studies state that sediment supply is the governing factor for the formation of the dune (Psuty, 1988), others state that vegetation takes on the leading role (Moore et al., 2016).

The exact underlying processes that govern each phase in the development of coastal dunes is still unknown. However, the evolution of a dynamic dune can still be described in several main observed phases, these are enumerated in the following:

1. **Embryo dunes** are the initial state of foredune development. They are formed due to the occurrence of aeolian sediment transport. Sediment is trapped by discrete humps of vegetation (Hesp, 2002).

2. **Established foredunes** develop from embryo dunes and are separated from embryo dunes by greater morphological complexity, height, width and age. The morphological development of established dunes is largely depend on: sand supply, presence of vegetation species, rate of aeolian sand sediment deposit and erosion, wind and wave conditions, degree of vegetation cover, significance of storm erosion, and ground water level (Hesp, 2002). In this stage blowouts begin to develop by factors such as high velocity wind erosion, topographic acceleration of the airflow over the dune crest, and hydrodynamic loads.

3. **Equilibrium height foredune is reached**. eventually the foredune reaches its maximum height and Marram grass growth reduces as sedimentation ceases to occur. The physics that govern this maximum height are still debated. Possible explanations are negative feedback between wind flow and topography and negative feedback between rhizome growth and the dune slope (Durán and Moore, 2013; Moore et al., 2016).

4. **Migration foredune landwards - end of the cycle -** , the vitality of Marram grass decays as sedimentation deceases. Therefore, the foredune migrates landward as the surface becomes more susceptible to erosion.

Based on the dune characteristics and evolution coupled to dynamic dune states an expectation of the dune parameters can be made. Stated expectations are relative to static dune development, the other end of the spectrum described in the framework of the conceptual dune model. The expected influence of dynamic dune characteristics on the dune parameters are summarized in table 4.1.

Variation in vegetation density and the presence of blowouts create an opportunity for sedimentation to take place further landward of the dune foot. It is therefore expected that the distance from the dune foot where the bed level does not change ($X_{\Delta Z_{b,o}}$) is relatively large for dynamic dune states.

The landward reach of sedimentation of dynamic dunes can cause a relatively large maximum average dune height (H_{max}). It is however, premature to state that a dynamic dune unconditionally has a larger maximum dune height (H_{max}) than a static dune state. Simply due to the large variation and the distinct development phases of dynamic dunes. In a snapshot in time an established foredune for instance may be migrating landward and decreasing in height, which would cause a relatively low (H_{max}).

It is expected that the characteristics distinct to dynamic dunes lead to a low dune slope (α) and a larger alongshore variability of the bed level change ($\sigma_{\Delta Z_b}$). The scour-shaped morphology of blowouts in the fore dune cause the dune slope (α) of a dynamic state to flatten out. The alternation between the presence of blowouts and regular foredunes in the alongshore direction of a dynamic dune causes a large spatial variability in sedimentation and erosion due to aeolian processes. It is therefore expected that this would lead to a large alongshore variability of the bed level change ($\sigma_{\Delta Z_b}$).

It is expected that the characteristics distinct to dynamic dune states lead to an increase in sediment availability and capacity, resulting in a relatively large average alongshore volume change (ΔV). The combination of a gentle dune slope (α) and a large variability in the presence of vegetation increases the sediment available for transport. The surface of blowouts are susceptible to erosion and therefore increase the sediment availability.

Dune parameter	Description	Grading
$X_{\Delta Z_{b,o}}$ $[m]$	Landward distance from the dune foot where the bed level does not change	+
H_{max} $[m]$	Maximum dune height	[+][a]
α [°]	Dune slope	-
$\sigma_{\Delta Z_b}$ $[m]$	Alongshore variability of the bed level change	+
ΔV $[m^3/m]$	Average alongshore volume change	+

Note: gradings and expectations are relative to static dune states, the other end of the spectrum of dune characteristics
[a] Dynamic dune development is too variable to make any unconditional statements on the H_{max} compared to the static dune state

Table 4.1: Overview expected dune parameters, dynamic dune state

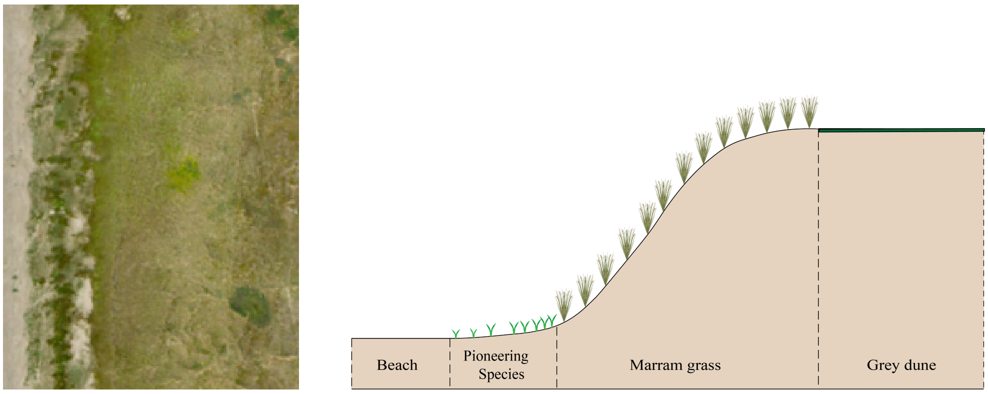
4.1.3. Static dune development

Static dunes are in a (previously) human controlled dune state and recognized by their uniform behaviour. Typical static dune characteristics are a low variability of the vegetation density, and the dune morphology. The main contributing factor to this uniformity is the uniform plantation of Marram grass, a consequence of past (and current) coastal management strategies. From an orthophoto of the static dune subregion (figure 4.5 (a)) it can be observed that there are barely any dynamic features present. Marram grass is evenly distributed on the foredune and the area directly behind the foredune is fully vegetated.

This report discusses the future dune development of a theoretical fully static dune. A schematization of the cross-section of a theoretical fully static dune is presented in figure 4.5 (b). Note that a dune is seldom in a fully static state, this can be observed in figure 4.5 (a) where small erodible areas without vegetation are present.

A series of events over time can be described that determines the development of a theoretical fully static dune over time (figure 4.6):

1. **Sedimentation around Marram grass**, sediment originates from the beach and is transported due to



(a) Top view of a static dune (b) Schematization of a cross section of a dynamic dune

Figure 4.5: Schematization of a static dune cross sectioon

aeolian sediment transport which is initiated above a certain wind velocity threshold (Bagnold, 1937). Marram grass can be seen as a roughness element that decreases the wind stress, and as the downward momentum flux of the airflow decreases sedimentation occurs surrounding the Marram grass (Raupach et al., 1993; Hagen and Armbrust, 1994).

More landward sedimentation decreases because sediment is largely captured by the Marram grass in the front. Sedimentation is expected to decrease up until a point where barely any sedimentation occurs. Marram grass is not able to survive at this point as it requires a certain supply of sediment to thrive (Maun, 2009). As the Marram grass is evenly developed over the static dune in alongshore and cross-shore direction this point of no sedimentation is at the same point in the cross-shore direction over the alongshore direction of the dune.

This dense and uniform distribution of Marram grass causes sedimentation to be evenly spread over the dune. Landward of the boundary where no sedimentation takes place other vegetation such as mosses can grow on the dune and the transition distance to a grey dune is relatively small compared to a dynamic dune. This is possible due to the absence of blowouts, and therefore there is less spatial variability in sedimentation.

2. **Dune growth**, the morphology of the dune progrades where Marram grass is present. Sedimentation occurs at the surrounding of Marram grass and grass is able to grow through the freshly deposited sand (Maun, 2009). In the landward area where sedimentation decays the morphology stays the same as sedimentation does not occurs here, and other vegetation types are present to protect the surface from eroding.
3. **New vegetation development (maximum heigth reached)**, due to the change in morphology, availability of nutrients, and adventitious root development Marram grass establishes at the dune foot. As the newly developed vegetation will capture sediment, less sediment is transported to the last row of vegetation. Eventually, the amount of sedimentation at the last row of vegetation will not be enough for the Marram grass to survive. Essentially, the newly developed vegetation at the dune foot has replaced the last row of Marram grass.
4. **Shift of sedimentation (maximum height reached) - end of cycle -**, the last row of Marram grass slowly deceases as sedimentation ceases to occur. A maximum height is read, which is due to two distinct reasons. First off, less sedimentation occurs as a large amount of the sediment transported from the beach is captured by the new vegetation present at the dune foot. Secondly, the last row of Marram grass has deceased and will consequently not be able to fulfil its 'dune-building' function.

Because sedimentation intolerant vegetation species can take over relatively quick the bed becomes non-erodible and the maximum height is preserved. Slowly other vegetation types that are intolerant against sand burial retake the surface from the decaying Marram grass in the back of the dune. This new sedimentation pattern causes a shift in morphology similar to point **2.** and the development-cycle restarts.

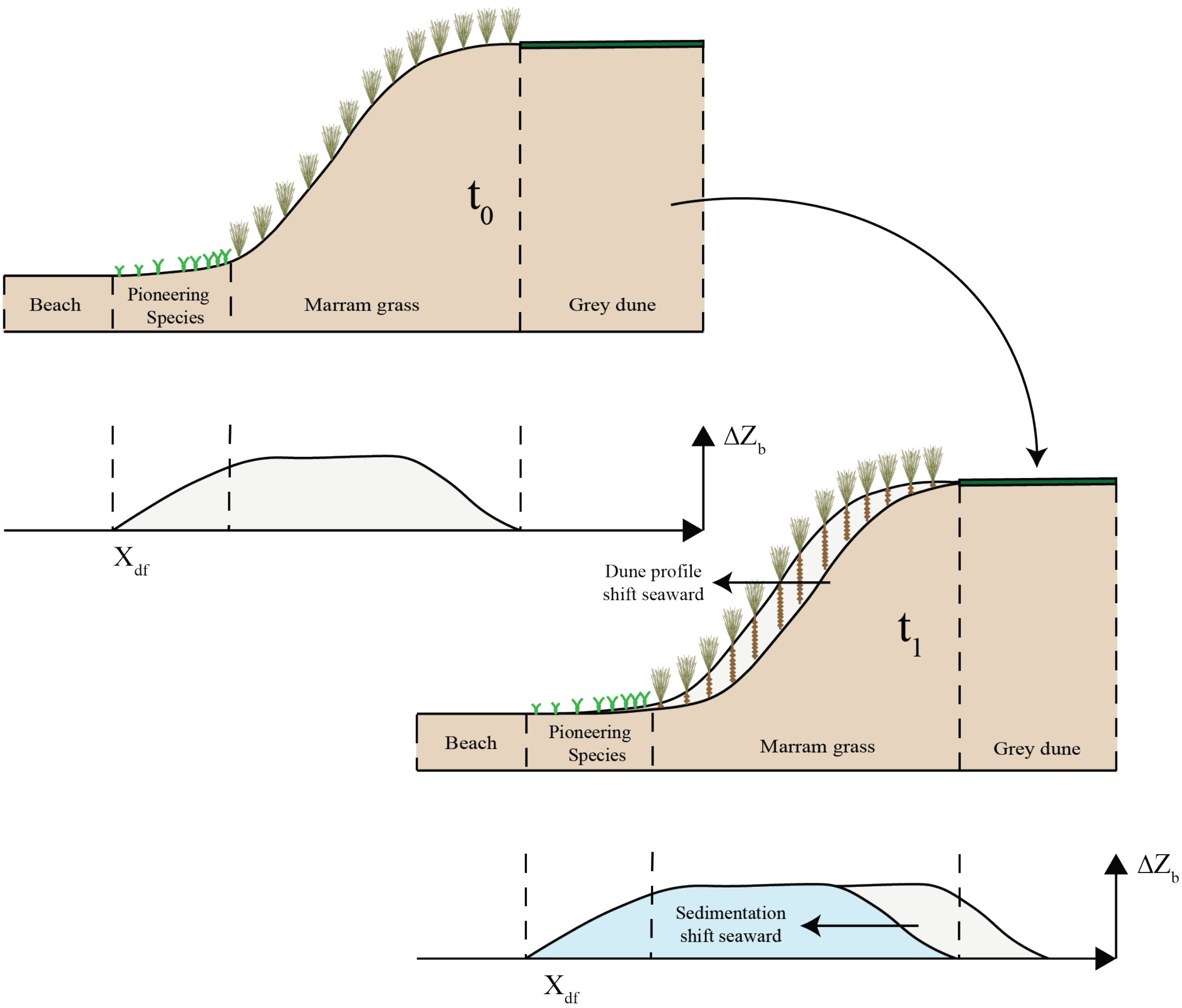


Figure 4.6: Evolution of a static dune in progradation

Based on the dune characteristics and evolution coupled to static dune states an expectation of the dune parameters can be made. Expectations are relative to characteristic coupled to dynamic dune development. The expected influence of the static dune characteristics on the dune parameters are summarized in table 4.2.

The landward distance where the bed level does not change ($X_{\Delta Z_{b,0}}$) is expected to be relatively low. The uniform and dense vegetation present on the foredune essentially acts as a wall against aeolian sediment transport further landward.

Due to the distinct evolution of a static dune it is expected that they have a relatively low maximum average dune height (H_{max}) and steep dune slope (α). This is attributed to the uniform progradation seaward, it is expected that the cross-shore profile reaches its maximum height (H_{max}) relatively early in comparison to dynamic dune states. Note that it is not possible to make any unconditional statements on the maximum dune height (H_{max}) of static dunes relative to dynamic dunes because of the variability in behaviour of dynamic dunes.

It is expected that the distinct characteristics of static dune states lead to a decrease in sediment availability, resulting in a relatively low average volume change (ΔV). The combination of a steep dune slope (α) and a large uniform presence of vegetation decreases the sediment transport available for transport.

Dune parameter	Description	Grading
$X_{\Delta Z_{b,o}}$ $[m]$	Landward distance from the dune foot where the bed level does not change	-
H_{max} $[m]$	Maximum dune height	[-][a]
α [°]	Dune slope	+
$\sigma_{\Delta Z_b}$ $[m]$	Alongshore variability of the bed level change	-
ΔV $[m^3/m]$	Average alongshore volume change	-

Note: gradings and expectations are relative to dynamic dune states, the other end of the spectrum of dune characteristics
[a] Dynamic dune development is too variable to make any unconditional statements on the H_{max} compared to a static dune state

Table 4.2: Overview expected dune parameters, static dune state

4.2. Validation

The described evolution and the expected dune parameters of respectively the dynamic and static dune states are validated in this section. The elevation data of two subregions classified as static and dynamic states are utilized to perform this validation. After the validation quantifications are utilized to determine the effect of different beach building types.

4.2.1. Dynamic dune state

Dynamic dunes are recognized by the presence of blowouts and spatial variability in vegetation density, and dune morphology. Due to these distinct features the sedimentation and dune profile of dynamic dunes is highly variable in cross and alongshore direction. The spatial variation of the sedimentation and features that induce this can be observed at the dynamic subregion presented in figure 4.7.

Figure 4.7: Dynamic dune bed level change between September 2017 - 2018

Sedimentation patterns visible in the projected bed level change confirm described effects of blowouts and embryo dunes. By comparing the sedimentation patterns to the aerial photograph it can be observed that the blowouts facilitate aeolian sediment transport further landward in line with the dominant wind direction (southwest). Sedimentation takes place landward where vital dune vegetation is present, this can be observed by the intensity of the green colour of the vegetation. At the dune foot embryonic dunes are present, these capture a large fraction of the transported sediment that originates from the beach, and are developing into more established foredunes.

