ALONGSHORE VARIATIONS IN FOREDUNE DEVELOPMENT

4 DECEMBER 2018

Jorick Joël Cornelis van der Heijden
MSc Thesis
6010067
Version: Final 1

Cover pictures: Aeolian processes and foredune dynamics at Rockanje (J.J.C. van der Heijden, 2017) and The Dutch Holland Coast south of Egmond aan Zee (J.J.C. van der Heijden, 2017)

MSc Thesis

In partial fulfillment of the requirements for the degree of
Master of Science in Earth Sciences
At Utrecht University

By J.J.C. van der Heijden

First supervisor: Dr. J.J.A. Donker
Second supervisor: Dr. T.D. Price
Utrecht University, Department of Physical Geography
MSc Program: Earth, Surface and Water

Utrecht University

Preface

It is been a privilege to write my thesis as, part of my MSc study Earth Surface and Water (Physical Geography, Utrecht University) on a topic that is very close to my heart. Writing an MSc thesis is a once in a lifetime experience.

I am especially grateful for the supervision of Dr. Jasper Donker during my research. His expert insights, knowledge and patience (it's been a long ride) helped me a lot. Dr. Timothy Price is thanked, for acting as an expert second supervisor from Utrecht University.

Finally, I want to thank all the people I discussed my thesis with. Especially mentioning my good friends Hua Zhi Li and Job for being always able to discuss/criticize some topics of my research. One afternoon of working on my thesis at my grandparents' house I especially recall, which was also a turning point in my thesis. I want to thank them for this. A last word is to my parents, who always gave me the opportunity to do my studies. The rest, encouragements and stability they give in my life is irreplaceable.

Jorick van der Heijden, December 2018

Abstract

The Dutch Holland Coast is an important protection to the sea. Along the Dutch Holland Coast, high and steep dunes act as a primary defense against flooding the hinterland. Dunes are accretionary landforms and show much variation as a result of wind, waves, fetch length and nearshore bathymetry. In order to get a better understanding alongshore variations in foredune development, the present study aims to identify the factors that control alongshore variations in foredune development.

The alongshore variations in foredune development along the Dutch North Holland Coast (DNHC) are studied between 2007 and 2016, using the coastal LiDAR dataset. The dataset consists of 3-D point clouds which are processed and computed into 1x1 m Digital Elevation Models (DEM's). These DEMs are used to calculate for each cross shore transect the foredune volume(*V*), foredune volume change(*ΔV*) and dune elevation(*Z*). The data is used to calculate volumetric changes in m^3/m. As a first step we focus on landscape scale along-shore variations (20-100 km). Next, we investigate regional (1 km – 10 km) variations from the landscape scale. Finally, we investigate local (100 -500 m) differences from the regional trends and investigate possible causes.

The following research question is answered: ***What causes the alongshore variation in foredune (volume) development along the Dutch Holland Coast?***

The study shows high variability in alongshore foredune development of (*ΔV*) on all scale-levels (landscape, regional and local). On landscape scale the overall ΔV is +9,4 m^3/m/year, on regional scale +10,5 m^3/m/year and ranging from around -1 m^3/m/year (blowouts) to +11,2 m^3/m/year (constructions on the beach). The most pronounced variation at landscape scale is found between the regions of Castricum aan Zee-Camperduin, the Hondsbossche Dunes and the Kop van Noord-Holland, with *ΔV* raging from approximately +8 m^3/m/year to +10 m^3/m/year. On regional scale the most pronounced variation on foredune development is caused by the presence of coastal towns and more natural areas. The differences in coastal zone management contribute here to an average development of *ΔV* at coastal towns and developed sections of +11,3 m^3/m/year and +10,1 m^3/m/year at more natural sections. Features that cause variations in the present study on local scale are blowouts and constructions on the beach. Blowouts show a clear effect on volume development prior to and after the blowout, with an averaged value of +8.1 m^3/m/year and +4.2 m^3/m/year after the blowout. At the blowout itself, negative values are observed (-0,9 m^3/m/year). Volumetric development at constructions on the beach roughly coincides with the general alongshore trend.

When linking foredune volume development to metrological conditions, major storms such as the Sinterklaasstorm (2013-2014) do have a considerable effect on foredune volume development, but the safety boundary level is always maintained. Following these storms, more natural areas show a much quicker recovery rate although being also the most affected by erosion. Blowouts respond to storms, especially high-water levels. The present study gives a confirmation of the usability of the LiDAR dataset (part of the JARKUS dataset) and the possibilities of mapping alongshore erosion and accretion in foredune behavior along the Dutch Holland Coast on landscape-scale and on regional-scale. At local-scale the time interval of measurements is too long to analyze small and very local variation. The study highlights and acknowledges the general consensus on dynamic foredune management strategies and their effects. Furthermore, insights are gained in the alongshore development of blowouts and how they affect alongshore foredune volume development, but only crude regularities are estimated. Not many studies have been conducted addressing the alongshore development of blowouts, instead studies have focused on all the dynamics *inside* blowouts. The insights that are gained are rudimental but could be used to learn more lessons about natural forcing properties on foredune volumes.

Table of contents

1. Introduction

1.1 Introduction of the study

Coastal geomorphology, such as the Dutch North Holland Coast, is often characterized by elongated shore parallel sedimentary forms including longshore bars, beaches, beach ridges and foredunes, e.g. *(Hesp, 2002)*. The coast is never the same; the morphodynamics and longer-term evolution of wave-dominated coasts, are shaped and reshaped constantly by erosion and accretion. The bar-beach-dune system is a highly dynamic environment, where wave- and aeolian processes are acting at a range of spatial and temporal scales, resulting into spatial variations in alongshore foredune development e.g. *(Hesp, 2002; Davidson-Arnott, 2011; Keijsers, 2015)*. The position of the coastline and the width of the near-shore zone impact the safety of the Dutch low-lying hinterland.
Dune building takes place when sand is blown from the beach in to the (for)dune zone, where sand is trapped by vegetation like Marram grass (*Amophila aernaria*) (Hesp, 2002). The reinforcing feedback between sand trapping and plant growth enables rapid dune building (i.e. foredune accretion). The input of sediment from the beach depends on the availability of sand (supply limited) and the prevailing wind climate and fetch length *(Van der Wal, 1998)*. Figure 1.1 shows a beach-dune system with position of the high-water line, dune foot and the typical cross-shore zones.
Yet some feedback mechanisms and interactions of the processes contributing to dune building and erosion, which may cause alongshore variation of foredune development in the beach-dune system are still less understood.
The figure is adapted from *(Masselink & Van Heteren, 2014; Keijsers, 2015)*.

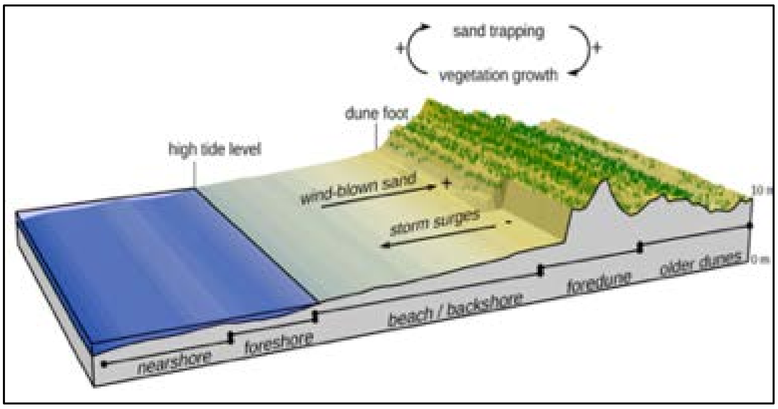

Figure 1.1; Beach-dune system after (Masselink & Van Heteren, 2014)

Coastal dune management along extensively developed coasts has traditionally focused on the suppression of the natural geo-morphodynamics of the coastal (fore)dunes to improve its role in flood defence *(Ruessink, et al., 2017)*.
Anthropogenic interventions can affect the availability and quality of erodible material (i.e. sand nourishments, groynes and hydraulic structures; affect local aeolian sediment transport (i.e. planting or removing of vegetation); and measures that have direct local effect on the topography of the beach of the foredune (i.e. mechanical construction of reconstruction of dunes). These interventions may disrupt natural patterns in beach-dune dynamics and may affect further alongshore foredune development.
From 2006 the annual coastal survey of the Netherlands (JARKUS) of the 'dry' part of a coastal transect (i.e. the beach and the dunes) is made by using modern mapping tools such as LiDAR (Light Detecting and Ranging) laser altimetry scanning measurements. LiDAR-bases Digital Elevation Models (DEMS) have been widely used for quantification of beach and dune volume changes *(Overton, et al., 2006; Mitasova, et al., 2010)*. The data is currently only used to extract larger scale profile information, while the use of the LiDAR data may also improve prediction and geospatial analysis on much smaller scale changes, patterns and dynamics in the beach-dune system. In order to gain and provide more information regarding some of the yet understudied processes/properties, the objective of this study is to get a better understanding in the properties that control the alongshore variations in foredune volume development (in terms of dune volume, dune volume changes and dune elevation) while using modern mapping tools for geospatial analysis in the form of LiDAR data.

1.1 Outline

The study is structured as follows: first, in chapter 2, the beach-dune system, aeolian processes foredune dynamics and coastal zone management are discussed based on a literature study. Chapter 3 describes the research aims and chapter 4 elaborates on the methods that are used to extract the results, which contribute to accomplish the research aims. The results can be found in chapter 5 and are together with the method discussed in chapter 6. Finally, the main conclusions are drawn based on the main results and discussion and are included in chapter

2. Literature background

This chapter will focus on the morphology and dynamics of the beach-dune system. First the general setting of the beach-dune system will be addressed, as it is a complex and far form completely understood system, this includes the multiple adjacent scales (both spatial and in time) in the beach-dune system. Secondly, the most profound foredune dynamics will be discussed. Thirdly, the (Dutch) coastal zone management will be described and linked to foredune dynamics. Finally, the coastal morphological dataset (in the form of the LiDAR dataset) will be discussed. In chapter three, based on the gaps in the current knowledge and understanding of the beach-dune system, the aims of this study will be described.

2.1 Beach-Dune System

When looking at beach-dune systems independently; a great deal of research has addressed coastal change from the perspective of understanding the linkages between hydrodynamic forcing properties and aerodynamic forcing properties (i.e. incident waves, secondary waves longshore currents, tidal currents and wind fields) and the sedimentary response (i.e. erosion and deposition) of the geomorphic system *(Sherman & Bauer, 1993)*. This view however puts the focus on short-term processes and has often embraced the position that landforms are passive elements in the relationship and that sediment processes are governed by the character of (1) hydrodynamic processes in the nearshore and (2) aerodynamic processes across the beach and the dunes. Hence, wave and currents acting within the surf zone control the lay out of the nearshore and the foreshore, which influences aeolian processes on the beach, which in turn influences the foredune. However, the wave-current dominated bar and beach and the wind-dominated dunes are together an integrated system with striking beach-dune interaction with strong coupling and mutually transformation. Sediment exchanges between bar, beach and dune environments are governed by complex feedback properties that impact the evolution of the integrated beach-dune system.

2.2 Supply from shore-face to the beach

Nearshore morphodynamics at the foreshore and back beach play several important roles in the overall dynamics of beach-dune systems, i.e. the effects of waves and currents *(Sherman & Bauer, 1993)*. In the last two decades, beach and aeolian systems have no longer been considered mutually independent systems *(Sherman & Bauer, 1993)*. A critical factor in foredune development is sediment supply from the shore face to the beach. At timescales of decades to centuries, the relative importance of sediment supply over transport potential increases *(Houser & Ellis, 2013)*. This sediment supply depends on (**1**) the welding and evolution of nearshore bars, (**2**) gradients in longshore transport, (**3**) sand waves and other nearshore processes such as (**4**) SPAWS and (**5**) nourishments:

(1) **Nearshore bars**: A study conducted by (*Agaard, et al., 2002)* showed that onshore sandbars migrate under high-energy storm surge conditions, with onshore sediment due to incident wave action as a major driver. Subsequent moderate wave energy events result in a dissection of the inner bar which is then driven further landward by onshore-directed mean currents associated with cell circulations. Eventually, sandbars can merge with the subaerial beach and the potential onshore sediment transport increases as new, dry sediment sources become available (after a while). In the case of the study by *(Agaard, et al., 2002)* it is showed that when evaluating long-term profile measurements (such as the Dutch Jarkus measurements) suggests that the whole

process of bar welding has supplied an amount of sand to the subaerial beach which approximately correspond to the annual sand deposition rate on the crest and lee of the foredunes. The processes of onshore-directed sediment supply are probably (at least in part), due to gentle shore face slopes *(Agaard, et al., 2002)*.

(2) **Gradients in longshore transport and alongshore currents:** alongshore currents control shoreline movements, leading to accretion or erosion. For instance, when looking at a system of barrier islands, the alongshore currents cause accretion at down drift end of the barrier islands and erosion on the up-drift end *(Keijsers, 2015)*. Sand exchange between nearshore and offshore determines the sand budget available for the coastline.

(3) **Alongshore sand waves:** High-angle waves from the dominant transport direction cause erosion of offshore located sand bars and beyond this inflection point high-angle waves deposit sediment *(Ashton & Murray, 2006)*.

Much of the deposition is spread by long-angle waves father down drift, i.e. towards the shore in the shape of a sand wave. These alongshore sand waves grow over time by merging; when one migrating feature overtakes another, the two features merge together, creating a larger shore bound sand wave which can merge with the beach and puts sediment into the beach-dune system *(Ashton & Murray, 2006)*.

(4) **SPAWS:** Recent observations have shown that along the Dutch Holland Coast (i.e. close to Egmond Aan Zee) subtidal crescentic bars may separate from the bar and migrate onshore as spatially coherent features, termed Shoreward Propagating Accretionary Waves (SPAWs). It is thought that this onshore migration of SPAWs plays a role in the sand exchange within the beach-dune system *(Price, et al., 2017)*

(5) **Nourishments:** Nourishments directly affect the dune volume changes as well as transport limiting factors *(De Vries, et al., 2012)*. See *section 2.8* for further details.

2.3 Aeolian processes and sediment transport

Aeolian transport provides the primary mechanism for sediment input to the coastal dune system *(Keijsers, et al., 2014)*. Coastal dune systems have been studied extensively, e.g. *(Sherman & Bauer, 1993; Van Dijk, Arens, & Van Boxel, 1999; Ruessink, et al., 2017)*, and there is a vast amount of literature that purely addresses the mechanics of sediment transport by wind dynamics, e.g. *(Nordstrom & Jackson, 1993)*. Overall there is a reasonably sound, conceptual understanding of aeolian transport processes under certain circumstances be claimed, especially over ideal surfaces. In basic terms; aeolian sediment transport starts when local wind exceeds a shear stress on the beach surface, exceeding that initiates the motion of sediments (Figure 2.1) (i.e. this occurs when wind velocity exceeds the sediment entrainment threshold, resulting in sediment being eroded from the beach and transported downwind), e.g. *(Nordstrom & Jackson, 1993; Sherman & Bauer, 1993; Keijsers, et al., 2014)*. The whole process of aeolian sediment transport is important for dune growth and the formation of new dunes. With suitable conditions for onshore directed aeolian sediment transport, sediment input into the dunes can be in the order of 10 to 100 m^3/m *(Delgado-Fernandez & Davidson-Arnott, 2010)*.

Figure 2.1; Sand blowing towards the dune (J.J.C. van der Heijden, 2017).

2.4 Supply from the beach to the dunes

The input of sediment from the beach to the dunes depends on the availability of sand (supply limited). On (natural) beaches, sediment transport is typically limited by various additional time varying effects. Whether the measured sediment input meets the potential depends on the presence of supply limiting factors, i.e. amongst others: moisture content, beach slope, lag deposits and beach width *(Davidson-Arnott, et al., 2008)*.

Moisture content: The results of *(Davidson-Arnott, et al., 2008)* show that where there is a considerable supply of dry sand (i.e. wet sand is more cohesive) the saltation system responds very rapidly to fluctuations in wind speed, i.e. to wind gusts. Where sand supply from the surface is limited by moisture, the mean transport rates are much lower, and this reflects in both a reduction in the instantaneous transport rate in a transport system that becomes increasingly intermittent *(Davidson-Arnott, et al., 2008)*

Beach slope: Beach slope or surface slope is another transport limiting process *(De Vries, et al., 2012)*. Several authors have investigated the effects of surface slope on sediment transport for aeolian applications e.g. *(Iversen & Rasmussen, 1994))*. On the process scale, the surface slope influences two parameters: (**1**) transport capacity and (**2**) threshold velocity needed for sediment motion.

Lag deposits: Van der Wall (1998) studied the characteristics of the sand on wide nourished beaches. At the study site (Ameland and Den Helder in particular), shell pavements developed after aeolian activity. The aeolian sand transport on the beach reduced, but the transport did not cease *(Van der Wal, 1998)*. A large variability in surface characteristics, probably enhances variation in aeolian sand transport over the beach *(Van der Wal, 1998)*.

Beach width - Fetch limited: Beach width (fetch limited) determines the maximum fetch length, which can be formulated as the distance downwind where transport takes place *(Keijsers, et al., 2014)*. The fetch effect states that longer fetch lengths lead to higher transport under given wind conditions until a certain limit is reached. This limit is the critical fetch length *(De Vries, et al., 2012)*. While winds are directly or obliquely onshore on a beach, the maximum available fetch distance is limited by the beach width. When the maximum available fetch is smaller than the critical fetch, aeolian sediment transport towards the dunes is limited due to beach width e.g. *(De Vries, et al., 2012; Keijsers, et al., 2014)*. Although the highest transport rates are expected during high wind velocities, these wind speeds are often accompanied by storm surges and wave run (Figure 2.2) (see sections about nearshore morphodynamics) that reduce the fetch length and increase moisture content of the beach surface and may even erode the foredune (Figure 2.2) *(Keijsers, et al., 2014)*. Consequently, most of the sediment input to the foredunes occurs during low- to medium-magnitude wind events *(Delgado-Fernandez & Davidson-Arnott, 2010)*.

