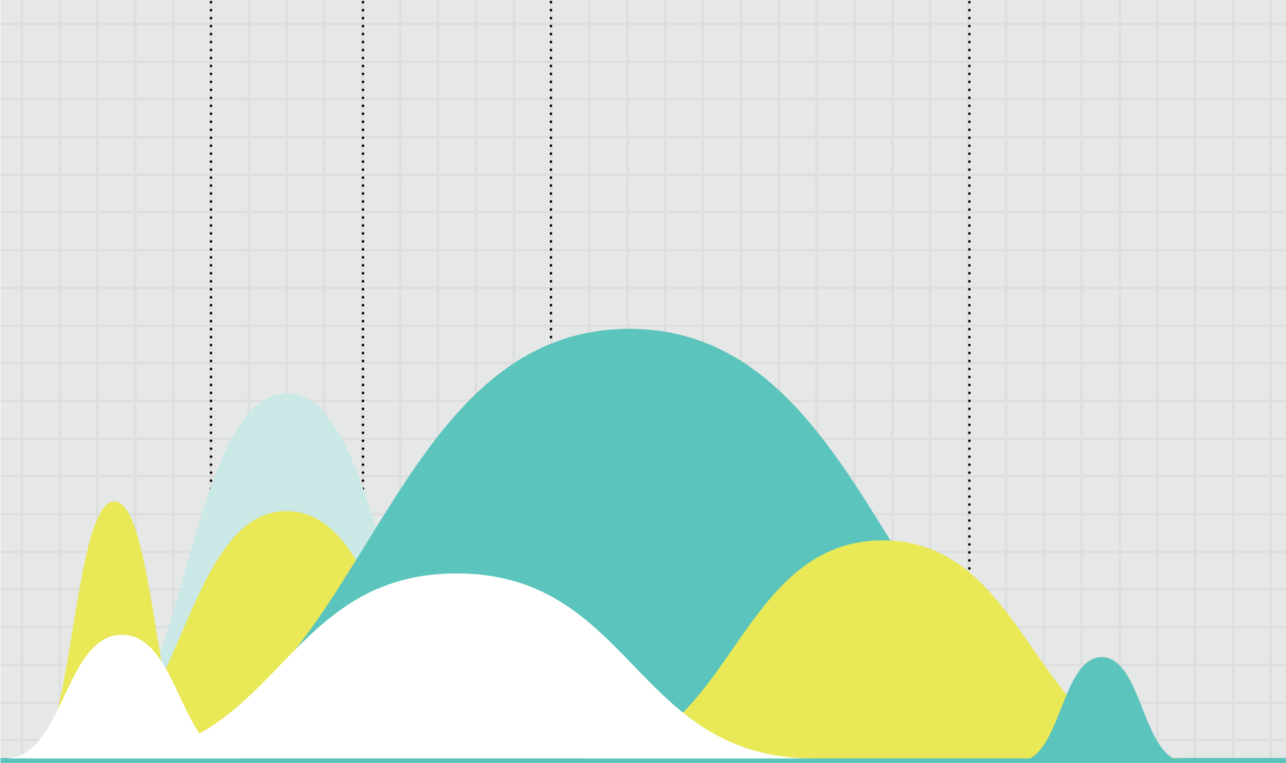

# BEACH-DUNE SYSTEMS NEAR INLETS

## LINKING SUBTIDAL AND SUBAERIAL MORPHODYNAMICS

Filipe Galiforni Silva

# Beach-dune systems near inlets

## Linking subtidal and subaerial morphodynamics

# BEACH-DUNE SYSTEMS NEAR INLETS

## LINKING SUBTIDAL AND SUBAERIAL MORPHODYNAMICS

DISSERTATION

to obtain
the degree of Doctor at the University of Twente,
on the authority of the Rector Magnificus
prof. dr. T. T. M. Palstra,
on account of the decision of the Doctorate Board,
to be publicly defended
on Thursday 25 April 2019 at 14.45

by

Filipe Galiforni Silva

born on 25 August 1989
in Suzano, São Paulo, Brazil

This dissertation has been approved by:

| | |
|---|---|
| prof. dr. K. M. Wijnberg | Promotor, University of Twente |
| prof. dr. S. J. M. H. Hulscher | Promotor, University of Twente |

Available online at `https://doi.org/10.3990/1.9789036547598`

Cover Design: Luiz Fernando Almeida da Silva (`https://www.behance.net/lfdestudio`)

Printed by: Ipskamp, Enschede, The Netherlands

Lay-out: *proefschrift* LaTeX template. Copyright 2014 Tim van Werkhoven (timvanwerkhoven@gmail.com)

ISBN: 978-90-365-4759-8

DOI: 10.3990/1.9789036547598

**Graduation committee:**

| | |
|---|---|
| prof. dr. G. P. M. R. Dewulf | University of Twente, Chairman/secretary |
| prof. dr. K. M. Wijnberg | University of Twente, Promotor |
| prof. dr. S. J. M. H. Hulscher | University of Twente, Promotor |

| | |
|---|---|
| dr. A. van der Spek | Deltares, Referee |

| | |
|---|---|
| prof. dr. V. G. Jetten | University of Twente |
| prof. dr. D. van der Wal | University of Twente |
| prof. dr. M. J. F. Stive | Delft University of Technology |
| prof. dr. ir. Z. B. Wang | Delft University of Technology |
| dr. A.C.W. Baas | King's College London |

This research is supported by the Netherlands Organisation for Scientific Research, Earth Sciences division (NWO-ALW), and co-funded by Hoogheemraadschap Hollands Noorderkwartier.

*The real risk is not changing. I have to feel that I'm after something. If I make money, fine. But I'd rather be striving. It's the striving, man, it's that I want.*

John Coltrane

*For my wife, Stephanie*

# Summary

Coastal dunes, tidal inlets, and beaches are among the most dynamic environments in geomorphology due to the influence of different energetic processes such as waves, wind, and currents over a relatively small area. If close to inlets, beach-dune systems may be affected by specific inlet processes that change beach characteristics and, consequently, coastal dunes. However, it is still unknown how and to what extent inlet-induced shoreline changes affect dune development. Therefore, the objective of this thesis is to understand how inlet-driven changes in adjacent coastlines affect dune development considering long-term inlet-driven changes (e.g. sand flats) and short-term inlet-driven changes (e.g. shoreline variability).

Regarding long-term changes, we found that the sand-flat geomorphological setting induces spatial variations in groundwater depths, which result in changes in sediment supply and, consequently, in coastal dune development. Moreover, results show that there is a threshold depth at which groundwater depth starts to affect dune development and that this threshold can vary spatially depending on topography. Furthermore, we found that on a sand-flat setting, storm surges may act as a depositional agent of sediment instead of an erosive agent as customarily thought. Results from both numerical modelling and field data show that supra-tidal shore-parallel deposition of sand occurs during storm surge flooding. Moreover, the amount of sand deposited is directly proportional to storm strength, and the amount of sand deposited suggests that it may add significant potential sand for aeolian transport and, consequently, dune growth.

Regarding short-term changes, we evaluated the effect of beach width changes and shoal attachment processes on a decadal time-scale. Us-

ing both numerical modelling and field data, we found that there is a preferred cross-shore position where the foredune tends to be built which is a function of beach width and sediment supply. For narrow beaches, foredunes tend to develop at higher elevations than wide beaches due to differences in wave dissipation during storm conditions, whereas dune volume is controlled by hydrodynamic erosion and dune recovery potential by sediment supply. Furthermore, if sediment supply is limited, the effect of beach width on dune volume only appears for beach widths larger than 300 meters, suggesting that limitation in supply can dominate dune growth on regular beaches. Furthermore, we found that cumulative shoal attachment events lead to increased rates of dune volume change, even though single attachment events did not necessarily yield an increase in dune growth. Moreover, we found that beach width increase and rate of alongshore sediment spreading of the shoal after attachment is key factors determining whether the shoal will or will not influence dune growth.

Therefore, inlet-driven processes and landforms may affect beach-dune systems nearby inlets by affecting how sand supply is exchanged by subtidal and subaerial zone and how it is distributed spatially. Sand-flats may create conditions that enhance the possibility of spatial variability in dune growth and morphology, with more supply and higher dunes in the exposed part. This is relevant especially in terms of coastal management since dune heights and resilience are a crucial aspect regarding coastal protection. Shoreline changes due to inlet-processes like channel migration and shoal attachment may affect supply and space for dune development, provided that timescale of beach width change is large enough to be translated into dune growth.

# Samenvatting

Duinen, zeegaten en stranden behoren tot de meest dynamische omgevingen in de geomorfologie, veroorzaakt door de invloed van verschillende processen zoals golven, wind en stromingen in een relatief klein gebied. In de buurt van zeegaten kunnen strand-duinsystemen beïnvloed worden door specifieke processen die de kenmerken van het strand en daarmee de duinen veranderen. Het is echter onbekend hoe en in welke mate deze processen van invloed zijn op de ontwikkeling van het duingebied. Het doel van dit proefschrift is dan ook om te begrijpen hoe veranderingen in de zeegaten de ontwikkeling van het duin beïnvloeden, rekening houdend met veranderingen op lange termijn (bv. zandvlaktes) en veranderingen op korte termijn (bv. variabiliteit van de kustlijn).

Met betrekking tot veranderingen op lange termijn hebben we vastgesteld dat de geomorfologische setting van zandvlaktes ruimtelijke variaties in de grondwaterdiepte beïnvloed, wat resulteert in veranderingen in het sedimentaanbod en daarmee in de ontwikkeling van de duinen. Bovendien blijkt uit de resultaten dat er een drempelwaarde is waarop de diepte van het grondwater de duinontwikkeling begint te beïnvloeden en dat deze drempelwaarde ruimtelijk kan variëren afhankelijk van de topografie. Verder vonden we dat op een zandvlakte, stormvloeden kunnen leiden tot depositie van sediment, in plaats van erosie zoals normaal gesproken wordt gedacht. Resultaten van zowel numerieke modellen als veldmetingen tonen aan dat kust-parallelle depositie van zand boven het getijdebereik optreedt tijdens stormvloedoverstromingen. Bovendien is de hoeveelheid afgezet zand direct evenredig met de stormsterkte, en de hoeveelheid afgezet zand suggereert dat het een aanzienlijk potentieel aan zand kan toevoegen voor eolische transporten en, als gevolg, duingroei.

Op korte termijn hebben we het effect van veranderingen in strandbreedte en de processen omtrent zandbanken op een tijdschaal van decennia onderzocht. Aan de hand van zowel numerieke modellen als veldmetingen vonden we dat er een voorkeurspositie aan de kust is waar de voorduin meestal wordt gevormd, welke afhankelijk is van de strandbreedte en het sedimentaanbod. Voor smalle stranden hebben voorduinen de neiging zich op grotere hoogte te ontwikkelen dan brede stranden door verschillen in golfdissipatie tijdens stormcondities, terwijl het duinvolume wordt beïnvloed door hydrodynamische erosie en duinherstelpotentieel door sedimentaanbod. Bovendien, als het sedimentaanbod beperkt is, is het effect van strandbreedte op het duinvolume alleen zichtbaar bij een strandbreedte groter dan 300 meter, wat suggereert dat beperking van het sedimentaanbod de duingroei op reguliere stranden kan domineren. Verder ontdekten we dat cumulatieve momenten van aanhechtingen van voorduinen leiden tot een verhoogde mate van verandering van het duinvolume, ondanks dat afzonderlijke gebeurtenissen dit niet lieten zien. Bovendien vonden we dat de toename van de strandbreedte en de mate van het langstransport van sedimenten van de voorduin na de aanhechting, belangrijke factoren zijn die bepalen of de voorduin al dan niet de duingroei zal beïnvloeden.

Als gevolg hiervan kunnen processen rondzeegaten en landvormen van invloed zijn op de strand-duinsystemen in de buurt van zeegaten door de manier waarop de zandaanvoer wordt uitgewisseld in de subgetijde en subaeriale zone, en hoe deze ruimtelijk wordt verdeeld. Zandvlakten kunnen omstandigheden creëren die de mogelijkheid van ruimtelijke variabiliteit vergroten in duingroei en morfologie, met meer aanbod en hogere duinen in het blootgestelde deel. Dit is met name relevant voor kustbeheerders, omdat duinhoogten en de veerkracht van het systeem een belangrijk aspect van kustbescherming zijn. Veranderingen aan de kustlijn als gevolg van processen rond zeegaten zoals migratie van geulen en de aanhechting van voorduinen kunnen van invloed zijn op het sedimentaanbod en de ruimte voor duinontwikkeling, mits de tijdschaal van de verandering van de strandbreedte groot genoeg is om te worden vertaald in duingroei.

# Acknowledgments

Finishing a PhD is an important milestone. You have the chance to develop your research skills and perform guided research within a topic that you like. Even though considered an individual achievement, it is remarkable to see how people around you play an essential role during this period in different levels and perspectives. With that said, I consider that it is important to thank everyone that was involved. It would be impossible to conclude this PhD without:

- The support, kindness, and love of my beloved wife, Stephanie. We took all the steps together during this time. She was with me during the happy and unhappy days. She even helped me in the field and with the ”the author” description. Her love inspires me to be a better person every day. I love you, Stephanie.

- My daily supervisor, Kathelijne. Her guidance helped me improve my research skills enormously. Also, she was always willing to help, discuss new ideas and talk about any topic with her usual friendly mood.

- My promotor, Suzanne. Her guidance and feedbacks were crucial, especially during the writing phase. Also, her managing and planning skills are examples that I will take for my whole career.

- Everyone who was involved in the CoCoChannel project. All meetings were always inspiring. Special thanks to Alma and all the good chats we had at the start of the project during my travels to Texel.

- The WEM group. Thank you all for the many coffee-breaks, soccer matches, lunch talks, conferences, Daghaps, and, of course, the Oktoberfest. A special thanks to Julliete (and Jared), Johan, Michiel, Andry, Isaac (and Vera), Leonardo, Juancho, Anke, Pieter, Marcela, Pepijn, Lara, Wenlong, Hero, Alejandro (and Maria), Angels (and Rodman), Hamideh (and Sattar).

- My good friends Juancho and Mireia, who helped me during my first months in the Netherlands, the always good company during lunch/dinners, late drinks and band rehearsals.

- My good friends Isaac and Leonardo, who shared lots of coffee-breaks and long discussions about everything but science. Also, Loretto (and Blanquita and Pelucita) and all her group mates who were always a pleasure to hang out with.

- My old bandmates Joep and Gerard (And Juancho as well), who we shared lots of fun, jam sessions, and drinks.

- The Brazilian community in Enschede, especially Lucas, Cris, Manoel, Beatriz, João, Isabel, Anderson, Milena, Liniker, Suellen, Felipe, Aline, André e Natália. Thank you for all the dinners and nice time spent together (even when Fernandinho was playing). Vai Corinthians!

- My family and long-time friends who were always available for a Skype/chat despite the time difference. Some of them even manage to come and visit our place in Enschede, which always gave us the warmth of good company. A special thanks to Nando, for the support with the cover, my parents Antonio and Laura, my sister Carol for all inspiring chats we had, even in difficult times, and Klaus for the always rousing welcome at home.

- Everyone that, in some stage, was involved directly or indirectly in this research.

- God, who was always there to remind me that his love is bigger than anything else and that his love must be shown to everyone surrounding me.

Thank you all for the support, love, help and fun times together.

# Contents

# CHAPTER 1

# Introduction

## 1.1 Beach-dune systems near inlets.

Coastal dunes, tidal inlets and beaches are among the most dynamic environments in geomorphology due to the influence of different energetic processes such as waves, wind and currents over a relatively small area (Sherman and Bauer, 1993; Fitzgerald et al., 1984). The behaviour of such systems is lead by bio-physical interactions that continually re-work the available sediment over time-scales of seconds to centuries. Among all coastal landforms that evolve from this integrated scheme (e.g. barrier islands, sea cliffs, tidal flats, and river deltas) (Luijendijk et al., 2018), coastal dunes, sandy beaches and tidal inlets have historically attracted humans and human activities due to their abundant occurrence and high economic, societal and biological values.

Coastal dunes can be defined as a natural wind-driven accumulation of sand that emerges in a coastal setting and are affected directly or indirectly by coastal processes. They are found in almost all latitudes and vary drastically in height, form and dynamics (Hesp, 2011; Martínez and Psuty, 2004).

Beaches are wave-deposited accumulations of sediment located between the shoreline and wave base (Short and Jackson, 2013; Wright and Short, 1984). The range of beach types is a result of a combination of wave energy, tidal energy and sediment composition, leading to wave-dominated, tide-modified and tide-dominated types of beaches.

Tidal inlets are major water channels that are maintained open by the action of tides, separating individual barrier islands, barrier spits and adjacent headlands (Hayes, 1979; Roos et al., 2013; Mulhern et al., 2017; FitzGerald and Miner, 2013). Tidal inlets are known by their importance in the exchange of water, sediment and nutrients between the ocean and the back-barrier basin (Fitzgerald, 1984). Furthermore, inlets are capable of storing and reworking a vast amount of sediment in their vicinity, developing great deposits of sand on both the seaside (i.e. ebb-tidal delta) and the basin side (i.e. flood-tidal delta).

Coastal stretches located close to inlets develop morphodynamic characteristics that comprise effects from inlets, beaches and dunes. Inlet processes can influence beach characteristics and morphodynamics, while beach characteristics affect subaerial processes and dune morphology and dynamics (Fitzgerald, 1984; Fitzgerald et al., 1984; FitzGerald, 1988; Short and Hesp, 1982; Fenster and Dolan, 1996). Thus, beach-dune systems near inlets can be defined as beach-dune systems that are directly or indirectly affected by inlet processes.

The current introduction is organised as follows: 1.2 shows the societaly importance of studies on beach-dune systems near inlets; 1.3 shows the current knowledge about these systems, highlighting what are tidal inlets, how they modify adjacent coastlines and how these changes affect beach-dune systems nearby; 1.4 shows currently unknown topics related to beach-dune systems near inlets; 1.5 states which problems are tackled in the current thesis and how they have been explored.

## 1.2 Relevance.

Coastal dunes, sandy beaches and tidal inlets are common worldwide. Estimates suggest that almost 15% of the world's coastlines consists of barrier islands (de Swart and Zimmerman, 2009). Considering that more than 70% of the world population lives in the coast (Bird, 2008), understanding the natural behaviour of coastal environments are necessary for sustainable and safe societal development.

Coastal dunes are also crucial in terms of coastal protection. Beaches and coastal dunes are vital for protection against storm surges. In the Netherlands, most inhabitants live below storm-surge level (Vellinga, 1982), and are protected from flooding by a combination of human interventions (e.g. control of water levels, sand nourishment) and the presence of sandy beaches and dunes (Stive et al., 2013; van der Nat et al., 2016; Oost et al., 2012; Borsje et al., 2011). Thus, the maintenance of sandy beaches and dunes are essential for coastal safety. Despite national efforts to maintain long-term coastal safety levels, sustainable approaches are under serious consideration to substitute long used approaches, especially within the relatively new "Building-with-nature" concept (de Vriend and van Koningsveld, 2012). Thus, gaining knowledge regarding coastal behaviour and specially beach-dune behaviour is crucial to find new sustainable ways to counteract undesired coastal behaviours.

Economically, coastal dunes have been used widely for tourism, water catchments and groundwater recharge, sand mining, housing and agriculture (Carter et al., 1992; Carter, 2013; Martínez and Psuty, 2004). Also, several types of fauna and flora are found on these sites, whereas intrinsic cultural and heritage values may also be present (Martínez and Psuty, 2004; Ab'Sáber and Bernard, 1953).

Tidal inlets are also common on barrier islands along the world, being important due to their use as navigation routes, sediment and nutrient exchange, tourism and ecological values (de Swart and Zimmerman, 2009). Shoal attachment and beach width changes due to inlet processes are particularly of interest to stakeholders. Shoal attachment processes can drive periods of local erosion and accretion of adjacent coastlines. In several cases, these areas are of high interest due to their societal or economic values. Furthermore, in countries like the Netherlands where coastal dunes are essential for coastal protection against flooding, it is necessary to understand how these coastline changes affect the adjacent coastal dunes and, therefore, whether measures have to be taken to maintain a local level of protection. Furthermore, erosional phases of coastline evolution due to these processes can affect the level of flood protection provided by the beach-dune system as well as the available area for societal activities (such as recreation, drinking water extraction, nature conservation).

## 1.3 Theoretical Background

### Subtidal morphodynamics near tidal inlets

Tidal inlets can be classified by the relative importance of tides and waves, resulting in states that range from tide-dominated to wave-dominated inlets (Hayes, 1979). Wave-dominated inlets have smaller ebb-tidal deltas than tide-dominated inlets, which tend to develop as pronounced channel margin bars instead of the shoals in from of the ebb jet (Carr-Betts et al., 2012).

In general, inlet morphology is composed by an ebb-tidal delta, a flood-tidal delta and its borders, which may be composed by barrier islands, sand spits, adjacent bedrock or glacial headland (Figure 1.1).

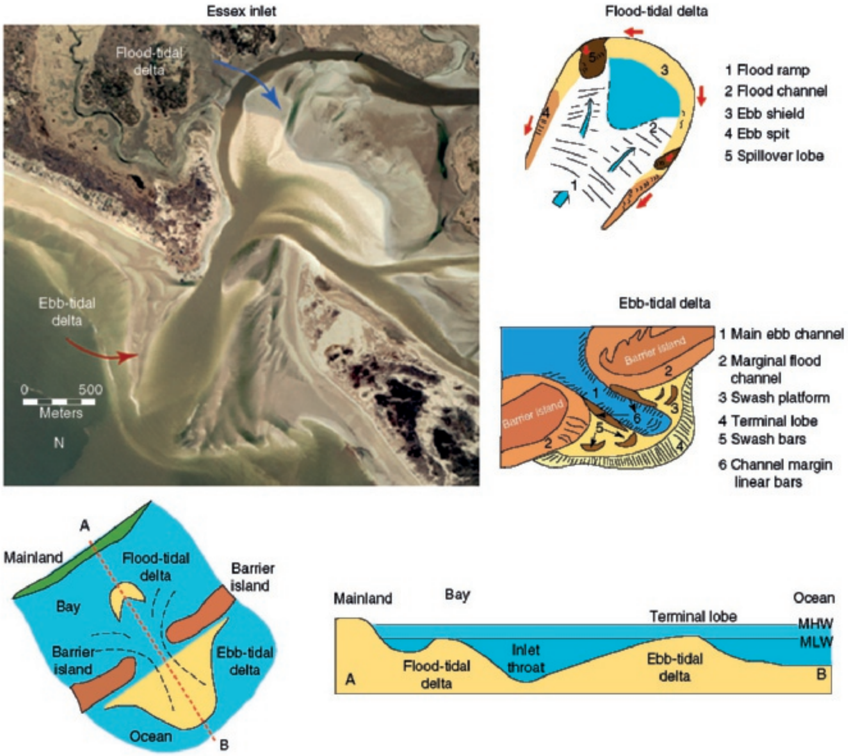

**Figure 1.1:** Overall morphological structure of an inlet system, highlighting ebb- and flood-delta models introduced by (Hayes, 1979). Reprinted from (FitzGerald and Miner, 2013)

At the landward side of the channel, flood-currents may form a sand deposit which is known as a flood-tidal delta. Its formation is defined by tidal range, wave energy, sediment supply and accommodation space (FitzGerald and Miner, 2013). It is composed by a flood ramp, flood channel, ebb-shield, ebb spit and spillover lobe.

At the seaward side of the channel, ebb-tidal currents, together with wave action, form a large sand deposit that is called ebb-tidal delta. The form of the ebb-tidal delta is conditioned by the relative balance between wave and tidal energy. The ebb-tidal delta is essentially formed by the main ebb channel, marginal flood channels, swash platform, terminal lobe, swash bars and channel margin linear bars. Wave-dominated ebb-tidal deltas develop close to the inlet mouth due to onshore wave-driven transport, which dominates over tidal flows. Tide-dominated ebb-tidal deltas develop as elongated bars that are much farther from the coast compared to wave-dominated inlets.

Tidal inlets are capable of retaining and reworking large amounts of sand in both short and long-term scales. Sand transport patterns can be divided in an onshore-offshore component, which is driven by tidal and wave-generated currents; and a longshore component, which delivers and removes sand from the tidal system and is mainly composed by wave-generated currents.

The tidal part of the onshore-offshore current is conditioned by the ebb and flood cycle. During the ebb-phase, currents accelerate at the inlet throat and decrease in the seaward portion, depositing sediment in the ebb-tidal delta region. When the tidal cycle reverses, landward currents initially enter through the marginal-flood channels, transporting sediment towards the back-barrier. Waves also are responsible for an onshore directed sand transport across the swash platform. As waves start to feel the bed, sediment will be put in motion by two main transport modes: bed load transport and suspended load. Waves start to shoal, and orbital motion of water particles start to turn into an ellipsoidal shape, stirring sediment to both directions (onshore and offshore) (Nielsen, 1981; Fredsøe and Deigaard, 1992; Aagaard et al., 2013). As waves become highly skewed, the net onshore component due to oscillatory motion is the highest, especially before wave breaking where steep leading faces of the waves result in strong fluid accelerations (Elgar et al., 1988).

The parallel component of the flow is mostly affected by the longshore current. Assuming a situation where waves approach the coastline obliquely, convergences/divergences of the mean momentum flux (radiation stress), together with associated breaking waves, will drive a shore-parallel wave-induced current called longshore current (Komar, 1998; Longuet-Higgins, 1970). Within the surf zone, longshore currents are responsible for transporting sediment parallel to the shore. As inlets induce a break in the alongshore transport, sediment bypasses the inlet by what is called sediment bypassing process. The longshore component is the main responsible mechanism for the inlet sediment bypassing process, which affects adjacent shorelines (Fitzgerald, 1984; Fitzgerald et al., 1984; FitzGerald, 1982, 1988; Fenster and Dolan, 1996). FitzGerald et al. (2000) divide mechanisms of sediment bypassing into three categories: stable inlet processes, ebb-tidal delta breaching and inlet migration and spit breaching, which all result in the transfer of a large amount of sand to the adjacent downdrift shoreline (Figure 1.2).

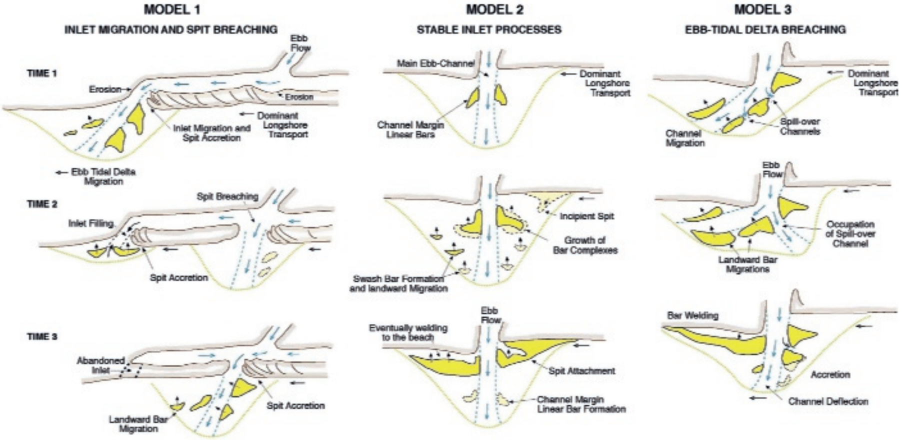

**Figure 1.2:** Mechanisms of sediment bypassing tidal inlets. Reprinted from (FitzGerald et al., 2000)

.

In general, longshore currents bring new sediment from up-drift, creating a closure trend in the inlet. Tidal currents are responsible for maintaining the channel open by creating shore-perpendicular currents that counterpose the closure trend. When inlets are naturally stable (tidal-driven processes dominates over wave-driven processes), sediment is transported into the main channel by longshore transport from the adjacent beach, flood-tidal flow in the marginal channels and wave action across the linear bars (Figure 1.2a). Once in the main channel, tidal currents will deposit this sand further in the ebb-tidal delta and flood-tidal delta. Wave action reworks the ebb-tidal delta and sand is transported landward by the periphery of the delta. Cumulative transport will create swash bars that will be further transported landward, creating a large bar complex that eventually attaches to the shoreline.

When inlets have a stable inlet throat but unstable (i.e. highly dynamic) main ebb channels, the main mechanism of sediment bypassing is called ebb-tidal delta breaching (Figure 1.2b). Longshore transport will produce a preferential accumulation of sand on the up-drift side of the inlet, deflecting the main ebb-channel down-drift. Such deflection would result in an inefficient channel configuration for tidal flow through the inlet, which would eventually result in a breaching on the ebb-tidal delta and, consequently, the development of a new main ebb-channel. As the new channel develops, the older channel tends to be filled by sand deposited in the up-drift side by longshore transport, which is now on large portions situated on the down-drift side of the new main ebb-channel. The remaining sediment that is not used to fill the former channel develops as a large bar system that is transported landward by wave-driven processes and, at some point, attaches the shoreline.

Lastly, when longshore transport largely dominates over the tidal component, deposition of sand on the up-drift will induce a spit formation and a migration of the inlet down-drift (Figure 1.2c). As the inlet moves down-drift, channel length increases and leads to significant water level differences between ocean and inner water body due to increased time needed to exchange water. Eventually, the spit is breached, forming a new inlet up-drift and leaving the former channel up to closure due to wave processes. Furthermore, not only the shoreline down-drift of the new opening already results in large amounts of bypassed sediment by the spit growth, but also wave-driven processes transport the former ebb-tidal delta landward.

The presence of a tidal inlet and an ebb-tidal delta, together with sediment bypass processes lead to effects on the adjacent shoreline in both the short-term and the long-term scales. In a long-term perspective, sediment bypassing may dictate the overall barrier form. Fitzgerald (1984) in a study in the East Frisian Islands, Germany, shows that sediment bypassing processes controls the overall shoreline shape, forming islands with bulbous ends and narrowest portions coinciding, in general, with their easterly down-drift ends. Fitzgerald (1984) also states that the location of the bar welding coincide with the bulbous portions, thus defining three different development models for those barrier islands: drumstick barrier island, humpbacked barrier island and down-drift bulbous barrier island. The location of the bar welding is conditioned by the size and morphology of the ebb-tidal delta, with the distance from the inlet increasing as the inlet size and down-drift skewness of the ebb-tidal delta increases. In the Wadden Sea, the formation of sand-flats on the vicinity of inlets is also associated with the long-term inlet and ebb-tidal dynamics (van Heteren et al., 2006; Elias and Van Der Spek, 2006).

In the short-term, phases of erosion and accretion of shoreline have been associated with inlet dynamics. Fenster and Dolan (1996) associated the spatial extent of the rate of change in shorelines adjacent to inlets with inlet dynamics, proposing zones on which inlet processes dominate shoreline variability and zones on which inlet processes influence shoreline trends. Furthermore, tidal pressure gradients along adjacent coastlines may account for a significant percentage of the total alongshore pressure gradient within the surf zone, which in turn may affect sediment transport patterns in this region (Hansen et al., 2013b,a). Despite the cyclical pulse of sediment due to welding of swash bars, onshore transport of these bars also may lead to erosive and accretive phases due to a protective role against waves, locally modulating longshore gradients (Robin et al., 2009).

### Subaerial processes: transporting the available sediment towards the dunes

As inlet-driven processes, together with nearshore processes, change beach characteristics (i.e. beach width, beach slope, grain size), it also affects subaerial processes at the beach, especially aeolian transport.

As sediment is transported into the swash zone, the wind is the principal agent responsible for transporting it further landward. In general, when the wind blows on the beach surface, it generates a boundary layer at the interface between air and surface. This region is slowed by friction resistance from the surface, generating shear stress at the beach surface which is proportional to the wind velocity (Shao, 2008). This induced shear stress may or may not exceed the threshold necessary to initiate motion of surface sand grains. When velocity is higher than the local threshold (i.e. shear stress produces lifting forces that are higher than retarding forces, namely gravity and inner-particle cohesive forces), stationary grains are put into motion towards the wind direction (Sherman and Bauer, 1993). Sand can move mainly by four transport modes (Figure 1.3): traction (grains that are not lifted but move by being dragged on top of other grains); saltation (grains are lifted and moved downwind by short distances after hitting the ground again); reptation (grains that are put in motion due to collision from fallen grains, leading to transport by velocities lower than the necessary to shift from a total stationary state); and suspension (once grains are lifted, they are carried through greater distances without bouncing back at the surface). When in a beach environment, sand may be put into motion by wind as long as it is exposed to wind action (thus, not submerged). Thus, sand may be put into motion starting from the foreshore (intertidal zone) up to the upper beach, depending on the thresholds for transport initiation.

The threshold that should be achieved to put grains in motion is not homogenous in the space-time domain. As specific characteristics change, higher wind velocities are necessary to put the grains into motion. The main limiting characteristics are grain size, surface moisture and the presence of crusts or biological matter (e.g. shells).

The influence of grain size is directly related to its influence on lifting forces. Driving lifting forces are related to wind shear near the

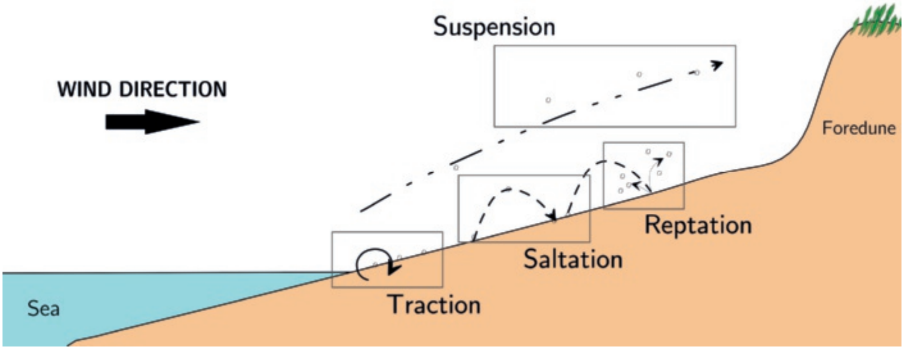

**Figure 1.3:** Schematic example of different transport modes initiated by aeolian forcing on a beach environment.

.

surface and hence are functions of the friction velocity. Under ideal conditions, threshold friction velocity can be expressed as a function of only particle size (Bagnold, 1941; Shao, 2008). For sand-size particles, it is possible to approximate the balance of forces only by aerodynamic drag and gravity force. Particle size will influence directly the former, which is a function of the friction velocity. As grain-size becomes smaller than sand, inter-particle cohesion forces cannot be neglected, and it leads to an overall increase in threshold velocity as a function of grain-size (Greeley and Iversen, 1985)

Surface moisture is one of the most important controls on the threshold for aeolian transport initiation (Houser and Ellis, 2013; Arens, 1996; Bauer et al., 2009). Moisture content increases sediment entrainment threshold, thus increasing the necessary stress to move a grain of sand from a static state (Bauer et al., 2009). When the moisture content is high enough, the wind is no longer capable of inducing sufficient stress to move the grains (Davidson-Arnott et al., 2008). Moisture content is controlled by a range of oceanographic (e.g. wave run-up, tides, wave spray), atmospheric (e.g. precipitation), or other processes (e.g. capillary rise from water table) (Davidson-Arnott et al., 2008; Houser and Ellis, 2013; Bauer et al., 2009). An important aspect of surface moisture is that it varies in both time and space, which may lead to variations in transport rate in both time and space (Delgado-Fernandez, 2010; Duarte-Campos et al., 2018). In the microscale, physical and biological crusts also can lead to a reduction of supply (Houser and Ellis, 2013). As water evaporates, this can lead to salt crusts on the beach surface that can limit aeolian transport. Moreover, the presence of surface shell layers also creates a physical limitation for aeolian transport to develop.

Short and Hesp (1982) link beach morphology with types of dunes emerging in the back-beach. The authors argue that the beach state has a direct consequence in the type of dune evolution in the back-beach, with dissipative states returning the highest rates of aeolian sand transport, whereas reflective beaches have a low potential of aeolian sediment transport. The beach state, together with hydrodynamic forcing will affect supply and, consequently, beach-dune interactions. Other aspects associated with beach morphology are beach width and slope. Beach slope is directly related to grain-size, modal wave height and wave period (Wright and Short, 1984). On the process-scale, bed slope influences transport capacity and threshold velocity for sediment motion (de Vries et al., 2012; Iversen and Rasmussen, 1994). For dunes, de Vries et al. (2012) found that dune volume changes are dependent to beach slope. Several studies have shown that beach width and beach morphology can control sediment supply (Bauer and Davidson-Arnott, 2002; Davidson-Arnott and Law, 1996; Hesp, 2002). Beach width controls supply, space and acts as a buffer for high energetic hydrodynamic events.

The cross-shore structure of aeolian transport is not homogenous. Field measurements have shown that transport rates change from zero to a saturated amount from the top of the swash zone up to some point downwind, where the rate ceases to increase (Bauer and Davidson-Arnott, 2003). Grains that start to be transported at some point at the beach induce an increased amount of grains downwind being transported due to collision effects that decrease the necessary threshold for grains to be dragged. Collision effect evolves exponentially into a cascade effect that increases the rate of transport downwind up to a saturation point, as long as the beach is wide enough. This is called fetch effect (Gillette et al., 1996; Bauer and Davidson-Arnott, 2003), and the distance where transport achieves saturation is called critical fetch distance. It is important to notice that the distance which wind act on the beach surface is not only a function of beach width but also wind direction related to the beach-normal component. That means that, when beach width is small, oblique winds will have a higher potential for aeolian transport than shore-normal winds.

In general, as sediment becomes available for aeolian transport, the wind is responsible for transferring this sediment toward the dunes. The sediment exchange depends on the balance between wind characteristics (e.g. speed and direction), beach morphology and limiting transport factors (e.g. surface moisture) and the synchronisation of proper conditions in time (Houser, 2009). Those processes are time-space dependent and consequently will have more or less influence depending on the scale of analysis. Variations in time and space may lead to variations on the total aeolian supply.

### Coastal dunes: building dunes from the sand supply

Coastal dunes may develop as long as there is sufficient sand supply from the sea, sufficient space at the beach for transport development and, usually, vegetation to capture the sediment (Hesp, 2002; Houser and Ellis, 2013). Variations in these conditions, together with climate and geological constraints will lead to different dune dynamics and morphology. Hesp (2002) suggest four main types of coastal dunes: foredunes, blowouts, parabolic dunes and transgressive dune fields. Here we will concentrate our discussion in foredunes only, which are the main focus of the current thesis.

Foredunes are shore-parallel ridges of vegetated dunes formed by aeolian transport in the back-beach (Hesp, 2002, 2011). They can be found on most coasts of the world and act as a vital landform for coastal defence against flooding and extreme surge levels. As sand is transported from the beach, wind deceleration due to the presence of vegetation, obstacles such as plant debris or wind gradients will lead to deposition of the sand in slabs (Hesp, 2011; Arens, 1996; Hesp, 1989). This will lead to the positive feedback that, assuming proper conditions of supply and vegetation growth, will lead to the development of a shoreline-parallel vegetated ridge named as foredune.

Foredunes can be distinguished in incipient and established foredunes. Incipient dunes (also known as embryo dunes or nebkah dunes), refers to the initial phases of dune development, prior to its full development as a shore-parallel ridge (Hesp, 2002; van Puijenbroek et al., 2017). Incipient dunes often develop as discrete patches of sand, and their development is closely related to vegetation. Plant densities will have a direct effect on wind, which will lead to more or less deceleration, turbulence and consequent deposition (Mohan and Tiwari, 2004; Hesp, 1983). Hesp (1983) found that vegetation density plays a more significant role than vegetation type on foredune formation in a case study in Australia. Furthermore, pioneer species of vegetation associated with incipient dunes are dependent on sand supply for continuous growth. Hesp (1989) shows positive feedback between vegetation and deposition. Thus, alongshore variations in both plant density and distribution may create alongshore variations in dune morphology (Hesp, 2011; Zarnetske et al., 2015; Goldstein et al., 2017).

Incipient dunes may evolve into established foredunes. Established foredunes are distinguished by changes in the types of vegetation. Vegetation in established foredunes has higher resilience in terms of environmental changes than vegetation usually found in incipient dunes (Martínez and Psuty, 2004). Furthermore, they usually do not require sand deposition for their growth.

Vegetation plays a big role in dune development. Plant seedlings and rhizomes often induce initial dune development, and plant growth and succession are crucial factors for dune development and establishment (Hesp, 2011). Furthermore, typical vegetation species will have an upper and lower limit of sand burial for its growth or decay, which varies between species (Maun, 2009; Van der Putten et al., 1993; Keijsers et al., 2015; van Puijenbroek et al., 2017). Thus, variables like climate (e.g. rainfall, sunlight), water table, wave interaction (e.g. swash, salt spray) are crucial for dune development.

Wave erosion is also a key part of foredune dynamics. Wave impact can lead to dune scarping, overwash and breaching (Sallenger, 2000; Hesp, 2002). Furthermore, wave impact may erode incipient dunes, resetting its growth stage. The rate of post-storm dune recovery, which is dependent on the ability of sediment transfer from the nearshore to the beach, is a crucial aspect of barrier island resilience and foredune dynamics (Houser et al., 2015). Duration and magnitude of the storm surge will determine the effect on the dune and, consequently, the time-scale needed for dune recovery. In that matter, the time interval between subsequent storms can also lead to an impact on foredune growth and dynamics (Houser and Hamilton, 2009). Nearshore characteristics such as the presence of bars, rip currents, and alongshore gradients on wave height can also lead to an alongshore variability in dune erosion and, consequently, alongshore variability in foredune dynamics (Castelle et al., 2015; Coco et al., 2014; Splinter et al., 2018).

## 1.4 Problem statements

Whereas a general framework for beach-dune systems regarding its development and dynamics is relatively well studied for open coastlines (Hesp, 2002; Houser and Hamilton, 2009; Hesp, 2011; Zarnetske et al., 2015; Houser and Ellis, 2013), beach-dune systems near inlets bring several other processes into account, such as shoal attachment, channel migration, inlet sediment exchange and the influence of the ebb-tidal delta in the wave processes. Besides that, due to the great diversity of barrier islands and their respective inlets (regarding e.g. morphology, geological background, sediment supply, space-time variability, oceanographic and meteorological forcing), it is hard to characterise and formulate conceptual models which include a large population of inlets and, therefore, its relations to the adjacent beach-dune systems (FitzGerald, 1996; Stutz and Pilkey, 2011).

Time-scales are essential to understand beach-dune systems near inlets. Over long-time scales (i.e. decades to centuries), the vicinity of an inlet is defined by long-term morphodynamic behaviour of the inlet system, which builds different characteristics of beach-dune systems. Dennis K. Hubbard (1979) published a model characterising the inlet morphology as a function of tide versus wave dominance. Tide-dominated inlets tend to present a deep main ebb-channel flanked by marginal linear bars, while wave-dominated inlets develop their ebb-tidal delta close to the inlet mouth. Between these two extremes, mixed-energy inlets may develop with merged morphological characteristics. Furthermore, Davis (2013) highlights the importance of adding more variables to the morphodynamic controlling factors, such as the tidal prism, sediment availability and sea-level change. Added to this, each inlet presents specific behaviour and, consequently, specific adjacent shoreline development. For example, sand flats may occur on the downdrift side of tidal inlets due to long-term patterns of shoal attachment, thereby defining suitable conditions for a non-uniform coastal dune-field development (e.g. Marsdiep Inlet – The Netherlands) (Elias and Van Der Spek, 2006; van Heteren et al., 2006). On the other hand, the adjacent shoreline can be influenced by a constant spit downdrift migration, which can develop conditions for a foredune-ridge sequence instead of a non-uniform dune field (e.g. Icapara Inlet - Brazil). Thus, different modes of morphologic development of adjacent coastlines may drive different conditions for dune growth. However, it is still unclear how these different types of dune morphologies near inlets precisely develop concerning inlet/ebb-delta dynamics.

Over shorter time-scales (i.e. years to decades), beach width variability and shoal attachment processes constantly change the beach-dune system. Several studies have shown that beach width and beach morphology can control sediment supply (Hesp, 2002; Bauer and Davidson-Arnott, 2002; Davidson-Arnott and Law, 1996), variability in sediment deposition on coastal dunes (Davidson-Arnott and Law, 1996; Burroughs and Tebbens, 2008; Keijsers et al., 2014), aeolian transport potential (Bauer and Davidson-Arnott, 2002; Delgado-Fernandez, 2010) and potential for dune erosion due to extreme events (Davidson-Arnott et al., 2005). However, few studies have addressed the effect of a time-varying beach width on dune evolution and integrated the beach width variability in a tidal inlet system context. Furthermore, shoal attachment and sediment bypassing directly affect beach morphology in coastlines close to inlets. Shoals have been recognised by their strong capacity of changing adjacent coastlines in several different temporal and spatial scales (Robin et al., 2009; Elias and Van Der Spek, 2006). Also, the cyclic behaviour of the shoals (Ridderinkhof et al., 2016) defines periods of sudden supply of sand to the adjacent coast, which may influence sediment supply to the dunes. However, little effort has been made to understand how these inlet-driven shoreline changes affect the development of coastal dunes.

In summary, it is currently unknown how inlet-induced shoreline changes may affect dune development across different scales. Long-term inlet-driven changes in the overall structure of the adjacent coastal landform may change conditions on which sediment exchanges between subtidal and subaerial zones. Localised changes due to inlet-processes like shoal attachment may also lead to long-term variability in supply that may change how dunes evolve in the area.

## 1.5 Objectives and research questions

The objective of this thesis is to understand how inlet-driven changes in adjacent coastlines affect dune development. In order to fulfil the proposed objective, four main research questions are proposed. Research questions 1 and 2 relate to effects on dune development of long-term changes in the adjacent coastline, focusing on sand flats built by long-term inlet processes (i.e. inlet-driven landforms). Research questions 3 and 4 relates to short-term changes in the adjacent coastline due to inlet processes, mostly related to sediment bypassing events (i.e. inlet-driven events).

1. How does the inlet-driven sand-flat setting influence dune development?
2. How is sediment exchanged between subtidal and subaerial zones in sand-flats close to inlets?
3. What is the effect of time-varying beach width for dune development at decadal scales?
4. How do shoal attachment processes affect dune behaviour at decadal scales?

## 1.6 Methodology

### Approach per research question

Different methods have been used for each research question, mixing analysis of field data from different sources with numerical modelling approaches. The methods applied for each research question are listed below.

1. To answer the first research question, we use long-term monitoring data of elevation on a sand-flat area, together with the application of a cellular automata model (DUBEVEG) developed to work in beach-dune environments. Here we focus mainly on how the effects of groundwater level, incorporated in the model, do induce different dune development over the sand-flat.

2. To answer the second research question, we use a combination of long-term data (e.g. elevation, water level, wave) with numerical modelling using a process-based model (i.e. XBeach) to evaluate scenarios where deposition onto the sand-flat occurs and discuss its importance for dune development.

3. To answer the third research question, we use an idealised modelling exercise to analyse how beach width changes, a common effect on coastlines adjacent to inlets, affect dune development. We use here the cellular automata model DUBEVEG. Real cases are also used for discussion purposes.