Typical dynamic dune development described in the conceptual dune model is confirmed by the evolution of the cross-shore profile, which is presented in figure 4.8. A clear prograding trend of the dune foot between

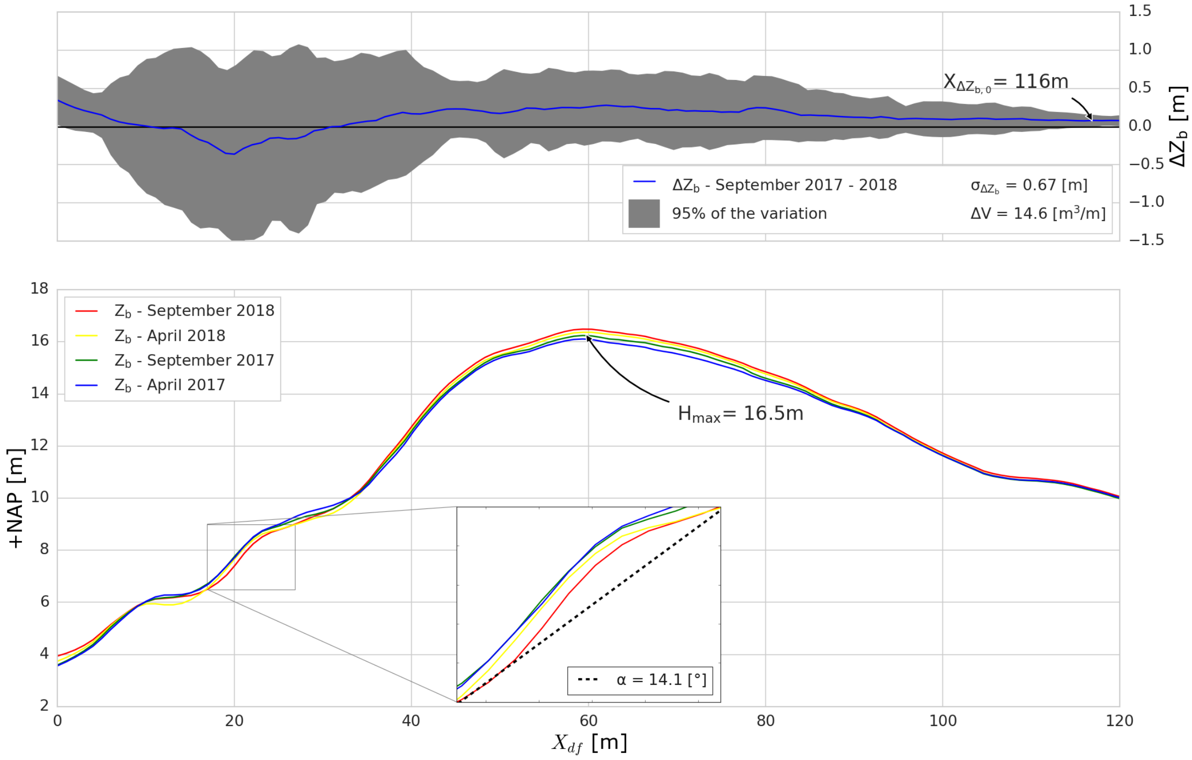


Figure 4.8: Dynamic dune; top: bed level change; bottom: dune cross-section

$X_{df} \approx 0-10m$ can be observed over the years. This signal is caused by embryonic dunes that are in the process of developing into more established foredunes. Directly landward of the dune foot a large amount of blowouts are present that cause a high alongshore variability in the dune morphology and bed level change and therefore no clear trend in dune development can be observed in the region between $X_{df} \approx 10-40m$. More landward between $X_{df} \approx 40-90m$ the dune crest is gradually growing in height, indicating that the dune has not reached its maximum height yet.

The alongshore variability of the bed level change is coupled to the presence of typical dynamic features. At the embryonic dunes sedimentation takes place with a low alongshore variability, which is reflected by the 95% variation interval between $X_{df} = 0-5m$. In the region of the blowouts between $X_{df} = 10-30m$ erosion and sedimentation is observed with a high alongshore variability. At the dune crest the variability of the bed level change slowly decays.

4.2.2. Static dune state

Static dunes are recognized by the absence of dynamic features, and the low variability of the vegetation density and dune morphology. These distinct characteristics cause the sedimentation and dune profile of static dunes to be relatively uniform. The spatial uniformity of the sedimentation and the presence of vegetation that induces this can be observed in figure 4.9.

The projected bed level change confirms typical static dune development described in the conceptual dune model. The bed level changes until a certain boundary. Subsequent to this boundary the bed level does not change, while vegetation is present in this region. The only region where there is spatial variability of sedimentation is at the small blowout present at the coordinates (107100,535125). Note that this feature is only illustrated, and it is not taken into account while quantifying the dune parameters related to static dune development.

The static dune is prograding seaward as a dune front while reaching a maximum height. In figure 4.10 it can be observed that the dune profile is steadily prograding over time between $X_{df} = 0-20$. Between

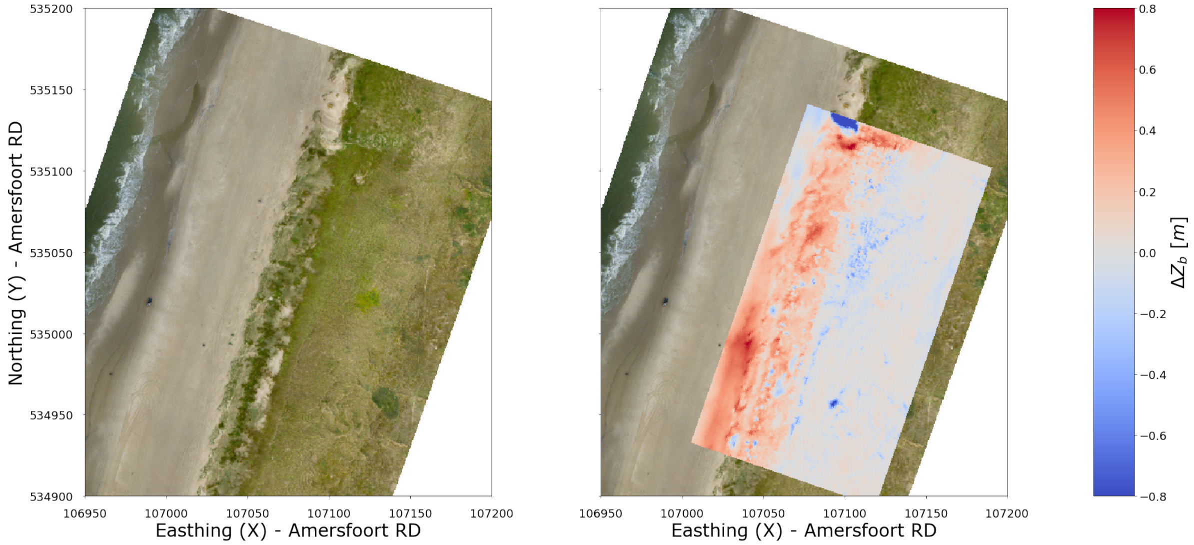


Figure 4.9: Static dune bed level change between September 2017 - 2018

$X_{df} = 20 - 50$ the profile is growing in height, and it is expected that this occurs until a small peak similar to the one observed between $X_{df} = 50 - 60$ is formed. This small peak gradually becomes smoother as Marram grass decays due to a decrease in sedimentation. At this point intolerant vegetation types slowly take over.

The interval of 95% of the variation of the bed level change confirms that static dune states have a relatively low alongshore variability. The interval illustrates that the alongshore variability in bed level change is more or less constant over the dune profile, until it completely decays more landward of the dune foot.

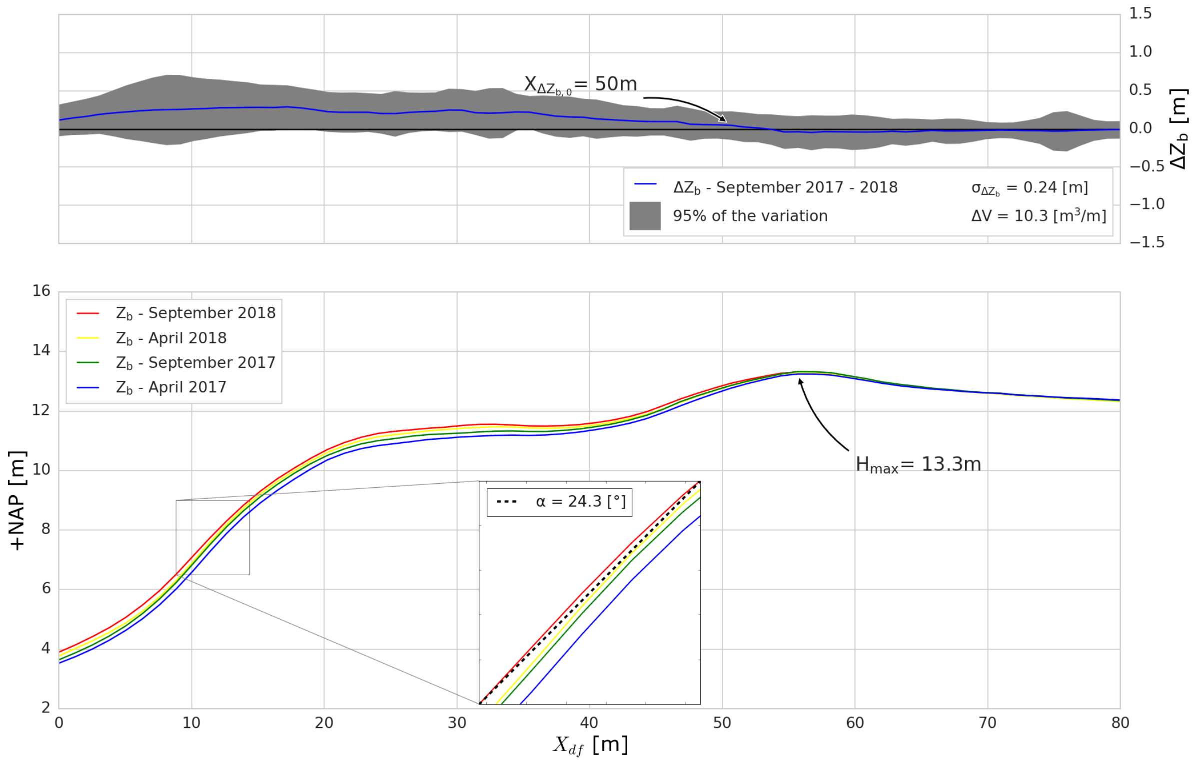


Figure 4.10: Static dune; top: bed level change; bottom: dune cross-section

4.2.3. Overview

Key differences between a static and dynamic dune state are validated by the quantifications of the dune parameters. Differences are expressed in percentages to emphasize the relative difference, an overview of the values is presented in table 4.3.

The landward distance of the dune foot where the bed level does not change ($X_{\Delta Z_{b,o}}$) of the static dune is 43% of the dynamic dune. This difference is due to the presence of blowouts at dynamic dunes that facilitate aeolian sediment transport further landward. At the static dune blowouts are absent and sedimentation is not able to reach further landward due to the presence of an uniform and dense distribution of vegetation.

The maximum dune height (H_{max}) of the static dune is 80% of the maximum height of the dynamic dune. This confirms that dynamic dunes are able to 'grow' more in height. Note it can not be concluded that dynamic dunes unconditionally have a larger height than static dunes, due to their large variability.

The dune slope (α) of the static dune is 24.3° compared to 14.1° at the dynamic dune, which confirms that static dunes have a steeper slope. This difference is physically explained by variability of the dune morphology and the presence of vegetation of dynamic dune states, which flattens out the dune slope.

The alongshore variability of the bed level change ($\sigma_{\Delta Z_b}$) of the static dune subregion is 36% of the dynamic dune. This is attributed to the differences in variability of the vegetation and morphology, where more variability in the dune morphology leads to more spatial variability of the sedimentation, due to complex interactions with the wind en the bed.

The dune parameters prove to effectively describe aeolian coastal dune development, and quantify the expected differences between a static and dynamic dune state. In the proceedings of this report the dune parameters are used to quantify differences in coastal dune development between the subregions with beach buildings present, versus the regions without.

Dune parameter	Dynamic dune	Static dune
$X_{\Delta Z_{b,o}}$ $[m]$	116	50
H_{max} $[m]$	16.5	13.3
α [°]	14.1	24.3
$\sigma_{\Delta Z_b}$ $[m]$	0.67	0.24
ΔV $[m^3/m]$	14.6	10.3

Table 4.3: Overview quantifications dune parameters dynamic and static dune state

4.3. Application

The effect of beach buildings on dune development is separated in their effect on the dune morphology, vegetation, and consequently on a larger temporal scale the dune state (characteristics). Effects on dune volumes are separated by their physical presence on aeolian sediment transport rates, and the relocation of sediment during construction and maintenance activities. Their effects are schematised in the conceptual model, which is presented in figure 4.11.

This section gives an overview and physically explains the observed effects of specific beach building types. The following subregions are included: large ribbon-development, small ribbon-development, and two pavilion types. Regions behind the beach buildings are static, dune development in their vicinity is therefore compared to the static dune case. Relative differences are emphasized by expressing the dune parameters in percentages of the static dune subregion. Differences between the observed maximum dune height (H_{max}) are not taken into account. The maximum dune height (H_{max}) is often found far from the dune foot, and is considered a result of a longer term evolution of the dune profile that is not necessarily influenced by the placement of these specific beach buildings. This section concludes with a summation of general observed influences.