In contrast to mentioned before, the location of the bars can also form a limiting factor, when the water between the bar and the beach becomes an obstacle for the sand that travels from the bar to the beach. This means that a wide beach can still be transport limited if it has bars that are not connected to the beach *(Hage, 2014)*. There can also be limited aeolian transport from the beach to the dunes when the bars and the beach are connected, because the area between the bars and the beach has a low elevation and has often a high soil moisture content *(Davidson-Arnott, et al., 2008; Hage, 2014)*.

Figure 2.2; Wave run-up, beach width, soil moisture and cliff erosion at Oostvoorne/Maasvlakte 2 (J.J.C. van der Heijden, 2017).

2.5 Foredunes

Foredunes are defined as shore-parallel dune ridges formed on the top of the backshore by aeolian sand deposition within vegetation such as marram grass (*Amophila aernaria*). Foredunes may range from relatively flat terraces to markedly convex ridges. Actively forming foredunes occupy a foremost dry and elevated part at the seaward position in a bar-beach dune system, however not all foremost dunes are foredunes. Other types of dunes may occupy a foremost position on eroding coasts or coasts where foredunes are unable to form *(Hesp, 2002)*. According to Hesp 2002: foredunes have been classified into a wide variety of types but tend to fall into two main types; incipient and established foredunes.

Figure 2.3; Incipient foredune south of Egmond (J.J.C. van der Heijden, 2017).

2.6 Foredune types and morphological development

Dune building takes place when sand is blown from the beach into the dune zone, where sand is trapped by vegetation like marram grass (Amophila aernaria) e.g. (*Hesp, 2002; Keijsers, 2015)*. The reinforcing feedback between sand trapping and plant growth enables rapid dune growth (i.e. foredune accretion).

Incipient foredunes: incipient foredunes or embryonic (Figure 2.3) dunes are new or developing foredunes forming within pioneer vegetation communities such as marram grass. Morphological development depends mainly on vegetation density, distribution, height and cover, wind velocity and rates of sand transport. Secondary factors such as the rate of occurrence of swash inundation, storm wave erosion, overwash incidence and wind direction also play an important role in determining subsequent foredune evolution *(Hesp, 2002)*.

Established foredunes: Established foredunes are developed from incipient foredunes and are commonly distinguished by the growth of intermediate plant species and by foredunes greater morphological complexity, height, width, age and geographical position *(Hesp, 2002)* and *(Keijsers, et al., 2014)*. The morphological development of established foredunes, depends on a number of factors including: (**1**) sand supply; (**2**) the degree of vegetation cover; (**3**) plant species present (a function of climate and biogeographical region); (**4**) the rate of aeolian sand accretion and erosion; (**5**) the frequency and magnitude of wave and wind forces; (**6**) the occurrence and magnitude of storm erosion, dune scarping, and overwash processes; (**7**) the medium to long-term beach or barrier state (stable, accreting or eroding); (**8**) sea/lake/estuary water level, and, increasingly (**9**), the extent of human impact and use (*Hesp, 2002)*.

2.7 Foredune dynamics

The development of coastal dunes is a result of erosive and accretive processes. In the Dutch case, nourishments and management interventions also influence the development of coastal dunes. The net result determines the dunes to be either in an erosive or accretive state *(De Vries, et al., 2012)*.

Erosion
Dune erosion (Figure 2.4) takes place when the water level exceeds the dune-foot level e.g. *(Sallenger, 2000; Van Rijn, 2007; Brodie & Spore, 2015)*. Wave battering during storm surges results in erosion of the lower parts of the seaward dune, the waves remove sand and undermine the slope, which may lead to instability, avalanching and eventually failure of the whole dune front. Depending on storm intensity, wave period and storm duration, dune erosion may amount to equivalents of several years of accretion *(Keijsers, et al., 2014)*. Local beach morphology (i.e. subtidal sandbanks, embryonic or incipient foredunes and beach volume) is postulated to be related to alongshore variability in foredune development.

Figure 2.4; Storm erosion at Oostvoorne/Maasvlakte 3 (J.J.C. van der Heijden, 2017).

Accretion
Section 4 describes that the reinforcing feedback between sand trapping and plant growth enables rapid dune growth (i.e. accreting dunes). Sand trapping is only possible when there is a large enough input of sand transported by aeolian transport to be trapped. The aeolian sediment transport also leads to sand loss to the landward side, i.e. towards the older dunes *(Keijsers, 2015)*. However, this should not be considered as a real sand loss, since the sand transported to the older dunes is less likely to be eroded during (severe) storm events. Still, the accretionary volumes are at least a magnitude lower than those associated with dune erosion by marine processes *(Keijsers, 2015)*. Depending on the balance between erosion and accretion, dune volume, morphology and topography change over time e.g. *(Houser & Ellis, 2013; Keijsers et al., 2014)*.

Foredune dynamics develop and interact on time scales from seconds to centuries, or in other words; on a micro (i.e. events), meso (i.e. cycles) and macro (i.e. trends) scales *(Houser & Ellis, 2013)*. The annual LiDAR measurements that are part of the JARKUS measurements (annual survey and mapping of the Dutch Coastal Zone) makes it difficult to analyze events that take place on a micro-scale. Micro-scale events tend to develop and sometimes disappear between seconds, hours or days and are not easy identified using annual surveys. Although major events, such as storm events, are believed to leave their mark on coastal development. As the year-by-year dynamic development of coastal foredunes, although being accretionary landforms, maybe me more due to temporal large-scale variations in erosion than to variations in natural accretion and by relatively small fluctuations in erosional behavior (i.e. caused by the erosive side of a sand wave) than as a result of variations in accretion *(Keijsers, 2015)*. Typically for the Dutch North Holland Coast one erosive storm can turn a year-by-year series of accretion into

Furthermore, several studies have been conducted, using the JARKUS dataset to identify cycles in foredune development on decadal timescales (with and without the use of laser altimetry) e.g. *(Pye & Blott, 2008; De Vries et al., 2012a; Keijsers, 2015)*. It is noticed that in most of the literature study regarding the time- and spatial scales, the addressed time-scales relate to coastal zone management and coastal engineering (i.e. meso scale). Hence, the extensive research of micro-scale processes such as for example: turbulence production and dissipations, entrainment and saltation of single sand particles and suspended sediment advection is acknowledged but not reviewed in this study

2.8 Blowouts

A blowout is a saucer-, cup-, or trough-shaped depression or hollow formed by wind erosion on a pre-existing sand deposit. The adjoining accumulation of sand, the depositional lobe, derived from the depression, and possibly other sources, is normally considered part of the blowout *(Carter et al., 1990; Hesp, 2002)*. Blowouts are common in coastal dune environments, particularly where beaches and foredunes are occasionally eroded and/or receding, but they also occur in stable and accretionary environments where wind and wave energy are high *(Hesp, 2002)*. In nature, there is a large degree of spatial and temporal variability in blowout morphology. The initial shape, size and location of blowouts and their subsequent development may depend on several factors e.g. *(Hesp, 2002)*: wave erosion; topographic acceleration of airflow over the dune crest; vegetation cover; high velocity wind erosion, sand inundation and burial; human activities (i.e. allowing carved foredune management). Initiation, presence or (forced) reactivation of blowouts can help to restore the natural dynamics of coastal dunes.

Spatial scales (size):
According to literature, e.g. *(Jungerius & Van der Meulen, 1989*) the size of a blowout can be very site-specific. typical widths of blowouts vary between 10 to 15 meters in cross-shore direction and typical lengths vary between 15 to 30 meters in alongshore direction.

Time scales:
Around active blowouts there is a range of different deposition rates, which are affected by the blowout. Depending on the size of the blowout: from up to 50 cm/year near the edge to some mm/year at distanced up to 100 meters from the blowout *(Van Boxel, et al., 1997)*.

2.9 Coastal Zone Management and its effects on foredune development

2.9.1 Dynamic Preservation policy

Sediment budget calculations, e.g. *(Beets et al., 1994; Beets & Van der Spek, 2000)*, reveal that since the last Ice Age, net sediment influx into the Dutch coastal zone gradually reduced and eventually ceased between 2500 and 2000 BP. The present natural sediment into the Dutch coastal zone is considered as negligible (Van der Meulen, et al., 2007; Keijsers, et al., 2014). A growing sediment demand is developing, since sea-level rise causes a larger accommodation space for sediments and the balance in the Dutch coastal zone between demand and supply of sediments is in deficit *(Pot, 2011; Keijsers, et al., 2014)*. The negative sediment balance along the Dutch coastal zone leads to a retreating coast e.g. *(Beets & Van der Spek, 2000)*. To counteract erosion the management of the Dutch Holland coast, has traditionally focused (before 1990) on the suppression of the natural geo-morphodynamics of the coastal (fore)dunes to improve its role in flood defence, resulting in more or the less fixed sand dykes by using *soft engineering* e.g. *(Ruessink, et al., 2017)*. The soft engineering approach involves i.e. the planting of Marram grass and the placement of sand fences to fixate and steer sediment between the sea and the foredune *(Arens, et al., 2001)* and has been implemented to encourage local sedimentation (aiming for accretion) in the beach-dune system. This intensive management strategy did not prevent an inland movement of the coastline. The Dutch government implemented in 1990 the Dynamic Preservation policy *(MinV&W, 1990)*. The Dynamic Preservation policy implies a soft engineering approach that counteracts the net sediment deficit by interfering with the sediment transfer process and through sand nourishments into the Dutch coastal zone. With the policy an operational goal was set: preservation of the reference coastline, the Basiskustlijn (BKL) *(Ruig & Hillen, 1997)*. The position of the momentary coastline (MKL) is annually compared with the BKL and nourishments are considered where the MKL is lower than the BKL. In 200 the policy was extended with a larger scale operational goal: preservation of the sand volume in the coastal zone, defined as the area between the 20-meter offshore depth contour (depth of closure) and the inner dune boundary *(Van Koningsveld & Mulder, 2004)*. Hence, the total average yearly sand nourishment volume was doubled *(MinV&W, 2000)*. The Dutch coastal management policy did evolve from a *hold-the-line* into a longer term orientated *maintain-the-system* approach.

Nourishments
Generally, three types of nourishments are applied along the Dutch coast *(Keijsers, et al., 2014)*:
(1) Dune reinforcements are placed directly on the dune face, thereby providing an immediate enhancement of dune volumes. Because the placed sand volumes can also be eroded, the net amount of dune erosion does not decrease as a result of a dune reinforcement. They are prone to quicker erosion because unconsolidated sediments tend to erode quicker *(Brodie & Spore, 2015)*. Safety levels do increase as the total amount of dune volume in the boundary profile increases.
(2) Beach nourishments provide further benefits to the foredunes to narrow, low dunes with narrow beaches. Through additional sediment input, i.e. widening of the beach provides a longer fetch length and increasing the elevation of the beach creates a larger volume of available sediment (fetch).
(3) Shore face nourishment are generally used in areas with wide, high dunes with the aim of increasing the beach and dune volume in the medium term since there is a time delay of years, approximately 8 years, between the onset of foreshore nourishment activities and noticeable changes in foredune morphology. This is because nourished sediments take time to accumulate and result in detectable changes in beach-dune system *(Bochev-Van der Burgh, et al., 2009)*. Sand is placed at a depth of 5-10 meters, corresponding to an existing offshore located sand bars *(Keijsers, et al., 2014)*. Apart from increasing the net sediment volume available in the nearshore (the on-shore sediment transport increases through

wave asymmetry and a decrease in longshore currents, shore face nourishments act as a wave filter, dampening the impact of larger waves *(Bochev-Van der Burgh, et al., 2009; Keijsers, et al., 2014)*.

In terms of maintaining the BKL, MKL and the overall safety level of the Dutch coast, nourishments are a success (Figure, 2.6)

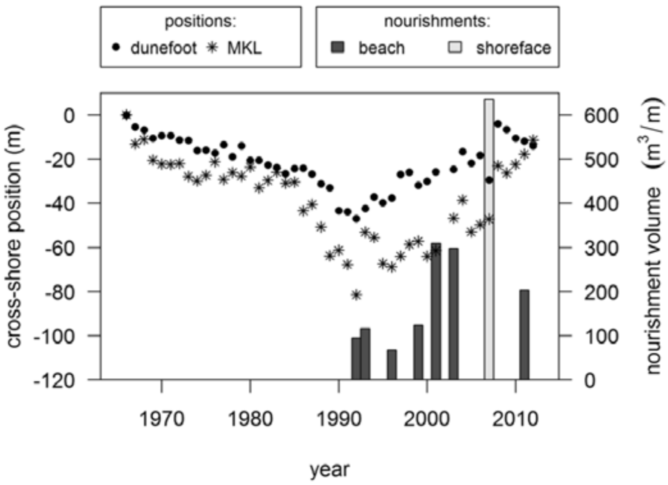

Figure 2.6; Effects of different nourishments types (the vertical bars) on MKL position and dune-foot position. The left axis shows the position of the MKL and dune-foot relative to their positions in 1966, where more negative values indicate more landward positions. The right axis shows the volume of the nourishment, after (Keijsers et al., 2014).

2.9.2 (Dynamic) Foredune Management strategies

With the success of the sand nourishment approach in stimulating the supply side of the sediment balance, the traditional soft engineering methods have been abandoned. Under this new dynamic dune management, dunes do not longer need to be reconstructed artificially after extensive storm damage *(Keijsers, et al., 2014)*. Dune recovery is purely left to natural processes governed by sediment supply, aeolian sediment transport and vegetation developments. The outcome of these processes is expressed in changes in dune volume and shape. According to De Jong et al. (2014) where supply is not limited, the dynamic dune management approach leads to comparable dune growth rates, as achieved by traditional soft engineering approaches *(Keijsers, et al., 2014)*.

Approximately 45.000 ha of coastal dunes in the Netherlands comprise multifunctional landscapes. With a hinterland situated below sea level, the importance of dune with respect to protection against marine flooding is obvious. According to the dynamic dune management strategy is for every part of the Dutch Holland Coast a certain strategy of dynamic dune management established. In the first place this management strategy focuses on the purpose of coastal protection against floods. The management of the Dutch Holland Coast is a combined effort of coastal managers, nature preservation organizations and municipalities, to enhance the multiple purposes and interest of the coast. This resulted in the following types of management *(HHNK, 2012)*:

- **Fixation of foredune volumes**: This strategy is used on areas where structural erosion creates susceptibility (i.e. flood risk) to a reduced safety level of the coastal defence. This strategy is also applied on areas where aeolian processes and aeolian sediment transport can hinder the other purposes and functions of the coast, i.e. recreation. In this management strategy, natural aeolian processes are not encouraged and sand is trapped and fixated by either (artificially planted) vegetation, sand fences and blow outs are filled directly when they emerge e.g. *(Hesp, 2002; Arens, et al., 2013)*. The strategy of fixating foredune volumes is applied to all the seaside towns in the study site, to protects coastal towns and boulevards. Between Petten and Julianadorp (North of the HPZ), this is the main management strategy. Typical spatial scales (i.e. alongshore length) adjacent to this foredune management strategy vary between ~ 20 kilometers (i.e. North of the HPZ) to < 2 kilometers at coastal towns and boulevards.

- **Carved:** This management strategy is applied where the safety level of the coastal defence is not negatively influenced by aeolian processes. With a carved management strategy, the natural aeolian processes are allowed within certain limits (the boundary profile needs to be maintained *(HHNK, 2009)*). For example, blowouts are not allowed to 'grow' to deep. When a blowout loses dune elevation, i.e. below +7.5m NAP, the blowout is evaluated and tested on impact on the safety level. When the safety level of the coastal cannot be maintained, the natural aeolian processes are partly suppressed with sand fences to trap and retain extra sediment.

- **Parabolic:** This management strategy is applied where the safety level of the coastal defence is not negatively influenced by aeolian processes and sometimes the safety level is increased by aeolian processes, i.e. mobile parabolic dunes that migrate landwards *(Arens, et al., 2013)*. Aeolian processes in the foredune are allowed and dynamics are encouraged. This strategy is usually applied in areas where the boundary profile is located far enough landward and no other purposes (i.e. recreation) of the coast are present. To enhance the "speed" in which the mobile dunes move and how "fast" they steer accretion in more landward located dune rows no sand fences and vegetation are artificially planted. The coastal management also aims to remove remnant roots *(Arens, et al., 2013)*. Along the Dutch North Holland Coast, the typical scales for alongshore stretches where parabolic foredune management is applied vary between

As described above, the Dutch North Holland Coast has a variety of applied types of dynamic foredune management. There is no uniform scale (in alongshore direction) for any of these regions, but typical scales vary between 2-10 kilometers. For instance, regions where parabolic foredune management (more natural areas without the presence of coastal towns) is applied can be larger compared to regions where a fixation strategy is applied (i.e. at Egmond, Bergen etc.), which are in most cases limited to the following distribution: Constructions on the South – Boulevard/Development – Constructions on the North.

2.9.3 Constructions on the beach

The dunes and beaches of Dutch North Holland Coast form a region where coast, safety and nature recovery often compete with other types of interests. The coast forms an attractive economic and recreational area, and this has over the past few years resulted in constructions on the beach, for instance pavilions and beach-cabins near coastal towns *(Huisman, 2013)*. Most of these buildings are seasonal but some are exploited year-round and their placement is prescribed by a number of license rules with respect to their distance from the dune-foot, their surface area, the distance between buildings and their type of foundation, to prevent a possible negative impact on foredune development *(HHNK, 2009; Huisman, 2013)*.