4. To answer the fourth research question, we use a combination of long-term data with idealised modelling of shoal attachment processes incorporated in the cellular automata model DUBEVEG. For this question, we focus on understanding the relationship between shoal attachment and dune development.

### Cellular automata models

Considering that three out of four research questions make use of the cellular automata model DUBEVEG, we further discuss the concept, applicability and advantages/disadvantages of such a modelling approach.

#### The cellular automata concept

Cellular automata models (CA) are a class of discrete numerical models which cells are disposed in an array and evolve through a finite number of possible states which are defined by feedback characteristics (Fonstad, 2013). It can be built in several dimensions, being the most common approach used the two-dimensional one. Cell states can change according to rules that account for information regarding the state of surrounding cells and the previous state of the cell itself. How the previous state of the cell, as well as surrounding cells, affect the state change is defined by what is called transition rules.

Transition rules are meant to control the dynamics of the system. They control whether the cell will change or not and if so, to which state. They can be solely internal, accounting only by internal characteristics of each cell (e.g. cell state of its surroundings), or also add some external aspects, which are addressed separately in each iteration (e.g. presence of a region where states are not allowed to change). Mathematical functions are used to control cell state transition and can be as complex as desired to achieve the aim of the model. To create a meaningful CA model of a natural system, a physical rationale for the mathematical functions representing each transition rule are of great importance. Transitions should be based on general rules or empirical estimates based on measurements and must account for all necessary processes important for the appearance of the desired pattern/phenomena.

The way neighbouring cells interact can also be different, ranging from Von Neumaan and Moore, or even a mixed way of iteration (Figure 1.4). The choice of neighbourhood rules depends on the tessellations of space chosen and the purpose of the model.

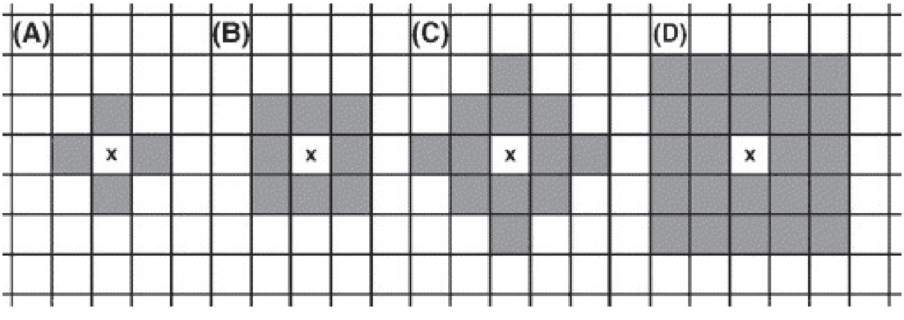

**Figure 1.4:** Examples of possible local neighbourhoods. Reprinted from (Fonstad, 2006)

.

Although CA models can be highly different depending on their main goal, Fonstad (2013) in his review about the use and challenges of cellular automata model in geomorphology highlights six main aspects that crosses among all CA applications: (1) the presence of a space of discrete cells, which can vary from 1 to several dimensions; (2) cells are tessellated in a lattice order, which can vary from triangular to square or hexagonal cells; (3) boundary effects, since cells in the border will not have the same number of neighbor cells; (4) cell states are discrete and not continuous; (5) the neighborhood concept; and (6) the transitional rules.

Main advantages of Cellular automata modelling are its flexibility and range of modelling possibilities with a relatively low computer effort. Rules are usually easily adaptable, and cellular automata can be efficiently written in several applications or programming environments. Furthermore, it is possible to couple different types of models within the CA scheme, as long as transition rules and space-time scales are taken into account.

### Cellular automata in coastal research

Cellular automata models have been used across several knowledge branches in Earth sciences in which self-organisation concepts emerge as the system develops in time, such as in ecology and vegetation dynamics, hydrology and geomorphology (Mendicino et al., 2013; Hyandye and Martz, 2016; Smith, 1991; Hogeweg, 1988; Fort, 2013; Baas, 2002; Chase, 1992; Coulthard et al., 2007; Balzter et al., 1998). In coastal systems, cellular automata models can be seen as a valuable tool since the coastal zone is categorised as a non-linear dissipative complex system due to its energy dissipation properties (wind and wave) and its non-linear interactions between morphology, sediment transport and fluid dynamics (Baas and Nield, 2007).

The best-known application of self-organisation concept and cellular automata models in coastal research is the long-discussed occurrence of beach cusps. The discussion started with Werner and Fink (1993), with their model introducing a new mechanism to explain the appearance of beach cusps by self-organisation, in detriment of the edge-wave theory introduced by Guza and Inman (1975). Several studies followed, with the application of CA models to understand beach cusps, coastline evolution and the significance of self-organisation concepts on coastal processes evolution (Coco, 2003; Ashton et al., 2001; Coco et al., 2000; Coco, 2004; Coco and Murray, 2007; Dearing et al., 2006). The self-organisation and cellular concept have been applied also in the estuarine setting (Bentley and Karunarathna, 2012; Dearing et al., 2006; Bentley, 2016), coastal dunes (Werner, 1995; Baas and Nield, 2007; Nield and Baas, 2007; Baas and Nield, 2010; Zhang et al., 2010), offshore sand waves (Knaapen et al., 2013) and beach-dune dynamics (Zhang et al., 2015; Keijsers et al., 2016; Barrio-Parra and Rodríguez-Santalla, 2014).

Interest in beach-dune modelling has been increasing in the past decades, mainly due to climate change, sea-level rise and land-use adaptations foreseen in the coming decades. Researchers are trying to solve the puzzle of upscaling and uncertainty, leading to efforts to develop tools that effectively predict dune development in the coming decades. Processes-based models and CFD tools have been emerging, as well as the use and development of cellular automata models. In one hand, we need to deal with considerable uncertainties in long-term simulations due to system non-linearities. Increasing small-scale accuracy does not necessarily mean better predictions in the long-term due to the system non-linearities. In that sense, cellular automata models present a smart bottom-up solution for complex systems, where simple interactive processes in the microscale evolve into macroscale patterns. However, although useful to understand feedback processes and system behaviour, it is unlikely that translation into the quantitative simulation for real cases could be done due to the level of simplification and lack of direct validation tools, leading to the same level of quantitative uncertainty.

Cellular automata models are meant to understand the behaviour and interaction of different processes, and how it translates into patterns in the longer-scale. Although rules can be thought of as over-simplified and common ground rules from process-based models may be overlooked, it can be useful to understand qualitatively how the system might behave due to certain conditions, such as shoreline behaviour and feedback interactions of different processes in coastal research. Qualitatively, CA models have been proved to be a useful tool, if thought and applied for what it is meant for.

The present thesis heavily relies on a cellular automata model developed to work in a land-sea interface that has been used in an idealised, exploratory way in order to understand basic relations and qualitative controls on beach-dune interaction in systems near inlets. It is the first attempt of applying such kind of modelling in such systems where beach dune systems are also subject to inlet processes.

## 1.7 Thesis outline

Each of the four research questions relates to one separate chapter. chapter 2 addresses RQ 1, with the main focus on spatial variability in groundwater levels and its effects on dune development in sand flats. chapter 3 addresses RQ 2, analysing storm-induced deposition on sand flats and how important they are for dune development. chapter 4 addresses RQ 3, focusing on beach width variability and its consequences for dune dynamics. chapter 5 addresses RQ 4, focusing on shoal attachment processes and their effects on dune development. chapter 6 presents a discussion, where the limitations of the present research are discussed, as well as an integrated overview of the main findings. chapter 7 presents the overall conclusions and recommendations for future research.

## CHAPTER 2

# The influence of groundwater depth on coastal dune development at sand flats close to inlets[1]

### Abstract

A cellular automata model is used to analyse the effects of groundwater levels and sediment supply on aeolian dune development occurring on sand flats close to inlets. The model considers, in a schematised and probabilistic way, aeolian transport processes, groundwater influence, vegetation development and combined effects of waves and tides that can both erode and accrete the sand flat. Next to three idealised cases, a sand flat adjoining the barrier island of Texel, the Netherlands, was chosen as a case study. Elevation data from 18 annual LIDAR surveys was used to characterise sand flat and dune development. Additionally, a field survey was carried out to map the spatial variation in capillary fringe depth across the sand flat. Results show that for high groundwater situations, sediment supply became limited inducing formation of Coppice-like dunes, even though aeolian losses were regularly replenished by marine import during sand flat

---

[1] Chapter published as: Galiforni Silva, F., Wijnberg, K.M., de Groot, A.V. and Hulscher, S.J. (2018). The influence of groundwater depth on coastal dune development at sand flats close to inlets. Ocean Dynamics, pp.1-13.

flooding. Long dune rows developed for high sediment supply scenarios which occurred for deep groundwater levels. Furthermore, a threshold depth appears to exist at which the groundwater level starts to affect dune development on the inlet sand flat. The threshold can vary spatially depending on external conditions such as topography. On sand flats close to inlets, groundwater is capable of introducing spatial variability in dune growth, which is consistent with dune development patterns found on the Texel sand flat.

## 2.1 Introduction.

Inlet processes can define several types of barrier island terminus-shapes (Fitzgerald, 1984; van Heteren et al., 2006; Mulhern et al., 2017). For barrier islands at the Dutch Wadden sea region, terminus-shapes are typically developed as wide sand flats. Those sand flats are large (scale of km) flat accumulations of sand built by inlet processes that face both the sea and the inland basin. Due to their overall setting, such areas have great potential for dune growth and development due to their beach width size, wind velocity and climate (Bauer et al., 2009; Houser and Ellis, 2013). However, not all sand flats promote dune growth or show similar dune development patterns. Spatial-variation of dune development across a single sand flat is not uncommon, as various dune types and growth rates can be seen onto the same sand flat.

Sand supply, surface moisture, vegetation characteristics and wind velocity are, among others, characteristics that can drive spatial variations in coastal dune development, although just a few studies have been published on sand flat environments (Hesp, 2002; van Heteren et al., 2006; Poortinga et al., 2015; Engelstad et al., 2017; van Puijenbroek et al., 2017). Zarnetske et al. (2015) argue that, for a straight beach, vegetation and sand supply are important factors that control foredune morphology, depending on the time-scale considered and coastline position variability. Regarding sediment supply, some authors have suggested that water table depth and consequently surface moisture are important determinants for sediment supply and, consequently, for dune development (Hesp, 2002; Bauer et al., 2009; Poortinga et al., 2015).

Surface moisture is known to affect aeolian sediment transport, which on natural beaches can be related to groundwater levels (Arens, 1996; Yang and Davidson-Arnott, 2005; Oblinger and Anthony, 2008; Bauer et al., 2009; Houser and Ellis, 2013). Water table fluctuations, which are related to several atmospheric (e.g. pressure, precipitation) and oceanographic (e.g. tidal cycle, wave run-up) variables, influence the variability of surface moisture and hence the potential for aeolian transport (Yang and Davidson-Arnott, 2005; Darke and Neuman, 2008; Houser and Ellis, 2013; Poortinga et al., 2015). In a study on the Dutch island of Ameland, Poortinga et al. (2015) suggest that high groundwater levels can be supply limiting in an event scale (i.e. length of days), and therefore limit the amount of sand available for aeolian transport. Water table levels are often higher than the tidal elevation, and this effect (termed overheight) behaves in inverse proportion to beach face slope and sediment size but is directly proportional to tidal range and wave infiltration (Turner et al., 1997; Horn, 2006). On sand flats where the slope is close to zero, amplitude fluctuations of the water table tend to be at a minimum, whereas lag between water table and tide tend to increase landward (Horn, 2002; Zhou et al., 2013).

Considering that the behaviour of the water table levels and the seepage exit point along the sand flat coastline can vary along the flat due to spatial morphological variations, spatial-variations in groundwater levels could potentially lead to variations in the amount of sediment available for aeolian transport. Thus, it can lead to spatially different types and rates of dune development along the same stretch of coast. However, no studies so far have related variations on dune development with potential spatial variations of groundwater levels on a sand flat setting. Therefore, the aim of this study is to improve current understanding of the spatial-variability of dune development on sand-flats, based on the hypothesis that spatial-variability of dune development is affected by groundwater levels and consequently by sediment supply spatial-variations. Given the focus of the present study on understanding trends emerging from local conditions and feedbacks, a cellular automata approach is chosen to test this hypothesis. Cellular automata models have been considered as a primary choice of simplified modelling in geomorphology due to the balance between flexibility and range of modelling possibilities with a relatively low-computer effort (Fonstad, 2006, 2013). Thus, the cellular automata model DUBEVEG (Keijsers et al., 2016) has been used to analyse dune development on both idealised and realistic case scenarios.

This chapter is organised as follows. In section 2, the model is described. In section 3, chosen cases are described. In section 4, idealised cases are tested under a range of conditions involving groundwater levels and initial topographic scenarios to evaluate the effects of groundwater level in a controlled environment. Further, the acquired insights are tested on a real case study on a real sand flat (Figure 2.1), where patterns, similarities and mismatches found on real datasets are evaluated and discussed.

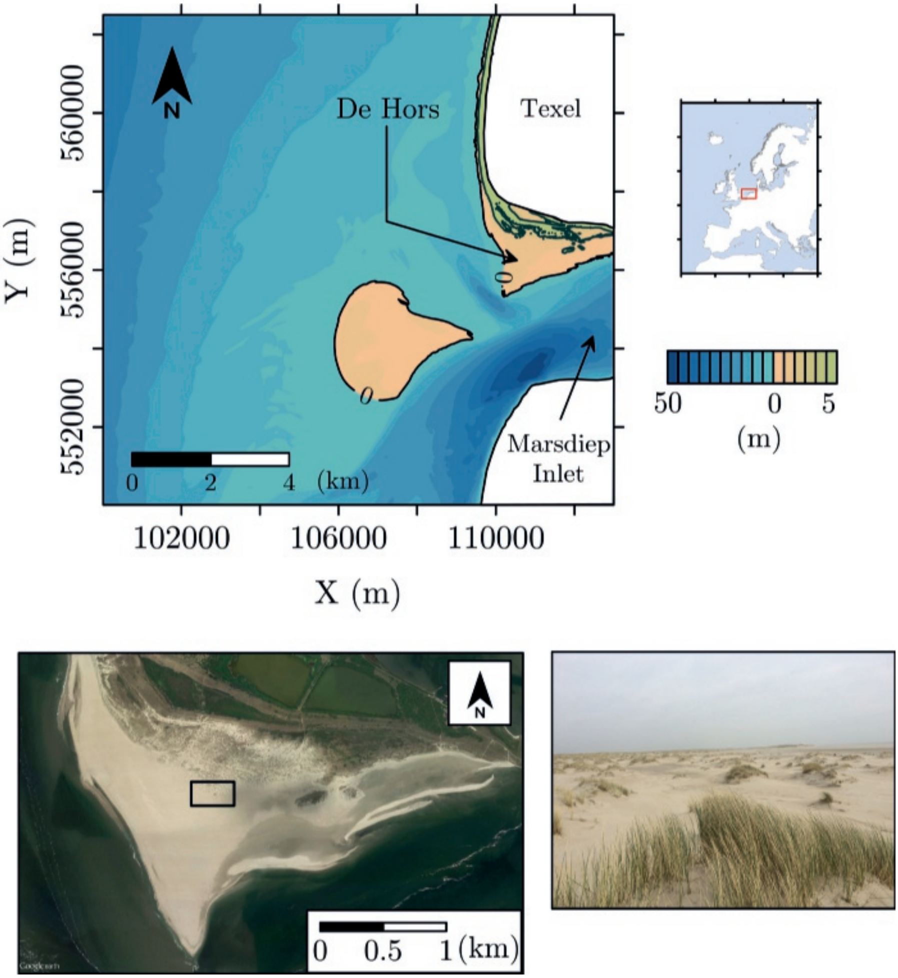

**Figure 2.1:** Study area. Upper panel shows the overall setting for the inlet and the sand flat. Lower panel show a satellite photography from Google Earth, highlighting differences on height and moisture, as well as a picture taken from the Coppice-shaped dune field (highlighted by the black rectangle)

## 2.2 The DUBEVEG model.

The DUBEVEG model (DUne, BEach and VEGetation, (Keijsers et al., 2016)), based on previous models proposed by Werner (1995) and Baas (2002), simulates beach-dune development considering aeolian sand transport, groundwater influence, biotic processes related to vegetation, and hydrodynamic sediment input and erosion in a probabilistic rule-based approach (Figure 2.2). Rules control the probability of discrete sand slabs being eroded, transported and deposited over a cellular grid domain. A ’sand slab’ is the model representation of a standard volume of sand, which can be visualised as a square flat box. All the rules are intended to represent complex processes by capturing the essential interaction between factors and variables that are important for dune development in coastal areas. Small scale interactions and feedback processes tend to result in emergent large-scale patterns and trends (Baas, 2002; Nield and Baas, 2007).

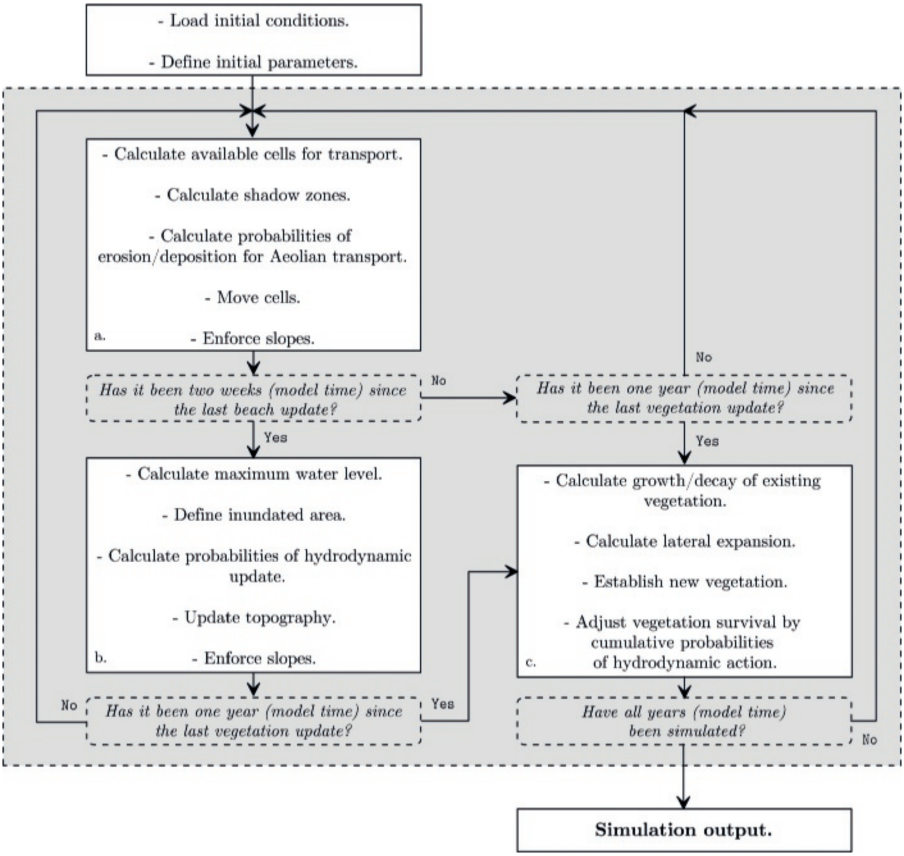

**Figure 2.2:** Model outline, highlighting the Aeolian module (a.), the hydrodynamic module (b.) and the vegetation module (c.), with the main processes and possible interaction scenarios

Individual slabs displaced over the domain are picked stochastically, based on a probability of erosion $\mathrm{P_e}$ and transported downwind by a hop distance $D$. Based on a deposition probability $P_d$, the individual slabs can either be deposited or transported a hop further. The iteration finishes once all moving slabs have been deposited. Both $P_e$ and $P_d$ values depend on the state of the cell on each iteration (e.g. vegetation cover or bare sand) and the surrounding cells (e.g. situated on a shadow zone). The model also accounts for avalanching due to angle of repose.

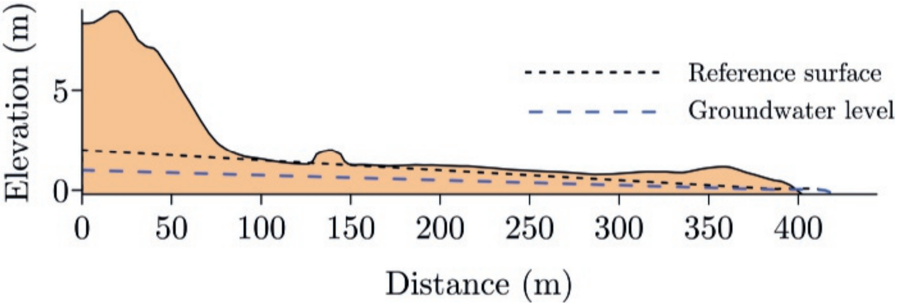

**Figure 2.3:** Groundwater concept applied in the DUBEVEG model.

The height and width of each square slab are predefined and can be related to a real-world scenario based on a potential aeolian transport per meter alongshore Q (m3/m/y):

$$Q = H_s \times L \times (P_e/P_d) \times n \tag{2.1}$$

where $H_s$ is the slab height (m), $L$ is the cell width (m), $P_e$ is the erosion probability, $P_d$ is the deposition probability and n is the number of iterations over one year (Nield and Baas, 2007; Keijsers et al., 2016).

Vertically, the amount of sand available to be transported depends on a pre-defined mean sea level and a groundwater level. In the model, the groundwater level represents the depth on which the degree of water saturation is sufficiently high to cancel any aeolian sediment transport. In reality, this level may vary to somewhere in between the vadose (or intermediate) zone and upper capillary fringe. Hence, the groundwater level is defined as an elevation proportional to a predefined reference surface, ranging from 0 (groundwater at mean sea level, thus farther from the surface) to 1 (groundwater level equals the reference surface) (Figure 2.3). Values are dimensionless, and refer to the proportion relative to the surface rather than groundwater depth and are used throughout the text to avoid misinterpretations relative to elevation/depth of the groundwater.

The hydrodynamics module represents the re-arrangement of the beach topography due to the action of the sea. For each inundated cell, a probability to return to its reference level is given

$$P_{\mathrm{hydro}} = (1 - R_{\mathrm{v}}) \times ((W_{\mathrm{E}} - W_{\mathrm{diss}}) + P_{\mathrm{inun}}) \times S \tag{2.2}$$

where $R_v$ is the resistance to erosion due to the vegetation V, $W_E$ is the maximum erosive strength of the waves, $W_{\mathrm{diss}}$ is a cumulative dissipation factor based on an inverse function of the remaining water depth in the cross-shore direction, $P_{\mathrm{inun}}$ is the probability of bed level change due to the inundation regardless of the presence of waves and S is the stochasticity term representing unaccounted or unpredictable conditions (e.g. grain size variability, wave/current interactions). Cell inundation and wave action also depends on the position relative to the surrounding topography (i.e. wave sheltering). The hydrodynamic module accounts for both sand erosion and accretion by the sea. For the inundated grid cells selected to change, the topography $Z_{\mathrm{topo}}$ returns to its reference level $Z_{\mathrm{eq}}$. If $Z_{\mathrm{topo}} < Z_{\mathrm{eq}}$, sediment input from the sea occurs (i.e. addition of sand slabs), whereas hydrodynamic erosion occurs (i.e. removal of sand slabs) when $Z_{\mathrm{topo}} > Z_{\mathrm{eq}}$. The amount of sand slabs introduced and removed are summed and represents the net sea input per iteration. This module runs after a number of iterations that represents two weeks in order to mimic a full neap-spring tide cycle. It uses a cumulative probability curve of daily maximum water levels to define a water level at each hydrodynamic iteration, whereas wave run-up estimates are based on empirical relations described in Stockdon et al. (2006). The empirical relation is chosen for consistency with the rule-based approach used in the model, since the model does not account for wave transformation equations to solve and estimate run-up. Combined, these determine the maximum water level that occurred in a two-week period, hence the topographic area subject to be affected by marine processes.

The vegetation module mimics the growth and decay of species that are common on dune systems by means of growth curves. The curves describe the growth rate or decay as a function of bed level change.

**Table 2.1:** Summary of the standard values used on the simulations. Most values used are based on Keijsers et. al. (2016)

| Parameter | Value | Unit |
|---|---|---|
| Cell width (Idealized) | 1 | (m) |
| Cell width (Real case) | 5 | (m) |
| Cell height | 0.1 | (m) |
| Probability of deposition of a bare sandy cell ($P_d$) | 0.1 | - |
| Probability of erosion of a sandy cell ($P_e$) | 0.5 | - |
| Shadow angle | 15 | degrees |
| Resistance to erosion due to vegetation ($R_v$) | 0.8 | - |
| Probability of bed level change due to inundation ($P_{inun}$) | 0.1 | - |
| Dune Sheltering | 0.8 | - |
| Wave dissipation strength | 0.012 | - |
| Time step Aeolian module | 50 | iterations per year |
| Time step Hydrodynamic module | 25 | iterations per year |
| Time step Vegetation module | 1 | iterations per year |

The vegetation is incorporated as a dimensionless value named vegetation effectiveness (Nield and Baas, 2007), which represents the effect of vegetation on the aeolian sand transport and can be related conceptually to vegetation cover. In the model, two vegetation types are defined: a pioneer species (e.g. *Ammophila sp.*) and a conservative species (e.g. *Hippophae rhamnoides*). Pioneer species show optimal growth when buried to some extent, but have less capacity to survive erosion events. The conservative species are more resistant to losses of sand and present optimal growth in neutral conditions (i.e. no bed level change). Establishment of new vegetation on bare cells and lateral expansion are included in the model, following Keijsers et al. (2016). The vegetation component not only adds a determinant factor for dune development, but also establishes a direct scale in time and space for the model due to the physiological characteristics incorporated indirectly on the growth curves, thus making comparisons to real-cases possible (Nield and Baas, 2007). Values used for all the simulations can be found in Table 2.1.

## 2.3 Case studies.

### Idealised cases

For the idealised cases, three domains are built and used to represent distinct situations that are present on the sand flat of De Hors. Case 1 represents the more wave-sheltered situation on the tidal basin side of the sand flat (East). Case 2 and 3 represent the sea side of the sand flat which is more exposed to wave attack, and differ in their initial topography by the presence/absence of a foredune. A summary of the scenarios can be seen in Table 2.2.

Case 1 has a domain size of 200 x 200 meters, and is defined as a horizontal surface at 1.3 meters above MSL with a small vegetated dune in the middle. The reference surface used is a plain domain of 1.3 meters above MSL, without any dune. Since the eastern section is sheltered from waves, the wave energy is initially settled at its minimum to account only for small erosive effects that can happen during storms. The wind is considered to be unidirectional, from west to east (left to right, in the model).

For case 2 and 3 (without and with a foredune) the initial elevation is based on two cross-shore profiles (400 meters long) derived from the 1997-LIDAR survey (a northern profile, with a foredune, and a profile located on the sand flat, without dunes), which were repeated over a distance of 200 meters alongshore. The reference surface is based on the initial topography without any dunes for both cases. The wave forcing is present and is directed from west to east, with wave dissipation starting at a water depth of 2 meters. For all idealised cases, initial values of vegetation effectiveness are assigned randomly with values between 0 and 0.5 at slabs higher than 2 meters above MSL and 0 at slabs less than 2 meters above MSL. All simulations have a time-span of 15 years. Water level input series were based on a tide gauge available at the harbour of Den Helder, on the opposite side of the inlet, and used for all cases.

For all cases, runs with groundwater levels ranging from 0 to 0.9 were carried out, and the final topographies after 15-year simulation were analysed and compared with respect to the type of dune morphology, dune volume, average crest height, crest spacing, 75% and 95% eleva-

**Table 2.2:** Summary of the simulated scenarios.

| Case | Location based | Type | Wave Action | Initial condition | Initial topographic characteristics |
|---|---|---|---|---|---|
| 1. | East | Idealised | Minimal | Idealised | Small dune in the middle |
| 2. | West (without foredune) | Idealised | Maximum | Simplified 1997 LIDAR-based | No dune present |
| 3. | West (with foredune) | Idealised | Maximum | Simplified 1997 LIDAR-based | Foredune on the landward position |
| 4. | Case study | Real case | Maximum | 1997 LIDAR-based | Distinct dune types based on topographic data |

tion percentiles and extent of dune area. For dune volume and dune area calculations, the 3-meter elevation contour is used to define the dune foot. Tests using different contours have been done, resulting in trends similar to those for 3-meter contour. Elevation percentiles are another statistic method to characterise the size of the aeolian topography that develops, e.g. a 75% elevation percentile value of 3 meters means that 75% of the elevation nodes are smaller than 3 meters.

### De Hors

The island of Texel, the westernmost island in a chain of barrier islands in the North of the Netherlands, was chosen for the realistic case. On its southern side, bordering the inlet, there is a sand flat (*de Hors*) of roughly 3 $\mathrm{km}^2$, where coastal dunes have been forming over the last decades. The inlet is a mixed-energy wave dominated inlet called the *Texel* inlet, with a predominant wind direction from southwest (Figure 2.1). Large parts of the plain are above the mean spring high tide level, being flooded only during energetic events. Morphologically, the sand flat can be divided into three sections: one particularly exposed to waves, a central region, and an inner part facing the basin (Figure 2.4a). In general, coppice-like dunes are found in the central part, whereas a continuous dune row with several small incipient dunes can be seen on the exposed and inner parts. Regarding grain size, recent surface sampling showed grain sizes ranging between fine to medium sand, with $\mathrm{D}_{50}$ values ranging from 210 to 395 $\mu$m.

For the realistic case, the initial elevation is based on the 1997-LIDAR survey at 5-meter grid resolution. Since the flat has shown low interannual variability in its height throughout the previous 18 years (Figure 2.4b), the reference surface was based on a smoothed version of the 1997-LIDAR survey using a Gaussian low-pass filter to remove any dune feature. The wind is considered unidirectional, from south to north (bottom to upper side in the model), to approximate the dominant wind direction. Like the idealised cases, initial values of vegetation effectiveness are assigned randomly with values between 0 and 0.5 for slabs more than 2 meters above MSL and 0 at slabs less than 2 meters above MSL. All simulations have a time-span of 15 years. Water level input series were based on a tide gauges available at the harbour of Den Helder, close to the sand flat. Like the idealised cases, groundwater scenarios ranging from 0 to 0.9 have been tested and the results compared to the actual data in terms of dune morphology, dune volume and dune area.

Detailed topographic data (5X5 meter grid) from 1997 to 2015 was used to evaluate the morphological evolution of both the sand flat and the dune area and compared with the model outputs. The data has been acquired annually by the Dutch authorities (Rijkswaterstaat) using LIDAR technology. Data were interpolated on a 5 x 5 grid (Inverse Distance Weighting, power 2) and the resulting digital elevation models were used to compute elevation statistics (average, variance, annual rate of change), as well as dune volume estimates. Dune volumes are defined using the 3-meter contour as the hypothetical dune-foot, whereas the waterline limit is defined by the mean water level retrieved from tide gauge available at the harbour of Den Helder, on the other side of the inlet. The area was separated into four different sectors based on a visual assessment of morphological differences: West, Central, East and ”Big Dune”, which is a big sand body forming in front of the dunes located at the East and Central areas (Figure 2.4a).

For estimates of the spatial variation in capillary fringe depth, a field survey was carried out on which approximately 70 holes were bored along the sand flat until water started to emerge within the hole (Figure 2.4c). Next, the elevation of both the surface and the hole depth to slack sand were measured using a RTK-GPS system. Although not ideal due to local changes on pore water pressure (thus changing variations on the local balance between pore pressure and atmospheric pressure), this method was considered sufficiently robust to address qualitatively the spatial variability within the sand flat and of sufficient accuracy for comparison to the schematised results of the cellular automata model.

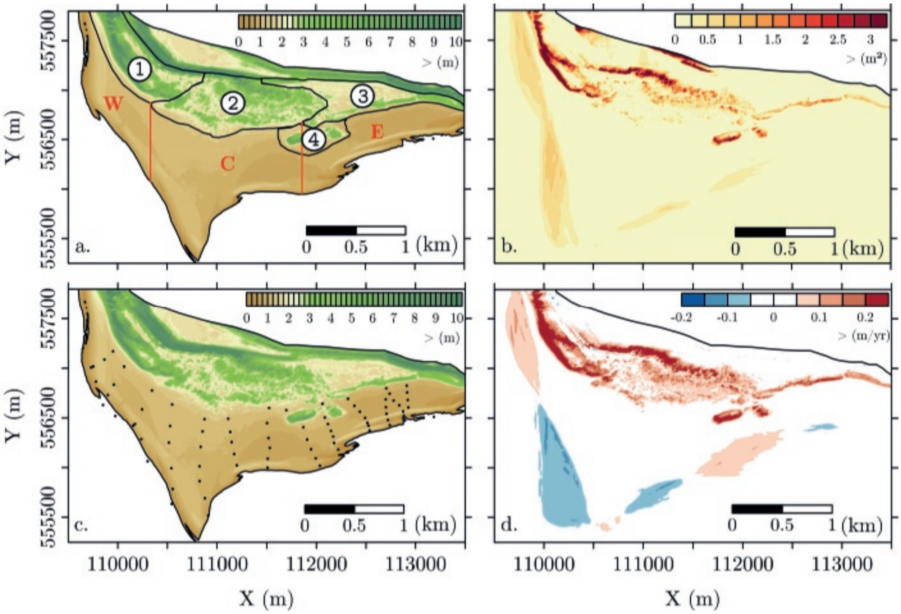

**Figure 2.4:** a: 2017 LIDAR-derived topographic map, highlighting the different dune areas: West (1), Center (2), East (3), Big Dune (4). Red letters show three distinct parts of the flat as mentioned throughout the text (W - West, C - Center, E - East); b: Variance map of the elevation, based on the topographic time-series from 1997 to 2015; c: Borehole survey locations used for the capillary fringe measurements; d: Annual rate of change, based on the topographic time-series. Cold colours mean erosive trend, whereas warm colours relate to accretionary trends.

## 2.4 Results.

### Idealised cases

Results from the Idealised cases suggest that there is a threshold level on which groundwater start to affect dune development. For Case 1 (Figure 2.5a), deep groundwater levels (0 to 0.6) resulted in a topography of continuous dune rows, exhibiting a downwind decrease in dune height and width (from west to east) due to a sediment supply decrease induced by vegetation. For groundwater levels closer to the surface (0.7 to 0.9), dunes tend to become smaller in width and height, and for groundwater level greater than 0.9, dunes develop as just small Nebkah/Coppice shaped dunes. Regarding vegetation development, most of vegetation growth occurs on the first dune, which is related to larger sand supply compared to the dunes behind it. The amount of vegetation decreases in the presence of small waves due to wave-induced erosion. Most of the vegetation present after 15-year consists of pioneer species rather than the conservative species, and its coverage area is small compared to the dune area.

The threshold level can also be seen on other morphological parameters such as volume growth and average crest height. (Figure 2.6). Regarding volume growth, groundwater values from 0 to 0.4 resulted in a total volume of approximately 200 $m^3/m$ (±4.5). Between 0.4 to 0.6, volume growth decreased an average of 3 percent per 0.1 step of groundwater level increase. From groundwater level of 0.7 to 1, the influence of groundwater level increased by an order of magnitude, with a reduction in the order of 20 percent per 0.1 step of groundwater level increase. In the average crest height results, values from 4.6 meters (±1.2) to 4 meters (±0.7) emerge between groundwater levels of 0 to 0.6, and values of 3.7 meters (±0.5) to 3.2 meters (±0.1) from 0.7 to 0.9 (reduction of 0.17 meter per 0.1 step of groundwater level increase). Values of average distance between crests are of the same order of magnitude between groundwater levels of 0 to 0.8, with a large deviation at the shallowest groundwater level due to the low number of dunes present under these conditions. Regarding percentile distributions of elevation, groundwater level from 0 to 0.6 had its 75% elevation percentile above the height of 3 meters (3.4 at 0 groundwater level to 3.1 at groundwater level at 0.6), whereas from groundwater levels between 0.7 and 0.9, values range from 2.4 to 1.7.

For Case 2, the results for groundwater levels ranging from 0 to 0.6 are very similar (Figure 2.5b). However, in this case, discontinuous dune rows appear at this location, with this time increasingly larger dunes from left (water line) to the right (inland), the opposite trend of Case 1. Once the groundwater level reaches levels higher than 0.7, it affects the overall size of any of the dunes that develop, with no elevation contour higher than 3 meters if the groundwater levels is at 0.9. Furthermore, although the amount of sand at the dunes reduces inversely with the groundwater level, the cross-shore location of the first dune does not change significantly.

Regarding vegetation development, despite small patches growing sparsely, especially under deep groundwater conditions, almost no growth occurred in most of groundwater conditions tested.. The cal-

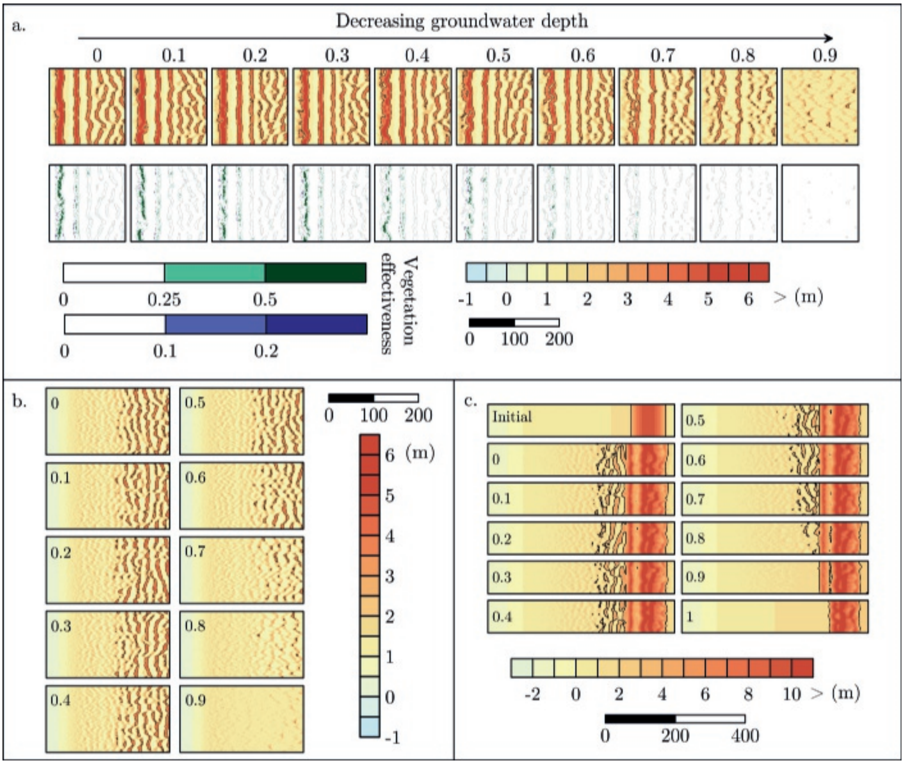

**Figure 2.5:** a: Simulation output after 15-year period for Case 1 (east side). Upper panels display topography for different groundwater settings. Vegetation is displayed in the lower panels, where grey lines represent 3-meter topographic contours. Pioneer vegetation displayed in green, whereas conservative species are displayed in blue; b: Topographic patterns after 15-year simulation for Case 2 (west side, with no initial foredune). Numbers represent the groundwater level applied; c: Topographic patterns after 15-year simulation for Case 3 (west side, with initial foredune). Numbers represent the groundwater level applied. For all panels, wind is from West (left of the figure)

culated dune volume growth for groundwater levels between 0 and 0.5 was of 67 $m^3/m$ (± 3.8), with values ranging from 72 to 60 $m^3/m$. From 0.6 to 1, the average change in volume growth reduces at an average rate of 19% of the highest volume, in contrast to the 4% growth rate between 0 to 0.5. The average crest height reduces from 3.4 meters (± 0.36) at groundwater level of 0 to 3.2 meters (± 0.12) at 0.9. Although on average similar, the spatial average standard deviation of elevation between 0 and 0.5 is 0.33 meter (± 0.02), whereas it reduces to approximately half of that between 0.6 and 0.8. Maximum dune height ranges from 5 to 4.5 between 0 and 0.5 (a reduction of 0.08 per scenario, in average), whereas it goes from 4.2 meters to 3.4 meters between 0.6 to 0.8 (an average reduction of 0.27 per groundwater level). Regarding values for elevation percentiles, Case 2 presented less prominent trends than Case 1, although drops on its values can be seen for groundwater levels higher than 0.6 (Figure 2.6).

For Case 3, like case 1 and 2, topographic developments for groundwater levels between 0 and 0.6 are similar, with a reduction of dune development for groundwater levels above 0.7 (Figure 2.5c). The dune type is similar throughout most of the scenarios, with this time a first dune row appearing in front of the initial dune, combined with small dune rows developing more seaward for groundwater levels of 0 to 0.6. For higher groundwater levels, small dunes appear in the upper beach region, until no dune is formed when groundwater is at 0.9.

In terms of volume growth, the same pattern observed for Case 1 and 2 can be seen, with similar values between groundwater levels of 0 and 0.6 (volume change in order of 1 percent between groundwater levels), with an increase in the volume change rate between 0.7 and 0.9 (of the order of 8 percent).

Since Case 3 represents a commonly occurring situation (beach with a well-developed foredune), an interesting aspect to analyse is the amount of sand transported by aeolian transport and imported/eroded by marine processes. Figure 2.7 shows boxplot distributions of both the net amount of sand being imported and eroded by the sea throughout the year (referred to as sea input) and the annual amount of wind transport across the full domain during the year (total amount of sand slabs that have been in transport). During the simulation, the volume in transport by the wind remains fairly constant between groundwater levels of 0 to 0.4. However, this amount starts to decrease constantly from 0.5 onward up to 0.9. Regarding sea input, an import trend can be seen in most conditions simulated, with a decrease in its median and spreading values. The decrease in its spreading is due to the decrease of available sand to be transported in each groundwater scenario. Deep groundwater levels require more sand to maintain the reference profile, whereas high groundwater levels require less sand to compensate the aeolian transport.

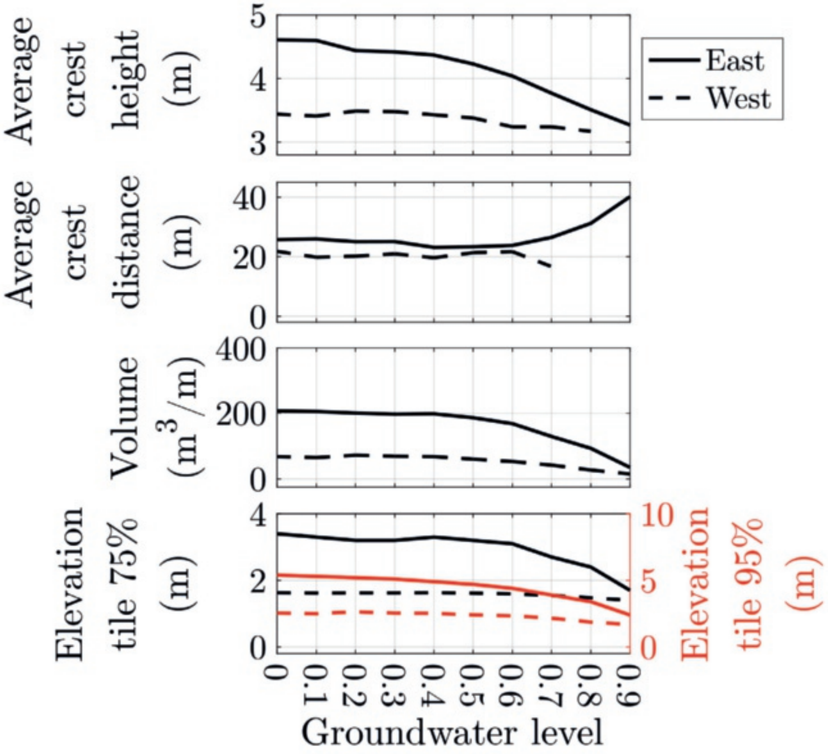

**Figure 2.6:** Topographic characteristics for Cases 1 (East) and 2 (West, no initial foredune).

## Real case - De Hors

### Observed development

The 18-year topographic dataset shows a steady dune growth in the area, with a total net accretion of 1.2.$10^6$ $m^3$, at an average accretion rate of 6.6.$10^4$ (±2.4.$10^4$) $m^3$/year. The west region accounted for 60,3% of the total amount of volume increase, at an average of 4.$10^4$ (±1.6.$10^4$) $m^3$/year, followed by the central region at 29,6% of the total accretion, at an average of 2.$10^4$ (±9.6.$10^3$) $m^3$/year. The east part accounted for only 5% of the total accretion, at an average rate of 3,2.$10^3$ (±3,7.$10^3$) $m^3$/year, being the only region where years with net erosion trends were observed (between 1998-1999 and 2004-2005). The remaining volume increase is related to the sand body that developed

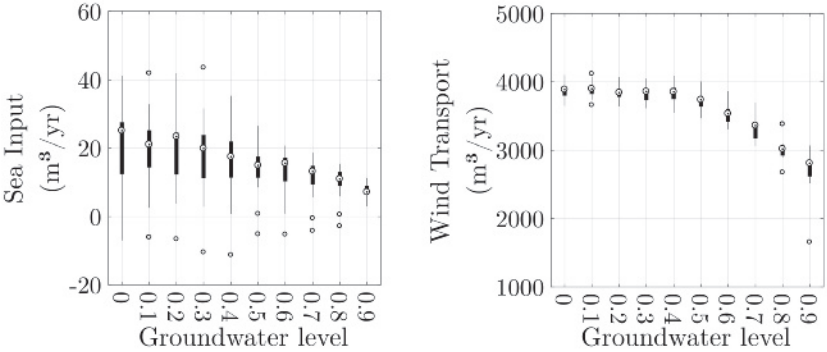

**Figure 2.7:** a: Variation in annual sediment input from the sea for Case 3. Values are defined by the total of sand slabs introduced/removed by the sea. N=15. b: Annual amount of sand that have been in transport by the wind. N=15.

**Table 2.3:** Statistics for topographic dataset. Average values are followed by its spatial standard deviation value within parenthesis. For the sand flat, regions are defined based on the longitude position of the boundaries between different dune locations (between west and central, and central and east)

| Region | Dune volume increase ($m^3$) | Average flat elevation height (m) | Average flat elevation variance ($m^2$) | Flat elevation rate of change (m/yr) |
|---|---|---|---|---|
| East | $5{,}9.10^4$ | 0,65 (±0,4) | 0,08 (±0,2) | 0,02 (±0,04) |
| Central | $2{,}5.10^5$ | 1,03 (±0,3) | 0,06 (±0,1) | 0,01 (±0,03) |
| West | $7{,}2.10^5$ | 0,86 (±0,4) | 0,26 (±0,3) | -0,03 (±0,05) |
| Total | $1{,}0.10^6$ | 0,89 (±0,4) | 0,12 (±0,2) | 0,004 (±0,04) |

in front of the eastern and central regions, which is treated separately due to its unique size and form.