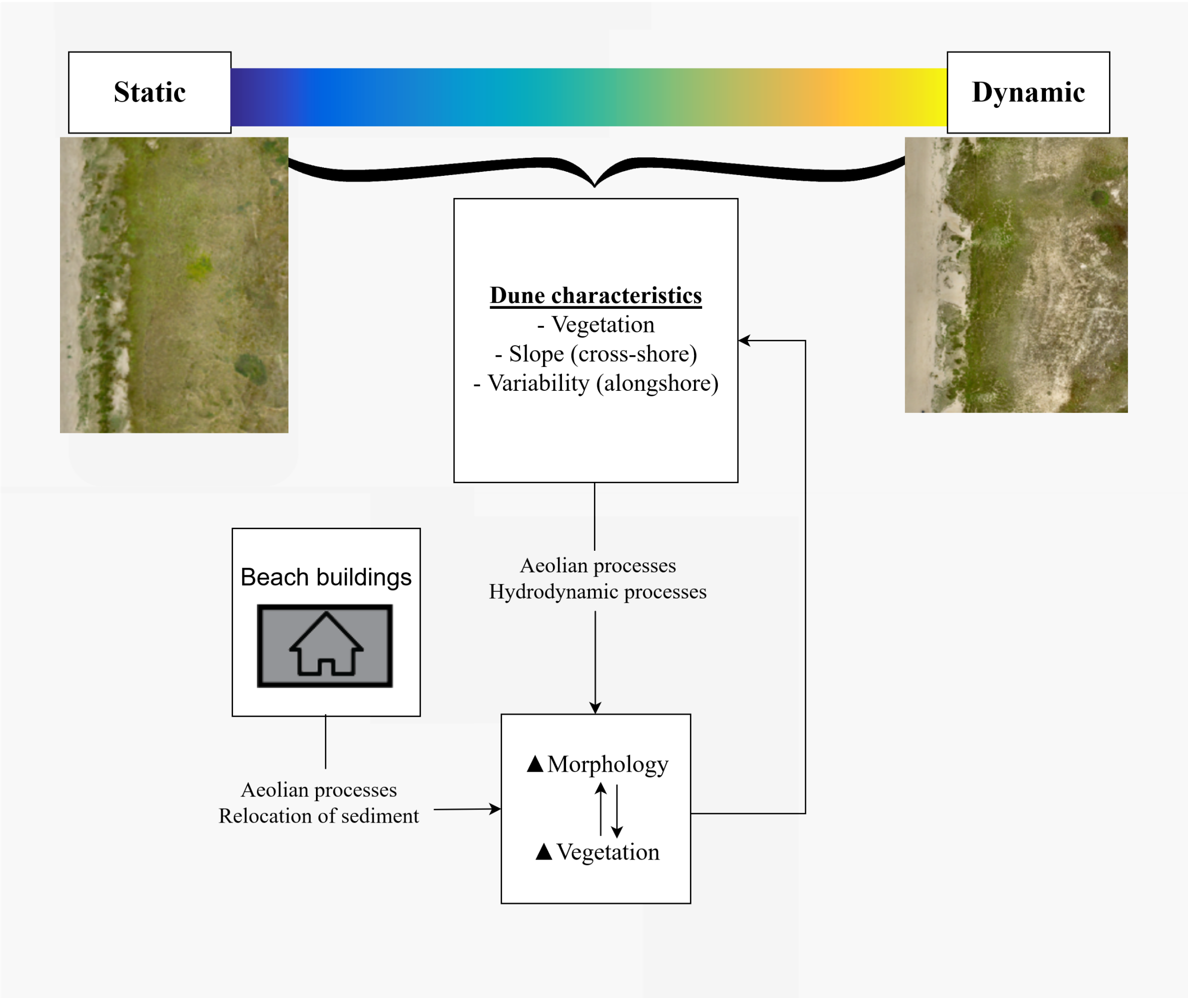


Figure 4.11: Conceptual dune model - beach buildings

4.3.1. Small ribbon-development

Small ribbon-development are small beach buildings placed seasonally and consecutively. They mainly function as a storage or changing room. Figure 4.12 presents a top view of small ribbon-development in the case area Sint Maartenszee. The dune behind the small-ribbon development is static, its influence on dune development is therefore identified by comparing the dune parameters to the static dune state. An overview of the dune parameters are presented in table 4.4.

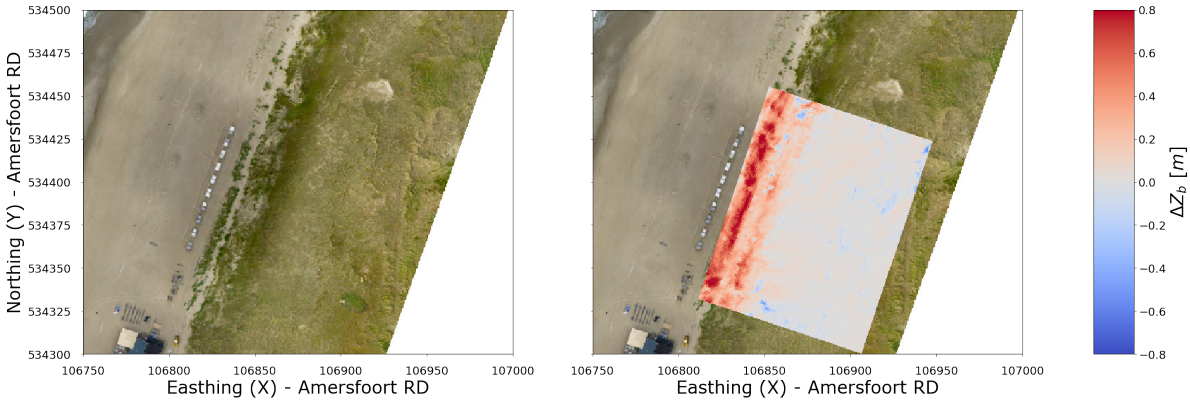


Figure 4.12: Small ribbon-development bed level change between September 2017 - 2018

Sedimentation patterns visible in the projected bed level change show that sediment transported from the beach is largely captured by a dense row of vegetation present directly at the dune foot. Possible explanations for the presence of this vegetation are elaborated at the end of this subsection. First its effects on the dune parameters are considered, these are visualized in figure 4.13.

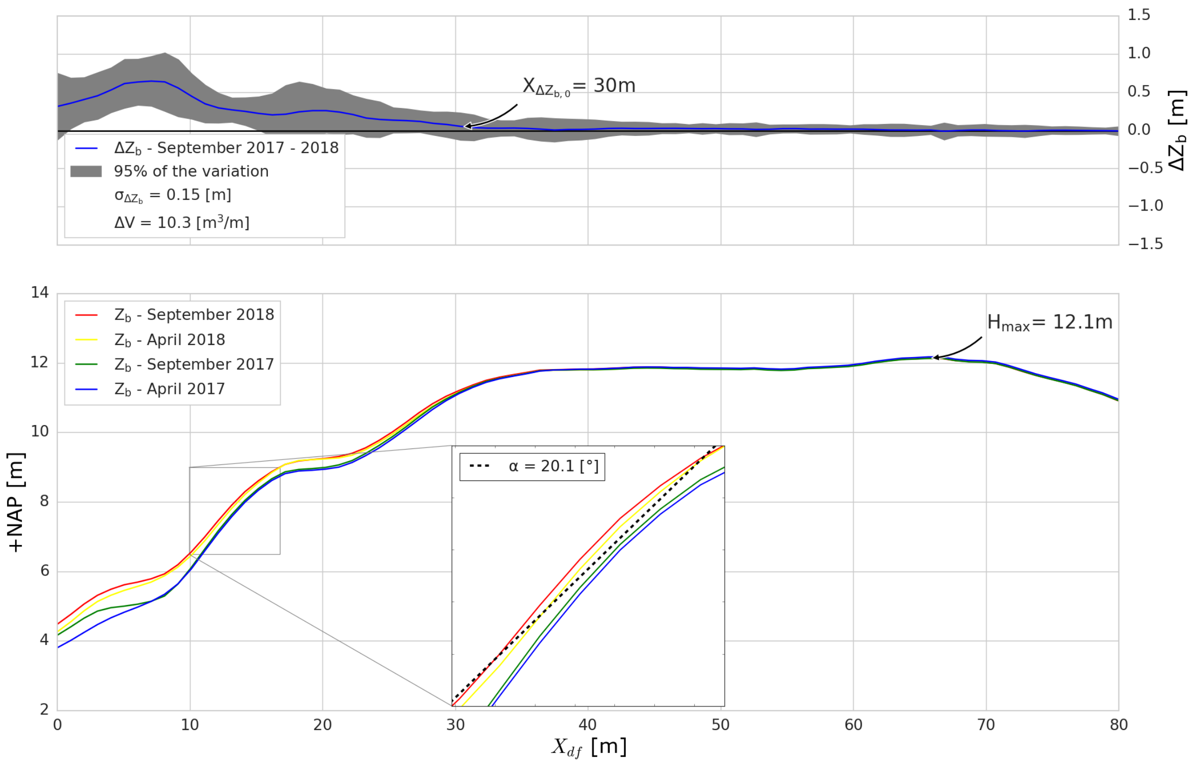


Figure 4.13: Small ribbon-development; top: bed level change; bottom: dune cross-section

The alongshore variability of the bed level change ($\sigma_{\Delta Z_b}$) is 62.5% of the variability of a static dune, and the landward distance of the dune foot where the bed level does not change ($X_{\Delta Z_b}$) is 60% of a static dune. The denser row of vegetation essentially functions as a wall against aeolian sediment transport further landward. Additionally, the dense vegetation captures sediment more uniformly, and this is reflected in the alongshore variability of the bed level change ($\sigma_{\Delta Z_b}$). The bed level change peaks at 0,6m in the first row of vegetation, hereafter another peak is observed at the second row of vegetation. From here it gradually decreases until sedimentation eventually decays to zero at 30m landward of the dune foot, compared to 50m at the static dune case.

The average alongshore volume change (ΔV) is identical to static dune development, this suggests that the beach buildings do not influence the sediment flux to the subsequent dune. Although sedimentation patterns are observed behind the structures, total sedimentation volumes are identical to the static dune case. There are multiple explanations for this phenomenon. First off, the structures do not influence sediment transport towards the subsequent dune. Second, after deconstruction the sedimentation patterns erode due to the effect of streamline curvature, which briefly causes a spike in aeolian transport rates and balances out any decreasing effects on the sediment transport flux during the time it was physically present.

The relocation of sediment for the construction (V_c) of the small ribbon-development has insignificant impact on the dune volume, and amounts to roughly $0.4m^3/m$. The first high frequency measurement is made on 19 April 2019, and the second is made two days after the construction of the ribbon-development on 5 March 2019. The DEMs are subtracted and the resulted DEM shows an relocation of sand equal to the width of the houses and a depth of roughly $0.2m$. The width of the houses is 2.0m, therefore the relocated amount of sediment amounts to about $0.4m^3/m$ in the area of the ribbon development. This is about 4% of the averaged sedimentation by aeolian sediment transport behind the ribbon-development. Additionally, the sediment is removed relatively far from the dune, and therefore does not directly impact the sediment availability at the dune. Note that the error in the measurements is relatively large, as the GCPs reported a measurement accuracy of 10cm. A photographic illustration directly after the construction of the small-ribbon development is presented in Appendix B.

The total volume that is relocated is relatively large, and therefore a significant local increase in dune volume can be caused by the location of deposit. The total alongshore length of the placement of the ribbon-development in this case is 75m. This results in a total sediment volume of approximately $30m^3$ that is relocated. The deposit location can therefore be significant for dune volumes if it is concentrated at one location point.

Dune parameter	Dynamic dune	Static dune	Small ribbon-development
$X_{\Delta Z_{b,o}}$ $[m]$	116	50	30
H_{max} $[m]$	16.5	13.3	12.1
α [°]	14.1	24.3	20.1
$\sigma_{\Delta Z_b}$ $[m]$	0.67	0.24	0.15
ΔV $[m^3/m]$	14.6	10.3	10.3
ΔV_c $[m^3/m]$	-	-	0.4

Table 4.4: Overview quantification dune parameters small ribbon-development

The trampling of pioneering vegetation during construction could be an explanation for the vigorous vegetation growth in the leeward side of the ribbon-development, by indrectly causing optimal sediment rates for Marram grass growth. In figure 4.14 it can be observed that north of the ribbon-development embryo dunes with pioneering vegetation are formed. These are located in a similar distance from the dune foot as the ribbon-development. It is believed that the construction of the beach buildings prevents the emergence of pioneering vegetation. This is confirmed by the tracks of the construction equipment in April 2018. In the presence of embryonic dunes a part of the aeolian sediment transport is trapped due to their presence, and a larger part of the bed becomes non-erodible. This causes a decrease in sediment supply available for transport further landward of the embryonic vegetation. Therefore, more sediment is available for aeolian transport towards the dune without embryonic dunes present. As a consequence of increased and potentially optimal sedimentation rates the vegetation becomes more intense behind the buildings.

Additionally, the dense row of vegetation could be the result of sheltering effects of the small-ribbon development against salt spray and high wind stresses in its leeward side, and thus causing optimal conditions for vegetation growth.

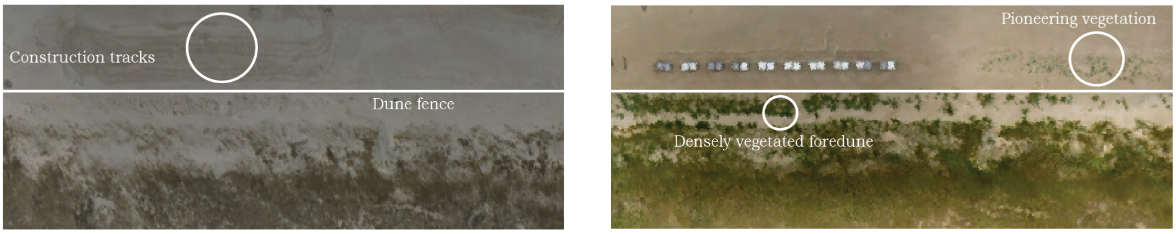


Figure 4.14: Trampling of pioneering vegetation during construction small ribbon-development

4.3.2. Large ribbon-development

Large ribbon-development are used as recreational houses during the summer, they are relatively large individual houses placed consecutively and seasonally. In this case they are placed in an angle with respect to the dune foot and the dominant wind direction (southwest). Placement of the buildings in Julianadorp can be observed in figure 4.15. The dune subsequent to the large ribbon-development is static, the influence on dune development is therefore be assessed by comparing the quantitative dune parameters to the static dune state. An overview of the dune parameters of the large ribbon-development subregion is presented in table 4.5.

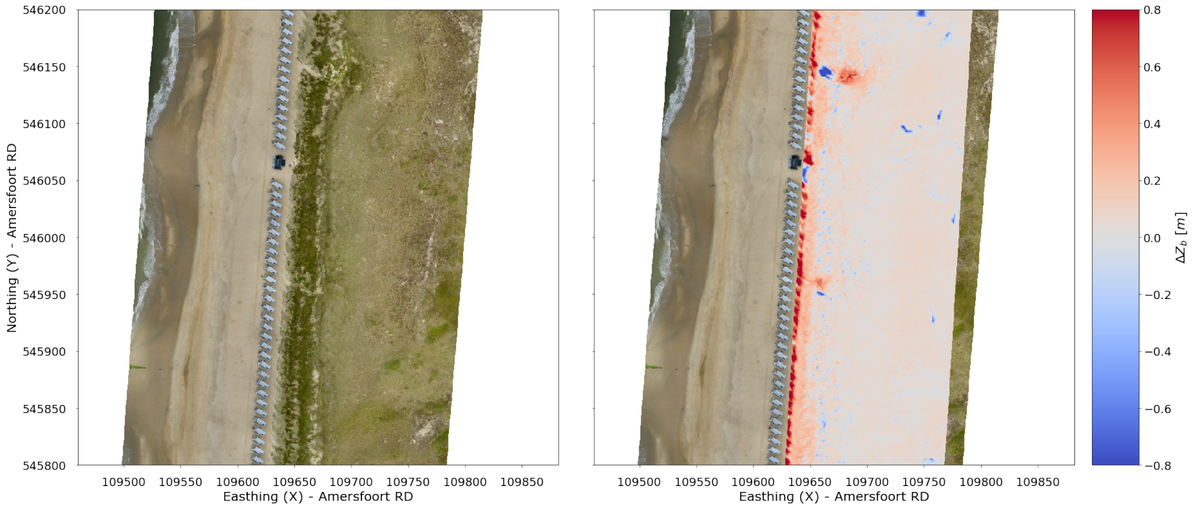


Figure 4.15: Large ribbon-development bed level change between September 2017 - 2018

Large ribbon-development influence aeolian sediment transport locally and this results in observed sedimentation patterns. The sedimentation patterns are in line with the orientation of the buildings. The passage width between the buildings is small enough for interaction flow to occur, and therefore the airflow is channelled through the passage in line with the buildings.