On the one hand, constructions on the beach could form an obstruction to aeolian sediment transport, and their construction and provision might lead to the removal or reduction in sediment input, while on the other hand, the constructions could retain sand in and around their foundations. It is presumed that in the (near) future constructions on the beach are increasing, both in number and size *(Huisman, 2013)*. Typical numbers of constructions on the beach are in this study expressed as density (number of constructions per meter in alongshore direction) and surface area (m^2).

2.9 Scales

The complex beach-dune system can be studied on timescales varying from seconds to decades on to centuries and on spatial scales from meters to kilometers. *(De Vries, et al., 2012)*

Timescales
Foredune dynamics can be studied on time scales from seconds to centuries, or in other words; on a micro (i.e. events), meso (i.e. cycles) and macro (i.e. trends) scales *(Houser & Ellis, 2013)*.
Not all the time-scales are subject of this study. The annual LiDAR measurements that are part of the JARKUS measurements (annual survey and mapping of the Dutch Coastal Zone) makes it difficult to analyze events that take place on a micro-scale events. Micro-scale events tend to develop and sometimes disappear between seconds, hours or days and are not easy identified using annual surveys. Although major events, such as storm, are believed to leave their mark on coastal development. Furthermore, several studies have been conducted, using the JARKUS dataset to identify cycles in foredune development on decadal timescales (with and without the use of laser altimetry) e.g. *(Pye & Blott, 2008; De Vries et al., 2012a; Keijsers, 2015)*. It is noticed that in most of the literature study regarding the time- and spatial scales, the addressed time-scales relate to coastal zone management and coastal engineering (i.e. meso scale). Hence, the extensive research of micro-scale processes such as for example: turbulence production and dissipations, entrainment and saltation of single sand particles and suspended sediment advection is acknowledged but not reviewed in this study.

This study aims on discovering and/or unravelling patterns and possible in alongshore foredune development on an annual to decadal scale, therefore addressing meso- and macro timescales.

Spatial scales
In spatial terms, the coastal setting that is subject of this study includes the surfzone, back beach and especially the foredune. In which the surfzone is the region from the top of the foreshore (i.e. where the upper limit of swash motions

happens) out to and including the breaking zone. Because this study conducts research on the bar-beach-dune interactions, the offshore or shore face region is not included in the study. Also, hydrodynamic processes within the surf zone are considered to be the dominant forcing properties on overall beach configuration over the timescales considered. Hence, no significant sediment exchange between the shore face and surf zone is presumed *(Sherman & Bauer, 1993)*. The typical spatial scales adjacent to decadal-scale morphological variability is in the order of > two kilometers e.g. *(De Vries, et al., 2012)*. This study focusses on:

(1) **Landscape scale**: at this scale-level the focus is on three large sections of the complete study site along the Dutch North Holland Coast, with a typical scale-level between 20-100 km. These sections are defined as **Castricum-Camperduin**, **HPZ** and **North of the HPZ** (Figure 2.7).

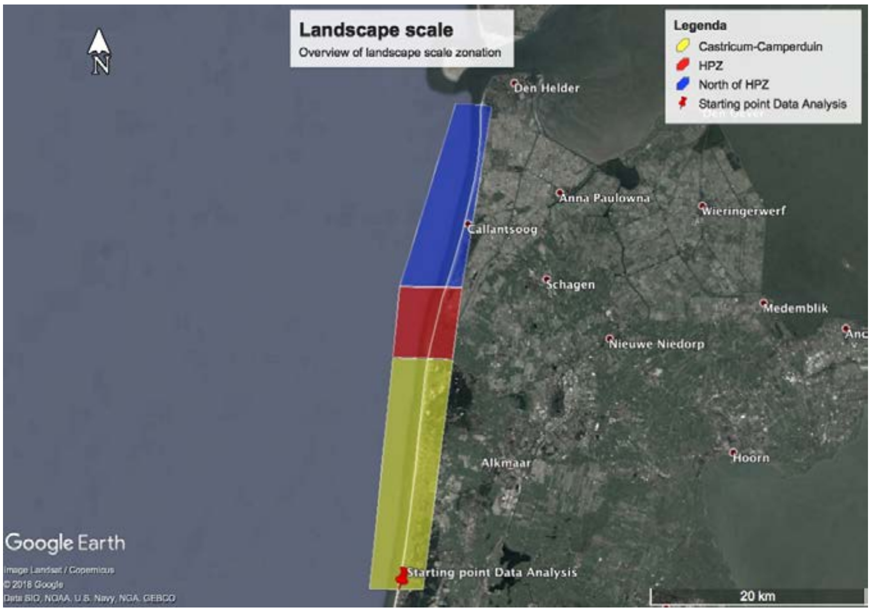

Figure 2.7; Study site, source: Google Earth

(2) **Regional scale**: at this scale-level the focus is on the alongshore variation in (ΔV) between coastal towns, regions with different foredune management strategies, hydraulic structures and

(3) **Local scale**: at this scale-level the focus is on the effects of alongshore of blowout development and beach pavilions and/or beach cabins.

Typical lengths for the regional scale-level are between 1 kilometer and 10 kilometers. The typical lengths for the local scale-level are between 0,10 kilometers and 2 kilometers. Due to the extensive development and usage of the Dutch North Holland Coast (recreation, coastal protection etc.) there is some overlap between the different scale-levels and their length-scales.

Spatial delimitations
Dune systems landwards of the foredune are sometimes included in this this study because there is in some cases process linkage to the beach. Although the dense vegetation cover on a managed foredune act as a barrier to the aeolian throughput of sand from the beach into the back dunes, alterations in coastal management projects increasingly intend to restore aeolian dynamics by reconnecting the beach-dune system with notches excavated through the foredune e.g. *(Ruessink, et al., 2017)*. Thus, presuming significant sediment exchange between foredunes, secondary dunes and even beyond, along certain parts of the Dutch Holland Coast.

Timescale vs spatial scale
The of modern mapping technology such as LiDAR measurements have been utilized before in studies addressing geospatial analysis in both short- and long-term evolutions in coastal topography, e.g. (Brodie & Spore, 2015; Mitasova, et al., 2010). However, there may not be an equilibrium between analyzing coastal topography on a small (i.e. local spatial scales) and the annual measurements, as small local trends may still be missed by the measurements.

3. Research aims

This chapter describes the knowledge gaps that became clear after the literature desk study and the filling, or at least the aim, of these knowledge gaps and understudied processes/properties. The complex beach-dune system remains a system with mechanisms and properties that are not completely understood.

On working on LiDAR data at regional and local scales in respect to alongshore foredune development

As already briefly mentioned before, the typical spatial scales adjacent to decadal-scale morphological variability is in the order of > two kilometers. The typical spatial scales in these studies is in the order of > 2 kilometers with an inter-transect width of 200 to 250 meters (corresponding with the JARKUS transects) *(De Vries, et al., 2012)*. Several studies have been conducted using the JARKUS dataset to identify cycles in foredune development on decadal timescales *(Van der Wal, 2004; De Vries., 2012)*. The large spatial scales of the JARKUS approach makes it more likely that previous researches did not focus on smaller scale (regional or local) variabilities and possible smaller on (much) smaller spatial scales as well as repeating smaller-scale effects (for instance, closely located alongshore blowouts). The high density of LiDAR data points and annual frequency of coastal mapping provides time-series in elevation data that can be used for extraction of new information about spatial patterns of coastal dynamics *(Mitasova, et al., 2009)*. The data is currently only used to extract larger scale profile information according to the JARKUS transect definition (alongshore width of 200-250 meters), while the use of this data may also improve predictions and analysis on (much) smaller (*section 2.9*) scale changes, patterns and dynamics in the beach-dune system. This study aims on investigating whether there are alongshore patterns and/or trends in foredune development on smaller spatial-scales.

On anthropogenic and natural forcing properties in the beach-dune system
The Dutch Holland coast is strongly modified by anthropogenic interventions and alterations. Keijsers (2015) computed a filter to identify and eliminate outliers in calculations of dune-volume change that were caused by human activities. This study aims identify the effects of anthropogenic forcing properties on alongshore foredune development, beyond the well-known effect of beach-groynes, the effects of the IJmuiden harbour walls and nourishments, hence on scale-levels like regional and local. The effects of (dynamic) foredune management are never been examined/or not extensively described in respect to LiDAR data on regional and local scale-levels. Examples of this are whether the effects of the realization since 2015 Hondsbossche Dunes as an effect on foredune development and the influence of constructions on foredune development. Apart from a monitoring report from the Hoogeheemdraadschap Hollands Noorderkwartier *(Huisman, 2013)*, there is little known, apart from qualitative studies, about the influences of constructions on the beach on foredune development. Applying the LiDAR dataset might be a possibility to conduct an exploring study on the effects of anthropogenic forcing properties at smaller scale-levels, without time-expensive studies based on monitoring.

3.2 Research questions

In order to gain and provide more information regarding some of the yet understudied processes/properties as described in the sections above, the objective of this study is to get a better understanding in the properties that control the alongshore variations in foredune volume development (in terms of dune volume, dune volume changes and dune elevation). This may provide coastal managers and coastal engineers better insights and new adaptive strategies to maintain a robust and dynamic coastline to enhance safety.

The main research question that this MSc research aims to answer is:

What causes the alongshore variation in foredune (volume) development along the Dutch Holland Coast?

To answer the main research question, sub-questions are defined:

(1) *Which topographic variations in the alongshore foredune development can be identified using the LiDAR dataset?*
(2) *What are the direct and indirect effects of anthropogenic forcing properties on the alongshore evolution of coastal foredunes?*
(3) *Which natural properties control variations in alongshore foredune development?*

4. Methods

This chapter addressees the regional setting and the chosen methods to prepare, process and analyze the data.

4.1 Overall regional setting

The Dutch Coastal area stretches over 430 kilometers form the SSW to the NNE, being part of a far larger coastal stretch from the Nord-Pas-de-Calais region in Northern France to the tip of the Danish Coast. The Dutch Coast faces the semi-enclosed North Sea, a small part of the Atlantic Ocean on Europe's continental shelf. The Dutch Coastal landscapes that developed over the last centuries are divided into three regions and are classified ad the Waddenzee area, the Dutch Holland Coast (Figure 4.1) and the Southwestern Delta (Ruessink & Jeuken, 2002; Vos, 2015). This study focusses on the wave-dominated barrier coast of the Dutch North Holland Coast.

The Dutch North Holland Coast is a slightly curved coast (figure 4.1), running from approximately SSW-NNE over almost 55 kilometers with an almost interrupted foredune row without barrier islands and tidal inlets expect for de tidal inlet between the Kop van Noord-Holland and Texel *(Ruessink & Jeuken, 2002)*. The typical profile for the Dutch North Holland Coast is a multiple barred coast. The profile contains striking foredune rows with typical widths between 150 meters and a few kilometers. This coastal foredune row acts as a naturally occurring coastal defence against (extreme) marine processes (i.e. inundation caused by dune breaches). The position of the coastline, strength of the dunes and the width of the near-shore zone impact safety of the Dutch low-lying hinterland. In the mid-north of the Dutch Holland Coast, the Hondsbossche and Pettemer Sea Defence (in all its iterations) fulfils this defensive role against marine processes.
The wave-dominated Dutch North Holland coasts characterizes with high foredunes, possibly linked to the high energetic wave climate, with heights of approximately 25 meters above NAP. the average beach slope is fairly flat and approximately between 1:30 and 1:60, with a typical beach width of <100 meters during low tide, e.g. *(Keijsers, 2015; Smit et al, 2017)*. The beach slopes and beach widths can vary in longshore direction e.g. near Den Helder the influence of the channels of the Texel tidal inlet causes steeper beach slopes whereas near IJmuiden the beach and the near shore zone are (much) wider. The median grain (predominantly quartz sands) size of natural beach sediments along the Dutch North Holland Coast is about 200-300 µm *(Ruessink & Jeuken, 2002)*.

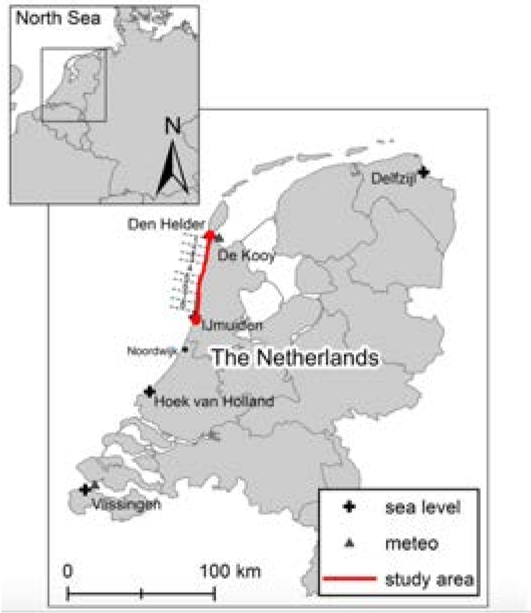

Figure 4.1; Study are, adapted from (Keijsers et al., 20215)

4.2 Motivation for (sub) sections

This section addresses the motivation for chosen zonation, i.e. the distribution of sub-sections.

4.2.1 Landscape scale

The landscape-scale is the largest scale-level analyzed on in this study. This means that the analysis on this scale-level aims on identifying larger trends over a period between 2007 and 2016 and at a spatial scale between 20-100 kilometers in alongshore direction. The whole coastal stretch between the starting point south of Castricum until south of Den Helder (i.e. in this study the Dutch North Holland Coast, see section 4.1 about the regional setting), is divided into three main sections, each with different characteristics:

- **Castricum – Camperduin (0 – 22 km):** The section of Castricum-Camperduin (C-C) is located between south of Castricum until just under the Hondsbossche and Pettemer Sea Defence (HPSD). The applied (dynamic) foredune strategies vary from

- **HPZ (22 – 28.3 km):** The section of the HPZ/HPSD is located at the former sea defence at Petten, which after a mega-nourishment is developed into the Hondsbossche and Pettemer Dunes.

- **North of HPZ: (28.3 – 46 km):** This section is located north of the HPZ/HPSD and is dominated by the presence of groynes and several in the past applied nourishments, both at the beach and at the fore-shore.

4.2.2 Regional scale

The backbone of the regional scale zonation is the distribution of coastal towns (Castricum aan Zee, Egmond aan Zee and Bergen aan Zee). On regional scale the present study extracts three types of spatial usage of the Dutch Holland Coast that might be important to variations in alongshore foredune development on regional scale:

- Natural area prior to the coastal town/development (N1);
- Boulevard/year-round (Mid);
- Natural area after the coastal town/development (N2).

The alongshore foredune development in these sections is calculated with input of the 3-D pointcloud LiDAR data and then compared to a greater alongshore signal. Table 1in appendix A shows a complete overview of the zonation at regional scale.

4.2.3 Local scale

On local scale the present study extracts two features that might be important to variations in alongshore foredune development on local scale: blowout development and constructions on the beach. These features typically range from 10-200m in alongshore direction for blowout development and up to 2 kilometers in alongshore direction for constructions on the beach.

Figure 4.2 shows a blowout at Castricum aan Zee, which is here used to describe the zonation around the blowouts. This zonation divided the area in the vicinity of the blowout into three regions:

- South (start to Mid S) which is defined as *prior to the blowout*;
- Mid (Mid S to Mid N which is defined as *at the blowout*;
- North (Mid N to End) which is defined as *after the blowout*.

The regions prior to- and after the blowout is set to a fixed alongshore length of 75m. The typical alongshore lengths of a blowout are very site-specific *(Jungerius & Van der Meulen, 1989)*. Therefore, no fixed coordinates are set for the Mid-section, which is interpreted first based on aerial photography of the Dutch Holland Coast and secondly using the LiDAR dataset (Figure 4.2).

Figure 4.2; Blowout sections of interests (own work).

Apart from the total development of (ΔV) at South, Mid and North, the year-by-year development at each of these blowout sections is analyzed in order to reveal regularities in for example how the alongshore foredune development in the vicinity of blowouts responses to storm events.

Although beach cabins and beach pavilions are always regulated by Water authorities such as the Hoogheemraadschap Hollands Noorderkwartier, the zonation of constructions of the beach is not straightforward as there is a large variety in constructions on the beach. Aerial photography is used to locate constructions on the beach and to measure their footprint (Figure 4.3). The footprint is defined as the density of the constructions for a specific coastal stretch in square meters (L= alongshore length, B= cross-shore width, measured along the perimeter).

It is then aimed to link the footprint of constructions on the beach to alongshore foredune development. This is done by comparing:

- The alongshore foredune development prior to constructions on the beach;
- The alongshore foredune development after constructions on the beach.

Figure 4.3; Constructions on the beach (own work).

4.3 Data

Height surveys of the Dutch Coastal Zone are executed with laser altimetry technology or light detection and ranging (LiDAR) in combination with a coordinate both within the RD-system and a local axis system (Figure 4.4). From 2006 Jarkus measurements of the ‘dry’ part of a coastal transect (i.e. the beach and the dunes) are made by using LiDAR (Light Detection and Ranging) scanning measurements. This dataset is also known as the JARUS dataset. This dataset contains annual elevation measurements covering the dune, beach and foreshore and has been used in several studies addressing annual to decadal-scale behavior of the coastline (including specifically dunes), e.g. *(Van der Wal, 2004; De Vries et al., 2012; Keijsers, 2015)*.