Regarding the area covered by dunes, all sectors present an overall trend of dune area increase throughout the period (Figure 2.8). West and Central areas present a faster rate of area expansion as the East and Big dune areas. The Central area presented an increase of more than 15 times of the initial dune area, whereas the West presented an increase of approximately 2 times over the initial dune area in the west. The western sector also presented two distinct periods of dune area expansion: one between 1997-2004 and another between 2005 and 2015. The increase in dune area expansion rate in 2005 is related to a sudden dune expansion in the south of the western sector, which might be related to a coastline change at the same period.

Regarding the sand flat, the topographic data shows a lower average flat elevation on the east side than in the central and west areas (Ta-

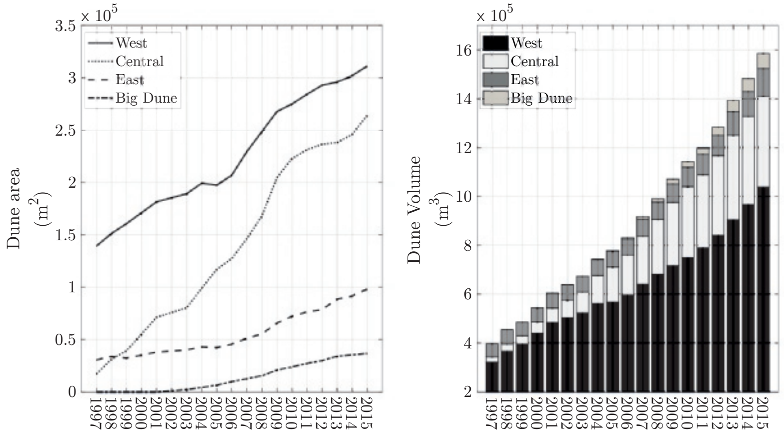

**Figure 2.8:** Left: Temporal evolution of Dune area, separated by its respective regions of analyse. Right: Evolution of dune volume throughout the time-series. Data for 2000 and 2002 has been linearly interpolated in time.

ble 2.3). The central area presented the highest average sand flat elevation among the areas. For the average temporal variance of the flat elevation, the west side showed the highest values, at an average of 0.26 (±0.28) $m^2$, compared with 0.08 (±0.17) $m^2$ for the east side and 0.06 (±0.11) $m^2$ for the central area. Regarding the elevation rate of change, values for the sand flat are close to 0 (between 0.005 and -0.005 m/yr). Locally, values can be higher or lower than 0.1 and -0.1 m/yr, respectively, being regarded as locations dominated by hydrodynamics processes. On the other hand, higher values can be seen at the dune area, with higher values in the west part than in the other regions (Figure 2.4d).

The spatial pattern in the depth of the top of the capillary fringe, as approximated from the boreholes, shows values of 0.4 meter to 0.6 meter on the east side, with higher values of around 0.7 meter to 0.8 meter in the central and western parts (Figure 2.9).

### Simulated development

The simulation over De Hors area shows that dune development varies with imposed groundwater levels (Figure 2.10). Deep groundwater levels (between 0 and 0.6) resulted in dunes developing over most of the plain, with an average crest height of 1.5 meter in the central part of the flat. In the western part, only small morphological features of a half meter order developed. On the eastern part of the flat, morphological features in the order of 1-meter height developed. For a high groundwater level (above 0.7), a much more pronounced spatial variability on the dune development over the flat occurred. The east side of the plain does not show any new dune development on the area, whereas on the central part, dunes higher than 2-meter height emerge only in the upper zone of the plain (i.e. farthest from the water line).

Comparing to observed patterns, some similarities appear. The spatial variability in dune development is similar to patterns found on the measured data. On the west side, the results are similar to those under low groundwater level conditions. Results with high groundwater level tend to represent three distinct areas as seen in the actual flat, especially the expanding dune field on the central area. The overall volume increase is well simulated, with values being around 81-91% of the measured dune volume increase between groundwater levels of 0.6 and 0.8. The same aspect can be seen in the dune area, with values ranging from 85-91% of the measured dune area for groundwater levels of 0.6 to 0.8. Trends on sediment input by marine processes are similar to those shown on Figure 2.6 for Case 3, with a predominance of accretive trends rather than erosive trends, especially on deep groundwater levels.

Comparing the simulations to the actual state after 15-years, three main differences can also be identified: (1) no development of a foredune on the east side; (2) the position, size and form of the dunes on the central part differs; and (3) the absence of a new dune ridge on the west side. Regarding 1, simulations show that when the probability of deposition of the cells is increased, the foredune on the east side emerges, although this also affected the size and distribution of dunes emerging in the central area (Figure 2.10). Regarding 2, dunes

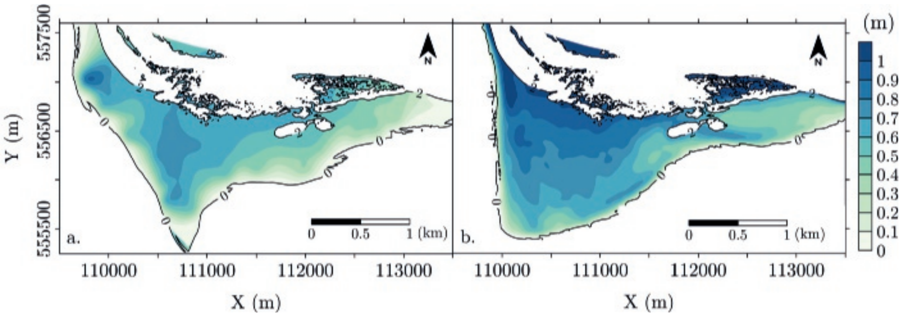

**Figure 2.9:** a: Approximate depth of capillary fringe estimated level. b: Groundwater level for 0.8 in model simulation.

tend to form in bigger slabs on the simulation than in the real data, although the overall region is similar, whereas the development of the new dune ridge on the simulation might be related to the absence of any shoreline variability within the model.

Regarding aeolian fluxes (amount of sand that crossed a given longshore shore transect), deep groundwater levels returned similar values for the three regions, resulting in values in the order of 30-40% of the total flux, with the western part showing the highest value (38%), followed by the East (32%) and Central with the lowest value of about 30% (Figure 2.11). High groundwater levels lead to different and more pronounced variation in regional fluxes, with a decrease on the flux related to the east area (5%) in comparison to the fluxes on the west (55%) and central areas (40%).

## 2.5 Discussion

Our findings suggest that groundwater level induces spatial variability in sediment supply and dune development in sand flat environments near inlets. Sand flats, such as De Hors, present large areas in which aeolian sand transport and dunes can develop. The groundwater level can raise surface moisture, thus limiting the aeolian transport and dune formation regardless of the available space (de M. Luna et al., 2011; Poortinga et al., 2015).

Conceptually, over a long-time scale, average deep groundwater levels imply that more sediment is available to be transported than

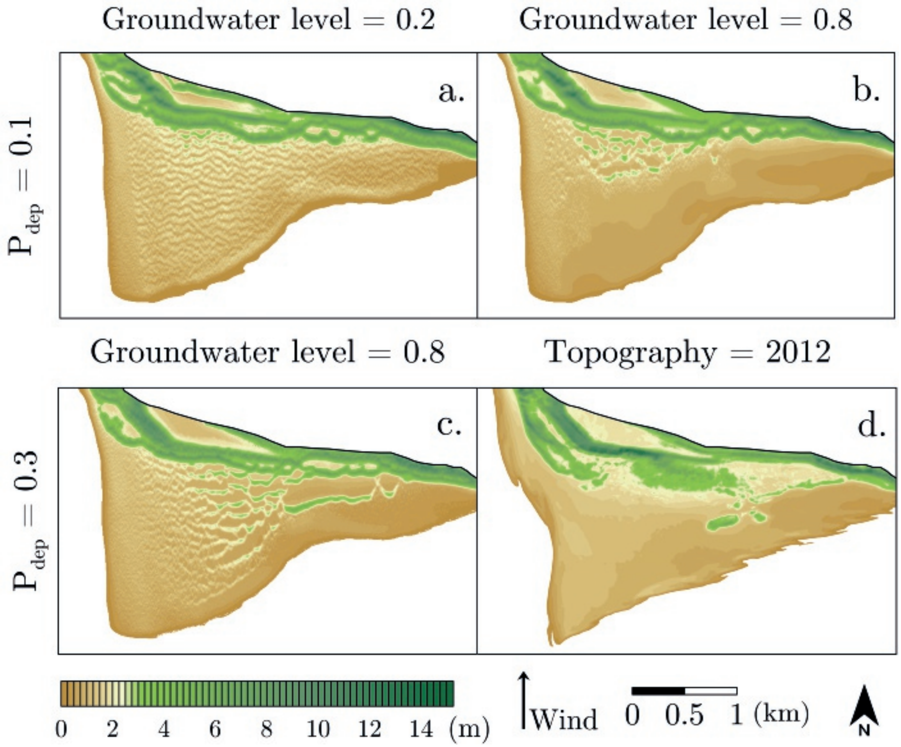

**Figure 2.10:** Topographic results of evolution of dune evolution for two groundwater levels (a and b), as well as one with different probability of deposition of a bare cell (c.). Real topographic data is displayed for comparison (d.)

at higher groundwater levels. Considering the relation between groundwater depth and sediment supply, the sand flat topography and groundwater level gradients across the area can determine which regions will have the highest potential for aeolian transport and dune development by spatially controlling the sediment supply. That effect can be exemplified by comparing the eastern and western parts of the plain. The eastern part is, on average, lower than the western and central parts. The lower elevation results in relatively higher groundwater levels and, therefore, a reduction in the available sand compared to the other areas. At De Hors, dune growth and sediment transport is much higher in the western, less moist side than it is in the inner, more humid eastern part.

An important part of this concept is the low height variability of the sand flat, which can be related to an import of sand by marine processes that compensates for the aeolian transport. To maintain the sand flat at a fairly constant height, a net input of sediment has to be achieved. Two hypotheses are proposed for this scheme: either the flat itself does not act as a primary source, being all the sand introduced solely by the intertidal area; or there is an input of sand from the sea onto the flat which compensates for the aeolian transport. Our results show a positive balance on the sea input, suggesting that more sediment has been introduced by the sea than has been eroded, and that deeper groundwater levels tend to require more sand input from the subtidal area. Considering the whole flat as a potential sediment source, energetic events that inundates the flat might have an accretive component to replenish the flat rather than an erosive component only (Wijnberg et al., 2017).

Variations in sediment supply can also lead to different dune types. All scenarios presented seem to have a threshold at which the groundwater level starts to influence the dune development. Our simulations show that this occurs between values of 0.5 and 0.7, depending on other characteristics such as the hydrodynamic conditions and initial topography. Therefore, the value of the groundwater parameter cannot be translated to a in-situ groundwater depth in meter that would lead to sufficient sand saturation to affect dune development using the current modelling approach.

Previous studies have suggested that dune type and sediment supply are closely related (Hesp, 2002; Martínez and Psuty, 2004; Nield and Baas, 2008). Nield and Baas (2007) found that sediment supply is a key part of the types of dunes that are predicted within a similar model when paired together with the vegetation. Nebkah dunes, for example, were only predicted on limited supply situations, whereas an increase of sediment supply leads to an evolution from barchan dunes to transverse dunes. Since groundwater essentially limits sediment availability, the same effect could be seen in our simulations, with variations in dune formation from medium to high groundwater levels.

Recent studies have addressed the importance of vegetation on dune-building processes (Durán and Moore, 2013; Durán Vinent and Moore, 2014; Keijsers et al., 2015; Zarnetske et al., 2015; Goldstein et al., 2017). Durán and Moore (2013) argue that maximum foredune heights are mainly controlled by vegetation zonation rather than sediment supply. Furthermore, they argue that the foredune formation time is controlled by the sediment supply (i.e. places with abundant vegetation and low sediment supply will tend to see the dunes build over a longer time period than at sites with abundant sediment supply). Vegetation in the present model is represented simply by a relation between erosion/deposition sediment rates and evolves as direct interactions with sediment supply and net vertical topographic evolution. Changes on specific vegetation parameters may allow changes on dune position and maximum dune height as suggested by Durán and Moore (2013). External influences on vegetation development such as salt spray and soil salinity are accounted within the stochasticity of the model, thus no tests varying specific vegetation parameters have been done. The overall trend regarding spatial variation in sediment supply due to groundwater levels tend to remain present even though including spatial variability in terms of vegetation characteristics might also affect dune growth and spatial distribution of dune morphology.

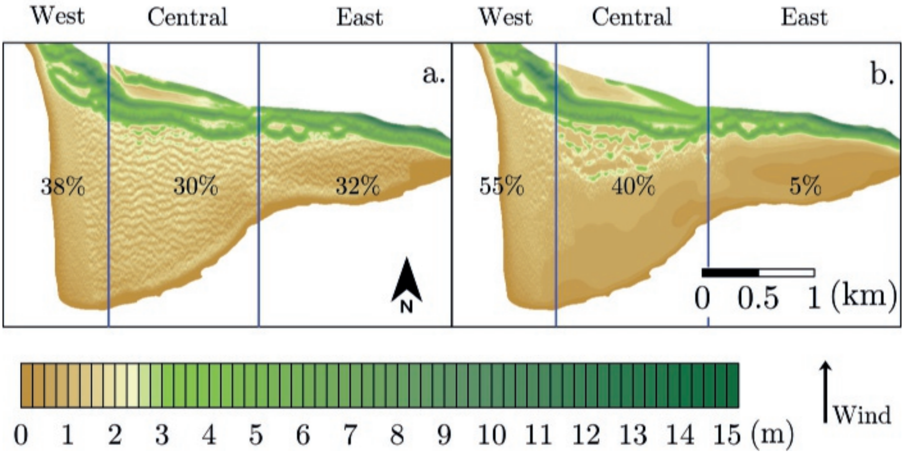

**Figure 2.11:** a: Percentage of total flux for each region, representative for a deep groundwater level (0.2); b: Percentage of total flux for each region, representative for a high groundwater level (0.8)

Intriguingly, the appearance of a new foredune on the east side is highly sensitive to the model setting for the probability of deposition. Increasing slightly the value to 0.3 lead to the appearance of this dune. Considering that a new foredune has evolved in the actual site in the inner part, our results suggest that there is a spatial dependence on probability of deposition which can lead to the appearance of the inner dune. One characteristic that can induce spatial variations on deposition probabilities is grain characteristics such as grain size. Another characteristic capable of induce spatial changes on deposition probability is the surface moisture, which theoretically could explain the spatial variability in the probability of deposition necessary for the inner foredune growth. However, the current model does not account for any direct spatial dependency on $\mathrm{P_d}$, explaining the no-appearance of all characteristics on just one simulation.

It is important to note that spatial variability in sediment supply can be related to other parameters than moisture, such as grain size distribution and beach armouring (Hesp, 2002; Hoonhout and de Vries, 2017). Temporal variability of these properties is assumed to be introduced stochastically and accounted for in the probability of erosion of a sandy cell. The probability of bare soil erosion and deposition are not imposed to be spatially dependent. Hence, any spatially coherent trends in these properties are not accounted for in the simulation. It is unknown, however, whether such spatial trends do exist.

## 2.6 Conclusion

A cellular automata model was used to understand the relation between groundwater level and aeolian dune development on sand flats close to inlets. Increasing groundwater levels lead to a decrease in sediment supply which affected the types of dunes that emerge in the tested scenarios. Coppice/Nebkah-like dunes only appear in scenarios where the groundwater is high enough to limit the sediment supply, whereas long dune rows appear when groundwater levels do not limit supply. Qualitatively, there is a threshold level at which the effect of groundwater reduction on sediment supply starts to affect dune growth and dune type. The threshold can vary spatially due to variations in the groundwater depth relative to the topography. Thus, groundwater level is capable of inducing spatial-variability in sediment supply and, therefore, influencing dune growth and distribution on a sand flat. This is consistent with volume change estimated from the data, where the eastern side presents much less dune growth than the rest of the flat due to its lower average elevation and, consequently, higher groundwater levels. The model is sufficiently robust to simulate specific characteristics found on the flat such as zonation related to dune morphology and trends on dune growth.

### Acknowledgements

This research forms a component of the CoCoChannel project (Co-designing Coasts using natural Channel-shoal dynamics), which is funded by Netherlands Organization for Scientific Research, Earth Sciences division (NWO-ALW), and co-funded by Hoogheemraadschap Hollands Noorderkwartier. We further wish to acknowledge Rijkswaterstaat for making their valuable bathymetric and topographic data sets freely available, as well as the water level data.

## CHAPTER 3

# Storm-induced sediment supply to coastal dunes on sand flats[I]

### Abstract

Marine supply of sand can control the development and morphology of coastal dunes. However, processes that control the sediment transfer between sub-tidal and the supra-tidal zone are not fully understood, especially in coastal settings such as sand-flats close to inlets. It is hypothesised that storm surge events induce sediment deposition on sand-flats, so that this may influence dune development significantly. Therefore, the objective of this study is to identify which processes cause deposition on the sand-flat during storm-surge conditions and discuss the relationship between the supra-tidal deposition and sediment supply to the dunes. We use the island of Texel as a case study, on which multi-annual topographic and hydrographic data sets are available. Additionally, we use the numerical model XBeach to simulate the most frequent storm surge events for the area. Results show that supra-tidal shore-parallel deposition of sand occurs in both the numerical model and the data. The amount of sand deposition is directly proportional to surge level and can account for more than half of the volume deposited at the

---

[I] Chapter submitted as: Galiforni Silva, F., Wijnberg, K.M. and Hulscher, S.J.M.H. (subm.). Storm-induced sediment supply to coastal dunes on sand flats.

dunes yearly. Furthermore, storms are also capable of remobilising the top layer of sediment of the sand-flat, making fresh sediment available for aeolian transport. Therefore, in a sand-flat setting, storm surges have the potential of adding significant amounts of sand for aeolian transport in periods after the storm, suggesting that storms play a significant role in the onshore sand supply between sub-tidal and subaerial zones in those areas.

## 3.1 Introduction.

Coastal dunes are important natural flood defence features. Dunes grow in the interface between land and sea by the interaction of biological, physical processes and geological conditioners (Hesp, 1983; Sherman and Bauer, 1993; Hesp, 2002; Bauer and Davidson-Arnott, 2002; Hesp and Walker, 2013; Delgado-Fernandez and Davidson-Arnott, 2011; van Puijenbroek et al., 2017). Generally, key aspects necessary for the development of coastal dunes are: availability of sediment, space for dune growth, suitable climate conditions (e.g. wind, waves, vegetation, rain, etc) and time for its development (Hesp, 1983, 2002; Bochev-van der Burgh et al., 2009; Bauer et al., 2009; Bochev-Van der Burgh et al., 2011; Keijsers et al., 2015; van Puijenbroek et al., 2017; Silva et al., 2018, 2019).

The amount of available sediment is a crucial aspect for dune development (Eastwood et al., 2011; Hesp, 2002; Short and Hesp, 1982; Houser, 2009). It can control aspects like dune type and morphology, vegetation growth and overall development. The sea is the primary source of sediment for coastal dunes. Wave-driven currents, oscillatory components of the incident wave motions and effects of infragravity waves on currents are responsible for transporting sediment onshore, leading to a continuous supply of sediment from the subtidal to the subaerial zone (Aagaard, 2014). Aagaard et al. (2004) link the occurrence of onshore bar migration and its subsequent welding to the coast with sediment supply towards the dunes. Anthony et al. (2006) show that for a tide-dominated beach in the coast of France, dune accretion yearly depends on bar welding phenomena related to storm processes, which could account for 48% of the overall dune change. Anthony (2013) shows that for the southern North Sea coastal system (i.e. French and Belgium coast), the highest rate of foredune accretion is associated with areas where sandbanks have migrated onshore in the past century, thus leading to an increased supply condition for the dunes.

Most studies on beach-dune systems and sediment transfer between sub-tidal and supra-tidal zones only consider locations away from inlets (Anthony et al., 2006; Anthony, 2013; Aagaard et al., 2004; Reichmüth and Anthony, 2007). Inlet-driven processes such as shoal attachment and channel migration can drive changes in the adjacent coastlines (Fitzgerald et al., 1984; Fenster and Dolan, 1996; Robin et al., 2009; Elias and Van Der Spek, 2006), which in turn can influence sub-tidal/sub-aerial sediment exchange and coastal dune behaviour (Ruessink and Jeuken, 2002; Aagaard et al., 2004; Anthony et al., 2006; Cohn et al., 2017). Furthermore, inlet-driven processes can define the overall shoreline shape, which can favour or disfavour the development of dunes. For barrier islands in the Dutch Wadden sea region, coastline stretches close to inlets commonly develop as sand flats due to long-term morphodynamics of its ebb-tidal delta systems, as illustrated by the example of De Hors in the Texel island (The Netherlands) (van Heteren et al., 2006; Elias and Van Der Spek, 2006). Those sand flats are large (scale of km) and present great potential for dune growth due to their large beach width, prevailing wind velocities, and climate (Bauer et al., 2009; Houser and Ellis, 2013). A recent analysis of annual topographic data (Wijnberg et al., 2017) suggested that supra-tidal storm deposits may form a source for sand supply towards the dunes. However, it is unclear during which conditions supra-tidal deposition occurs and whether the amount deposited can be considered significant for dune growth and development.

Therefore, the objective of this study is to identify processes and storm properties that cause deposition on the sand-flat during storm-surge flooding and discuss the relationship between the supra-tidal deposition and sand supply to the dunes. We use a site in the Netherlands (Texel island) as a case study, for which we analysed multi-annual topographic data sets together with the application of a numerical model to investigate bed level changes at the sand flat during storm-surge flooding events.

The paper outline is as follows: Section 3.2 shows the study area characteristics; Section 3.3 shows the available data, its treatment and usage and explains the numerical model, its concepts, initial conditions and assumptions. Section 3.4 presents the results separated by data analysis, field survey and numerical results, followed by a discussion section (3.5) and conclusion (3.6).

## 3.2 Study area.

On the southern side of the Texel island (The Netherlands), bordering the Marsdiep Inlet, long-term ebb-tidal dynamics built a sand flat (named ”De Hors”) where dunes have been emerging over the past 20 years, at least (Figure 3.1). The flat has an approximate area of 3 $\mathrm{km}^2$. According to Silva et al. (2018), around $1.2.10^6$ $\mathrm{m}^3$ of sand has been deposited in the dunes between 1997 and 2015. Furthermore, dunes can be separated into three distinct zones: a western part, more exposed to wave action, a central zone, and an eastern part, which receives less wave action. According to Silva et al. (2018), the western zone accounted for 60% of the total dune volume increase, which emerged mostly as a linear dune ridge, similar to foredunes found along the coast away from the inlet. The central dune zone accounted for about 30% of the total dune volume increase and emerged as coppice-like dunes. The eastern zone presented the lowest dune volume increase and evolved as a linear dune ridge.

The Marsdiep inlet can be classified as a mixed-energy wave dominated inlet, with a gorge width of 3 km and a channel depth up to 50 meter (Elias and Spek, 2017). The inlet has an asymmetric ebb-tidal delta that is largely conditioned by side-effects due to engineering projects (i.e. construction of the ”Afsluitdijk”) (Elias and Van Der Spek, 2006; Elias and Spek, 2017). The sand flat is exposed to wind most of the times and is flooded only during storm surge conditions. The main wind direction is from the southwest, whereas waves predominantly come from southwest and northwest directions (Figure 3.1). The mean tidal range is 1.34 meters, with a mean spring high tide level (MSHTL) of 0.84 meters.

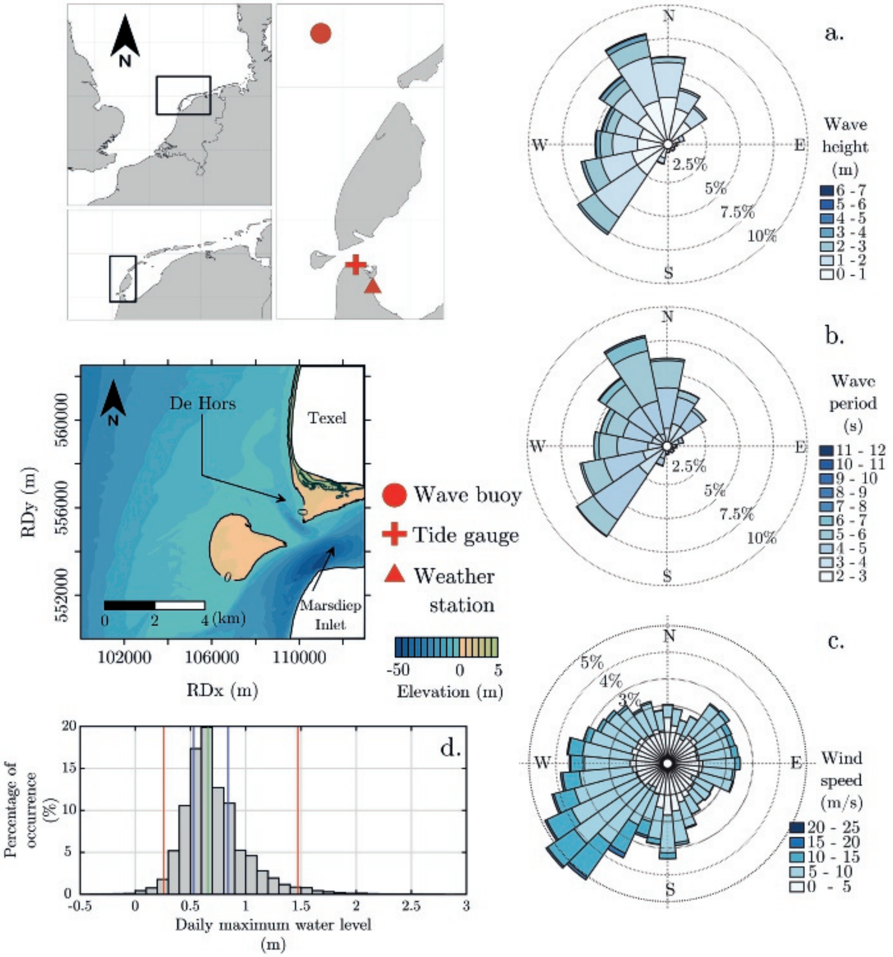

**Figure 3.1:** Study area of Texel. Red symbols represent the locations of the wave buoy (circle), weather station (triangle) and tide gauge (cross) used in this paper. Directional histograms for Wave Height (a.), Wave period (b.) and Wind speed (c.) show the overall characteristics of the area for wave climate and wind direction. Histogram of daily maximum water levels (d.) has also been plotted, with the blue lines representing the 25 and 75 quartiles (mean spring high tide, approximately), and the red lines 2.5 and 97.5 limits.

In the present paper, a storm is defined by its maximum water level following the classification used by the Dutch Ministry of Infrastructure and Water Management ('Rijkswaterstaat"). Storms with maximum water levels between mean spring high tide and 1.9 meters above MSL are classified as mild, whereas maximum water levels between 1.9 and 2.6 meter above MSL are classified as normal storms, and above 2.6 meters are classified as an extreme storm. To determine the local storm climate, we used a time series of hourly water levels collected at a tide gauge in the channel margin together with hourly wave information from a wave buoy (Figure 3.1). Daily maximum water levels were extracted from the time series and used as a proxy for storms. Results show that 73,31% of the daily maximum water levels lie below the mean spring high tide level, whereas 26,15% can be considered mild storms. From the mild storms, the majority lies between MSHTL and the 97,5 quartile (22,26%), with only 3,88% representing water levels above the 97,5 quartile. Only 0,54% can be considered storms (0,5%) or extreme storms (0,04%).

Waves related to storms are separated from each storm class (i.e. mild, storm and extreme storm) in Table 3.1. Mild storms present waves coming from three directions (SW, W and NW), with relatively similar occurrence (25,8%, 30.1% and 23.4%). For storms and extreme storms, waves tend to come from more northern directions.

## 3.3 Methodology

To achieve the proposed goal, we take two main approaches: numerical modelling and data analysis. The data analysis is meant to highlight morphological behaviour of the sand flat, focusing on the occurrence of deposition in zones above the MSHTL. Furthermore, data analysis will also deal with a field campaign meant to qualitatively measure the effects of a single storm onto the sand flat. The numerical modelling is used to analyse in depth which processes control the deposition and identify which storm conditions will lead to sand deposition.

**Table 3.1:** Characteristics of the local storm climate. Occurrence relates to the percentage of occurrence of storms with those characteristics over the population of mild, storm or extreme storms.

| Storm | Wave Direction | Wave Height (m) | Period (s) | Occurrence (%) |
|---|---|---|---|---|
| Mild | SW | 2 - 3 | 5 - 6 | 17,3 |
| | SW | 3 - 4 | 5 - 6 | 8,5 |
| | W | 2 - 3 | 5 - 6 | 5,2 |
| | W | 3 - 4 | 5 - 6 | 16,7 |
| | W | 4 - 5 | 5 - 6 | 8,2 |
| | NW | 3 - 4 | 6 -7 | 8,8 |
| | NW | 4 - 5 | 6 -7 | 14,6 |
| Storm | SW | 3 - 4 | 6 -7 | 9,1 |
| | W | 2 - 3 | 5 - 6 | 6,8 |
| | W | 3 - 4 | 6 - 7 | 25,0 |
| | W | 4 - 5 | 6 - 7 | 15,9 |
| | NW | 3 - 4 | 6 - 7 | 15,9 |
| | NW | 4 - 5 | 6 - 7 | 11,4 |
| Extreme Storm | W | 4 - 5 | 6 - 7 | 33,3 |
| | NW | 5 - 6 | 7 - 8 | 33,3 |
| | NW | 5 - 6 | 8 - 9 | 33,3 |

### Data and Field Campaign.

To analyse beach-dune behaviour over the sand flat area, we used annual LiDAR data from 1997 up to 2018 provided by the Dutch Ministry of Infrastructure and Water Management ('Rijkswaterstaat"). Survey dates vary over the years, with a tendency of flights being done after the most energetic period (Figure 3.2). The data is available in a horizontal resolution of 5 meters up to 2013, when a finer horizontal resolution of 2 meters became available, with vertical accuracy within 0.08 meters. From the LiDAR data, we analysed changes in elevation and volume of both the dune field and the sand flat. For the present study, the dune area has been defined by the limit threshold contour of 3 meters, whereas the sand-flat area has been defined as the area between dunefoot and mean spring high tide level (i.e. MSHTL). To analyse the stability of the sand flat, we created variance maps using the entire data set. Variance maps show the elevation variance at each grid node, which highlights areas on which elevation changes occurred in a larger magnitude. Furthermore, elevation difference maps have been used to define erosion and accretion trends between surveys. Thus, areas with low growth trend and high variance values mean that even though no accretion/erosive trend occurs, the elevation varies considerably in time. Moreover, to determine whether a location presented more accretive or erosive events in time, we built maps of occurrence of accretion and erosion events (i.e. number of times which a certain location had accretion or erosion events larger than 0.15 meters). Thus, areas where more accretive or erosive events happened can be highlighted. Therefore, trend maps are meant to show the overall growth trend of the location, variance maps are meant to show if the location is stable in time regardless its trend, and occurrence maps are meant to show areas where more accretive or erosive events occurred, regardless its variability and trends over time.

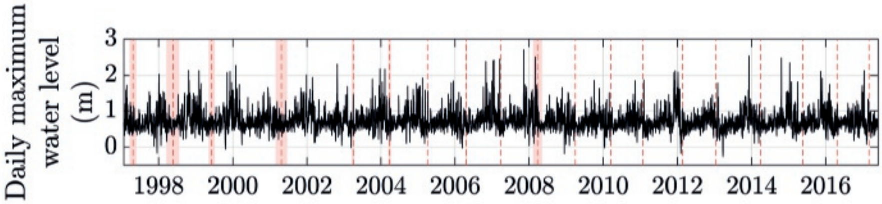

**Figure 3.2:** Daily maximum water level time-series highlighting the periods when the topographic surveys were executed. Dashed red lines represent the exact date used in the analysis, whereas the pink-shadowed region represent the period during which the measurements were (only for surveys where the exact date were not available).

To analyse the effects of a storm on the surface layer of sediment at the sand flat, we executed a field campaign on January, 2017, where six rods with washers were deployed over the flat to check whether remobilisation of the sand occur and, if so, in which order of magnitude (Figure 3.3). Elevation data was acquired using an RTK-DGPS system.

Regarding the validation of the numerical model, one hydrodynamic dataset was available to assess model performance for the present study. The ferry that links Texel island with the mainland crosses the Marsdiep inlet every half an hour from 6 AM up to 9:30 PM with an Acoustic Doppler current profiler (ADCP) mounted, performing detailed flow measurements. The data acquired and treated by the Royal Netherlands Institute for Sea Research (NIOZ) has been made available for the year of 2009 by Duran-Matute et al. (2014). One limitation of the data set is that the ferry does not sail at night. Furthermore, the ferry also does not sail when the water level exceeds 2 meters above NAP. That would introduce gaps and limit the number of possible storms for validation to only periods of mild storms. To assess model performance, we use the storm of 04/10/2009, which reached maximum water levels of 1.8 meters and was measured for three hours.

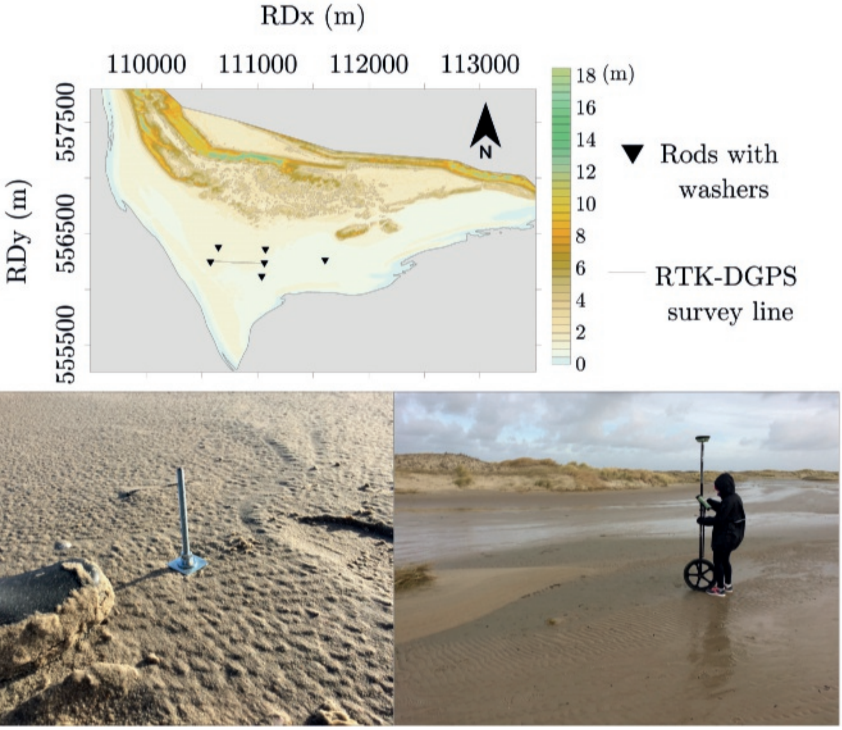

**Figure 3.3:** Location of the rods with washers, as well as RTK-DGPS survey transects.

## The XBeach Model.

Considering that the available measurements are surveyed in an annual basis, we choose to apply a numerical model using the most frequent storm conditions to identify in which storm conditions does deposition onto the sand-flat occur in an event scale.

### Model Structure

The XBeach model (Roelvink et al., 2009) is a process-based model developed to simulate hydrodynamic and morphodynamic processes on sandy coasts. It has been developed to work on a time-scale of storms and for coastal stretches of the order of kilometres in length. The model solves the 2D horizontal shallow water equations, including capabilities of time-varying wave action balance, roller energy balance, advection-diffusion equation, sediment transport and bottom change (Elsayed and Oumeraci, 2017; Roelvink et al., 2009; Deltares, 2018). Overall, the model includes the hydrodynamic processes of short-wave transformation (refraction, shoaling and breaking), long wave transformation, wave-induced setup and unsteady currents, as well as overwash and inundation. The morphodynamic processes include bed load and suspended sediment transport, dune face avalanching, bed update and dune breaching (Deltares, 2018). The main difference of the XBeach model compared to other process-based models for coastal areas is the capability of including the effects of infragravity waves through solving long-wave motions created by time-dependent cross-shore wave height gradients (Roelvink et al., 2009). For the present study, the model has been run in surfbeat mode, where the short wave variations on the wave group scale and the long waves associated with them are resolved (Deltares, 2018). The model has been extensively validated and applied in different scenarios (de Vries, 2009; Roelvink et al., 2009; McCall et al., 2010; Elsayed and Oumeraci, 2017; Vet, 2014; Nederhoff, 2014). Detailed information on model formulation and validation can be found on Roelvink et al. (2009) and Deltares (2018).

### Scenarios

Based on the local storm climatology (Table 3.1), we selected 12 actual storms events that occurred between 1990 and 2017 to represent the most frequently occurring storm conditions in each of the three storm categories. Choices have been made to ensure that we simulate at least one storm from each wave direction represented. The bathymetry and topography for all scenarios are based on LiDAR and bathymetric data available for the year 2009, the same year of the storm chosen for validation, thus only hydrodynamic boundary conditions have been changed for each scenario. Bathymetric data is available at 20x20 meter grid, with vertical accuracy between 0,11-0,4 meters, whereas topographic LiDAR data is available at 5x5 meter grid, with vertical accuracy within 0.08 meters. For each storm, its wave characteristics have been gathered from data available from a nearby wave buoy (Figure 3.1). Final scenarios are shown in Table 3.2.

From the simulations, we relate bed level change on the flat with local hydrodynamic characteristics (i.e. $Hrms$, $u$ and $v$ convergence, $Sxx$, $Sxy$, $Syy$), in order to check which process would explain most of the bed level change. We do this by analysing how the morphology and hydrodynamic evolve in time, by choosing a location where deposition occurs and following the time-series of bed level change and hydrodynamic processes. Furthermore, to check if storm strength influences the amount of deposited volume onto the sand flat, we correlate final sand volumes deposited with imposed storm characteristics (i.e. Maximum water level imposed at the boundary, $Hm0$, wave direction and $Tp$). Both sand volume and hydrodynamic variables are standardised using z-scores to ensure that standard deviations are comparable.

#### Validation

Considering that the XBeach model has been validated in a broad range of applications, we use default settings for the present study. Additionally, we used the above-mentioned dataset for a limited validation check.

Validation results show relatively good agreement between measured and simulated currents, with root mean square error (RMSE) values

**Table 3.2:** Characteristics of the simulated scenarios. Deposited volume refers to the deposited sand onto the sand flat from the simulation results.

| Scenario | Date | Duration simulated (hours) | Hm0 | Dir | Tp | Max. Water Level | Deposited volume ($m^3$) | Storm class |
|---|---|---|---|---|---|---|---|---|
| a. | 25-26/10/2005 | 8 | 3,0 | 235 | 5,6 | 1,7 | 474 | Mild |
| b. | 1/10/2008 | 7 | 3,0 | 258 | 5,3 | 1,7 | 1198 | Mild |
| c. | 29/10/2017 | 8 | 3,8 | 310 | 6,4 | 1,7 | 7084 | Mild |
| d. | 23/11/2009 | 8 | 2,9 | 253 | 5,4 | 1,9 | 7339 | Mild |
| e. | 04/10/2009 | 8 | 3,8 | 297 | 6,3 | 2,1 | 14680 | Storm |
| f. | 25/10/1998 | 8 | 4,0 | 292 | 6,5 | 2,4 | 15322 | Storm |
| g. | 21/12/2003 | 9 | 5,8 | 350 | 8,1 | 2,5 | 26958 | Storm |
| h. | 27/10/2002 | 9 | 3,5 | 247 | 6,2 | 2,6 | 10717 | Storm |
| i. | 30/01/2000 | 9 | 3,6 | 298 | 6,7 | 2,6 | 16173 | Storm |
| j. | 22/10/2014 | 9 | 4,7 | 323 | 7,1 | 2,8 | 19363 | Extreme Storm |
| k | 09/11/2007 | 10 | 5,8 | 337 | 8,1 | 3,0 | 29863 | Extreme Storm |
| l. | 26/02/1990 | 10 | 5,0 | 285 | 7 | 3,2 | 18601 | Extreme Storm |

below 0.5 m/s. The best fit is associated with meridional components (i.e. perpendicular to the inlet throat), with a $R^2$ of 0.63 and RMSE of 0.17. For the zonal components (i.e. parallel to the inlet throat), the model underestimated values, especially when the flow presented high velocities, with $R^2$ of 0.51 and RMSE of 0.41 (Figure 3.4).

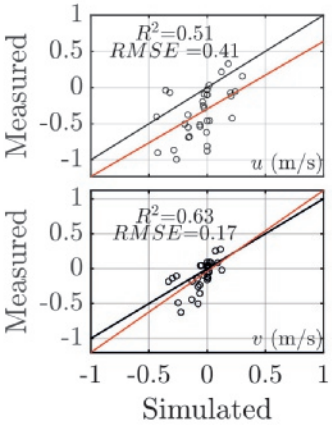

**Figure 3.4:** Validation results. Comparison of zonal and meridional components of the depth-averaged flow between simulated and measured data. The location of each point is defined by the ferry location at the time of the measurement and paired with the simulation accordingly. R-squared and RMSE are displayed for in the upper part of each scatter plot. Black line is a diagonal reference line (i.e. from (-1,-1) to (1,1), whilst red line represent the least-squares lines.)

## 3.4 Results

### Supra-tidal development

Figure 3.5 presents elevation difference maps between each year individually. Maps show that deposition patterns in the supra-tidal zone occur between at least 10 different years. For some years like between 1998-1999 and 2003-2004, the deposition happens extending from the north to the south of the flat, and it happens at least 100 meters landward of the mean spring high tide level (i.e. higher elevations). For other periods like (j., l. and r.), the deposition happens much closer to the MSHTL, although also oriented from north to south. For others, the deposition occurs only in the southern tip of the flat, like m. Erosion patterns higher than 0.15 meters occur only between a few years, and mostly at locations close to the MSHTL. When looking at the map of accretion/erosion occurrence (balance of occurrence of accretion and erosive trends between years - Figure 3.6b), we can also see that a zone with more accretive than erosive years occurs in a well-formed shore-parallel shape above MSHTL. Thus, we conclude that there is a zone of sediment deposition in the west margin of the flat above mean spring high tide level.

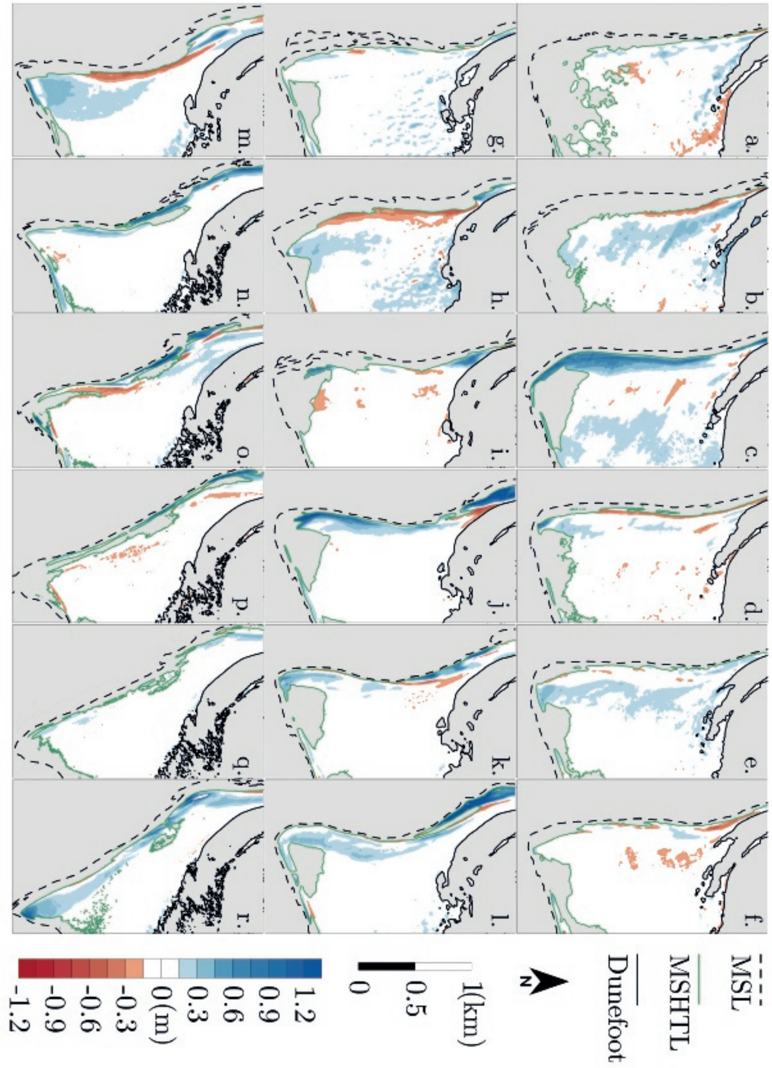

**Figure 3.5:** Difference maps for the periods between 1997 and 2017 focusing on the supratidal area. Calculations are done using the next minus the previous survey. Most plots show the an one-year difference, with exception of plots c and d which represent the difference between 1999-2001 and 2001-2003, respectively, due to the absence of surveys in the years 2000 and 2002.

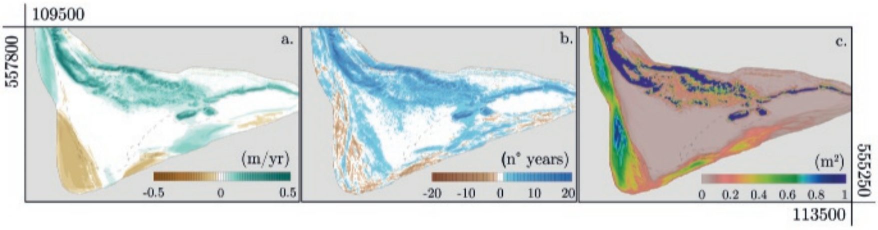

**Figure 3.6:** a - Average annual elevation change based on LiDAR data from 1997 up to 2017. Dashed lines show the average position of the MSHTL. b - Net accretion/erosion occurrence of events greater than 0.15 meters. c - Variance of the elevation.

In terms of volume, the supra-tidal depositional zones account for values in the order of $10^4 \mathrm{m}^3$, with average values of $6.4.10^4$ ($\pm$ $4.4.10^4$) $\mathrm{m}^3$ over the surveyed period, and maximum numbers reaching values one order of magnitude higher (Figure 3.7). Deposited volume over the sand flat shows no correlation with either maximum water levels or median values of storm surge levels between surveys.

Even though there is a deposition zone, the flat does not present any growth or erosive trend between MSHTL and dunefoot, suggesting a low elevation variability in a year to year basis. Figure 3.6a shows the average year to year elevation change. In the upper part, accretion trends relate to dune growth, with elevation change up to 0.5 meters per year. Also, regions of accretion and erosion on levels below mean spring high tide level (MSHTL - dashed lines) range to values between -0.25 and 0.25, approximately. Average annual elevation change in the central part of the flat is minimal, with values within the measurement error. Variance maps related to the elevation between each year (Figure 3.6c) also show that values are higher for sub-tidal zones and zones where dunes have been growing compared to the centre of the sand-flat, which has variance values smaller than 0.01 for most of the zone. This suggests that not only average values are close to 0, but also values have been similar, with low variability and small deviation. Thus, to maintain the rate of change close to 0, erosive years must be higher in magnitude than accretive years. Moreover, the location above the mean spring high tide level means that either the deposition is caused by water levels above mean spring high tide level or by other transport agents like Aeolian transport.