With the presence of dynamic features sedimentation is able to reach further landward despite the presence of the beach buildings. At the coordinates (109650,546150) a small dynamic feature is present. It can be observed that the erodible surface is susceptible to erosion, and aeolian transport occurs further landward than average.

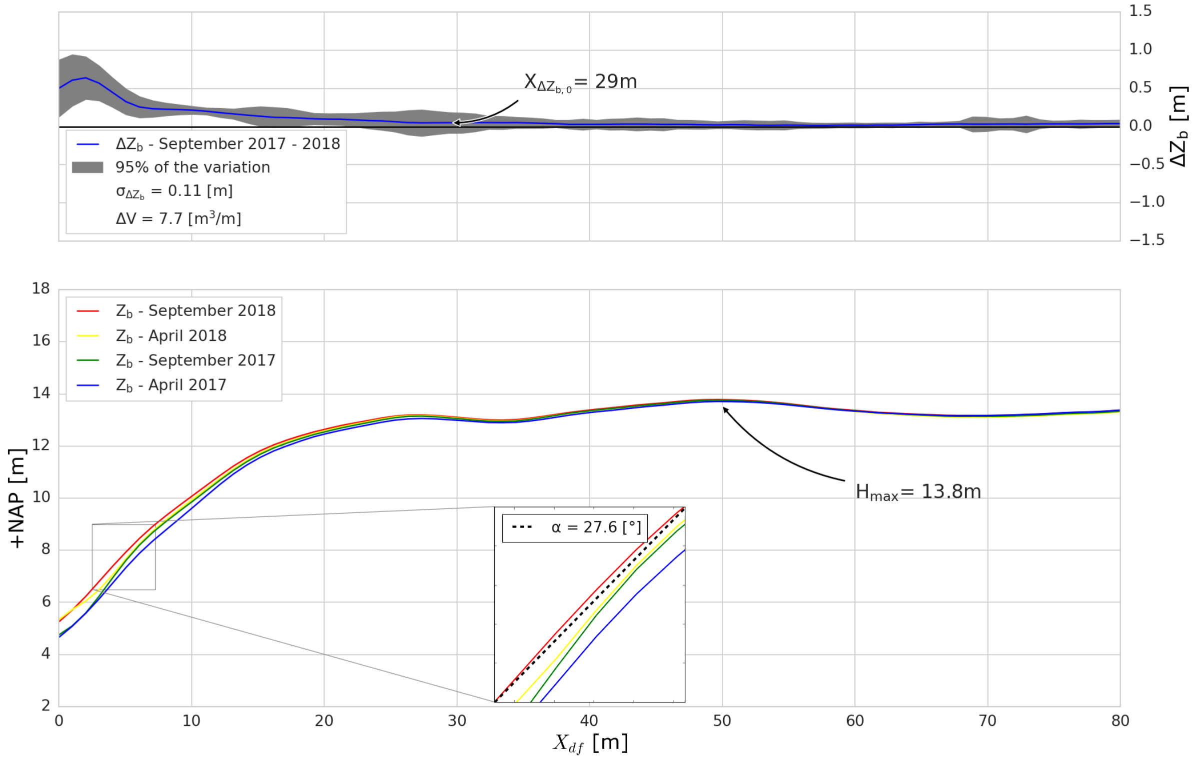


Figure 4.16: Large ribbon-development; top: bed level change; bottom: dune cross-section

The presence of the large ribbon-development seem to cause an extreme dense uniform row of vegetation. The vegetation may be explained by similar physical processes as with the small ribbon-development, which are in this case magnified. First off, optimal sedimentation rates prevail due to local sediment patterns and absence of pioneering vegetation due to construction processes. Secondly, the presence of the structure shelters a larger area directly behind it against salt spray and high wind speeds. Lastly, sedimentation patterns that occur due to the physical presence of the buildings are relatively large, and this results in an uniform alongshore increase of sedimentation rates, which causes optimal sedimentation volumes for Marram grass growth. The dense row of vegetation has its impact on the dune parameters, which are presented in figure 4.16.

The landward distance of the dune foot where the bed level does not change ($X_{\Delta Z_b}$) is 58% of the static dune subregion. This relatively low alongshore variability is likely explained by the dense row of vegetation that blocks sediment transport further landward. This resembles the effect of the dense row of vegetation present at the small-ribbon development. The small dynamic feature at the coordinates (109650,546150) confirms that the dense vegetation is the main cause for a relative low distance landward of the dune foot where the bed level does not change ($X_{\Delta_{Z_{b,0}}}$).

The alongshore variability of the bed level change ($\sigma_{\Delta Z_b}$) is 46% of the variability of a static dune, which is a consequence of the dense row of vegetation and the physical presence of the beach buildings. The uniform and dense row of vegetation causes the sediment to be captured uniformly. Additionally, the small passage width (c) causes interaction flow at the beach buildings, and sediment is channelled in line with the direction of the buildings. This results in uniform sedimentation patterns that cause a decrease in the alongshore variability of the bed level change.

The combination of dense vegetation and a steep dune slope α causes the sediment transport due to aeolian processes to decrease rapidly over the cross-section of the dune. This in turn has its consequence for the evolution of the cross-section of the dune. This example showcases an extreme version of a static dune. The evolution of the dune profile illustrates that there is an uniform progradation of the dune profile, while the dune reaches a maximum dune height (H_{max}), essentially creating a 'plateau shaped' dune similar to the one observed in the static dune case. It should be noted that the maximum dune height (H_{max}) of the large ribbon-development is slightly larger than the static dune case.

The average alongshore volume change (ΔV) of the large ribbon-development is 75% of the static dune case, this can not be attributed to a decrease of aeolian sediment transport by their physical presence. This reduction is similar to the sediment volume that is relocated during the construction of the buildings (ΔV_c). Therefore, it is believed that the decrease in average total sedimentation in relation to a static dune can be mainly attributed to the relocation of sediment for construction purposes (ΔV_c).

Dune parameter	Dynamic dune	Static dune	Large ribbon-development
$X_{\Delta Z_{b,o}}$ $[m]$	116	50	29
H_{max} $[m]$	16.5	13.3	13.8
α [°]	14.1	24.3	27.6
$\sigma_{\Delta Z_b}$ $[m]$	0.67	0.24	0.11
ΔV $[m^3/m]$	14.6	10.3	7.7
ΔV_c $[m^3/m]$	-	-	2.3[a]

[a] This volume can deviate as it is partly based on an estimation from a photograph

Table 4.5: Overview quantification dune parameters large ribbon-development

The relocation of sediment for the construction (ΔV_c) for a sand banquet amounts to $2.3m^3/m$, and is approximately the same as the difference in average volume change (ΔV) with the static dune. To prepare the placement of the buildings a sand banquet is constructed by relocating sediment from the dune foot. In figure 4.17 (a) a photograph of this phenomenon is given. In figure 4.17 (b) an estimation of the volume is made. The height of the scarp is estimated from a reference in a picture and can deviate from reality. The dune slope is extracted from the DEM and the total width of the sand banquet is measured at the construction site. The estimation resulted in a relocation of $2.3m^3/m$ sediment of the dune foot. While there is a reduction of $2.6m^3/m$ of total average sedimentation in comparison with the static reference case. In this case, 88% of the decrease in the average volume change relative to the static case can be explained by the relocation of sediment for a sand banquet.

Creating a sand banquet in this case reverses dune building by aeolian processes, and its decreasing effect on the average volume change (ΔV) is comparable to the relocation of sediment for construction purposes (V_c). Sediment is relocated from the dune foot and evenly redistributed over the first $25m$ seaward of the dune foot. Sediment transported from the beach by aeolian processes are first required to fill the scarp formed at the dune foot to its natural position. When the steepness of the slope at the dune foot has reduced sufficiently sediment located from the beach can be transported to the landward side of the dune foot. This specific interference therefore delays natural dune development.

(a) (b)

Figure 4.17: Creation of a sand banquet for the placement of the large ribbon-development

4.3.3. Pavilion type I

There are two types of pavilions within the case areas in terms of influence on dune development in their vicinity. Where the placement distance to dune foot, functionality, and the degree of human interventions distinguish these types. Pavilions are often located close to a beach entrance, it therefore challenging to isolate the effect of the pavilion from the beach entrance. Both pavilion types have a static dune state in their vicinity, thus their effect on coastal dune development is assessed by comparing the quantitative dune parameters to the static dune state.

The first type is a pavilion that is placed close to the dune foot, on stilts, and it functions as a restaurant. The pavilion is placed on the beach permanently and it is located next to a beach entrance. Its placement can be observed in figure 4.18. An overview of the dune parameters of the Pavilion type I subregion is presented in table 4.6.

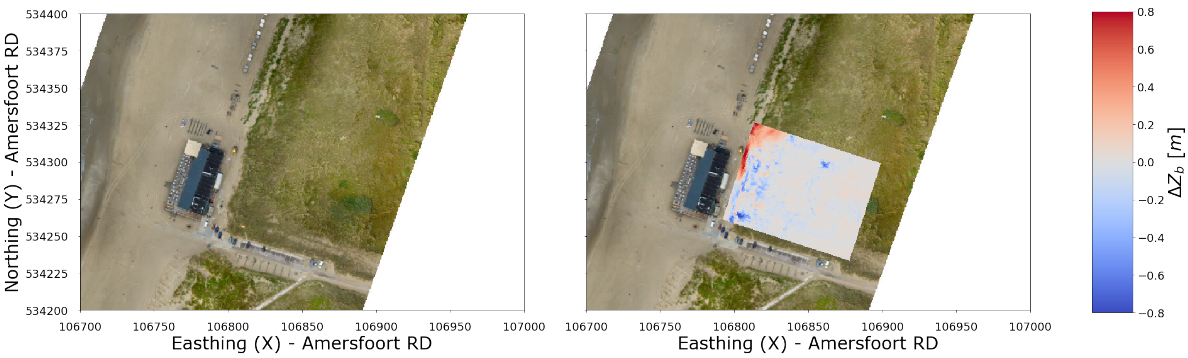


Figure 4.18: Pavilion type I bed level change between September 2017 - 2018

The areas with erosion indicate that Marram grass is not able to survive in the area, as the surface is susceptible to erosion. This is likely due to a lack of sedimentation, which makes it challenging to survive for Marram grass. Within the case areas it is observed that efforts were made to plant new Marram grasses to restore deteriorated vegetation that likely decayed due to a lack of sedimentation behind pavilions close to the dune foot. When there is no vital Marram grass present, the surface becomes more vulnerable to erosion. It is likely that this occurrence leads to eroded areas directly behind the pavilion, while further landward of the dune foot sand burial intolerant vegetation species take over and the area becomes more resistant towards erosion. A photograph of the newly planted Marram grass is presented in Appendix B.

The dune foot directly behind the pavilion is locally fixed. This is caused by the cross-shore location of the pavilion, the relocation of sediment for maintenance purposes, the steep slope, and the presence of a beach entrance next to the pavilion. This is elaborated by comparing the dune parameters that are presented in figure 4.19 to the static dune subregion.

The average alongshore volume change (ΔV) is 10% of the static dune subregion, which can not be fully attributed to a blockage of aeolian sediment transport. Aeolian sediment transport does occur directly behind the pavilion. By the local dune manager it is noted that in this area sedimentation occurs throughout the summer period. The deposit is relocated when it becomes too large, and consequently obstructs daily practices of the restaurant. At this point the sediment is relocated to other areas, it was noted that this occurs about three times per summer. By relocating the sediment behind the pavilion it is removed from the sediment budget of the dune system. It is challenging to make accurate estimations of the volume that is relocated for maintenance purposes (V_c), due to the frequent relocation of sediment. Between the measurement period September-April sedimentation resulted in a deposit of $5.0 m^3/m$. But this value is expected to turn out larger, as sediment is relocated multiple times within a measurement period. The area between the pavilion and the dune fence is used by the restaurant. A photograph of this area is presented in figure 4.20 (b).

The presence of a beach entrance adjacent to the beach pavilion is expected to cause an additional loss of sedimentation. The local dune manager noted that sedimentation does occur in beach entrances, and that occasionally sediment is relocated whenever sediment volumes become excessive and obstruct accessibility

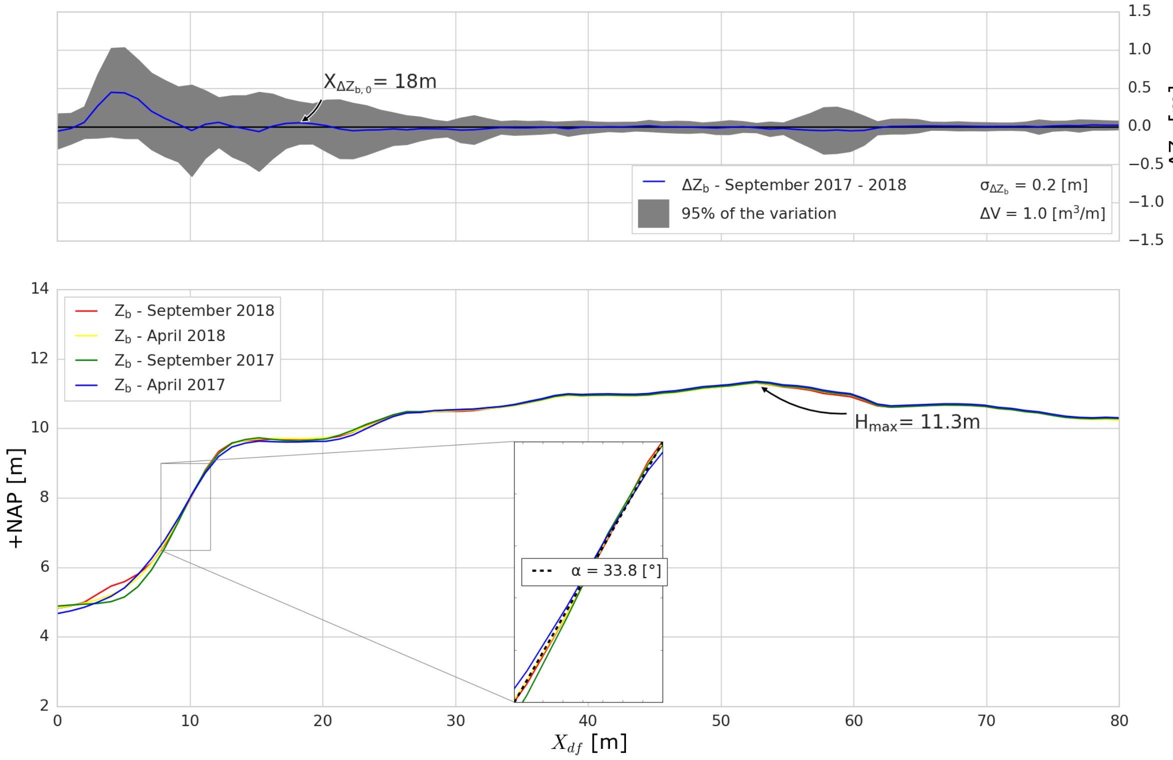


Figure 4.19: Pavilion type I; top: bed level change; bottom: dune cross-section

(a) Top view of the operational area and beach entrance

(b) Photograph of operational area adjacent to the pavilion

Figure 4.20: Cause of cut-off of sediment supply landward of pavilion type I

of the beach. By relocating sediment the road is revealed, a non-erodible surface. This causes a 'cut-off' in sediment supply for aeolian transport from the direction where the beach entrance is present.