Airborne LiDAR is one of the most effective and reliable means of terrain data collection. Using LiDAR data for digital elevation model (DEM) generation has become the standard practice in spatial related areas *(Liu, 2008)*. LiDAR-based DEMS have been widely and successfully used for quantification of beach and dune volume change, e.g. *(Mitasova, et al., 2004)* and *(Overton, et al., 2006)*. Generating altimetry data is done by the use of a laser altimeter. This device is operated from an airplane (Figure 4.4). The laser altimeter sends out infrared laser pulse, the pulse is reflected at the surface and a detection system can measure the time between an emitted pulse and
its return pulse *(Van der Zon, 2013)* and converts that to distance. Every pulse reaches a different point on the surface, e.g. *(Mitasova, et al., 2004; Saye, et al., 2005)*. Therefore, Airborne LiDAR offers a useful method of obtaining topographic information for coastal dunes and intertidal areas above the low water mark, at least where very thick shrub vegetation or forest vegetation is not present *(Saye, et al., 2005)*.

The position and orientation of the airplane (and consequently the LiDAR system) is determined through RTK-GPS and an internal navigation system with high detail. By combining the distance information gathered by the LiDAR system with the position and orientated, the recorded point cloud can be converted to real-world coordinates. With the latest LiDAR systems, the range of points at a time are measured, between a few thousand up to 400.000 pulses are emitted (not all at once).

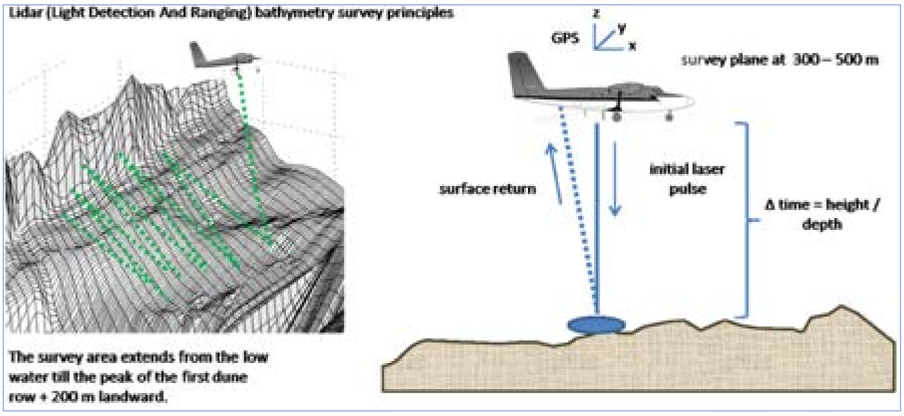

Figure 4.4; LiDAR principles, after (Pot, 2011)

The LiDAR technology has resulted in the availability of extensive 3D point cloud dataset, with an average point density of the dataset between 6 and 10 points per m^2 and a grid with a resolution for this study of 0.5 x 0.5 meters. With the high density of data points and for the Dutch Holland Coast annual frequency of coastal mapping there are time series of elevation data that are used for the extraction of new information about possible spatial patterns in coastal dynamics (in the form foredune volume development and dune elevation development).

4.4 Data preparation and processing

4.3.1 Data preparation

Due to the large size of the LiDAR 3-D point cloud dataset the LiDAR dataset is retrieved in a compressed format (.Laz, which saves 10-20% of storage space) in order to reduce storage space but without losing data, making the files easier to handle and exchange. The compressed format is more sophisticated than the regular .Zip-files, therefore a special executable tool provided by *LasTools* is used (laszip.exe) to decompress the LiDAR .las data for the Dutch North Holland Coast. This tool makes it also possible to filter by elevation, return number and other parameters and one can export in a variety of formats, including ASCII and Shapefiles. As final part of the preparation the decompressed .las data is processed and converted into a Matlab structure (i.e. .mat), containing x, y and z coordinates.

4.3.2 Data processing

Effectively processing LiDAR dense point cloud data and generating an efficient and usable DEM (grid) was challenging. First the LiDAR stored in the Matlab structure is read in perspective to the Dutch Coast, after which the coastal stretch between Heemskerk and Texel is computed by picking a starting point in alongshore direction (y-coordinate), a cross-shore coordinate (x-coordinate) and an orientation of these two coordinates in shore normal direction.
The creating of the grid is done by sorting the coastline for this study on y-coordinates and removing the double entries. After this an interpolation is performed on the 3-D dataset which crated interpolants for the x-coordinates and for the orientation to the coast. This done 10 times (i.e. *looping*) in step sizes in alongshore (north and south, ymin and ymax) direction of 5000m in respect to the center coordinate of the starting point and with a minimal and maximal x-coordinate in respect to the center coordinate of -800m to 800m (xmin, xmax). With this approach, the complete Dutch North Holland Coast is included from the starting point with excluding the island of Texel from the dataset.
The x-coordinate of the coastline and the orientation of the coastline at the center are set (y-coordinate), in order to translate this coordinate system such that the x-coordinate and y-coordinate of the coastline at the centre are (0, 0).
The data points are then rotated to a shore normal x-coordinate and a shore normal y-coordinate. DEM's are processed from the LiDAR data by averaging point elevations within each grid cell. The main shapes of the foredunes consist then as series of contour lines. When processing the LiDAR point clouds into DEM's the input of the point clouds, the xmin/xmax, ymin/ymax and a search radius (i.e. grid distance in x and y direction) is processed to a set of matrices consisting of a horizontal or mesh grid, height values (based on fitted averages in height values), root-mean-square differences (Ei) and the number of points (N).
The next step is about processing the DEM's with removing disconnected points and filling the holes. After Ruessink (2014): a DEM from a UAV flight contains one major object with some holes and a number of isolated parts outside this main object. This is caused by either a too small pixel size in the generation of the DEM or a limited number of points because measurements were performed along the edges of the main object. These holes are then filled by interpolating data points, resulting in the number of data points to increase (as the holes are filled with 'extra' elevation values).
The final steps in processing the point clouds to usable DEM's is to determine the RD-coordinates of the grid points by using inverse rotation and translation This increases the usability of the DEM for the Dutch Holland Coast by making it possible to link regions/data points to the RD-coordinate system to determine the exact location of for instance a variation in alongshore foredune development. The DEM data is then finally stored as a whole in a new set of equal sized matrices (see Figure 4.5 for an example). For every 5000 meters in alongshore direction of the Dutch North Holland Coast a DEM is produced, roughly between Heemskerk and den Helder. This constrains the alongshore extent of this study. These sets of matrices form the core of the further data analysis.

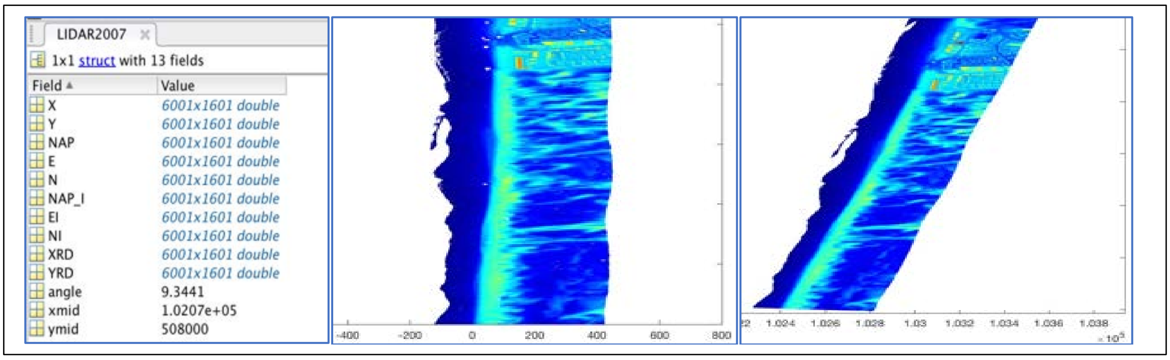

Figure 4.5 Shows an example of matrices from a processed DEM and the difference when just the X, Y and NAP (elevation values) are plotted to check whether there are large holes in the DEM or when the DEM is plotted in respect to the RD-coordinates and with interpolated values (XRD, YRD, NAP_I).

For every year between 2007 and 2016, 10 segments of the Dutch Holland Coast are processed from 3-D point cloud to DEM's. Due to the extensive size of the dataset, in terms of storage space as well as coverage of the Dutch Holland Coast, it was not possible to processes all the DEM's at once.

4.5 Data analysis

The dataset makes it possible to zoom in to a scale-level of 1m inter-transect width, therefore not coinciding with conventional JARKUS transects or beach poles along the Dutch Holland Coast (i.e. profiles that are spaced 200 to 250 m apart), therefore being capable of exploring smaller scale topographical variations in alongshore foredune development. Essentially, the profiles in this data analysis are spaced 1m apart, extracting alongshore evolution initially in m/m or m^3/m.

4.5.1 Dune volume analysis

The generated DEM's allow extraction of foredune features. The features within the scope of the study are volumes of sediment (*V*), volumetric variability in foredune development (*ΔV*) and dune elevation (*z*). The features are calculated by comparing year-by-year elevation values and contour lines for a semi-fixed calculation block.

Dune volume (*V*) is the volume of sediment per meter in alongshore direction above the dune-foot level, seaward of a fixed inland boundary point (Figure 4.6). To prevent '*sand losses'* in the volumetric calculation, this boundary needs to be the same at any time. In this study, the fixed inland boundary point is denoted as ($\mathbf{X_{LB}}$).

The dune-foot is denoted as **(X_{DF})** and is similar to the dune-foot parameter after *(Ruessink & Jeuken, 2002)*. This level is in this study initially fixed at +3.0m - +1.5 meters NAP (depending on the calculation run), which refers to the elevation at which the profile slope changes clearly from beach to dune e.g. *(Ruessink & Jeuken, 2002; Van der Wal, 2004)*.

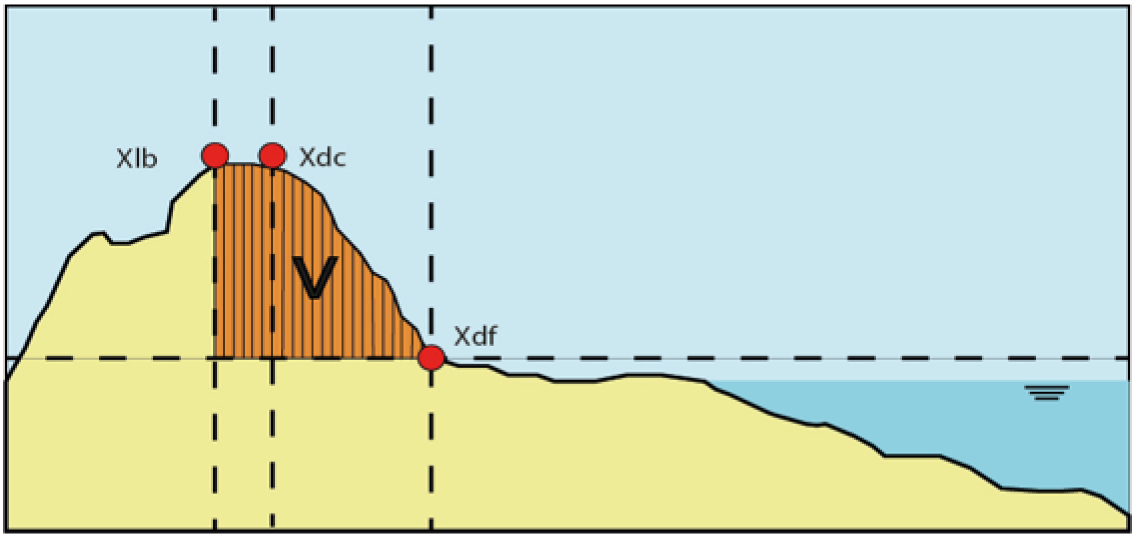

Figure 4.6; Dune volume calculation block (own work).

($\mathbf{X_{DC}}$) is the dune crest position taken at a generalized z-value (i.e. > 10 meters in the first run). To that extend, the dune crest position is defined as the point with the maximum peak in negative curvature landward of the dune-foot level.($\mathbf{X_{LB}}$) is considered as the farthest-inland referential position. The difference between two consecutive values of *Volume (= V)* may yield variability in dune volume, i.e. **($\Delta V = V_t - V_{t-1}$)**, which represents the main parameter of interest in this research and is relevant for all research questions. Figure 4.6 contains a schematic representation of the dune volume calculation block.

Volumetric calculation

The schematic calculation block is computed with the aim to calculate the following parameters; (1) elevation contour, (2) volumetric loss per transect, (3) volume per transect. This is done for every sub-section (i.e. 10 times over 10 years) of the Dutch North Holland Coast.

Every run of the calculation compared one year with another year. Elevation values below the dune-foot level (+ NAP 3.0 m) are initially excluded from the calculation block and do not contribute to (*V*) and (*ΔV*). Hence, $z_i < 3.0$ gives no values. Then the first time the contour line reaches the 10-meter contour point ($z_j < 10.0$) is determined and the location of this 10 meter contour point is indexed to prevent getting the result of an 10 meter contour point that is too close to the edge of the grid, this can lead potentially unstable result due to possibly a limited number of points along the edges of the grid. In order to calculate the (Δ*V*) between two years per grid point, an assumption is made that the dune-crest is located within ~60 meters from the 10-meter contour point. Then the (*ΔV*) between two years is calculated when the 10-meter contour point is located within ~60 meters from the edge of the grid.

Then the total (*ΔV*) is a summation between the volumetric losses in 2007-2013. The results of the volumetric calculation are stored in a matrix with (1) alongshore coordinates in the RD coordinate system (in alongshore meter-by-meter) and (2) (*ΔV*) between 2007-2013.

Moving average filter

A filter is used to reduce noise in the calculation. The small spatial scales that are used in this study, e.g. inter-transect width of 1 meter, resulted in a very noisy distribution of (*ΔV*) when they are projected in respect to the alongshore direction. This is done by computing a centered moving average filter. The moving average filter is computed with a window size of 10 meters. This window is picked because it still gains form the extensive size and possibilities of the LiDAR dataset by slightly reducing the sampling frequency (i.e. reducing the noise caused by very small and local fluctuations) without losing to much of the spatial resolution, e.g. *(Castelle, et al., 2015)* used a window size of 100 meters to remove small-scale features.

4.6 Metrological forcing conditions

Analyses of meteorological forcing conditions that may have led to coastal erosion during the period of the study were carried out using hourly mean wind speed measured at the IJmuiden between January 1, 2007 and November 5, 2016. Hourly water levels recorded at IJmuiden tide gauge stations between January 1, 2007 and December 31, 2016 were used to determine the frequency of potentially erosive extreme water levels between the first and the last LiDAR surveys. Two critical water levels were considered to be conducive to dune erosion: extreme water levels with a return period of 10 years and 100 years determined from 36 years of tide gauge records from IJmuiden buitenhaven.

5. Results

This chapter contains the results of an analysis of variations in alongshore foredune development at landscape scale and regional scale scaled variation. First, a description of the environmental boundary conditions is given, and important events are highlighted. Second, a description of changes at landscape scale is given and changes are linked to the highlighted boundary conditions. Thirdly, we study variations at regional scale, responses to large environmental effects are studied and compared between regions and region type. Finally, the results on the local spatial scale is presented, with a focus on dune development around blow-outs and constructions on the beach.

5.1 Environmental boundary conditions

This subsection describes the environmental boundary conditions at the study site.

5.1.1 Wind

Figure 5.1 shows a wind rose with the distribution and magnitude of wind at the IJmuiden measurement station between 2011-2018. The prevailing wind direction is South-West.

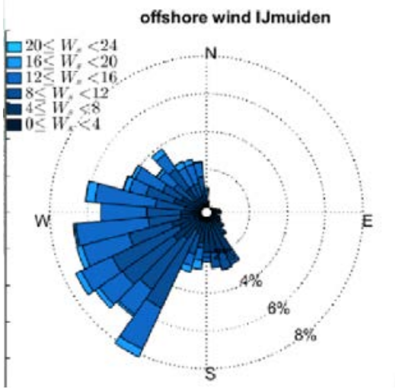

Figure 5.1; Wind data distribution

5.1.2 Water levels

The tide gauge data at IJmuiden clearly shows that high water levels, that could potentially have strong impacts on dune volumes, were mostly generated during the relatively stormy years of 2013 and 2014 (Figure 5.2). The year of 2013 reaching almost 0.5 m about the boundary level at IJmuiden. These high-water levels occurred during the Sinterklaasstorm of early December 2013. During the Sinterklaasstorm, a maximum water level of 2.93 m was recorded, linked to sustained strong winds on December 5 and 6, 2013. These were exceptionally high-water levels and were likely to be even higher on during these events due to wave run-up that further increases the water level on open beaches.

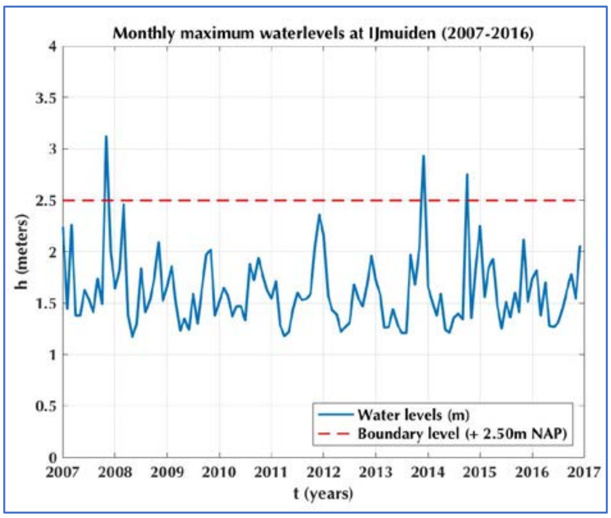

Figure 5.2; Monthly maximum water levels (own work).