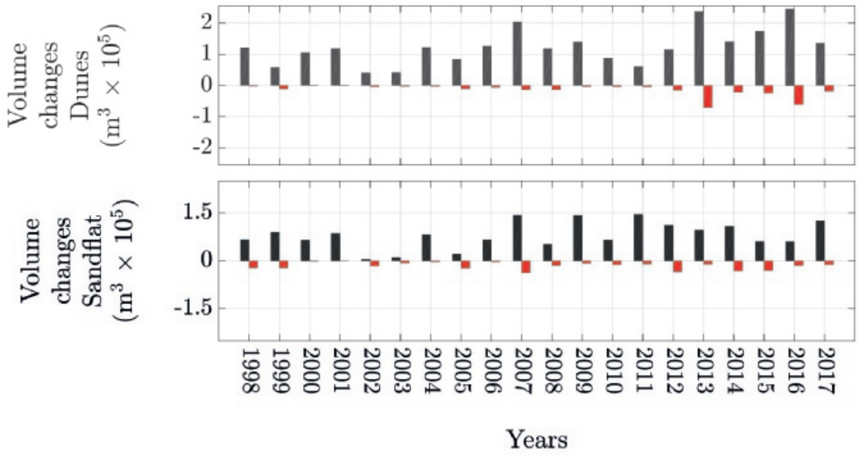

**Figure 3.7:** Annual volume changes for the sand flat and dune area considering only cells which change were greater than 0.15 meters (approximately the maximum possible error based on the allowed error for each LiDAR survey.)

Regarding dune growth, on average $1.1.10^5(\pm 4.4.10^4)\mathrm{m}^3$ of sand per year is deposited on the dunes, which represents a change in height of 0.28 meters per year on average. Overall, a total of $2.3.10^6\mathrm{m}^3$ of sand has been deposited in the dune part between 1997 and 2017. This sediment resulted in an average increase in elevation of 2.51 meters and an expansion of the dune field by $9.2.10^5\mathrm{m}^2$. Potentially, when comparing the volume of sand deposited at the sand flat and the dunes, the yearly average volume deposited on the sand flat over the years represents roughly 59% of the yearly average volume change of the dunes.

Results from the field survey show that expressive bedforms (average height of 11 centimetres and length of 150-250 centimetres, approxidimately) developed on the west portion of the sand flat, gradually diminishing their size towards the east, where they disappeared (Figure 3.8). This suggests that a decrease in flow velocity occurred from west to east. This also suggests that the top of the sand flat was reworked, with elevation change occurring in almost all rods, with values being higher in the western part due to the bedforms. (Figure 3.8).

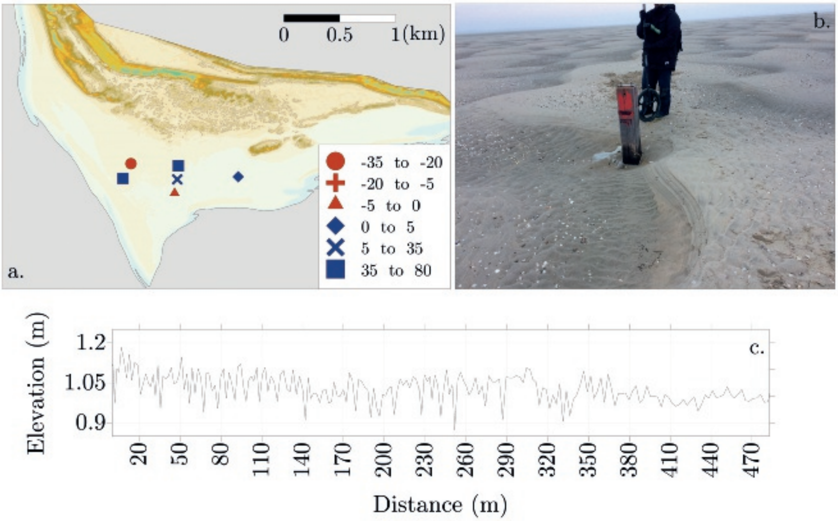

**Figure 3.8:** a. Results from the survey, showing the change in surface elevation over the storm flooding event, in cm; b. Picture showing and example of bed form developed after the storm at the sand flat; c. Elevation data along the transect shown on Figure 3 showing the bed forms formed during the storm event of January/2017.

### Modelled scenarios

Simulation of the storm surge events shows that deposition above the MSHTL happened in almost all scenarios tested. For most scenarios, the sediment is deposited in a clear shore-parallel north-south deposition patch, with volumes varying from $0.7.10^4$ up to $3.10^4\mathrm{m}^3$ of sand. The maximum deposition values occurred for storms h. and i., which are labelled as extreme storms (Figure 3.9). Only two storms did not yield a significant deposition pattern at the sand flat above MSHTL (storms a and b, Table 3.2), with volume values of 474 $\mathrm{m}^3$ and 1198 $\mathrm{m}^3$ deposited over 2320 and 6203 $\mathrm{m}^2$, respectively. These values are distributed in small patches over the plain. Values found in the simulations for the shore-parallel supra-tidal deposition are of the same order of magnitude as the ones derived from the LiDAR data.

Furthermore, simulation results suggest that the amount of sediment deposited tends to be higher for stronger storms. The amount of deposited sand over the sand flat shows a positive correlation (R>0.8) with hydrodynamic forcing conditions ($Hm0$, $Tp$, dir and $W.L$) (Figure 3.10). Considering that higher water levels and wave energy are associated with stronger storms, positive values of correlation suggest that stronger storms would lead to more deposition at the sand flat. Even though correlation with main wave direction is also positive, the presence of deposition for all directions suggests that high correlation values are due to the relation between wave energy and wave direction rather than a principal mechanism towards more deposition onto the sand flat.

We further analyse the relation between hydrodynamic processes and morphological evolution along a cross-shore transect for scenario k analysing the time evolution of 7 parameters: local water level, wave height, cumulative bed level change, bed level change, bed level, convergence values of u in the cross-shore direction (i.e. perpendicular to the shoreline) and zonal components (u) of the flow (Figure 3.11). We also extracted a time-series from a point in the sand flat where deposition occurred and followed the evolution of water level, wave height, convergence values of u in the cross-shore direction (i.e. perpendicular to the shoreline) and cumulative erosion/accretion (Figure 3.12).

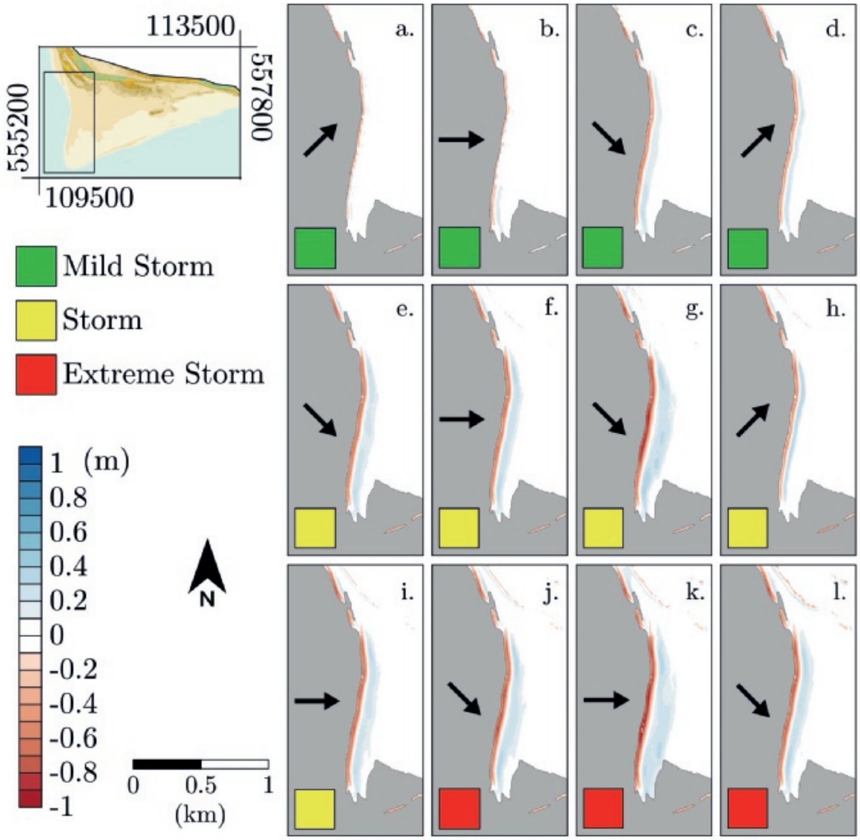

**Figure 3.9:** Final elevation change after XBeach simulation for all tested scenarios. Arrows represent the main wave direction for the period, whereas the coloured box shows the storm strength.

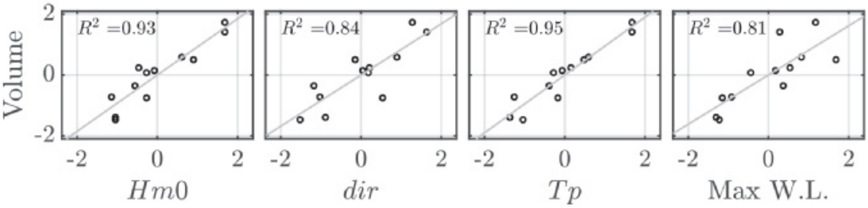

**Figure 3.10:** Scatter plot based on zscores for the initial boundary conditions used for each scenario (Hm0, Tp, dir and maximum water level) against total volume deposited onto the sand flat.

Regarding currents, Figure 3.11g. shows the cross-shore component of the depth-integrated currents. Before inundation of the sand flat, the system is dominated by an offshore directed current, related to the formation of an undertow current to compensate onshore directed wave-driven mass fluxes. As water inundates the flat, the offshore directed current loses strength, with a predominance of an onshore-directed current in the upper part of the beach. It is important to notice that as the undertow loses strength, water fluxes in this zone of the beach are less intense compared to water fluxes in elevations above MSHTL.

Most of the deposition occurred at the beginning of the inundation. Using scenario k. as an example, we extracted information from a profile and a point in space, as highlighted in Figure 3.11. Results show that deposition occurred mostly between 2:00 and 4:00 hours, which is also the period when water levels reached sufficient elevation to inundate the flat. Between 2:00 and 4:00, values of wave height found in the flat are in the order of 0.1-0.2 meters. After 4:00, the increase of water levels reduces wave dissipation and, in turn, allow wave height in the order of 0.5-0.6 meters on the flat. This suggests that the deposition is a wave-driven process, which may be associated with wave breaking. As the water starts to inundate the flat, wave breaking start to erode the beach. As the breaking evolves as an onshore-directed water flux, it transports the eroded sediment in the down-wave direction. This process occurs for the period in which water depth is small enough to dissipate most of the wave energy, which is supported by the really small waves on the flat. As water depth increase, there is a reduction of wave dissipation, that in turn reduces the sediment transport capacity.

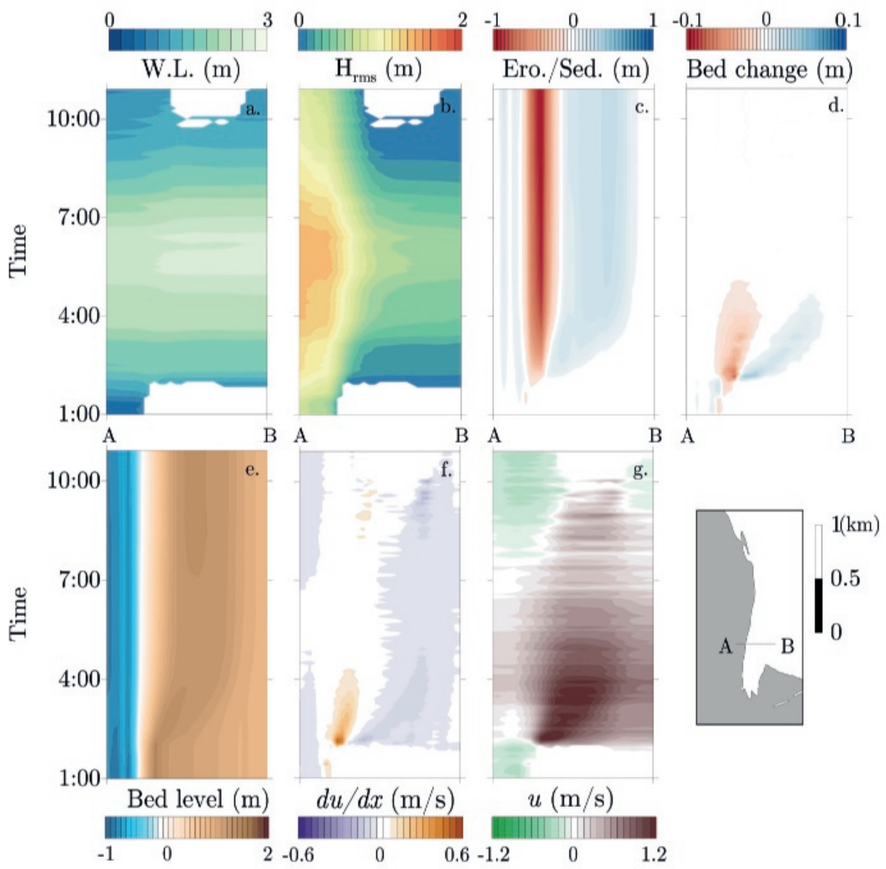

**Figure 3.11:** Evolution of hydrodynamic and morphological characteristics along the transect A-B taken from scenario k. Y-axis represent the time, whereas the X-axis represent the distance between A and B (left to right), shown on the small reference plot. Variables shown are: local water level relative to NAP (a.), Wave height (b.), cumulative bed level change (c.), bed level change (d.), Bed level (e.), cross-shore convergence of u (f.) and zonal components (u) of the flow (g.)

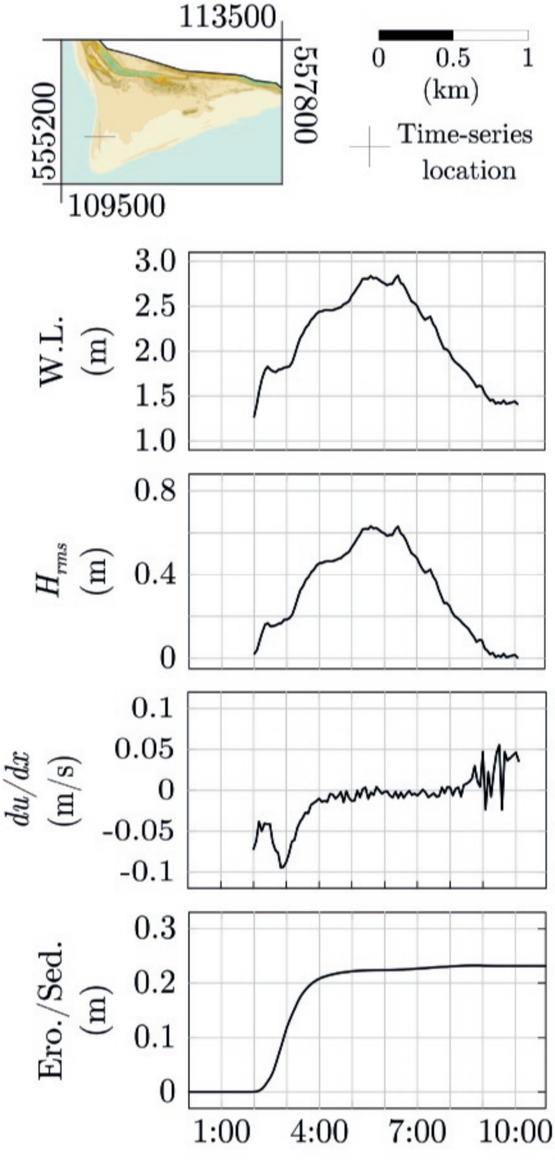

**Figure 3.12:** Time series of hydrodynamic and morphological characteristics extracted from scenario k.

Convergence values of the cross-shore current component (u) help to explain the mechanism of deposition further. Positive values of du/dx occur immediately at the beginning of the inundation phase, as water level reaches values of 1.8 meters (Figure 3.12). Positive values, which relate to a divergence of currents, can be related to an immediate acceleration of water fluxes due to wave breaking in the cross-shore direction. Moreover, the divergence of currents will also lead to erosion of the beach. As the water starts to inundate the upper part of the beach, wave-driven water fluxes start to decelerate in the cross-shore direction, resulting in a zone of convergence, leading to deposition.

Results show that most sediment is eroded from positions below the MSHTL (Figure 3.13). Using the transect A-B from scenario k. as an example, results show that median values of elevation where sediment was eroded are 0.61 meters, whereas sediment was deposited on a median elevation of 1.34. Moreover, 85% of the deposition over the whole period occurred in elevations above the MSHTL, whereas 34% of the erosion occurred in elevations above MSHTL. That suggests that sediment tend to be transported from a regularly hydrodynamically active zone (i.e. below MSHTL) to a zone with a sparser occurrence of hydrodynamic processes (i.e. above MSHTL). Moreover, results show that accretion also occurred in areas below 0 meters. This deposition occurs mainly before the inundation of the sand-flat and is mainly associated with the offshore-directed current which develops before the inundation phase. Sediment is eroded from the upper beach and transported towards the sea, being then deposited in regions below mean sea level.

Using the volume deposited on the sand flat from the simulations, it is possible to estimate the amount of sediment deposited on the sand flat, in reality, using regression techniques. Using both the initial water level and wave height from the simulations as predictors, we could pair the results with measured water levels and wave height in reality. Estimates of sand being deposited on the sand flat show that, between 1997-2017 (i.e. dates which we have LiDAR data and dune volume estimates), the amount of sand predicted to be deposited on the sand flat accounts for 67% of the total sand deposited at the dunes (Figure 3.14). Curves remain similar up to the year of 2007, where divergence occurs due to a mild period in terms of storms. The maintenance of the volume increase in the LiDAR data suggests that even though storm-induced deposition may account for a significant portion of the deposited volume, it is not the only source mechanism of sand for dune growth.

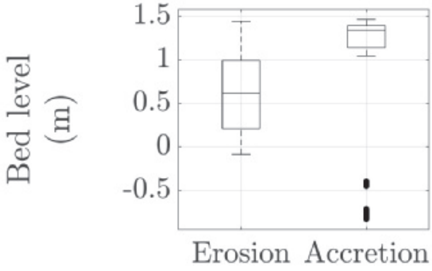

**Figure 3.13:** Box plot of the elevation where erosion or accretion occurred extracted from scenario k. as example.

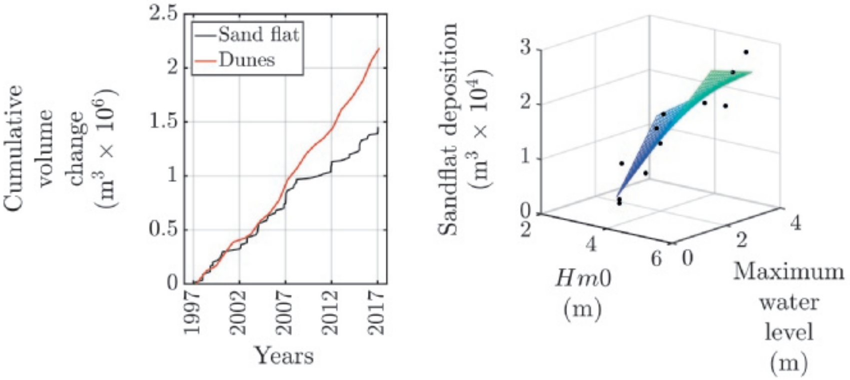

**Figure 3.14:** Left: Cumulative volume changes from the dunes using LiDAR data (Dunes) and estimated sand flat deposition using regression model as predictor (Sand). Regression model has been built using simulation results with maximum water level at the boundary and wave height as predictors for deposition. Right: Scatter plot of the regression model used with regression surface.

## 3.5 Discussion.

Overall, both elevation survey data and modelling results suggest that: (i) there is a shore-parallel deposition pattern that occurs at the sand-flat in areas above the MSHTL (ii) the deposition can be linked to storm events and (iii) the amount of sediment deposited might have a significant importance for dune growth in the area.

As mentioned by Wijnberg et al. (2017), the magnitude of the sand-flat surface area is in the order of $2\mathrm{km}^2$. Considering the total amount of sand accreted at the dunes and considering the sand flat as its only source, the same amount would represent a lowering in the order of 1 meter in height of the sand flat. Considering the stability of the sand flat in a yearly scale, which can be seen through the variance and rate of changes at the sand flat, Wijnberg et al. (2017) suggests that either the sand flat has been continuously replenished by sand or that it is not the primary source of sediment for the dunes. Our elevation survey data results suggest that sand deposited above MSHTL can contribute with more than 50% of the sediment supply of the dunes on a yearly basis. Furthermore, numerical modelling results support that storms may act as a depositional mechanism onto sand-flats, depositing similar shore-parallel supratidal deposits of sand as seen in the elevation data. Also, estimates pairing modelling results and actual data also suggest that cumulative depositions would be on the same order of magnitude of volume changes at the dunes. The potential to contribute to more than half of the yearly average deposited volume in the dunes suggests that, for a sand-flat setting like Texel, the sediment deposited through storm surge flooding can be seen as an important mechanism in terms of sediment exchange between subtidal and subaerial zone and, subsequently, dune growth.

Furthermore, storms can also induce another mechanism that might make potential sediment available for the dunes. Results from the field survey related to the washers show that a storm is capable of remobilising the top layer of the sand flat for a great area of the flat. Hoonhout and de Vries (2017) suggested that in a mega-nourishment setting, wind transport would lead to a sorting process of the sediments at the beach surface that, within a certain period of time, would induce an armouring effect that could reduce the potential of the surface to act as a sediment source. Considering that large parts of the sand-flat remain exposed most of the time, there is a possibility of armouring effects reducing the capacity of the flat to serve as a sediment source. Thus, the occurrence of remobilisation of the top layer after storms would mix sediments from the top layer, making sediment previously armoured to be available again for wind transport. Although possible, to what extent the armouring effect does also occur in a sand-flat setting and what effect this has on the sediment transport towards the dunes remains to further research.

Although modelling results suggest that the amount of sand deposited is directly proportional to storm strength (i.e. storm surge level plus wave energy), data analysis does not show statistical evidence that it happens in reality. This discrepancy may be explained by: the annual time interval of the surveys; cumulative effect of multiple storms before the total dispersion of the deposition of the previous one; the date which the measurement has been taken, since surveys done close to storms would have a higher probability of picturing the shore-parallel deposition pattern; changes in the sand-flat shape between storms, which might lead to slightly non-uniform hydrodynamic forcing in time, thus influencing the potential capacity of sand to be transferred from the sub-tidal to the subaerial zone.

Currently, it is hard to quantify exactly how much sand related to storm deposition or remobilisation of previously deposited sand contributes to dune growth. LiDAR results show that the sediment deposited on the sand flat represents more than half of the sediment necessary to maintain the dune increase at the rates that have been measured. However, being available for transport does not mean that the sediment will end up at the dunes, since other hydrodynamic processes (e.g. next storm surge, erosion due to channel migration) may transport it back to the sub-tidal area. Moreover, wind also can transport this sand back to the sub-tidal zone depending on its direction. Furthermore, limiting factors such as surface moisture and lag deposits can reduce the capacity of the wind considerably to transport the sand from the sand flat towards the dunes (Delgado-Fernandez and Davidson-Arnott, 2011; de Vries et al., 2012; Bauer et al., 2009; Houser and Ellis, 2013; Duarte-Campos et al., 2018). Thus, synchronisation of capable wind events, bed/grain characteristics and available sediment plays a key role (Houser, 2009). Nevertheless, considering the capacity of sediment deposition suggested by our results together with the dominant wind direction, it is probable that at least part of this sediment contributes to dune growth.

Berm formation and supra-tidal shore-parallel depositional ridges on open coastal beaches have been already related to deposition of sediment related to swash processes (Houser and Ellis, 2013). Several authors exemplify that exchange of sediment between sub-tidal and subaerial zones depend on surf and swash processes during calm conditions or migration of sub-tidal and intertidal bars landward (Houser and Ellis, 2013; Aagaard et al., 2004; Jackson et al., 2004; Houser and Barrett, 2010). Our present research suggests that, for a sand-flat setting, a supra-tidal shore-parallel depositional ridge can also form during a storm surge flooding, inducing the deposition of a certain amount of sand that is in the same order of magnitude of the amount of dune volume increase.

## 3.6 Conclusion

A sand-flat at the tip of the island of Texel (NL) has been analysed to identify processes and storm properties that cause deposition on the sand-flat during storm-surge flooding and discuss the relationship between the supra-tidal deposition and sand supply to the dunes. The case was approached by an integrated analysis of LiDAR surveys, field survey and numerical modelling. Results suggest that supra-tidal deposition of sand is directly proportional to storm surge levels and wave energy, and the amount of sand deposited may account for more than half of the volume deposited at the dunes in a yearly basis. Sediment is mostly eroded from areas below MSHTL and deposited further landward by a wave-driven onshore directed flow. Furthermore, simulation results suggest that most of the deposition occurs at the beginning of the sand-flat inundation and it is controlled by the convergence of the cross-shore component of the wave-driven flow. Furthermore, storms are also capable of remobilising the top layer of sediment of the sand-flat, making fresh sediment available for Aeolian transport if an armouring effect occurred, especially in the west part of the sand-flat. Therefore, in a sand-flat setting, storm surges have the potential of transferring a significant amount of sand from the sub-tidal to the supra-tidal zone. This suggests that storms play a significant role in supplying sand for the dunes to grow in a sand-flat setting.

**Acknowledgements**

This research forms a component of the CoCoChannel project (Co-designing Coasts using natural Channel-shoal dynamics), which is funded by Netherlands Organization for Scientific Research, Earth Sciences division (NWO-ALW), and co-funded by Hoogheemraadschap Hollands Noorderkwartier. We further wish to acknowledge Rijkswaterstaat and KNMI for making their valuable bathymetric and topographic data sets freely available, as well as the water level, wave and wind data. Furthermore, we would like to thank Prof. Dr. Dano Roelvink for his help and discussions on the application of the XBeach model.

CHAPTER 4

# The effects of beach width variability on coastal dune development at decadal scales[I]

## Abstract

A cellular automata model is used to evaluate, over decadal time spans, the effect of beach width changes on the development of coastal dune systems. The model includes the effects of aeolian transport, hydrodynamic erosion and accretion, groundwater and vegetation growth. Simulations using fixed and mobile beach widths scenarios were carried out for a 90-year period. Unlimited and limited sediment supply conditions were regulated by groundwater depth. The final topographies were compared based on morphological characteristics such as dunefoot position and volume increase. Results show that there is a preferred cross-shore position where the foredune tends to be built which is a function of beach width and sediment supply. For narrow beaches, foredunes tend to develop at higher elevations than wide beaches due to differences in wave dissipation, whereas dune volume is controlled by hydrodynamic erosion and dune recovery potential by sediment supply. Furthermore, if sediment supply is limited, the effect of beach width on dune volume

---

[I] Chapter published as: Galiforni Silva, F., Wijnberg, K. M., de Groot, A.V. and Hulscher, S.J.M.H. (2019), The effects of beach width variability on coastal dune development at decadal scales. Geomorphology 329 (2019) 58–69

only appears for beach widths larger than 300 meters, suggesting that limitation in supply can dominate dune growth on regular beaches whereas, on wide systems such as sand flats and spits, beach width size dominates. These results suggest that for a decadal scale, beach width controls the space available for dune formation, thus the position of the most seaward dune, but the effect of beach width on dune volume can be overruled by other supply limiting conditions such as groundwater depth.

## 4.1 Introduction.

Coastal dunes are geomorphological landforms essential for flood defence against extreme surge levels. Its dynamics are conditioned by a bio-geophysical balance between aeolian transport, hydrodynamic processes (e.g. waves, tides, storms surges), beach morphology and geology, sediment availability and vegetation type and density (Hesp, 1983; Sherman and Bauer, 1993; Hesp, 2002; Bauer and Davidson-Arnott, 2002; Hesp and Walker, 2013; Delgado-Fernandez and Davidson-Arnott, 2011). When wind blows across the beach surface above a velocity threshold, it initiates aeolian sediment transport. Over time, this sediment is deposited or/and captured by vegetation at the upper beach, leading to a bio-geophysical balance that controls dune initiation, growth and stabilisation (Hesp, 1983; Bochev-van der Burgh et al., 2009; Bauer et al., 2009; Bochev-Van der Burgh et al., 2011; Keijsers et al., 2015; van Puijenbroek et al., 2017). The amount of available sediment that can be transported towards the dunes is intrinsically related to grain size, surface moisture, shell pavement (i.e. surface lag), sediment armouring and beach morphology. Sediment supply and transport capacity are capable of controlling the type of dune-field that can emerge (Eastwood et al., 2011).

Several studies have shown that beach width and beach morphology can control sediment supply (Hesp, 2002; Bauer and Davidson-Arnott, 2002; Davidson-Arnott and Law, 1996), variability in sediment deposition on coastal dunes (Davidson-Arnott and Law, 1996; Burroughs and Tebbens, 2008; Keijsers et al., 2014), aeolian transport potential (Bauer and Davidson-Arnott, 2002; Delgado-Fernandez, 2010) and potential for dune erosion due to extreme events (Davidson-

Arnott et al., 2005).

Beach width often exhibits multi-annual to decadal scale variation (Clarke and Eliot, 1983; Stive et al., 2002; Quartel et al., 2008). Natural processes near tidal inlets, such as shoal attachment, bar welding, channel migration, as well as anthropogenic influence (i.e. nourishments), can directly affect beach morphology and, consequently, beach width (Wijnberg, 2002; Aagaard et al., 2004; Anthony, 2013; Heathfield and Walker, 2015; Cohn et al., 2017). However, few studies have addressed the effect of a time-varying beach width on dune evolution. Shoal attachments, shoreline sand waves and shore nourishments may drive changes in dune development over time. For example, a potential twofold effect of shoreline sand waves on dune dynamics is, for a wider beach width, an increased protection against storm wave attack and increased sand supply and, for the narrow beach width, a reduction of sand supply and less protected dunes (Stewart and Davidson-Arnott, 1988; Davidson-Arnott and Heyningen, 2003). Moreover, the local effect of rapid change in beach width over an annual to decadal scale has also been rarely studied.

An important reason for this is the lack of long-term data in relevant variables such as beach morphology, vegetation cover, meteorological and hydrodynamic conditions with high spatio-temporal resolution. For this reason, the use of numerical models that can work in such scales has been increasing in the past years, ranging from deterministic approaches (Durán Vinent and Moore, 2014; Barchyn and Hugenholtz, 2012) to rule based, probabilistic-based approaches (Nield and Baas, 2007; Eastwood et al., 2011; Keijsers et al., 2016) and coupled approaches (Zhang et al., 2015). In geomorphology, cellular automata models have been considered as a primary choice of reduced complexity modelling, with its strengths relying on its flexibility, relative low-computer effort requirements and range of modelling possibilities (Fonstad, 2006, 2013). Thus, the use of cellular automata models can be seen as a potential tool to analyse bio-physical interactions and responses due to small changes in an idealised, qualitative way. The objective of the present study is to evaluate the effect of changes on beach width for dune development in a decadal scale using a cellular automata model.

Section 2 describes the cellular automata model, highlighting its modules and assumptions. Section 3 describes all chosen test scenarios used as initial conditions for the model. Section 4 describes the results divided by two main groups defined by the initial conditions. Section 5 presents a discussion of the results and the comparison between model results and real patterns.

## 4.2 The DUBEVEG model.

The DUBEVEG model (Keijsers et al., 2016) is a cellular automata model built to simulate dune development in the coastal land-water interface. It includes an aeolian sediment transport component, hydrodynamic sediment input and erosion, groundwater and biotic processes related to vegetation. Sand transport, vegetation growth, and dune development are simulated by probabilistic rules that mimic crucial bio-physical feedback interactions for dune growth, dune development and decay (Figure 4.1). It is meant to analyse trends, patterns and feedback concepts important for dune evolution in a coastal scheme. The model structure is divided in three modules which interact throughout the simulation and subsequently reorganise the ”sand slabs” (square-shaped model representation of a standard volume of sand) that are displaced over the domain: an aeolian transport module, a hydrodynamic module and a vegetation module.

The transport module is the core of the model and represents aeolian sediment transport by assigning probabilities of erosion and deposition to each sand slab at the surface. The probabilities can change according to several factors such as presence of vegetation and the state of surrounding cells. Based on these probabilities, certain cells move downwind and self-organise themselves in bedforms and dunes. By the movement of the slabs downwind, the model mimics the amount of sand that moves a certain distance over a period of time. Thus, the model does not explicitly use wind strength or related shear stress, but rather simulates the sediment transport itself assuming that for each time step, there is a certain probability that the slab will be or not transported (in reality, wind threshold to initiate transport is achieved or not). Thus, sediment transport can vary in time and space randomly. Vertically, the number of cells available for transport is defined by a specified mean sea level and the groundwater level. The

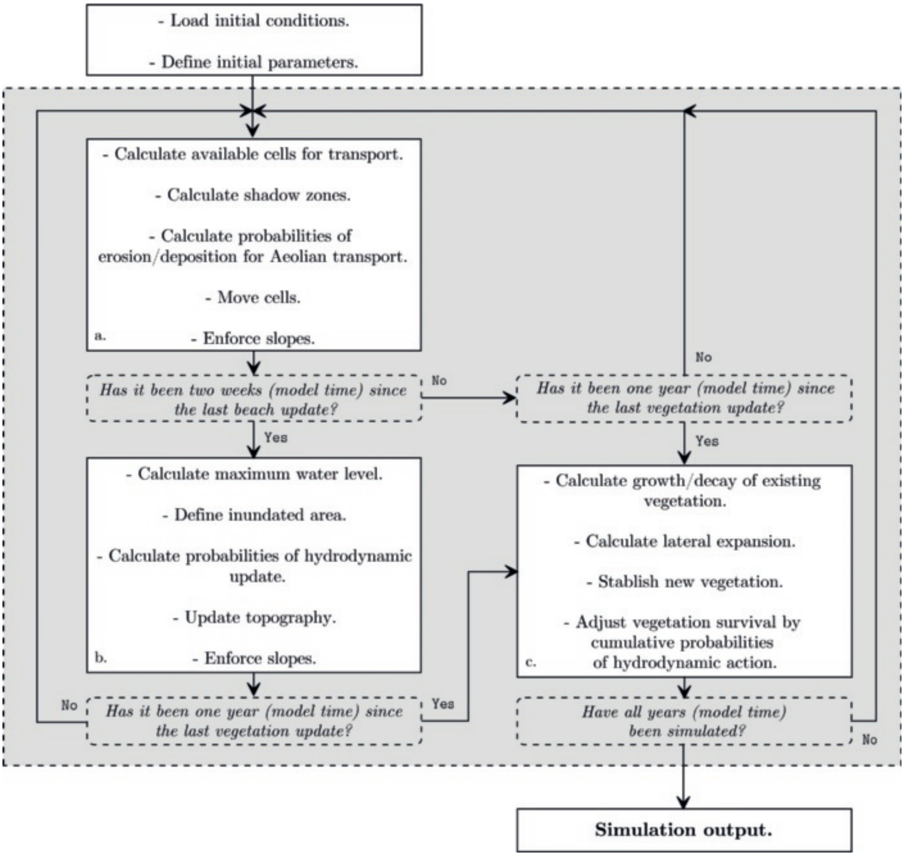

**Figure 4.1:** Model outline, highlighting the aeolian module (a.), the hydrodynamic module (b.), the vegetation module (c.) with the main processes and possible interaction scenarios. Adapted from Silva et al. (2018)

groundwater level is defined as a proportion of a pre-defined reference surface and represents the depth at which water saturation (e.g. moisture content) is high enough to shut down aeolian transport. The reference surface conceptually represents an equilibrium ”profile” for the storm surge impact simulated by the hydrodynamic module.

The hydrodynamic module represents a re-arrangement of the beach topography due to hydrodynamic forcing and is simulated using a rule-based approach that gives a probability $P_{hydro}$ to each cell to return to its reference height, as defined by the reference surface.

$$P_{hydro} = (1 - R_v) \times ((W_E - W_{diss}) + P_{inun}) \times S \qquad (4.1)$$

where $R_v$ is the resistance of erosion due to the vegetation, $W_E$ is the maximum erosive strength of the waves, $W_{diss}$ is a cumulative dissipation factor based on an inverse function of the remaining water depth in the cross-shore direction, $P_{inun}$ is the probability of bed level update due to the inundation regardless of the presence of waves and $S$ is the stochasticity term representing unaccounted or unpredictable conditions (e.g. grain size variability, wave/current interactions). The total water level is defined as a sum of an imposed water level (i.e. tide gauge measurements) plus a wave run-up estimate based on an empirical parametrisation described in Stockdon et al. (2006). Inundated cells receive a certain probability $P_{hydro}$ based on Equation (4.1) which is used to define whether the cell will be reset to its reference profile height or not, being 1 a full chance of reset and 0 a null chance. As a result, this can lead to either erosion or accretion of the cells depending on the elevation of the cell relative to the reference profile. Therefore, the hydrodynamic module controls the sediment balance of the model. It ensures sufficient feeding and erosion from the sea to maintain a certain long-term equilibrium scheme for the overall beach elevation on which dunes may develop.

The vegetation module mimics the growth and decay of dune vegetation using growth curves as a function of bed level change. The vegetation is incorporated by a dimensionless value called vegetation effectiveness, which mimics how vegetation affect the potential for aeolian sand transport and deposition (Nield and Baas, 2007). Also, vegetation plays a role in the hydrodynamic module, as represented in Equation (4.1). New vegetation can appear either by lateral expansion or by random establishment over bare cells. The probability of establishment, which represents germination from seeds and rizhomes, is assumed to be constant for all bare cells. According to Nield and Baas (2007), comparison between model results and real cases are acceptable due to the physiological characteristics introduced by the vegetation, which adds a direct scale in time and space to the model. Regarding vegetation cover, the model accounts for two species: incipient and conservative. The used parameters for all scenarios are presented in Table 4.1.

A common validation practice among cellular automata modellers is the comparison of patterns that emerge within the model with pat-

**Table 4.1:** Summary of standard values used on the simulations. Values used are based on Keijsers et al. (2016)

| Parameter | Value | Unit |
|---|---|---|
| Cell length and width | 1 | Meters |
| Cell height | 0.1 | Meters |
| Probability of deposition on a sandy cell ($P_d$) | 0.1 | - |
| Probability of erosion of a sandy cell ($P_e$) | 0.5 | - |
| Shadow angle | 15 | Degrees |
| Resistance to erosion due to vegetation ($R_v$) | 0.5 | - |
| Dune Sheltering | 0.8 | - |
| Wave dissipation strength ($W_{diss}$) | 0.012 | - |
| Probability of reset due to inundation ($P_{inun}$) | 0 | - |
| Maximum erosive strength ($W_E$) | 1 | - |

terns on real sites. Deterministic validation approaches in cellular automata modelling have been done recently and yield also some level of confidence in cellular model results (Zhang et al., 2015; Keijsers et al., 2016). Although an important advance, such approaches do not necessarily mean that, for the long-term, uncertainties are small enough to make model results reliable. In a non-linear system, different combinations can lead to similar results and final results can differ due to small variations on initial conditions. In the present study, we make use of the validation done by Keijsers et al. (2016), together with some real world data comparison. Validation and further details on the model can be found in Keijsers et al. (2016).

## 4.3 Test scenarios.

In order to evaluate the effects of varying beach width on dune development, static and dynamic scenarios have been tested. Static scenarios are defined as a case with a non-varying shoreline position in time, whereas dynamic scenarios are defined by forced changes in beach width by shoreline migration throughout the simulations. Simulations were carried out for a model time of 90 years to account for several decadal periods. For all simulations, the hydrodynamic and vegetation modules are called after two-weeks and one-year model time, respectively. For all simulations, initial values of vegetation effectiveness are assigned randomly with values between 0 and 0.5 at slabs higher than 2 meters above MSL and 0 at slabs below 2 meters above MSL.

To evaluate the amount of variability in results arising from internal stochasticity and the number of necessary replicates, three different cases have been chosen (Table 4.2). Whiskers would indicate the range of possible outcomes for the same initial conditions. In the present study, whiskers extremes are used to evaluate the range of possible outcomes for the same initial conditions. Furthermore, it can be used to conclude whether outcomes are consistently different or not among different simulation conditions. Furthermore, to determine the amount of replicates necessary, we used the Confidence Interval method (Hoad et al., 2011; Law, 2014). The method aims at finding the number of replicates necessary to narrow the confidence interval up to a specified precision $d_{min}$. Precision $d$ is defined as half width of the Confidence Interval in terms of percentage of the sample mean:

$$d_n = \frac{100 \times t_{n-1,\alpha/2} \times s_n/\sqrt{n}}{\bar{X}_n} \tag{4.2}$$

where $n$ is the number of replications, $t$ is the student t value, $\bar{X}_n$ is the mean and $s_n$ is the standard deviation. For the present research, a stopping criteria is chosen when: values of $d$ are smaller than 5% or after a sudden drop of rate of change with the increase of replicates (thus increasing number of replicates do not lead to a decrease in precision values).

For the static scenarios, simulations over 20 idealized beach widths were carried out, with values ranging from a beach width of 50 meters (e.g. regular beaches) up to 1000 meters (e.g. sand flats near inlets, spits). The initial topography was built based on an available beach topographic measurement of the Dutch coast. This surface was processed to remove the foredune and smoothened using a Gaussian low-pass filter. Then, two nodal points were defined (1.5-meter and 0-meter contour), and the cross-shore position of each node was changed to represent the aforementioned beach widths. The initial profile was also used as the model reference surface.

Water level time-series from a tide-gauge in the North Sea (Texel Inlet) were used, so the same water level time series is used in all simulations. Two groundwater level settings are used to simulate distinct sediment supply cases: a limited supply case (i.e. high groundwater levels) and an unlimited supply case (i.e. deep groundwater levels).

From the output, the domain was divided in 100 cross-shore profiles alongshore and for each profile, dune volume, foredune distance to the 0-meter contour and the initial profile height at the position of the new foredune were calculated. Dune volume was calculated by integrating all cells above 3-meter contour. Foredune distance to the 0-meter contour is calculated by the cross-shore distance between the dunefoot (i.e. 3-m contour) and the 0-meter contour. Initial profile height at foredune position is the height of the initial profile at the final dunefoot location (i.e. at the end of the simulation). The parameter average of all cross-shore profiles is used to define final values for each scenario. Results are compared both over time and between different initial beach widths and slopes. Slopes are defined between 0 and 1.5 meter contour, displayed as the onshore directed gradient. The relation between beach slope and beach width is a negative exponential function, on which small beach width have higher values of beach slope.

For the dynamic scenarios, variations in beach width in time during the simulation are implemented by changing the reference profile (thus, shifting the shoreline) accordingly, in a similar approach used by Keijsers et al. (2016) for sea-level rise adaptation. Three different cases have been tested in this scheme: A- beach width of 1000 meters eroding until 500 meters; B - beach width of 500 meters eroding to a beach width of 150 meters, and C - periodic beach width change ranging from 300 meters to 200 meters, based on shoal attachment events observed on the island of Terschelling (NL) (Ridderinkhof et al., 2016). Furthermore, a range of shoreline retreat rates have been tested for case A and B, in which the shoreline retreats to its final position in 15, 45 and 90 years and remains stable at the final position for the remainder of the simulation. For C, the same cycle of shoreline advance and retreat is repeated every 15 years, in line with shoal attachment behaviour found by Ridderinkhof et al. (2016). From these results, final topographies are evaluated in the same way done in the static scenarios and compared in terms of morphology, volume growth and fore-

**Table 4.2:** Summary of number of replicates used to evaluate internal stochasticity of the model

| Test case | Initial Beach Width (m) | Final Beach Width (m) | Return Period (years) | Number of Replicates |
|---|---|---|---|---|
| Static | 150 | 150 | n.a. | 36 |
| Static | 500 | 500 | n.a. | 36 |
| Static | From 50 up to 1000 | same as initial | n.a. | 20 |
| Dynamic (Case A) | 1000 | 500 | 15, 45 and 90 | 20 |
| Dynamic (Case B) | 500 | 150 | 15, 45 and 90 | 20 |
| Dynamic (Case C) | 300 | 200 | 15 (subsequently) | 36 |

dune position.

Model results are compared qualitatively to observed dune development on two sites at the Dutch coast: Egmond beach, as an example of narrow beach and the island of Ameland, as an example of wide beaches. Egmond is a sandy beach located in the western coast of the Netherlands with a beach width in the order of 100 meters. Ameland is one of the barrier islands from the Wadden Sea, with length of about 24 kilometres and a visible pattern of beach width change due to shoal attachments on its west side. Both sites have annual LIDAR data available from 1997 up to 2017 with spatial resolution of 5 meters (up to 2012) and 2 meters (after 2012), which are analyzed together with satellite images from Google Earth to avoid misinterpretations due to spatial and time resolution limitations found in the LIDAR data set (e.g. appearance and erosion between surveys, limiting grid size for incipient dunes).

## 4.4 Results

### Internal variability

Three main differences can be pointed out from the internal variability test: simulations using a narrow beach (150 meters) present higher internal variability than a wider beach (500 meters); there is an overlap of quartile values when comparing unlimited and limited supply for narrow beaches; the dynamic case presents less internal variability than the narrow case, even though final beach widths are similar (Figure 4.2).

Higher variability on narrow beaches means that the range of possible outcomes (i.e. dune characteristics) is wider than those for wide beach widths. As an example, the range of initial profile elevation at the final foredune position for an unlimited supply case for a narrow beach condition is approximately 0.5 meters, which is more than 10 times the range for a wide beach scenario. For dynamic cases, the effects of internal stochasticity are relatively small and results for the two supply conditions produces no overlap between boxplots whiskers. In general, narrow beaches can produce a higher range of outcomes for the same initial conditions than wider beaches.

Regarding replicates, results show that all criteria are met when at least 20 replicates are done (Figure 4.3). Also, the number of replicates necessary is sensitive to the parameter chosen, with some parameters leading to the achievement of the 5% precision criteria within 5 replicates.