This essentially causes the area behind pavilions to be enclosed in two areas were sediment transport can barely occur. This enclosed area can be observed in figure 4.20 (a). The relatively low average alongshore volume change (ΔV) is therefore caused by a combination of the relocation of sediment for maintenance purposes (V_c), steep dune slope (α) and the leakage of sediment to the lowered beach entrance.

The alongshore variability of the bed level change ($\sigma_{\Delta Z_b}$) is 83% of the static dune case. A large part of this variability occurs between $X_{df} = 0 - 30m$. In this area erosion occurs in the dune area enclosed by the beach entrance and the operational area, while this gradually transforms to sedimentation more north of the enclosed area.

The dune slope (α) of 33.8° adjacent to the pavilion approaches the angle of repose of dry sand. This is likely due to the occurrence of sedimentation that gradually steepens the dune slope, while the dune foot is unable to prograde. At a certain point the slope has reached its maximum, which approaches the angle of repose.

The lack of sediment supply, the steep dune slope (α), and the consequent relocation of sediment deposits cause the dune cross-section to become fixed and the distance of landward of the dune foot where the bed level does not change ($X_{\Delta Z_{b,0}}$) to be only 36% of the static dune state. The consequence on the evolution of the dune cross-section is presented in figure 4.19.

Dune parameter	Dynamic dune	Static dune	Pavilion type I
$X_{\Delta Z_{b,o}}$ $[m]$	116	50	18
H_{max} $[m]$	16.5	13.3	11.3
α [°]	14.1	24.3	33.8
$\sigma_{\Delta Z_b}$ $[m]$	0.67	0.24	0.2
ΔV $[m^3/m]$	14.6	10.3	1.0
ΔV_c $[m^3/m]$	-	-	5.0[a]

[a] This volume can turn out larger, as it is possible that sediment is relocated multiple times within a measurement period.

Table 4.6: Overview quantification dune parameters pavilion type I

4.3.4. Pavilion type II

Pavilion type II is a beach pavilion placed on stilts further away from the dune foot, it functions as an office for beach lifeguards. Because of its functionality it is not required to relocate sediment for maintenance purposes, which does occur at pavilion type I. The pavilion is placed permanently, a top view is presented in figure 4.21. Fundamental differences with the type I pavilion are: larger stilt height, greater distance from the dune foot (d), and an open structure. An overview of the dune parameters of the Pavilion type II subregion is presented in table 4.7.

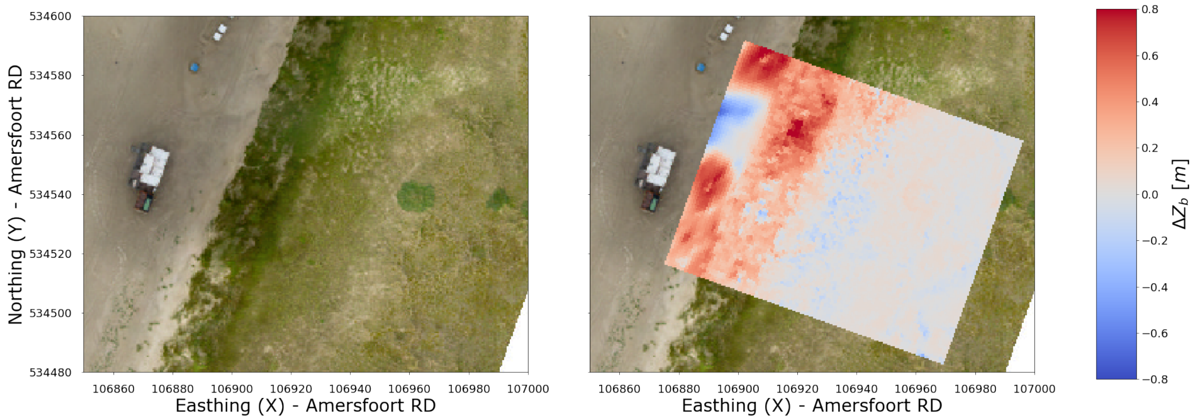


Figure 4.21: Pavilion type II bed level change between September 2017 - 2018

Pavilion type II promotes sedimentation further landward in line with the dominant wind direction (southwest). This is likely caused by a series of events. The pavilion functions as a lifeguard house, there is no need to clear the area behind the pavilion from sedimentation for operational purposes, as observed at Pavilion type I. Therefore, the sediment supply is uninterrupted by maintenance. Secondly, the presence of the pavilion causes a zone of deposition in the leeward side of the pavilion, which can be observed in figure 4.22. An explanation for this could be that in the first stages of placement sedimentation occurs in the leeward side of beach buildings as a result of a decrease of shear stresses induced by the wind. Eventually a certain threshold between high wind speeds and sediment availability results in the transport of the sediment further landward despite the presence of the physical structure pavilion type II. The alteration of wind flow in the vicinity of pavilion type II and the resulting deposit have its impact on the dune parameters, which are visualized in figure 4.23.

Figure 4.22: Deposit in the leeward side of pavilion type II

The average alongshore volume change (ΔV) is 120% of a static dune, which suggests that the presence of the pavilion increases the sediment flux transported further landward. This can be attributed to the fact that sediment is not relocated for construction and maintenance purposes ($V_c = 0m^3/m$). In this case the physical presence of the beach buildings results in a promotion of sediment transport, and thus in a relative increase of the average alongshore volume change (ΔV) in relation to the static dune subregion.

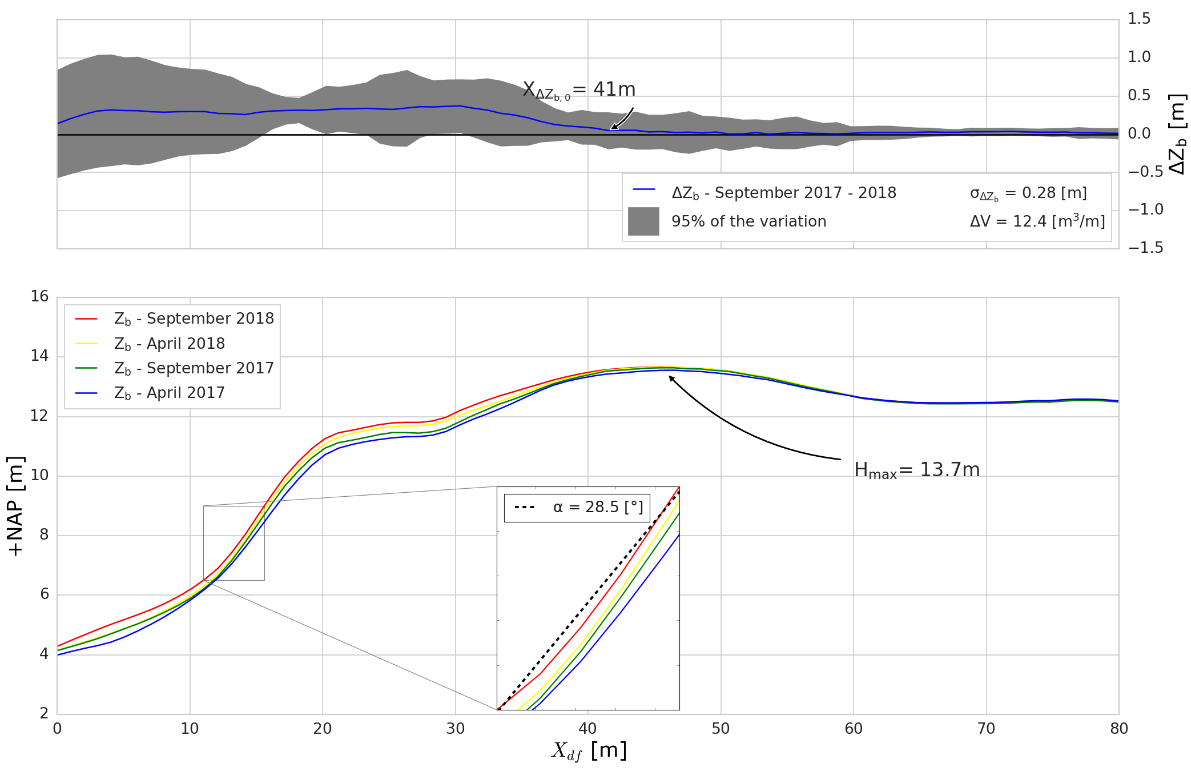


Figure 4.23: Pavilion type II; top: bed level change; bottom: dune cross-section

The alongshore variability of the bed level change ($\sigma_{\Delta Z_b}$) is 117% of the static dune case, this can be attributed to the dynamic behaviour in the leeward side of the pavilion. Between $X_{df} = 0 - 20m$ there is a large variability in the bed level change as sediment from the deposit in the leeward side of the pavilion has been transported further landward by aeolian forces. From $X_{df} = 20$ onward the variability in the bed level change gradually decays until the signal caused by the landward transport sediment from the deposit extinguishes.

The landward distance from the dune foot where the bed level does not change ($X_{\Delta Z_{b,0}}$) is 82% of the static dune case, this relative reduction might be caused by the relatively steep dune slope (α), which is 28.5° compared to 24.3° at the static dune subregion. It must be noted that the sedimentation in line with the dominant wind direction as a result of the transport of sediment from the leeward deposit reaches up until $85m$ from the dune foot. However, the resulted volume is not significant enough to result in an increase of the landward distance of the dune foot where the bed level does not change ($X_{\Delta Z_{b,0}}$).

The cross-section of the dune subsequent to Pavilion type II shows dynamic behaviour. Interestingly, between $X_{df} = 30 - 60m$ a more parabolic cross-section with a clear maximum dune height (H_{max}) can be observed. This deviates from the plateau-like cross-section observed at the static dune case and the other beach building types. This might be caused by the deposit in the leeward side of the pavilion that is susceptible to erosion and facilitates sediment transport further landward, which increases the dynamics in the cross-shore profile.

Dune parameter	Dynamic dune	Static dune	Pavilion type II
$X_{\Delta Z_{b,o}}$ $[m]$	116	50	41
H_{max} $[m]$	16.5	13.3	13.7
α [°]	14.1	24.3	28.5
$\sigma_{\Delta Z_b}$ $[m]$	0.67	0.24	0.28
ΔV $[m^3/m]$	14.6	10.3	12.4
ΔV_c $[m^3/m]$	-	-	0^a

[a] The pavilion is placed permanent and maintenance does not occur.

Table 4.7: Overview quantification dune parameters pavilion type II

4.3.5. Influence of beach buildings

Beach buildings only influence aeolian sediment transport locally, their effect on dune volumes therefore seem limited to local sedimentation patterns in their leeward side. Validity of this is given that the building dimensions and the distance from the dune foot remain proportional relative to the dune, and the distance between consecutive buildings are sufficiently large for unhindered sediment transport. Larger individual beach buildings can even increase the yearly average volume change relative to the reference dune due to the reach of sedimentation patterns further landward. An overview of the dune parameters that describe coastal dune development of the beach building types is presented in table 4.8.

The second effect, which is dominant over the presence of buildings, is caused by the relocation of sediment for construction and maintenance purposes. Relocating sediment from the dune foot has direct impact on dune volumes in its vicinity. Pavilion type I illustrated that the consequent relocation of sediment can cause a local fixation of the dune, which leads to steepening of the dune slope and consequently a blockage of aeolian sediment transport further landward. Furthermore, pioneering vegetation is trampled by vehicles during construction and maintenance activities. The absence of this specific vegetation type could lead to optimal sedimentation rates in the leeward side of buildings and therefore cause vigorous vegetation growth at the dune foot.

The promotion of a static dune state is an import factor in the effect beach buildings induce on coastal dune development. Dense vegetation found in the vicinity of beach buildings determine the distribution of transported sediment that originates from the beach. This often results in a relatively low landward distance from the dune foot where the bed level does not change ($X_{\Delta Z_{b,0}}$) and a low alongshore variability of the bed level change ($\sigma_{\Delta Z_b}$) compared to the static dune subregion.

Dune parameter	Static dune	Small ribbon-development	Large ribbon-development	Pavilion type I	Pavilion type II
$X_{\Delta Z_{b,o}}$ $[m]$	50	30	29	18	41
H_{max} $[m]$	13.3	12.1	13.8	11.3	13.7
α [°]	24.3	20.1	27.6	33.8	28.5
$\sigma_{\Delta Z_b}$ $[m]$	0.24	0.15	0.11	0.2	0.28
ΔV $[m^3/m]$	10.3	10.3	7.7	1.0	12.4
ΔV_c $[m^3/m]$	-	0.4	2.3^a	5.0^b	0^c

[a] This volume can deviate as it is partly based on an estimation from a photograph
[b] This volume can turn out larger, as sediment is relocated multiple times within a measurement period.
[c] The pavilion is placed permanent and relocation for maintenance does not occur.

Table 4.8: Overview dune parameters

The following section discusses the significance of the following building characteristics: cross-shore positioning, building dimensions, along-shore and local positioning, and construction and maintenance methods. The expectations are based on the conceptual dune model, available data and literature. Gradings for these building characteristics are summarised in table 4.9.

Effect type	Vegetation	Volume	Stabilizing /Mobilizing
Cross-shore positioning	++	++	Closer to dune foot - stabilizing
Dimensions, alongshore- and local positioning	+	+	Larger dimensions - stabilizing
Construction	+	++	Stabilizing
Maintenance	0	++	Stabilizing

Note: [++] = significant [+] = some, [0] = no influence. Gradings indicated in blue are backed by the data; other gradings are based on expectations derived from the conceptual dune model.

Table 4.9: Overview influence beach building characteristics

Cross-shore positioning

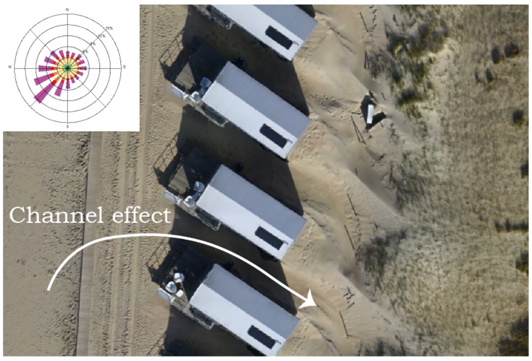
The cross-shore positioning of buildings has a large nett effect on dune development. It essentially determines the significance of their effect on coastal dune development in their vicinity.

Vegetation growth as a result of the presence of beach buildings seems to increase when beach buildings are built closer to the dune foot. There are two possible reasons for this phenomenon. First off, local sediment patterns of buildings reach up until the dune and cause optimal sedimentation for Marram grass growth. An example of this occurrence at the large ribbon-development is presented in figure 4.24 (a). Secondly, if the buildings are placed closer to the dune foot it is likely that the sheltering effects against salt spray and high wind stresses increases, which consequently results in an increase of vegetation growth.

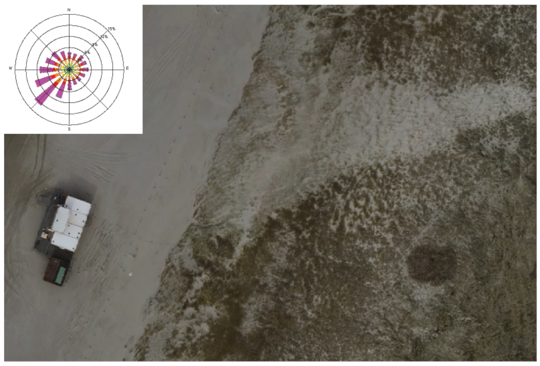
It is more likely that the relocation of sediment for construction and maintenance purposes (V_c) has a direct impact on dune volumes in their vicinity when buildings are placed close to the dune foot. This causes the building site to be close to the dune foot, and consequently it can have direct impact on dune volumes.