5.2 Topographic variations at landscape scale

The greater alongshore signal of alongshore foredune development is in a first analysis scanned for large sections that show deviations from the trend in the greater signal between 2007 and 2016. This the largest scale that is addressed in this study and aims to extract larger scale regional variabilities in (*ΔV*). At landscape scale, a minor trend in increasing *(ΔV)* is observed in an SW-NE direction (Figure 5.3). As observed in Figure 5.3, in some regions along the Dutch Holland Coast there are almost none (very low) or no apparent alongshore development of (*ΔV*) between 2007-2016. There are no values between ~16.5 and ~18.0 kilometers (the Kerf Schoorl) from the starting point north of Heemskerk; just before and just after the HPSD; the total alongshore evolution of (*ΔV*) shows very low to almost no values for the coastal sections just southward (20 – 22 kilometers) and just northward of the Hondsbossche Dunes. This is explained by the topographic set up, before 2014-2015 no sandy coastline was present at the regions surrounding the Hondsbossche Dunes. Due to the set filter for the moving average at this scale-level, some regions show no values because the filter size is focused on landscape-scale (i.e. between 10 and 100 kilometers).

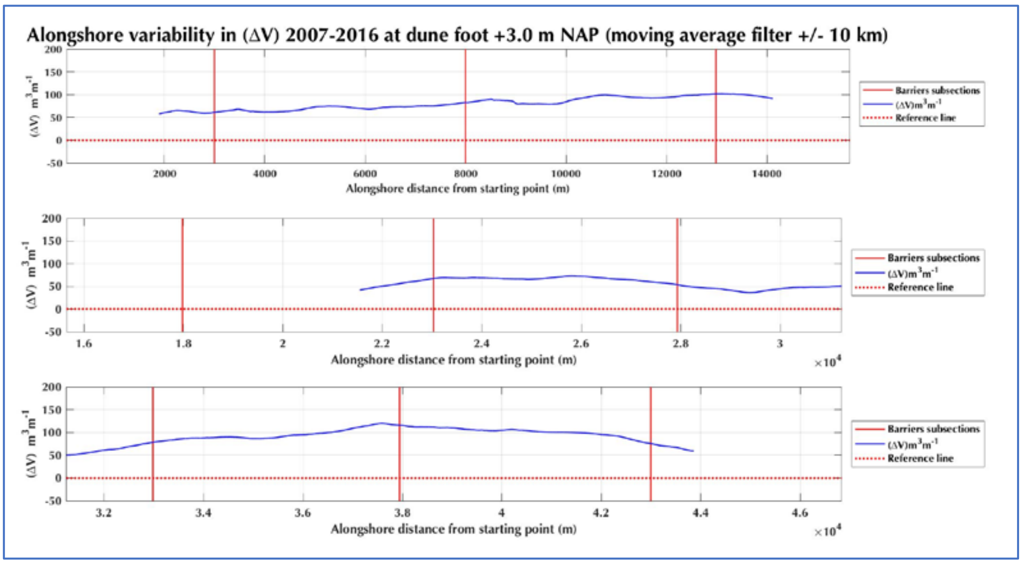

Figure 5.3; Alongshore foredune development along the Dutch Holland Coast

An overview of the topographic variations in alongshore foredune development (*ΔV*) at landscape scale along the Dutch North Holland Coast between 2007 and 2016 is provided in figure 5.3. The y-axis represents the development of (*ΔV*) in m^3/m and the x-axis represents the alongshore distance from the starting point north of Heemskerk (kilometer 0) to the end of the analysis at Julianadorp (kilometer ~47).

Overall is observed that dune growth, i.e. positive development of (*Δ*V) was relatively constant between 2007 and 2016. As observed in Figure 5.3, in some regions along the Dutch Holland Coast there are almost none (very low) or no apparent alongshore development of (*ΔV*) between 2007-2016. There are no values between ~16.5 and ~18.0 kilometers (the Kerf Schoorl) from the starting point north of Heemskerk; just before and just after the HPSD;
The total alongshore evolution of (*ΔV*) shows very low to almost no values for the coastal sections just southward (20 – 22 kilometers) and just northward of the Hondsbossche Dunes. This is explained by the topographic set up, before 2014-2015 no sandy coastline was present at the regions surrounding the HPSD.

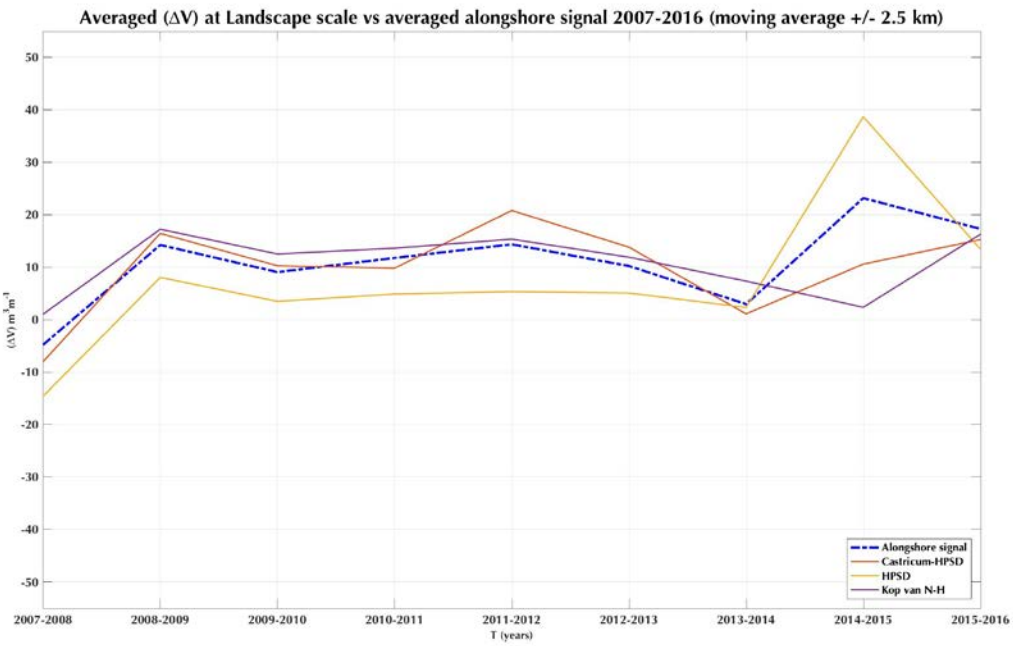

Figure 5.4; Averaged foredune volume change (ΔV) 2007-2016.

The LiDAR data is used for mapping variations in foredune volumes over the study site between each annual survey, which enabled calculations for changes in sediment volumes over the coastal foredunes (Figure 5.4). Overall is a relatively constant dune growth observed between 2007-2016, with a total average (i.e. all the sections) alongshore mean of the foredune volume change of 8,84 m^3/m/y and a total value for the whole study area of roughly 10 x 10^7 m^3 within the study period. The mean of the foredune volume change is positive.

Changes in *(ΔV)* were different from one period to another. 2007-2008 and the period between 2013-2014 being far the most erosive, presenting the lowest values for average dune growth at both three sections over the complete observation period of -7,36 m^3/m in 2007-2008, coinciding with the previously described high water levels during this time period (Figure 5.2). Contrasting with the other sections between 2007-2008, the Kop van North-Holland section had positive values for *(ΔV)*, i.e. +1,34 m^3/m. Another strikingly difference in *(V)* between other years is observed in 2013-2014, with an average total growth of +4,43 m^3/m, as a result of the storms of late 2013 (i.e. the Sinterklaasstorm). As observed from Figure 5.4, the coastal stretches between Castricum and the (former) HPSD had overall less foredune volume growth compared to the Kop van Noord-Holland area. The period of 2014-2015 does not reflect the pattern that is observed between other years, since in this period a mega nourishment took place to reinforce the HPSD. The trend for the Castricum-HPSD section is more representative for the overall development. Slightly contrasting with the other sections between 2007-2008, the Kop van North-Holland section had overall positive values for *(ΔV)*, i.e. +1,34 m^3/m, for this time period and is considered to be fairly stable. The Kop of North-Holland section was however the only section that had decreasing values after the implementation at the HPSD mega-nourishment.

5.3 Alongshore foredune development at regional scale

An overview of the topographic variations in alongshore foredune development (*ΔV*) at regional scale between 2007 and 2016 is presented in Figure 5.5. The y-axis represents the development of (*ΔV*) in m^3/m and the x-axis represents the alongshore distance from the starting point north of Heemskerk (kilometer 0) to the end of the analysis at Julianadorp (kilometer ~47). The colored markers indicate the type of section: green is "natural", blue is "developed", yellow is "HPSD" and 'red' represents sections with no data.

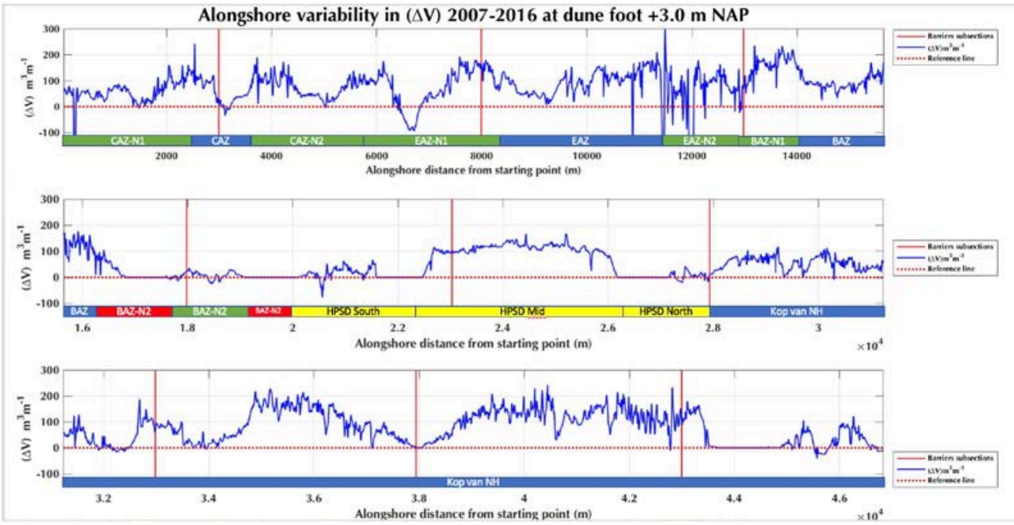

Figure 5.5; Alongshore variability at landscape scale (2007-2016).

From Figure 5.5 is observed that in general positive dune growth is established in most of the sections, ranging on averaged from ~ -100 m^3/m to ~+200 m^3/m over 10 years and resulting in a trend between ~+8 and ~+11 $m^3/m/y$.
There is much regional deviation. The following section zooms in on these deviations.

Figure 5.6 shows the averaged (ΔV) at the sections Castricum aan Zee, Egmond aan Zee and Bergen aan Zee compared to the greater alongshore signal at regional scale. At regional scale, a comparison is made between the natural sections (N1, N2) and the more developed sections (Mid) at coastal towns. The moving average filter is set to 10 meters.

CAZ N1, CAZ Mid and CAZ N2
It is clear that changes in (*V*) were different from one location to another (Figure 5.6, top subplot); starting with low values for (*ΔV*) in 2007-2008, where after there is an overall positive development of (*ΔV*) observed at CAZ N1, CAZ Mid and CAZ N2; +3,48 m^3/m, +8,14 m^3/m and +9,534 m^3/m, with a standard deviation of s = 3.2. A drastic decrease in averaged (*ΔV*) is observed at EAZ N1 between 2013-2014, -24.79 m^3/m. Hence, at CAZ N1 a high response to the high-water levels in this year (Figure 5.6), coinciding with the Sinterklaasstorm is observed, reaching the lowest values in (*ΔV*) off all the observations. There is an offset between the development of (*ΔV*) in CAZ N1-N2 and CAZ Mid, with differences with a magnitude in the order of ~2.1 m^3/m.

EAZ N1, EAZ Mid and EAZ N2
Figure 5.6b shows that *(ΔV*) at all sections of EAZ was evenly distributed between 2007-2016, with the lowest standard deviation of the observed data; s = 1,5 m^3/m. Similar to the values at CAZ, lower values are observed in 2007-2008 and 2013-2014, but not as drastic as at CAZ. Overall there is a positive development of (*ΔV*) observed at EAZ N1, EAZ Mid and EAZ N2; +8.,98 m^3/m, +11,44 m^3/m and + 8,81 m^3/m. No large responses to events of high water can be observed between 2007-2016, as well as no clear distinction between (*ΔV*) in more natural (N) sections or developed (Mid) sections.

BAZ N1, BAZ Mid and BAZ N2
Figure 5.6c shows a large spread (s = 6,6 m^3/m) in the observed data of (ΔV) compared to CAZ (N1, Mid and N2) and EAZ (N1, Mid, N2). The typical value for the development of (ΔV) at BAZ N1 is 21,80 m^3/m, at BAZ Mid 14,43 m^3/m and at BAZ N2 8,67 m^3/m. An increase in (*ΔV*) is observed after 2013-2014 at BAZ N2 compared to the development of (*ΔV*) at this location. The development of (*ΔV*) at BAZ N2 was before 2013-2014 clearly below the average values. In contrast, the development of (*ΔV*) at BAZ N1 was clearly above the average values.

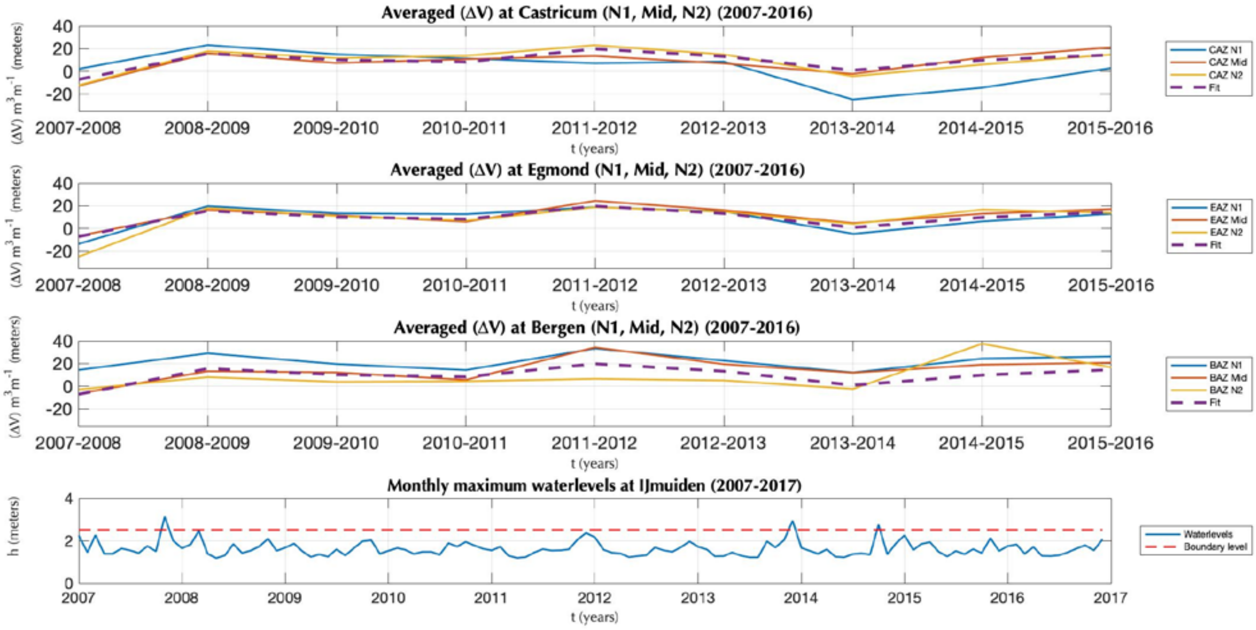

Figure 5.6 Subplots with alongshore foredune development at Castricum aan Zee (a), Egmond aan Zee (b), Bergen aan Zee (c) and maximum water levels (d) (2007-2016).

Overall is observed that foredune volumes developed positively between 2007-2016. Periods in which the averaged dune volume change is lower (e.g. around 2012-2013-2014), the maximum recorded water levels are high (Figure 5.6d). In the periods where the most foredune volumes were lost, the maximum water levels exceeded the boundary level at IJmuiden.

5.4 Alongshore foredune development at local scale

5.4.1 Blowouts

Figure 5.7 shows the volumetric development prior (South), at (Mid) and after (North) multiple blowouts along the Dutch North Holland Coast between 2007-2016. From Figure 5.7 is observed that the general trend shows variations in foredune development in the vicinity of blowouts. Positive development prior and after the blowout is observed, with the sections after the blowout showing a lower positive development then prior to the blowout. Prior to the blowouts the foredune development is in general positive: +8,37 m^3/m. This is similar to the overall alongshore foredune development along the Dutch Holland Coast (section 5.2). After the blowout the development is positive: +4,12 m^3/m. A clear difference is observed at the blowout, where the development has an average value of -0,703 m^3/m with a standard deviation of 30,32 m^3/m, which is a large spread in the data.