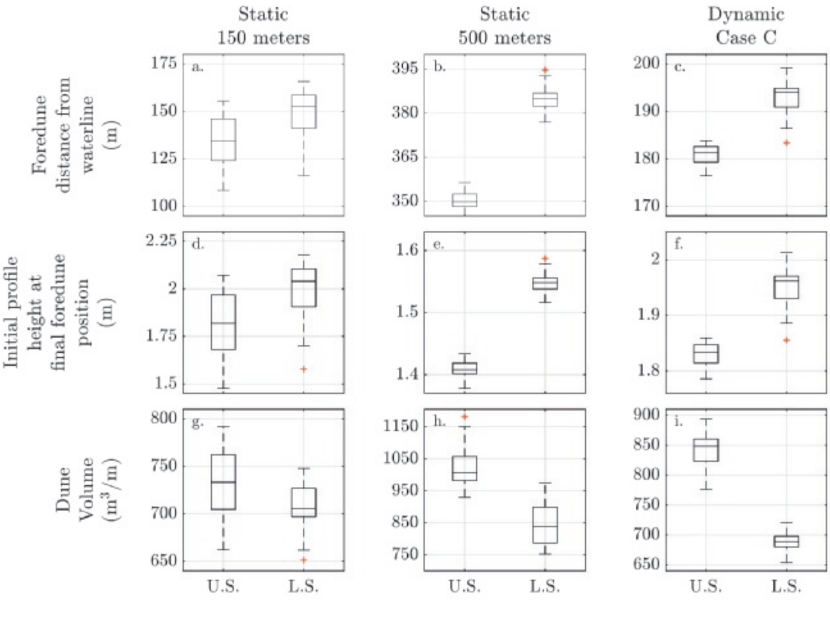

**Figure 4.2:** Internal variability of morphological characteristics after 90-year using the same input and parameter values for three different scenarios. Top and bottom edges of each box represent the 75th and 25th percentiles, whereas whiskers represent data extremes not considered as outliers (95% quartile). Outliers are represented as red marks. U.S. = Unlimited supply. L.S. = Limited supply. Note different scaling of y-axis between the three scenarios

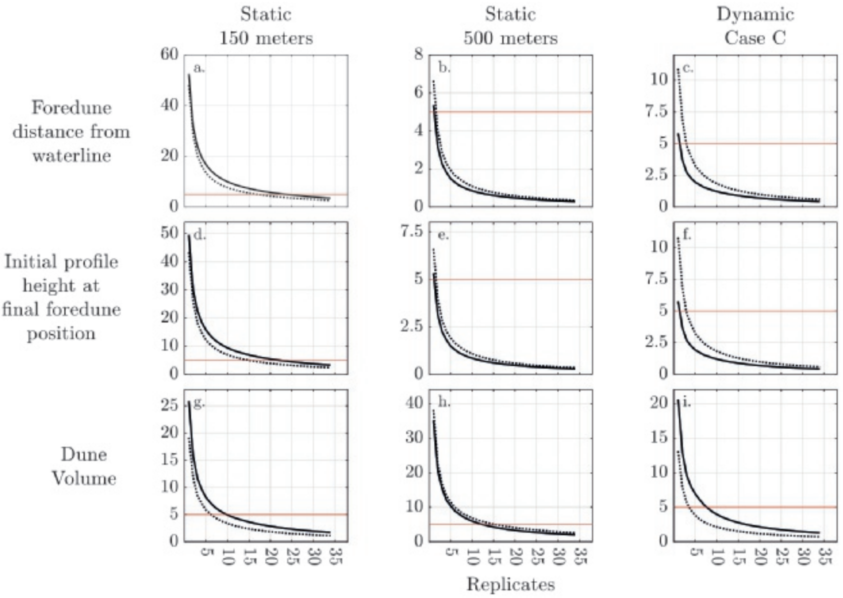

Figure 4.3: Precision evolution for increasing number of replicates, in %. The red line represents the reference of 5, chosen as the threshold for the number of replicates. Black line represent unlimited supply conditions whereas dotted lines represent limited supply conditions.

## Static scenarios

### Unlimited supply scenario

Over time, results show a trend of dunes evolving in a preferential position along the beach profile. The location varies according to the initial beach width conditions and maintain its position since early stages. For most cases, this position is reached within 15-30 years (Figure 4.4a). Dunes start as small bedforms in the area landward to the aforementioned position, evolving into dunes as vegetation starts to grow. The following years are defined by a rearrangement of dunes behind the recently built foredune into a sequence of long dune rows (Figure 4.5). The presence of a stable position can be seen in all cases, regardless of its initial beach width. Dune volume increases steadily throughout the entire simulation (Figure 4.4c). Although different in magnitude, all beach width scenarios had an increase of at least 4 times the volume after 15 years by the end of the simulation.

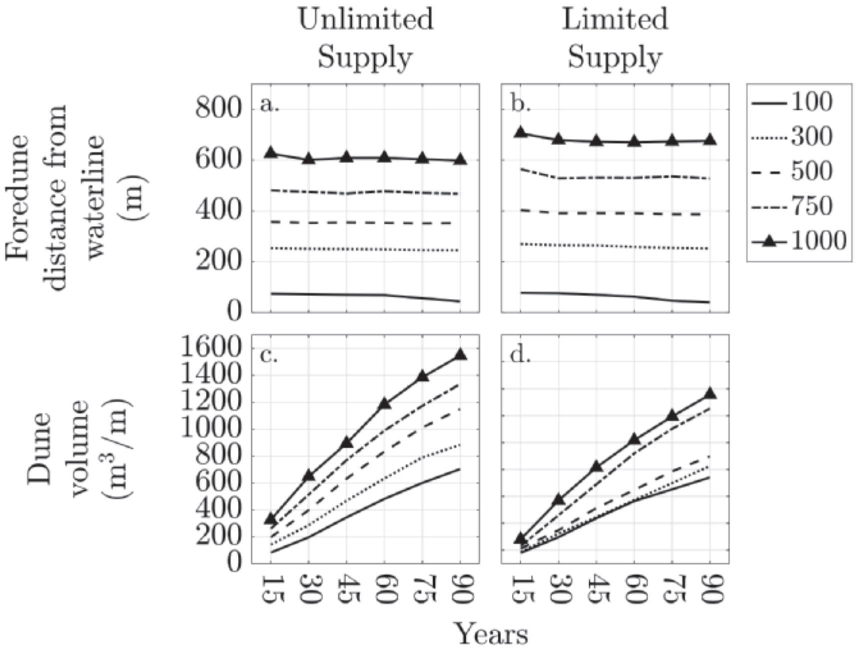

**Figure 4.4:** Beach-dune morphological evolution for 5 distinct beach width for an unlimited supply scenario (left) and a limited supply scenario (right).

Comparing different initial beach widths, the final foredune distance to the waterline tends to increase with the initial beach width (Figure 4.6a). When compared to the slope, an inverse dependency appears, with higher values of slope leading to a reduction of final dune volume, although not in a linear scheme (Figure 4.6b). Alternatively, the initial profile height at the final foredune position decreases with the increase of the initial beach widths. This means that the foredune on a wide beach tends to develop at lower elevations than on narrow beaches. Regarding dune volume, final values tend to increase linearly with the increase of beach width (Figure 4.6e). Similar to the foredune position, dune volume tends to increase prominently for slopes smaller than 0.01 (Figure 4.6f). In terms of morphology, results show an overall trend of long dune rows developing over the area landward of a limit position. For beach width of 100 meter, the foredune develops a crest height of up to 20 meters, which is higher

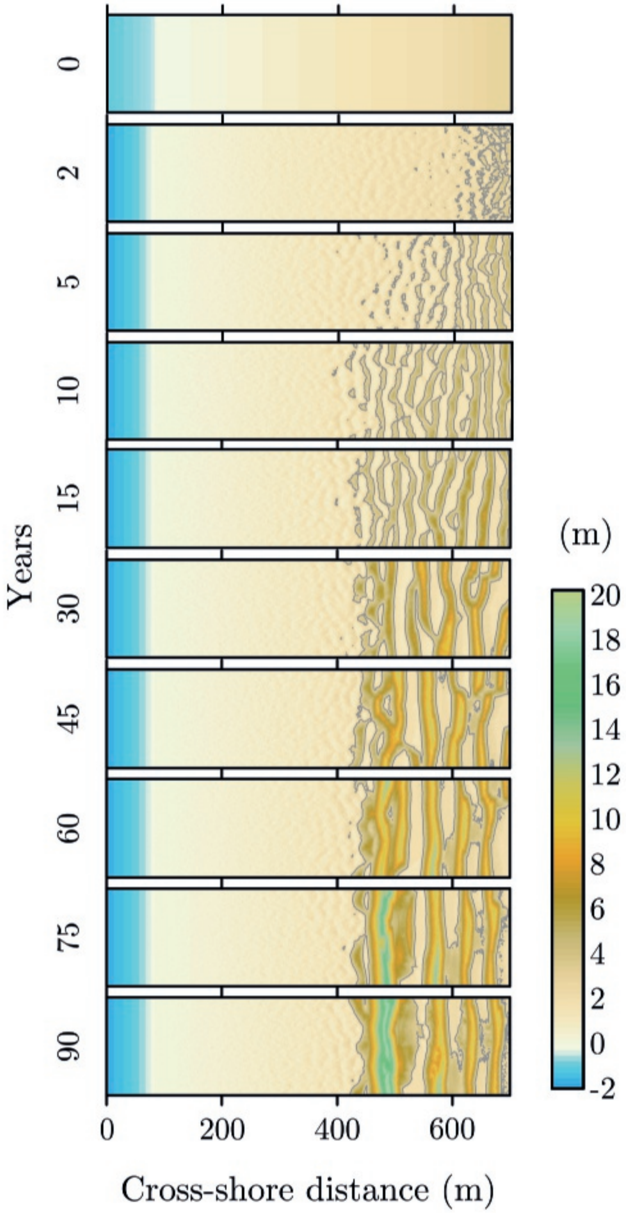

**Figure 4.5:** Dune evolution over time for an unlimited supply scenario

than for wider beaches. For wider beach widths, due to the available space, a sequence of dune rows emerges. For most cases, the seaward most dune eventually tends to be higher than the ones behind it (Figure 4.7).

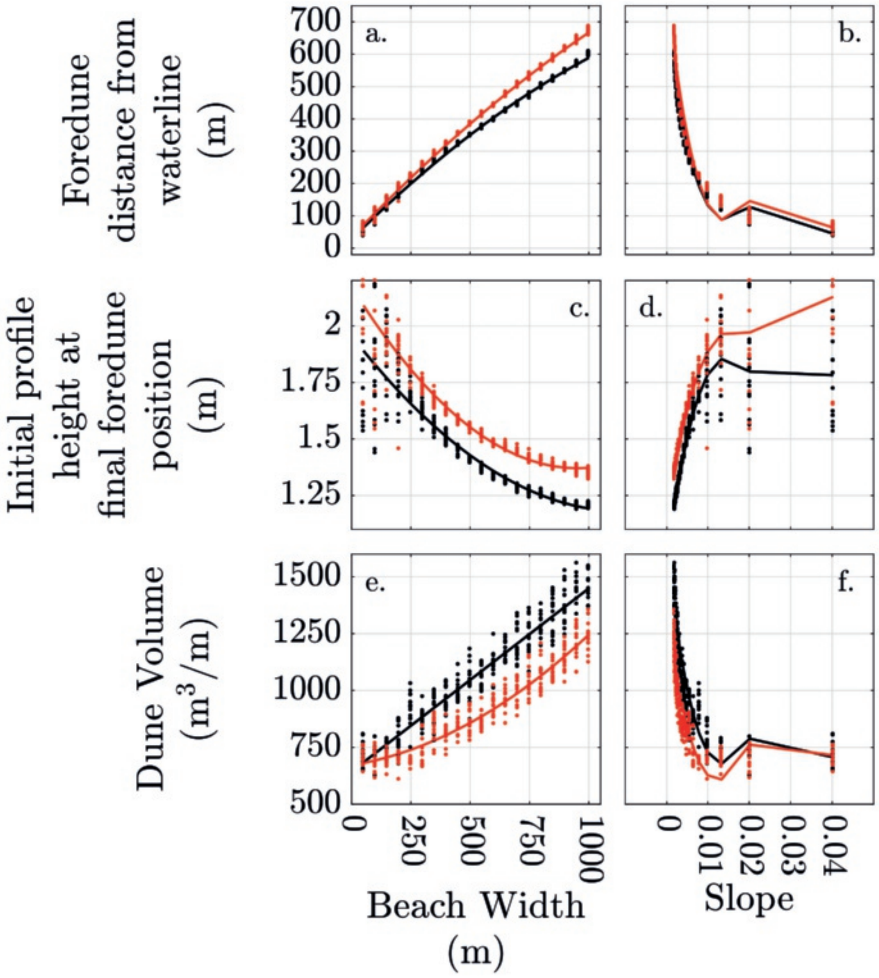

**Figure 4.6:** Differences of beach-dune morphological characteristics after 90-year simulation. Black lines and dots represent unlimited supply scenarios, whereas red lines and dots represent limited supply scenarios. Dots represent average values whereas lines are approximate fitting curves.

### Limited supply scenario

Patterns regarding foredune distance from the waterline and profile initial height at foredune position, for the limited sediment supply scenario, are similar to the unlimited scenario, with changes in magnitude only. Over time, the foredune reaches its stable position within 15-30 years, although for most beach width cases its location is farther from the sea than the unlimited supply condition (Figure 4.4a and b). Dune volume also follows the same pattern as the unlimited supply scenario in time, although with smaller values, especially for wider beach widths (Figure 4.6).

When comparing different beach widths, increasing the beach width resulted in longer foredunes distances from the waterline compared to the unlimited supply scenario. The same dependency pattern appears when comparing the initial profile height at the foredune position, which tend to develop in higher positions than the unlimited scenario.

Interesting though, the dependency changes for dune volume, which presents a quadratic dependency for limited supply scenarios, in contrast to the linear-shaped behaviour in unlimited supply scenarios. In terms of morphology, the overall trend is similar to those found on unlimited supply scenarios, with embryonic dunes emerging up to a certain cross-shore position, with the most seaward one growing more substantially than the ones behind it. The main difference, due to the limitation in supply, is the spacing of the dunes, which is larger than if the supply is not limited.

### Dynamic scenarios

For dynamic scenarios, final values of foredune position and dune volume after 90-year simulation are illustrated in Figure 4.8. Overall, results show a spatiotemporal pattern that dunes tend to be build closer to the waterline for retreat periods of 45 and 90 years. In Case A, for unlimited supply conditions, the average dune volume and average foredune position are considered statistically significant different between all retreat scenarios (Table 4.3). Moreover, for a retreat period of 45 and 90 years, foredunes tend to develop closer to the final waterline position than for a retreat period of 15 and the static scenario, with values ranging between 350-300 meters. The same spatiotemporal pattern can be seen in Case B 4.8, with values of foredune position being closer to the waterline for retreat period of 45 and 90 years in an unlimited supply condition. For a limited supply

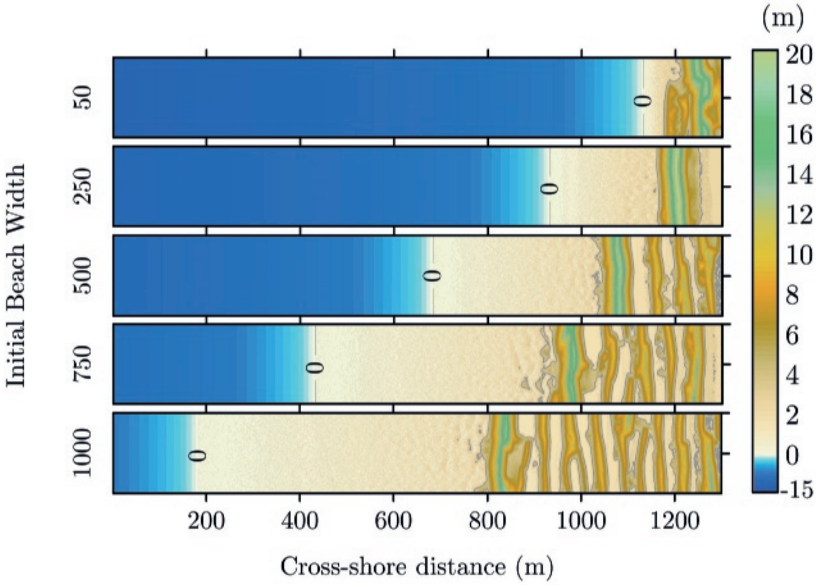

**Figure 4.7:** Morphological differences on dune evolution after 90-years for 5 different beach width.

condition, this pattern is less prominent. Average dune volume and foredune position for retreat periods of 45 years are not significantly different from those for static and 90-year retreat scenario. However, Case B presents a spatiotemporal pattern similar to the unlimited supply condition of longer retreat periods translating into foredunes positioned closer to the waterline. For Case C, limited supply scenarios did not yield statistically different average values between static and dynamic scenarios. For unlimited supply, results from static and dynamic scenarios are statistically different, with mean values of static scenario being slightly lower than the dynamic scenario. Furthermore, the range of possible outcomes are much higher for the static than the dynamic scenario.

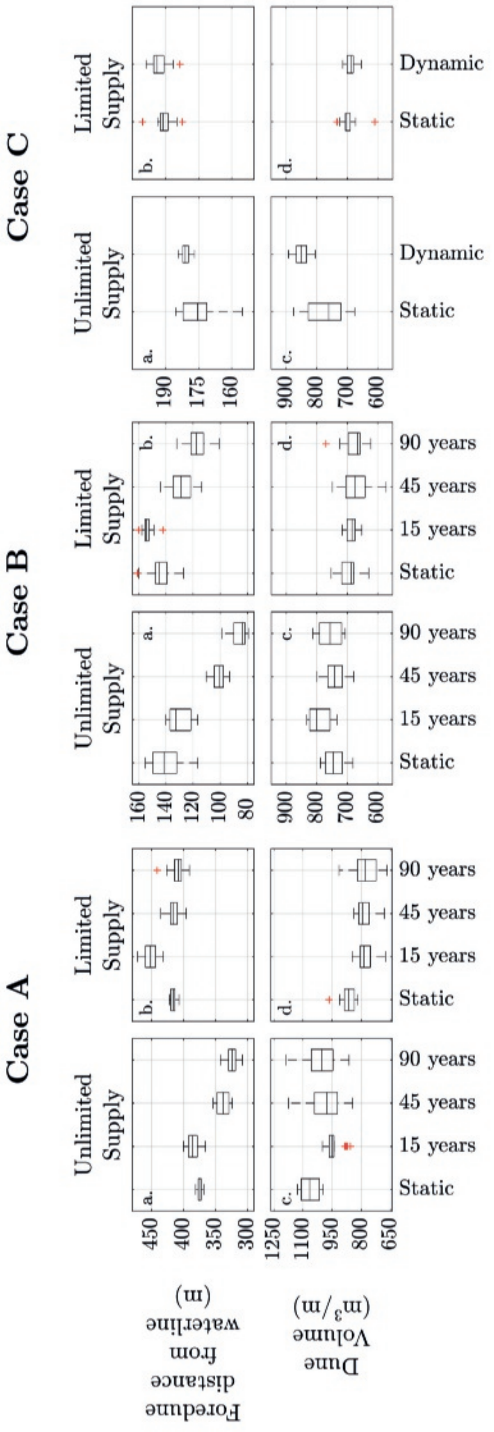

**Figure 4.8:** Differences of beach-dune morphological characteristics for the dynamic case A, B and C for two distinct supply conditions. Static scenarios represent static simulations with beach width of 500, 150 and 200 meters, respectively.

Regarding dune volume, for Case A, static scenarios present higher values than all dynamic scenarios. For Case B, only retreat periods of 15 years resulted in a significant different mean than all the other scenarios for an unlimited supply conditions. No statistical difference emerge when considering limited supply conditions for Case B. For Case C, dynamic scenarios yield higher values than the static scenario for an unlimited supply condition, whereas no significant difference can be seen for a limited supply condition.

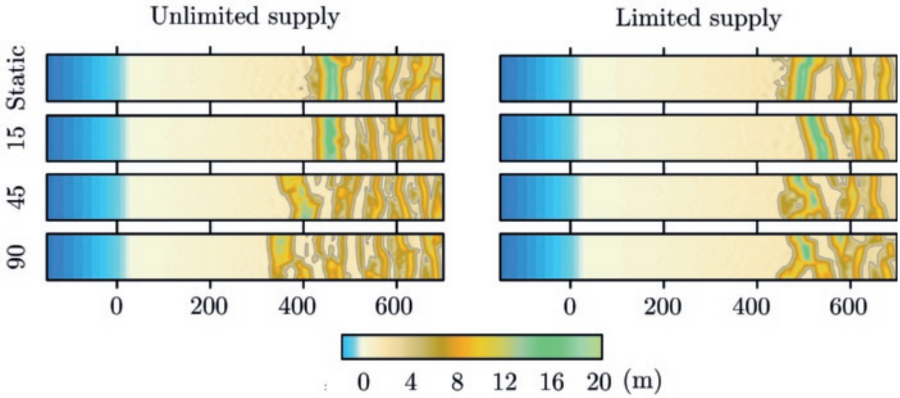

**Figure 4.9:** Topography results after 90-year simulation for case A for both unlimited and limited supply scenarios.

Morphologically, static and dynamic scenarios with 15-year retreat period yield higher foredunes than dynamic scenarios with a retreat period of 45 and 90 years. Furthermore, the same trend of dune rows landward to the foredune remains for the cases where space is available (Figure 4.9).

**Table 4.3:** Welch's t-test results for the dynamic cases. P-values and final test results are displayed. H = 1 indicates rejection of null hypothesis (equal means) at the 5% significance level

| | Case A | | | | | | | | Case B | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foredune distance to waterline (m) | | | | Dune Volume ($m^3/m$) | | | | Foredune distance to waterline (m) | | | | Dune Volume ($m^3/m$) | | | |
| | Unlimited supply | | Limited supply | | Unlimited supply | | Limited supply | | Unlimited supply | | Limited supply | | Unlimited supply | | Limited supply | |
| | p | H | p | H | p | H | p | H | p | H | p | H | p | H | p | H |
| Static - 15 years | $p < 0.001$ | 1 | $p < 0.001$ | 1 | $p < 0.001$ | 1 | $p < 0.001$ | 1 | 0.007 | 1 | $p < 0.001$ | 1 | $p < 0.001$ | 1 | 0.268 | 0 |
| Static - 45 years | $p < 0.001$ | 1 | 0.749 | 0 | 0.001 | 1 | $p < 0.001$ | 1 | $p < 0.001$ | 1 | $p < 0.001$ | 1 | 0.872 | 0 | 0.057 | 0 |
| Static - 90 years | $p < 0.001$ | 1 | 0.026 | 1 | 0.006 | 1 | $p < 0.001$ | 1 | $p < 0.001$ | 1 | $p < 0.001$ | 1 | 0.154 | 0 | 0.106 | 0 |
| 15 years - 45 years | $p < 0.001$ | 1 | $p < 0.001$ | 1 | 0.023 | 1 | 0.564 | 0 | $p < 0.001$ | 1 | $p < 0.001$ | 1 | $p < 0.001$ | 1 | 0.174 | 0 |
| 15 years - 90 years | $p < 0.001$ | 1 | $p < 0.001$ | 1 | 0.006 | 1 | 0.809 | 0 | $p < 0.001$ | 1 | $p < 0.001$ | 1 | 0.004 | 1 | 0.345 | 0 |
| 45 years - 90 years | $p < 0.001$ | 1 | 0.110 | 0 | 0.640 | 0 | 0.842 | 0 | $p < 0.001$ | 1 | $p < 0.001$ | 1 | 0.119 | 0 | 0.612 | 0 |

| | Case C | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Foredune distance to waterline (m) | | | | Dune Volume ($m^3/m$) | | | |
| | Unlimited supply | | Limited supply | | Unlimited supply | | Limited supply | |
| | p | H | p | H | p | H | p | H |
| Static - Dynamic | 0.006 | 1 | 0.087 | 0 | $p < 0.001$ | 1 | 0.170 | 0 |

### Real cases

Regarding real cases, Egmond presents a local erosion trend of the foredune (Figure 4.10a). The beach width ranged from 75 meters up to 135 meters. Satellite images from 2005 and 2007 show a retreat of the dunefoot by about 5 meters, which in 2013 ends with a retreat of approximately 20 meters. In 2013, a linear group of incipient dunes start to emerge close to the foredune position of 2005 (Figure 4.10b, 2013). This small linear incipient dune belt disappeared in 2015 and can be seen again in 2017, on a position similar to that the foredune of 2005, suggesting a preferential position of dune growth. Regarding profile height, comparing the position of the new belt of incipient dunes with the average height at the location using all available LIDAR data yield average values of 2.6 (±0.5) meters.

For Ameland, shoreline evolution patterns due to shoal attachment build two interesting locations: one east of the attached shoal, with a sudden increase of beach width after 1997; and a second location on the west of the shoal where the beach width is wide for at least 15 years 4.11a). For the East location, incipient dunes start to emerge in front of the foredune after 2005, which is in accordance with the time of beach width increase 4.11b, red box). For the west part, incipient dunes also emerge in front of the foredune, although this time expanding much further than the eastern region 4.11b, purple box). Also, regarding profile height, comparing the position of the new belt of incipient dunes with the average height yield lower values for the western part than the eastern part, with average values of 1.8 (± 0.2) and 2.4 (± 0.1) for the wider and narrower beach width, respectively. Differently than Egmond's case, the locations at the Ameland case present different shoreline orientation regarding the main wind direction quadrant (W-SW). That means that the East sector present potential enough fetch in a higher percentage of the wind events than the West sector. Nevertheless, the development of incipient dunes after 2005 suggests that both sites present enough aeolian sediment transport for dune development.

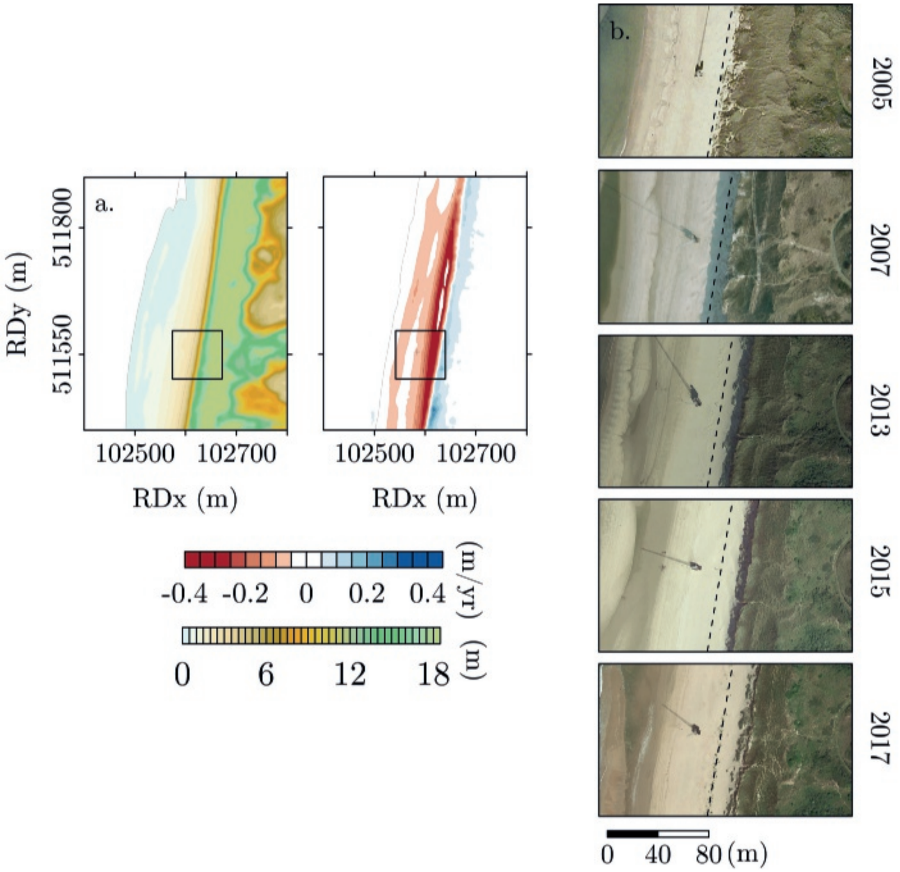

**Figure 4.10:** Real example of Egmond beach. a. Topographic map and the rate of change on elevation, showing erosive pattern of the stretch of coast. b. Sequence of satellite images showing the development of new incipient dune belt at a location seaward of the current foredune (Source: Google Earth). Dashed lines represent the dunefoot position in 1997.

## 4.5 Discussion.

Three main characteristics can be pointed out when comparing results of simulations for different beach width conditions: 1. there is a preferential cross-shore position where the foredune tends to grow, on which the vertical growth tend to overcome horizontal expansion; 2. the foredune distance from waterline increases with the beach width, whereas the elevation on which the foredune develops decreases with beach width (lower for wider beaches); 3. for limited

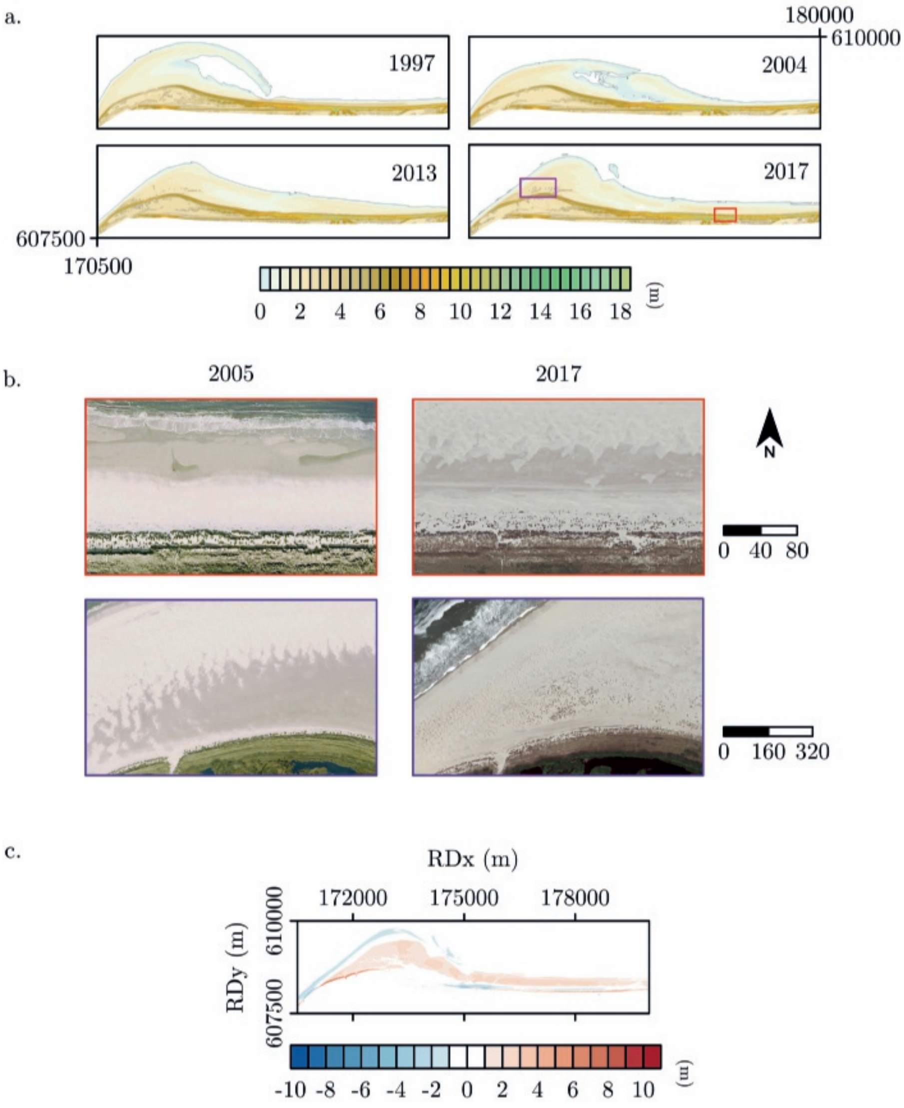

**Figure 4.11:** Real example of Ameland. a. Sequence of topographic maps showing the shoreline behavior due to shoal attachment; b. Sequence of satellite images showing dune development in a wide beach in the west (purple box) and east (red box). Note the scale difference. (Source: Google Earth); c. Difference map between LIDAR survey of 1997 and 2017

supply conditions, a minimum beach width size seems to exist beyond which the width starts to effectively affect dune volume.

Results show a tendency of dunes to expand until a limit point in the cross-shore direction, as shown by static simulations, on which most horizontal expansion takes place in the first 30 years of simulations for most scenarios. The dune system will change from a horizontal expansion trend to a vertical growth trend of the foredune when it reaches a preferential position. Data from Egmond beach also suggest an existence of a preferential position, where a position seems to exist on which the foredune tend to be rebuilt after an erosion period. For Ameland, the response of expanding dunefield after widening of the beach also seems consistent with model results. Ruessink and Jeuken (2002) have shown that, for the Dutch coast, shoreward extensions of beach width lead to similar patterns on dunefoot, which is in accordance with our findings. Furthermore, Ruessink and Jeuken (2002) imply that time-space variability in beach characteristics control the residual dunefoot variability. An increase/decrease in beach width would lead, if enough time is given, to an expansion/retreat of the dunefoot. This explains also why dunes tend to develop closer to the waterline in the dynamic scenarios for longer retreat periods (45 and 90 years). For longer periods, dunes have time to reach its preferential cross-shore position and increase vertically, becoming established and resistant to retreat. Thus, the probability of dunes surviving closer to the waterline is higher as they also act as a buffer for the retreat period. Expansion and retreat of dunefoot due to changes in beach characteristics can also be seen in evolution models for coastal dune fields proposed by Hesp (2002, Figure 3, accretion cycle) and Hesp and Walker (2013, Figure 8a and b). The main difference would be the time over which the progradation is considered, being the one in the present study dealing with sudden changes on a scale of years while these other studies relate to foredunes experiencing long-term beach progradation.

The foredune position can be seen as a function of the beach width or slope and sediment supply. de Vries et al. (2012) have already shown a correlation between beach slope and dune volume change for the Dutch coast. Our results suggest that the relation between beach width, slope and foredune position is not linear. Moreover, our results suggest that the foredune position can also be seen as a function of the initial profile elevation. For Ameland which has similar tide level and wave forcing between two considered sites with different beach width, dunes tend to form on lower elevations on wider beaches than narrow ones, which is in line with our model results. A hypothesis is that the position is conditioned by hydrodynamic erosion and available space at the upper beach for dune growth. Wider beaches would dissipate more wave energy than narrow beaches, which would increase the limit for dune extension. This is in line with our model results, which shows an inverse relationship between foredune position and slope. A wide beach offers an increased surf zone for energy dissipation and, consequently, limits wave run-up in the beach face. Therefore, steeper slope translates into hydrodynamic action reaching higher elevations on the profile, thus shifting foredune position to higher elevations than in mild slopes.

Our results further suggest that for narrow beaches, supply limiting factors such as groundwater can be more important than beach width in terms of dune volume, as can be seen on the dune volume increase results. Delgado-Fernandez and Davidson-Arnott (2011) already discussed that limiting factors such as surface moisture and ice/snow are capable of preventing transport events even though potential wind speed and enough fetch was present. de Vries et al. (2012) also suggest that transport limiting processes govern dune volume development, whereas Keijsers et al. (2014) suggest that, for beaches smaller than 200 meters, temporal variability in dune volume is correlated with storm proxies. Our results suggest that, for narrow beaches, hydrodynamic sediment input outside the intertidal area (i.e. upper beach) is negative for both unlimited and limited supply conditions (Figure 4.12b). Having an erosive trend in the upper beach means that the total aeolian input that deposits at the foredune is reduced by hydrodynamic action. For wider beaches as sand flats, the hydrodynamic input outside the intertidal area is positive, which means that the influence of erosion is reduced, leading to a more prominent influence of local supply conditions (e.g. groundwater level) for the overall dune volume. The erosive control on narrow beaches also explains the high variability found in our results for narrow beaches, since erosion closer to the dunefoot is more frequent and dune morphology would not be controlled in majority by supply, but also by erosion, which is in accordance to Keijsers et al. (2014).

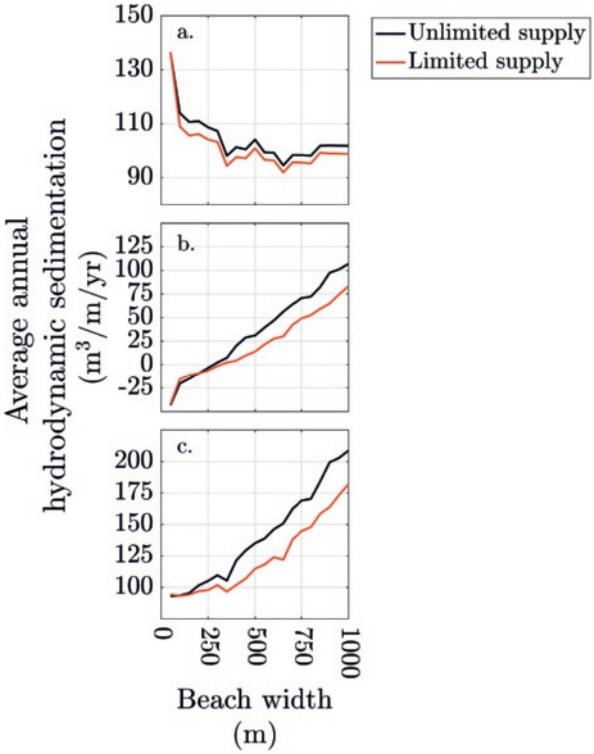

**Figure 4.12:** Annual average sea input for static scenarios, showing the net input in the intertidal area (a.), upper beach (b.) and whole profile (c.). Positive values referring to hydrodynamic accretion and negative values to hydrodynamic erosion

To model the influence of beach width on dune development, it is crucial that all other parameters are unaltered throughout different scenarios, so dune changes can be analysed solely on regards of beach width change. However, in reality, it is extremely difficult (if not impossible), to find different sites where all conditions that influence dune development are the same except for beach width. Thus, in this paper direct comparison with real data is maintained solely at the qualitative scale. Even so, it is important to note that dune differences between different sites in the presented real cases are not only influenced by the variations on beach width, but also by different wind strength and direction, grain size variability, local groundwater variations and shell pavement, which could not be accounted. Also, it is important to mention that, for narrow beaches, beach width can be a limitation not only for space, but also for potential aeolian transport if beach width size is smaller than a potential critical fetch length. Critical fetch relates to a saturation of transport after some distance on which an increase in the fetch do not translate into more sand being transported (Bauer and Davidson-Arnott, 2002). If beach width is larger than potential critical fetch, small changes in beach width would have a limited effect in terms of aeolian transport, though it might influence dune position due to increased space and wave dissipation. On the other hand, if beach width is small, small changes in beach width do not only affect space and wave dissipation, but also potential transport. Nevertheless, the model suggest that only beach width changes can lead to similar beach-dune variability as found in the real cases, though its percentage of influence remain uncertain.

A relationship between hydrodynamic forces and the aeolian/biological forces is also seen by Durán Vinent and Moore (2014) on the scope of barrier island evolution. The authors argue that if dune recovering processes dominate, islands tend to become high in elevation and low regarding vulnerability to storms, whereas a perpetual long-term trend of low elevation and high vulnerability to storms might be present when erosion processes dominate. Considering this binary state, our study elaborates on the former, suggesting that the balance between hydrodynamic erosion and recovery capacity can also control dune states in smaller temporal scales. In narrow beaches, the hydrodynamic erosion and dune recovery potential control dune volume, whereas sediment supply and beach width would control the foredune position. Moreover, considering a changing beach width scenario, the increase on beach width does not necessarily translate into volume changes at the dunes, since the amount of sand transported toward the dunes can be significantly limited by other factors than yield by the potential increase of beach width. In contrast, dynamic tests showed that for narrow beaches, periodic increment in beach width may increase dune volume in the long-term. For wider beaches, changes in beach width only affect the foredune position.

## 4.6 Conclusion

A cellular automata model was used to evaluate the effect of varying beach width on coastal dune development at yearly to decadal scales. Several simulations were done using idealised beach profiles, different sediment supply conditions and static/dynamic behaviour of the shoreline. Results show that there is a preferential cross-shore position where the foredune tend to grow which varies with beach width. Moreover, foredunes at narrow beaches tend to develop at higher elevations than at wider beaches, whilst supply limitation factors such as groundwater depth can dominate over the effect of beach width increase on dune volume for narrow beaches. Furthermore, beach width controls the aeolian deposition zone where incipient dunes can emerge, thus controlling the space available for dune development. Therefore, beach width controls the space available for dune formation, thus the position of the most seaward dune, but the effect of beach width on dune volume can be overruled by other supply limiting conditions such as groundwater depth. Thus, for time-varying beach widths, initial beach widths and retreat time would define what would be the most important controls for foredune dynamics.

### Acknowledgements

This research forms a component of the CoCoChannel project (Co-designing Coasts using natural Channel-shoal dynamics), which is funded by Netherlands Organization for Scientific Research, Earth Sciences division (NWO-ALW), and co-funded by Hoogheemraadschap Hollands Noorderkwartier. We further wish to acknowledge Rijkswaterstaat for making their valuable bathymetric and topographic data sets freely available, as well as the water level data.

## CHAPTER 5

# The effects of shoal attachment on coastal dune development: case study in Terschelling (NL)[I]

## Abstract

Tidal inlet-driven processes are capable of changing the adjacent shoreline due to shoal attachment, ebb-tidal delta variability and channel migration. However, few studies have attempted to understand whether these changes also affect the adjacent coastal dunes. The present study aims at understanding how shoreline changes induced by shoal attachment processes affect coastal dunes disposed at the adjacent subaerial beach. For this, we use a barrier island (Terschelling) located on the coast of the Netherlands as a case study. Shoals in the island have an average cycle period of 15 years and sizes of $10^2$ up to $10^4$ meters. We analysed both bathymetric and topographic data available for the area, together with the application of a cellular automata model for dune development to explore idealised scenarios of inlet-driven shoreline movements. The model has been adapted to consider the effect of different shoreline behaviour due to shoal attachment, on which we tested ten different scenarios

---

[I] Chapter submitted as: Galiforni Silva, F., Wijnberg, K. M. and Hulscher, S.J.M.H. (subm.) The effects of shoal attachment on coastal dune development: case study in Terschelling (NL).

regarding beach width increase and rate of alongshore spreading. Elevation data shows that beach width varied most in the coastal section controlled by ebb-tidal processes. Furthermore, rates of dune volume change in the ebb-tidal controlled zone differed significantly from those outside the zone, even though shoal attachments did not yield an immediate change in dune growth. This suggests that either the increased average beach width or its high variability induce higher rates of dune growth at the attachment zone. Modelling results show that 3 out of 10 scenarios of shoal attachment tested yield significantly higher final dune volumes than stretches with no shoal influence, suggesting that beach width increase and rate of alongshore sediment spreading of the shoal after attachment are key factors determining whether the shoal will influence dune growth or not. Therefore, in the studied time-scale, we found that shoal attachment is capable of increasing local rates of dune growth, considered that its size/volume is large enough to induce a high and persistent increase in beach width.

## 5.1 Introduction.

Coastlines near tidal inlets are heavily conditioned by inlet processes, which can drive long-term variations in sand supply, wave protection and erosive phases due to channel migration (FitzGerald et al., 2000). Progradation periods in adjacent coastlines occur due to spit growth, bar welding processes and longshore transport gradients, whereas retreat periods are related to a result of storms, inlet migration and longshore transport gradients (FitzGerald, 1988; Fenster and Dolan, 1996; FitzGerald et al., 2000; Siegle and Asp, 2007; Silva et al., 2016).

In a mixed-energy setting, one of the main sand input processes to a coastline stretch happens in the form of shoals (Gaudiano and Kana, 2001). A shoal (or swash bar) is an accumulation of sand that detaches from the ebb-tidal delta and is transported towards the coastline. Its attachment on the downdrift side of the inlet follows a cyclic behaviour with periods that vary from multiple years to multiple decades (Ridderinkhof et al., 2016).

Kana (1995) relates shoal bypassing events and their volumes to the tidal prism. In a study at Teignmouth inlet (UK), Siegle et al. (2004) show that ebb-tidal sandbars are heavily conditioned by waves, highlighting the importance of the temporal distribution of storms defining the cyclic behaviour of bars. Other authors argue that sediment composition (Burningham and French, 2006) and changes in inlet ebb-channel orientation associated with storm events (O'Connor et al., 2010) are also important factors in defining shoal behaviour. Ridderinkhof et al. (2016) show that shoal growth and migration is related to wave energy and bathymetry, whereas the migration speed increases proportionally with incident wave energy and inversely to tidal prism due to residual tidal currents.

The size and period of attachment differ among different inlet systems. Ridderinkhof et al. (2016) show that for inlets on the Wadden Sea, the average period of cyclic between successive shoal attachments can range between 4 and 130 years. Faster attachment periods have also been described (FitzGerald and Pendleton, 2002), although several inlets present average periods within the range shown by Ridderinkhof et al. (2016) (Siegle et al., 2004; Burningham and French, 2006; Gaudiano and Kana, 2001). As of size, Hofstede (1999b) estimates that a single shoal can supply the coast with up to $10^7$ $\mathrm{m}^3$ of sand. Gaudiano and Kana (2001) estimates an annual transport rate of $12 \mathrm{X} 10^3$ $\mathrm{m}^3$ of sand from Midway's ebb-tidal delta to Pawleys Island (US). FitzGerald (1982) states that shoals can have widths ranging from 40-300 meters and lengths from 300 to over 1500 meters. After attachment, the rate of persistence will be related to the capacity of the longshore transport to redistribute the new sand alongshore.

Shoals have been recognised by their strong capacity of changing adjacent coastlines in several different temporal and spatial scales (Robin et al., 2009; Elias and Van Der Spek, 2006; Do et al., 2018; Isla, 1997). Fitzgerald et al. (1984) attribute the shape of the East Frisian Islands to inlet sediment bypassing. Fenster and Dolan (1996) investigated shoreline migration trends in two inlet-driven regions in the West Coast of the United States associated with shoal attachment processes. The authors did not find any significant statistical relation between tidal prism and the longshore extent of the influence of the inlet on the adjacent shoreline. However, they found that downdrift inlet shoreline accretion dominates when stable bypassing processes occur. Hayes (1977) state that at Kiawah Island (US) the effect of shoal attachment was able to induce a beach progradation of over 1300 meters.

Notwithstanding the importance of shoals as a feeding component for the coastline and a direct driver for shoreline changes, little effort has been done to understand how these inlet-driven shoreline changes affect the subaerial beach, especially the coastal dunes. Coastal dunes are critical in a risk and management perspective, and its maintenance and behaviour is a major concern for researchers, managers and stakeholders.

Several studies have shown that beach morphology can control sediment supply to the dune system (Davidson-Arnott and Law, 1996; Bauer and Davidson-Arnott, 2002; Hesp, 2002; Silva et al., 2019). Davidson-Arnott and Law (1996) shows that beach width appears to be the dominant factor in controlling sediment transport from the beach and the total volume of sediment into the dune zone. (Hesp and Smyth, 2016) using modern CFD modelling tools show that beach morphological state (e.g. dissipative or reflective) influence the maximum capacity of onshore aeolian sediment transport, with dissipative beaches presenting the maximum potential for sediment delivery to the dunes. Eastwood et al. (2011) show that different dune-fields can emerge as a function of sediment supply and transport capacity. Lentz et al. (2013) associate variations in sediment availability and wave properties close to the shoreline, that consequently influence dune morphology, with the inner-shelf geologic framework along Fire Island (USA). Furthermore, it is currently known that shoreline changes can influence coastal dune behaviour (Ruessink and Jeuken, 2002; Aagaard et al., 2004; Anthony et al., 2006; Cohn et al., 2017). Houser et al. (2008) suggest that long-term rates of shoreline change and alongshore variability in foredune heights are correlated. Shoreline sand waves are capable of changing sediment availability to the dunes by locally increasing beach width and, consequently, increasing potential sediment supply (Stewart and Davidson-Arnott, 1988; Davidson-Arnott and Heyningen, 2003). Aagaard et al. (2004) link intertidal bar welding with long-term accretion rates in foredunes.