Dimensions, alongshore- and local positioning

If dimensions and the distance from the dune foot remain proportional relative to the dune, and the distance between consecutive buildings are sufficiently large for unhindered sediment transport, sediment transport



(a) Ribbon-development close to dune foot



(b) Pavilion further from dune foot

Figure 4.24: Sedimentation patterns

is not blocked further landward. An explanation for this could be that if the buildings block sediment and it is not relocated by vehicles, eventually a certain threshold between high wind speeds and sediment availability results in the transport of the sediment further landward. This is observed at Pavilion type II, presented in figure 4.24 (b).

The dimensions of the beach buildings determine the significance of local sedimentation patterns created by aeolian sediment deposits in their leeward side. The dimensions consist of building length, width, and height. Within the case areas various sediment patterns are observed and their shape and volume is determined by a combination of the building dimensions and the angle with the dominant wind direction. The angle with the dominant wind direction determines the area of the windward facade, and therefore the significance of the alteration in airflow.

Sedimentation patterns that emerged from smaller beach buildings have an insignificant effect on dune volumes landward of the beach buildings. Smaller sedimentation patterns from the large ribbon-development can be observed in figure 4.24 (a).

Larger building dimensions lead to sedimentation patterns that could reach into the dune and cause a significant increase in dune volume. This is the case for Pavillion type II, where the average volume change (ΔV) is 120% of the static dune. The full reach of the resulting sediment pattern can be observed in figure 4.24 (b).

The direction of the dominant wind conditions determines the direction and distribution of sedimentation patterns, however not unconditionally. For instance, when the passage width between the buildings is small enough for interaction flow to occur and the airflow of the wind is channelled through the buildings. Due to a channel effect of the airflow between the buildings the orientation of the sedimentation patterns behind the beach buildings is in line with their placement orientation, this phenomenon is observed in figure 4.24 (a).

The length of the stilts seem to determine the volume of sedimentation in the leeward side of a pavilion, where larger stilt length resulted in greater deposits in their leeward side. As long as the stilts are short enough for a structure on top of the stilts to cause a separation of the airflow that intersects with an erodible surface, deposits behind them are expected to occur.

Construction methods

The impact of relocation of sediment during construction is dependent on the cross-shore location and the construction method of a beach building. The cross-shore location determines the distance between the origin of the sediment and the dune, and consequently if construction affects dune volumes. The construction method determines if and how much sediment volume is relocated.

The creation of a sand banquet can reverse dune building by aeolian processes. Sand banquets refer to the distribution of sediment further landward onto the beach, to create a plateau-like building ground. These are used to place beach buildings horizontally on the ground. The volume and origin of the sediment determines the effect of the sand banquet. The data suggests that the sediment volume that is relocated directly from the dune foot is of an comparable amount to the dune volume loss. At the large ribbon-development an average volume change (ΔV) of 74% of the static dune case was observed. The loss compared to the static dune case is of a comparable to sediment volume for the construction of the sand banquet ΔV_c, which accounts for 88% of the volume loss. The sediment that is removed from the dune foot has to be regained through aeolian sediment transport. The sand banquet for the placement of the large ribbon-development is schematised in figure 4.25.

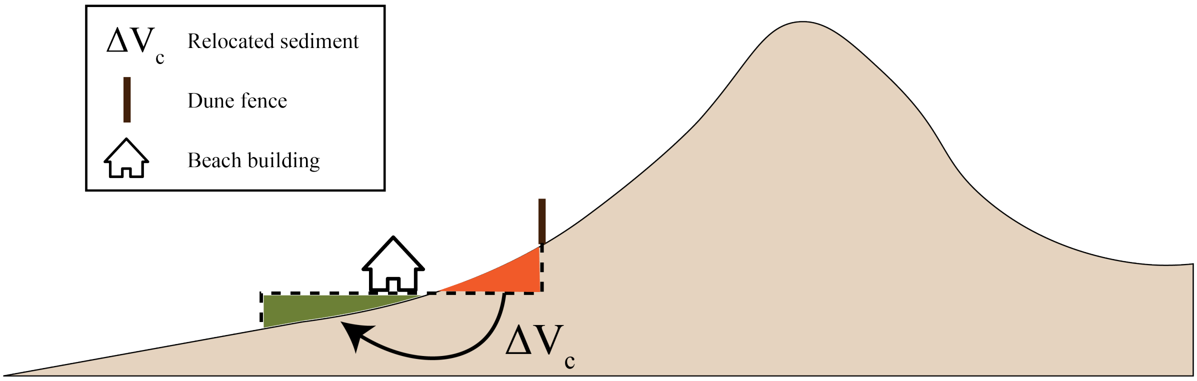
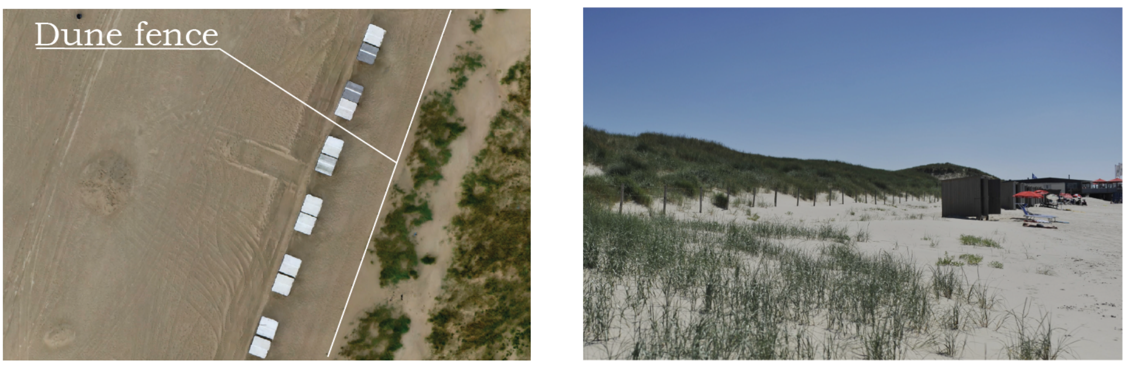


Figure 4.25: Schematization of the sand banquet created for the large ribbon-development

Although, this is not backed by the data, it is believed that the construction of seasonally placed pavilions does not significantly affect dune volumes. The stilts for pavilions that are placed seasonally are left in the ground during winter. From this follows that construction activities are mainly above ground and the relocation of sediment during construction is limited.

The trampling of vegetation during construction seems to cause vigorous vegetation growth behind the dune fence in the landward side of the buildings. An illustration of this is presented in figure 4.26 (a). During construction and maintenance activities vehicles are used to relocate sediment, their tracks trample pioneering vegetation in the construction area. Pioneering vegetation normally captures a part of the sediment transported by aeolian transport from the beach. If this does not occur in the region in the vicinity of the beach buildings, it is believed that optimal sedimentation rates prevail behind the buildings. This effect combined with the fact that vehicles do not pass the dune fence, and therefore are unable to trample vegetation behind it, seems to cause vigorous vegetation growth behind the ribbon-development. An example of the presence of pioneering vegetation next to small ribbon-development is presented in figure 4.26 (b).



(a) Vigorous vegetation growth behind dune fence

(b) Pioneering species next to small ribbon-development

Figure 4.26: Proposed effect trampling of vegetation by vehicles

Maintenance

The consequent relocation of deposits by aeolian transport to increase accessibility for vehicles in the leeward side of beach buildings placed close to the dune foot can cause a locally fixed dune. The dune slope adjacent to the beach building gradually steepens until the dune is locally fixated. Pavilion I proved that if sediment is consequently relocated for maintenance purposes, the dune can be fixed locally. In this case the deposited sediment is relocated. The combination of a steeper slope and the reoccurring relocation of sediment causes the region of the dune behind the pavilion to become fixed, up until the dune slope approaches the angle of repose. Note that this phenomenon only occurs when the pavilion is placed close to the dune foot, the dune foot is therefore unable to migrate seaward, and the dune slope steepens.

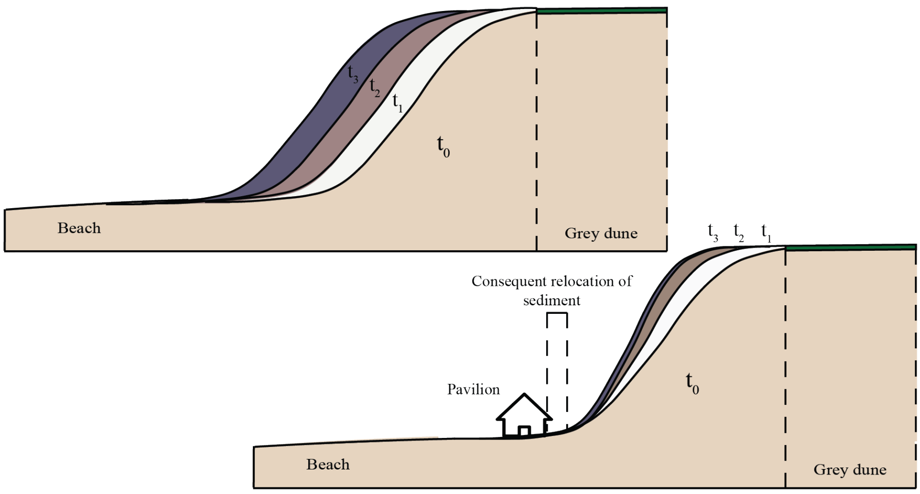


Figure 4.27: Schematisation impact consequent relocation of sediment for maintenance purposes

5
Dune Management Measures

Suitable strategies for dune management to mitigate or stimulate effects of beach buildings are presented here. It should be noted that often there is not enough space on the beach to freely move the location of the beach buildings in the cross-shore direction. This is due to the limited space on the beach, which is partly a consequence of the legal boundary where beach buildings are allowed to be placed. This legal boundary is enclosed by a seaward region of the beach that acts as a space for vehicles in case of an emergency, and a landward region that is defined by the dune fence and sustains the adjacent dune.

The relocation of the dune fence
Relocating the dune fence is a tool to regulate the stabilizing/mobilizing effect of seasonal beach buildings. This only applies to seasonal beach buildings that are not placed on stilts, this facilitates the possibility to assign a new location by relocating the dune fence every year. Additionally, it is prevented that the physical presence of the beach buildings stand in the way of the dune progradation in the longer term. Effects that are induced by relocating the dune fence are schematised in figure 5.1.

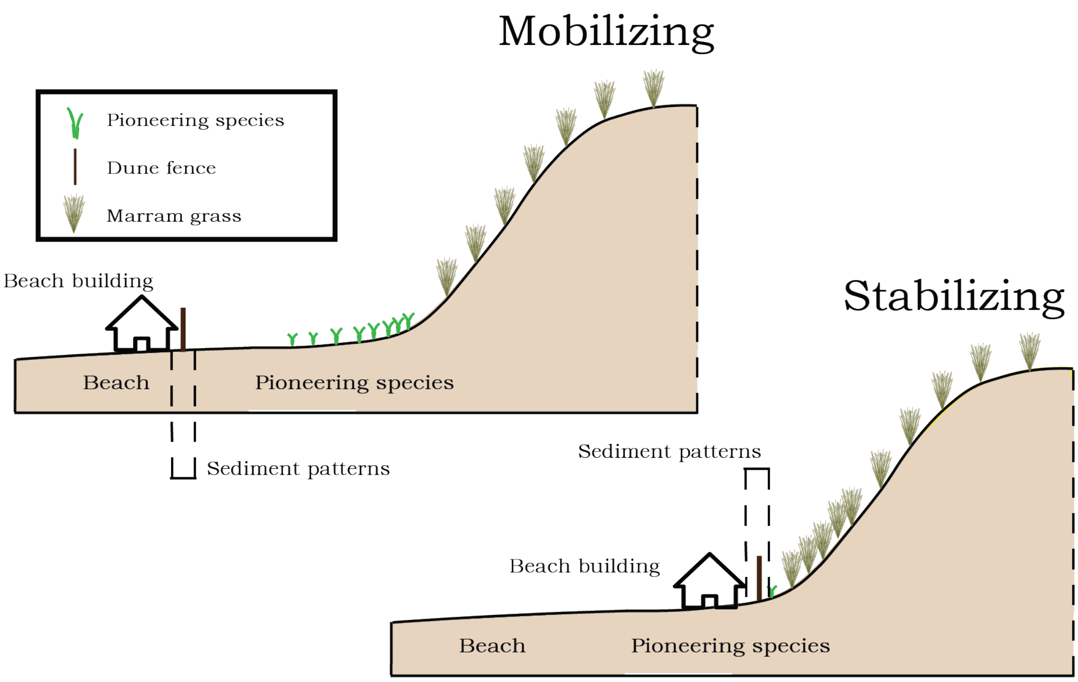


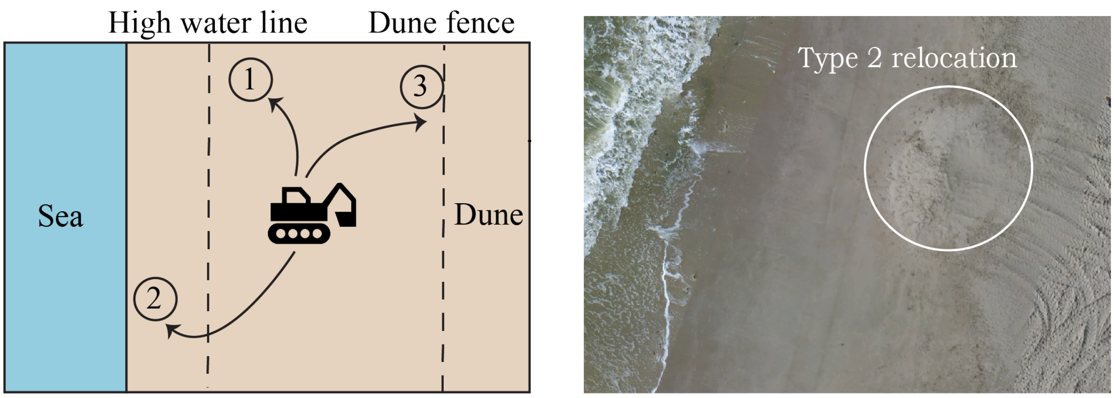
Figure 5.1: Relocation of the dune fence as a tool

By placing the dune fence further from the dune foot, the physical presence of the beach building is forced to be located further from the dune area, as the dune region behind the fence is restricted for construction vehicles. Pioneering species are therefore able to grow, sedimentation patterns do not reach into the dune and the sheltering effect caused by the physical structure of the buildings decreases. This limits the stabilizing effect that is observed in the dune areas adjacent to beach buildings and it is expected that this promotes the further landward transport of sediment transport.

On the contrary, if the dune fence is located more landward, the area where normally pioneering vegetations emerge is used as a construction site. Consequently, sedimentation patterns reach into the dune, sheltering effects against high wind speeds and salt spray occur, and pioneering vegetation is absent to function as a first 'filter' of the sediment transported from the beach. Optimal grow conditions for Marram grass prevails in the adjacent dune, and consequently the dune stabilizes.