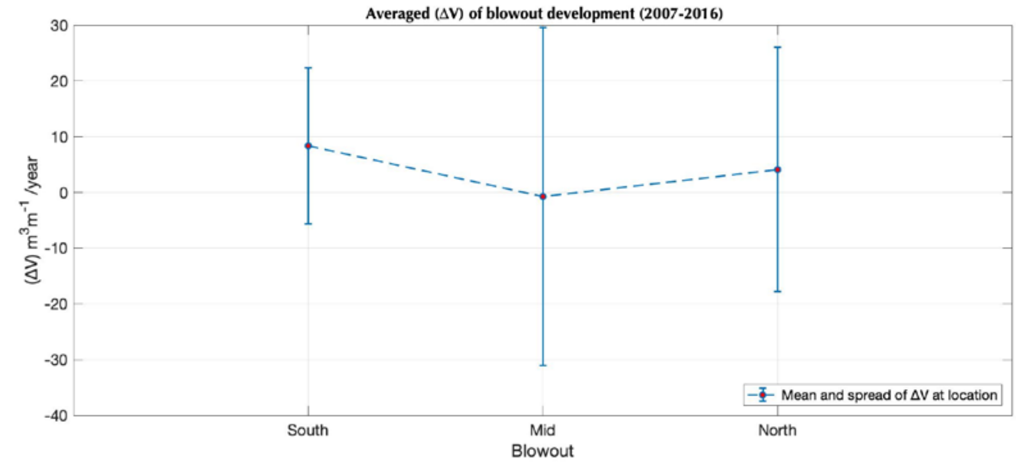

Figure 5.7;Averaged foredune development prior to (South), at (Mid) and following (North) the blowouts.

Storm response
In previous sections it is described that periods of negative foredune development roughly coincides with periods that showed high water levels (i.e. 2007-2008 and 2013-2014). The following Figure (Figure 5.8 contains the mean and spread in alongshore foredune development in the vicinity of blowouts (South, Mid and North). The overall mean between 2007-2016 is compared to a series of years after major storm events (2008-2010), without major storm events (2010-2013) and a period with major storm events (2013-2015).

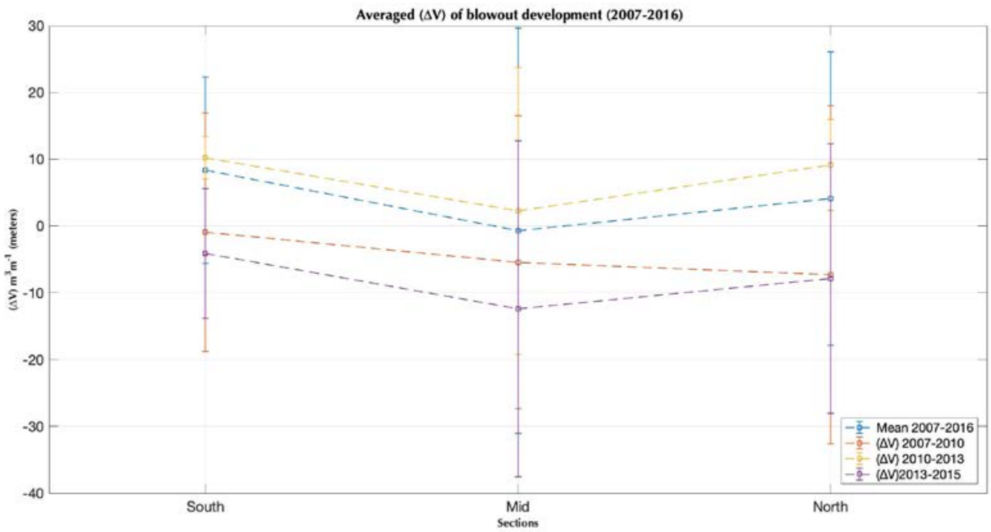

Figure 5.8; Comparison of averaged foredune development prior to (South), at (Mid) and following (North) the blowouts in respect to years with major storm conditions and more fair conditions.

As observed from Figure 5.7 the overall alongshore development of blowouts is the highest during years without storm events (2010-2013). The mean for *(ΔV)* at all three sections during this period is positive. +7,21 m^3/m for, which results in overall dune growth at all sections. This coincides with the observations on regional scale. The years with storm events, 2007-2010 and 2013-2015 show an overall negative development of foredune volume prior to, at and after the blowouts. The mean values of *(ΔV)* between 2007-2010 are; prior to the blowouts -0,94 m^3/m, (2) at the blowouts -5,45 m^3/m and (3) after the blowouts -7,30 m^3/m. The overall mean value for all three sections is -8,13 m^3/m. the overall mean for all three sections is -4,57 m^3/m. The mean values of (ΔV) between 2013-2015 are; prior to the blowouts -4,14 m^3/m, (2) at the blowouts -12,41 m^3/m and (3) after the blowouts -7,85 m^3/m. The overall mean value for all three sections is -8,13 m^3/m.

5.4.2 Constructions on the beach

Figure 5.9 shows the alongshore foredune development at sections with extensive constructions on the beach.

CAZ SS, CAZ Mid and CAZ SN
It is clear that changes in (*V*) were different from one location to another (Figure 5.9a top subplot); starting with low values for (*ΔV*) in 2007-2008, where after there is an overall positive development of (*ΔV*) observed at CAZ SS, CAZ Mid and CAZ SN; +12,57 m^3/m, +0,91 m^3/m and +3,99 m^3/m, with a standard deviation of s = 2,37 m^3/m.
CAZ SS has a constructions density of 9,85 m^2/m, CAZ Mid a constructions density of 13,50 m^2/m and CAZ SN a constructions density of 12,27 m^2/m. In contrast to the greater alongshore signal, the foredune development increases after 2013-2014 (the Sinterklaas Storm year).

EAZ SS, EAZ Mid and EAZ SN
Figure 5.9b shows that *(ΔV)* at all sections of EAZ was relatively evenly distributed between 2007-2016 with the lowest standard deviation of the observed data; s = 1,78 m^3/m. Similar to the values at CAZ, variable values are observed in 2007-2008 and 2013-2014, but not as drastic as at CAZ. Overall there is a positive development of (*ΔV*) observed at EAZ SS, EAZ Mid and EAZ SN; +8,98 m^3/m, +11,06 m^3/m and + 13,94 m^3/m. A quick response to events of high water can be observed between 2007-2016. EAZ SS has a constructions density of 10,37 m^2/m, EAZ Mid a constructions density of 5,16 m^2/m and EAZ SN a constructions density of 13,64 m^2/m.

BAZ SS, BAZ Mid and BAZ SN
Figure 5.9c shows a very small spread (s = 0,6 m^3/m) in the observed data of (ΔV) compared to CAZ (SS, Mid and SN) and EAZ (SS, Mid, SN). The value for (ΔV) at BAZ SS is +13,76 m^3/m, at BAZ Mid +11,24 m^3/m and at BAZ SN +14,51 m^3/m. An increase in (*ΔV*) is observed after 2013-2014 at BAZ N2 compared to the development of (*ΔV*) at this location. The development of (*ΔV*) at BAZ SN was after 2013-2014 clearly below the average values. The development of (*ΔV*) at BAZ SS was below the average values of the greater alongshore signal until 2011-2012.
BAZ SS has a constructions density of 10,37 m^2/m, at BAZ Mid 3,16 m^2/m and at BAZ SN 1,08 m^2/m

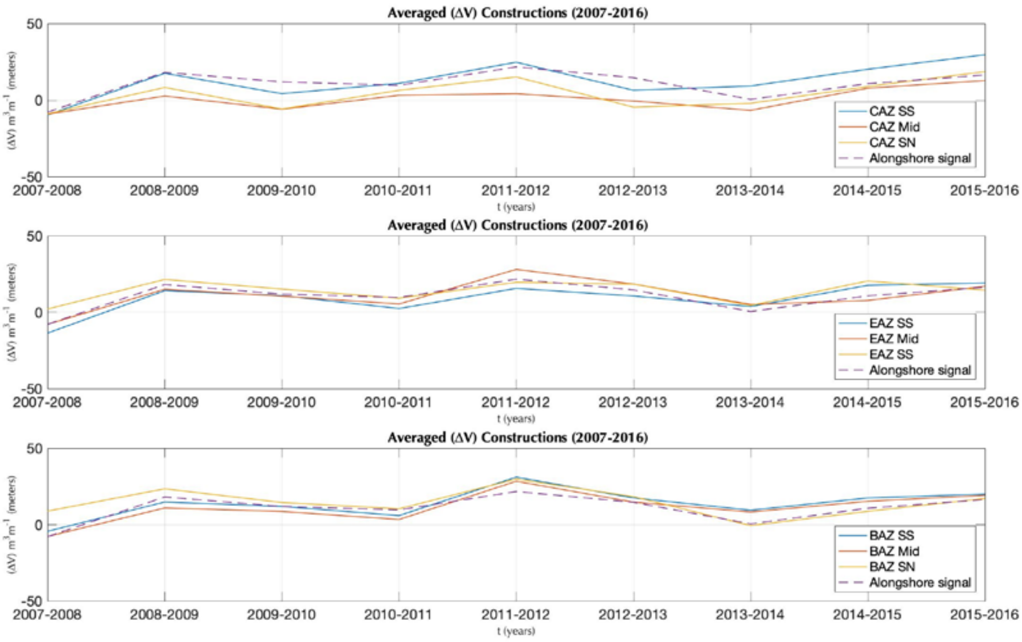

Figure 5.9; Subplots with alongshore foredune development at Castricum aan Zee (a), Egmond aan Zee (b), Bergen aan Zee (c) with seasonal constructions on the south (SS), year-round in the middle (mid) and seasonal construction to the north (SN) between 2007-2016.

6. Discussion

This chapter contains a discussion on the results of the present study. This chapter therefore aims to describe and discuss the possible forcing properties that control variations in alongshore foredune development on landscape, regional and local scale. These properties can for example be controlled by anthropogenic intervention of more natural developing properties.

6.1 Dune volume calculations

This section discusses the results of the present study. The chosen method to obtain the results of calculating alongshore development in foredune volumes (ΔV), based on raster DEM's, uses as input data the annual LiDAR measurements of the Dutch Holland Coast. Using LiDAR data for DEM generation has become the standard application for modern mapping technology and geospatial analysis *(Liu, 2008; Mitasova, et al., 2010)*. LiDAR-based DEMS have been widely and successfully used for quantification of beach and dune volume change, e.g. *(Mitasova, et al., 2004; Overton, et al., 2006; Fabbri, et al., 2017)*. The applied method highlights dynamics in the alongshore development of foredunes, in terms of (V), (ΔV) and (z). Coastal zone management is extensively described due to its presumes effects on foredune development.

According to *(De Vries, et al., 2012)* there is no general definition for dune volume and is the dune volume defined as the volume of sand above the dune-foot level until a certain landward limit. The dune-foot level along the Dutch coast is widely assumed to be +3 meters NAP and although this study made calculation runs between +1.5 meters NAP and +3 meters NAP to for example investigate why low/no values were calculated in some situations, no further refinement of the dune-foot level is made in the overall results at landscape-, regional and local scale-levels and the dune-foot level generalization of +3 meters NAP is adopted similar to e.g. *(Ruessink & Jeuken, 2002; De Vries et al, 2012)*.
Another approach of defining the dune-foot level is described by Brodie and Spore (2015) in a two-step process, where the first step "guesses" the dune-foot level as finding the point on the cross-shore profile that was the farthest from a linear fit (between the position of the MWH contour and maximum observed elevation on that profile similar to e.g. *(Mitasova, et al., 2011)*. This location is then refined by selecting the point with the maximum positive curvature within +/- 10 meters in the cross-shore direction of "first guess" *(Brodie & Spore, 2015)*. Overall this approach provides a more dynamic dune-foot position when computed correctly, a more dynamic dune-foot position, i.e. there are several processes that may cause (temporally) dune-foot erosion, may lead to unnoticed variations in dune volume compared to the approach in this study.

In the present study dune, volume is calculated as a summation under the data points on the dune-face between the *dune-foot*, *dune-crest* and *landward boundary point*, this results in a slightly less complicated calculation, but also possibly less accurate compared to calculating dune volumes as the integral under the points on the dune-face between *dune-foot*, *dune-crest* and *landward boundary points* as the integral fit better represents the dune-face and therefore *makes a better connection between the points and sand volumes*, hence no volumes of sand are 'lost' in the calculation. It is noticed that integrating as a function requests a different and potentially more difficult calculation and is possibly better suited for a smaller scale study. The various sensor components fitted in LiDAR instruments possess different precision *(Liu, 2008)*. There may be an error in the laser range measured due to time measurement error, wrong atmospheric correction and ambiguities in target surface which results in range walk. Error is also introduced in LiDAR data due to complexity in object space, e.g. sloping surfaces might lead to uncertainty in X, Y and Z coordinates. Finally, the accuracy of the laser range varies with different types of terrain covers *(Liu, 2008)*.

The moving average filter is computed with a window size of 10 meters. This window is picked because it still gains form the extensive size and possibilities of the LiDAR dataset by slightly reducing the sampling frequency (i.e. reducing the noise caused by very small and local fluctuations) without losing to much of the spatial resolution, e.g. *(Castelle, et al., 2015)* used a window size of 100 meters to remove small-scale features. Still, the main advantages of the LiDAR dataset with almost complete coverage of the Dutch (dry) coastal zone is slightly less utilized because such a high sampling frequency and adjacent spatial resolution are less suited for landscape scale analysis.

6.2 Results

6.2.1 Landscape scale

The positive development in (ΔV) at the Kop of Noord-Holland strongly depends on the construction of coastline retaining groynes and the applied beach nourishments, e.g. *(Arens, et al., 2010; Pot, 2011)*. Human interventions seem to act as a major forcing property for the alongshore development of (*ΔV*), as dynamic foredune management is not applied. The whole coastal stretch from the Kop van Noord-Holland to Petten has an applied foredune management that aims on retaining foredune volumes. As a result, when comparing the larger alongshore signal in (*ΔV*) northward of Petten with the more southward located regions of the study site (i.e. between Castricum and Camperduin), the alongshore development of (*ΔV*) is slightly larger and less vulnerable to storms (i.e. less erosion after the Sinterklaas Storm). Although it was possible to identify and map erosion-accretion patterns at high level of detail, varying form landscape to local scale-levels, the underlying sediment transport processes (induced by i.e. nourishments, offshore located sandbars which merge with the beach) are in this study only described in a generic approach. According to *Browder & McNinch (2006*) and *Mitsova et al. (2010)* these processes cannot be fully described without the incorporation of nearshore bathymetry measured simultaneously with topography and aeolian processes.

6.2.2 Regional scale

All sections show a decrease in foredune volumes at regional scale between 2007-2008, linked to the high-water levels in this period (Figure 5.2). These findings coincide with another LiDAR based evaluation study of the Dutch Holland Coast *(Huisman, 2013)*. At all sections a considerable decrease between 2013-2014 is observed, which coincides by the Sinterklaasstorm of December 2013 (Figure 5.2). This storm caused on average one of the highest water levels in the Netherlands since the Watersnoodramp of 1953, which also coincided with spring tide. Foredune volumes started to increase after 2007-2008, indicating that the most severe erosion took place around 2007-2008, this is possibly linked to high water levels during the November Storm of 2007 *(Huisman, 2013)*, as dune erosion is often linked with high water level during storms *(Keijsers, 2015)*. For the Dutch North Holland Coast (*ΔV*) is mainly negative when high water levels exceed + 2.5-meter NAP *(Keijsers, 2015)*. The response to the Sinterklaas Storm in sections which allow dynamic foredune management is higher compared to sections with fixation of foredune volumes. In turn, during periods without storms/high water levels foredune volumes increased considerably quicker.

Observations between 2007-2016 showed clear response after the high water- and storm events. Alongshore variation in the morphology and development of coastal dunes is in several studies linked to short-time events like storms, e.g. *(Cowell, et al., 2003; Houser & Ellis, 2013)*. The relatively quick recovery of coastal foredune volumes after a storm event can be explained that after a storm event sand volume are often temporally relocated instead of lost. Dune recovery after storm erosion on a high-energy beach in Brittany (France) by *(Suarez, et al., 2012)* showed that dune recovery already started in the month following a major storm event. As many previous studies have shown, post-storm dune recovery processes are the result of sediment transfers between the nearshore, foreshore, the tidal beach and the dune toe *(Carter, et al., 1990; Hesp, 2002; Suarez, et al., 2012)*.

Depending on the magnitude and duration of the storm surge, erosion of the foredune occurs over hours and days, whereas recovery of the foredune can take years to decades *(Lee, Nicholls, & Birkemeier, 1998)*. This differential timescale of erosion and recovery is an important factor in alongshore variations in foredune development. Apart from storm surges, the strong negative development in foredune volumes may be caused by the erosive side of a sand wave on *(Keijsers, 2015)*.

The impact of erosion in natural areas is larger compared to developed sections. This is mainly explained by that at developed sections with i.e. settlements, coastal towns and boulevards the aim is on retaining foredune volumes. Previously conducted research by *Huisman (2013)* shows coinciding results. This study describes that although being more dynamic and quick responding, natural areas show slightly more erosion at the Dutch Holland Coast. Figure 6.1 shows an overview of foredune erosion along the Polish Baltic Coast. It is identified that at coastal settlements foredune development is more stable compared to regions without settlements *(Łabuz, 2014)*.