Even though shoreline movements and beach morphology can control sediment supply and dune development, little effort has been done to understand the effects of inlet-driven shoreline movements on sediment supply and dune development. O'Connor et al. (2010) in a study on inlet-associated beach systems in the Ireland coast linked decadal variations of the beach system with inlet dynamics. Even though dunes were not the central objective of the study, the authors suggest an influence of inlet dynamics in the dune vegetation line and the dune role as a sink zone for subaqueous inlet-driven shoals. Adams et al. (2016) in a 14-month study shows that ebb-tidal delta induces a recirculation pattern that can change adjacent barrier island morphology. However, effects on dune development were outside the scope of the study. Silva et al. (2018) in a study in a sand flat adjacent to the Marsdiep inlet (NL) show that dune volume is not spatially homogeneous over the sand flat, being larger in the more wave-exposed zone than in the more sheltered zone due to spatial variations in supply conditions. Although, the authors argue that groundwater level can induce such spatial variability on sand supply, other conditions such as inundation frequency (Silva et al., 2016) and storm-induced sand deposition (Wijnberg et al., 2017) may also contribute to supply variability.

Therefore, the objective of the present chapter is to understand how changes in beach width lead by shoal attachment processes affect dune growth, under the hypothesis that local dune growth is higher in places where a shoal attachment takes place. The objective is investigated through long-term data analysis of bathymetric and topographic data from a case study in The Netherlands, together with an idealised numerical modelling approach.

The chapter outline is as follows: Section 5.2 shows the study area characteristics, whereas 5.3 explains the available data, its treatment and usage; Section 5.4 explains the numerical model, its concepts, initial conditions and assumptions. Section 5.5 presents the results separated by its subtidal part, subaerial development and numerical results. Results are followed by a discussion section (5.7) and conclusion (5.8).

## 5.2 The Island of Terschelling.

Terschelling is a barrier island located at the northern coast of the Netherlands (Figure 5.1). It has an orientation of about 73 degrees N (Grunnet and Ruessink, 2005) and has a length of approximately 30 km and width that varies between 2-4.5 kilometres, approximately.

Median grain size ranges from 220-260 $\mu$ m at the foreshore zone to 150-160 $\mu$ m in the outer nearshore bar zone (Ruessink and Kroon, 1994). Waves present two preferred directions, with an average significant wave height of 1.37 meters and a period of 6 seconds. Tides are semi-diurnal and meso-tidal, with spring tidal range in the order of 2.8 meters. Wind direction is directed mainly towards the northeast quadrant. Beach widths range is of the order of 100-400 meters on the attachment zone, and around 350 meters outside the attachment zone.

On the west side, Terschelling is bordered by the Vlie inlet, which has a tidal prism of $934.10^6\mathrm{m}^3$ (Ridderinkhof et al., 2016). According to Ridderinkhof et al. (2016), shoals have a cycle frequency of approximately 16 years, with an average migration velocity of 212 (± 69) $\mathrm{m/yr}$. Furthermore, Ridderinkhof et al. (2016) states that the longshore sediment transport at the coast is $0.4.10^6\mathrm{m}^3.\mathrm{yr}^{-1}$. Shoal length varies from 750-3000 meters whereas shoal widths vary from 400-1800 meters.

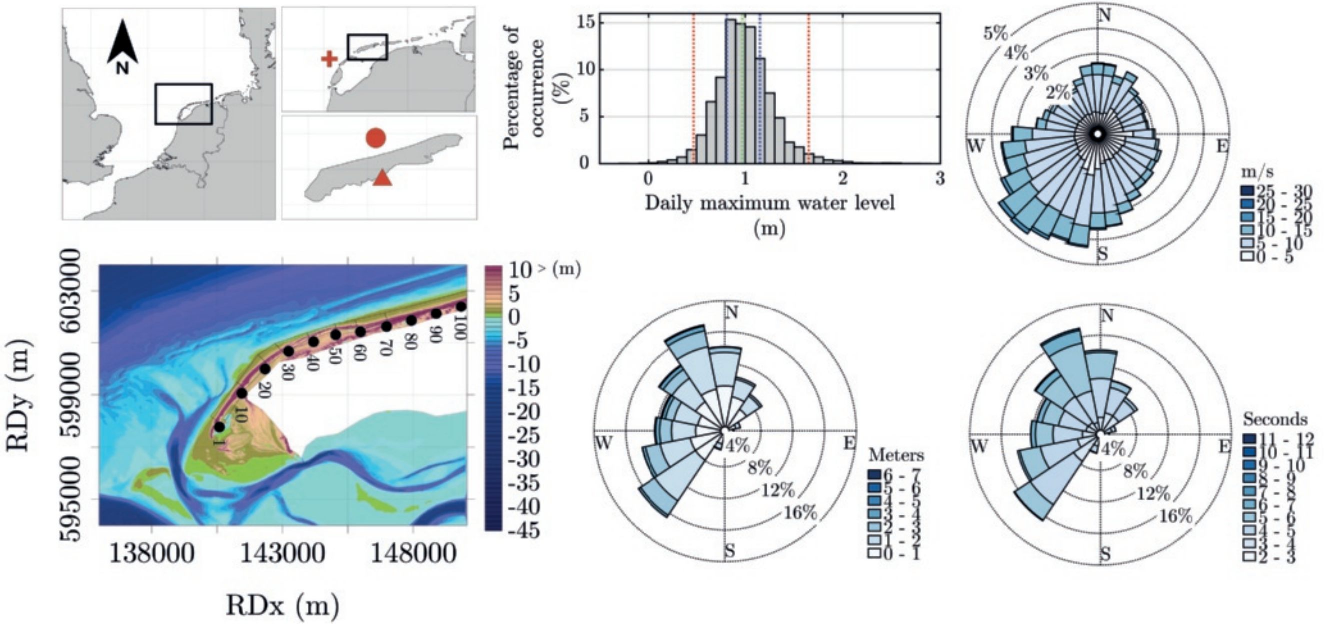

**Figure 5.1:** Study area of Terschelling. Red symbols represent the locations of the wave buoy (cross), weather station (triangle) and tide gauge (circle) used in this paper. Histogram and directional histograms on the right show the overall characteristics of the area for wave climate and wind direction. For the histogram, daily maximum water levels have been used, with the blue lines representing the 25 and 75 quartiles, and the red lines 2.5 and 97.5 limits.

## 5.3 Dataset and analysis.

In this study, bathymetric data with a resolution of 20 x 20 meters available for the years 1992, 1995, 1998, 2000, 2004, 2007, 2010, 2013 and 2016 have been used to track shoal attachment periods, the location of attachment and shoreline evolution due to these subtidal processes. Furthermore, yearly LiDAR data available from 1997 up to 2017 have been used to analyse beach width variability and dune growth. LiDAR data is available in a minimum resolution of 5 meters, with a maximum resolution of 2 meters from 2013 onwards. From the LiDAR data, 100 cross-shore profiles have been extracted which were spaced approximately 100 meters alongshore and used to derive shoreline position, foredune position and dune volume. Shoreline position was estimated by the location of the 0-meter contour, whereas foredune position and dune volume were calculated considering the dunefoot as the 3-meter contour. The dunefoot level along the Dutch coast is widely assumed to be approximately 3 meters + NAP (Dutch reference level, which is close to the mean sea level) (de Winter et al., 2015; Ruessink and Jeuken, 2002; Quartel et al., 2008; Keijsers et al., 2014; de Vries et al., 2012; Silva et al., 2019; Duarte-Campos et al., 2018; Donker et al., 2018). The value is based on early measurements which dunefoot was defined as a visible break in slope between beach and dune and was roughly 3 meters + NAP (de Vries et al., 2012). Thus, dune volume was calculated as the volume above the 3-meter contour and the dunefoot the 3-meter contour itself.

From these parameters, an Empirical Orthogonal Functions (EOF) analysis has been performed in order to find patterns in variability within each parameter that could be related to any of the shoal attachments. The EOF analysis decomposes the signal or data set onto orthogonal basis, which relates spatial and temporal patterns and its relative explained variance. It has been often used in several Earth Science branches and is a powerful exploratory tool to probe the physics underlying the variability in a geophysical field of interest (Monahan et al., 2009; Zhang and Moore, 2015). Thus, the main idea here is to find whether shoal attachment or inlet-driven shoreline changes may be correlated with shoreline variability, thus being decomposed in a separate orthogonal variable.

## 5.4 The DUBEVEG model

The DUBEVEG model (Keijsers et al., 2016) is a cellular automata model built to simulate dune development in the coastal land-water interface. It includes a wind component, hydrodynamic modules and biotic processes related to vegetation. Sand transport, vegetation growth, and dune development are simulated by probabilistic rules that mimic crucial bio-physical feedback interactions for dune growth, development and decay. Given an initial topography $T$ displayed into grid cells in a 2D matrix, cells will re-adjust themselves within the grid following probabilities of erosion and deposition, which are conditioned by characteristics of each cell node and its surrounding cells. Per iteration, a group of cells are chosen randomly to be transported in a pre-defined direction (which is our wind direction). The groundwater level limits the vertical amount of cells that can be transported. Thus, sediment supply conditions can be simulated by changing groundwater levels to be closer or farther from the topographic surface, as shown by Silva et al. (2018).

Sediment can be removed from or introduced to the domain through the hydrodynamic module. The model requires a conceptual equilibrium profile ($Ep$) which is a level that the topography returns to when affected by the hydrodynamic model. This can lead to either a positive (accretion) or negative (erosion) sediment balance. Therefore, the model assumes sufficient feeding from the sea to maintain the equilibrium scheme. Regarding vegetation cover, the model accounts for two species: incipient and conservative, following the approach introduced by Nield and Baas (2007). Further details on the model can be found in Keijsers et al. (2016) and Silva et al. (2018)

To address the effect of shoals on dune development, the model has been adapted to represent idealised conditions for shoal attachment. It is assumed that shoals reach the beach down-drift of the tidal inlet, supplying this beach with a fixed amount of sediment in a periodic process with a certain period. For the present study, a period of 15 years have been chosen to approximately match shoal frequency found for Terschelling by Ridderinkhof et al. (2016). When the shoals attach to the beach, we assume that it drives only shoreline changes. In the model, shoals land at one specific point alongshore. At this point, the coastline follows a sinusoidal behaviour in time, whilst the disturbance moves down-drift with a specific decay rate, with a solution of the form of:

$$y_k = A \times e^{\sqrt{\frac{\omega}{2a}}x} \times \cos(\omega t - kx) \tag{5.1}$$

Where $y_k$ represents the shoreline (i.e. 0-meter contour), A is amplitude proportional to the wavelength, $e^{-f(x)}$ describes the decay as a function of the alongshore position x, and the cosine represents the progressive shoreline sand wave (Figure 5.2). Detailed information on the variables are displayed on Table 5.1. The solution is based on Thevenot and Kraus (Eq. 4, 1995) for general shoreline sandwaves and assuming a one-line coastline model:

$$\frac{\partial y_k}{\partial t} - a\frac{\partial^2 y_k}{\partial x^2} = 0 \tag{5.2}$$

From the shoreline solution, 20 equally distributed positions alongshore have been chosen, and from these full idealised cross-shore beach profiles have been built. Each cross-shore profile was extrapolated alongshore in separate 2D domains. Then, each domain was used as the initial and equilibrium (Ep) topography in the model. Cross-shore profiles have an initial beach width (i.e. the distance between 3-meter contour and 0-meter contour) of 100 meters, on which any cross-shore disturbance introduced by the shoal is added. The cross-shore disturbance is added by moving the 0-meter contour seaward or landward following Equation 1. The new position of the 0-meter contour is linearly interpolated up to a pre-defined node from which no change is introduced landward (Figure 5.3). For the present study, we chose the fixed node as the 1-meter contour, which roughly represents the mean spring high tide level. As the shoreline evolves in time, so does the equilibrium profile, introducing the extra sediment balance from shoal to each position alongshore. This approach has been chosen since it is not the purpose of the model to simulate subtidal evolution, but rather subaerial evolution. Thus, the shape of the beach due to hydrodynamic forcing can be adjusted per-iteration without in-model calculations.

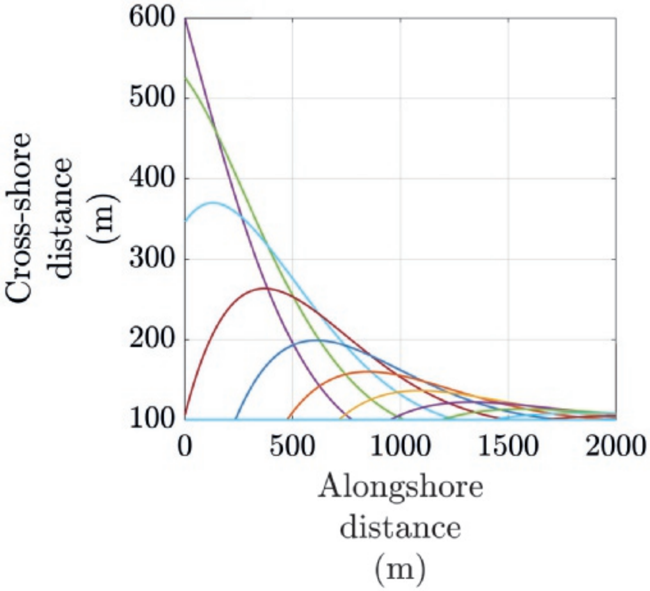

**Figure 5.2:** Example of shoreline movement based on Equation ??

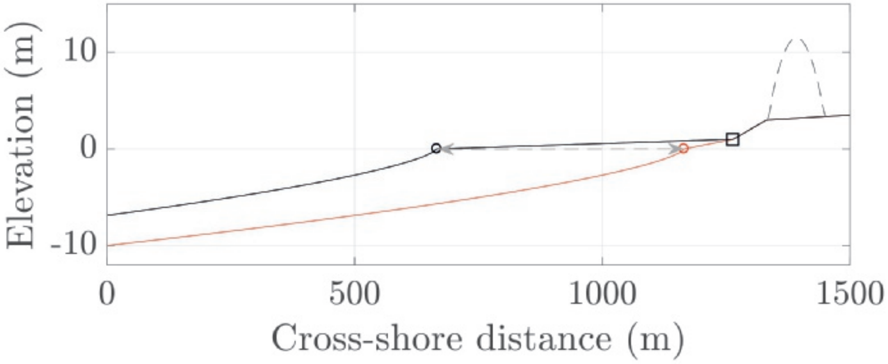

**Figure 5.3:** Example of beach width movement, highlighting the node points used to adjust the equilibrium profile in time. Red and black line represent two different moments in time. Circles represent node points used to adjust beach width, whereas the black square represents the most landward node point where no change is induced by the shoal. Values below 0-meter contour are based on Dean (1991)

Two periods regarding the progressive shoreline wave (which influences the rate of dispersion of the shoal) were tested, being 5 and 15

**Table 5.1:** Specific notations and functions used in the shoreline decay solution form.

| Name | Notation | Function/Value |
|---|---|---|
| Amplitude | A | L/6 |
| Angular frequency | $\omega$ | $2\pi/T$ |
| Period | T | 5 and 15 |
| Wave number | k | $2\pi/L$ |
| Wavelength | L | 250, 500, 1000, 2000 and 3000 |
| Constant | a | 10 |

years. Periods have been chosen to ensure that previous shoal is completely dispersed before the next attachment. Regarding the wavelength of the progressive wave (which influences the size of the shoal), five values were tested, all in meters: 250, 500, 1000, 2000, and 3000. Simulations spanned for 90 years, in which multiple shoal attachment events occurred, always assuming that there is sufficient feeding from the sea to maintain the equilibrium level. Water level timeseries were gathered from nearby tide-gauges in the North Sea. Simulations were performed using two different sediment supply scenarios controlled by groundwater depth (Silva et al., 2018). Dune volume and final foredune position were extracted from the simulations by the same methods used in the LIDAR data and compared in both time and different locations alongshore. Furthermore, we performed five simulations for each combination of conditions, and the average values are used. The number of simulations was chosen based on the Confidence Interval method (Hoad et al., 2011; Law, 2014), which aims at finding the number of replicates necessary to narrow the confidence interval up to a specified precision $d_{min}$, defined as half-width of the confidence interval in terms of percentage of the sample mean. Using five simulations yield precision values in the order of 2-2.5 %, which is lower than the suggested threshold precision (i.e. 5%). In total, a sum of 1000 simulations was performed.

It is important to note that the main purpose of the model is to be used as an exploratory tool rather than a predictive tool. In the present study, we explore different scenarios in order to investigate system reactions to different initial forcing conditions induced by the idealised shoal attachment process. Thus, even though some parameters are

**Table 5.2:** Summary of simulation scenarios based on shoreline disturbances characteristics.

| Simulation Letter | Period (years) | Wavelength (m) |
|---|---|---|
| a. | 5 | 250 |
| b. | 15 | 250 |
| c. | 5 | 500 |
| d. | 15 | 500 |
| e. | 5 | 1000 |
| f. | 15 | 1000 |
| g. | 5 | 2000 |
| h. | 15 | 2000 |
| i. | 5 | 3000 |
| j. | 15 | 3000 |

chosen based on the island of Terschelling (e.g. initial beach width, shoal attachment period), the idea behind the modelling is to explore what would happen if different conditions were imposed.

## 5.5 Observed effects of shoal attachment on dunes

### Subtidal evolution

Overall, bathymetric maps show five beach width change events associated directly (i.e. attachment of the shoal) or indirectly (i.e. shoreline sheltering due to shoal) to shoals (Figure 5.4 and 5.6 ). Labels for each event are showed in Table 5.3 and used within the text. Direct changes due to shoal attachment (Events 1 and 2) happened between 1995 and 1998, approximately between profile 20 and 30; and between 2012 and 2016, between profiles 10 and 20 (Figure 5.5). Both events were capable of inducing, in average, beach width change of 12% of the average beach width. Maximum values of change induced by the attachment increased the beach width is around 40% for event 1 and 112% for event 2. Interesting, even though attachment produced in average accretion of beach width, there were some locations were erosion occurred, with values that reached a maximum of 18% and 53% of the average beach width for events 1 and 2, respectively. Nevertheless, average and median values show that an overall increase of beach width took place due to the attachment.

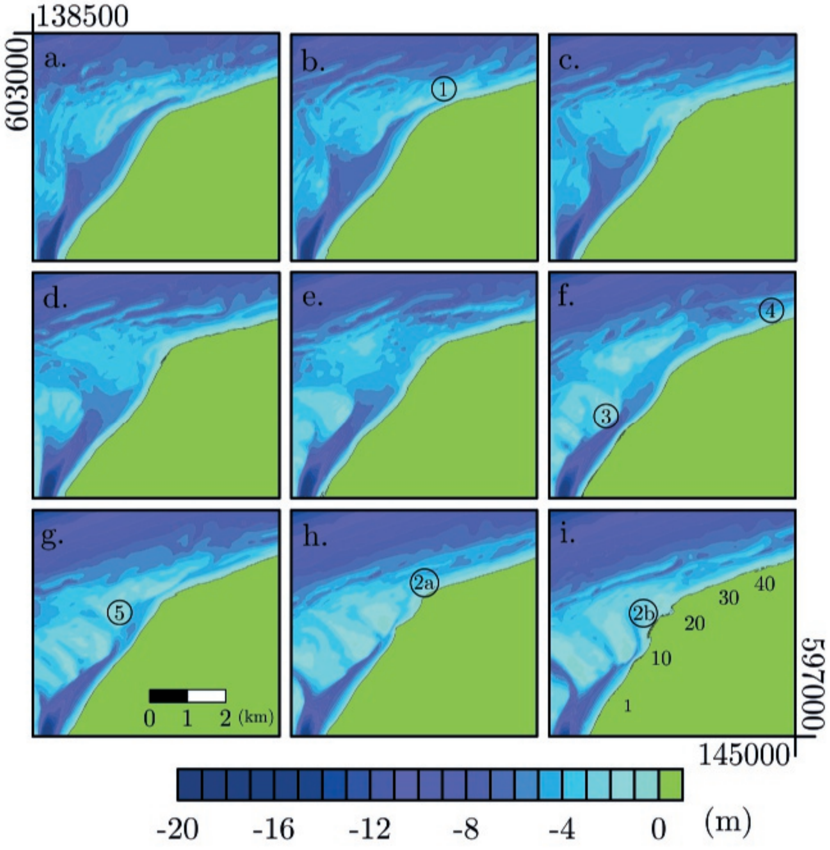

**Figure 5.4:** Bathymetric maps from 1992 (a.), 1995 (b.), 1998 (c.), 2000 (d.), 2004 (e.), 2007 (f.), 2010 (g.), 2013 (h.) and 2016 (i.). Numbers without circle show the approximate location of the profiles, whereas numbers with circle relate to the shoal events displayed on Table 5.3

Even though shoals induce an increase in beach width, the coast presents an overall erosive trend, with values in the order of -1 meter per year. Furthermore, even though shoals are capable of inducing a considerable amount of beach increase, the total increase of beach width is already spread over the coast after a period shorter than the shoal attachment period, which is approximately 15 years. For shoal 1, the total average increase of beach width was on the order of 90 meters between 1997-1999. This increase of beach width is eroded after

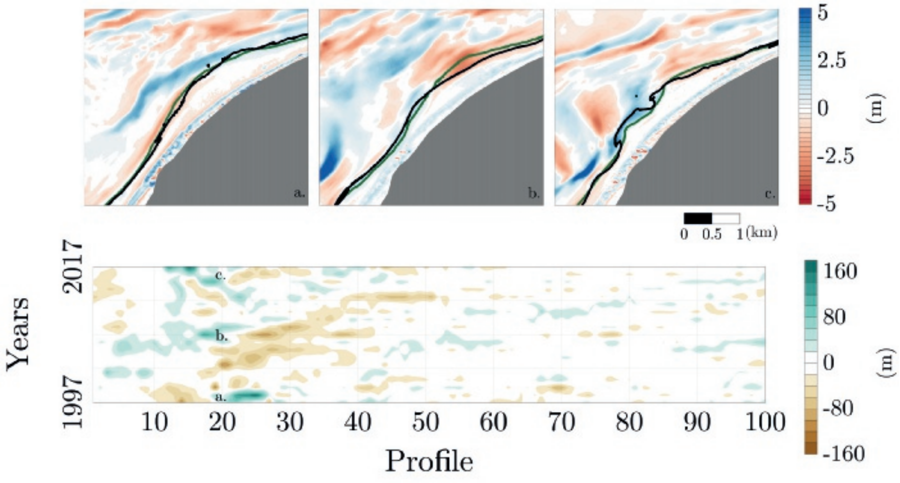

**Figure 5.5:** Beach width changes based on LIDAR data between 1997 and 2017. Upper panels show bathymetric difference maps for specific time and location specified with letters a, b and c. Black lines represent 0-m contour of the most recent year, whereas green line represent 0-meter contour of the past year.

five years, whereas for shoal 2a, the total average increase (40 meters, approximately) was already eroded after two years.

As of shoal events 3 to 5 (Table 5.3), these events yield a lower average beach width increase than shoals that attached the coast, with average values of around 13 meters per year, compared to the approximately 40 meters increase seen in the events 1 and 2. That means that effects induced by the shoal proximity from the coast were able to increase the beach width, in average, around 6% of the average beach width, which is around half of the value found for shoals 1 and 2, which increased beach width, in average, around 12% of the average beach width. Despite the fact that the average amount of increase was smaller, the shoal 3 was able to increase a total amount of around 100 meters from 2000 up to 2007, which is around 44% of the average beach width between profiles 1-10.

The EOF analysis shows that specific shoal attachment processes could not be separated in one specific EOF component. Part of the variance related to the first and second shoal appears in the first EOF, whereas the second EOF shows changes in the shoreline that represent part of the shoal between 2004-2007. Moreover, peaks in the

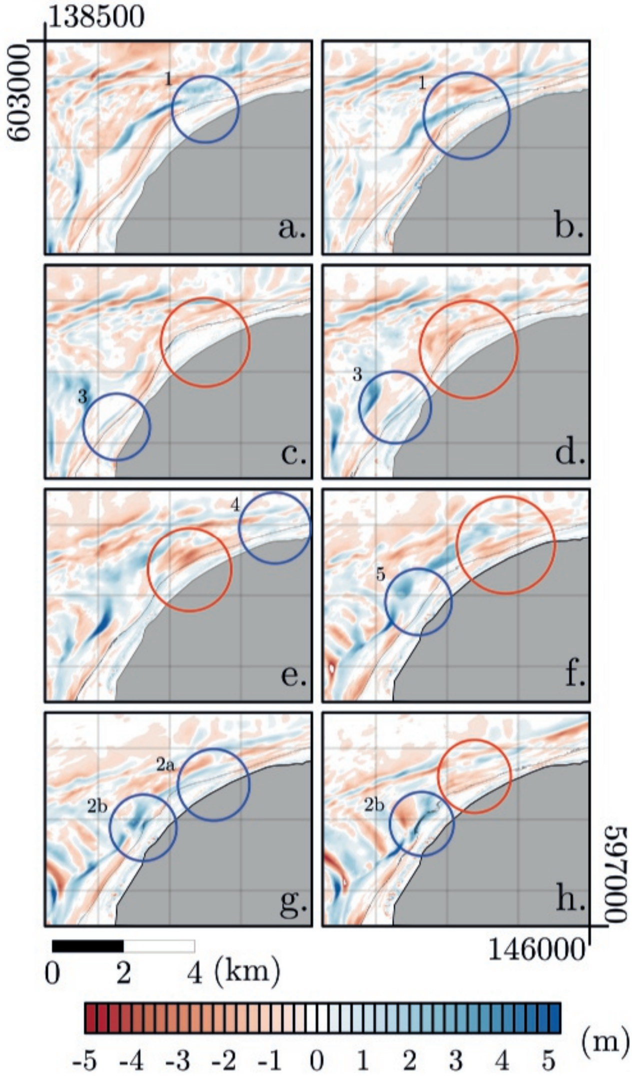

**Figure 5.6:** Bathymetric difference maps for periods between 1995-1992 (a), 1998-1995 (b), 2000-1998 (c), 2004-2000 (d), 2007-2004 (e), 2010-2007 (f), 2013-2010 (g), 2016-2013 (h). Blue and red circles highlight phases of shoreline increase and decrease.

loadings, together with the shift in sign from the scores, also can be related to periods when shoal attaches the shore or influence local variations, such as in the shadow zone in 2007. However, it also represents some variance that cannot be accounted directly to shoals, like

**Table 5.3:** Statistics for shoreline change on regards of each handpicked shoal

| Year | Shoal | Profiles | Shoreline change | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Mean | Median | Standard Deviation | Min | Year (min) | Max | Year (max) | 25th percentile | 75th percentile |
| 1997-1999 | 1 | 21-30 | 43,2 | 36,4 | 64,7 | -71,4 | 1997-1998 | 159,4 | 1998-1999 | -2,6 | 83,5 |
| 2011-2013 | 2a | 21-30 | 20,0 | 16,8 | 19,2 | -9,0 | 2012-2013 | 63,5 | 2011-2012 | 6,7 | 31,0 |
| 2016-2017 | 2b | 11-20 | 58,9 | 54,6 | 138,7 | -140,4 | 2016-2017 | 291,9 | 2016-2017 | -28,7 | 134,8 |
| 2000-2007 | 3 | 1-10 | 14,1 | 12,2 | 19,9 | -22,6 | 2006-2007 | 71,6 | 2001-2002 | 0,0 | 24,4 |
| 2004-2007 | 4 | 41-50 | 2,5 | 0,0 | 20,6 | -39,3 | 2006-2007 | 37,9 | 2004-2005 | -8,7 | 19,5 |
| 2005-2010 | 5 | 11-20 | 17,1 | 17,0 | 32,1 | -59,4 | 2009-2010 | 107,9 | 2006-2007 | 0,1 | 30,5 |

the increase in beach width in the year 2007, between profiles 40-50 (Figure 5.8 and 5.7). That means that the variance introduced by shoal attachment merge within variance related to other processes that are controlling shoreline movement (e.g. longshore gradients, channel-migration). Nevertheless, the EOF analysis shows that most of the variance is concentrated between profiles 1-50, suggesting that different processes control shoreline movement within this zone than profiles 51-100. The zone between profiles 1-50 is the zone closer to the inlet, which suggests that the shoreline in these locations are more prone to be affected by ebb-tidal processes such as channel migration, ebb-tidal wave dissipation, shoal attachment, and so on. All shoal attachments seen in the data happened between profiles 1-50, which also presents an ebb-tidal controlled bathymetry. Thus, even though specific variance in shoal attachment could not be separated from the variance due to other processes, the EOF was capable to define the alongshore zone of influence of ebb-tidal processes in shoreline movements, as well as its importance for the total variance of the shoreline movements, since most of the variance is associated with this zone.

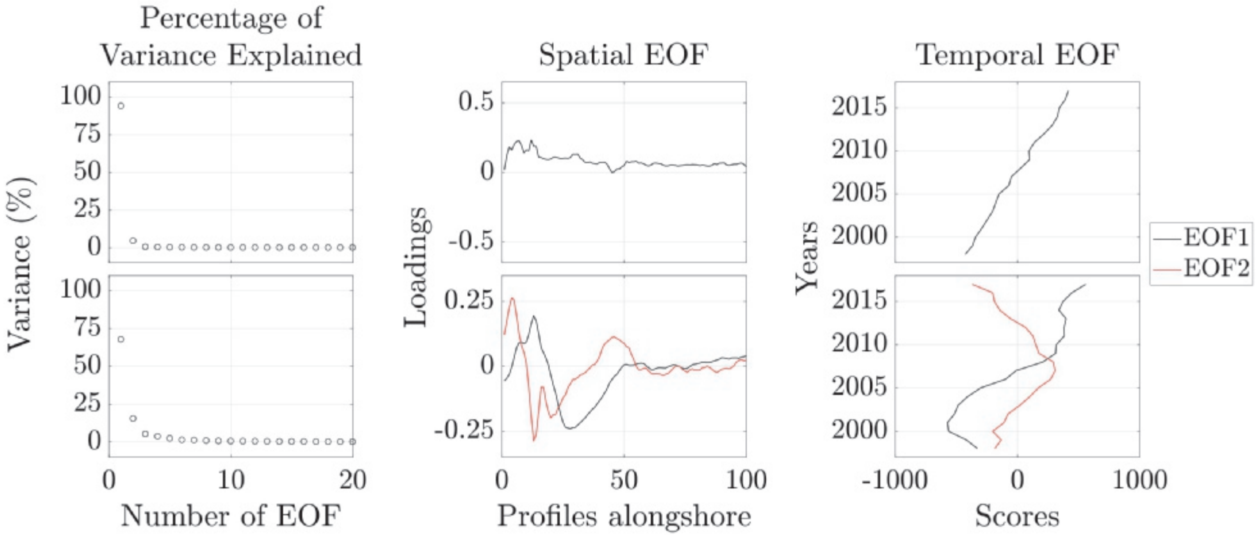

**Figure 5.7:** EOF components derived from dune volume (upper panels) and shoreline location (lower panels) estimated from the LIDAR surveys.

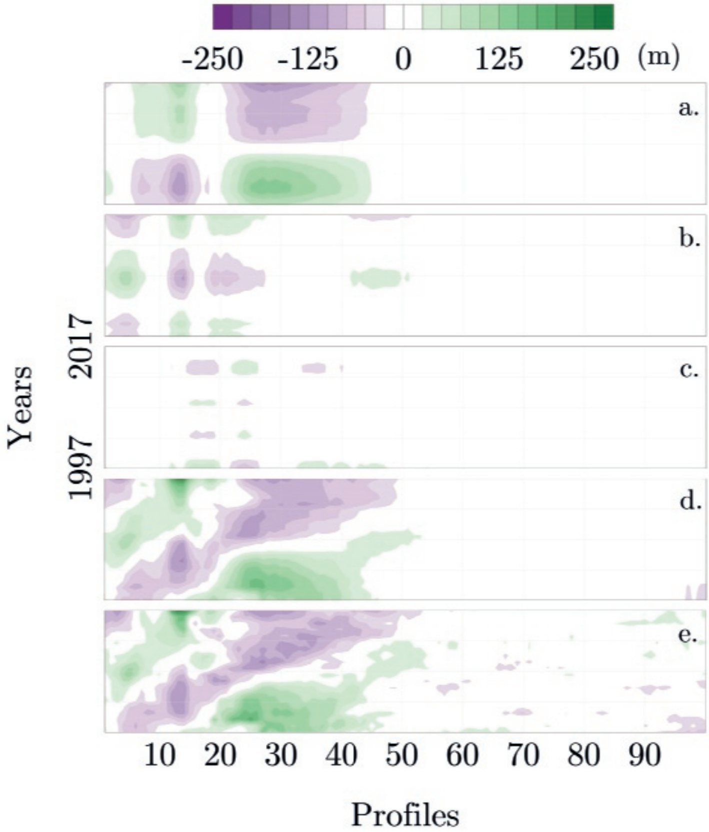

**Figure 5.8:** EOF reconstruction of the shoreline position using the first EOF (a.), the second EOF (b.), the third EOF (c.), and the the first three EOF's (d.). Mean-removed data is plotted for comparison (e.).

The average rate of change map shows an erosive trend in the channel south of profile 1-10 and an accretion trend on the ebb-tidal area. (Figure 5.9). Interesting, values between ± 0.25 meters per year dominate the region north of the ebb-tidal dominated shoreline zone, suggesting that the average variability of this region is small and, in some areas, within the measurement error (10 cm, approximately). Beach width rate of change variance is also smaller from profile number 50 up to 100, suggesting less shoreline variability north of profile 50, which is also seen in the EOF analysis, on which most variance is concentrated between profiles 1-50.

**Table 5.4:** Statistics for shoreline change divided by profiles.

| Profiles | Mean | Median | Standard Deviation | Min | Year (min) | Max | Year (Max) | 25th percentile | 75th percentile |
|---|---|---|---|---|---|---|---|---|---|
| 1-10 | -0.4 | -1.3 | 22.8 | -48.8 | 2012.0 | 152.6 | 2017.0 | -12.2 | 8.7 |
| 11-20 | 7.5 | 1.9 | 49.2 | -140.4 | 2017.0 | 291.9 | 2017.0 | -16.2 | 24.6 |
| 21-30 | -8.1 | -11.2 | 40.1 | -95.2 | 2007.0 | 159.4 | 1999.0 | -31.9 | 12.7 |
| 31-40 | -9.0 | -11.2 | 23.9 | -77.1 | 2007.0 | 50.5 | 2015.0 | -22.4 | 5.6 |
| 41-50 | -3.5 | 0.0 | 24.9 | -73.0 | 2012.0 | 84.2 | 2017.0 | -18.9 | 13.1 |
| 51-60 | -2.4 | -5.0 | 17.9 | -65.4 | 2012.0 | 40.2 | 2010.0 | -15.1 | 5.0 |
| 61-70 | -0.9 | 0.0 | 18.4 | -77.6 | 2000.0 | 51.8 | 2010.0 | -12.6 | 10.1 |
| 71-80 | 0.3 | 0.0 | 17.4 | -58.0 | 2007.0 | 38.6 | 2010.0 | -8.5 | 12.2 |
| 81-90 | 0.9 | 0.0 | 15.5 | -36.7 | 2008.0 | 41.4 | 2005.0 | -10.4 | 13.7 |
| 91-100 | 3.6 | 5.1 | 18.4 | -38.6 | 2015.0 | 63.0 | 2006.0 | -9.7 | 15.5 |

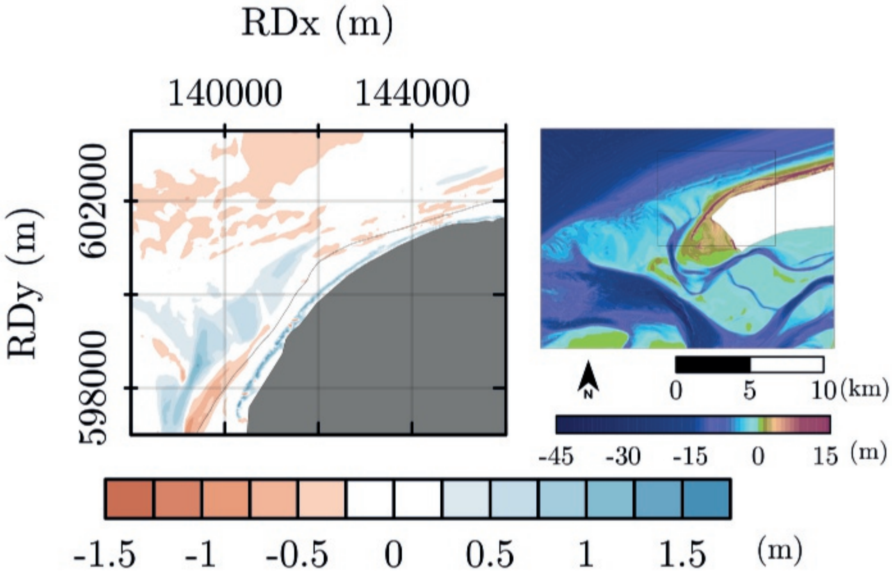

**Figure 5.9:** Average difference maps based on bathymetric data.

### Relation between beach width and dune development

Subaerial dune development over the period presents two main characteristics: instant change in beach width does not translate into instant dune volume change; western profiles (i.e. ebb-tidal controlled zone) presents a higher rate of change than the remaining part of the coastline (Figure 5.10).

The beach-dune system along the island present high morphological alongshore variability (Figure 5.11). Dunes tend to be higher between profiles 1-35 and profiles and between profiles 80-100. The same pattern is followed by dune volume, where average values are higher in those zones. On the other hand, the beach width presents a much

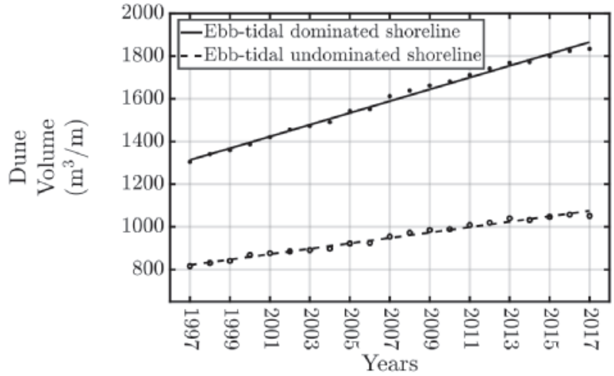

**Figure 5.10:** Dune volume evolution extracted from the LIDAR data, separating the profiles within and without the attachment zone.

higher variability between profiles 1-50 than 51-100. Median values of beach width also present a higher range between profiles 1-50 than profiles 51-100.

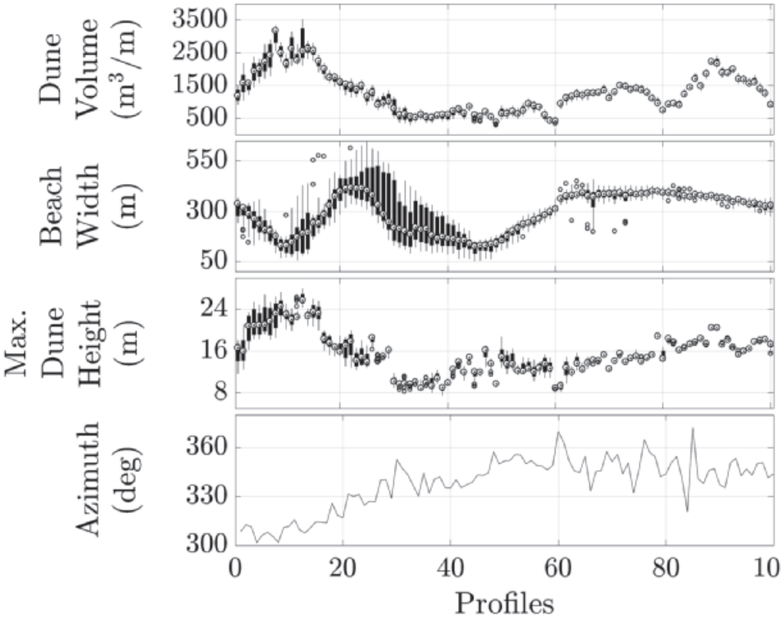

**Figure 5.11:** Boxplots of the morphological data alongshore extracted from the LiDAR data.

Using information gathered from the effects of shoal/ebb-tidal dy-

**Table 5.5:** T-test for rate of dune volume change alongshore.

| Group | Mean | Variance | Observations | t-value | t-critical (two-tail) |
|---|---|---|---|---|---|
| Between profile 1 and 50 | 0.42 | 0.26 | 20 | 5.6 | 2.09 |
| Between profile 50 and 100 | 0.08 | 0.16 | – | – | – |

**Table 5.6:** T-test for the slopes from the regression lines derived from dune volume from ebb-tidal dominated shoreline and the non-dominated shoreline.

| Group | Slope | Standard error | Observations | t-value | t-critical (two-tail) |
|---|---|---|---|---|---|
| Between profile 1 and 50 | 27.63 | 14.69 | 21 | 23.59 | 2.02 |
| Between profile 50 and 100 | 11.8 | 96.9 | – | – | – |

namics on beach width, two distinct zones are separated: one between profiles 1-50, which is controlled by ebb-tidal dynamics (i.e. affected by shoal attachment, channel migration and ebb-tidal processes) and another between profiles 51-100, which variance is not related to ebb-tidal processes. Analysing volume values between two different zones (between profile 1 and 50, which is the area of variability regarding shoal attachment) and between 50 and 100 (area related to have small/no influence of shoal attachment), results show that the first zone presents higher average values of volume per longshore component, with values of 1589 (172) $\mathrm{m}^3/\mathrm{m}$ and 948 (79) $\mathrm{m}^3/\mathrm{m}$, respectively. Furthermore, a paired t-test shows that the two zones are statistically different ($P < 0.05$) in terms of rate of change per longshore distance (Table 5.5). Also, t-test of the slopes of the regression lines for dune volume evolution shows that both trends are statistically different ($P < 0.05$) in terms of slope (Table 5.6).

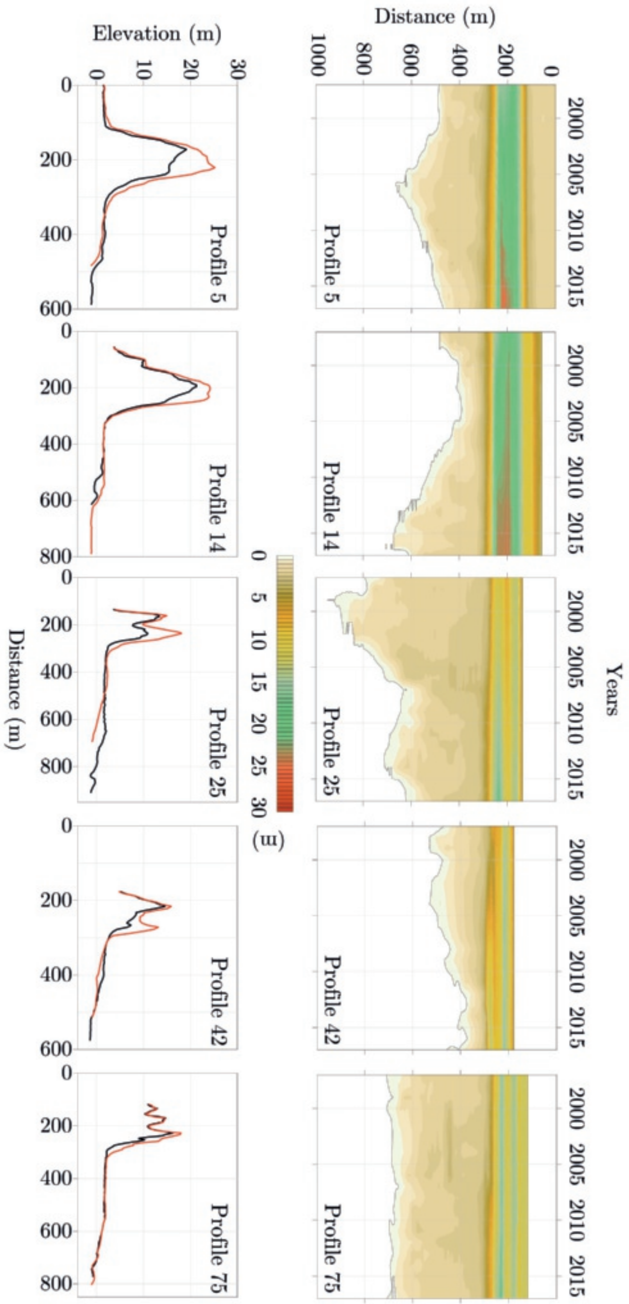

**Figure 5.12:** Evolution in time of five different profiles alongshore. Black lines represent the profile in 1997, whereas the red line represents the profile in 2017.

In time, both zones presented a steady growth in terms of volume. In terms of area, a higher rate of change can be seen between the years 2002 and 2006 at the area outside the shoal zone, which represents an expansion of the dune field. No peaks or cycle patterns that could be related to beach width changes seem to happen. Regarding morphology, dunes outside the shoal zone tend to present a progradation behaviour, with more than one peak at the same profile (Figure 5.12). Profile 42 is an example on which it is possible to see the built of a new foredune in time in front of the previous one. On the other hand, dunes in the shoal zone do not present a progradation characteristic, with most new sediment being used to build/maintain the active foredune. Both zones present embryo dunes in front of the foredune (Figure 5.14).

Analysing the EOF components for dune volume, the first component already represents most of the variance in the data with 94% of the variance explained (Figure 5.7). The first EOF shows the overall development of the area, with slightly higher loading values between profiles 1 and 30. That means that in that area, changes are felt in a higher degree than the rest of the coastline. The temporal EOF shows a linear development of the area towards one main direction which can be related to the steady dune growth seen in the area. Considering that a high amount of variance explained, as well as the linear development of the temporal EOF, beach width changes introduced by the shoals do not leave an immediately detectable footprint on dune volume evolution. However, considering that between profiles 1-30, a zone controlled by ebb-tidal processes, loading values are slightly higher than the rest of the profiles, the overall trend of dune growth in this zone is higher than for the zone not controlled by ebb-tidal processes, suggesting that long-term effects of ebb-tidal processes might enhance sediment transfer from beach to the dunes.