Strategic placement of relocated sediment
Occasionally it is unavoidable that sediment has to be relocated, because it is simply obstructing the functionality of a beach building. Strategic relocation of sediment in this case can be an effective way to mitigate the effect of the relocation on dune development. Example of observed deposited locations in the case areas, which are schematised in figure 5.2, are the following:

1. On the beach, landward of the waterline. In this case, the relocated sediment is still in the beach-dune system and is available for aeolian sediment transport towards the dune. By depositing it this way, it will be gradually transported to the dune over time. But the volume in the region it was taken is partly lost, as the sediment is dispersed during aeolian transport towards dune.
2. On the beach, seaward of the waterline. Relocated sediment is deposited behind the waterline, it will be taken out of the beach-dune system as the sediment is transported offshore during high-tide. An image of this deposit type is presented in figure 5.2 (b).
3. Directly in front of the foredune. Occasionally the sediment is dumped directly in front of the foredune. Sediment is available for aeolian transport and will be captured by dune grasses relatively fast.



(a) Sediment deposit locations

(b) Relocation of sediment behind the high water line

Figure 5.2: Sediment deposit options

Include operational area in building dimensions
It is advised to include the operational area behind a pavilion that requires the consequent relocation of sediment in it dimensions. Current dune management anticipates on the future dune progradation based on the JarKus transects. A beach building is placed based on this future progradation to prevent that its physical presence interferes with the natural progradation of the dune foot. The consequent relocation of sediment makes it impossible for the dune foot to prograde naturally, and a fixed dune foot is the consequence. By including this operational area sufficient space is provided behind the pavilion. This space between the pavilion and the dune area facilitates the possibility to deposit relocated sediment in the dune area adjacent to it. This is because the dune foot is able to prograde naturally and the dune slope remains relatively gentle in comparison to the fixed dune state observed at pavilion type I. This concept is schematised in figure 5.3.

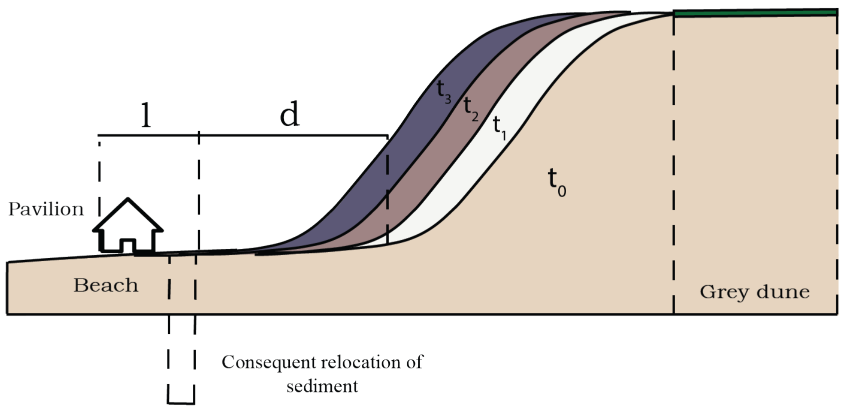


Figure 5.3: Inclusion of the operational area in beach building dimensions

Trade-off between permanent and seasonal

There is a trade-off between permanent and seasonally placed beach buildings. Permanent buildings can be placed further from the dune foot, and therefore relocation of sediment during construction and maintenance is not required for the years its placement is anticipated on. However, placement takes up a broader part of the beach. On the other hand seasonal buildings can be placed closer to the dune foot and promote static dune development through stimulation of vegetation growth. However, the relocation of sediment for construction purposes does take place, and affects dune volumes periodically.

6 Discussion

Although the results of this study provide promising steps towards understanding the influence of beach buildings on coastal dune development, some caveats must be made on the limitations of the research.

Beach entrances
The effect of beach entrances in the vicinity of beach buildings is not clear. Beach entrances are frequently present nearby beach buildings, and provide access to the beach. The local dune manager noted that sedimentation does occur in beach entrances, and that occasionally sediment is relocated whenever sediment volumes become excessive and obstruct accessibility of the beach. This could affect the measurement results in two ways. First off, as sedimentation occurs a part of the sediment transported from the beach is captured by the beach entrance. Without its presence this sediment would have accumulated at the dune area. Secondly, if the deposited sediment is concentrated at one location it would cause an artificial increase in dune volumes locally.

Limited beach building types
The case areas provide limited beach building types. There are endless possibilities for the dimensions, construction methods, and placement periods of beach buildings. Although a large variety of building types is present in the case areas, this study can not cover the influence of specific building properties. It is still unclear what the exact impact is if parameters such as the stilt length, ratio between dimensions, and distance from the dune foot deviate from the study specific placement scenarios.

Measurement period
Most quantifications utilize the bed level change between September 2017 - September 2018. The remaining elevation measurements are performed with photogrammetry, and are left out of the analysis. The photogrammetry measurements proved to provide degraded results in the regions with vegetation. Although it is not expected that the influence of the physical presence of beach buildings strongly deviate per year, results would have been more reliable with an extended LiDAR measurement period.

Site specific conditions
The distance between the case locations Sint Maartenszee and Julianadorp is roughly ten kilometres, and it is expected that the measurements are subjected to site specific conditions. The coastal zone management of Julianadorp and Sint Maartenszee is regulated by the same waterboard HHNK. However, assumptions are made that the wind and hydrodynamic conditions, sediment available for aeolian transport, and biotic conditions do not significantly deviate by comparing coastal dune development of Sint Maartenszee to Julianadorp. The potential effect of shoreface nourishments on sediment availability within the case areas is not accounted for.

The influence of beach buildings on dune development could deviate when subjected to alternate conditions. Especially, considering the importance of the relocation of sediment for construction and maintenance purposes. Coastal zone management policy may strongly vary within the Netherlands, as this is regulated by distinct regional waterboards. Hence, case locations in other regions may show different results.

Building deconstruction effects
This study considers the effect of construction and maintenance activities on dune volumes. However, the

potential relocation of sediment during deconstruction is not included. This would cause an underestimation of total relocation volumes associated with construction and maintenance activities.

Maintenance effects

The relocation of sediment for maintenance purposes occurs sporadically, it is therefore challenging to identify from measurements if it occurs, to what extent sediment is relocated, and how frequent. The relocation of sediment does not only occur behind a pavilion for operational purposes. It can for instance be required to relocate aeolian deposits after a severe storm from the surrounding of beach buildings to regain accessibility (NOS, 2019). The frequency of the measurements is not high enough to account for these relocations. This could result in an underestimation of the impact of the sediment relocation for maintenance purposes (V_c), and an overestimation of yearly average dune volume changes (ΔV) in the dune region where it is deposited.

Influence on separate processes

The results of this study rely on the nett effect of specific beach building types on coastal dune development in terms of dune volume and vegetation. Coastal dune development is governed by complex interactions between physical and biological processes. It is still unclear what the effect of beach buildings is on singular processes such as sediment transport rates, vegetation growth, and hydrodynamic loads. Distinguishing between these processes is not possible using the current data.

Interpolation of elevation

The interpolation of the elevation data potentially causes an exaggeration of the uniformity in bed level change in the presence of dense vegetation. Bare sand and vegetation pixels within the subregions are classified. Subsequently, elevation data from the vegetation pixels are removed, and the elevation between the pixels are interpolated. This interpolation is performed to remove the vegetation height. It is expected that mentioned effect on the uniformity is limited as large spatial variability in the bed level change is observed in regions where uniform vegetation is present (Pavilion type I).

Prograding coast

The conceptual dune model is based on, and measurements are taken at a prograding coast. The dynamic dune subregion reports a progradation rate of the dune foot of 1.5m/year. It is unclear what the effect of beach buildings would be at a retrograding coast, where hydrodynamic processes become more dominant.

Influence on vegetation

Seasonally placed beach buildings seem to increase the vigour of vegetation in its vicinity, the explanation for this phenomenon still relies on a hypothesis and the occurrence can still be a coincidence. This study suggests that these influences are due to, either alone or in a combination, sheltering effects against salt spray and high wind stresses or optimal sedimentation rates caused by the physical presence of the structure and the trampling of pioneering vegetation during (de)construction activities.

Beach use

This study could not account for the usage of the beach by individuals for recreational purposes. Regions with beach buildings can have large amounts of human activity in their vicinity, especially during high season. This could result in a decrease in sediment availability for transport, trampling of pioneering vegetation, and the relocation of sediment.

7 Conclusions

The main objective of this research is to investigate the influence of specific types of beach buildings on aeolian coastal dune development, and identify suitable dune management measures accordingly. Their influence is determined with high resolution LiDAR elevation measurements taken with an UAV of two case areas in the Netherlands with different types of beach buildings present. Effects induced on dune development are separated by their physical presence, and the relocation of sediment during construction and maintenance activities. How these effects relate to key processes is schematised in a conceptual dune model (figure 7.1). The dune state in the vicinity of beach buildings is mainly static, their influence is therefore compared to static dune development with quantitative parameters that describe aeolian coastal dune development. This research concludes with its key findings by answering the research questions composed in section 1.3.

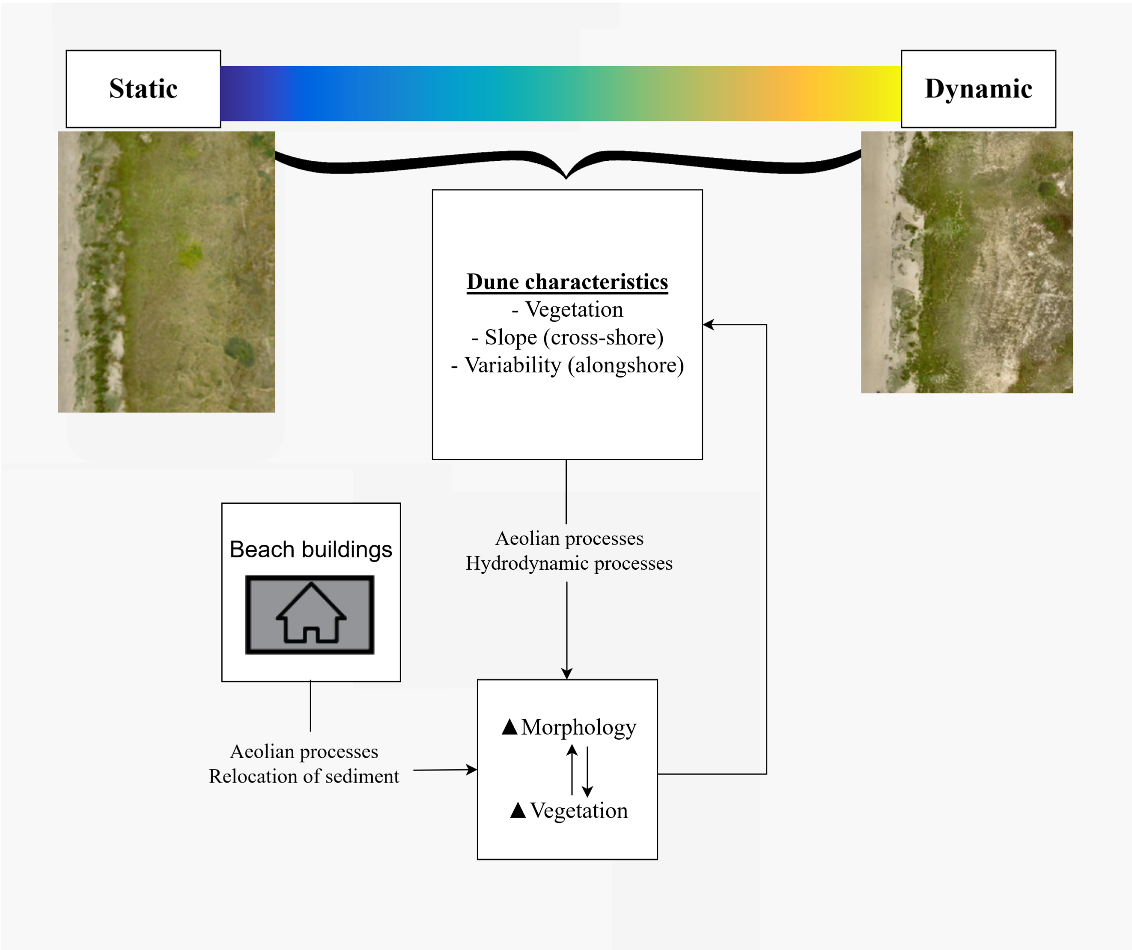


Figure 7.1: Conceptual dune model - beach buildings

1. What is the difference in coastal dune development in the areas with buildings in front of the dune versus areas without, in terms of:

(a) **Dune volume**
The presence of beach buildings only influences aeolian sediment transport locally and therefore often do not cause significant differences in average alongshore volume changes. Relocation of sediment for construction and maintenance purposes can lead to a significant decrease of average alongshore dune volume changes.

The yearly average dune volume change (ΔV) in the dune area adjacent to beach buildings, which do not require a large amount of relocation of sediment for construction and maintenance, ranges between 10.3 - 12.4m^3/m. In comparison to the reference static dune, which amounts to 10.3m^3/m.

The remaining beach building types report a yearly average volume change (ΔV) of 1.0 and 7.7m^3/m in the dune area in their vicinity. The relative volume loss compared to the reference static dune is mainly attributed to the relocation of sediment for construction and maintenance purposes.

(b) **Vegetation development**
Foredunes adjacent to consecutive buildings (ribbon-development) are found to be densely vegetated, resulting in a more static dune state system landward. Possible explanations could be:

- Construction, maintenance and use of beach buildings prevent embryo dune development, resulting in optimal sedimentation rates for vigorous Marram grass growth adjacent to ribbon-development.
- Local sedimentation patterns caused by an interaction of the airflow with the physical structure of beach buildings reach into the dune and cause optimal sedimentation rates for vigorous Marram grass growth.
- The physical structure of beach buildings provide a sheltered area against onshore stresses such as salt spray and high wind speeds, and thus favouring grow conditions locally.

A decrease in Marram grass vitality is observed in the dune region adjacent to Pavilion type I, where the yearly average alongshore volume change (ΔV) is 1.0m^3/m. This can possibly be attributed to the positive feedback mechanism between sedimentation rates and Marram grass vitality.

(c) **Dune state (characteristics)**
The stabilization to a static dune state is an import component in the effect beach buildings induce on coastal dune development. Dense vegetation and a steep dune slope (α) found in the vicinity of beach buildings determine the distribution of the transported sediment that originates from the beach.

The development of dense vegetation on a foredune leads to a decrease of the landward reach and the variability of sedimentation, and consequently to an uniform progradation of the dune. A landward distance of the dune foot where the bed level does not change ($X_{\Delta_{Z_{b,0}}}$) of 30m are reported at the ribbon-development, compared to 50m at the reference static dune. Additionally, an alongshore variability of the bed level change ($\sigma_{\Delta Z_b}$) of 0.11 and 0.15m are reported at the ribbon-development, compared to 0.24m at the reference static dune.

2. What is the difference in effect on coastal dune development caused by different beach building characteristics, in terms of:

(a) **Maintenance**
The consequent relocation of deposits by aeolian transport to increase accessibility for vehicles in the leeward side of beach buildings placed close to the dune foot can cause a locally fixed dune. The dune slope adjacent to the beach building gradually steepens until the dune is locally fixated. The dune region adjacent to pavilion type I has a relative steep dune slope (α) of 33.8°, which approaches the angle of repose of dry sand (34°), compared to 24.3° of the reference static dune case. A consequence of this steep dune slope and fixed dune foot is that the yearly average volume change (ΔV) of the dune area is limited to 1.0m^3/m.