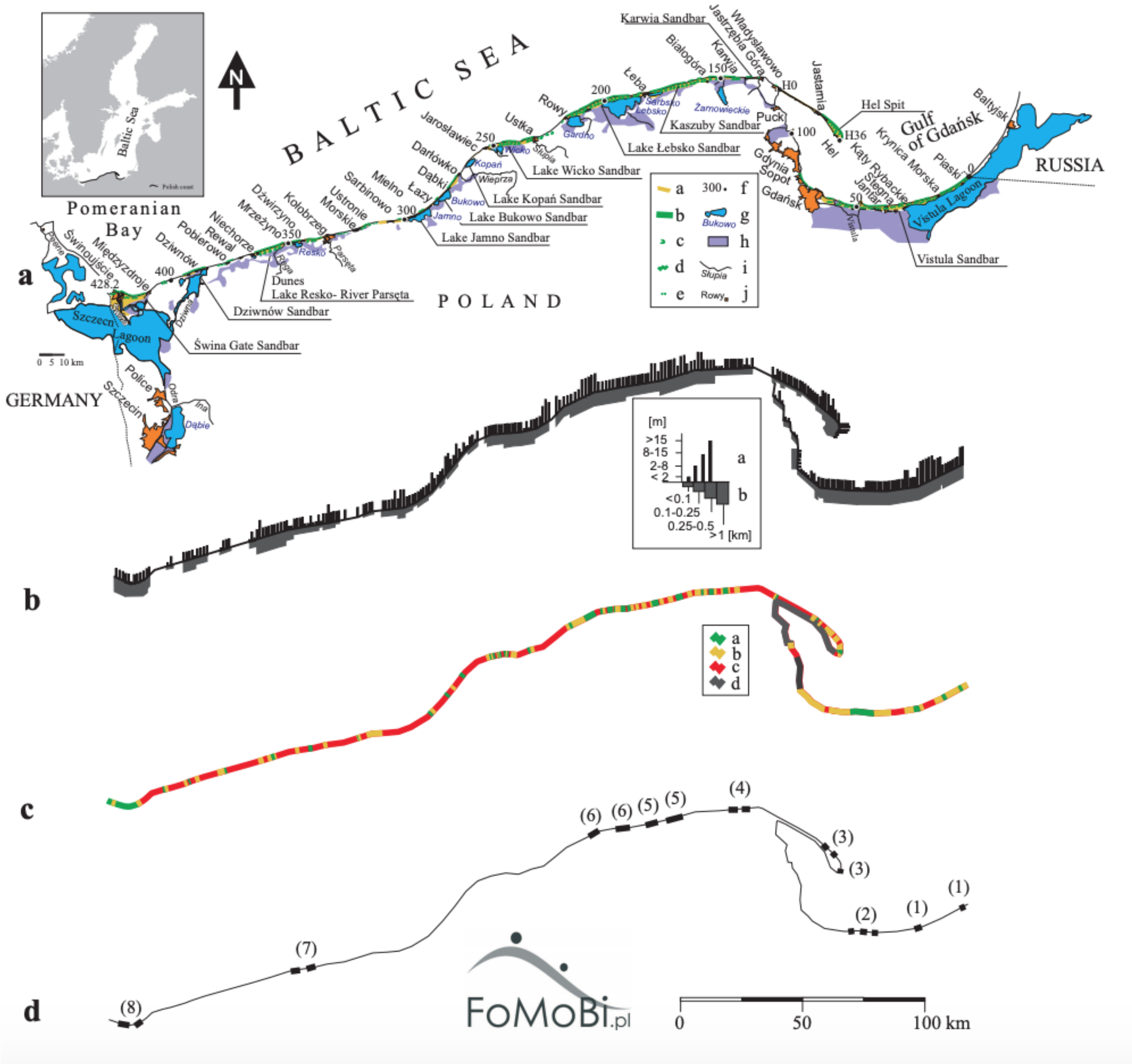

Figure 9; Polish Baltic Sea Coast, B shows the development of foredune volumes, settlements are indicated with their names on A. Comparing B and A shows the effect of settlements on variations in foredune development in the study of (Łabuz, 2014), after (Łabuz, 2014).

Dune recovery and constructing processes are often facilitated and enhanced by aeolian transport growth of vegetation *(Hesp, 2002; Arens, et al., 2010; Suarez, et al., 2012)*. These dynamics are allowed with dynamic foredune management in more natural areas but are not allowed in developed areas *(Arens, et al., 2010; Huisman, 2013)*. The coastline is extensively developed and the foredune management strategies allow foredune dynamics north and south of Egmond aan Zee, while at Egmond aan Zee the foredune dynamics are limited in order to retain foredune volumes *(Arens, et al., 2009; Elias & Bruens, 2013)*. Finally, although high water levels impact the dune frequently as a result of high-energy wave climate, coastal foredunes at a field site in southwest Washington, USA, show rapid growth *(Cohn, et al., 2018)*. According to Cohn et al. (2018), high water levels are not necessarily destructive to foredunes and instead under certain conditions they can contribute, along with wind induced sediment transport, to dune growth.

6.2.3 Local scale

6.2.3.1 Blowouts

Based on the LiDAR dataset and the method of calculating foredune volume change *(ΔV)* in m^3/m between 2007-2016 in the vicinity of blowouts, the alongshore mean of foredune volume change in the vicinity of blowouts at all sections is positive after a period of no major storm events and negative after a period of major storm events.
Overall is observed that prior to and after the blowouts the values for foredune volume change are higher than at the blowouts. Blowout have resulted in a loss of sediment volume from the beach ad dune system and increased the variability in the foredune row, this is also observed by e.g. *(Jewell, Housers, & Trimble, 2014)*.

The initial and/or reactivation of blowouts manifest as alongshore variation in vegetation density or total loss of vegetation, which may occur in response to a number of factors; including wave-run up during storms *(Hesp, 2002)*.
This causes a steeper beach and a lower elevation at the dune base following storms with high water levels.
The persistence of the blowouts is a consequence of a previous blowout or break in the foredune at that location. Considering the relatively slow rate of foredune recovery following storms at blowouts *(Houser & Ellis, 2013; Jewell, Housers, & Trimble, 2014)*, it is safe to assume that the incipient foredune will have a relatively low elevation compared to adjacent dunes, and so there is a potential for the blowout to be reactivate by relatively small disturbances to the foredune, which can occur during storms *(Jewell, Housers, & Trimble, 2014)*. This may explain the overall lower foredune volumes directly at the blowouts (section Mid), do not recover quickly in a period without storms with high water levels.

The large spread in the data at the blowouts (Mid) section indicates a high variety in foredune volumes directly at the blowouts. This resulted in that apart from an overall lower development of foredune volumes compared to prior and after the blowout, no regularities for this section can be found.

Wind plays an important role in blowout initiation and development *(Hesp, 2002)*, and the response time of a system with blowout to react to changes induced by high wind speeds, e.g. *(Jungerius, Witter, & van Boxel, 1991)* is short. This is expected in the view of the ease with which sand is moved by wind. More specifically, blowout evolution depends, to varying degrees on the width and depth of the dune gap and the type and extent of vegetation cover the strength of the winds and the directional variability of these winds e.g. *(Houser & Ellis, 2013)*.
However, in existing literature it is suggested that the relaxation time following high magnitude events is too long in respect to the recurrence interval of these events *(Jungerius, Witter, & van Boxel, 1991)*. This means that that the sensitivity of blowouts to high wind events is low on longer time-scale. Since the focus of this study is on volumetric changes in alongshore foredune development, analysis of windspeed and wind direction is limited and is recommended to be extended when one investigates the alongshore development of foredune volumes in the vicinity of blowouts.

6.1.3.2 Constructions on the beach

With the LiDAR dataset and the method of calculating foredune volume change (ΔV) in m^3/m between 2007-2016 in the vicinity of constructions on the beach, the alongshore mean of foredune volume change in the vicinity of constructions on the beach at all sections is positive after a period of no major storm events and shows relatively low response following a period of major storm events. In literature however, it is described that constructions on the beach potentially have negative influences on aeolian processes and thus dune building *(Hoonhout & van Thiel de Vries, 2013; Huisman, 2013)*. *Nordstrom and Jackson (1993)* mentioned constructions on the beach already as limiting factors to dune building, because of the interruption of fetch area/blockage of aeolian sediment transport.

The development of (*ΔV*) between 2010-2013 is comparable with the results of *Huisman (2013)*, which calculated generally positive values. An explanation of these generally positive might be that because of the year-round exploitation of beach pavilions there is no yearly period where erosion can take place.

The findings of *Van der Valk & Van der Meulen (2013)* described that in general a sequence of constructions on the beach (i.e. beach cabins) caused seaward of the beach cabins significant accretion and landward of the beach cabins significant less accretion. This coincides with the findings of *Huisman (2013)* but in the present study, this is not clearly observed as the present study focused on alongshore behavior and not on cross-shore behavior. Density of constructions seems however to play a role in foredune volume development.

The averaged positive trend in foredune volume development results in no exceedance of the safety boundary level, even with constructions at the beach being present. This averaged positive trend roughly coincides with the findings of *(Hoonhout & van Thiel de Vries, 2013)*. The presence of constructions on the beach is supposed to be far less important compared to nourishment volumes *(Arens, et al., 2010)*. Dutch Coastal Policy, where constructions on the beach are also incorporated, seems to have the largest effect on accretion and erosion in years without major storm events.

In this study the first calculations resulted in so-called volume plots which provided useful information but also some noisy, unclear distribution plots. It was unclear where the exact regions of interest where and the volume plots did not provide a sound first look on the elevation differences or on the coastal setting as a whole. Hence, the possibilities of the LiDAR data in the form of high quality DEM's and DTM's was not completely utilized in the first analysis which made them very time-costly and inefficient.

Several studies have been conducted using laser altimetry to calculate the development of foredune volumes (*V*)
An important aspect is whether the *alongshore* development of (*V*) and (*ΔV*) or in a more regional/local setting. For example, *Fabbri et al. (2015)* calculated (V) for a DEM by using the *Surface Volume* tool in the *ArcMap* software package, which calculates the area and volume of the region between the surface and the reference plane. The tool allows extrapolation of (*V*) in m^3, the geomatic area and the topographic area (in 3-D). When comparing the approach and results from Fabbri et al. (2015) with this study on alongshore variability in, it strikes that it aimed on analyzing three regions of interest, instead of analyzing a larger alongshore signal in (*ΔV*) on landscape scale-levels. Potentially, applying *ArcGIS* and *ArcMap* calculations are more suited for conducting research on a set region of interest.

Another study which combined laser altimetry and the *ArcMap* package by Huisman (2013) used different parameters for quantifying the influences of constructions on the beach. In this study the ArcMap 3D Spatial Analyst tool, *Raster Math-Minus*, was used to make Δz calculations and volumetric calculations *(Huisman, 2013)*. The applied method deviated from this study; (*ΔV*) was calculated starting at the constructions (i.e. at + ~4 meters NAP) until +15m NAP. As a result of a different function and a different *calculation block*, the results did deviate slightly compared to this study but were generally in the same magnitude.

Dune volume changes are a combination of accretion and erosion. Years with a low volumetric development can so be caused by low accretion, sever erosion or a combination of both. This can have consequences for interpretation, one can for instance miss how well a particular section responded to a storm and will just see erosion. However, based on the metrological conditions (i.e. 2013-2014) there is a clear erosion event.

6.3 Lessons learned

This study gives a confirmation of the usability of the LiDAR dataset the possibilities of mapping alongshore erosion and accretion in foredune behavior along the Dutch Holland Coast on landscape-scale and on regional-scale. The study highlights and acknowledges the general consensus on dynamic foredune management strategies and their effects e.g. *(Keijsers, 2015)*. Furthermore, insights are gained in the alongshore development of blowouts and how they affect alongshore foredune volume development, but only crude regularities are estimated. Not many studies have been conducted about the alongshore development of blowouts, instead studies have focused on all the dynamics *inside* blowouts, e.g. *(Hesp, 2002)*. The insights that are gained are rudimental but could be used to learn more lessons about natural forcing properties on foredune volumes.

6.4 Recommendations and improvements

As mentioned before, setting a good scope is vital for more detailed analysis, the LiDAR dataset can in potential provide this detail, if processed correctly and efficiently. Analyzing the whole Dutch Holland Coast on a detailed level is time-intensive, hence choices have to be made. Research regarding the small scale alongshore development of foredune volumes can in theory best be monitored with a time-interval far smaller than annual measurements. For instance, monthly measurements, although time- and cost intensive, can provide a clearer view on small scale alongshore development. The modern mapping technology such as LiDAR measurements have been utilized before in studies addressing geospatial analysis in both short- and long-term evolutions in coastal topography, e.g. *(Mitasova, et al., 2010; Brodie & Spore, 2015)*. However, there may not be an equilibrium between analyzing coastal topography on a small (i.e. local spatial scales) and the annual measurements, as small local trends may still be missed by the measurements.

7. Conclusion

The alongshore variations in foredune development along the Dutch Holland Coast are studied between 2007 and 2016, using the coastal LiDAR dataset, being part of the JARKUS (annual coastal measurements) dataset. The dataset consists of 3-D point clouds which are processed and computed into Digital Elevation Models (DEM's) consisting of X (cross-shore), Y (alongshore) and Z (elevation) data points which are used for calculating topographic features of the foredunes. In this study, these topographic features are reduced to three main parameters of interest: foredune volume (*V*), foredune volume change (*ΔV*) and dune elevation (*Z*). To identify alongshore variations in (*ΔV*), the alongshore development of (*ΔV*) is the point of focus in the data analysis in respect to the alongshore trajectory of the Dutch North Holland Coast between Heemskerk and Julianadorp. The high-density details in the LiDAR dataset made it possible to explore the possibilities of analyzing alongshore variations on a local scale, i.e. between two beach pavilions or after a sequence of beach cabins, as the resolution could be tweaked as detailed as meter-by-meter alongshore variations.

Which topographic variations in the alongshore foredune development can be identified using the LiDAR dataset?
The results of this study show that the alongshore development of (*ΔV*) showed variability on all the scale-levels (landscape, regional and local). The LiDAR data proved useful on all landscape and regional scales, but on local scales the interval of measurements is with the conventional LiDAR approach too long. On regional scale regions with extensive development showed lower variation of alongshore foredune volumes, but slightly higher overall volumetric development in the order of $\Delta V=1,5\ m^3/m$. The storm response of more developed regions is lower compared to more natural regions, but natural regions have a higher recovery rate.
On local scale-level blowouts cause alongshore variation in foredune development compared to regions without blowouts, although there is an effect observed that prior to the blowouts there is more positive development of foredune volumes than at regions after the blowouts. Constructions on the beach are presumed to have an effect on aeolian transport dynamics and dune building, but the present study provided to conformation as the differences are not clearly seen on a yearly timescale.

What are the direct and indirect effects of anthropogenic forcing properties on the alongshore evolution of coastal foredunes? The largest *anthropogenic forcing property* is the Dutch coastal management as a whole. This may be a very generic description, but the results of this study show that in essence every movement of every sediment particle is planned or can be explained by the Dynamic Preservation policy and Dynamic Foredune Management strategies. Nourishments (beach and foreshore) are very effective. At sections where considerable amounts of constructions on the beach are allowed, lower foredune changes are observed. This may be due to the present year-round beach pavilions and beach cabins but cannot completely explained by their presence since year-round beach pavilions cause higher foredune volume change.

Which natural properties control variations in alongshore foredune development? The most striking *natural* variation in the alongshore development of (*ΔV*) may be caused by storm impacts (i.e. the Sinterklaas Storm of 2013). The year-by-year development of coastal foredunes, although being accretionary landforms, maybe more due to temporal large-scale variations in erosion than to variations in natural accretion and by relatively small fluctuations in erosional behavior (i.e. caused by the erosive side of a sand wave) than as a result of variations in accretion. Regions with applied Dynamic Foredune Management strategies allow multiple blowouts to be present. Regularities prior to and after the blowouts are observed, where prior to the blowouts the highest foredune volumes are calculated. At the mid-section of the blowout no regularities in alongshore direction can be observed, due to the many different shapes and sizes of blowouts.

What causes the alongshore variation in foredune (volume) development along the Dutch North Holland Coast?
The main conclusion of this research is that no clear natural periodic/cyclic patterns in alongshore foredune development can be observed. The pattern is: much development and anthropogenic forcing results in a more or less constant foredune volume development of which can be considered as a low development of compared to coastal regions where regionally or locally more natural aeolian processes are allowed as part of Dynamic Foredune Management strategies. In turn, the more natural regions are also more prone to dune erosion.

1 References

Łabuz, T. (2014). Erosion and its rate on an accumulative Polish dune coast: the effects of the January 2012 storm surge. *OCEANOLOGIA*, 307-326.

Arcadis. (2005). *Integrale beoordeling zwakke schakels Noord-Holland, basisrapport veiligheid.* Haarlem: Provincie Noord-Holland.

Arens, S., Geelen, L., van der Hagen, H., Slings, R., ., & . (2009). *Duurzame verstuiving in de Hollandse duinen. Kans, droom of nachtmerrie. (In Dutch).* Arens Bureau voor Strand- en Duinonderzoek. Amsterdam : Arens Bureau voor Strand- en Duinonderzoek; Waternet; Dunea; PWN.

Arens, S., Jungerius, P., Van der Meulen, F., ., ., & . (2001). Habitat conservation: managing the physical environment. *Coastal Dunes.* Chichester: Wiley.

Arens, S., Mulder, J., Slings, Q., Geelen, L., Damsma, P., ., & . (2013). Dynamic Dune Management, integrating objectives of nature development and coastal safety: Examples from the Netherlands. *Geomorphology*, 205-213.

Arens, S., van Puijvelde, S., Brière, C., ., ., ., ... (2010). *Effecten van suppleties op duinontwikkeling.* Den Haag: Ministerie van EL&I, directie IFZ/Bedrijfsuitgeverij.

Ashton, A., & Murray, B. (2006). High-angle wave instability and emergent shoreline shapes: 1. Modeling of sand waves, flying spits, and capes. *Journal of Geophysical Research* .

Beets, D., & Van der Spek, A. (2000). The Holocene evolution of the barrier and the back-barrier basins of Belgium and the Netherlands as a function of late Weichselian morphology, relative sea-level rise and sediment supply. *Geologie en Mijnbouw/Netherlands Journal of Geosciences*(79 (1)), 3–16.