## 5.6 Modelling results

Results of dune volume show that for a shoreline wave period of 5 years, higher shoreline variability in the western side did not translate into higher dune volume (Figure 5.13). On the other hand, for shoreline periods of 15 years, western sectors presented higher final

**Table 5.7:** Paired T-test results comparing dune volume from attachment and non-attachment zones for the modelled scenarios where a persistence occurred.

| Scenario | Persistence (m) | Volume | | | | Paired t-test | | |
|---|---|---|---|---|---|---|---|---|
| | | Within zone | | Outside zone | | p | df | tstat |
| | | Mean | Std | Mean | Std | | | |
| f. | 400 | 692 | 4 | 677 | 4 | $p<0.001$ | 5.7 | 7.9 |
| h. | 800 | 704 | 8 | 677 | 8 | $p<0.001$ | 15.7 | 8.1 |
| j. | 800 | 710 | 9 | 689 | 15 | $p<0.001$ | 17.9 | 4.0 |

dune volumes than the eastern sector for a wavelength of 1000, 2000 and 3000 meters. Spatial autocorrelation shows persistence in correlation values for these three scenarios, suggesting a spatial dependency for dune volume for these three cases, which is confirmed by using paired t-tests between both areas. No persistence occurred in other scenarios. Similar spatial patterns happen for both unlimited and limited supply conditions, although simulations with unlimited supply conditions resulted in dunes with a larger volume of 14 (2,9) $\mathrm{m}^3/\mathrm{m}$ on average.

Regarding beach width, final results show beach width between 100 and 110 for all shoreline scenarios, with no apparent spatial trend alongshore. Correlation analysis shows no spatial dependency on beach width for both unlimited and limited supply scenarios.

Morphologically, dunes remain mostly as a foredune after 90-year simulation, with seldom occurrence of incipient dunes in front of it. Main differences are in the dune height, which follows the spatial pattern presented in the dune volume.

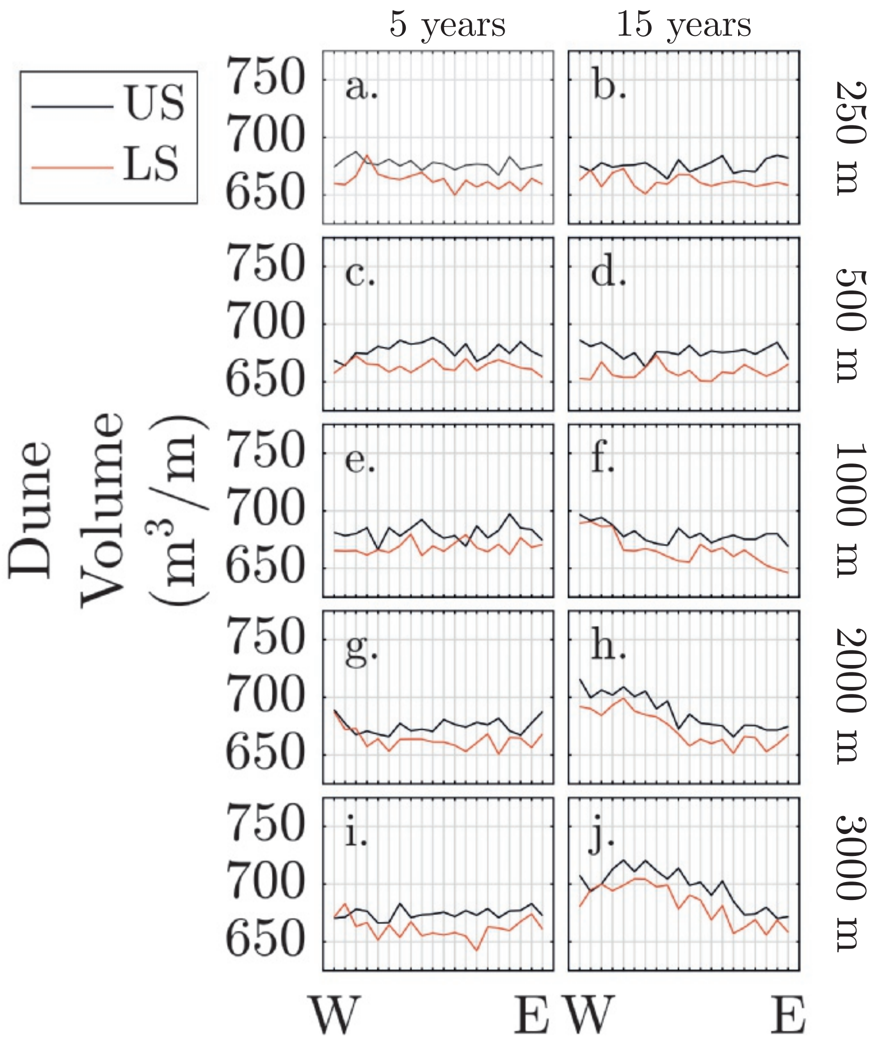

**Figure 5.13:** Dune volume estimates based on numerical simulations. Letters represent the shoreline movement showed on Table ??. Black lines represent unlimited supply scenarios, whereas red lines represent a limited supply scenario.

## 5.7 Discussion

Three main aspects can be highlighted when analysing the results: 1- instant change in beach width due to shoals does not translate into instant dune volume change; 2- even though instant attachment does not translate into immediate dune growth, frequent shoal attachment may lead to local increase in dune growth rates; 3 - the occurrence of local changes in dune growth, in the long-term, is closely related to the size and extent of the shoreline change signal introduced by the attachment of the shoal.

Results show that a shoal is capable of increasing beach width directly by attachment or indirectly by creating a shadow zone to the coast. Increasing beach width would lead to increased space for dune development, increased potential supply and increased dune protection against wave attacks due to the increased potential for wave dissipation (Davidson-Arnott and Law, 1996; Hesp, 2002; Davidson-Arnott et al., 2005; Delgado-Fernandez, 2010). Davidson-Arnott and Law (1996) show that beach width influences the total volume of sand transported towards the dunes on an annual basis. Moreover, the authors argue that over periods of months to years, the potential sediment source to the dunes will vary directly with the beach width. Our results for Terschelling suggest that even though the shoal induce beach width change, sediment is redistributed alongshore before being able to increase dune volume significantly. Although the increase in beach width would lead to higher wave protection and larger source for aeolian transport to develop, no immediate signal in dune volume could be seen. Monthly to yearly signals in dune growth due to beach width increase require an in-phase synchronisation of capable on-shore wind components and suitable beach surface conditions with the attachment (Houser, 2009).

These results are somewhat not in agreement with some previous authors. Ruessink and Jeuken (2002) found that shoreline sandwaves, which change beach width, do leave a signal at the dunefoot alongshore, with non-uniform dunefoot behaviour accounting for at least 80% of the residual variability of the dunefoot. One possible explanation could be related to the initial beach width on which the sandwave propagates or the shoal attaches. For wide beaches, the induced increase of supply and space might not be significant due to its already large enough beach width (i.e. Available Fetch > Critical Fetch). In opposite, small variations in narrow beaches (Available Fetch < Critical Fetch) would lead to a significant increase in source width and, therefore, potential sediment supply. Moreover, the previous authors deal with an isotropic situation, on which the signal propagates equally alongshore, leading to similar beach width variability regardless of its alongshore position. In contrast, for shoals, the attachment zone would have higher variability in beach width than locations not directly affected by the shoal attachment. Thus, the rate of dispersion would be determinant on whether dunes would or would not have time to expand with the local increase in beach width.

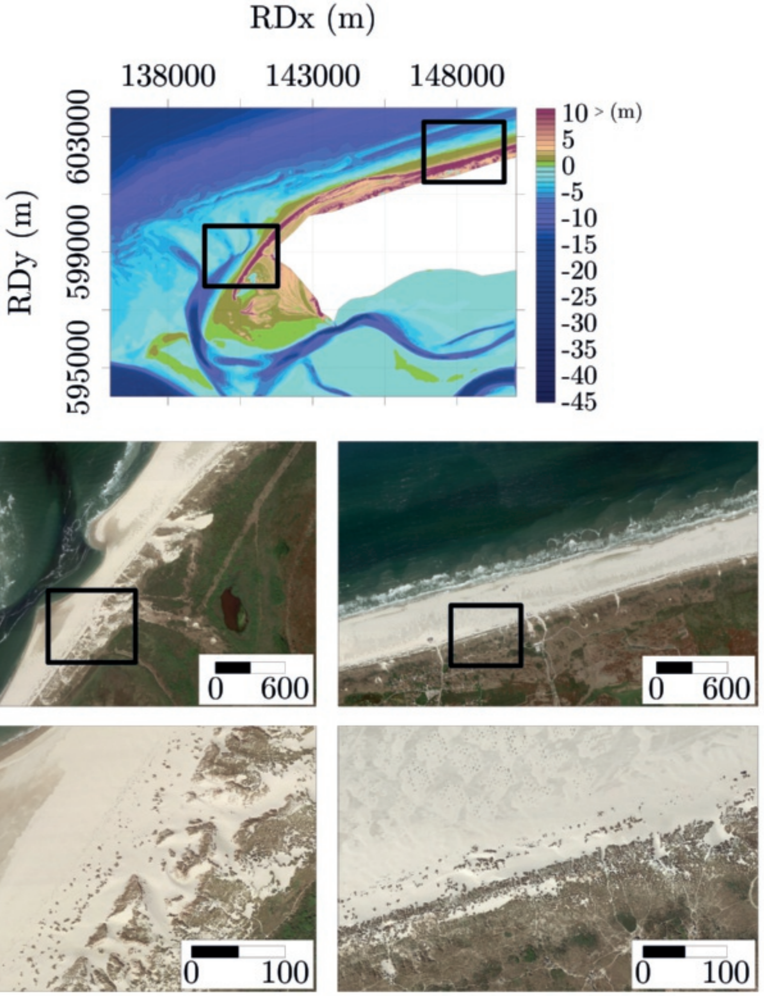

**Figure 5.14:** Satellite images from both zones, exemplifying the occurrence of embryo dunes. Scales in meters. Source: Google Earth.

Although variations in beach width do not immediately translate in a significant change in dune volume or position, our results show that the effect of ebb-tidal processes in the shoreline lead to a greater supply of sand toward the foredune. One hypothesis is that, in the long-term, the periodic increase in source width translates into a larger potential of sediment transport on average. If source width is, in average, larger, that would translate into a higher potential for sediment transport and, consequently, higher potential of foredunes in these regions being significantly higher than dunes which do not present this frequent increase and decrease in beach width. Periodic increase in source width leads to a potential higher supply in the long-term than in regions where an increase in source width is limited. Nordstrom and Jackson (1992) argue that sediment transport rates are directly related to source width, with a complete transport shut-down if source width is small enough, in an event scale. Moreover, Delgado-Fernandez (2011) shows that a single event can account for a significant amount of the total transport measured over a year, and the author also states that fetch distance may be more important than wind characteristics. Thus, greater average beach widths can lead to a higher probability of increasing sediment supply and, therefore, would lead to higher dune growth, following the synchronisation concept exposed by Houser (2009). Also, average greater beach widths would raise the potential of embryo dunes which would not only retain this volume but also serve as a buffer during energetic storm events.

In the long-term, dune volume and position can be affected by periodic changes in beach width. Thus, how the shoal changes the shoreline, beach width and beach state are essential to determine whether it will or will not affect dune volume and how it would. Our modelling results suggest that shoal type (size and volume) and consequently how it changes beach width, has different outcomes in terms of dune evolution. Modelling results show that a higher dune volume is expected only for shoals that increase beach width considerably and that have a slow rate of dispersion. A small beach width increase with a fast longshore redistribution would give an increase in terms of potential sediment supply that might be too small compared to other agents (e.g. overall aeolian transport or erosive processes) to be mirrored at the foredune even in a long time-scale. Although even a small beach width increase would translate in a higher potential supply toward the dune (Cohn et al., 2017), our results suggest that the scale of change should be higher or of the same order of magnitude than current supply to be translated into significant different dune growth.

Foredunes in most barrier islands are not alongshore uniform (Houser and Ellis, 2013). Although not fully understood (Houser et al., 2008; Zarnetske et al., 2015; Goldstein et al., 2017), our results suggest that shoal attachment may lead to alongshore variations in foredune morphology due to increased average beach width. Uniformity of foredunes in barrier islands depends on several conditions such as beach width, as well as wind conditions and transport limiting factors. In the long-term, if the beach width increase in the attachment zone is large enough, and if the rate of longshore dispersion is slow enough, the local increase on supply and wave protection would lead to a possible period of increased dune growth compared to other stretches of the coast. Consequently, this would lead to a longshore variability in dune growth directly related to shoal attachment.

Many previous studies show that the welding of intertidal bars is a key process for sediment exchange between subtidal and subaerial beach profiles (Aagaard et al., 2004; Cohn et al., 2017). Beach width variations due to subtidal processes have the capacity of increasing beach width, thus making sediment available for aeolian transport in the intertidal zone (de Vries et al., 2017). In a similar concept, shoals have the capacity of increasing beach width in a periodic scheme adding a local shoreline disturbance that can locally increase sediment transfer from subtidal areas to the dunes. The island of Terschelling shows that dune growth in the area of shoal attachment is higher than the remaining part of the island. Although dune growth is steady for both non-shoal and normal coasts, the frequent attachment of large enough shoals and the consequent increase of beach width lead to an overall higher dune volume. If time is enough, incipient dunes tend to form in front, which will serve as a buffer for erosive phases and lead to an overall higher rate of dune growth in these areas. Moreover, increased beach width would lead to more space for dunes and increase of potential aeolian supply.

In summary, inlet-driven processes that affect adjacent coastlines such as shoal attachment, channel migrations and beach width variations are capable of inducing changes in local coastal dunes. Our observation results show that the rate of volume increase in dunes that emerge within the ebb-tidal dominated zone are significantly higher than dunes outside the zone. Furthermore, modelling exercise shows that the potential of shoreline change that inlet-processes have are key to define whether changes at the dunes will be notable. Dunes were significantly larger in the shoal attachment zone only in modelling scenarios where changes in beach width were large and persistent.

## 5.8 Conclusion

A case study on the island of Terschelling has been done in order to understand how shoal attachment processes influence dune growth. The case was approached through a combination of data analysis of pre-existing topographic and bathymetric data, combined with an idealised and exploratory numerical modelling using a cellular automata model. Results show that a sudden increase in beach width related to shoals does not translate into peaks of dune volume change. However, in the long-term, areas of attachment present a significantly higher rate of dune increase than areas not directed influenced by the shoal, suggesting that either the increase average beach width or its variability induce higher dune growth. Furthermore, numerical results suggest that only specific shoal size and spreading characteristics can define a volume footprint at the dunes. Therefore, in the studied time-scale, consequent shoal attachments are capable of inducing a local increase in dune growth, considered that its size/volume is large enough to induce a high and persistence increase in beach width.

### Acknowledgements

This research forms a component of the CoCoChannel project (Co-designing Coasts using natural Channel-shoal dynamics), which is funded by Netherlands Organization for Scientific Research, Earth Sciences division (NWO-ALW), and co-funded by Hoogheemraadschap Hollands Noorderkwartier. We further wish to acknowledge Rijkswaterstaat and KNMI for making their valuable bathymetric and topographic data sets freely available, as well as the water level, wave and wind data. Furthermore, we would like to thank Dr. Alma de Groot for making the model available and her comments in initial stages of the research, and Dr. Angels Fernandez-Mora for the discussions regarding the shoreline model.

# CHAPTER 6

# Discussion

## 6.1 Synthesis

The main dune development aspect affected by inlet-induced processes and landforms is sediment supply. Sediment supply is one of the necessary components for coastal dune development (Swift, 1978; Houser and Ellis, 2013; Short and Hesp, 1982). In the present study, all inlet-induced changes on the adjacent coastline have, ultimately, made an effect on the sediment supply and, consequently, on beach-dune dynamics.

Inlet-induced landforms such as sand-flats may present spatial variability in supply due to elevation conditions that will lead to spatial variability in dune development. In the sandflats along the Dutch coast, the average elevation of the inner (i.e. non-exposed to waves) portion of the sandflat is often lower than the outer (i.e. exposed to waves) portion of the sandflats (Silva et al., 2016). Differences in elevation may lead to differences in upper beach conditions (e.g. surface moisture) that would affect sediment supply. One hypothesis on the spatial variability in sandflat elevation might be related to the uneven impact of waves along the sand flat coastline, that will lead to an uneven sediment exchange between subtidal and subaerial beach. Considering that wave-induced processes are responsible for most of the onshore sediment transport (Aagaard, 2014), it is fair to think that spatial variability in wave attack would also affect subtidal/subaerial sediment exchange.

Although in real cases several other characteristics also change due to this uneven average elevation/wave impact and spatial distribution of the sand flat (e.g. grain-size, inundation frequency, wind direction), model results showed that, if just elevation is different, groundwater level (and thus, surface moisture), is already capable of inducing the spatial variability in sediment supply. The groundwater level can raise surface moisture, thus limiting the aeolian transport and dune formation regardless of the available space (de M. Luna et al., 2011; Poortinga et al., 2015). Over a long time-scale, average deeper groundwater levels would translate into an increased available supply compared to shallow groundwater levels. As the shape of the sandflat induces different sediment exchange and, therefore, different elevation along the flat, that would translate into an exposed region with higher sediment supply than the non-exposed part of the flat.

Furthermore, the sandflat landform will enhance the importance of mechanisms such as storm surges to act as a source of sediments instead of an erosive agent only. Sand supply induced by storms appears to be a major contributor for dune growth in sand flats close to inlets. As the flat is inundated during storm surges, the shallow depth associated with the low slope will enhance the potential for wave dissipation, reducing the potential of dune erosion. At the same time, deceleration will result in gradients that induce deposition of the sediment at the exposed part of the flat. Beach deposition is often related to either post-storm conditions, where wave-induced onshore sediment transport is responsible for restating pre-storm equilibrium conditions, or associated with overwash or inundation events that lead to inland sediment deposition (Houser and Ellis, 2013; Engelstad et al., 2017; Sallenger, 2000). Recent studies on overwash and inundation from Hurricanes in the US also suggest a potential seaward sediment transport during storm surge ebb due to hydraulic gradients between the basin and seaside of barrier islands (Sherwood et al., 2014; Hoekstra et al., 2009). Considering that simulations using both Cellular automata modelling and a process-based modelling suggest a net sedimentation onto the sand flat, together with the measured stability of elevation in the sand flat, storm surges seem to be an important mechanism of sand supply for the sand flat and, consequently, for the dunes, especially in the exposed part.

Thus, our results suggest that, as inlet processes create sand flat landforms in the vicinity of the inlet, differences in sandflat elevation and potential onshore sediment transfer from wave-driven processes will lead to spatial variability in sediment supply for the dunes, which in turn would lead to variability in sand deposition, dune growth and morphology across the sand flat, as seen in the Dutch sand flats.

As of inlet-driven events, such as shoal attachment and beach width changes, the change in beach width will often represent a change in potential supply and space for dune development. In literature, changes in beach width have been associated with supply changes in terms of transport potential and availability of sediment for Aeolian transport (Bauer and Davidson-Arnott, 2003; Davidson-Arnott and Heyningen, 2003; Short and Hesp, 1982). If beach width is smaller than the potential critical fetch, an increase in beach width would potentially maximise sand fluxes up to the limit of the critical fetch. This would lead to increased volumes and foredunes closer to the waterline, as long as space is available. If beach width is wide enough, increases in beach width do not affect sand supply, but instead will affect the space available for dunes to grow and, consequently, in the dune position. Dunefoot variability has already been related to changes in beach width due to shoreline sandwaves (Ruessink and Jeuken, 2002). Our results suggest that an important variable in this scheme is the time-scale on which the processes occur. Our results suggest that footprints in the dunes of any variability in beach width are closely related to the amount of time that the beach width stays in a particular position. If beach width increases and decreases in a fast mode, the probability of leaving a footprint in the dunes, either in the form of a volume of position, is small. The same holds for shoals, where dune volume increased at regions of shoal attachment when the shoal simulated was big enough and with a slow rate of dispersion.

Considering that inlet processes change beach width and that time/space-scale is a key component for the interaction between the beach-dune system and inlet processes, the amount of sediment transport moved by inlet processes seems to be a central part of whether changes in adjacent dune can be expected. Shoals have been considered one of the main sand input processes to a coastline adjacent to an inlet (Gaudiano and Kana, 2001; Hofstede, 1999a). Also, tidal prism and wave energy are closely related to migration speed and sand volume of the shoals (Ridderinkhof et al., 2016,?; Hicks and Hume, 1996). Thus, inlet characteristics such as tidal prism, sand storage capacity and wave conditions may determine in which extent shoal attachment processes may change dune development in a decadal scale. Tidal inlets with favourable characteristics to develop bigger shoals will lead to higher probabilities of changes in dune growth.

## 6.2 Beach-dune systems near inlets vs. away from inlets

Supply is a crucial aspect for dune development regardless of its location in the coastline (Hesp, 2002; Hesp and Walker, 2013; Houser and Ellis, 2013). In coasts away from inlets, the source of sediment for dune growth may be related to bar welding, longshore and cross-shore sediment transport (Houser and Ellis, 2013). If the shoreline is located in the vicinity of inlets, sediment bypassing at tidal inlets can control shoreline development on the downdrift shoreline, and therefore, be a primary supply of sand (Vila-Concejo et al., 2003; Fitzgerald, 1984; Fitzgerald et al., 1984; Siegle et al., 2004; Gaudiano and Kana, 2001). In both locations (i.e. close or far from inlets), the lack of supply would eventually stop Aeolian transport and, therefore, dune development.

Notwithstanding that in both locations wave-induced processes are the main component for sediment exchange between subtidal and subaerial zones, our results suggest that other components such as storms may be also important in an inlet-induced landform like sandflats. As sediment is transferred to the subaerial zone and can be potentially reworked by Aeolian processes, transporting sediment toward the dunes occur similarly in both locations. Surface moisture, shell pavements, grain-size and limitation in fetch length will define whether the wind is capable of moving surface sand grains or not. The main difference between both locations may be how each limitation characteristics will behave in time, space and magnitude. Taking beach width as an example, there are cases where both coastlines away and close to inlets will have similar beach width sizes. However, inlet-induced landforms such as sand flats can define beach width in the scale of kilometres, that would not be common in a dissipative beach away from inlets. Moreover, shoals can add a significant and sudden increase in beach width, that may maximise Aeolian transport potential. Even though bar welding may also increase beach width, the magnitude of changes expected in some shoal attachment zones is more significant.

When compared to coastlines far away from tidal inlets, even though some processes such as beach width changes can still happen, the mechanism that induces such changes is different and, consequently, the time-scale. One of the main processes associated with beach width changes in coastlines away from tidal inlets is the shoreline sandwave. As sandwaves propagate alongshore, they create phases of wider or narrower beach widths. The main difference between such processes is its alongshore anisotropic situation. For sand waves, the variability tends to be somewhat constant regardless of the position alongshore. For shoal attachments, for example, the disturbance is at the maximum at the shoal attachment point and may present a decay farther from the attachment zone. Moreover, the shoal attachment process deals with a sudden increase in beach width, rather than a more controlled change due to lateral migration of the shoreline sand wave.

**Figure 6.1:** Alongshore shoreline sand waves at Southampton Beach, Long Island, NY. Extracted from Larson et al. (2002)

As of supply changes due to groundwater effects, there is no pattern in the literature relating alongshore variability of dune development stages as we found for sand flats. Sand flats seem to present a pattern of elevation variability that is not found in open coastlines away from inlets. Even though changes in on-shore supply can change alongshore due to local changes in nearshore processes, this tends to be on a process-scale, which might not lead to a footprint at the dune. Moreover, although surface moisture is known as one of the most important limiting factors for aeolian transport and is also linked to groundwater levels, its dynamics are not well understood.

The role of storm surges as a mechanism to increase potential supply for coastal dunes is also a major difference between coastlines away from inlets and inlet-built landforms. Storm surges possess a major erosive role in beaches away from inlets, scarping the dunes and transferring sediment from the upper beach and dunes back to the subtidal area. In those areas, deposition related to storm surges is often left to deposition inland such as those related to hurricanes in the USA. Considering both the stability in elevation from the sand flats close to inlets and the potential parallel-ridge deposited after storms surges in the sand flat in a volume that is comparable to those measured at the dunes, our results suggest that storms may be an important mechanism of sand supply for dunes in sand flats close to inlets.

## 6.3 Implications for society

Coastal dunes and tidal inlets are important for safety, economic and societal reasons. Considering the widespread human interests in coastal areas, predicting and understanding the beach-dune dynamics and its relation with tidal inlets on a proper scale for stakeholders is essential for planning and management purposes. In this sense, managed coastal dune systems have become increasingly common over the past decades (Bochev-van der Burgh et al., 2009; Bochev-Van der Burgh et al., 2011; Bochev-Van der Burgh, 2012). The current research brings some new thoughts on the morphodynamics of beach-dune systems near inlets and how can we apply these new ideas in a management perspective.

Traditionally, reactive interventions have been continuously applied in the coastal zones through hard structures or nourishment programs. However, these assessments can drive several other issues when analysing the problem from a wider perspective. Hard structures, for example, can easily solve local problems in detriment of suitable conditions from other places, thus being not sustainable considering different space-time scales and interests. Besides that, the maintenance of such assessments can drive expensive efforts, thus also being a challenge in economic perspectives. Then, the so-called Building-with-Nature (BwN) approach has been developed and applied throughout the past years as a feasible and sustainable alternative for human interventions in coastal areas (de Vriend and van Koningsveld, 2012).

The BwN idea is linked to a pro-active concept that natural processes could be managed through using its dynamics, thus addressing the causes rather than consequences of, for example, the coastal erosion. Hence, counteracting measures towards destructive forces can be shifted to stimulating measures towards constructive forces, thereby providing solutions using natural forces as essential part of the approach. For coastal dunes, the planting of marram grasses for stability and the construction of sand drift dykes for stimulation of new foredunes are examples of BwN initiatives which have been taken in the Dutch coast during the past centuries.

Inlet dynamics can be seen as potential sources of sediments considering BwN approaches. Considering that adjacent beaches are periodically supplied by sand through shoal attachment dynamics, understanding these dynamics may lead to soft engineering approaches that might trigger or stimulate shoal attachment during erosion phases on adjacent shorelines. Our results suggest that, if it is possible to control in some extent shoal attachment and adjacent shoreline dynamics, the size of the shoal and its spreading time will be essential for further dune development of the area. Moreover, the amount of sediment necessary to be attached should be enough for the current erosive profile recover and further supply for dune development. As an example of a potential application of the knowledge acquired in the current thesis is the island of Texel. Currently, a big shoal approaches the adjacent coast of Texel, triggering a robust erosive phase before the attachment. This erosive phase is causing several problems to the community and stakeholders from the island and raised worries regarding coastal protection of the island. Thus, our results suggest that if it is possible to accelerate the shoal attachment process, this may lead to an increase of dune growth and maintenance, considering that the volume of sand is big enough to sustain a large beach width for an extended period of time.

In case of sand flats, our results show that, in terms of dune development, the non-exposed part will have less potential for dune growth and recover after a storm, being in one sense the most problematic for stakeholders. In the other hand, not being exposed to waves reduces the risk of dune breaching and inundation considerably. Nevertheless, assuming that a minimum dune height is required from coastal risk assessment from coastal managers, it is important to consider that inner part has fewer mechanisms of sediment exchange between subtidal and subaerial zones and, therefore, it is crucial that supply in the upper zone is guaranteed to maintain dune height in the desired levels.

Nourishment has been a common approach to coastal management in the Netherlands. Nourishment is related to the addition of a certain volume of sand from a different domain, thus altering the overall local sediment budget and, therefore, counteracting phases of erosion in coastlines (Jong et al., 2014; Keijsers, 2015). Nourishments may affect supply to the dunes, considering a certain delay in time for this sediment to adjust itself or to be transferred for subtidal zones to subaerial zones when applied in locations below water level (Bochev-van der Burgh et al., 2009). Considering that our results suggest that shoal size and rate of dispersion are important factors for an increase in dune volume, a hypothesis would be that coupling nourishment approaches with shoal attachment phases may increase the probability of an effect in dune growth. Increasing the effect on the dunes may increase its capacity as a buffer during erosive phases and reduce the necessity of interventions between shoal attachment phases.

## 6.4 Challenges and limitations

To highlight the challenges and limitations encountered in the present research and use them as suggestions for further research, we further discuss them in the present topic. Although several limitations have already been pointed out throughout the chapters, specific and integrated problems will be further discussed and even raise suggestions for further research.

Several types of beach-dune systems may emerge in the vicinity of inlets. Barrier islands in the Dutch and German coast present shapes that are highly conditioned by inlet processes, defining a clear inlet-induced shape either as an increased beach width/shoreline progradation at shoal attachment locations (Fitzgerald et al., 1984; McBride et al., 2013) or as sand flats (van Heteren et al., 2006). Although other types of beach system nearby inlets have been reported in the literature (e.g. spit progradation, Junior (2006)), it is currently unknown how specific are sand flats like the one in the Netherlands, which should be further analysed in future research. Nevertheless, shoal attachment and sediment bypassing have been reported as a common process among different inlets (FitzGerald, 1988). Thus, current results may be considered as a transferable knowledge throughout different systems in the globe.

In a modelling perspective, cellular automata models have their strengths in their simplicity and relative low computational-effort (Silva et al., 2018; Keijsers et al., 2016; Fonstad, 2013). Such models are meant to analyse how specific parameters affect overall system development and how sensitive parameters are in the initial conditions. However, quantitative predictions that are useful for stakeholders are not in the scope of such models. Thus, modelling results have to be analysed in a qualitative perspective, even though quantitative values may be necessary to distinguish different scenarios. As an example, results show that dune volume is only significantly locally increased by individual shoals if they are big enough and/or have a slow rate of dispersion. However, it is currently unknown what would be the quantitative threshold in real cases.

Furthermore, find alternatives for the validation of cellular automata models are important for further model reliability. The matter has been already raised previously (Fonstad, 2006, 2013), and recent advances have been made (Keijsers et al., 2016; Zhang et al., 2015). However, considering the model stochasticity and the relative stochastic behaviour of dune growth initiation, together with the few time series available for long-term validation, it is important to further research and define quantitative standards and solutions for further cellular model validation in applications in coastal zones. Approaches commonly used in process-based models are not necessarily the best approach for a cellular automata model in coastal research since different outcomes can emerge from a certain range of input parameters that do not mean that the result is wrong. In this thesis, one approach that yields potential is the evaluation of the precision evolution with the increase of the replicates. This approach can show which parameters will be more variable within the certain range of input values defined. From that, the researcher might be able to define more suitable parameters for further RMSE analysis with real data.

The current DUBEVEG model is simplified toward a unidirectional sand transport or a combination of direction parallel and perpendicular to the grid cells. Using alternatives for tessellations of two-dimensional space (e.g. hexagonal grid cells) may help the introduction of multi-directional aeolian sand transport without a directional bias on the results (Nield and Baas, 2007).

The equilibrium profile applied in the model refers to a beach profile to which the beach tend to go under hydrodynamic forcing considering sufficient sea supply to reach those positions. Thus, the model does not control supply within the domain but rather assumes that sufficient sediment is always available to maintain the beach at certain position. Although a clever way of controlling sediment balance within the domain, adaptations on this scheme have to be considered when coupling cellular automata models such as the one used in the present research with process-based models such as XBeach and Delft3D.

In terms of field survey and data, the lack of hydrodynamic and topographic data during storm surges hinder validations approaches for XBeach simulations, as well as the analysis of sedimentation and hydrodynamic behaviour onto the sand flat during storms. Nevertheless, XBeach model has been used and validated for several different cases, and returned fair results in a great amount of different scenarios considering the chosen time-scale.

The methodology applied in the current research proved to be sufficient to achieve the proposed objectives. Even though several limitations are present in the current research, it is important to highlight that a better understanding of how inlet-driven landforms and processes may affect dunes was achieved. The highly idealised cellular model was able to yield interesting thoughts regarding how inlet-driven landforms may add spatial variability in supply for the dunes. Furthermore, how supply conditions may hinder supply effects due to beach width increase, and how space is an important aspect for dune growth. Moreover, how storms can act as a source of supply for the dunes and which types of shoal are expected to statistically increase local dune growth, findings that raise several other questions and may be further explored by the scientific community and coastal managers.

CHAPTER 7

# Conclusions and recommendations

Through a series of data analyse of long-term field data, modelling experiments of idealised scenarios of beach-dune interaction and simulations of real-cases using different tools, the research questions posed in chapter 1 have been further analysed, and answers are presented in this section.

## 7.1 Conclusions

1. How does the inlet-driven sand-flat setting influence dune development?

   By the usage of a cellular automata model, we detected that spatial variability in groundwater levels on the sand flat define spatial variability in supply that, in turn, reflect on spatial variability in dune development. In the model, increasing/decreasing the groundwater level lead to an overall decrease/increase in sediment supply for the dunes. That reflected in the type of dunes that emerge, where coppice/nebkah dune types only appeared in limited conditions of supply, whereas long dune rows appeared when supply was not limited. Furthermore, results show that there is a threshold on which groundwater limitation in supply is translated into changes in dune development. In the case of groundwater, this threshold is achieved by a depth relation which may only translate in spatial variability in supply as long as spatial variability in groundwater depth occurs. Considering the sand flat of Texel inlet (De Hors), simulations show that groundwater level is capable of inducing spatial variability in sediment supply and, therefore, influencing dune growth and distribution on the sand flat. Results are consistent with volume change estimates from LIDAR data, where the eastern side of the sand flat (where average elevation is lower and, consequently, higher groundwater levels) presents much less dune growth than the rest of the flat. The same pattern is also seen in different sand flats along the Dutch coast. However, in real cases, spatial variability in sand supply at sand flats may be not only related with groundwater levels, since other supply limiting condition such as wind direction, grain-size, the rate of inundation and surface moisture may also induce spatial variability in dune development onto sand flats. Nevertheless, considering all other limiting factor equal, modelling results show that groundwater alone may be enough to add spatial variability in supply, as long as groundwater levels are higher than the threshold level.

2. How is sediment exchanged between subtidal and subaerial zones in sand-flats close to inlets?

   Using a combination of data analysis of elevation and wave data, as well as the application of a process-based numerical model, we were able to identify the occurrence of storm-induced deposition onto sand-flats, important storm characteristics related to the magnitude of the deposition, and its potential importance for dune growth. Results showed that storm-induced supratidal deposition is a potentially important mechanism of sediment exchange and sediment supply for dune growth. The amount of sediment deposited may account for around half of the volume deposited at the dunes yearly. Furthermore, numerical results show that the magnitude in the volume of the sand deposition is directly proportional to the storm strength. Storms are also capable of remobilising the top layer of sediment of the sand-flat, making fresh sediment available for Aeolian transport when an armouring effect occurs. Although simulations showed that one storm is capable of depositing sand onto the sand flat in an amount that is significant compared to the yearly deposition, the influence of subsequent storms on the sand ridge deposition may hinder the capacity of deposited sand to be used by aeolian processes to feed the dunes. Nevertheless, considering the evidence from both elevation data and numerical simulations, in a sand flat setting, storm surges have the potential of not only eroding dunes but also transferring a significant amount of sand from the sub-tidal to the supra-tidal zone. This amount is significant when compared to dune growth, suggesting that storms may play a significant role as a supply mechanism to dune growth in sand flat settings.

3. What is the effect of time-varying beach width for dune development at decadal scales?

   A modelling exercise using a cellular automata model was done to evaluate the effect of varying beach width on dune development at decadal scales. Several simulations using idealised beach widths and different supply conditions were done. Furthermore, simulations using static beach widths (i.e. fixed shoreline position over time) and dynamic beach width (i.e. moving shoreline position over time) were also performed. Results suggest that there is a preferred position on which dunes tend to grow which is a function of the beach width. Consequently, beach width also controls the space available for dune development. Furthermore, dunes on narrow beaches tend to develop in higher elevations than dunes on wider beaches, which might be related to an equilibrium related to the hydrodynamic forcing and slope. Moreover, on narrow beaches, supply limitations such as groundwater depth may dominate over the effect of beach width increase, suggesting that limiting supply factor might have a more significant influence than beach width. Therefore, it is possible to conclude that, in a decadal scale, beach width control the space available for dune formation, thus the position of the most seaward dune, but other supply limiting factors may overrule the effect of beach width on dune volume. For time-varying beach width, initial beach widths and retreat time would define what would be the most important controls for foredune dynamics.

4. How do shoal attachment processes affect dune behaviour at decadal scales?

   Through a case study in a barrier island in the Netherlands, we tried to understand how shoal attachment processes may affect dune behaviour on a decadal scale. We used a combination of data analysis of long-term elevation and bathymetric data, together with an idealised and exploratory numerical exercise using a cellular automata model. Results from both data and numerical modelling suggest that an immediate increase in beach width due to shoal attachment does not translate into an immediate increase in dune growth. However, in the long-term, areas of frequent attachment present a significantly higher rate of dune increase than areas where shoal attachment does not frequently occur. That means that either the increase in average beach width due to shoal attachment or its variability, induce a higher rate of dune growth. An increase in beach width may induce an increase in supply, as long as initial beach width is small enough compared to the potential critical fetch. Furthermore, numerical results show that only specific shoal size and spreading characteristics may translate into different dune volumes in the back beach. Big shoals with slow spreading alongshore have a higher potential of leaving a footprint at dune volume than small shoals with fast-spreading characteristics. However, it is still unknown quantitatively what would be the threshold for such a footprint. Moreover, different periods of attachment may also affect the probability of a significant increase in dune volume due to its more frequent increase in beach width. Therefore, in the studied time-scale, shoal attachment is capable of inducing spatial variability alongshore in coastal dunes in barrier islands, considered that its size/volume is large enough to induce a high and persistent increase in beach width.

Considering the above-mentioned answers for the proposed questions, it is possible to conclude that inlet-driven processes and landforms may affect beach-dune systems nearby inlets by affecting how sand supply is exchanged by subtidal and subaerial zone and how it is distributed spatially. Sand-flats will create conditions that will enhance the possibility of spatial variability in dune growth and morphology, with more supply and higher dunes in the exposed part. This is relevant especially in terms of coastal management for which dune heights and resilience are a crucial aspect regarding coastal protection. Shoreline changes due to inlet-processes like channel migration and shoal attachment may affect supply and space for dune development, considering that time-scale of beach width change is large enough to be translated in dune growth.

## 7.2 Recommendations

- Cellular automata models are ideal for exploratory and idealised modelling. However, subtidal processes are currently not solved within the model, which hinder modelling exercises of full modelling of the sediment exchange in the form of bars or shoals. Thus, it is highly recommended that research aiming at (1) translating known hydrodynamic processes into rules and (2) coupling methods to allow the use of models that are meant to solve such processes. The hydrodynamic component of the model lacks of rules that represent sediment transport from hydrodynamic processes, relying solely on the equilibrium profile scheme. For more complex situations and further applicability in coastal management projects, it is highly recommended to improve these components of the model. Moreover, it highly recommended extending validation and performance exercises using the DUBEVEG model. Currently, there are still approximations (e.g. equilibrium profile, groundwater level) that, although they are based on accepted knowledge, may need further research and evaluation to improve model estimates further.

- For quantitative predictions and the development of tools for coastal management, it is important to understand further how small scale variability may affect the long-term evolution of beach-dune systems. Several authors describe the problems of uncertainty for long-term simulations, even when data sets used for boundary conditions are rich. The understanding of the effect of non-linearities on long-term evolution should be further discussed and researched.

- Regarding storms, it is important to research solutions for the gathering of long-term data of energetic coastal events. The lack of data and its challenging conditions for usual instruments hinder our understanding of the hydrodynamics and sediment transfer related to storms. Few data sets are available with measurements of storms, most relying on morphological data of pre- and post-storm conditions and hydrodynamic data from offshore zones. The development of a dataset of measurements of hydrodynamic data such as currents, waves and sediment transport in the nearshore during storm conditions is crucial to understand how sediment is exchanged from subtidal from subaerial zones during such conditions.

- For further assessment of the use of inlet dynamics for Building-with-Nature approaches to solve erosive phases in adjacent coastlines, it is important to research further the possibilities of stimulating/triggering shoal attachment processes using soft-engineering approaches that will have a minimum negative impact for the overall balance of the coastal system. To solve phases of erosion, it may be required to know whether it is possible to define when the shoal would attach the coast, and understanding what would be the consequences for the overall sediment balance of managing the shoal cycle. Furthermore, current research is based on the idea that only beach width changes due to channel migration or shoal attachment processes. It is recommended that further research consider whether other variables such as grain-size are also affected by such processes. Furthermore, the idealised approach used to define how shoals spread over the coast may be further improved by the use of real data from different sites

# Bibliography

Aagaard, T. (2014). Sediment supply to beaches: Cross-shore sand transport on the lower shoreface. *Journal of Geophysical Research: Earth Surface 119*(4), 913–926. (pp. 50, 137).

Aagaard, T., R. Davidson-Arnott, B. Greenwood, and J. Nielsen (2004). Sediment supply from shoreface to dunes: linking sediment transport measurements and long-term morphological evolution. *Geomorphology 60*(1-2), 205–224. (p. 108).

Aagaard, T., B. Greenwood, and M. Hughes (2013). Sediment transport on dissipative, intermediate and reflective beaches. *Earth-Science Reviews 124*, 32 – 50. (p. 5).

Aagaard, T., J. Nielsen, S. G. Jensen, and J. Friderichsen (2004). Longshore sediment transport and coastal erosion at Skallingen, Denmark. *Geografisk Tidsskrift-Danish Journal of Geography 104*(1), 5–14. (pp. 50, 51, 51, 75, 79, 108, 134).

Ab'Sáber, A. N. and W. Bernard (1953, dec). Sambaquís da região lagunar de cananéia: I - observações geográficas. II - especulações prehistóricas. *Boletim do Instituto Oceanográfico 4*(1-2), 215–238. (p. 3).

Adams, P. N., K. M. Keough, and M. Olabarrieta (2016). Beach morphodynamics influenced by an ebb-tidal delta on the north florida atlantic coast. *Earth Surface Processes and Landforms 41*(7), 936–950. (p. 109).

Anthony, E. J. (2013). Storms, shoreface morphodynamics, sand supply, and the accretion and erosion of coastal dune barriers in the southern North Sea. *Geomorphology 199*, 8–21. (pp. 50, 51, 79).

Anthony, E. J., S. Vanhee, and M. H. Ruz (2006). Short-term beach-dune sand budgets on the north sea coast of France: Sand supply from shoreface to dunes, and the role of wind and fetch. *Geomorphology 81*(3-4), 316–329. (pp. 50, 51, 51, 108).

Arens, S. M. (1996). Patterns of sand transport on vegetated foredunes. *Geomorphology 17*, 339–350. (pp. 10, 12, 25).

Ashton, A., A. B. Murray, and O. Arnoult (2001). Formation of coastline features by large-scale instabilities induced by high-angle waves. *Nature 414*(6861), 296–300. (p. 19).

Baas, A. C. (2002). Chaos, fractals and self-organization in coastal geomorphology: simulating dune landscapes in vegetated environments. *Geomorphology 48*(1-3), 309–328. (pp. 19, 27, 28).

Baas, A. C. W. and J. M. Nield (2007). Modelling vegetated dune landscapes. *Geophysical Research Letters 34*(6). (pp. 19, 20).

Baas, A. C. W. and J. M. Nield (2010). Ecogeomorphic state variables and phase-space construction for quantifying the evolution of vegetated aeolian landscapes. *Earth Surface Processes and Landforms 731*(April). (p. 20).

Bagnold, R. A. (1941). *The Physics of Blown Sand and Desert Dunes (Dover Earth Science)*. Dover Publications. (p. 10).

Balzter, H., P. W. Braun, and W. Köhler (1998). Cellular automata models for vegetation dynamics. *Ecological Modelling 107*(2-3), 113–125. (p. 19).

Barchyn, T. E. and C. H. Hugenholtz (2012, sep). Predicting vegetation-stabilized dune field morphology. *Geophysical Research Letters 39*(17), n/a–n/a. (p. 79).

Barrio-Parra, F. and I. Rodríguez-Santalla (2014). A free cellular model of dune dynamics: Application to el fangar spit dune system (ebro delta, spain). *Computers & Geosciences 62*, 187–197. (p. 20).

Bauer, B. O. and R. G. Davidson-Arnott (2003). A general framework for modeling sediment supply to coastal dunes including wind angle, beach geometry, and fetch effects. *Geomorphology 49*(1-2), 89–108. (pp. 11, 11, 139).

Bauer, B. O. and R. G. D. Davidson-Arnott (2002). A general framework for modeling sediment supply to coastal dunes including wind angle , beach geometry , and fetch effects. *Geomorphology 49*(1), 89–108. (pp. 11, 15, 15, 50, 78, 78, 78, 103, 108).

Bauer, B. O., R. G. D. Davidson-Arnott, P. a. Hesp, S. L. Namikas, J. Ollerhead, and I. J. Walker (2009, apr). Aeolian sediment transport on a beach: Surface moisture, wind fetch, and mean transport. *Geomorphology 105*(1-2), 106–116. (pp. 10, 10, 10, 24, 24, 25, 50, 51, 74, 78).

Bentley, I. (2016). *A novel cellular automata based estuarine morphodynamic model*. Ph. D. thesis, University of Glasgow. (p. 20).

Bentley, I. and H. Karunarathna (2012). A novel cellular automata approach to estuarine morphodynamic modelling. *Coastal Engineering Proceedings 1*(33), 27. (p. 20).

Bird, E. C. F. (2008). *Coastal Geomorphology: An Introduction*. JOHN WILEY & SONS INC. (p. 2).

Bochev-Van der Burgh, L. (2012). *Decadal-scale morphologic variability of foredunes subject to human interventions*. Ph. D. thesis, University of Twente. (p. 143).

Bochev-Van der Burgh, L., K. Wijnberg, and S. Hulscher (2011). Decadal-scale morphologic variability of managed coastal dunes. *Coastal Engineering 58*(9), 927 – 936. (pp. 50, 78, 143).

Bochev-van der Burgh, L. M. v., K. M. Wijnberg, and S. Hulscher (2009). Dune morphology along a nourished coastline. *Journal of Coastal Research* (56), 292–296. (pp. 50, 78, 143, 145).

Borsje, B., B. van Wesenbeeck, F. Dekker, P. Paalvast, T. Bouma, M. van Katwijk, and M. de Vries (2011). How ecological engineering can serve in coastal protection. *Ecological Engineering 37*(2), 113–122. (p. 3).

Burningham, H. and J. French (2006). Morphodynamic behaviour of a mixed sand–gravel ebb-tidal delta: Deben estuary, suffolk, UK. *Marine Geology 225*(1-4), 23–44. (p. 107, 107).

Burroughs, S. M. and S. F. Tebbens (2008). Dune retreat and shoreline change on the outer banks of north carolina. *Journal of Coastal Research 24*(2B), 104–112. (pp. 15, 78).

Carr-Betts, E., T. M. Beck, and N. C. Kraus (2012). Tidal inlet morphology classification and empirical determination of seaward and down-drift extents of tidal inlets. *Journal of Coastal Research 282*, 547–556. (p. 4).

Carter, R. W. G. (2013). *Coastal Environments*. Elsevier Science. (p. 3).

Carter, R. W. G., T. G. F. Curtis, and M. J. Sheehy-Skeffington (1992). Coastal dunes: geomorphology, ecology and management for conservation. Proceedings of the third European dune congress, Galway, June 1992. (p. 3).