(b) **Construction**
The creation of sand banquets for construction purposes can result in a decrease of dune volume change. The sediment volume that is relocated periodically from the dune foot is of a comparable amount to the loss of dune volume. The yearly average volume change (ΔV) of the large ribbon-development is $7.7m^3/m$, compared to $10.3m^3/m$ of the static dune case. It is estimated that $2.3m^3/m$ of this difference in volume can be attributed to the creation of a sand banquet (ΔV_c).

The construction of smaller beach buildings does not result in a decrease of dune volume changes. This is attributed to the relative large distance from the dune foot, and the small sediment volume that is relocated. Measurements before and after construction of small ribbon-development revealed that this relocation volume (ΔV_c) is approximately $0.4m^3/m$.

The trampling of pioneering vegetation by vehicles during construction can cause optimal sedimentation rates for Marram grass growth landward of beach buildings. It is proposed that the sediment transport availability increases locally due to the absence of pioneering vegetation species.

(c) **Cross-shore positioning**
The cross-shore positioning of beach buildings has a large nett effect on dune development. It essentially determines the significance of the induced effect on coastal dune development in their vicinity.

If beach buildings are placed closer to the dune foot, effects induced by their physical presence are larger, which provides the opportunity for their sheltering effects and sedimentation patterns to reach into the dune. Additionally, it is more probable that the relocation of sediment for construction and maintenance purposes (V_c) has a direct impact on dune volumes in their vicinity when beach buildings are placed closer to the dune foot.

(d) **Dimensions, alongshore and local positioning**
The effect of beach buildings on aeolian processes is limited to sedimentation patterns where:

- The building dimensions determine the significance of local sedimentation patterns.
- The distance between consecutive buildings determines the airflow regime. The airflow regime determines whether the sediment flux between buildings is either unhindered, increased or blocked.
- The angle of the dominant wind direction determines the direction of sedimentation patterns. In the occurrence of interaction flow between consecutive buildings the direction of the sediment patterns become in line with the buildings.

If therefore the building dimensions and the distance from the dune foot remain proportional relative to the dune, and the distance between consecutive buildings are sufficiently large for unhindered transport, aeolian sediment transport is not blocked further landward. An explanation for this could be that in the first stages of placement sedimentation occurs in the leeward side of beach buildings as a result of a decrease of shear stresses induced by the wind. Eventually a certain threshold between high wind speeds and sediment availability results in the transport of the sediment further landward despite the presence of the physical structure of a beach building.

For instance, at the permanent pavilion type II where the relocation of sediment is absent and it is located further from the dune foot, a yearly average volume change (ΔV) of $12.4m^3/m$ in the adjacent dune region is observed. This is an increase relative to the reference static dune, which has a yearly average alongshore volume change (ΔV) of $10.3m^3/m$. This increase in volume is attributed to the sedimentation pattern that reaches into the dune caused by the pavilion.

3. What are effective dune management measures to cope with the effect of beach buildings on coastal dune development?

It is advised to include the area that is used for operational purposes behind a larger beach pavilion into its dimensions when anticipating on the future progradation of the dune foot. The consequent relocation of sedimentation in this area makes it impossible for accretion to occur and for the dune foot to prograde towards the physical structure.

The relocation of the dune fence is a tool to regulate the stabilizing/mobilizing effect of beach buildings. By placing the dune fence further from the dune foot pioneering species are able to grow, sedimentation patterns do not reach into the dune and the sheltering effect induced by the physical presence of the beach buildings decreases. This promotes dynamic dune development. While placing the dune fence closer to the dune the opposite occurs, and the dune is expected to stabilize towards a static dune state.

Sediment that is relocated for construction and maintenance purposes can function as a dune management tool. The sediment can be relocated in front of a dune above the high water line, and therefore facilitate natural transportation of the sediment to the adjacent dune area by aeolian forces. Additionally, the sediment can be utilized to stabilize the dune and restore a breach in the foredune.

There is a trade-off between permanent and seasonally placed beach buildings. Permanent buildings can be placed further from the dune foot, and therefore relocation of sediment during construction and maintenance is not required for the years its placement is anticipated on. However, aeolian effects are present year-round and placement takes up a broader part of the beach. On the other hand seasonal buildings can be placed closer to the dune foot and promote static dune development through stimulation of vegetation growth. However, the relocation of sediment for construction purposes does take place, and affects dune volumes periodically.

It should be noted that often there is not enough space on the beach to freely move the location of beach buildings in the cross-shore direction. This is due to the limited space on the beach, which is partly a consequence of a legal boundary, which restricts the area where beach buildings can be placed. This legal boundary is enclosed by a seaward region of the beach that acts as a space for vehicles in case of an emergency, and a landward region that is physically defined by a dune fence and sustains the adjacent dune.

8
Recommendations

This study has identified suitable steps for future research in the process, these are elaborated here.

Logging of data
Mapping the frequency and volume of the relocation of sediment for construction and maintenance purposes can be beneficial to optimize beach building placement. Creating an inventorization of relocation volumes for maintenance purposes behind specific pavilions, beach entrances, and beach buildings would be a valuable contribution. By investigating the amount of these volumes more insights can be gained on how significant the relocation of sediment is to coastal dune development, and in what specific placement configuration the need for relocation is minimal. Gained insights can be used for future placement accordingly.

By creating an extensive inventory of the used construction methods for beach buildings the identification of the most efficient method in terms of sediment relocation becomes more convenient. An inventorization of distinct construction methods, coupled relocation volumes, and beach building dimensions within the Netherlands can make it easier to identify the most efficient construction methods that consequently result in minimum dune volume loss.

Investigate different location with distinct beach building types
A suitable topic for future research would be to apply a similar research to a different location with distinct conditions in terms of hydrodynamics, wind, coastal zone management, and beach building types. By quantifying dune parameters similarly to this study more insight can be gained in the effect of beach buildings while other conditions prevail. For instance, in a retrograding coast, will beach buildings provide a sheltering effect against hydrodynamic loads? Additionally, if the dune parameters are quantified consistently with this study they could provide as a calibration tool to further validate or even expand the conceptual dune model by investigating static and dynamic dune development when other conditions prevail.

Increase frequency of measurements
By increasing the frequency of the measurement at Julianadorp and Sintmaartenszee unknown variables such as the effects of deconstruction, unknown construction effects and total relocation volumes can be quantified. This study utilizes the measurements of directly before construction, and directly after deconstruction. It is therefore unclear how much sediment is relocated for the construction and deconstruction. It is advised to perform a minimum of four measurements per year, one just before construction, one just after construction, one just before deconstruction and one just after deconstruction. These measurements facilitate the quantification of the exact amount that is relocated for the deconstruction, and construction. Consequently it can be easier to determine seasonal effects, and observe to what extent the creation of a sand banquet similar to the Landal development resets during high wind speeds in winter.

Validation by sand traps
The results of this study suggest that the physical presence of beach buildings only influence aeolian sediment transport locally in the form of sedimentation patterns. It seems that the structures do not influence the total yearly sediment transport flux in their landward side outside of the reach of sedimentation patterns when the dimensions and the distance to the dune foot are held within reasonable boundaries.

A suitable topic for follow-up research would be to validate this concept by deploying sand traps in the leeward side of an area with beach buildings and an area without. It is advised to measure the sediment flux in the leeward side with a large range of wind conditions. A study by Sutton and Neuman (2008) proposed that roughness elements allow sediment transport to occur at a lower wind velocity threshold than an unsheltered surface, and possibly enhance sediment transport in calmer conditions. While in more energetic conditions roughness elements suppress the sediment flux compared to unsheltered surfaces. Therefore, it is key that during such a study a broad range of wind conditions are taken into account in the measurements to rightfully convert them to a yearly sediment transport flux with meteorological data.

Validate vegetation hypothesis

An useful follow-up study could validate the observed relation between Marram grass growth and beach buildings by isolating distinct conditions in the field. This research proposes the following reasons for vigorous Marram grass growth adjacent to beach buildings: sheltering against salt spray and high wind stresses, and optimal sedimentation rates due to either alone or in combination the prevention of embryo dune development and sedimentation patterns caused by the physical presence of beach buildings. An inventorization in the field can be done to asses Marram grass vitality at site specific locations where these conditions are isolated.

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A
Additional literature

A.1. The Ammophila problem

Densely vegetated areas with Marram grass are found in locations where a recurring amount of sediment is deposited. While, a decline in sediment deposition causes the vitality of Marram grass to decline or even to die off. For over centuries the reason for this decline (increase) in vitality of Marram grass coupled with a decrease (increase) of sediment deposition has been debated by dune ecologists and is still not entirely known (Maun, 2009). An overview of current explanations is summarized below:

Explanations where no sedimentation takes place and leads to decrease in vitality Marram grass

- **Nutrient deficiency**, Willis (1965) proposed that the main reason for decline of Marram grass due to decrease of sedimentation was a deficiency of the macro-nutrients: nitrogen, potash and phosphorous. The hypothesis was tested by adding the previous-mentioned nutrients to Marram grass seedlings, this caused increased growth but the vegetation did not flower. While, sand burial promotes both vegetation growth and the flowering of Marram grass. Later Boudreau and Houle (2001) did a soil analysis in thriving and deteriorating Marram grass and concluded that the concentration of nitrogen in deteriorating Marram grass was three times higher than in thriving Marram grass. From this they concluded that the most obvious reason was the stimulated effectiveness of absorption of nutrients by Marram grass when sedimentation takes place.

- **Competition with other vegetation**, different studies proposed that due to inability of other vegetation types than Marram grass to grow in accretive conditions, competition is nonexistent (Salisbury et al., 1952). Consequently, when sedimentation through aeolian sediment transport starts to decrease, the habitat becomes suitable for other grasses than Marram grass and competition emerges unfavourable to Marram grass. However, there are also studies who contradict the contribution of competition emergence. Hope-Simpson and Jefferies (1966) found that in a habitat where Marram grass was the only vegetation species the vitality of Marram grass still reduces due to decreasing sedimentation.

- **Decrease of root production/depth**, Willis (1965) concluded that in a dune environment at lake Michigan Marram grass did not replace old roots for new ones when sedimentation did not occur. This resulted in less nodes and thus a decrease in opportunity for adventitious root growth. Furthermore, Marshall (1965) claimed that continuous root growth is essential for dune grass to thrive, because new roots are more efficiently in the absorption of nutrients than older ones. However, this argument is debated by a study by Hope-Simpson and Jefferies (1966), where only the bark of the older roots was lost, while preserving their functionalities.

- **Growing presence of organic matter**, Waterman (1919) found that Marram grass roots where unable to grow when decaying organic material was present. Therefore, the hypothesis was that roots where able to grow in an environment where sediment recently accumulated as decaying organic material was not present yet. However, also this conclusion was rebutted by a experimental study by Zaremba and Leatherman (1984) where organic matter did not lead to a decrease in Marram growth. Even an increase in growth was observed when they added algae litter, most probably because of the relative high concentration of nitrogen, which could lead to enhanced growth of the Marram grass.

- **Growth of damaging micro-organisms**, van der Putten et al. (1988) proposed that the decrease of vitality of Marram grass when there is no sedimentation present is because of the growth of damaging micro-organisms. This was confirmed with two types of studies. First, young Marram grasses were grown in sediment from the sea floor and from the rhizosphere from a dune where Marram grass thrived. The Marram grass in the sea floor showed significantly increased growth, here they inferred that because sediment that has recently originated from the sea floor did not contain micro-organisms yet it showed a large stimulation of growth in comparison to the matured sediment from the dune. Secondly, two samples of identical sand were taken from the rhizosphere from a dune with Marram grass, where one sample was sterilized and the other was not. The same experiment was performed for these two types of soils and the sterilized sand showed considerable more growth of the Marram grass, which confirmed the hypothesis. Later a study by De Rooij-van der Goes (1996) further confirmed the hypothesis and an effort to find the organism responsible for the observed growth was made. However, the study suggested that a combination of different organisms and not one individual organism is responsible for the decay. Nevertheless, this theory also has its critics. Maun (2009) in his turn poses three key arguments against the theory. First off, he states that the time for these organisms to move into the newly accreted sediment is much smaller than the time Marram grass needs to develop new roots. Second, when new roots develop they were directly infected by micro-organisms, this leads to an extra argument against the premises that the burial of sand safeguards the roots of Marram grass against micro-organmisms. Finally, Maun (2009) states that in the study by van der Putten et al. (1988) fertilizers were used for both soil samples, which could led to enhanced growth of the damaging micro-organisms through the fertilizers nutrients and therefore create an exaggerated degree of damage by the organisms in the study environment.

- **Decrease in Mycorrhizal fungi**, Boudreau and Houle (2001) stated that the growth of Mycorrhizal fungi is correlated to the root development of Marram grass. Mycorrhizal fungi is important for the growth of Marram grass as they provide the roots with phosphorous and other nutrients that stimulate plant growth (Maun, 2009). Little and Maun (1996) did an experiment to test the three key soil factors, harmful micro-organisms, degree of burial and Mycorrhizal fungi and their influence on plant growth. Their study rejected the statement that sedimentation allows Marram grass roots to escape from damaging micro-organisms. All experiments showed stimulation of leaf growth except the experiment where plants had been infected with harm-full micro-organisms prior to burial. While, Mycorrhizal fungi in combination with burial and infection of harmful micro-organisms showed stimulation in plant growth. From this they concluded that the presence of Mycorrhizal fungi was crucial to plant growth.

Explanation sedimentation stimulates growth Marram grass

- All studies available on the effect of sedimentation on vegetation growth agree on two things. First off, sand burial is strongly correlated with dune plant growth. Secondly, strongly weakened plant species can be reborn by the reoccurring of sedimentation. However, the reason why the burial of sand is positive for the growth of dune plant species is still heavily debated. Some studies point out one factor associated with sand burial. Others such as Eldred and Maun (1982) indicate that it is due to a combination of interactions between resources and abiotic factors. More specifically a episode of burial would stimulate plant growth due to increased soil volume, increase in soil resources, growth of Mycorrhizal fungi, hormonal response of the plant itself to sedimentation and increase in sink capacity.

B
Site visits

B.1. Images

(a) Side-view, static dune

(b) Pioneering vegetation, static dune

(c) Back dune, static dune

(d) Front view, static dune

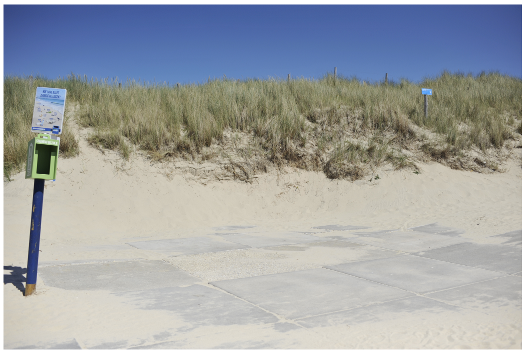
(a) Establishing foredune, dynamic dune

(b) Blowout, dynamic dune

(c) Back dune, dynamic dune

(d) Dune crest, dynamic dune

(a) Parking site behind pavilion



(b) Beach entrance

(c) Sand banquet large ribbon-development

(d) Redistribution of sediment to create 'plateau-like' building ground