Beets, D., van der Valk, L., & Stive, M. (1994). Holocene evolution of the coast of Holland. *Marine Geology*, 423-443.

Bochev-Van der Burgh, L., Wijnberg, K., Hulscher, S., ., ., & . (2009). Dune morphology along a nourished coastline. *Journal of Coastal Research*, 292-296.

Brodie, K., & Spore, N. (2015). *Foredune Classification and storm response: automated analysis of terrestrial LIDAR DEMS.* Coastal & Hydraulics Laboratory, Coastal Observation & Analysis Branch. Duck, NC: USACE.

Browder, A., & McNinch, J. (2006). Linking framework geology and nearshore morphology; correlation of paelo-channels with shore-oblique sandbars and gravel outcrops. *Marine Geology*, 141-162.

Carter, R., Hesp, P., Nordstrom, K., ., ., ., & . (1990). Erosional landforms in coastal dunes. In R. Carter, P. Hesp, & K. Nordstrom, *Erosional landforms in coastal dunes* (pp. 217-249). London: Wiley.

Castelle, B., Marieu, V., Bujan, S., Splinter, K., Robinet, A., Sénéchal, N., & Ferreira, S. (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*, 135-148.

Cohn, N., Ruggiero, P., de Vries, S., Kaminsky, G., ., ., & . (2018). New Insights on Coastal Foredune Growth: The Relative Contributions of Marine and Aeolian Processes. *Geophysical Research Letters*, 4965-4973.

Cowell, P., Stive, M., Niedorada, A., Swfit, D., de Vriend, H., Buijsman, M., . . . de Boer, P. (2003). The coastal tract (part 2): applications of aggregated modeling of loworder coastal changes. *Journal of Coastal Research 19* , 828-848.

Davidson-Arnott, R. (2011). Wave dominated coasts. *Treatise on Estuarine and Coastal Science*, 73-116.

Davidson-Arnott, R., Yang, Y., Ollerhead, J., Hesp, P., Walker, I., ., & . (2008). The effects of surface moisture on aeolian sediment transport threshold and mass flux on a beach. *Earth Surf Processes Landforms, 33*, 55-74.

De Jong, B., Keijsers, J., Riksen, M., ., ., & . (2014). Soft engineering versus dynamic approach in coastal dune management: a case study on the North Sea barrier island of Ameland. *J Coast Tes*.

De Vries, S., Southgate, H., Kanning, W., Ranasinghe, R., ., & . (2012). Dune behavior and aeolian transport on decadal timescales. *Coastal Engineering*, 41–53.

De Winter, R., & Ruessink, B. (2017). Sensitivtiy analysis of climate change on dune erosion: cae study for the Dutch Holland Coast. *Climatic Change*, 685-701.

Delgado-Fernandez, I., & Davidson-Arnott, R. (2010). Meso-scale aeolian sediment input to coastal dunes: The nature of aeolian transport events. *Geomorphology*, 217-232.

Elias, E., & Bruens, A. (2013). *Beheerregister Noord-Holland. Feiten & Cijfers ter ondersteuning van de jaarlijkse toetsing van de kustlijn.* Delft: Deltares.

Fabbri, S., Giambastiani, B., Sistilli, F., Scarelli, F., Gabbianelli, G., ., ... (2017). Geomorphological analysis and classification of foredune ridges based on Terrerstrial Laser Scanning (TLS). *Geomorphology*, 436-451.

Hage, P. (2014). *Video monitoring of meso-scale aeolian activity on a narrow beach.* Utrecht Universtiy , Faculty of Geosciences. Utrecht: Utrecht Universtiy.

Hesp, P. (2002). Foredunes and blowouts: initiation, geomorphology and dynamics. *Geomorphology* , 245-268.

HHNK. (2009). *Beleidsregels strandpaviljoens en vergelijkbare objecten (in Dutch).* Juridische zaken. Heerhugowaard: Hoogheemraadschap Hollands Noorderkwartier.

HHNK. (2012). *Een deltavisie van Hollands Noorderkwartier. Basis voor verdere ontwikkeling.* Heerhugowaard: Hoogheemraadschap Hollands Noorderkwartier.

Hoonhout, B., & van Thiel de Vries, J. (2013). *Invloed van strandbebouwing .* Delft: Deltares .

Houser, C., & Ellis, J. (2013). Beach and Dune Interaction. *Treatise on Geomorphology* (pp. 267-288). San Fransico: J.F. Shroder.

Huisman, M. (2013). *De effecten van strandbebouwing op de ontwikkeling van de eerste duinenrij.* Vrije Universiteit Amsterdam / Hoogheemraadschap Hollands Noorderkwartier, Earth Sciences . Amsterdam: VU Amsterdam.
Iversen, J., & Rasmussen, K. (1994). The effect of surface slope on saltation threshold . *Sedimentology* , 721-728.
Jewell, M., Housers, C., & Trimble, S. (2014). Initiation and evolution of blowouts within Padre Island National Seashore, Texas. *Ocean & Coastal Management* , 156-164.
Jungerius, P., Witter, J., & van Boxel, J. (1991). *The effects of changing wind regimes on the development of blowouts in the coastal dunes of the Netherlands.* University of Amsterdam. Landscape and Environmental Research Group.
Keijsers, J. (2015). *Modelling foredune dynamics in response to climate change.* Wageningen: Wageningen University.
Keijsers, J., Poortinga, A., Riksen, M., Maroulis, J., ., ., ... (2014, March 6). *Spatio-Temporal Variability in Accretion and Erosion of Coastal Foredunes in the Netherlands: Regional Climate and Local Topography.* Retrieved June 11, 2017, from PLoS One: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3946338/
Lee, G., Nicholls, R., & Birkemeier, W. (1998). Storm-driven variability of the beachnearshore profi le at Duck, North Carolina. *Marine Geology*, 163-177.
Liu, X. (2008). Airborne LiDAR for DEM generation: some critical issues. *Progress in Physical Geography*, 31-49.
Masselink, G., & Van Heteren, S. (2014). Response of wave-dominated and mixed-energy barriers to storms. *Marine Geology*, 321-347.
MinV&W. (1990). *Kustverdediging na 1990: beleidskeuze voor de kustlijnzorg (1st coastal policy document, in Dutch).* Den Haag, the Netherlands : Ministerie van Verkeer en Waterstaat.
MinV&W. (2000). *3e Kustnota. Traditie, Trends en Toekomst (3rd coastal policy document, in Dutch).* Den Haag, the Netherlands : Ministerie van Verkeer en Waterstaat .
Mitasova, H., Drake, T., Bernstein, D., Harmon, R., ., & . (2004). Quantifying rapid changes in coastal topography using modern mapping techniques and GIS. *Environmental & Engineering Geoscience, 10*(1), 1-11.
Mitasova, H., Hardin, E., Overton, M., Kurum, M., ., ., & . (2010). Geospatial analysis of vulnerable beach-foredune systems. *J Coast Conserv*, 141-161.
Mitasova, H., Hardin, E., Starek, M., ., ., ., & . (2011). *Landscape Dynamics from LiDAR Data time series.* Retrieved from Geomorphometry : http://www.geomorphometry.org/system/files/Mitasova2011geomorphometry.pdf.
Mitasova, H., Overton, M., Recalde, J., Bernstein, D., Freeman, C., ., ... (2009). Raster-based analysis of coastal terrain dynamics from multitemporal lidar data. *Journal of Coastal Research , 25*(2), 207-215.
Nordstrom, K., & Jackson, N. (1993). The role of wind direction in eolian transport on a narrow sandy beach. *Earth Surface Processes and Landforms*, 675-685.
Overton, M., Mitasova, H., Recalde, J., Vanderbeke, N., ., ., & . (2006). Morphological evolution of a shoreline on a decadal time scale. *International Conference on Coastal Engineering* (p. 3851(11)). San Diego, California: McKee Smith, J.
Pot, R. (2011). *System-description Noord-Holland Coast.* Delft University of Technology, Civil Engineering and Geosciences. Delft: Delft University of Technology.
Price, T., van Kuik, N., de Wit, L., António, L., Ruessink, B., ., ... (2017). SHOREWARD PROPAGATING ACCRETIONARY WAVES (SPAWs): OBSERVATIONS FROM A MULTIPLE SANDBAR SYSTEM. *Coastal Dynamics*, 1-9.
Pye, K., & Blott, S. (2008). Decadal-scale variation in dune erosion and accretion rates: An investigation of the significance of changing storm tide frequency and magnitude on the Sefton coast, UK. *Geomorphology*, 652-666.
Ruessink, B., & Jeuken, M. (2002). Dunefoot Dynamics Along the Dutch Coast. *Earth Surface Procceses and Landforms , 27*, 1043-1056.
Ruessink, B., Arens, S., Kuipers, M., Donker, J., ., & . (2017). Coastal dune dynamics in response to excavated fore dune notches . *Aeolian Research*.
Ruig, J., & Hillen, R. (1997). *Developments in Dutch coastline management: conclusions from the second governemental Coastal Report (in Dutch).*
RWS. (2016). *Kustlijnkaarten 2007-2016 (in Dutch).* Den Haag: Rijkswaterstaat.
Sallenger, J. (2000). Storm Impact Scale for Barrier Islands. *Journal of Coastal Research* , 890-895.
Saye, S., Van der Wal, D., Pye, K., Blott, S., ., & . (2005). Beach-dune morphological relationships and erosion/accretion: An investigation af five sites in England and Wales using LiDAR data. *Geomorphology*, 128-155.
Sherman, D., & Bauer, B. (1993). Dynamics of Beach-Dune Systems . 413-447.
Smit, Y., Ruessink, G., Brakenhoff, L. B., Donker, J. J., ., & . (2017, July 10). Measuring spatial and temporal variation in surface moisture on a coastal beach with a near-infrared terrestial laser scanner. *Aeolian Research*.
Suarez, S., Cariolet, J., Cancouët, Ardhuin, F., Delacourt, C., ., ... (2012). Dune recovery after storm erosion on a high-energy beach: Vougot Beach, Britanny (France). *Geomorphology*, 16-33.
Van Boxel, J., Jungerius, P., Kieffer, N., Hampele, N., ., & . (1997). Ecological effects of reactivation of artificially stabilized blowouts in coastal dunes. *Journal of Coastal Conservation*, 57-62.
Van de Graaff, J. (2002). Coastal protection, structures and (sea)dikes. In J. van de Graaff, J. Chen, D. Eisma, K. Hotta, & H. Walker, *Engineered Coasts.* Kluwer Academic Publishers.
Van der Meulen, M., Van der Spek, A., De Lange, G., ., ., & . (2007). Regional sediment deficits in the dutch lowlads: implications for long-term land-use options. *Journal of Soil Sediments*, 9-16.
Van der Wal, D. (1998). Effects of fetch and surface texture on aeolian sand transport. *Journal of Arid Environments*, 533-547.
Van der Wal, D. (2004). Beach-dune interactions in nourishment areas along the Dutch coast. *Journal of Coastal Research, 20*, 317-325.

Van der Zon, N. (2013). *Kwaliteitsdocument AHN2.* AHN.
Van Dijk, P., Arens, S., & Van Boxel, J. (1999). AEOLIAN PROCESSES ACROSS TRANSVERSE DUNES. II: MODELLING THE SEDIMENT TRANSPORT AND PROFILE DEVELOPMENT. *Earth Surface Processes and Landforms*, 319-333 .
Van Koningsveld, M., & Mulder, J. (2004). Sustainable coastal policy developments in the Netherlands. A systematic approach revealed. *Journal of Coastal Research*, 375.
Van Rijn, L. (2007). United view of sediment transport by currents and waves . *Journal of Hydraulic Engineering, 133*(6), 649-667.
Wijnberg, K. (2002). Environmental controls on decadal morphologic behaviour of the Holland coast. 227-247.
Wijnberg, K., & Terwindt, J. (1994). Extracting decadal morphological behaviour from high-resolution long-term bathymetric surveys along the Holland coast using eigenfunction analysis. *Marine Geology*, 301-330.
Xu, L., Ivanov, P., Hu, K., Chen, Z., Carbone, A., Stanley, H., ... (2005). Quantifying signals with power-law correlations: A comparative study of detrended fluctuations analysis and detrended moving average techniques. *Physical Review*, 1-13.

Appendix A.

Table 1. Zonation

Kop van NH				**(27,86 - 45,40 km)**
HPSD	**HPSD-N**	HPSD-N	**Short description:** Between 2014 and 2015 the sea defense was reinforced with a mega nourishment and the realization of the Hondsbossche Dunes took place **Foredune management strategy:** Parabolic and carved.	**(26,67 - 27,86 km)**
	HPSD-C	HPSD-C	**Short description:** Between 2014 and 2015 the sea defense was reinforced with a mega nourishment and the realization of the Hondsbossche Dunes took place **Foredune management strategy:** Parabolic and carved.	**(17,51 - 26,67 km)**
	HPSD-S	HPSD-S	**Short description:** Region south of the HSPD. **Foredune management strategy:** Parabolic and carved.	**(15,93 - 17,51 km)**
Castricum- HPSD	BN-Natural	Bergen-N2	**Short description:** Generally natural, but with one construction. **Constructions:** Yes, seasonal and year-round. **Constructions density:** 0,0 m2/m2. **Blow-outs:** Yes, 3 significant blow-outs.. **Foredune management strategy:** Parabolic and carved.	**(15,93 -20,04 km)**
	Bergen	Bergen-SN	**Short description:** Region north of Bergen Boulevard with seasonal constructions for recreation and one year-round pavilion. **Constructions:** Yes, seasonal and year-round. **Constructions density:** 1,08 m2/m **Blow-outs:** Yes, 4 blowouts.. **Foredune management strategy:** Fixation of foredune volumes.	**(15,28 - 15,93 km)**
		Bergen-C	**Short description:** Region at the boulevard of Bergen with year-round and seasonal constructions for recreation. **Constructions:** Yes, seasonal. **Constructions density:** 3,16 m2/m. **Blow-outs:** No. **Foredune management strategy:** Fixation of foredune volumes.	**(14,24 - 15,28 km)**

	Bergen-SS	**Short description:** Region south of Bergen with seasonal constructions for recreation. **Constructions:** Yes, seasonal. **Constructions density:** 10,37 m2/m. **Blow-outs:** Yes, four significant blowouts. **Foredune management strategy:** Fixation of foredune volumes.	**(13,76 - 14,24 km)**
BS-Natural	Bergen-N1	**Short description**: Natural area of the Dutch North Holland Coast. **Constructions:** No, natural area. **Constructions density**: - **Blow-outs:** Yes, 6 significant blowouts. **Foredune management strategy:** Parabolic.	**(12,86 - 13,76 km)**
EN-Natural	Egmond-N2	**Short description:** Generally natural, but with some constructions. **Constructions:** Yes, seasonal and year-round. **Constructions density:** 0,0 m2/m2. **Blow-outs:** Yes, 8. **Foredune management strategy:** Parabolic and fixation of foredune volumes. .	**(11,46 - 12,86 km)**
Egmond	Egmond-SN	**Short description:** Region north of Egmond with seasonal constructions for recreation. **Constructions:** Yes, seasonal and year-round. **Constructions density:** 13,64 m2/m **Blow-outs:** No. **Foredune management strategy:** Fixation of foredune volumes.	**(10,69 - 11,46 km)**
	Egmond-C	**Short description:** Region at the boulevard of Egmond with year-round and seasonal constructions for recreation. **Constructions:** Yes, seasonal. **Constructions density:** 5,16 m2/m. **Blow-outs:** No. **Foredune management strategy:** Fixation of foredune volumes.	**(9,29 - 10,69 km)**
	Egmond-SS	**Short description:** Region south of Egmond with seasonal constructions for recreation. **Constructions:** Yes, seasonal. **Constructions density:** 10,37 m2/m. **Blow-outs:** Yes, four significant blowouts. **Foredune management strategy:** Fixation of foredune volumes.	**(8,33 - 9,29 km)**

Region	Section	Description	Range
ES-Natural	Egmond-N1	**Short description:** Generally natural. **Constructions:** Yes, one year-round. **Constructions density:** only one pavilion. **Blow-outs:** Yes, four significant blowouts. **Foredune management strategy:** Parabolic.	**(5,84 - 8,33 km)**
CN-Natural	Castricum-N2	**Short description:** Generally natural, but with some constructions. **Constructions:** Yes, seasonal and year-round. **Constructions density:** 0,63 m2/m (very local). **Blow-outs:** No. **Foredune management strategy:** Fixation of foredune volumes.	**(3,66 - 5,84 km)**
Castricum	Castricum-SN	**Short description:** Region north Castricum with seasonal constructions for recreation. **Constructions:** Yes, seasonal and year-round. **Constructions density:** 12,27 m2/m **Blow-outs:** No. **Foredune management strategy:** Fixation of foredune volumes.	**(3,22 - 3,66 km)**
	Castricum-C	**Short description:** Region at Castricum with seasonal and year-round constructions for recreation. **Constructions:** Yes, seasonal and year-round. **Constructions density:** 13,50 m2/m **Blow-outs:** No. **Foredune management strategy:** Fixation of foredune volumes.	**(2,92 - 3,22 km)**
	Castricum-SS	**Short description:** Region south of Castricum with seasonal constructions for recreation. **Constructions:** Yes, seasonal. **Constructions density:** 9,85 m2/m **Blow-outs:** No. **Foredune management strategy:** Fixation of foredune volumes.	**(2,55 - 2,92 km)**
CS-Natural	Castricum-N1	**Short description**: Natural area of the Dutch North Holland Coast. **Constructions:** No, natural area. **Constructions density**: - **Blow-outs:** Yes, 3 significant blowouts. **Foredune management strategy:** Carved.	**(0 - 2,55 km)**