Castelle, B., V. Marieu, S. Bujan, K. D. Splinter, A. Robinet, N. Sénéchal, and S. Ferreira (2015). Impact of the winter 2013–2014 series of severe western europe storms on a double-barred sandy coast: Beach and dune erosion and megacusp embayments. *Geomorphology 238*, 135–148. (p. 14).

Chase, C. G. (1992). Fluvial landsculpting and the fractal dimension of topography. *Geomorphology 5*(1-2), 39–57. (p. 19).

Clarke, D. and I. Eliot (1983). Mean sea-level and beach-width variation at scarborough, western australia. *Marine Geology 51*(3), 251 – 267. (p. 79).

Coco, G. (2003). Test of self-organization in beach cusp formation. *Journal of Geophysical Research 108*(C3). (p. 19).

Coco, G. (2004). The role of tides in beach cusp development. *Journal of Geophysical Research 109*(C4). (p. 19).

Coco, G., D. a. Huntley, and T. J. O'Hare (2000). Investigation of a self-organization model for beach cusp formation and development. *Journal of Geophysical Research 105*(C9), 21991. (p. 19).

Coco, G. and a. B. Murray (2007). Patterns in the sand: From forcing templates to self-organization. *Geomorphology 91*(3-4), 271–290. (p. 19).

Coco, G., N. Senechal, A. Rejas, K. Bryan, S. Capo, J. Parisot, J. Brown, and J. MacMahan (2014). Beach response to a sequence of extreme storms. *Geomorphology 204*, 493–501. (p. 14).

Cohn, N., P. Ruggiero, S. de Vries, and G. García-Medina (2017). Beach growth driven by intertidal sandbar welding. In *Proceedings of Coastal Dynamics 2017*. (pp. 51, 79, 108, 134, 134).

Coulthard, T., D. Hicks, and M. V. D. Wiel (2007). Cellular modelling of river catchments and reaches: Advantages, limitations and prospects. *Geomorphology 90*(3-4), 192–207. (p. 19).

Darke, I. and C. M. Neuman (2008). Field study of beach water content as a guide to wind erosion potential. *Journal of Coastal Research 245*, 1200–1208. (p. 25).

Davidson-Arnott, R. G., K. MacQuarrie, and T. Aagaard (2005). The effect of wind gusts, moisture content and fetch length on sand transport on a beach. *Geomorphology 68*(1-2), 115–129. (pp. 15, 78, 131).

Davidson-Arnott, R. G. D. and A. G. V. Heyningen (2003). Migration and sedimentology of longshore sandwaves, long point, lake erie, canada. *Sedimentology 50*(6), 1123–1137. (pp. 79, 108, 139).

Davidson-Arnott, R. G. D. and M. N. Law (1996). Measurement and prediction of long-term sediment supply to coastal foredunes. *Journal of Coastal Research 12*(3), 654–663. (pp. 11, 15, 15, 78, 78, 108, 108, 131, 131).

Davidson-Arnott, R. G. D., Y. Yang, J. Ollerhead, P. A. Hesp, and I. J. Walker (2008). The effects of surface moisture on aeolian sediment transport threshold and mass flux on a beach. *Earth Surface Processes and Landforms 33*(1), 55–74. (p. 10, 10).

Davis, R. A. (2013). A new look at barrier-inlet morphodynamics. *Journal of Coastal Research 69*, 1–12. (p. 14).

de M. Luna, M. C. M., E. J. R. Parteli, O. Durán, and H. J. Herrmann (2011). Model for the genesis of coastal dune fields with vegetation. *Geomorphology 129*(3-4), 215–224. (pp. 43, 138).

de Swart, H. and J. Zimmerman (2009). Morphodynamics of Tidal Inlet Systems. *Annual Review of Fluid Mechanics 41*(1), 203–229. (pp. 2, 3).

de Vriend, H. and M. van Koningsveld (2012). *Building with Nature: Thinking, acting and interacting differently.* Dordrecht, the Netherlands: Ecoshape, Building with Nature. (pp. 3, 143).

de Vries, J. V. T. (2009). *Dune Erosion during storm surges*. Phd thesis, Delft University of Technology, Delft. (p. 58).

de Vries, S., H. N. Southgate, W. Kanning, and R. Ranasinghe (2012). Dune behavior and aeolian transport on decadal timescales. *Coastal Engineering 67*, 41–53. (pp. 11, 11, 74, 100, 101, 112, 112).

de Vries, S., A. Verheijen, B. Hoonhout, S. Vos, N. Cohn, and P. Ruggiero (2017). Measured spatial variability of beach erosion due to aeolian processes. In *Proceedings of Coastal Dynamics 2017*. (p. 134).

de Winter, R., F. Gongriep, and B. Ruessink (2015). Observations and modeling of alongshore variability in dune erosion at Egmond aan Zee, the Netherlands. *Coastal Engineering 99*, 167–175. (p. 112).

Dean, R. G. (1991). Equilibrium Beach Profiles : Characteristics and Applications. *Journal of Coastal Research 7*(1), 53–84. (p. 115).

Dearing, J. A., N. Richmond, A. J. Plater, J. Wolf, D. Prandle, and T. J. Coulthard (2006). Modelling approaches for coastal simulation based on cellular automata: the need and potential. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 364*(1841), 1051–1071. (pp. 19, 20).

Delgado-Fernandez, I. (2010). A review of the application of the fetch effect to modelling sand supply to coastal foredunes. *Aeolian Research 2*(2-3), 61–70. (pp. 10, 15, 78, 131).

Delgado-Fernandez, I. (2011). Meso-scale modelling of aeolian sediment input to coastal dunes. *Geomorphology 130*(3-4), 230–243. (p. 133).

Delgado-Fernandez, I. and R. Davidson-Arnott (2011). Meso-scale aeolian sediment input to coastal dunes: The nature of aeolian transport events. *Geomorphology 126*(1-2), 217–232. (pp. 50, 74, 78, 101).

Deltares (2018). Xbeach manual. (p. 58, 58, 58, 58).

Dennis K. Hubbard, George Oertel, D. (1979). The role of waves and tidal currents in the development of tidal-inlet sedimentary structures and sand body geometry: Examples from north carolina, south carolina, and georgia. *SEPM Journal of Sedimentary Research Vol. 49*. (p. 14).

Do, A. T., S. de Vries, and M. J. Stive (2018). Beach evolution adjacent to a seasonally varying tidal inlet in central vietnam. *Journal of Coastal Research 341*, 6–25. (p. 107).

Donker, J., M. van Maarseveen, and G. Ruessink (2018, oct). Spatio-temporal variations in foredune dynamics determined with mobile laser scanning. *Journal of Marine Science and Engineering 6*(4), 126. (p. 112).

Duarte-Campos, L., K. Wijnberg, and S. Hulscher (2018). Estimating annual onshore aeolian sand supply from the intertidal beach using an aggregated-scale transport formula. *Journal of Marine Science and Engineering 6*(4), 127. (pp. 10, 74, 112).

Durán, O. and L. J. Moore (2013). Vegetation controls on the maximum size of coastal dunes. *Proceedings of the National Academy of Sciences 110*(43), 17217–17222. (pp. 45, 45, 46).

Duran-Matute, M., T. Gerkema, G. J. De Boer, J. J. Nauw, and U. Gräwe (2014). Residual circulation and freshwater transport in the Dutch Wadden Sea: A numerical modelling study. *Ocean Science 10*(4), 611–632. (p. 57).

Durán Vinent, O. and L. J. Moore (2014). Barrier island bistability induced by biophysical interactions. *Nature Climate Change 5*(December), 158–162. (pp. 45, 79, 103).

Eastwood, E., J. Nield, A. Baas, and G. Kocurek (2011). Modelling controls on aeolian dune-field pattern evolution. *Sedimentology 58*(6), 1391–1406. (pp. 50, 78, 79, 108).

Elgar, S., R. T. Guza, and M. H. Freilich (1988). Eulerian measurements of horizontal accelerations in shoaling gravity waves. *Journal of Geophysical Research 93*(C8), 9261. (p. 6).

Elias, E. P. L. L. and A. J. F. v. d. Spek (2017). Dynamic preservation of texel inlet, the netherlands: understanding the interaction of an ebb-tidal delta with its adjacent coast. *Netherlands Journal of Geosciences 96*(4), 293 – 317. (p. 52, 52).

Elias, E. P. L. L. and A. J. F. Van Der Spek (2006). Long-term morphodynamic evolution of Texel Inlet and its ebb-tidal delta (The Netherlands). *Marine Geology 225*(1-4), 5–21. (pp. 8, 15, 15, 51, 51, 52, 107).

Elsayed, S. M. and H. Oumeraci (2017). Effect of beach slope and grain-stabilization on coastal sediment transport: An attempt to overcome the erosion overestimation by xbeach. *Coastal Engineering 121*, 179 – 196. (p. 58, 58).

Engelstad, A., B. G. Ruessink, D. Wesselman, P. Hoekstra, A. P. Oost, and M. V. D. Vegt (2017). Observations of waves and currents during barrier island inundation. *Journal of Geophysical Research: Oceans*, 1–22. (pp. 24, 138).

Fenster, M. and R. Dolan (1996). Assessing the impact of tidal inlets on adjacent barrier island shorelines. *Journal of Coastal Research 12*(1), 294–310. (pp. 2, 6, 8, 51, 106, 107).

FitzGerald, D. and M. Miner (2013). Tidal inlets and lagoons along siliciclastic barrier coasts. In *Treatise on Geomorphology*, pp. 149–165. Elsevier. (pp. 2, 4, 5).

FitzGerald, D. M. (1982). Sediment bypassing at mixed energy tidal inlets. In *Coastal Engineering 1982*. American Society of Civil Engineers. (pp. 6, 107).

Fitzgerald, D. M. (1984). Interactions between the ebb-tidal delta and landward shoreline: Price inlet, south carolina. *SEPM Journal of Sedimentary Research Vol. 54*. (pp. 2, 2, 6, 8, 8, 24, 140).

FitzGerald, D. M. (1988). Shoreline erosional-depositional processes associated with tidal inlets. In *Hydrodynamics and Sediment Dynamics of Tidal Inlets*, pp. 186–225. Springer New York. (pp. 2, 6, 106, 146).

FitzGerald, D. M. (1996). Geomorphic Variability and Morphologic and Sedimentologic Controls on Tidal Inlets. *Journal of Coastal Research* (23), 47–71. (p. 14).

FitzGerald, D. M., I. V. Buynevich, M. S. Fenster, and P. A. McKinlay (2000). Sand dynamics at the mouth of a rock-bound, tide-dominated estuary. *Sedimentary Geology 131*(1), 25–49. (p. 106, 106).

FitzGerald, D. M., N. C. Kraus, and E. B. Hands (2000). Natural mechanisms of sediment bypassing at tidal inlets. Technical report, Engineer Research and Development Center Vicksburg MS Coastal and Hydraulics Lab. (p. 6, 6).

FitzGerald, D. M. and E. Pendleton (2002). Inlet formation and evolution of the sediment bypassing system: New inlet, cape cod, massachusetts. *Journal of Coastal Research 36*, 290–299. (p. 107).

Fitzgerald, D. M., S. Penland, and D. Nummedal (1984). Control Of Barrier Island Shape By Inlet Sediment Bypassing: East Frisian Islands, West Germany. *Marine Geology 60*(1), 355 – 376. Hydrodynamics and Sedimentation in Wave-Dominated Coastal Environments. (pp. 1, 2, 6, 51, 107, 140, 145).

Fonstad, M. (2013). 2.9 cellular automata in geomorphology. In J. F. Shroder (Ed.), *Treatise on Geomorphology*, pp. 117 – 134. San Diego: Academic Press. (pp. 17, 18, 26, 79, 146, 146).

Fonstad, M. a. (2006). Cellular automata as analysis and synthesis engines at the geomorphology–ecology interface. *Geomorphology 77*(3-4), 217–234. (pp. 18, 26, 79, 146).

Fort, H. (2013). Two cellular automata designed for ecological problems: Mendota CA and barro colorado island CA. In *Emerging Applications of Cellular Automata*. InTech. (p. 19).

Fredsøe, J. and R. Deigaard (1992). *Mechanics of Coastal Sediment Transport*. World Scientific. (p. 5).

Gaudiano, D. J. and T. W. Kana (2001). Shoal bypassing in mixed energy inlets: Geomorphic variables and empirical predictions for nine south carolina inlets. *Journal of Coastal Research 17*(2), 280–291. (pp. 106, 107, 107, 140, 140).

Gillette, D. A., G. Herbert, P. H. Stockton, and P. R. Owen (1996). Causes of the fetch effect in wind erosion. *Earth Surface Processes and Landforms 21*(7), 641–659. (p. 11).

Goldstein, E. B., L. J. Moore, and O. D. Vinent (2017). Lateral vegetation growth rates exert control on coastal foredune hummockiness and coalescing time. *Earth Surface Dynamics 5*(3), 417–427. (pp. 13, 45, 134).

Greeley, R. and J. D. Iversen (1985). *Wind as a geological process on Earth, Mars, Venus and Titan.* University Press, Cambridge. (p. 10).

Grunnet, N. M. and B. G. Ruessink (2005). Morphodynamic response of nearshore bars to a shoreface nourishment. *Coastal Engineering 52*(2), 119 – 137. (p. 109).

Guza, R. T. and D. L. Inman (1975). Edge waves and beach cusps. *Journal of Geophysical Research 80*(21), 2997–3012. (p. 19).

Hansen, J. E., E. Elias, and P. L. Barnard (2013). Changes in surfzone morphodynamics driven by multi-decadal contraction of a large ebb-tidal delta. *Marine Geology 345*, 221–234. (p. 8).

Hansen, J. E., E. Elias, J. H. List, L. H. Erikson, and P. L. Barnard (2013). Tidally influenced alongshore circulation at an inlet-adjacent shoreline. *Continental Shelf Research 56*, 26–38. (p. 8).

Hayes, M. O. (1977). Development of kiawah island. In *Coastal Sediments 1977*, pp. 828–847. ASCE. (p. 107).

Hayes, M. O. (1979). *Barrier island morphology as a function of tidal and wave regime*, Chapter 1, pp. 1–28. Academic Press, New York. (pp. 2, 4, 4).

Heathfield, D. K. and I. J. Walker (2015). Evolution of a foredune and backshore river complex on a high-energy, drift-aligned beach. *Geomorphology 248*, 440–451. (p. 79).

Hesp, P. (1983). Morphodynamics of incipient foredunes in new south wales, australia. *Developments in Sedimentology 38*(C), 325–342. (pp. 13, 13, 50, 50, 78, 78).

Hesp, P. (2002). Foredunes and blowouts : initiation , geomorphology and dynamics. *Geomorphology 48*(1-3), 245–268. (pp. 11, 12, 12, 12, 13, 13, 14, 15, 24, 24, 45, 47, 50, 50, 50, 78, 78, 100, 108, 131, 140).

Hesp, P. (2011). *Dune Coasts (Treatise on Estuarine and Coastal Science Chapter)* (Vol. 3 ed.), Volume 3. Elsevier Inc. (pp. 1, 12, 12, 13, 13, 14).

Hesp, P. A. (1989). A review of biological and geomorphological processes involved in the initiation and development of incipient foredunes. *Proceedings of the Royal Society of Edinburgh. Section B. Biological Sciences 96*, 181–201. (pp. 12, 13).

Hesp, P. A. and T. A. Smyth (2016). Surfzone-beach-dune interactions: Flow and sediment transport across the intertidal beach and backshore. *Journal of Coastal Research*, 8–12. (p. 108).

Hesp, P. A. and I. J. Walker (2013). *Coastal Dunes*, Volume 11. Elsevier Ltd. (pp. 50, 78, 100, 140).

Hicks, D. M. and T. M. Hume (1996). Morphology and size of ebb tidal deltas at natural inlets on open-sea and pocket-bay coasts, north island, new zealand. *Journal of Coastal Research 12*(1), 47–63. (p. 140).

Hoad, K., S. Robinson, and R. Davies (2011). Autosimoa: a framework for automated analysis of simulation output. *Journal of Simulation 5*(1), 9–24. (pp. 84, 116).

Hoekstra, P., M. ten Haaf, P. Buijs, A. Oost, R. K. Breteler, K. van der Giessen, and M. van der Vegt (2009). Washover development on mixed-energy, mesotidal barrier island systems. In *Proceedings of Coastal Dynamics 2009*. WORLD SCIENTIFIC. (p. 138).

Hofstede, J. L. (1999a). Process-response analysis for hörnum tidal inlet in the german sector of the wadden sea. *Quaternary International 60*(1), 107–117. (p. 140).

Hofstede, J. L. (1999b). Regional differences in the morphologic behaviour of four german wadden sea barriers. *Quaternary International 56*(1), 99–106. (p. 107).

Hogeweg, P. (1988). Cellular automata as a paradigm for ecological modeling. *Applied Mathematics and Computation 27*(1), 81–100. (p. 19).

Hoonhout, B. and S. de Vries (2017). Field measurements on spatial variations in aeolian sediment availability at the sand motor mega nourishment. *Aeolian Research 24*, 93 – 104. (pp. 47, 73).

Horn, D. P. (2002). Beach groundwater dynamics. *Geomorphology 48*(1-3), 121–146. (p. 25).

Horn, D. P. (2006). Measurements and modelling of beach groundwater flow in the swash-zone: a review. *Continental Shelf Research 26*(5), 622–652. (p. 25).

Houser, C. (2009). Synchronization of transport and supply in beach-dune interaction. *Progress in Physical Geography 33*(6), 733–746. (pp. 12, 50, 74, 131, 133).

Houser, C. and G. Barrett (2010). Divergent behavior of the swash zone in response to different foreshore slopes and nearshore states. *Marine Geology 271*(1), 106 – 118. (p. 75).

Houser, C. and J. Ellis (2013). Beach and Dune interaction. In A. Press. (Ed.), *Treatise on Geomorphology*, Volume 10, pp. 267–288. San Diego. (pp. 10, 10, 11, 12, 14, 24, 25, 25, 51, 74, 75, 75, 134, 137, 138, 140, 140).

Houser, C. and S. Hamilton (2009). Sensitivity of post-hurricane beach and dune recovery to event frequency. *Earth Surface Processes and Landforms 34*(5), 613–628. (p. 14, 14).

Houser, C., C. Hapke, and S. Hamilton (2008). Controls on coastal dune morphology, shoreline erosion and barrier island response to extreme storms. *Geomorphology 100*(3-4), 223–240. (pp. 108, 134).

Houser, C., P. Wernette, E. Rentschlar, H. Jones, B. Hammond, and S. Trimble (2015). Post-storm beach and dune recovery: Implications for barrier island resilience. *Geomorphology 234*, 54–63. (p. 13).

Hyandye, C. and L. W. Martz (2016). A markovian and cellular automata land-use change predictive model of the usangu catchment. *International Journal of Remote Sensing 38*(1), 64–81. (p. 19).

Isla, F. I. (1997). Seasonal behaviour of mas chiquita tidal inlet in relation to adjacent beaches, argentina. *Journal of Coastal Research 13*(4), 1221–1232. (p. 107).

Iversen, J. D. and K. R. Rasmussen (1994). The effect of surface slope on saltation threshold. *Sedimentology 41*(4), 721–728. (p. 11).

Jackson, N. L., G. Masselink, and K. F. Nordstrom (2004). The role of bore collapse and local shear stresses on the spatial distribution of sediment load in the uprush of an intermediate-state beach. *Marine Geology 203*(1-2), 109–118. (p. 75).

Jong, B. D., J. G. Keijsers, M. J. Riksen, J. Krol, and P. A. Slim (2014). Soft engineeringvs.a dynamic approach in coastal dune management: A case study on the north sea barrier island of ameland, the netherlands. *Journal of Coastal Research 296*, 670–684. (p. 145).

Junior, D. R. d. N. (2006). *Morfologia e Sedimentologia ao longo do sistema praia-duna frontal de Ilha Comprida, SP*. Ph. D. thesis, Universidade de São Paulo. (p. 145).

Kana, T. W. (1995). A mesoscale sediment budget for Long Island, New York. *Marine Geology 126*(1), 87 – 110. Large-Scale Coastal Behavior. (p. 106).

Keijsers, J. (2015). *Modelling foredune dynamics in response to climate change*. Ph. D. thesis, Wageningen University. (p. 145).

Keijsers, J. G., a. V. De Groot, and M. J. Riksen (2015). Vegetation and sedimentation on coastal foredunes. *Geomorphology 228*, 723–734. (pp. 13, 45, 50, 78).

Keijsers, J. G. S., A. V. D. Groot, and M. J. P. M. Riksen (2016). Modeling the biogeomorphic evolution of coastal dunes in response to climate change. *Journal of Geophysical Research: Earth Surface 121*(6), 1161–1181. (pp. 20, 26, 27, 29, 31, 79, 80, 83, 83, 83, 83, 85, 113, 113, 146, 146).

Keijsers, J. G. S., A. Poortinga, M. J. P. M. Riksen, and J. Maroulis (2014). Spatio-temporal variability in accretion and erosion of coastal foredunes in the Netherlands: regional climate and local topography. *PloS one* 9(3), e91115. (pp. 15, 78, 101, 101, 112).

Knaapen, M., J. Willis, and J. Harris (2013). Modeling dune dynamics in situations with bimodal sediment. In *MARID IV*, pp. 153–158. (p. 20).

Komar, P. D. (1998). *Beach Processes and Sedimentation (2nd Edition)*. Prentice Hall. (p. 6).

Larson, M., J. D. Rosati, and N. C. Kraus (2002). Overview of regional coastal sediment processes and controls. Technical report, US Army Corps of Engineers. (p. 142).

Law, A. M. (2014). *Simulation Modeling and Analysis*. McGraw-Hill Education - Europe. (pp. 84, 116).

Lentz, E. E., C. J. Hapke, H. F. Stockdon, and R. E. Hehre (2013). Improving understanding of near-term barrier island evolution through multi-decadal assessment of morphologic change. *Marine Geology 337*, 125–139. (p. 108).

Longuet-Higgins, M. S. (1970). Longshore currents generated by obliquely incident sea waves: 1. *Journal of Geophysical Research 75*(33), 6778–6789. (p. 6).

Luijendijk, A., G. Hagenaars, R. Ranasinghe, F. Baart, G. Donchyts, and S. Aarninkhof (2018). The state of the world's beaches. *Scientific Reports 8*(1). (p. 1).

Martínez, M. L. and N. P. Psuty (2004). *Coastal Dunes - Ecology and conservation*. Springer. (pp. 1, 3, 3, 13, 45).

Maun, A. (2009). *The Biology of Coastal Sand Dunes (Biology of Habitats Series)*. Oxford University Press. (p. 13).

McBride, R. A., J. B. Anderson, I. V. Buynevich, W. Cleary, M. S. Fenster, D. M. FitzGerald, M. S. Harris, C. J. Hein, A. H. F. Klein, B. Liu, J. T. de Menezes, M. Pejrup, S. R. Riggs, A. D. Short, G. W. Stone, D. J. Wallace, and P. Wang (2013). *Morphodynamics of Barrier Systems: A Synthesis*, Volume 10. (p. 145).

McCall, R., J. V. T. de Vries, N. Plant, A. V. Dongeren, J. Roelvink, D. Thompson, and A. Reniers (2010). Two-dimensional time dependent hurricane overwash and erosion modeling at santa rosa island. *Coastal Engineering 57*(7), 668–683. (p. 58).

Mendicino, G., J. Pedace, and A. Senatore (2013). Cellular automata based modeling for the assessment of ecohydrological dynamics at the hillslope scale: Preliminary results. *Procedia Environmental Sciences 19*, 311–320. (p. 19).

Mohan, M. and M. K. Tiwari (2004). Study of momentum transfers within a vegetation canopy. In *Proceedings of the Indian Academy of Sciences (Earth and Planetary Sciences)*, Volume 113, pp. 67 – 72. (p. 13).

Monahan, A. H., J. C. Fyfe, M. H. P. Ambaum, D. B. Stephenson, and G. R. North (2009). Empirical orthogonal functions: The medium is the message. *Journal of Climate 22*(24), 6501–6514. (p. 112).

Mulhern, J. S., C. L. Johnson, and J. M. Martin (2017). Is barrier island morphology a function of tidal and wave regime? *Marine Geology 387*, 74–84. (pp. 2, 24).

Nederhoff, C. (2014). Modeling the effects of hard structures on dune erosion and overwash. Master thesis, Delft University of Technology, Delft. (p. 58).

Nield, J. M. and A. C. Baas (2008). The influence of different environmental and climatic conditions on vegetated aeolian dune landscape development and response. *Global and Planetary Change 64*(1-2), 76–92. (p. 45).

Nield, J. M. and A. C. W. Baas (2007). Investigating parabolic and nebkha dune formatrion using a cellular automaton modelling approach. *Earth Surface Processes and Landforms 33*(5), 724–740. (pp. 20, 28, 29, 31, 31, 45, 79, 82, 82, 113, 147).

Nielsen, P. (1981). Dynamics and geometry of wave-generated ripples. *Journal of Geophysical Research 86*(C7), 6467. (p. 5).

Nordstrom, K. F. and N. L. Jackson (1992). Effect of source width and tidal elevation changes on aeolian transport on an estuarine beach. *Sedimentology 39*(5), 769–778. (p. 133).

Oblinger, A. and E. J. Anthony (2008). Surface Moisture Variations on a Multibarred Macrotidal Beach: Implications for Aeolian Sand Transport. *Journal of Coastal Research 245*, 1194–1199. (p. 25).

O'Connor, M. C., J. A. G. Cooper, and D. W. T. Jackson (2010). Decadal behavior of tidal inlet-associated beach systems, northwest ireland, in relation to climate forcing. *Journal of Sedimentary Research 81*(1), 38–51. (pp. 107, 108).

Oost, A., P. Hoekstra, A. Wiersma, B. Flemming, E. Lammerts, M. Pejrup, J. Hofstede, B. van der Valk, P. Kiden, J. Bartholdy, M. van der Berg, P. Vos, S. de Vries, and Z. Wang (2012). Barrier island management: Lessons from the past and directions for the future. *Ocean & Coastal Management 68*, 18 – 38. Special Issue on the Wadden Sea Region. (p. 3).

Poortinga, A., J. G. S. S. Keijsers, S. M. Visser, M. J. P. M. P. M. Riksen, and A. C. W. W. Baas (2015). Temporal and spatial variability in event scale aeolian transport on Ameland, The Netherlands. *GeoResJ 5*, 23–35. (pp. 24, 24, 25, 25, 43, 138).

Quartel, S., a. Kroon, and B. Ruessink (2008). Seasonal accretion and erosion patterns of a microtidal sandy beach. *Marine Geology 250*(1-2), 19–33. (pp. 79, 112).

Reichmüth, B. and E. J. Anthony (2007). Tidal influence on the intertidal bar morphology of two contrasting macrotidal beaches. *Geomorphology 90*(1), 101 – 114. (p. 51).

Ridderinkhof, W., H. E. de Swart, M. van der Vegt, and P. Hoekstra (2016). Modeling the growth and migration of sandy shoals on ebb-tidal deltas. *Journal of Geophysical Research: Earth Surface 121*(7), 1351–1372. (p. 140).

Ridderinkhof, W., P. Hoekstra, M. van der Vegt, and H. de Swart (2016). Cyclic behavior of sandy shoals on the ebb-tidal deltas of the wadden sea. *Continental Shelf Research 115*, 14–26. (pp. 15, 85, 85, 106, 107, 107, 107, 110, 110, 110, 113, 140).

Robin, N., F. Levoy, and O. Monfort (2009). Short term morphodynamics of an intertidal bar on megatidal ebb delta. *Marine Geology 260*(1-4), 102–120. (p. 8).

Robin, N., F. Levoy, O. Monfort, and E. Anthony (2009). Short-term to decadal-scale onshore bar migration and shoreline changes in the vicinity of a megatidal ebb delta. *Journal of Geophysical Research 114*(F4). (pp. 15, 51, 107).

Roelvink, D., A. Reniers, A. van Dongeren, J. van Thiel de Vries, R. McCall, and J. Lescinski (2009). Modelling storm impacts on beaches, dunes and barrier islands. *Coastal Engineering 56*(11-12), 1133–1152. (p. 58, 58, 58, 58, 58).

Roos, P. C., H. M. Schuttelaars, and R. L. Brouwer (2013). Observations of barrier island length explained using an exploratory morphodynamic model. *Geophysical Research Letters 40*(16), 4338–4343. (p. 2).

Ruessink, B. and A. Kroon (1994). The behaviour of a multiple bar system in the nearshore zone of terschelling, the netherlands: 1965–1993. *Marine Geology 121*(3), 187 – 197. (p. 110).

Ruessink, B. G. and M. C. J. L. Jeuken (2002). Dunefoot dynamics along the dutch coast. *Earth Surface Processes and Landforms 27*(10), 1043–1056. (pp. 51, 100, 100, 108, 112, 131, 139).

Sallenger, A. H. (2000). Storm Impact Scale for Barrier Islands. *Journal of Coastal Research 16*(3), 890–895. (pp. 13, 138).

Shao, Y. (2008). *Physics and Modelling of Wind Erosion (Atmospheric and Oceanographic Sciences Library)*. Springer. (pp. 9, 10).

Sherman, D. J. and B. O. Bauer (1993). Dynamics of beach-dune systems. *Progress in Physical Geography 17*(4), 413–447. (pp. 1, 9, 50, 78).

Sherwood, C. R., J. W. Long, P. J. Dickhudt, P. S. Dalyander, D. M. Thompson, and N. G. Plant (2014). Inundation of a barrier island (chandeleur islands, louisiana, USA) during a hurricane: Observed water-level gradients and modeled seaward sand transport. *Journal of Geophysical Research: Earth Surface 119*(7), 1498–1515. (p. 138).

Short, A. D. and P. A. Hesp (1982). Wave, beach and dune interactions in southeastern australia. *Marine Geology 48*, 259–284. (pp. 2, 11, 50, 137, 139).

Short, A. D. and D. W. D. Jackson (2013). Beach Morphodynamics. In *Treatise on Geomorphology*, Volume 10, pp. 106–129. (p. 1).

Siegle, E. and N. E. Asp (2007). Wave refraction and longshore transport patterns along the southern Santa Catarina coast. *Brazilian Journal of Oceanography 55*(2), 109–120. (p. 106).

Siegle, E., D. a. Huntley, and M. a. Davidson (2004). Physical controls on the dynamics of inlet sandbar systems. *Ocean Dynamics 54*(3-4), 360–373. (pp. 106, 107, 140).

Silva, F. G., P. H. G. de Oliveira Sousa, and E. Siegle (2016). Longshore transport gradients and erosion processes along the Ilha Comprida (Brazil) beach system. *Ocean Dynamics*, 1–13. (p. 106).

Silva, F. G., K. M. Wijnberg, A. V. de Groot, and S. J. Hulscher (2019). The effects of beach width variability on coastal dune development at decadal scales. *Geomorphology 329*, 58–69. (pp. 50, 108, 112).

Silva, F. G., K. M. Wijnberg, A. V. de Groot, and S. J. M. H. Hulscher (2018). The influence of groundwater depth on coastal dune development at sand flats close to inlets. *Ocean Dynamics*. (pp. 50, 52, 52, 81, 109, 113, 113, 116, 146).

Silva, F. G., K. M. Wijnberg, and S. J. H. M. Hulscher (2016). The role of water level in aeolian dune development near inlets. In *18th Physics of Estuaries and Coastal Seas Conference, PECS 2016. Delft University*. (pp. 109, 137).

Smith, R. (1991). The application of cellular automata to the erosion of landforms. *Earth Surface Processes and Landforms 16*(3), 273–281. (p. 19).

Splinter, K. D., E. T. Kearney, and I. L. Turner (2018). Drivers of alongshore variable dune erosion during a storm event: Observations and modelling. *Coastal Engineering 131*, 31–41. (p. 14).

Stewart, C. J. and R. G. Davidson-Arnott (1988). Morphology, formation and migration of longshore sandwaves; long point, lake erie, canada. *Marine Geology 81*(1), 63 – 77. (pp. 79, 108).

Stive, M., M. De Schipper, A. Luijendijk, S. Aarninkhof, C. Van Gelder-Maas, J. Van Thiel De Vries, S. De Vries, M. Henriquez, S. Marx, and R. Ranasinghe (2013). A new alternative to saving our beaches from sea-level rise: The sand engine. *Journal of Coastal Research 29*(5), 1001–1008. cited By 82. (p. 3).

Stive, M. J., S. G. Aarninkhof, L. Hamm, H. Hanson, M. Larson, K. M. Wijnberg, R. J. Nicholls, and M. Capobianco (2002). Variability of shore and shoreline evolution. *Coastal Engineering 47*(2), 211 – 235. Shore Nourishment in Europe. (p. 79).

Stockdon, H. F., R. a. Holman, P. a. Howd, and A. H. Sallenger (2006). Empirical parameterization of setup, swash, and runup. *Coastal Engineering 53*(7), 573–588. (pp. 30, 82).

Stutz, M. L. and O. H. Pilkey (2011). Open-Ocean Barrier Islands: Global Influence of Climatic, Oceanographic, and Depositional Settings. *Journal of Coastal Research 27*(2), 207–222. (p. 14).

Swift, D. J. P. (1978). *Coastal Sedimentation*. Van Nostrand Reinhold. (p. 137).

Thevenot, M. M. and N. C. Kraus (1995). Longshore sand waves at southampton beach, new york: observation and numerical simulation of their movement. *Marine Geology 126*(1-4), 249–269. (p. 114).

Turner, I. L., B. P. Coates, and R. Acworth (1997). Tides, waves and the super-elevation of groundwater at the coast. *Journal of Coastal Research 13*(1), 46–60. (p. 25).

van der Nat, A., P. Vellinga, R. Leemans, and E. van Slobbe (2016). Ranking coastal flood protection designs from engineered to nature-based. *Ecological Engineering 87*, 80 – 90. (p. 3).

Van der Putten, W. H., C. Van Dijk, and B. A. M. Peters (1993). Plant-specific soil-borne diseases contribute to succession in foredune vegetation. *Nature 362*. (p. 13).

van Heteren, S., A. P. Oost, A. J. F. van der Spek, and E. P. L. Elias (2006). Island-terminus evolution related to changing ebb-tidal-delta configuration: Texel, The Netherlands. *Marine Geology 235*(1-4), 19–33. (pp. 8, 15, 24, 24, 51, 145).

van Puijenbroek, M. E., J. Limpens, A. V. de Groot, M. J. Riksen, M. Gleichman, P. A. Slim, H. F. van Dobben, and F. Berendse (2017). Embryo dune development drivers: Beach morphology, growing season precipitation, and storms. *Earth Surface Processes and Landforms 4144*. (pp. 13, 13, 24, 50, 50, 78).

Vellinga, P. (1982). Beach and dune erosion during storm surges. *Coastal Engineering 6*(4), 361 – 387. (p. 3).

Vet, P. D. (2014). Modelling sediment transport and morphology during overwash and breaching events. Master thesis, Delft University of Technology, Delft. (p. 58).

Vila-Concejo, a., Ó. Ferreira, a. Matias, and J. M. a. Dias (2003). The first two years of an inlet: Sedimentary dynamics. *Continental Shelf Research 23*(14-15), 1425–1445. (p. 140).

Werner, B. T. (1995). Eolian dunes: Computer simulations and attractor interpretation. *Geology 23*(12), 1107. (pp. 20, 27).

Werner, B. T. and T. M. Fink (1993). Beach cusps as self-organized patterns. *Science 260*. (p. 19).

Wijnberg, K. M. (2002). Marine Environmental controls on decadalmorphologic the Holland coast. *Marine Geology 27*. (p. 79).

Wijnberg, K. M., A. J. van der Spek, F. G. Silva, E. Elias, M. van der Wegen, and J. H. Slinger (2017). Connecting subtidal and subaerial sand transport pathways in the Texel inlet system. In *Coastal Dynamics Proceedings*, Number 235, pp. 323–332. (pp. 45, 51, 73, 73, 109).

Wright, L. and A. Short (1984). Morphodynamic variability of surf zones and beaches: A synthesis. *Marine Geology 56*(1-4), 93–118. (pp. 1, 11).

Yang, Y. and R. G. D. Davidson-Arnott (2005). Rapid Measurement of Surface Moisture Content on a Beach. *Journal of Coastal Research 21*(3), 447–452. (p. 25, 25).

Zarnetske, P. L., P. Ruggiero, E. W. Seabloom, and S. D. Hacker (2015). Coastal foredune evolution : the relative influence of vegetation and sand supply in the US Pacific Northwest. *Journal of the Royal Society Interface 12*. (pp. 13, 14, 24, 45, 134).

Zhang, D., C. Narteau, and O. Rozier (2010). Morphodynamics of barchan and transverse dunes using a cellular automaton model. *Journal of Geophysical Research: Earth Surface 115*(3), 1–16. (p. 20).

Zhang, W., R. Schneider, J. Kolb, T. Teichmann, J. Dudzinska-Nowak, J. Harff, and T. J. Hanebuth (2015). Land–sea interaction and morphogenesis of coastal foredunes — a modeling case study from the southern baltic sea coast. *Coastal Engineering 99*, 148–166. (pp. 20, 79, 83, 146).

Zhang, Z. and J. C. Moore (2015). Empirical orthogonal functions. In *Mathematical and Physical Fundamentals of Climate Change*, pp. 161–197. Elsevier. (p. 112).

Zhou, P., G. Li, Y. Lu, and M. Li (2013). Numerical modeling of the effects of beach slope on water-table fluctuation in the unconfined aquifer of Donghai Island, China. *Hydrogeology Journal* (19), 383–396. (p. 25).

# About the author

Filipe Galiforni Silva was born and raised in Suzano, São Paulo (Brazil) on August 25, 1989. In 2008, he moved to the city of São Paulo to start his BSc studies in Oceanography at the University of São Paulo. He developed an early passion for science, which lead him to a continuous undergraduate research internship from 2009 until 2012. In 2013, he started his Master studies at the same institution, advised by Dr Eduardo Siegle. His research was focused on beach morphodynamics along the beach-dune system of an exposed barrier island. The period at the University of São Paulo was rich in terms of scientific and professional experiences. He had the opportunity of conducting several field surveys in coastal environments and being part of a research crew in a vessel for measurements in deep-sea environments.

Doing a PhD was a natural choice. He decided to take up the challenge and do his PhD abroad, with the idea of pursuing cultural experience and broadening his network. In November 2014, he moved to the Netherlands to start his PhD at the University of Twente, within the CoCoChannel project (NWO). During his PhD, he focused on beach-dune systems near inlets, working closely with his advisors and colleagues. Furthermore, he was involved in an internal grant to pursue internal collaborations with potential partners abroad.

Personal hobbies include drumming and music, sports and, of course, food.

## Peer-reviewed journal papers

- **Galiforni Silva, F.**; Wijnberg, K. M. ; Groot, A. V. ; Hulscher, S. J. H. M. (2019). The effects of beach variability on coastal dune development at decadal scales. Geomorphology. v. 329, p. 58-69.
- **Galiforni Silva, F.**; Wijnberg, K. M. ; Groot, A. V. ; Hulscher, S. J. H. M. (2018). The influence of groundwater depth on coastal dune development at sand flats close to inlets. Ocean Dynamics. v. 1, p. 1-13.
- **Galiforni Silva, F.**; Sousa, P. H. G. O. ; Siegle, E. (2016) Longshore transport gradients and erosion processes along the Ilha Comprida (Brazil) beach system. Ocean Dynamics (Print), v. 66, p. 853-865
- **Galiforni Silva, F.**; Wijnberg, K. M.; Hulscher, S. J. H. M.. (2019). Storm-induced sediment supply to coastal dunes on sand flats. Earth Surf. Dynam. Discuss., https://doi.org/10.5194/esurf-2019-6, in review.
- **Galiforni Silva, F.**; Wijnberg, K. M.; Hulscher, S. J. H. M. (Subm.). The effects of shoal attachment on coastal dune development: case study in Terschelling (NL).

## Conference papers and abstracts

- **Galiforni Silva, F.**; Wijnberg, K. M. ; Hulscher, S. J. H. M. (2019) Modelling the effects of storm surges on sand flats: case study in Texel (NL). In: NCK Days, 2019, Enkhuizen. Book of Abstracts - NCK Days 2019.
- **Galiforni Silva, F.**; Wijnberg, K. M. ; Groot, A. V. ; Hulscher, S. J. H. M. (2018) Analyzing the effect of beach width changes on coastal dune development using a Cellular automata model. In: 10th International Conference on Aeolian Research - ICAR X, 2018, Bordeaux. Book of Abstracts of the 10th International Conference on Aeolian Research.
- Wijnberg, K. M. ; Van Der Spek, A.; **Galiforni Silva, F.**; Elias, E. ; Van Der Wegen, M. ; Slinger, J. H. (2017) Connecting subtidal and subaerial sand transport pathways in the Texel inlet system. In: Coastal Dynamics, 2017, Helsingør. Proceedings of Coastal Dynamics 2017. v. 1. p. 323-332.
- **Galiforni Silva, F.**; Wijnberg, K. M. ; Groot, A. V. ; Hulscher, S. J. H. M. (2017) On the importance of tidal inlet processes for coastal dune development. In: Coastal Dynamics, 2017, Helsingør. Proceedings of Coastal Dynamics 2017. v. 1. p. 1131-1141.
- **Galiforni Silva, F.**; Wijnberg, K. M. ; Hulscher, S. J. H. M. (2017) Observation of storm surge flooding on dune topography in inlets. In: NCK Days, 2017, Den Helder. Book of Abstracts - NCK Days 2017.

- Groot, A. V. ; De Vries, S. ; Arens, B. ; Bodde, W. ; De Winter, W. ; Donker, J. ; Duarte-Campos, L.; **Galiforni Silva, F.**; Goessen, P. ; Hage, P. ; Hoonhout, B. ; Keijsers, J. ; Montreuil, A. ; Mulder, J. ; Nolet, C. ; Rauwoens, P. ; Riksen, M. ; Ruessink, G. ; Smit, M. ; Smit, Y. ; Strypsteen, G. ; Van Der Valk, B. ; Van Puijenbroek, M. ; Wijnberg, K. M. ; Williams, I. (2017) State of the art of aeolian and dune research on the Dutch and Belgian coast. In: NCK Days, 2017, Den Helder. Book or Abstracts - NCK Days 2017.
- **Galiforni Silva, F.**; Wijnberg, K. M. ; Hulscher, S. J. H. M. (2016) Dune systems near inlets: A first insight. In: NCK Days - 2016, 2016, Ouddorp. Book of abstracts - NCK Days 2016. v. 1. p. 60-60.
- **Galiforni Silva, F.**; Wijnberg, K. M. ; Hulscher, S. J. H. M. (2016) The role of water level in aeolian dune development near inlets. In: 18th PECS - Physics of Estuaries and Coastal Seas Conference, 2016, Scheveningen (NL). 18th PECS - Physics of Estuaries and Coastal Seas Conference.
- Sousa, P. H. G. O.; **Galiforni Silva, F.** ; Paula, D. P. (2016) Wave climate influence on severe coastal erosion of Icaraí Beach (CE) Brazil. In: ECSA 56 Coastal systems in transition: From a 'natural' to an 'anthropogenically-modified' state, 2016, Bremen. ECSA 56 Coastal systems in transition: From a 'natural' to an 'anthropogenically-modified' state.
- Sousa, P. H. G. O.; **Galiforni Silva, F.**; Aragon, C. C. ; Siegle, E. (2016) Morphodynamic instability and erosive processes at a barrier island: Ilha Comprida, Brazil. In: ECSA 56 Coastal systems in transition: From a 'natural' to an 'anthropogenically-modified' state, 2016, Bremen. ECSA 56 Coastal systems in transition: From a 'natural' to an 'anthropogenically-modified' state.
- **Galiforni Silva, F.**; Sousa, P. H. G. O. ; Siegle, E. (2015) Space-time beach variability in an exposed barrier island: the case of Ilha Comprida (SP), Brazil.. In: NCK Days - 2015, 2015, Camperduin - NL. NCK Days 2015 - Book of Abstracts.
- **Galiforni Silva, F.**; Sousa, P. H. G. O. ; Siegle, E. (2014) Wave climate analysis and its relation with erosion processes along the beach system of Ilha Comprida (SP), Brazil.. In: 17th PECS - Physics of Estuaries and Coastal Seas, 2014, Porto de Galinhas, PE. Proceedings of the 17th Physics of Estuaries and Coastal Seas (PECS) conference. v. 1. p. 1-3.
- **Galiforni Silva, F.**; Sousa P. H. G. O.; Siegle, E. ; Tessler, M. G. (2013) Efeitos de sistemas frontais nas características morfo-sedimentares de um trecho de praia em Ilha Comprida - SP. In: XIV Congresso da Associação Brasileira de estudos do Quaternário, 2013, Natal. XIV Congresso da Associação Brasileira de Estudos do Quaternário.
- Sousa P. H. G. O.; **Galiforni Silva, F.**; Aragon, C. C. ; Andrade, T. S. ; Siegle, E. (2013) Mapeamento da erosão costeira na Ilha Comprida (SP). In: XIV Congresso da Associação Brasileira de estudos do Quaternário, 2013, Natal. XIV Congresso da Associação Brasileira de Estudos do Quaternário.

- Sousa P. H. G. O.; **Galiforni Silva, F.**; Aragon, C. C.; Siegle, E. (2013) Ocupação e riscos associados na Ilha Comprida, SP. In: XXV Semana Nacional de Oceanografia, 2013, São Paulo. XXV Semana Nacional de Oceanografia.
- **Galiforni Silva, F.**; Tessler, M. G. ; Rodrigues, M. (2012) Análise do padrão de incidência de ondas na região centro-sul da Ilha Comprida por modelagem numérica. In: 20º Simpósio Internacional de Iniciação Científica, 2012, São Paulo. 20° Simpósio de Iniciação Científica.
- **Galiforni Silva, F.**; Rodrigues, M. ; Tessler, M. G. (2012) Caracterização Hidrodinâmica da região centro-sul da Ilha Comprida por modelagem numérica. In: 20º Simpósio Internacional de Iniciação Científica, 2012, São Paulo. 20º Simpósio Internacional de Iniciação Científica.

## Book chapters

- Mahiques, M. M.; Siegle, Eduardo; Carrio, J. A.; **Galiforni Silva, F.**; Sousa, P. H. G. O.; Martins, C. C. (2016) The beaches of the State of São Paulo. In: Andrew D. Short; Antonio H. F. Klein. (Org.). Brazilian Beach Systems. 1ed.: Springer International Publishing, v. 17, p. 397-418.

Coastal dunes, tidal inlets, and beaches are among the most dynamic environments in geomorphology due to the influence of different energetic processes such as waves, wind, and currents over a relatively small area. If close to inlets, beach-dune systems may be affected by specific inlet processes that change beach characteristics and, consequently, coastal dunes. However, it is still unknown how and to what extent inlet-induced shoreline changes affect dune development. The objective of this thesis is to understand how inlet-driven changes in adjacent coastlines affect dune development considering long-term inlet-driven changes (e.g. sand flats) and short-term inlet-driven changes (e.g. shoreline variability).